Prompt neutrinos from the atmosphere to the forward region of LHC

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

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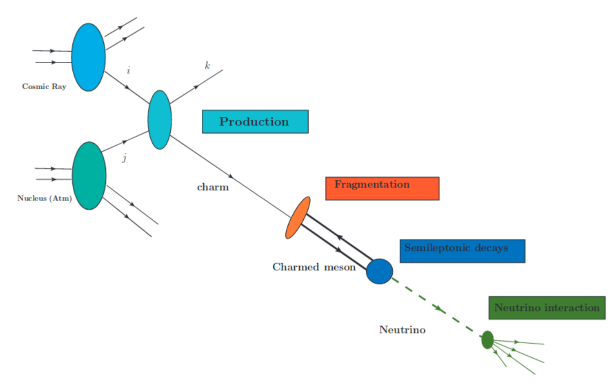
Underlying concept: prompt ν production



from V. Goncalves et al. [arXiv:2103.05503]

$*$ The mechanisms for prompt ν production in the atmosphere (above) is the same as for LHC collisions, except that the latter are induced by *pp* interactions instead of CR + Air (that we in any case approximate as superposition of *pA*, in turn approximated in terms of *pp* and *pn*).

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:

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

$*$ prompt neutrino flux:

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

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

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

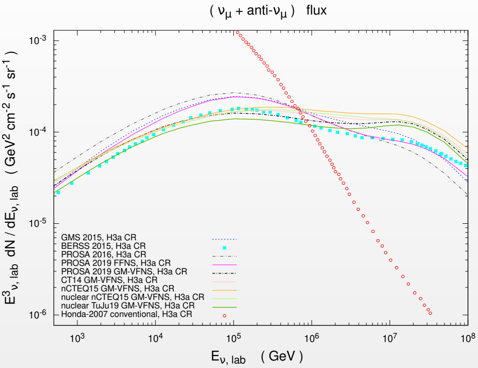
$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm},$ with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \mathrm{X}$

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.

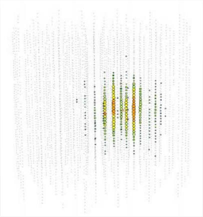
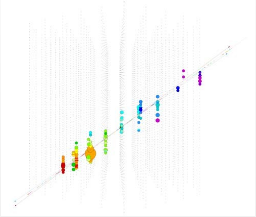
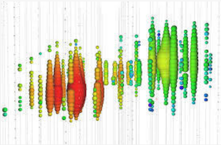
$(\nu_\mu + \bar{\nu}_\mu)$ atmospheric fluxes: conventional $\rightarrow$ prompt transition



* 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 $E_\nu \sim (6-9) \cdot 10^5$ GeV.
* Transition prompt conventional absent at colliders

Experiments for detecting high -energy neutrinos

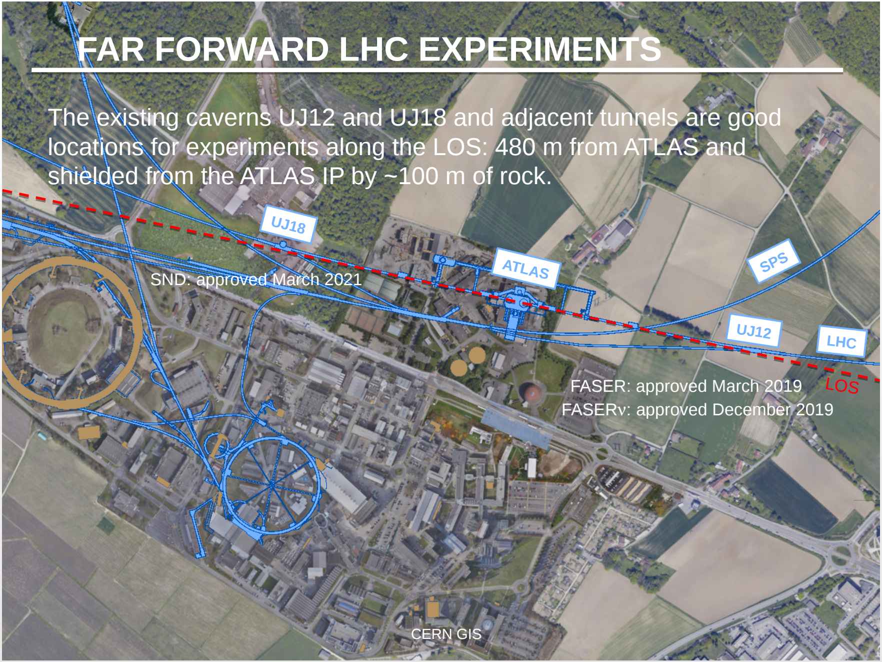
∗ Atmospheric neutrinos at ANTARES, IceCube, KM3NeT, Baikal-GVD...
track / shower events from CC and NC ν induced DIS in ice/water.

