Neutrino physics at the LHC

Elena Graverini, with material from the SND@LHC and FASERν collaborations

École Polytechnique Fédérale, Lausanne

SPS annual meeting 2022

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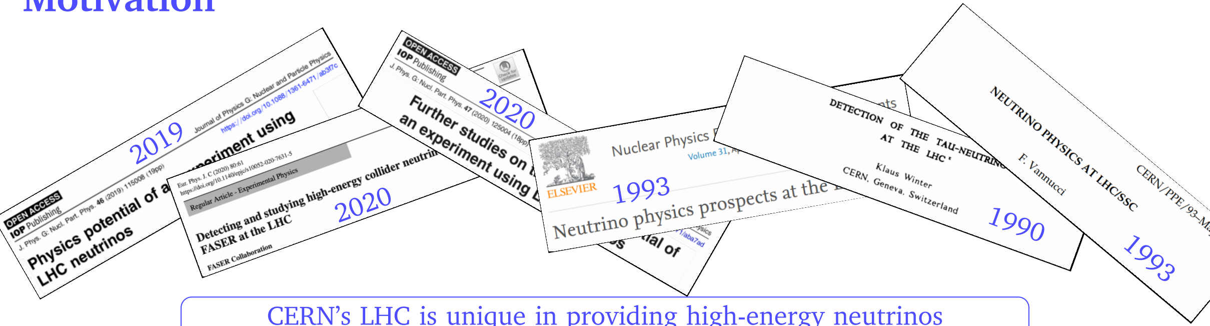
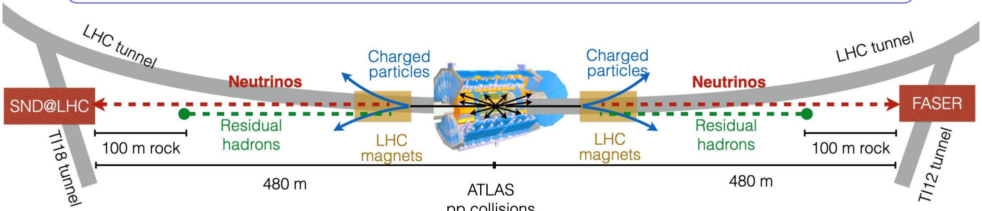
Motivation

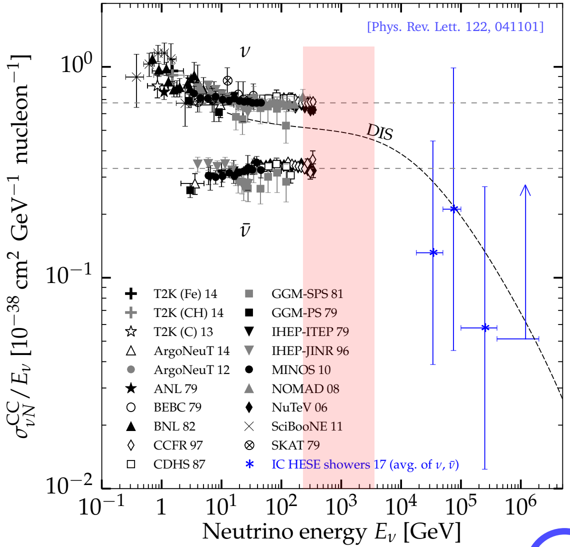


CERN's LHC is unique in providing high-energy neutrinos
and measuring $pp \to \nu X$ in an unexplored domain



Neutrino physics at the LHC

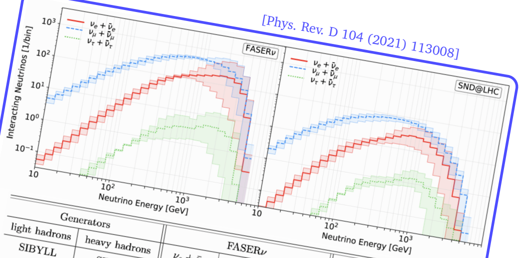
- $2\times$ compact, complementary detectors on either side of the ATLAS interaction point
  - **FASERν** on axis: $\eta > 8.8$
  - **SND@LHC** off axis: $7.2 < \eta < 8.4$
  - aim: collect 290 fb^{-1} luminosity in Run 3
  - expect $\mathcal{O}(10000)$ interacting neutrinos (all flavours)
- LHC neutrinos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



