SND@LHC: a roadmap for neutrino detection at LHC and HL-LHC

16th Pisa Meeting on Advanced Detectors, La Biodola, May 27 2024

Elena Graverini

Swiss National Science Foundation

EPFL

IN SUPREMÆ DIGNITATIS 1343

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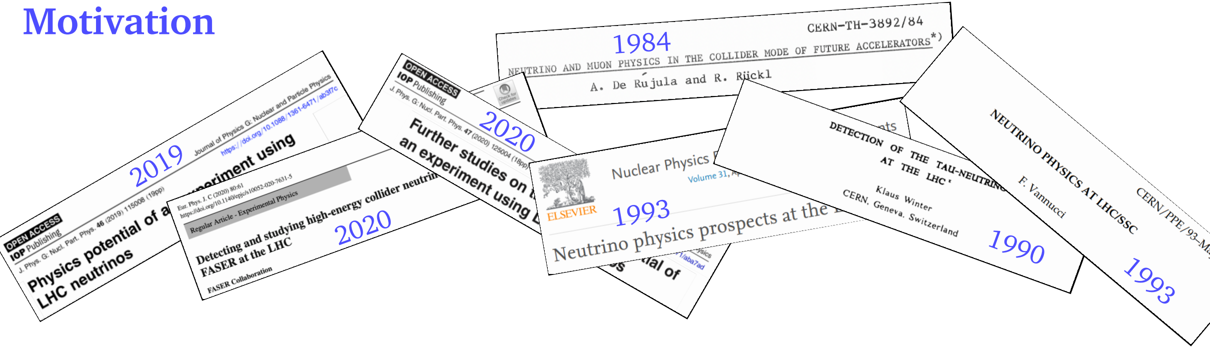
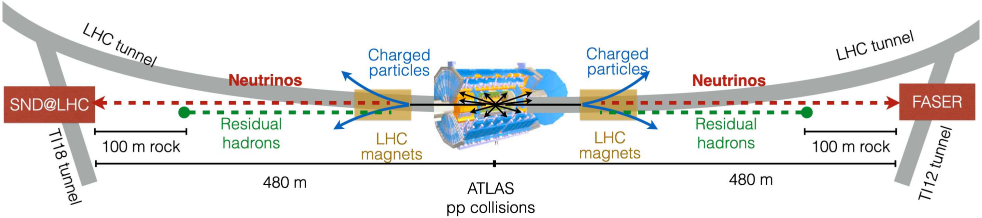
Motivation

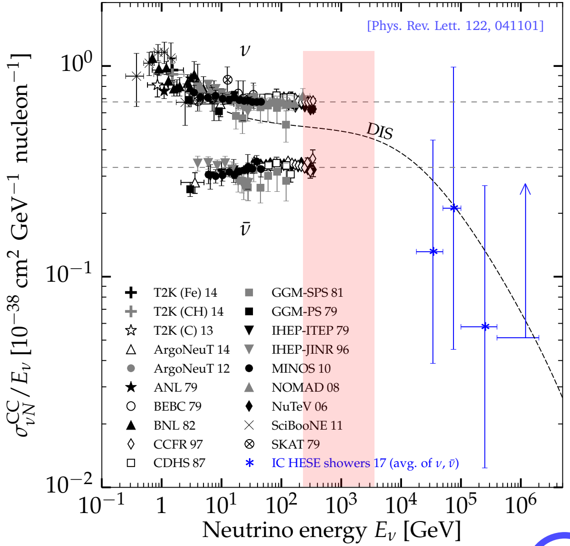


CERN's LHC is unique in providing high-energy neutrinos



Neutrino physics at the LHC

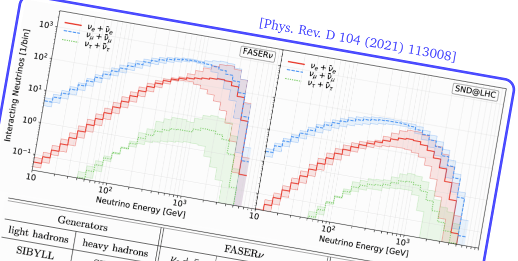
- 2× complementary detectors on either side of the ATLAS interaction point
  - **FASERν** on axis: $\eta > 8.8$
  - **SND@LHC** off axis: $7.2 < \eta < 8.4$
  - Run 3 aim: collect 290 fb^{-1} luminosity
  - expect $\mathcal{O}(10000)$ interacting neutrinos (all flavours)
- LHC neutrinos range from 10^2 GeV to TeV
  - unexplored area
  - first detection of collider TeV neutrinos
  - relatively large interaction cross-section
  - explore ν interactions at unprecedented energies



Physics with neutrinos

- forward neutrinos are mainly produced in hadron decays
- measurements will provide novel input to validate/improve generators
- first data on forward charm, hyperon, kaon

[Phys. Rev. D 104 (2021) 113008]



Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7	134	790	7.6
DPMJET	DPMJET	3457	7088	97	395	1034	18.6
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2	267	1123	11.5
QGSJET	Pythia8 (Soft)	970	5351	16.1	185	1015	7.2
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$	245^{+149}_{-111}	991^{+132}_{-200}	$11.3^{+7.3}_{-4.0}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$	195^{+71}_{-61}	976^{+146}_{-185}	$8.8^{+2.7}_{-1.5}$

