Addendum to the AdvancedSND LoI

Over the six months since the submission of the AdvSND LoI [1], the Collaboration has been intensively discussing with the CERN civil engineering team and the High Luminosity LHC (HL LHC) planning officers to fully understand the constraints related to the civil engineering modifications required for TI18. These modifications are necessary to optimize the physics performance of the AdvSND detector and profit of the LHC High-luminosity.

Through these discussions, it became evident that the excavation of the TI18 floor must be limited to comply with specific boundaries. Exceeding these boundaries could compromise the tunnel's structural stability, necessitating extensive excavation to restore the integrity of the concrete structures. Additionally, substantial temporary mechanical reinforcements would be required to ensure stability during construction. Addressing these structural stability concerns would make it impossible to meet the schedule constraints of the HL LHC.

Given these constraints, the following decisions and modifications have been made compared to the original Letter of Intent. This document outlines these changes in detail:

- **Compact configuration:** The "baseline" configuration cannot be implemented and we adopt a modified version of the "minimal" configuration, named "compact" hereafter. The key changes include moving the whole detector upwards by 10 cm, shortening the target and decreasing the active cross-section of the HCAL to 40×40 cm^2.

- **Muon momentum and charge measurement:** To maintain similar muon momentum resolution and charge identification performance as the baseline configuration in the LoI, we propose using the available silicon modules from the CMS TOB to equip the magnetized HCAL. The silicon strips provide a resolution of about 30 μm, compared to the 150 μm of the wire chambers, thereby recovering the expected performance of the momentum resolution.

- **Shortening the neutrino target:** The length of the neutrino target has been reduced to stay within the structural safety limits for excavation. The total mass of the tungsten (W) target will be about 1.3 tons, which is 60% larger than the one used in Run 3.

- **Physics advances:** theoretical developments suggest the use of separate pseudorapidity intervals to effectively constrain charm production, potentially improving our systematic error.

The adoption of a detector setup where high-resolution trackers are integrated in the calorimeter to also measure muon momentum brings the developments proposed for AdvSND close to the current concept of the neutrino detector for the SHiP experiment. Although the neutrino energy is very different at the HL LHC and at the SPS, the background muon rate is expected to be similar and the experience that will be gained from the SND@LHC upgrade with silicon tracking stations and a magnetized hadronic calorimeter will be invaluable for SHiP. Most of the manpower that is involved in designing, building and operating the SND@LHC upgrade are also members of the SHiP Collaboration. Their work will be a direct contribution to a central part of the SHiP detector.

Optimisation of the detector configuration in TI18

Preliminary studies indicated that the amount of concrete waste generated from the civil engineering work would be approximately 130 m^3 for the "baseline" configuration and 40 m^3 for the "minimal" configuration. In both scenarios, the majority of the excavation is necessary not for accommodating the detector but for reinforcing the tunnel's concrete structure to prevent any weakening.

A critical factor is ensuring a solid concrete slab 30 cm thick at the base of the tunnel to prevent potential structural deformations or damage. In order to comply with these constraints a compact configuration was proposed, and it is illustrated in Figure 1.

Besides the civil engineering constraints outlined above, the optimization of the detector layout was inspired by the idea to preserve a wide angular (pseudo-rapidity) range in the acceptance to the neutrino flux and a wide azimuthal coverage which ensures a statistically rich sample. A wide η coverage is guaranteed by the transverse size of the neutrino target, i.e. 40×40 cm^2. The azimuthal coverage is granted by ensuring that the detector, although off-axis, contains the beam spot in its acceptance. This is shown in Figure 2 where the relative position of the detector with respect to the neutrino beam is shown for the different possible crossing angle configurations of the proton beams: Run 4 and 5 show a very large azimuthal acceptance while only Run 6 shows a significant reduction. This is due to the need to move the whole detector 10 cm upward. The ensuing reduction on the overall integrated statistics is roughly 40% in the assumption that the three configurations will be equally populated in terms of integrated luminosity. Nevertheless, while the Run 4 configuration is already defined, the implementation of the changes in the crossing angles for the other Runs is subject to further studies. Moreover, as it will be outlined in the following sections, the current structure of the magnetised calorimeter allows studying a large fraction of events originating therein, thus making the overall available statistics essentially equal to the LoI. Finally, it is worth noting that the overall increase of statistics with respect to the Run 3 configuration is huge, amounting to a factor of 100.