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

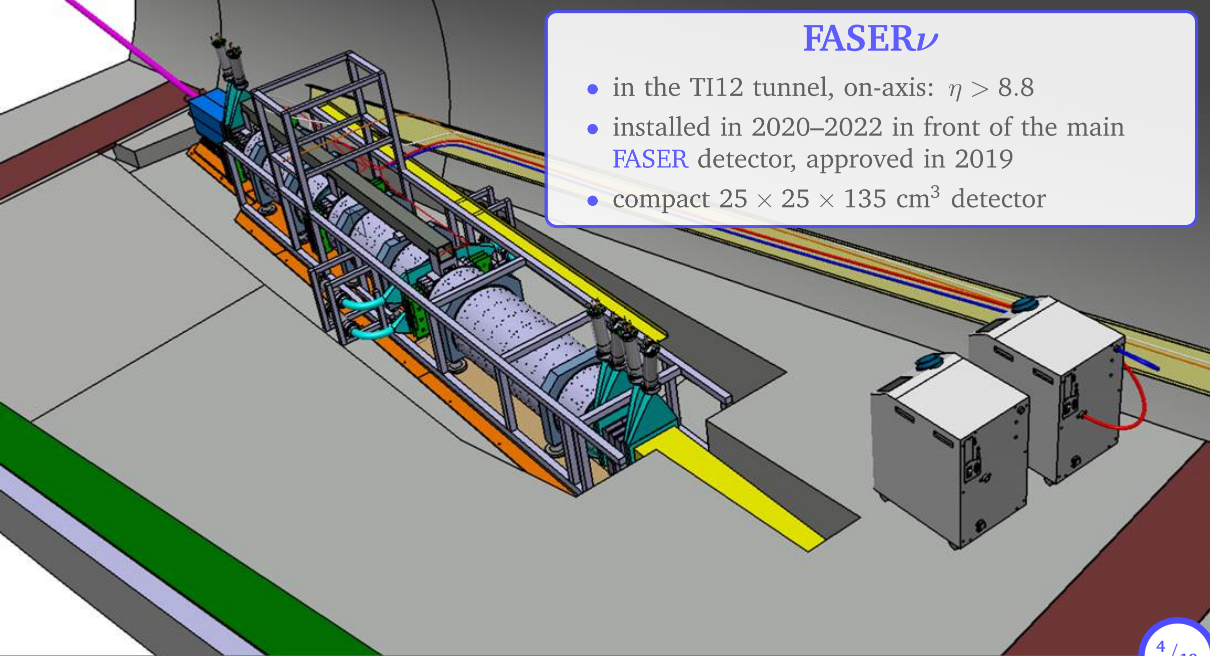
[Phys. Rev. D 104 (2021) 113008]



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



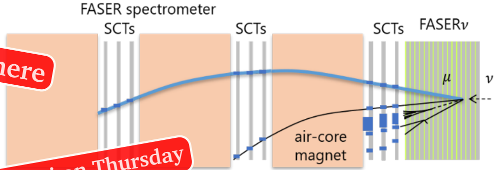
FASERν

- in the TI12 tunnel, on-axis: $\eta > 8.8$
- installed in 2020–2022 in front of the main FASER detector, approved in 2019
- compact $25 \times 25 \times 135\ \mathrm{cm}^3$ detector