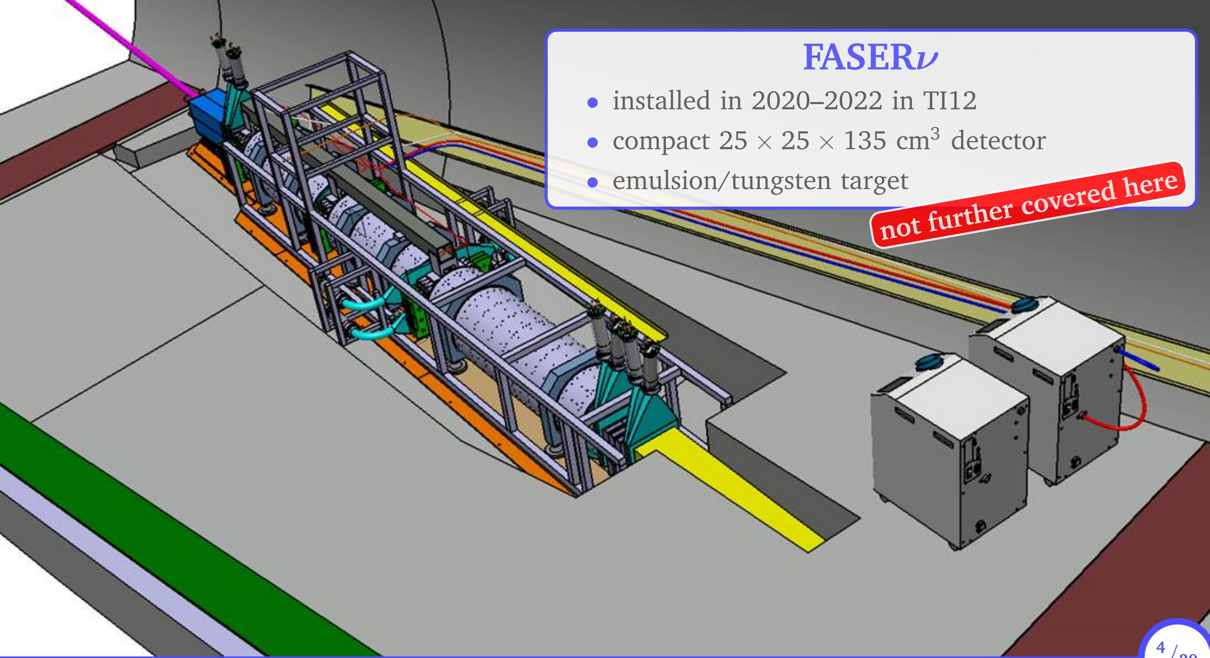
Neutrino physics at LHC energies

- probe charm quark production with ν_e. Relevant for:
  - **future colliders**: FCC-*hh* will probe same x at larger angles
  - **cosmic ray physics**:
    - energy scale corresponds to VHE atmospheric neutrinos, main BG for astrophysical neutrinos
    - charm production leading production mechanism for VHE atmospheric neutrinos

FASERν

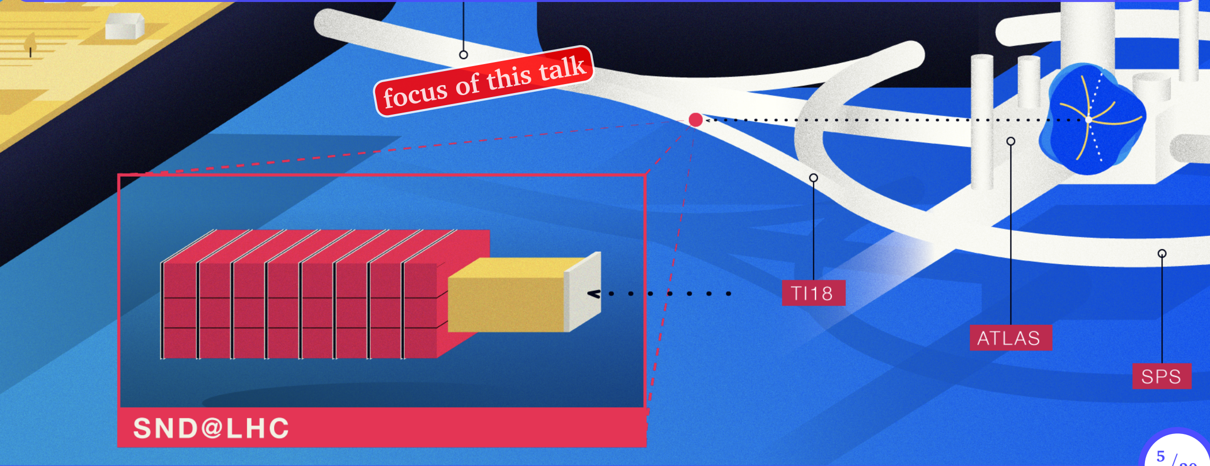
- installed in 2020–2022 in TI12
- compact $25 \times 25 \times 135\ \text{cm}^3$ detector
- emulsion/tungsten target