The other parameters considered in the optimisation process were:

- The transverse size of the HCAL was reduced, by employing the same transverse size of the target for the sensitive layers. This choice has in turn the benefit to make the stations more compact, with a thickness of 8 mm as in the target, thus shortening the length of the HCAL by about 20 cm.
- The coil was placed in the horizontal plane rather than in the vertical one, in order to save 10 cm vertically.
- The overall length of the detector was shortened by reducing the gap between the target and the HCAL, given that the two volumes will be cooled by the same box, unlike the setup outlined in the LoI where cooling was only needed for the target. The curvature radius of the coil was also optimised.
- The overall magnetised iron length of HCAL was preserved in order to keep the performance in terms of muon momentum resolution and ensure at least 10 interaction lengths for the hadronic calorimeter.

- Finally, the target was shortened from 100 to 58 layers to fit into the available space.

The impact of the new design to the current infrastructure in the TI18 tunnel has been studied and it is reported in a dedicated EDMS document [2]. In this document the reduced excavation work is described together with envisaged solutions for the transportation of CE tools and detector components and the first version of the schedule of the operations. It emerges that the civil engineering work is compatible with the LS3 activities as the work can be done in parallel to the tunnel excavation work for the HL upgrade. Based on this document, an external consultant has been contacted to provide the cost estimate which will be delivered in the coming months. This estimate requires the measurement in situ of the concrete thickness which will be performed during the next YETS.