∗ LHC neutrinos at SND@LHC and Faserν, also sensitive to CC and NC ν induced DIS, but in heavier target (emulsion)

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.



Particle Fluxes at far-forward LHC experiments

∗ Not all kinds of particles produced in the forward region of the LHC IP can be seen at the location of the experiments: LHC optical elements and rock are on the way.

∗ Among the particles produced at the IP or nearby, forward ν, μ and some kinds of BSM particles will reach the detectors.

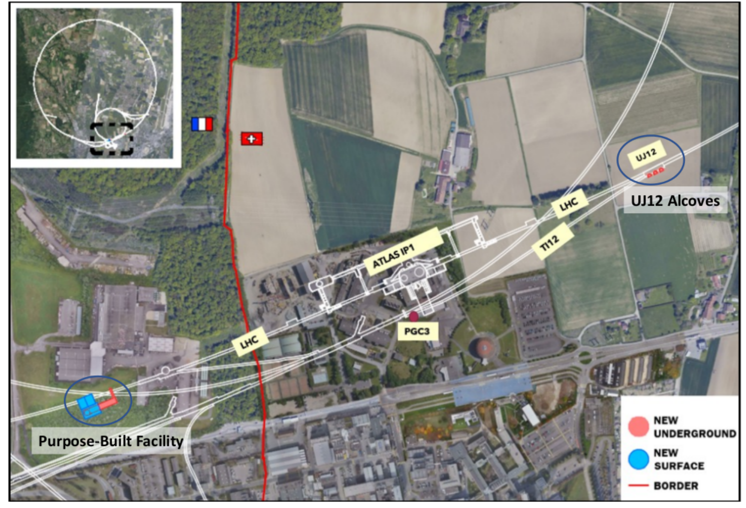
∗ ν forward fluxes: intense and very energetic, with $\mathcal{O}$(TeV) particles (peak in the energy spectrum much larger than for fluxes seen in other accelerator neutrino experiments, like e.g. DUNE).

∗ ν: search complementary to searches at ATLAS/CMS/LHCb for which ν are just "missing energy".

∗ BSM LLPs: searches in the low mass / large $c\tau^0$ domain, complementary to searches at ATLAS/CMS/LHCb for which LLPs decaying beyond the spatial limits of the detector infrastructure are "missing energy".

∗ Present far-forward experiments limitations: limited size.

Possibilities for a FPF at the LHC



- dedicated facility
- enlargement of one of the existing caverns with alcoves

QCD opportunities with forward neutrinos during the HL-LHC phase

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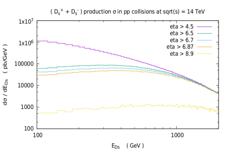
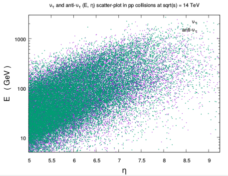
New facility: Forward Physics Facility @ CERN capable of hosting a suite of experiments exploiting forward neutrinos produced at one of the LHC interaction points and propagating for several hundred meters in the direction tangent to the accelerator arc

New pilot experiments:
Faser2, Faser-ν, SND@LHC, MilliQan

Physics Opportunities:
* Proton Parton Distribution Functions
* Nuclear Parton Distribution Functions
* NP QCD and Tuning of Monte Carlo event generators
* Forward charged pions and kaons
* Forward heavy-flavoured hadrons



Forward heavy-flavour
* NP effects in heavy-flavour production
* Interplay with perturbative effects
* Universality of FF
* Intrinsic heavy-flavour and higher-twist



Open questions:
* how to disentangle SM and BSM effects ?
* how to measure forward lepton fluxes and disentangle them from cross-sections ?

See also W. Bai, M. Diwan, M.V. Garzelli, Y.-S. Jeong, M.H. Reno, *"Far-forward neutrinos at the LHC"*, hep-ph/2002.03012, JHEP **2006** (2020) 032.

Proton Parton Distribution Functions
* Low x ($x < 10^{-6}$) gluon at $Q^2 > 1$ GeV^2 not probed by other experiments so far!