not further covered here

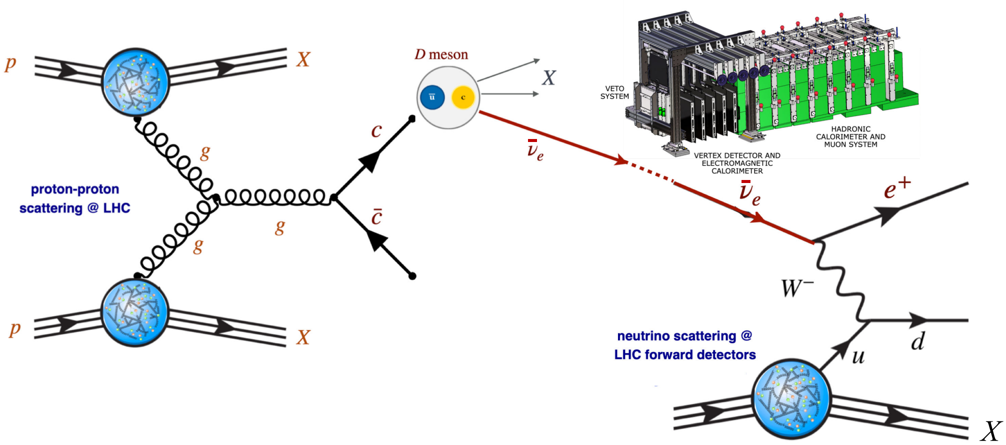


Scattering and Neutrino Detector at the LHC

- 480 m from IP1, in the TI18 tunnel; slightly off-axis: $7.2 < \eta < 8.4$
- approved by CERN Research Board in 2021, taking data since 2022
- SND@LHC collaboration: 180 members from 23 institutes in 13 countries and CERN

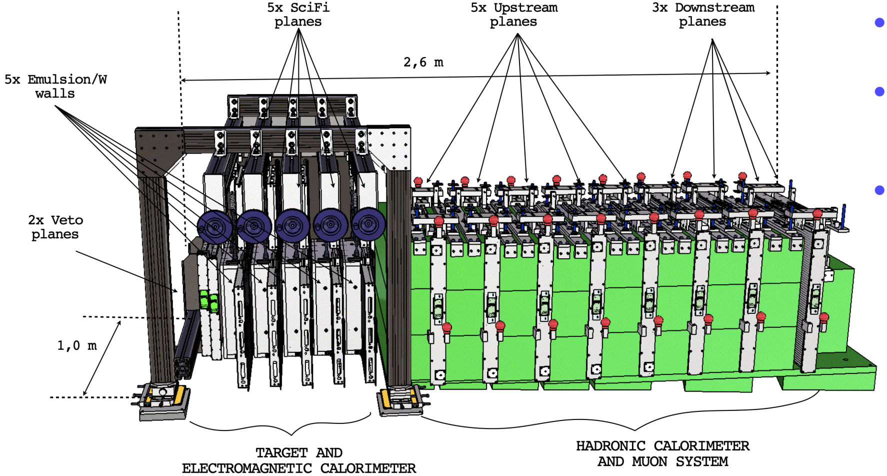


The concept



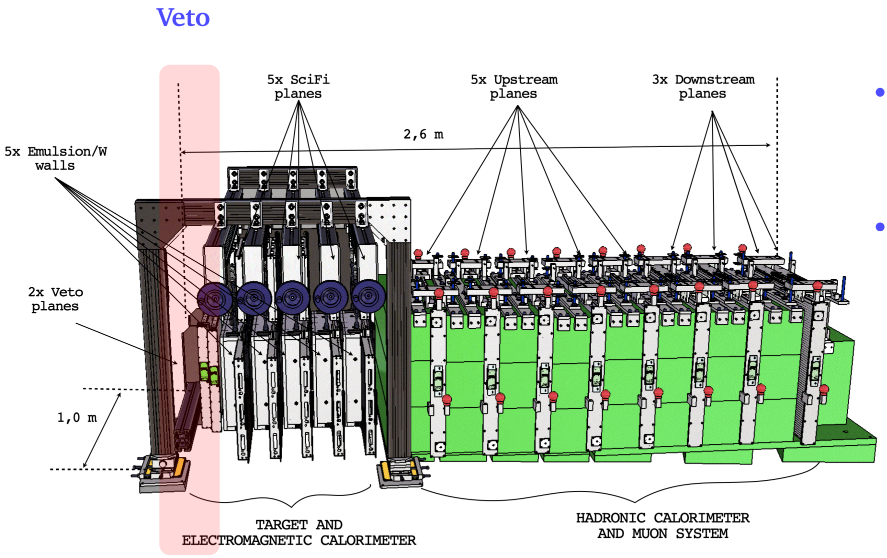
p
X
p
X
g
g
g
proton-proton
scattering @ LHC
c
$\bar{c}$
D meson
X
$\bar{\nu}_e$
VETO
SYSTEM
HADRONIC
CALORIMETER AND
MUON SYSTEM
VERTEX DETECTOR AND
ELECTROMAGNETIC
CALORIMETER
$\bar{\nu}_e$
e^+
W^-
d
u
neutrino scattering @
LHC forward detectors
X

The SND@LHC detector



- hybrid, standalone detector
- optimised for the identification of the three neutrino species
- ...and the detection of scattering FIPs