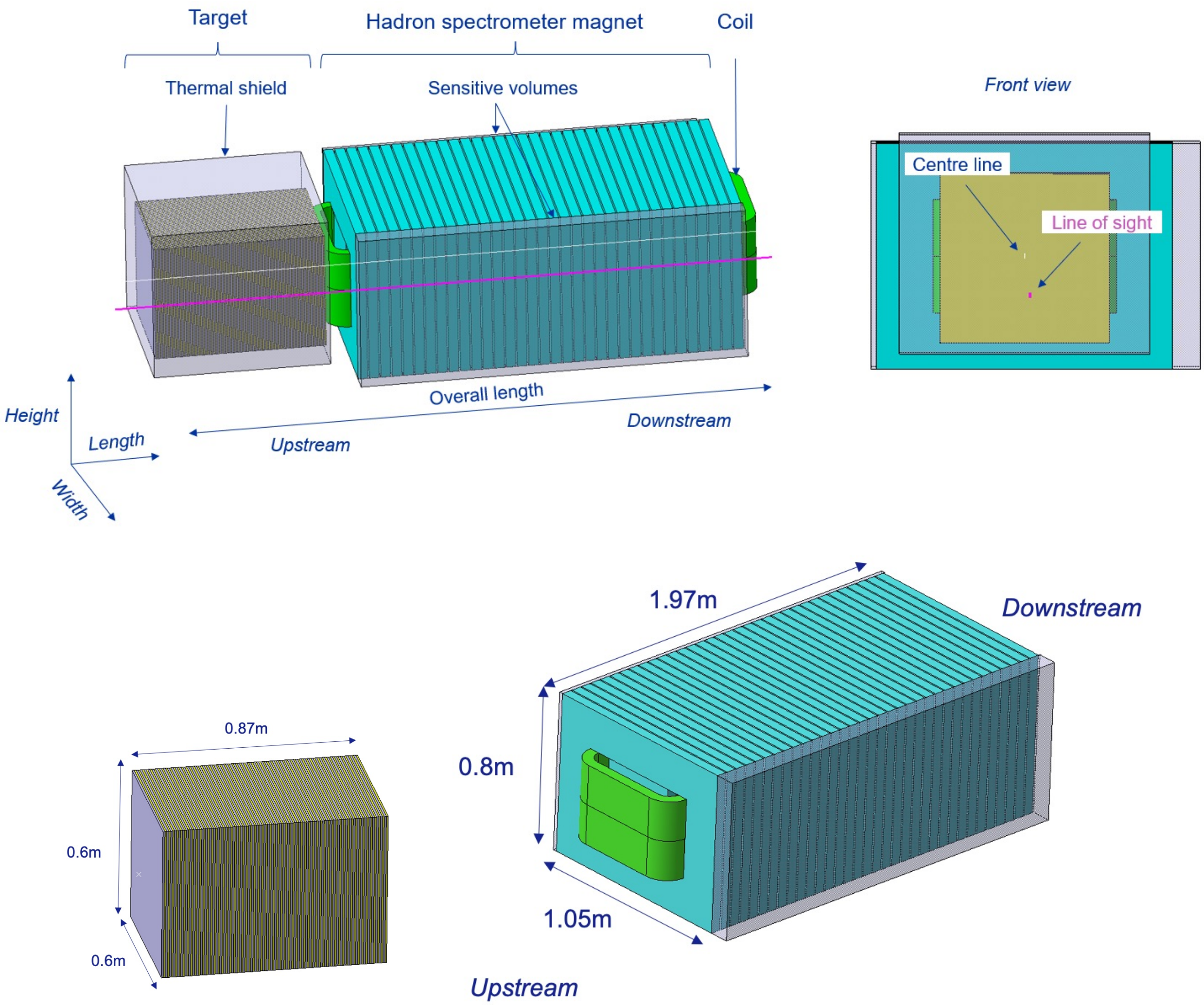

Figure 1: Compact configuration

Figure 2 shows the cross-section of the target superimposed on the expected line of sight and the neutrino fluxes depending on the beams' crossing angles in ATLAS, as foreseen by the current Hi-Lumi-LHC plans. The design of the new space in TI18 to host the detector is illustrated in Figure 3 which shows the integration of the compact configuration with

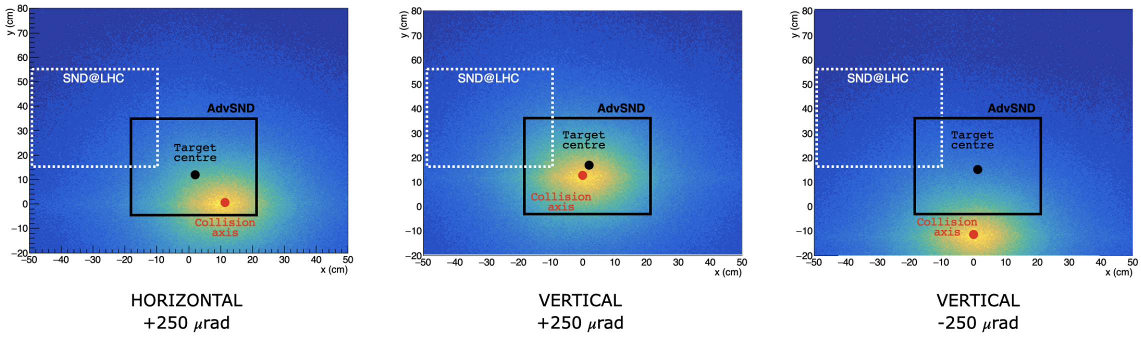

Figure 2: The cross section of the proposed AdvSND target position is superimposed to the expected neutrino fluxes for the different crossing angle configurations (for Run4 the crossing angle is 250 μrad horizontal)

the magnetized HCAL. The excavated volume amounts to less than 5 cubic meters which significantly simplifies all the aspects, including the waste disposal which can be performed through the LHC tunnel (either via IP1 or via IP2), rather than using the TI18 tunnel through the SPS. As the whole excavation amounts to a smaller volume than it was for FASER (which took 7 weeks), we are assured that the operation will fit within the time in the HL LHC schedule for the concurrent Civil Engineering work foreseen in IP1.

