A new Scattering and Neutrino detector at the LHC

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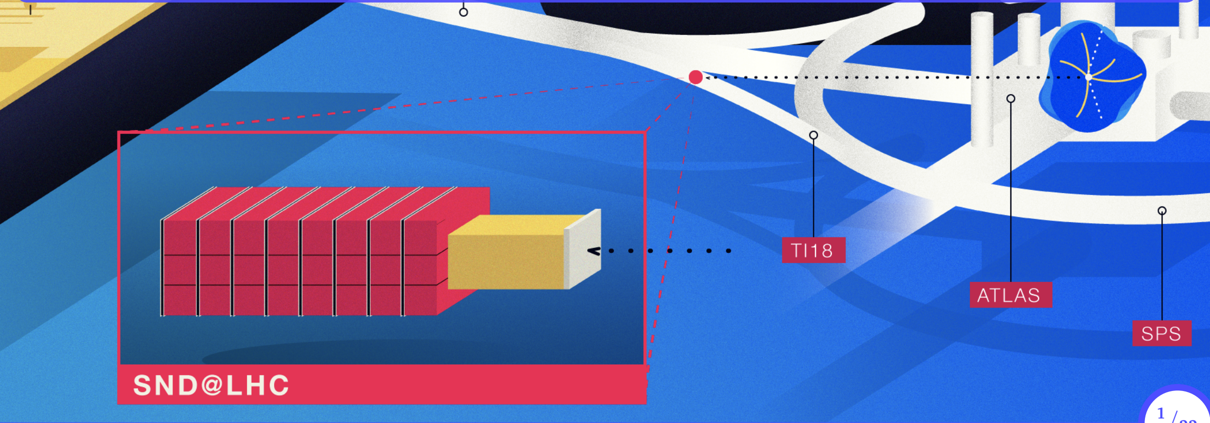
Les Rencontres de Physique de la Vallée d'Aoste:
results and perspectives in particle physics

La Thuile, March 12, 2022

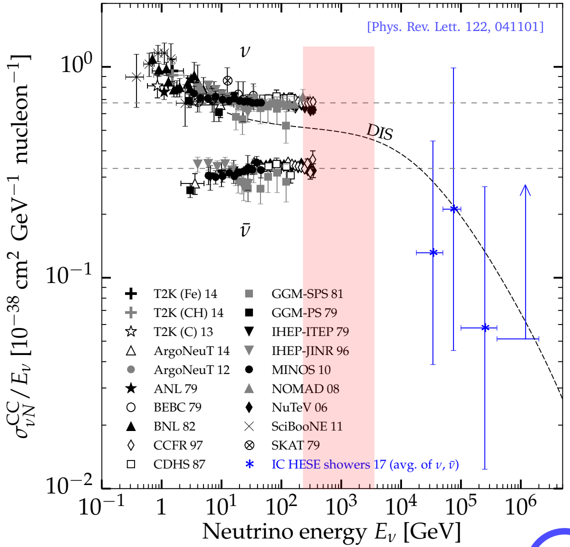
Scattering and Neutrino Detector at the LHC

- compact experiment observing forward neutrinos produced in LHC *pp* collisions
- 480 m far from ATLAS IP1, in the TI18 tunnel, slightly off-axis: $7.2 < \eta < 8.4$
- approved by CERN Research Board one year ago, now installed and commissioning ongoing
- SND@LHC collaboration: 180 members from 23 institutes in 13 countries and CERN



Motivation

- LHC neutrinos range from 10^2 GeV to TeV
  - relatively large interaction cross-section
- 250 fb^{-1} luminosity in Run 3
- 1 ton compact detector:
  - expect $\sim$2000 neutrino interactions
  - of all flavours!
- off-axis range probes heavy flavour decays
- ν_e, ν_τ produced mainly in charm decays
  - measure charm production in unexplored energy range
- low-energy ν_μ also from π, K decays