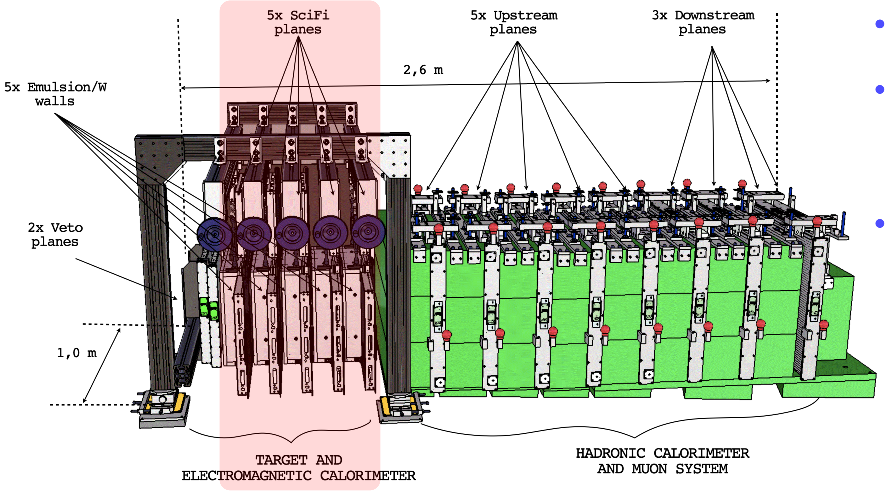
The SND@LHC detector



- upstream veto: two planes of scintillating bars
  - tag and discard events with incoming muons
- **plus one:** see Giulia Paggi's poster! (Mon + Tue morning)

The SND@LHC detector

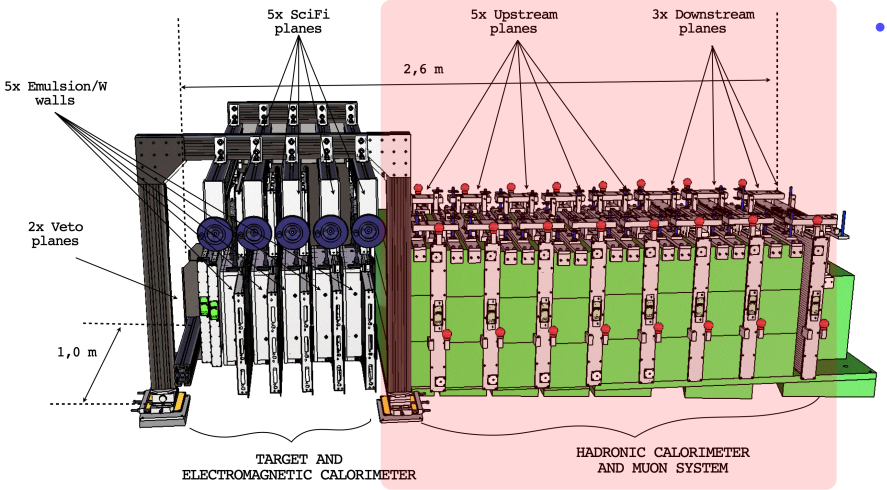
Target region: vertexing, τ ID, energy measurement (ECAL)



- 40 X_0 sampling calorimeter $\longrightarrow$ contain whole shower
- emulsion cloud chambers (ECC): interleaved tungsten plates / emulsions
  - vertexing, τ identification
- scintillating fiber planes (SciFi): timing / position