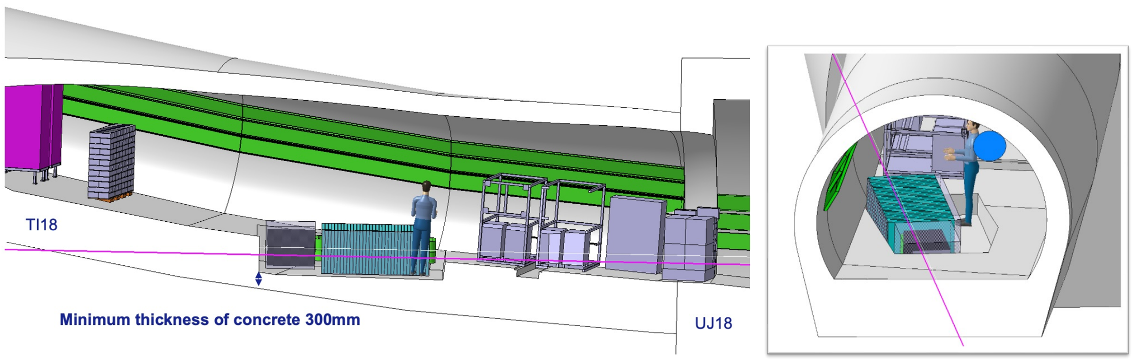

Figure 3: Integration of the detector in TI18: Left side view; Right: front view

Charge and momentum measurement in the HCAL

The proposed HCAL design consists of 34 magnetized iron slabs, each 5 cm thick. We can achieve a magnetic field strength of about 1.7 T with a magnetized length of 1.70 m. The availability of surplus silicon tracker modules, on top of those intended for the tungsten neutrino target, allows the assembly of planes with a required size of 40×40 cm^2. There are enough silicon modules to equip all 34 active layers of the HCAL, enabling high-precision measurements of the muons' charge and momentum.

Figure 5 shows an event display where a neutrino interaction is located in the most downstream part of the neutrino target, made of tungsten slabs interleaved with silicon trackers. Even in this case, one can see the muon coming out of the hadronic shower for a

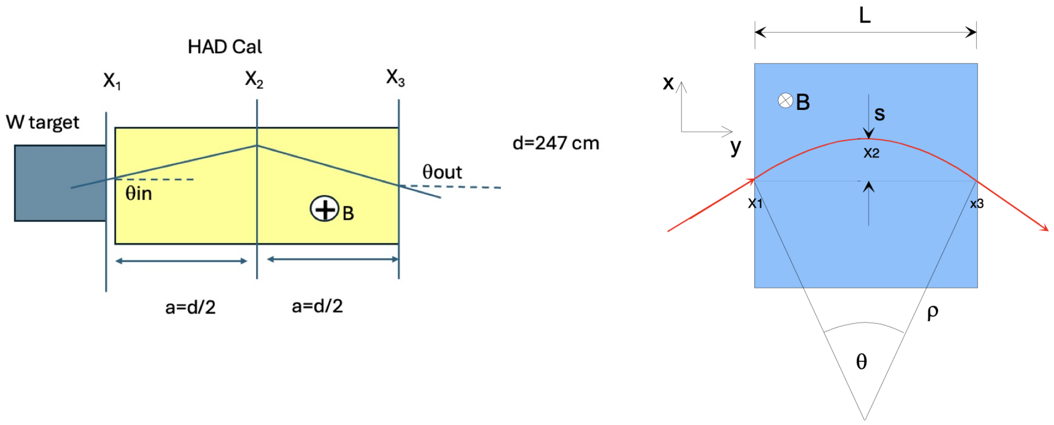

Figure 4: Left: sketch of the three tracking planes to be used to estimate the momentum. Right: outline of the variables used for the momentum measurement.

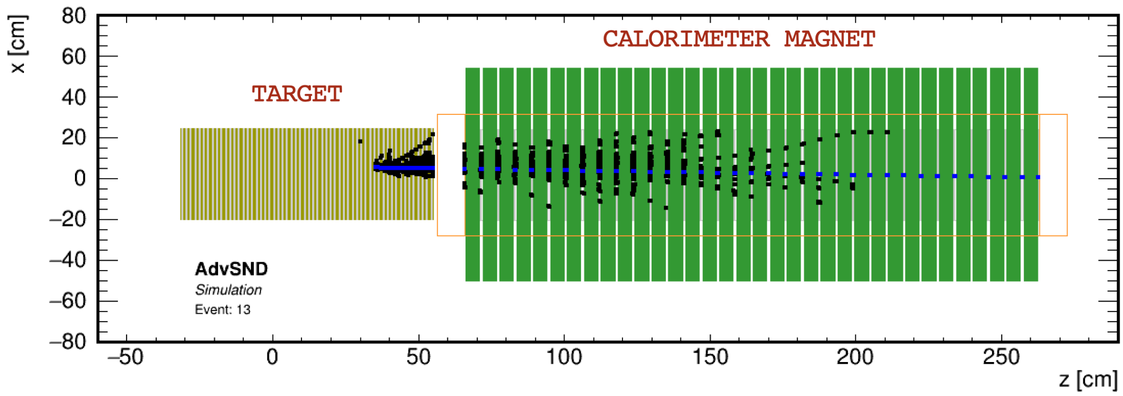

Figure 5: Layout of the detector in the minimal configuration with the magnetised HCAL.

large fraction of the second half of the HCAL, despite the large size of the hadronic shower and its origin being located downstream. If one defines a muon track as isolated when there are no other hits within 1 cm from the muon itself, the Monte Carlo simulation shows that there are on average 20 layers available to trace the muon along the HCAL.