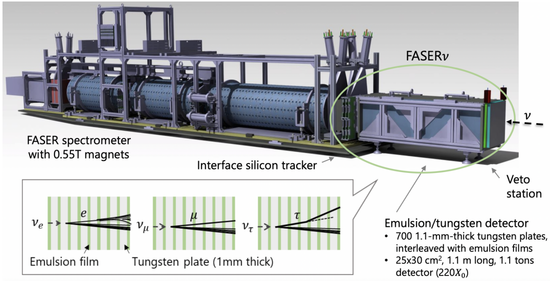
The FASERν concept

not further covered here

see talk by T. Moretti on Thursday

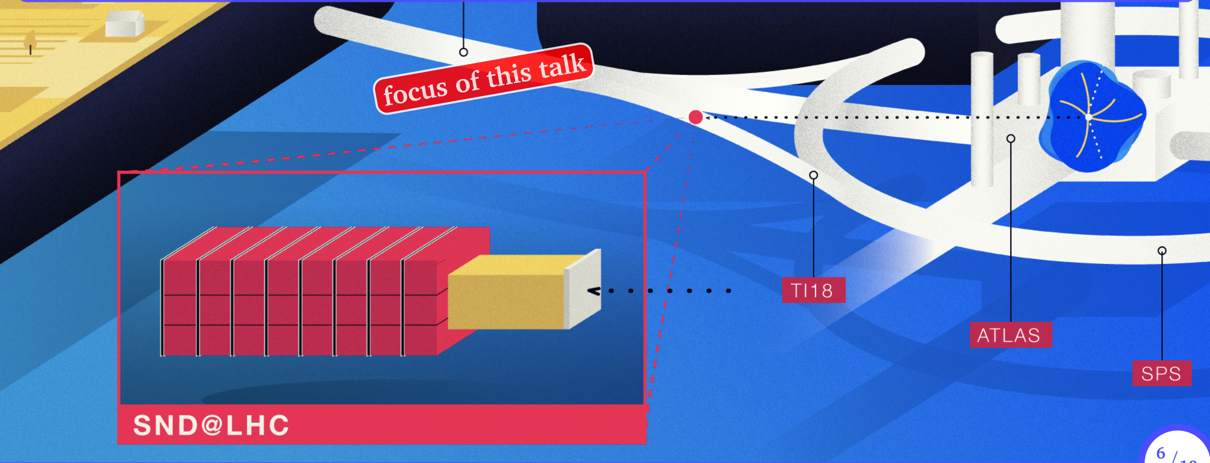


- in front of the main FASER detector:
  - interface silicon tracker
  - emulsion/tungsten target
  - veto plane
- distinguish all flavours by topology
- muon identification: track length (8λ)
- muon charge identification
- neutrino energy measured by ANN with topological and kinematical variables



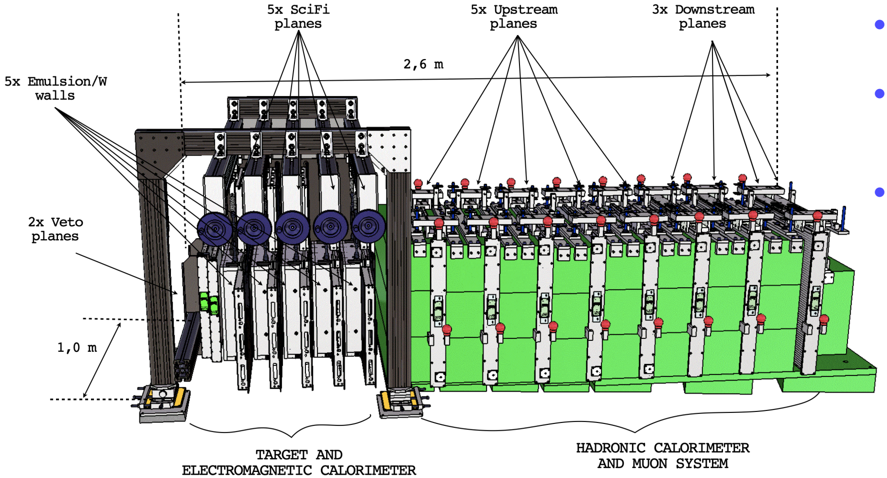
Scattering and Neutrino Detector at the LHC

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



The SND@LHC concept

...focus of next talk (E. Zaffaroni) too :)