The SND@LHC detector

Downstream region

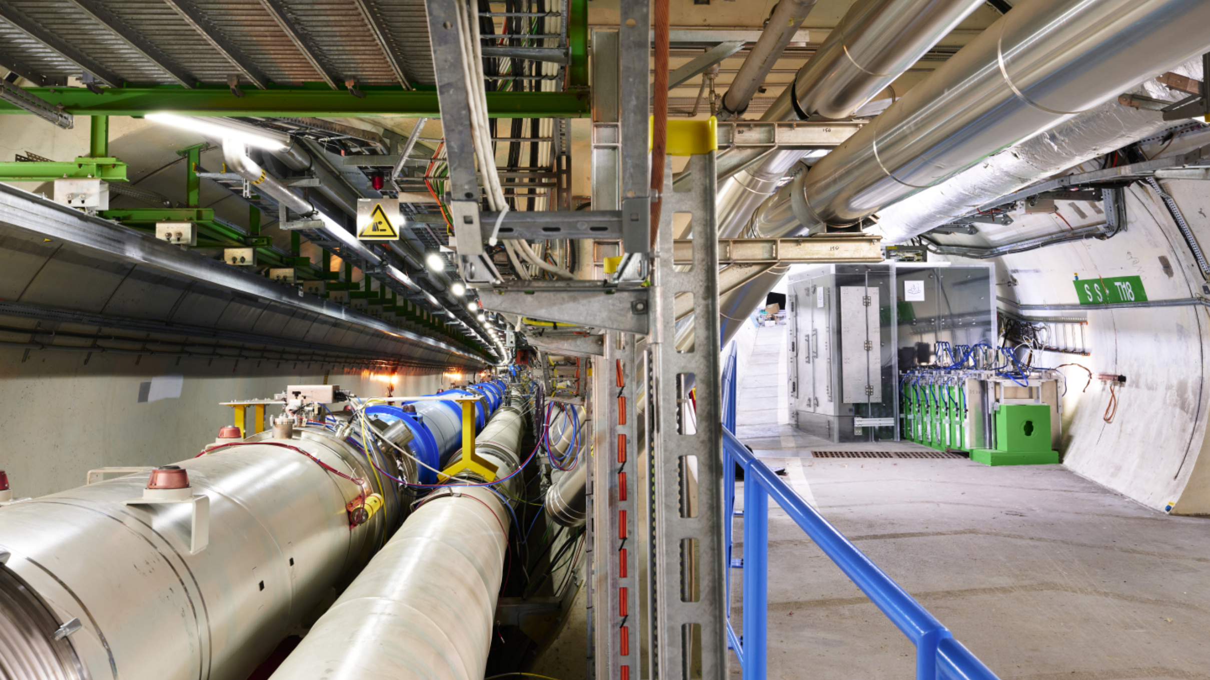


- muon system: timing, muon ID, energy measurement (HCAL)
  - interleaved plastic scintillator bars / iron planes
  - sampling every λ

Installation: souvenir pics

September 2021

March 2022



Two-phase event reconstruction

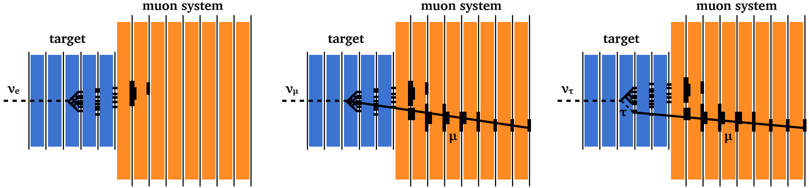
Online, using electronic detectors

- identify scattering candidate (neutrino or FIP)
- identify muon candidates (downstream muon planes), EM shower (SciFi)
- measure neutrino energy (SciFi + muon, hit counting or machine learning techniques)

Offline, with nuclear emulsions

[J. Phys. G: Nucl. Part. Phys. 46 115008]

- develop & scan films extracted in quick access after ∼25 fb^{-1} exposure (∼3 months)
- reconstruct ν interaction vertex, τ candidates
- match showers with events recorded by electronics detectors



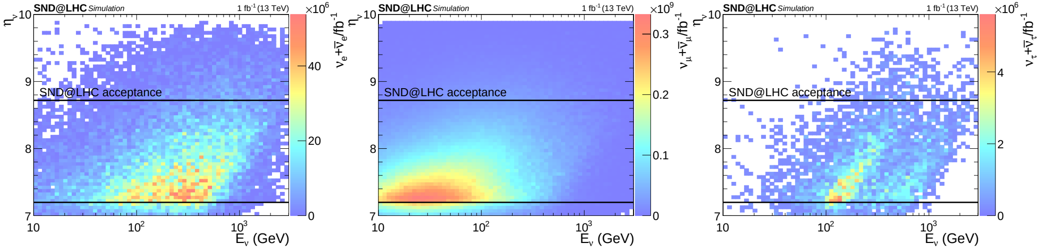
Simulation & expected neutrino flux

[thanks CERN Fluka team!]

Expected flux 290 fb^{-1}

Flavour	Neutrinos in acceptance	CC neutrino interactions ⟨E⟩ [GeV]	CC Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC Yield
ν_μ	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	3.0×10^{12}	480	419	480	157
ν_e	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	4.4×10^{11}	680	158	720	58
ν_τ	2.8×10^{10}	740	23	740	8
$\bar{\nu}_\tau$	3.1×10^{10}	740	11	740	5
all	7.3×10^{12}		1930		625

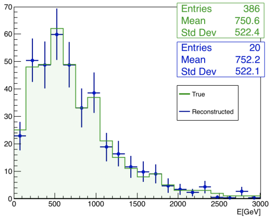
- ν production in *pp* collisions at LHC simulated with FLUKA + DPMJET-3
  - full description of all machine elements from IP1 to TI18
- ν_τ production with PYTHIA8
- ν interactions in detector: GENIE
- detector response: GEANT4

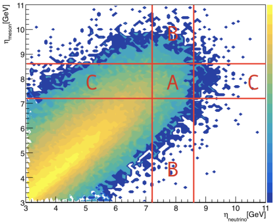


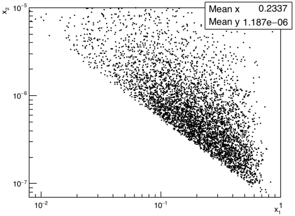
Neutrino physics: ν_e and charm

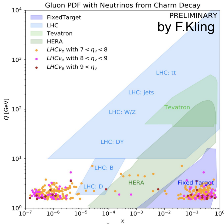
[LHCC-P-016]

- 90% of $\nu_e + \bar{\nu}_e$ produced in charm decays: insight on heavy-quark production
  - statistical subtraction of ν_e component from kaon decays ($\sim$20% syst.)
  - energy response from simulation + calibrated with hadron beam from SPS (2023)
- Measure $\sigma\,(pp \to \nu_e X)$ and derive charmed hadron yield ($\sim$5% stat, $\sim$35% syst.), open charm
  - angular correlation between ν_e and X_c, and between X_c and parent charm
  - average lowest momentum fraction accessible at SND@LHC: $x \sim 10^{-6}$
  - constrain PDF using SND@LHC data: taking ratio of cross-sections at different energies/rapidities reduces scale uncertainty [JHEP 11 (2015) 009]
  - use LHCb measurement in $\eta < 4.5$, $\sqrt{s} = 7, 13$ TeVs [Nucl. Phys. B871 (2013) 1-20] [JHEP 03 (2016) 159]





