

# Snowmass2021 - Letter of Interest

## *Far-forward neutrinos at the LHC and QCD*

### Thematic Areas:

- ☐ (EF1) EW Physics: Higgs Boson properties and couplings
- ☐ (EF2) EW Physics: Higgs Boson as a portal to new physics
- ☒ (EF3) EW Physics: Heavy flavor and top quark physics
- ☐ (EF4) EW Physics: EW Precision Physics and constraining new physics
- ☐ (EF5) QCD and strong interactions: Precision QCD
- ☒ (EF6) QCD and strong interactions: Hadronic structure and forward QCD
- ☐ (EF7) QCD and strong interactions: Heavy Ions
- ☐ (EF8) BSM: Model specific explorations
- ☐ (EF9) BSM: More general explorations
- ☐ (EF10) BSM: Dark Matter at colliders
- ☒ (CF7) Cosmic probes of fundamental physics

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### Abstract: (maximum 200 words)

Tau neutrino fluxes in the far-forward region of the LHC come from heavy-flavor decays, dominated by  $D_s$  decays and the decays of  $\tau$ 's in  $D_s \rightarrow \tau \nu_\tau$ . Theoretical predictions for tau neutrino fluxes at high rapidity and at high energy probe QCD dynamics of heavy-flavor production in kinematic regions where measurements have not yet been made. We will investigate uncertainties in the theory predictions for forward  $\nu_\tau + \bar{\nu}_\tau$  fluxes that come from parton distribution functions, fragmentation functions, missing higher-order contributions in the pQCD calculation of the partonic cross-sections, intrinsic transverse momentum, and other effects. We will determine the potential of experimental measurements of LHCb and more forward rapidity measurements to constrain the parton distribution function fits. Furthermore, narrowing the theoretical uncertainty in predictions of forward charm production will have implications for the theoretical determination of the prompt atmospheric neutrino flux, a background to measurements of the high-energy diffuse astrophysical flux from the highest-energy cosmic accelerators.

## Far-forward Neutrinos at the LHC and QCD

The far-forward region at the Large Hadron Collider (LHC) is a complementary region to the central and forward regions covered by the ATLAS, CMS and LHCb experiments. Particle detection in the far-forward region will probe fundamental QCD and physics beyond the standard model (BSM). Interesting messengers of far-forward physics are neutrinos<sup>1-3</sup>. Several experiments for the far-forward region at the LHC are under design or already in preparation. These experiments: Faser- $\nu$ <sup>4,5</sup> (related to the Faser<sup>6,7</sup> effort), XSEN<sup>8,9</sup> and SND@LHC<sup>11</sup>, for example, have the potential to measure neutrinos that come from high-energy collisions at the LHC, extracted along the direction tangent to the beam line. In some cases, data-taking is already planned for Run 3.

Neutrinos are produced directly by  $W$  and  $Z$  boson decays, and by light- and heavy-hadron decays. It has been shown with a Pythia8.2 evaluation<sup>9</sup> that for pseudorapidities larger than  $|\eta| > 6.7$ , heavy flavor significantly dominates over  $W$  and  $Z$  boson production of neutrinos. In particular,  $D_s$  and  $B$ -meson decays are essentially the only sources of  $\nu_\tau$  for such large  $|\eta|$  values. Thus, measurements of  $\nu_\tau$  events will probe heavy-flavor production in kinematic regimes in which no measurements have been made.

Measurements of neutrino fluxes in the far-forward region will yield a better understanding of forward heavy-flavor production in  $pp$  collisions, useful to understand QCD dynamics and non-perturbative aspects, particularly as they influence the low transverse momentum and large rapidity distributions of the heavy hadrons<sup>10</sup>. Parton distribution functions will be probed in both small and large longitudinal momentum fraction  $x$  regimes. New measurements of forward neutrino fluxes will ultimately help to better understand  $\nu$ -induced deep-inelastic scattering, both in inclusive and heavy flavor production. Furthermore, detailed studies and data analyses will require and lead to new tunes of Monte Carlo codes that will be useful for many other collider studies.

In this regime, with neutrino energies up to multiple-TeV, BSM physics can be probed. One example is active neutrino oscillations into a fourth sterile neutrino species. Accurate predictions for the neutrino fluxes are needed to untangle BSM effects. Neutrinos are also a potential background to other BSM particles, for example, light long-lived exotic particles, as e.g. discussed in ref. 12.