Nuclear Parton Distribution Functions
* Measurements of CC and NC ν - *A* and $\bar{\nu}$ - *A* DIS cross-sections using various targets
* *u* and *d* quark flavour separation
* DIsentangling strange sea asymmetries
* Complementary to EIC *e-A* scattering studies

NP QCD and Tuning of MC event generators
* New data for testing the robustness of phenomenological models describing NP physics in MC (e.g. NP MPI, beam remnant effects, hadronization, branching fractions) and tuning their parameters.

Forward charged pions and kaons
* NP effects in light-flavour production
* Cosmic Ray EAS applications

Work supported by BMBF contract O5H18GUCC1

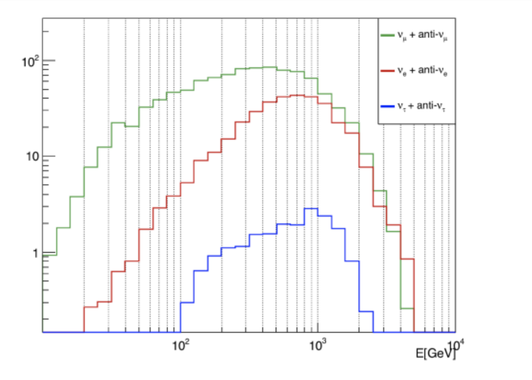
For further info:
* 2nd Forward Physics Facility Meeting online – 27 – 28 May 2021
https://indico.cern.ch/event/1022352 !Registration open!
* Forward Physics Facility Kick-off meeting – 9 – 10 Nov 2020

presented at the APS Meeting "Quarks to Cosmos", April 2021

How to disentangle particle fluxes from particle cross-sections ?

- ∗ The detectors will measure observables from the **convolution** of **fluxes** (production + propagation) and **interaction** σ with target.
- ∗ Capability to distinguish might be more important for SM precision constraints than for BSM searches...
- ∗ For example, SM objectives of the LHC ν experiments may include:
  - Constraining forward particle production in *pp* collisions (of interest for better modelling soft physics and tuning the related parameters in MC event generators): it works well under the assumption: *"we precisely know neutrino cross-sections"*.
  - Constraining PDFs/nPDFs through neutrino DIS with target in detector (of interest for SM and BSM programs at HL-LHC and for atmospheric prompt neutrinos): it works under the assumption: *"we precisely know neutrino fluxes"*.

MC predictions of energy distributions of CC DIS ($\nu + \bar{\nu}$)-induced events



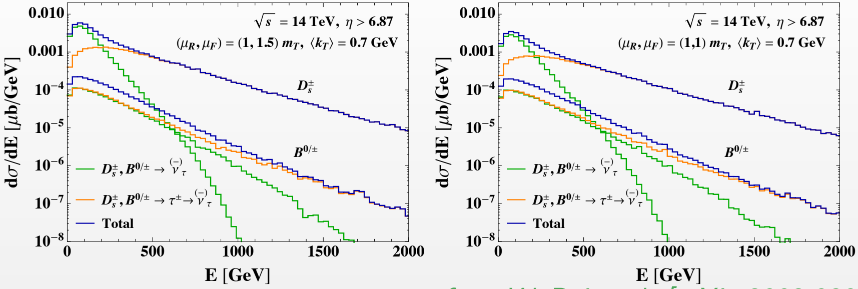
from SND@LHC technical proposal (2021)

∗ Energy spectra of the different kinds of CC DIS interacting neutrinos. The normalisation corresponds to $L_{int} = 150$ fb^{-1} and 830 Kg of Tungsten.

∗ No conventional to prompt neutrino transition in the energy spectra for ν-events at colliders (π, K, D all decay in the vacuum).

∗ No conventional contribution to ν_τ in both cases.

Energy distribution of forward $\nu_\tau + \bar{\nu}_\tau$



,

from W. Bai et al. [arXiv:2002.03012]

* direct decay and chain decay contribute to the total in different energy regions
* contributions from B meson decays are one-two order of magnitude smaller than those from D mesons.
* What are the dominant uncertainties on these distributions ?

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:

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

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

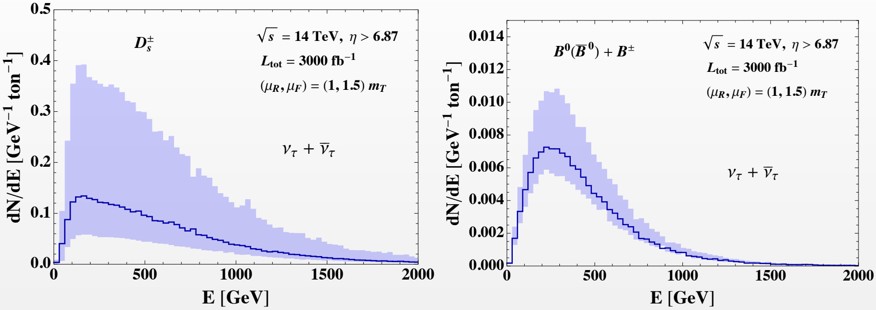
μ_F, μ_R reabsorb IR and UV divergences,

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.