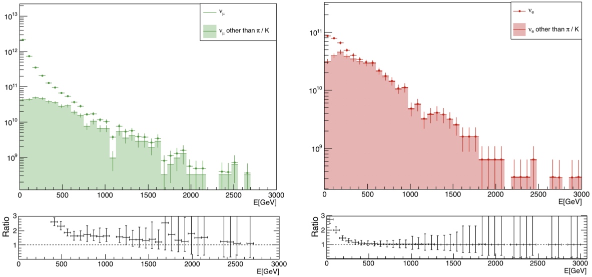




Neutrino physics: $e/\mu/\tau$ comparison

[LHCC-P-016]

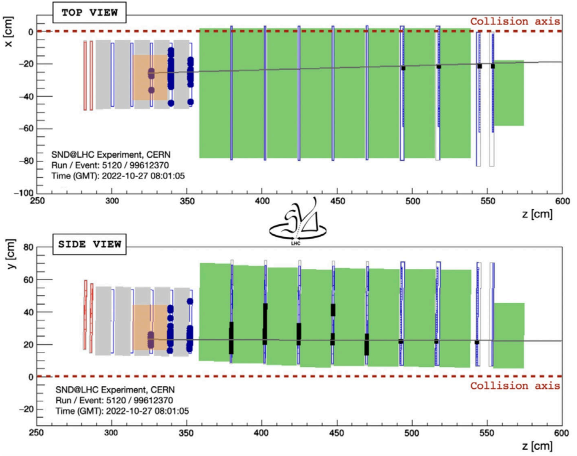
- ν_e and ν_τ only come from charm decays in SND@LHC
  - ratio $N_{\nu_e+\bar{\nu}_e}/N_{\nu_\tau+\bar{\nu}_\tau}$ depends only on decay branching ratios and charm fractions
  - sensitive to cross-section ratio of the two ν flavours: e-τ LFU in neutrino sector (unc. $\sim$30%)
- ν_μ neutrinos contamination by π/K decays flat above 600 GeV
  - ratio $N_{\nu_e+\bar{\nu}_e}/N_{\nu_\mu+\bar{\nu}_\mu}$ for $E_\nu > 600$ GeV probes e-μ LFU (uncertainty $\sim$15%) and is unaffected by charm fractions and branching ratio uncertainties



First results

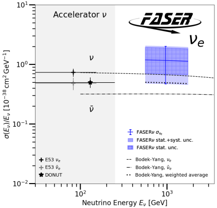
2023: first collider neutrinos

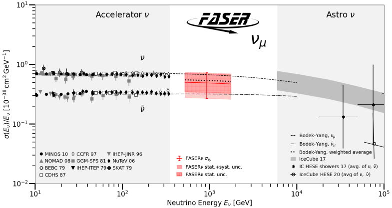
- FASER and SND@LHC published the first observation of collider muon neutrinos using their 2022 datasets [PRL 131 (2023) 031801-031802]
- FASER: expected 151 ± 41 events with ~ 2 events of bkg; observed 153 (16σ)
- SND@LHC: expected 4.2 with 0.09 bkg; observed 8 events (6.8σ)
- SND@LHC with 2022-2023 dataset: observed 32 events (12σ)

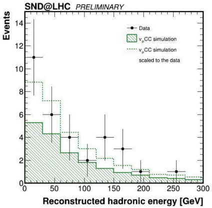


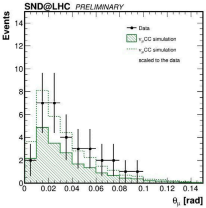
...in two flavours

- FASERν analysed part of the dataset to obtain the first cross-section in the TeV range [arXiv:2403.12520]
- SND@LHC observed 6 shower-like (0μ) events (over ~ 0.1 expected bkg)
  - shower patterns identified, vertex association in progress
- kinematics of muon neutrino events at SND@LHC in agreement with predictions