This sets the scale for the resolution needed to identify and track the muon. The idea is to increase the granularity of the tracking stations within the magnetized calorimeter to trace the muon early in the shower. This enables an accurate determination of the sagitta of its trajectory using the HCAL. Each station offers a spatial resolution of approximately 30 µm in the bending coordinate.

With such advanced tracking capabilities, the HCAL effectively functions as a spectrometer, capable of measuring the momentum of muons produced in neutrino interactions and providing good charge separation for muon momenta up to about 1 TeV/c.

To estimate the expected momentum resolution, we use the three positions where the muon trajectory is measured: at the entrance, exit, and midpoint of the calorimeter, as illustrated schematically in in Figure 4. The muon momentum can then be determined by measuring the sagitta of the trajectory

$$s = \rho \left(1 - \cos\frac{\theta}{2}\right) \simeq \rho\frac{\theta^2}{8} = 0.3\frac{BL^2}{8p}$$

where ρ is the radius, θ the bending angle, p the muon momentum, $B = 1.7$ T the magnetic field strength and $L = 1.76$ m the magnetised length. The sagitta is measured by three silicon planes

$$s = x_2 - \frac{x_1 + x_3}{2}$$

each point being measured with an accuracy σ_x, hence the error on the momentum is

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \sqrt{\frac{3}{2}}\frac{8p\sigma_x}{0.3BL^2}$$

Taking muons of 1 TeV/c, a momentum resolution of about 20% is expected. This shows that, with the current arrangement, a momentum resolution comparable to the LoI "baseline" configuration can be achieved. This is a conservative estimate of the achievable resolution as all the stations of the HCAL will be used to measure the muon trajectory.

Physics performance

The main change with respect to the LoI is related to the reduced mass of the target and the change in vertical position which affect the expected neutrino yields. The updated expectations of the neutrino fluxes and interactions in the tungsten target is shown in Table 1, assuming an integrated luminosity of 3000 fb^{-1} and the +250 µrad-H beam configuration.

The effect of the crossing angle on the neutrino yield was also studied. Table 2 shows the expected number of neutrino CC DIS interactions in the three different beam configurations envisaged for HL-LHC: +250 µrad-H, +250 µrad-V and -250 µrad-V, assuming an integrated luminosity of 1000 fb^{-1} in each of them.

We are studying the possibilities offered by the new structure of the HCAL: the high granularity of the sensing layers will make the upstream part of the HCAL a good target to identify muon- and electron-neutrinos interactions thus adding to our overall neutrino interactions statistics. In particular the ability to detect and measure electron neutrinos will be an asset given that most of high energy electron neutrinos are produced by the charmed meson decays.

The concept of combining a calorimeter and high-resolution tracking stations within a magnetised volume is relatively novel and it is also under study for use in SHiP.

Preliminary estimates based on the longitudinal development of hadronic and electromagnetic showers in the HCAL show that 25% of muon and electron neutrinos interacting in Iron layers are fully contained in the detector — with the exception of the muon produced in ν_μ CC DIS interactions. The right panel of Figure 6 shows the fraction of ν_e CC DIS interactions occurring in the HCAL that have a longitudinal development fully contained in the detector, as a function of the interaction position. A display of one of those is shown in the left panel of the same figure. The corresponding neutrino yield is reported in Table 3, assuming 3000 fb^{-1} and the +250 µrad-H beam configuration. An overall increase of about

30% with respect to the number of interactions in the target can be achieved, thus making the available neutrino statistics comparable with that reported in the LoI. Therefore, the expected physics performance would stay practically the same as in the LoI [1] and it is summarised in Table 4.