We plan to focus our study on providing accurate theory predictions for forward neutrino fluxes from heavy-flavor decays. This builds on our work reported in ref. 10. Using as a core of our calculation hard-scattering amplitudes for heavy-quark production including next-to-leading order radiative corrections<sup>13,14</sup>, we investigated the impact on the neutrino flux of the renormalization and factorization scale choices, and of non-perturbative transverse momentum smearing effects, constrained by LHCb data on  $D_s$  production in the  $2 < y < 4.5$  rapidity range.

Figure 1 shows the large uncertainty range associated with renormalization and factorization scale ( $\mu_R, \mu_F$ ) variations around a central scale choice

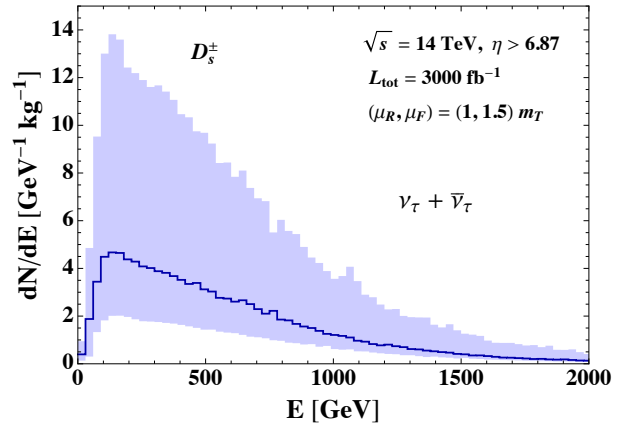


Figure 1: The neutrino energy distribution of  $\nu_\tau$  charged-current deep-inelastic scattering events per kg of lead, induced by neutrinos with  $\eta > 6.87$  from the decay of  $D_s^\pm$  produced in  $pp$  collisions at  $\sqrt{s} = 14$  TeV, for an integrated luminosity  $\mathcal{L} = 3000 \text{ fb}^{-1}$ . The shaded band shows the uncertainty associated with a 7-point scale variation around the central scale choice of  $(\mu_R, \mu_F) = (1, 1.5)m_T$ .

that depends on the transverse mass  $m_T$ ,  $(\mu_R, \mu_F) = (1, 1.5)m_T$  for the number of forward  $\nu_\tau$  events from  $D_s^\pm$  production in  $pp$  collisions at  $\sqrt{s} = 14$  TeV. The scale variation band is taken over a seven-point set of scales that are factors of 0.5 and 2 of the central scale choice.

The large scale uncertainty in the theoretical prediction is one of several. Beside the uncertainty related to missing perturbative contributions of higher-order, we will assess the uncertainties associated with a number of ingredients to the prediction: parton distribution functions, fragmentation functions, intrinsic transverse momentum, multiple parton interactions and the potential role of intrinsic charm. An intermediate step to this program is to study the potential of experimental measurements of LHCb and more forward rapidity measurements to constrain new parton distribution function fits, for fixed fragmentation function inputs. Our theoretical effort, in a different energy regime, is also relevant to make predictions for the DsTau (NA65) experiment.<sup>15</sup> This experiment is designed to detect  $D_s \rightarrow \tau \nu_\tau$  with emulsion detectors, where  $D_s^\pm$  are produced by a 400 GeV proton beam incident on a tungsten or molybdenum target.

A more complete understanding of forward production of charm hadrons and their decays to neutrinos will have implications for theoretical predictions of the prompt atmospheric neutrino flux.<sup>16–20</sup> Hadrons produced by high-energy cosmic ray interactions with air nuclei decay or re-interact in the atmosphere. The very short lifetimes of charm hadrons relative to pions and kaons allow the prompt neutrinos from charm to dominate the atmospheric neutrino flux at neutrino energies above  $\sim 10^5 - 10^6$  GeV. Theoretical uncertainties in the prompt neutrino flux impact background evaluations for measurements, for example by the IceCube Neutrino Observatory<sup>21;22</sup>, of the diffuse neutrino flux produced in the highest energy cosmic accelerators.

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