Energy distribution of CC $(\nu_\tau + \bar{\nu}_\tau)$ events



,

from W. Bai et al. [arXiv:2002.03012]

∗ Huge uncertainty band from state-of-the-art QCD calculations.

∗ Missing higher-order pQCD contributions are probably large.

∗ In case of bottom production, uncertainty is smaller (+60%, -20%) than for charm (+300%, -60%) in relation to the fact that $m_b > m_c$ $\Rightarrow \alpha_S(\mu_R = m_b) < \alpha_S(\mu_R = m_c)$.

e ∗ Additional uncertainties due to focus in forward region.

ν fluxes in the atmosphere vs. LHC

$*$ production mechanisms: the same as at the LHC, complicated by the presence of nuclear effects in pO collisions in the atmosphere.

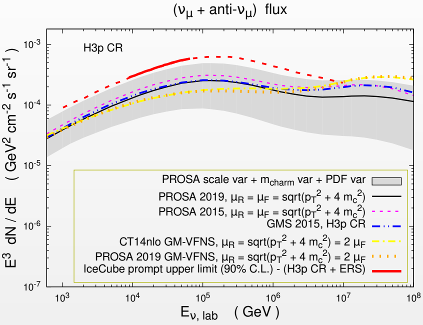
$*$ E_ν energy range: higher, because the most energetic CR interact with the atmosphere at $\sqrt{s_{NN,CR}} \sim 300$ TeV, whereas $\sqrt{s_{NN,LHC}} = 13$ - 14 TeV,

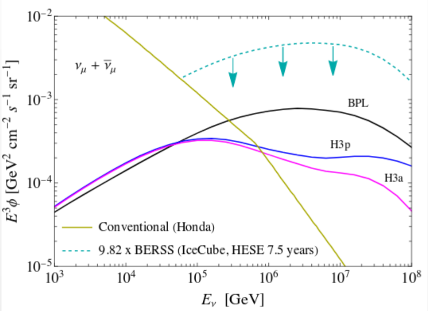
$*$ Rapidity coverage probed: wider in the atmosphere, than in far-forward ν experiments at the LHC ($\eta_\nu > 7$)

$\Rightarrow$ Importance of very forward physics aspects is enhanced in collider studies with forward experiments, w.r.t. neutrino telescopes.

$*$ Complication at LHC: geometry of the line beam affects ν_e and ν_μ fluxes. ν_τ unaffected, like in the atmosphere.

Prompt ν fluxes: uncertainties and IceCube upper limits

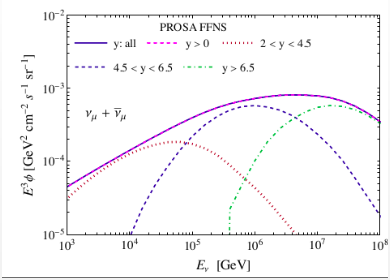


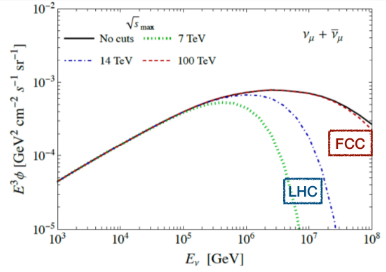


* Theory uncertainties on prompt ν are large (due not only to QCD, but also to CR composition)

* IceCube has put some constraints on prompt neutrinos.

Prompt ν fluxes and LHC phase-space coverage



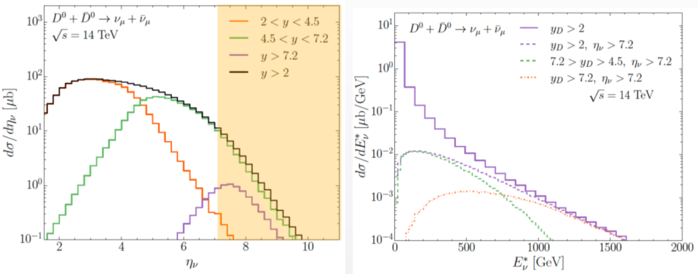


∗ To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4 < y_c < 7$.