Flavour	ν in acceptance All	ν in acceptance not from π/K	CC DIS All	CC DIS not from π/K	NC DIS All	NC DIS not from π/K
ν_μ	7.9×10^{13}	7.6×10^{12}	6.8×10^4	1.8×10^4	2.1×10^4	5.4×10^3
$\bar{\nu}_\mu$	6.5×10^{13}	8.9×10^{12}	2.5×10^4	9.8×10^3	9.1×10^3	3.6×10^3
ν_e	1.1×10^{13}	7.7×10^{12}	2.2×10^4	1.9×10^4	6.6×10^3	5.7×10^3
$\bar{\nu}_e$	1.1×10^{13}	8.1×10^{12}	1.0×10^4	9.0×10^3	3.8×10^3	3.3×10^3
ν_τ	6.4×10^{11}	6.4×10^{11}	1.0×10^3	1.0×10^3	3.4×10^2	3.4×10^2
$\bar{\nu}_\tau$	8.6×10^{11}	8.6×10^{11}	5.7×10^2	5.7×10^2	2.3×10^2	2.3×10^2
Tot	1.7×10^{14}	3.4×10^{13}	1.3×10^5	5.7×10^4	4.1×10^4	1.8×10^4

Table 1: Number of neutrinos in the Target acceptance, CC DIS and NC DIS neutrino interactions, assuming 3000 fb^{-1} and the +250 µrad-H configuration, as estimated with DPMJET+FLUKA and GENIE generators.

Flavour	+250 µrad Horizontal	+250 µrad Vertical	-250 µrad Vertical
$\nu_\mu+\bar{\nu}_\mu$	3.1×10^4	3.8×10^4	2.1×10^4
$\nu_e+\bar{\nu}_e$	1.1×10^4	1.4×10^4	7.2×10^3
$\nu_\tau+\bar{\nu}_\tau$	5.4×10^2	9.0×10^2	3.8×10^2
Tot	4.2×10^4	5.3×10^4	2.8×10^4

Table 2: Number of neutrinos CC DIS interactions for three crossing angle configurations, assuming 1000 fb^{-1} in each of them.

Novel ideas on the estimate of systematics

Given recently reported advances in the phenomenology of LHC neutrinos[3, 4], we have revised our analysis strategies with a focus on the reduction of systematic uncertainties by exploiting correlations in the observables accessible to AdvSND: neutrino flavour, energy and pseudorapidity. This approach is only possible with the high statistics and large pseudorapidity range of AdvSND and it is an evolution of the LoI plans, which were based on techniques developed for SND@LHC. We outline below the strategies to constrain systematic uncertainties on the main physics goals of AdvSND.

AdvSND is sensitive to lepton flavour universality violation via the measurement of two ratios: tau neutrino to electron neutrino interaction rates (R_{13}), and electron neutrino to muon neutrino interaction rates (R_{12}).

Flavour	Target	HCAL	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	9.3×10^4	3.5×10^4	1.3×10^5
$\nu_e+\bar{\nu}_e$	3.2×10^4	1.3×10^4	4.5×10^4
$\nu_\tau+\bar{\nu}_\tau$	1.6×10^3	6.0×10^2	2.2×10^3
Tot	1.3×10^5	4.9×10^4	1.8×10^5

Table 3: Number of neutrinos CC DIS interactions in the Target and in the HCAL, assuming $3000\,\mathrm{fb}^{-1}$ and the +250 µrad-H configuration. Longitudinal shower containment is required for interaction in the HCAL.

Measurement	Uncertainty Stat.	Uncertainty Sys.	Uncertainty Stat.	Uncertainty Sys.
Charmed hadron yield	5%	35%	1%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	5%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	1%	5%
ν_μ and $\overline{\nu}_\mu$ cross-section	-	-	1%	5%

Table 4: Measurements proposed by AdvSND in the analyses of neutrino interactions with HL-LHC data compared with estimates for the current detector in Run 3. Statistical and systematic uncertainties are reported [1].