Physics goals

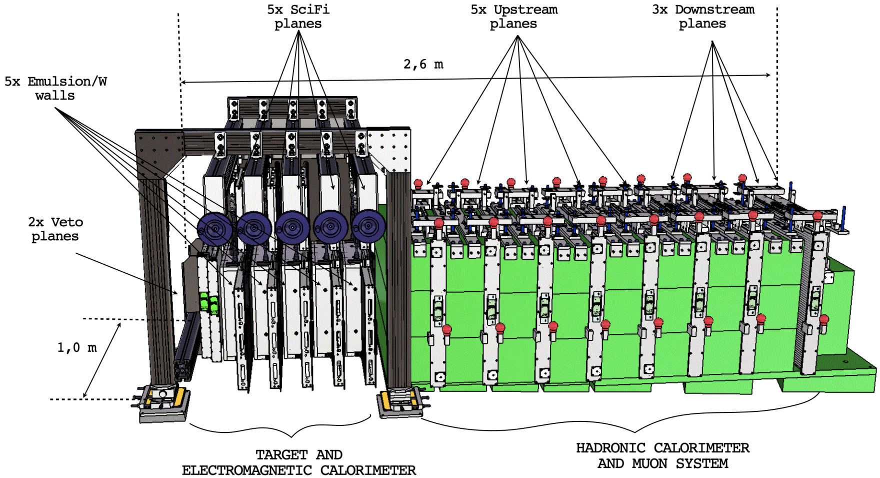
Neutrino physics at LHC energies

- measure $pp \to \nu X$ cross-sections
- 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
- probe consistency of SM: LFU in the neutrino sector

Search for new physics

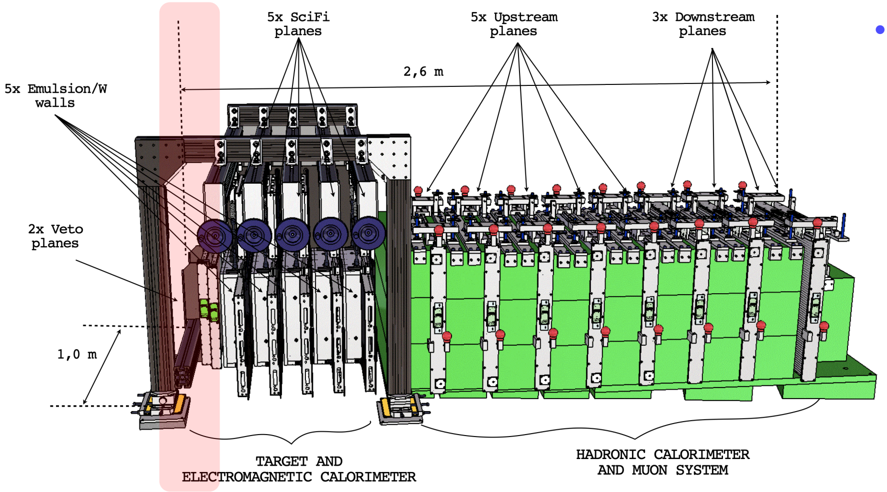
- direct search of feebly interacting particles through scattering signature
- e.g. $\chi + p/e \to \chi + p/e$, or $\chi + p/n \to \chi + X$

Detector overview



Detector overview

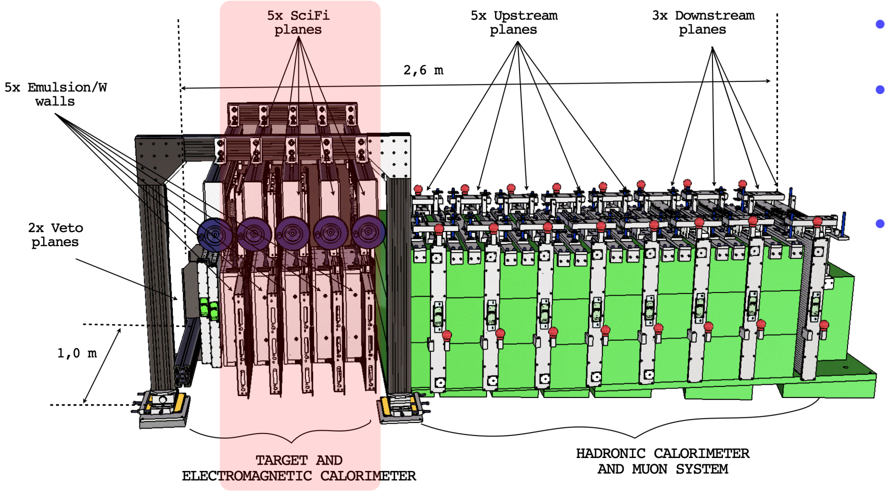
Veto



- upstream veto: two planes of scintillating bars
  - tag and discard events with incoming muons