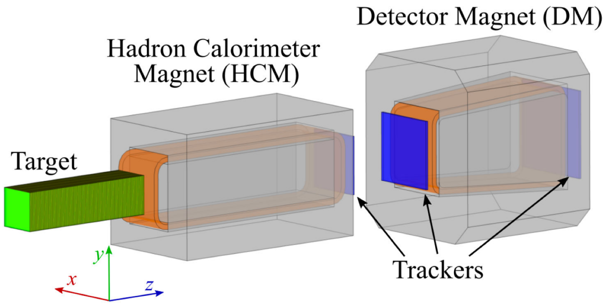


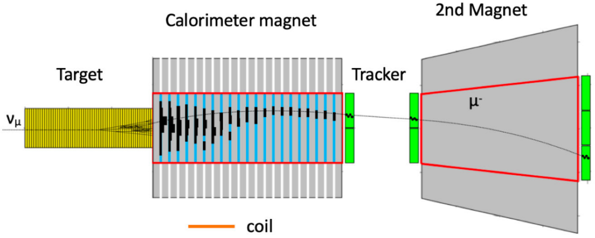


The future

AdvSND

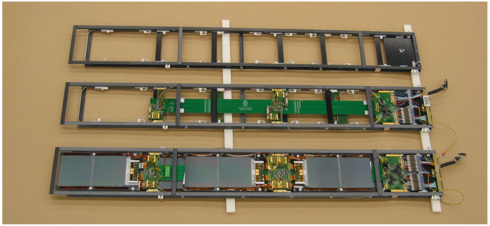
- continue with an improved detector in Run 4 and beyond
- AdvSND - Far (TI18, current location of SND@LHC): Run 4
  - civil engineering to improve acceptance
  - calorimeter + spectrometer magnets: separate ν from $\bar{\nu}$
  - charm production measurements with improved statistics
  - lepton flavour universality
- AdvSND - Near (UJ57/UJ56, near IP5): Run 5
  - overlap with LHCb acceptance where c, b measured
  - reduce systematic uncertainties for AdvSND - Far
  - measure ν cross-sections

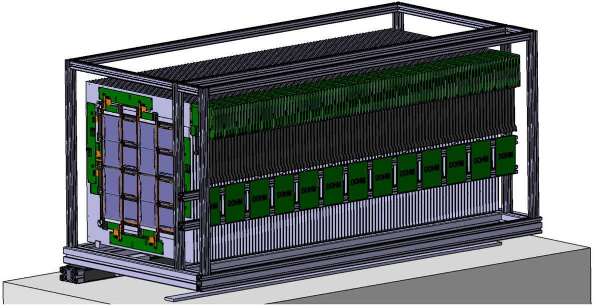




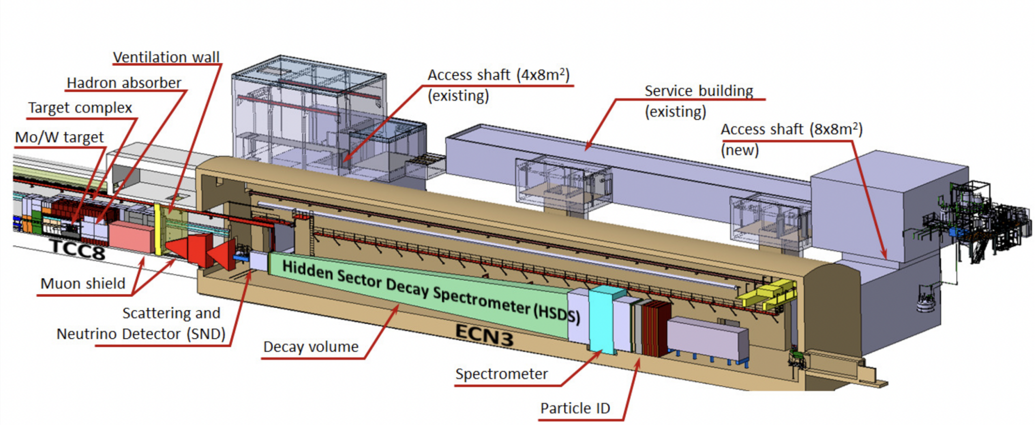
AdvSND target

- CMS Silicon Trackers as vertex/ECAL
- CMS board approved reuse of TOB modules + spares on Feb 9, 2024
- geometry: map 8 10×20 cm^2 modules to one 40×40 cm^2 SND target station
- 100 sandwiches of W+silicon
- prototype under construction
  - will test performance in summer
- option: pixel layers
  - use developments for ALICE ITS3: large scale MOnolithic Stitched Sensors (MOSS)
  - could replace 50 layers with MOSS sensors overlapping in central region ($\longrightarrow$ form tracklets!)





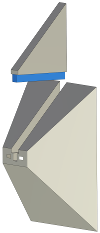
SND @ Beam Dump Facility

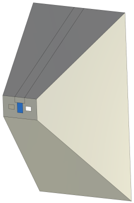


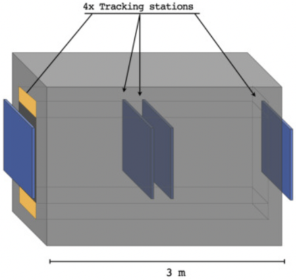
- BDF + SHiP very recently approved by CERN directorate for construction in North Area
- SHiP experiment made of two parts: hidden sector decay spectrometer (FIPs) + scattering and neutrino detector (LDM + neutrino physics)
- 400 GeV/c p beam extracted from SPS; expect several 10^{20} proton-target collisions

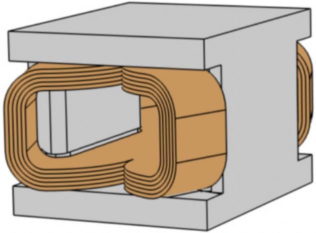
SND @ BDF

- instrumented target/tracker for LDM and neutrino interactions
  - radial dependence of flux $\longrightarrow$ long and narrow
  - doubles up as sampling calorimeter
  - integrated in the last section of the muon shield
- followed by muon spectrometer
- design can and will be reoptimised!