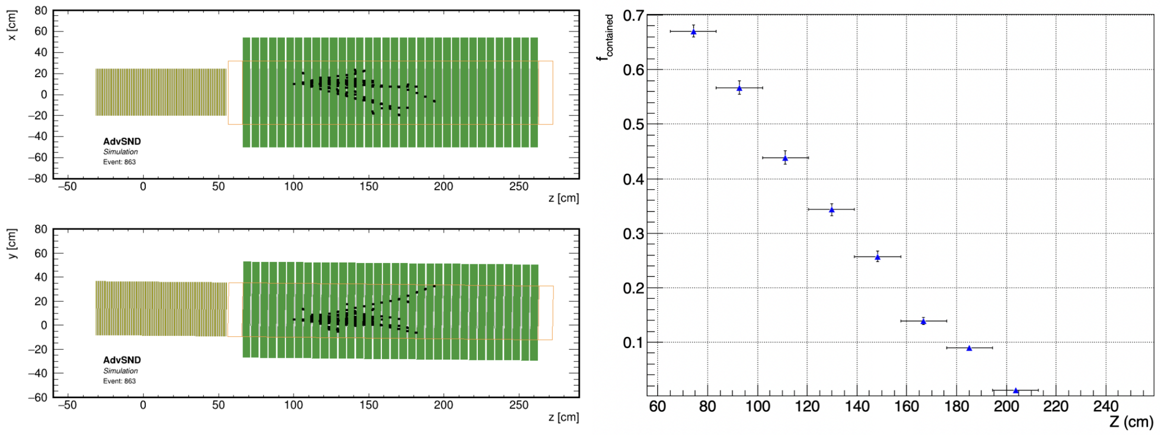

Figure 6: Left: display of an electron neutrino interaction occurring in the HCAL. Right: fraction of ν_e CC DIS interactions occurring in the HCAL and fully contained in the detector, as a function of the longitudinal position of the interaction.

The high yield of tau neutrinos in AdvSND will reduce the statistical uncertainty from 30% in Run 3 to less than 5% in the HL-LHC. We expect the dominant systematic uncertainty due to D_s fragmentation functions, currently around 20%, to be reduced by ongoing analyses of NA65[5] and SHiP-charm[6] data.

The strategy to reduce the uncertainty on R_{12} is twofold. The low-energy muon neutrino flux, which originates in pion decays, will be constrained by forward measurements of π^0 production by LHCf[7], which are expected to reach a precision better than 10%. The ratio will then be measured in regions of neutrino energy and pseudo-rapidity where the charm-parent component of the muon neutrino flux dominates. Given the high yield of events, this fiducial region can be optimised to reduce the contamination of muon neutrinos from pion decays, therefore reducing the systematic uncertainty to the few percent level.

The precision of neutrino interaction cross section measurements at the LHC will be limited by neutrino flux uncertainties. The LHCf pion production measurements will allow constraining the low energy component of the muon neutrino flux. The low-nu method, recently studied in the context of LHC neutrino experiments[4], can be used to extrapolate the low energy flux to the charm-decay dominated high energy part of the muon neutrino flux with an uncertainty better than 10%. The method relies on selecting a subset of interactions for which the energy dependence of the neutrino interaction cross section is theoretically clean. This constraint also applies to the high energy portion of the electron neutrino flux, which shares its production mechanism with the high energy muon neutrinos.

The strategy for constraining the gluon PDF at low x outlined in the SND@LHC technical proposal and AdvSND LoI relied on the ratio of charm production measurements with forward neutrinos to a reference measurement by LHCb. The precision of this approach is limited by the lack of overlapping acceptance between AdvSND and LHCb. It has recently been shown that measuring ratios of neutrino yields between different pseudorapidity ranges in the forward region results in powerful constraints on the gluon PDFs[3].

We have performed a preliminary study of this approach using the framework detailed in [8] based on POWHEG and Pythia8 for generating $c\bar{c}$ events and simulating the parton showers, respectively. Electron neutrinos and antineutrinos intercepting the AdvSND detector are coarsely binned in neutrino energy and pseudorapidity. The charged-current neutrino-tungsten cross section and the target dimensions are folded in to obtain a prediction for the event yield.

We then apply variations of the renormalization and factorization scales, the charm quark mass (m_c), and the PDFs, following the prescription in the SND@LHC technical proposal. As shown in Figure 7, the scale and m_c uncertainties have a large impact on the overall normalization. In the same figure, we show the impact of the theory parameter uncertainty on the shape of the neutrino yield by normalizing the distribution to unity for each set of parameter variations. The normalized distributions are much less sensitive to the scale and m_c uncertainties.

To quantify the potential impact of the AdvSND data on the PDF uncertainties, we constructed a χ^2 test which takes into account the correlated effect of scale and m_c uncertainties on the shape of neutrino event yield distribution. Assuming an integrated luminosity of 3 ab^{-1}, a strong constraint on the low x part of the gluon PDF is obtained, as shown in