Detector overview

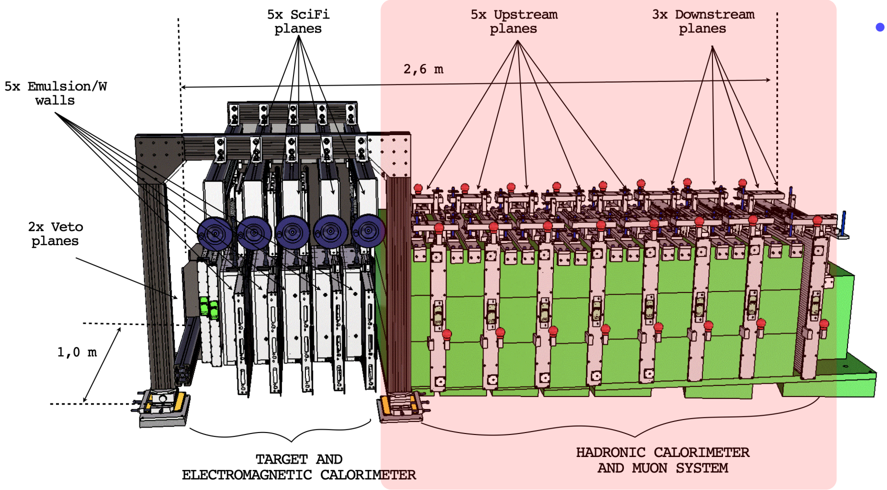
Target region: vertexing, τ ID, energy measurement (ECAL)



- 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

Detector overview

Downstream region

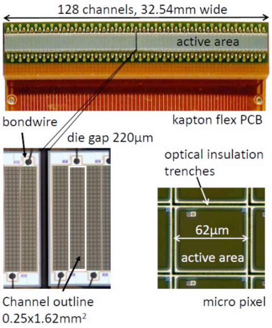


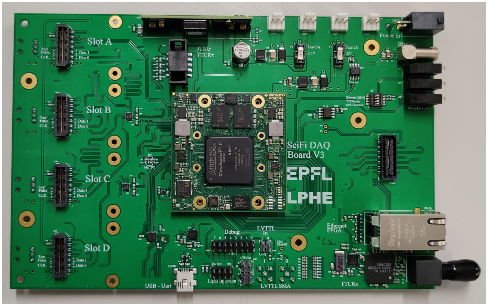
- muon system: timing, muon ID, energy measurement (HCAL)
  - interleaved plastic scintillator bars / iron planes
  - sampling every λ

Data aquisition

- all electronic detectors read out by SiPMs
- 37 identical DAQ boards – synced with LHC bx clock
- *triggerless* experiment: real-time data reduction based on software
  - all front-end recorded hits are sent to servers for processing
  - noise reduction: keep events with $\mathtt{N}_{\mathtt{min}}$ (configurable) detector planes hit
  - expected output of 400k hits/s (available bandwidth 1M hits/s)

⟶ keep possibility to loosen FE thresholds on SciFi to raise efficiency





Two-phase event reconstruction

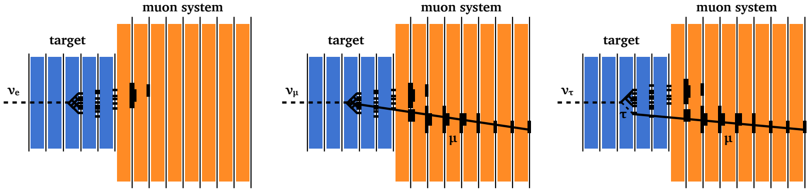
Online, using electronic detectors

- 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)