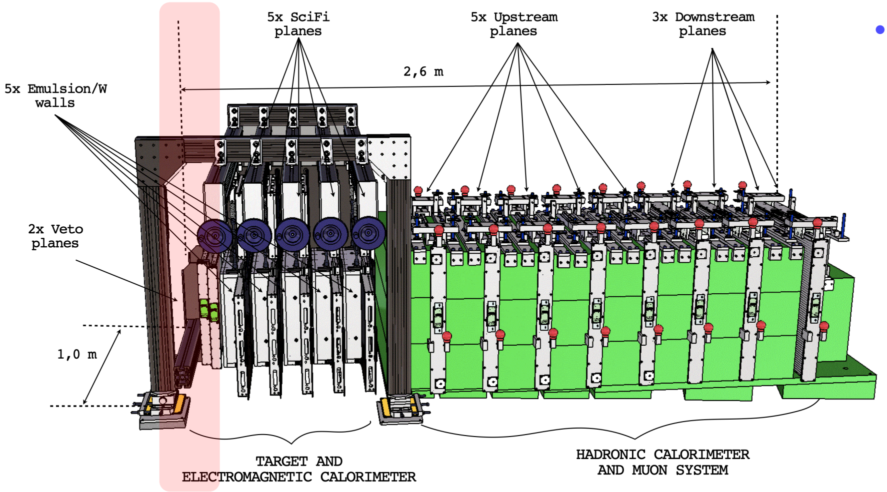


- hybrid, standalone detector
- optimised for the identification of the three neutrino species
- ...and the detection of scattering FIPs

The SND@LHC concept

...focus of next talk (E. Zaffaroni) too :)

Veto

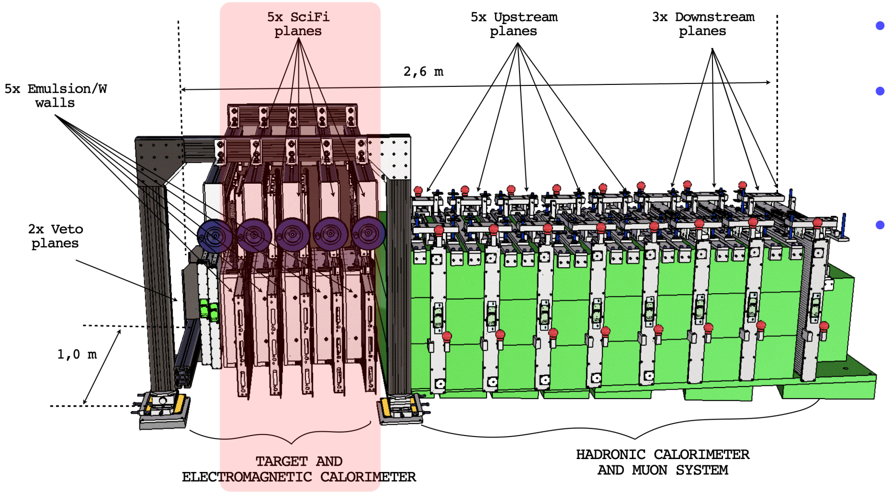


- upstream veto: two planes of scintillating bars
  - tag and discard events with incoming muons

The SND@LHC concept

...focus of next talk (E. Zaffaroni) too :)