∗ The $\sqrt{s} = 14$ TeV at LHC is in any case a limitation, FCC would be better (see also analysis in V. Goncalves et al, [arXiv:1708.03775]).

∗ Neutrinos detected in far-forward experiments at LHC give us any useful information ? ⇒ Explore the connection between (E_ν, y_ν) and y_c.

Prompt ν fluxes at the LHC

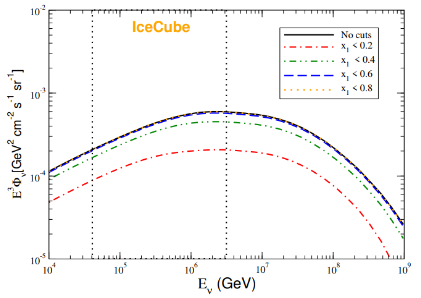


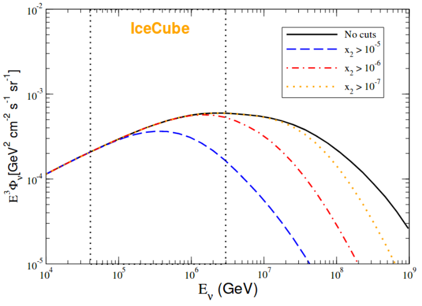
* At the LHC, charmed mesons with $4 < y_c < 7$ give rise to neutrino populating a wide rapidity spectrum, with a maximum around $\eta_\nu \sim 5$.

* These neutrinos constitutes the majority of neutrinos for $\eta_\nu \gtrsim 7.2$ (region probed by SND@LHC, and at future FPF).

* The energy spectrum of these neutrinos is peaked at $\sim$ 100 GeV in CM frame, but extends also to the TeV. For $E_\nu \sim$ 700 GeV half neutrinos at the LHC come from charm with $4.5 < y_c < 7.2$, whereas another half come from charm with $y_c > 7.2$. On the other hand, most energetic neutrinos at the LHC come from charmed mesons with higher rapidities.

Prompt ν fluxes and large-x PDFs





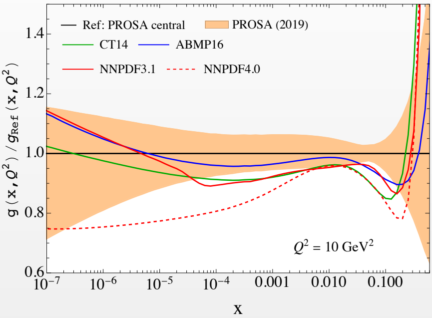
, *from V. Goncalves et al. [arXiv:1708.03775]*

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

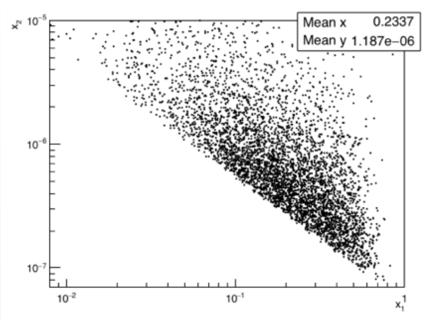
∗ Region particularly relevant: $0.2 < x < 0.8$, partly testable through ν experiments at the LHC.

∗ On the other hand, for ν at the PeV scale, knowledge of PDF down to $x > 10^{-6}$ is enough.

PDFs uncertainties at low and large-x and x coverage of forward ν LHC exp.



W. Bai et al., [arXiv:2212.07865]



SND@LHC technical proposal (2021)

∗ Differences in gluon PDFs at large x are not covered by the uncertainties associated to each single PDF set.

∗ The coverage of forward ν experiments can help constraining PDFs at extreme x-values, actually more extreme than what is needed for atmospheric prompt ν at the PeV scale.

Conclusions

∗ There is some kinematical overlap between the charm hadron production region explorable in far-forward experiments at the LHC and the one explorable in VLVνT's.

∗ Atmospheric ν's with $E_{\nu,LAB} \sim \mathcal{O}(\text{PeV})$ mostly come from charm produced within LHC $\sqrt{s}$ in the rapidity range $4.5 < y_c < 7.2$, which in turn produce neutrinos even in the ν rapidity range of the SND@LHC detector $\eta_\nu > 7.2$ and future (like FPF).

∗ If one builds a detector (ADV-SND@LHC ?) in the range $4 < \eta_\nu < 6$:

- even better connection with LHC data (crucial for QCD people to better understand the interplay between perturbative and non-perturbative QCD effects)
- best overlap for the present region of interest for prompt ν fluxes