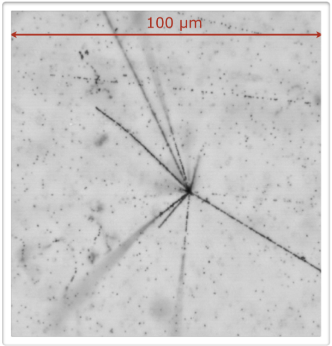
Offline, with nuclear emulsions

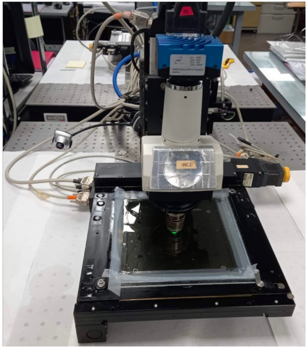
[J. Phys. G: Nucl. Part. Phys. 46 115008]

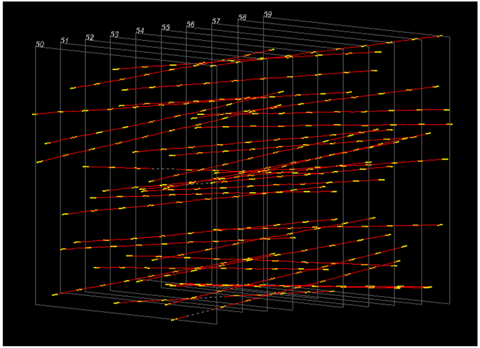
- develop & scan films extracted in quick access after $\sim$25 fb^{-1}exposure ($\sim$3 months)
- reconstruct ν interaction vertex, τ candidates
- match showers with events recorded by electronics detectors



Nuclear emulsions







- sub-micrometric position resolution
- optical system for scanning emulsion films
- commissioned with cosmic rays tracks

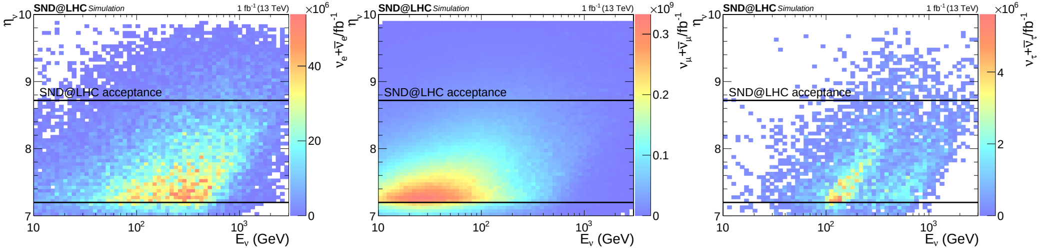
Simulation & expected neutrino flux

[thanks CERN Fluka team!]

note: estimates for 150 fb^{-1}! to be updated for 250 fb^{-1}

Flavour	Neutrinos in acceptance	CC neutrino interactions $\langle E \rangle$ [GeV]	CC Yield	NC neutrino interactions $\langle E \rangle$ [GeV]	NC Yield
ν_μ	2.1×10^{12}	450	730	480	220
$\bar{\nu}_\mu$	1.8×10^{12}	485	290	480	110
ν_e	2.6×10^{11}	760	235	720	70
$\bar{\nu}_e$	2.8×10^{11}	680	120	720	44
ν_τ	1.5×10^{10}	740	14	740	4
$\bar{\nu}_\tau$	1.7×10^{10}	740	6	740	2
all	4.5×10^{12}		1395		450

- 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

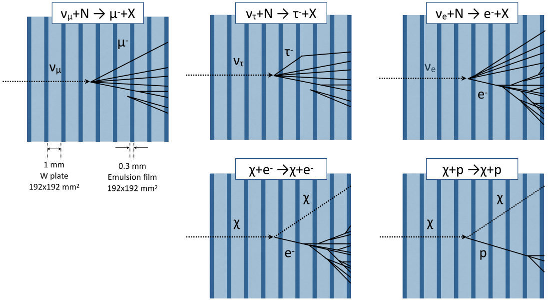


Physics performance: key features

[MC simulation studies]