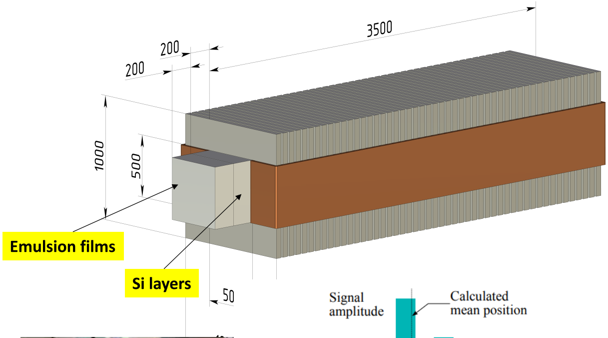


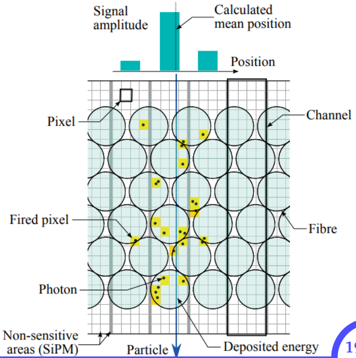




SND @ BDF target tracker

- experimental signatures of ν_τ:
  - double kink (τ production and decay): requires superior vertex and tracking capabilities ($\beta\gamma c\tau < 1$ mm)
  - kinematic of decay products: final state neutrinos carry away a significant fraction of τ energy. Need large data sample to perform statistical analysis
- **two** complementary strategies:
  - layered calorimeter "à la SND@LHC" made of magnetized iron / scifi planes
  - two blocks of W instrumented with emulsion films and silicon





Summary and plans

- two experiments started studying forward neutrinos from LHC collisions in 2022
- physics reach of LHC expands:
  - study TeV-range νN interaction for all three flavours
  - access parton momenta down to $x \sim 10^{-6} \longrightarrow$ constrain QCD uncertainties
- first measurements demonstrate very low background and ν_e, ν_μ visible
- many ideas and plans to expand this field both at HL-LHC and at the BDF

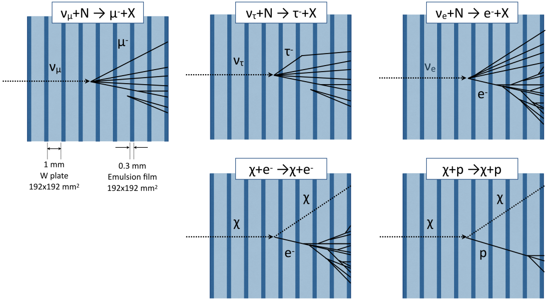
Spare slides

Physics performance: key features

[MC simulation studies]

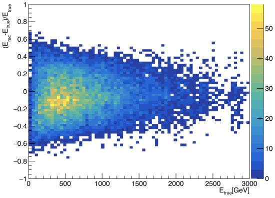
Flavour identification

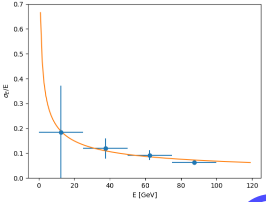
- ν_μ ID efficiency $\sim$77% driven by acceptance and occupancy (μ in donwstream Muon planes)
- ν_e identified by presence of EM shower in the ECC brick (99% efficiency)
- ν_τ ID relies on topological criteria (secondary vertex), $\sim$50% efficient



Energy measurement

- SND@LHC is a non-homogeneous sampling calorimeter
- overall energy resolution $\sim$20-30%
- response modelled with linear regression, ML alternative under construction



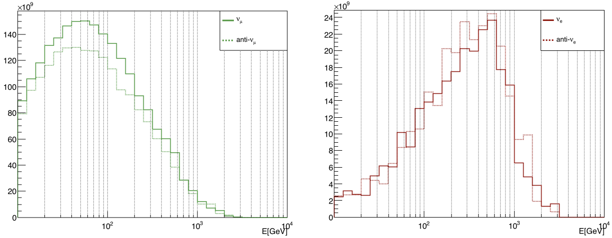


Consistency check

[Rep. Prog. Phys. 79 (2016) 124201]

$$\frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}} = \frac{1}{2}\left\{1 - 2\sin^2\theta_W + \frac{20}{9}\sin^4\theta_W - \lambda\left(1 - 2\sin^2\theta_W\right)\sin^2\theta_W\right\}$$

- if dN/dE is the same for ν and $\bar{\nu}$, NC/CC cross section ratio equals ratio of observed events
- for deep inelastic scattering, it is a function of θ_W and of the properties of the target material
- can be measured with 10% precision and compared to SM predictions



Scattering signatures and NP

[LHCC-P-016] [JHEP 03 (2022) 006] [A. Boyarsky, SND@LHC open session 16/06/2022]

- not main goal, but dense detector also ideally suited to detect feebly interacting particles
- e.g.: decay of mediators produced in collisions: $pp \to \mathcal{N} + X$, $\mathcal{N} \to$ visible
- e.g.: light dark matter scattering, similar to NC neutrinos interactions: $\chi + N \to \chi + N$
  - consider $pp \to V + X$, $V \to \chi\chi$ where χ scatters on SND@LHC target
  - direct detection complementary to missing-energy approach (NA64)
- time-of-flight techniques ($\sigma_t = 200$ ps) sensitive to larger masses (~ 10 GeV for $E_\chi \sim 1$ TeV)
- opportunity for upgraded detector AdvSND operating in Run4+