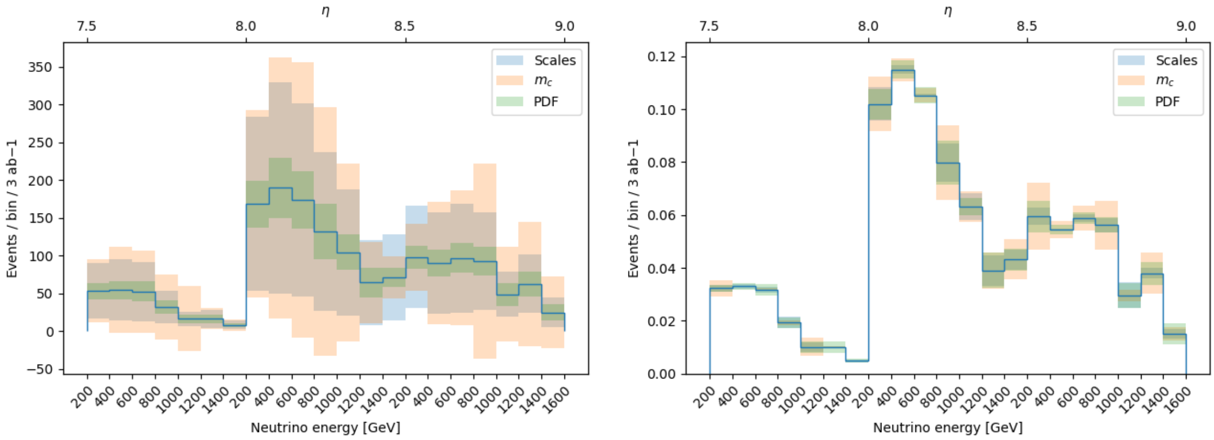

Figure 7: Left: electron neutrino and antineutrino interaction yields in bins of neutrino energy and pseudorapidity, including variations of the theory parameters. Right: impact of the theory parameters on the shape of the neutrino yield distribution.

Figure 8. In the same figure, we show the more modest constraint obtained by SND@LHC using the same method, assuming an integrated luminosity of 300 fb^{-1} and no access to the most forward pseudorapidity bin.

Our preliminary studies based on this approach confirm that PDF variations induce distinctive correlation patterns in the AdvSND observables, different from those obtained from other theory uncertainties, such as the factorisation and renormalisation scales. This indicates that the AdvSND data alone can significantly constrain the gluon PDF at low x.

Admittedly, the calculations of the neutrino and muon fluxes expected in this kind of experiment are not based on solid theory and are still in their infancy. This implies that we shall inevitably learn something from the data.

Updated Cost estimate

The main changes with respect to the LOI are related to the shortening of the W target, to the suppression of the stand-alone magnetized muon spectrometer and the change to the HCAL sensing planes which are now all silicon based.

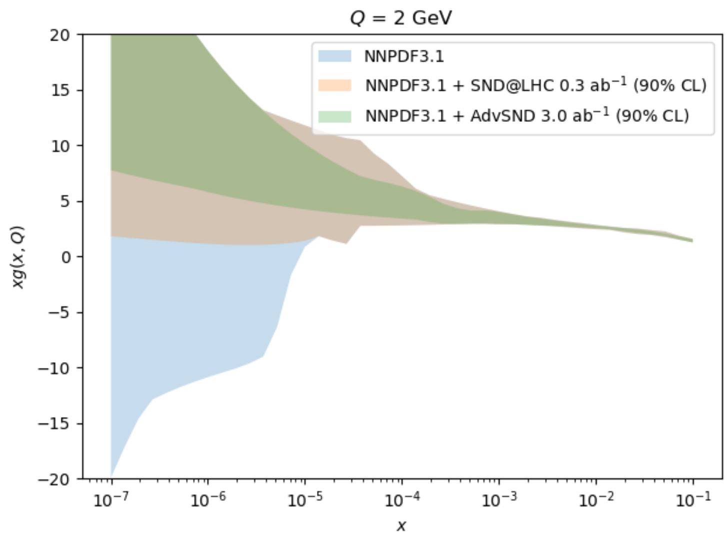

Figure 8: Expected constraint on the gluon PDF uncertainty from the AdvSND data, compared to what could be obtained with a similar analysis of the complete Run 3 SND@LHC data.

	Estimated cost (kCHF)
Target material (W)	200
Target Si planes readout and services	140
Fast timing layers (RPC)	130
HCAL Magnet	200
HCAL Si planes readout and services	85
HCAL cooling and readout infrastructure	240
DAQ HW	30
Total	965

Table 5: Cost estimates in kCHF for the proposed (modified minimal configuration) configuration of the AdvSND detector. We have listed the most expensive option for the fast timing devices.

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