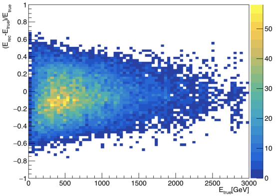
Flavour identification

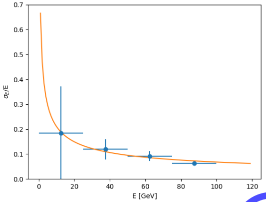
- ν_μ ID efficiency $\sim$77% driven by acceptance and occupancy (μ in donwstream Muon planes)
- ν_e identified by presence of EM shower in the ECC brick (99% efficiency)
- ν_τ ID relies on topological criteria (secondary vertex), $\sim$50% efficient



Energy measurement

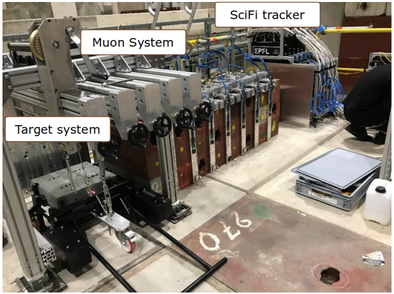
- SND@LHC is a non-homogeneous sampling calorimeter
- overall energy resolution $\sim$20-30%
- response modelled with linear regression, ML alternative under construction

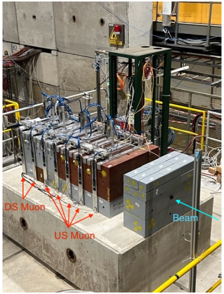




Commissioning

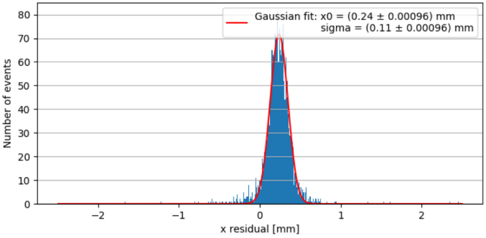
- Detector commissioned at SPS before installation (August-October 2021)
  - cosmic rays on SciFi: test of DAQ / event building; tune simulation parameters
  - SPS H6 muon beam on full detector: test of electronics response
  - SPS H8 pion beam on Muon system: calibrate energy measurement
- Commissioning in TI18 until February 2022
  - from now on: longer commissioning runs (calibrate thresholds / dark rate) with (rare) cosmics, then with ramping-up LHC collisions starting from mid-May.

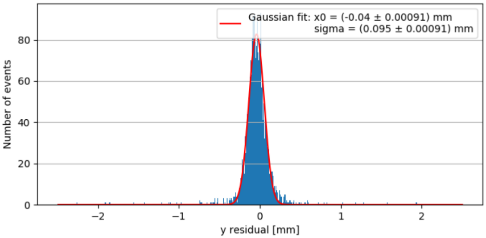




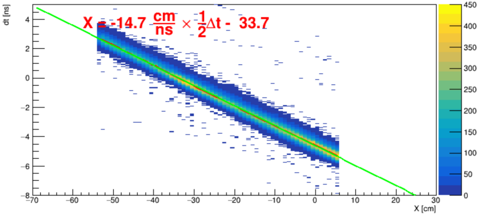
Commissioning results

SciFi resolution <100 μm after alignment

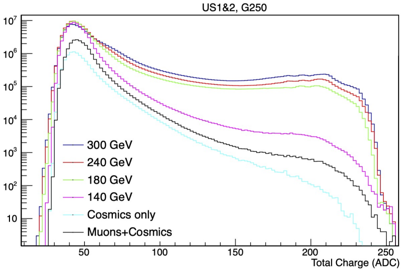




Δt between two ends of scintillator bar



charge per event as a function of beam energy in upstream muon stations



Installation

- Installation in TI18 started in November 2021:
  - first half of November: mechanical structure, iron blocks, cooling plant
  - end of November: SciFi; beginning of December: Muon system
- Last week: alignment survey, start neutron shield/cold box installation
- Ongoing this week: monitoring system (temperature, humidity) + box installation
- Soon: equip 1/5 of target with sensitive films for BG measurement