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

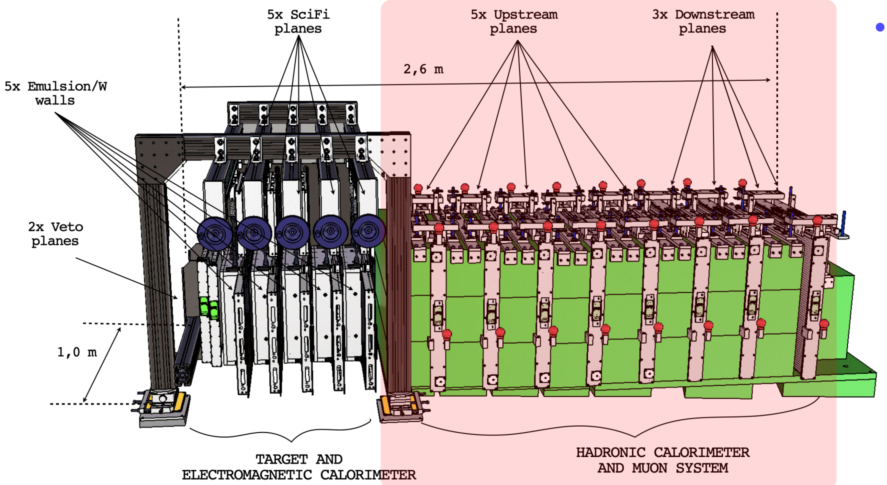


- 40 X_0 sampling calorimeter $\longrightarrow$ contain whole shower
- emulsion cloud chambers (ECC): interleaved tungsten plates / emulsions
  - vertexing, τ identification
- scintillating fiber planes (SciFi): timing / position

The SND@LHC concept

...focus of next talk (E. Zaffaroni) too :)

Downstream region



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

Installation "summary"

September 2021

March 2022

Two-phase event reconstruction

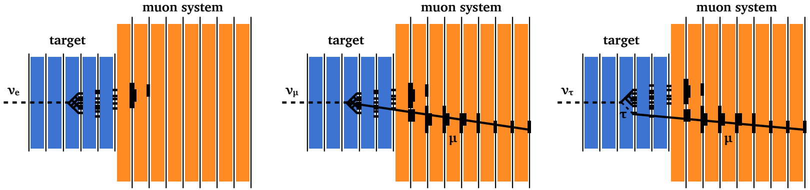
Online, using electronic detectors

- 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

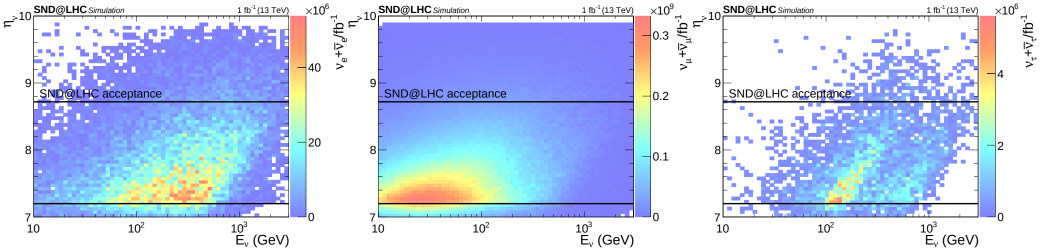


Simulation & expected neutrino flux

[thanks CERN Fluka team!]

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

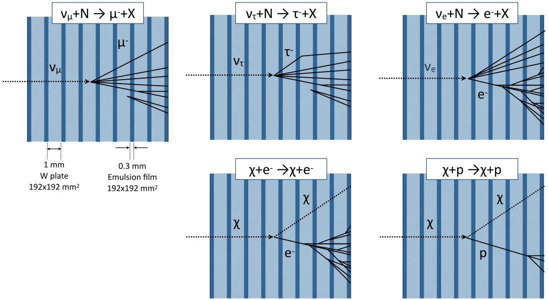


Physics performance: key features

[MC simulation studies]

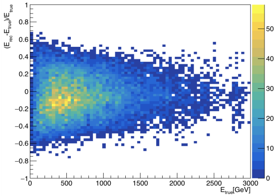
Flavour identification

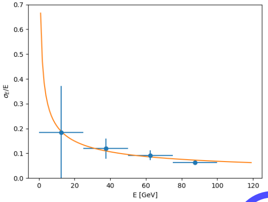
- ν_μ ID efficiency $\sim$77% driven by acceptance and occupancy (μ in donwstream Muon planes)
- ν_e identified by presence of EM shower in the ECC brick (99% efficiency)
- ν_τ ID relies on topological criteria (secondary vertex), $\sim$50% efficient