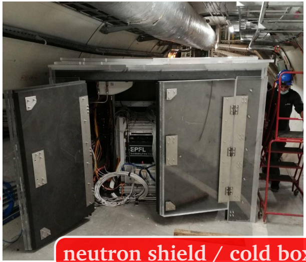


Installation: souvenir pics

September 2021

December 2021

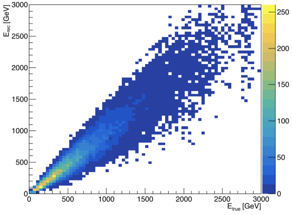
Installation: souvenir pics

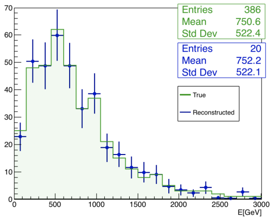


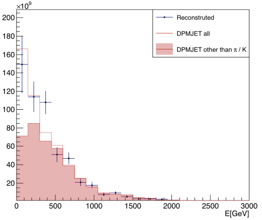
Neutrino physics: ν_e and charm

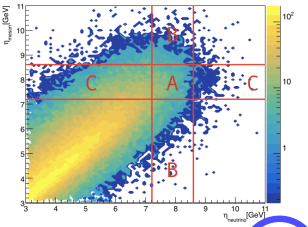
[LHCC-P-016]

- 90% of $\nu_e + \bar{\nu}_e$ produced in charm decays
  $\Longrightarrow$ $\nu_e + \bar{\nu}_e$ flux gives insight on heavy-quark production
- Measure $\sigma\,(pp \to \nu_e X)$ ($\sim$15% uncertainty)
  - obtain energy response from simulation
  - unfold spectrum of observed events
  - assume SM cross-sections for CC interactions
- Derive charmed hadron yield ($\sim$5% stat, $\sim$35% syst.)
  - statistical subtraction of ν_e component from kaon decays ($\sim$20% syst.)
  - acceptance effect: exploit angular correlation between ν_e and parent charm





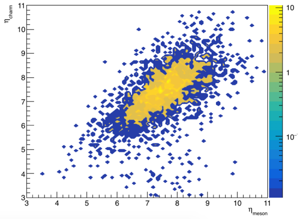


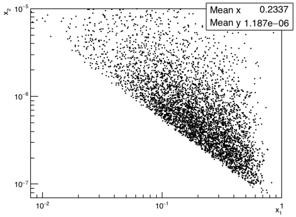


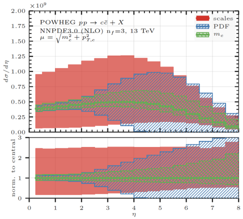
Neutrino physics: QCD

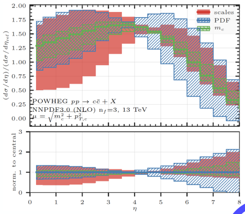
[LHCC-P-016]

- measurement of the charmed hadrons can be translated into measurement of the corresponding open charm production
  - angular correlation between charmed hadron and parent charm
- charm production at LHC dominated by gluon-gluon scattering
- average lowest momentum fraction accessible at SND@LHC $\sim 10^{-6}$
  - here, gluon PDF completely unknown, theory work ongoing on resummation
- constrain PDF with 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]





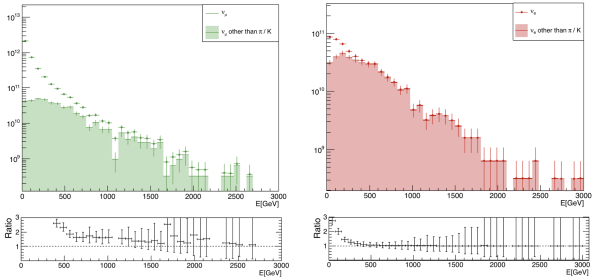




Neutrino physics: $e/\mu/\tau$ comparison

[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

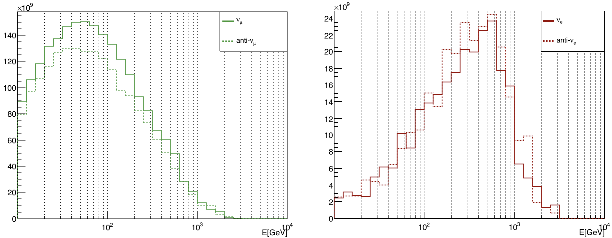


Consistency check

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

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

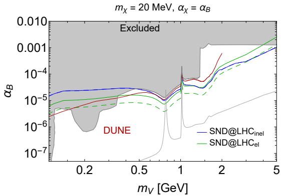
- if dN/dE is the same for ν and $\bar{\nu}$, NC/CC cross section ratio equals ratio of observed events
- for deep inelastic scattering, it is a function of θ_W and of the properties of the target material
- can be measured with 10% precision and compared to SM predictions

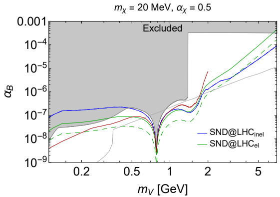


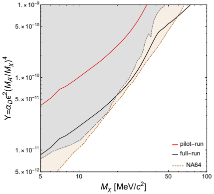
Scattering signatures

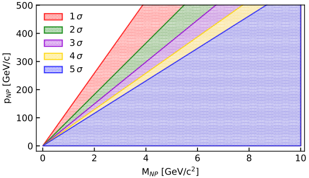
[LHCC-P-016] [JHEP 03 (2022) 006]

- dense detector ideally suited to detect feebly interacting particles produced in *pp* collisions
- light dark matter scattering similar to NC neutrinos interactions: $\chi + N \rightarrow \chi + N$
  - sensitivity: excess of $\sim$100 events
  - consider $pp \rightarrow V + X$, $V \rightarrow \chi\chi$ 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 ($\sim$ 10 GeV for $E_\chi \sim$ 1 TeV)



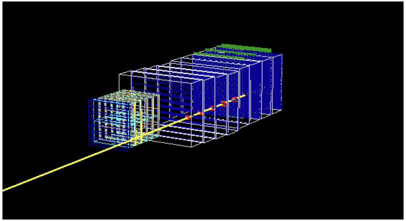




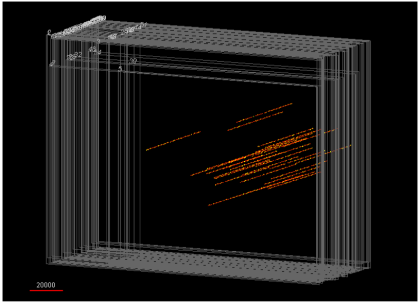


Early measurements (2022)

1. muon-induced background measurement with electronic detectors
   - muon rates and track topology
   - comparison with simulations
2. study of neutrino interactions with electronic detectors only
3. response of nuclear emulsions: 1/5 of target instrumented with emulsions to be extracted in July
   - evaluate background in the emulsion target
   - define/update the replacement frequency



Simulated muon passing through the muon system



Simulated muons reconstructed in the emulsion target

Summary and plans

- SND@LHC installation on schedule
- data taking coming soon with LHC Run 3
- probe neutrinos in heavy flavour decays
  - cross-sections at uncharted energies
  - probe charm production
  - suitable for SM tests in the neutrino sector
- ongoing: installation of monitoring system
- upcoming: long commissioning runs
  - optimization of detector settings
  - measure background
- first stable beams & intensity ramp up: from mid-June!

What's next?

- advanced SND@LHC envisaged for HL-LHC: far + near detector
- far detector similar to current experiment + muon spectrometer
  - replace nuclear emulsions (possible technologies are under study)
  - charm production measurement and neutrino sector LFU tests at 1% precision
- near detector to overlap with LHCb pseudorapidity range
  - search suitable location in existing caverns
  - meant to reduce systematic uncertainties
  - perform cross section measurements