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



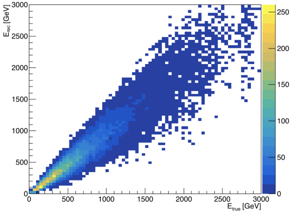


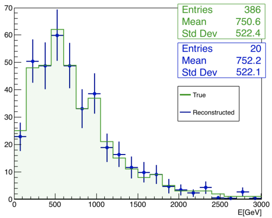
Neutrino physics: ν_e and charm

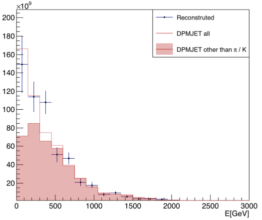
[LHCC-P-016]

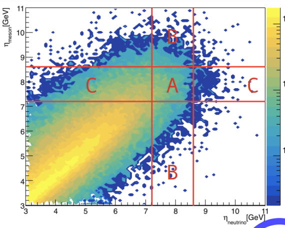
- 90% of $\nu_e + \bar{\nu}_e$ produced in charm decays

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





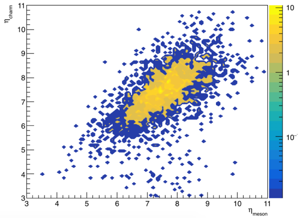


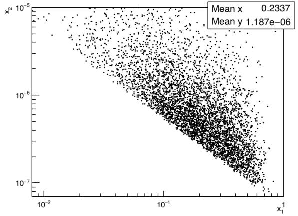


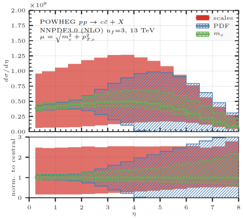
Neutrino physics: QCD

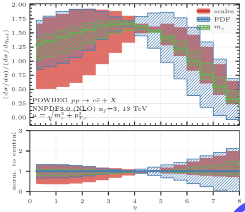
[LHCC-P-016] [M. V. Garzelli,SND@LHC open session 16/06/2022]

- 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]





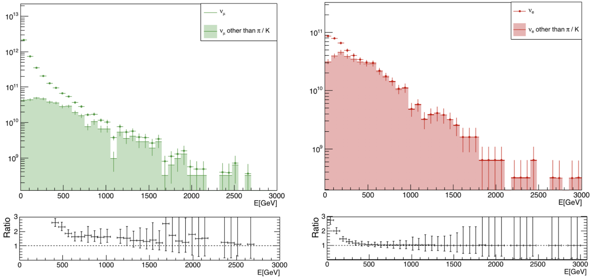




Neutrino physics: $e/\mu/\tau$ comparison

[LHCC-P-016]

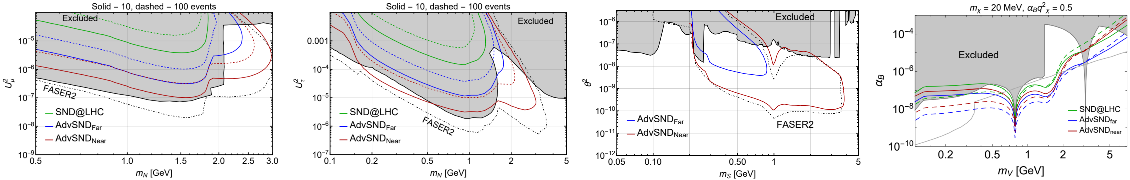
- ν_e and ν_τ only come from charm decays in SND@LHC
  - ratio $N_{\nu_e+\bar{\nu}_e}/N_{\nu_\tau+\bar{\nu}_\tau}$ depends only on decay branching ratios and charm fractions
  - sensitive to cross-section ratio of the two ν flavours: e-τ LFU in neutrino sector (unc. $\sim$30%)
- ν_μ neutrinos contamination 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



Scattering signatures and NP

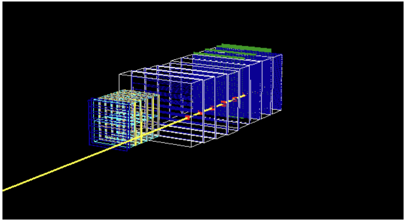
[LHCC-P-016] [JHEP 03 (2022) 006] [A. Boyarsky, SND@LHC open session 16/06/2022]

- 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+

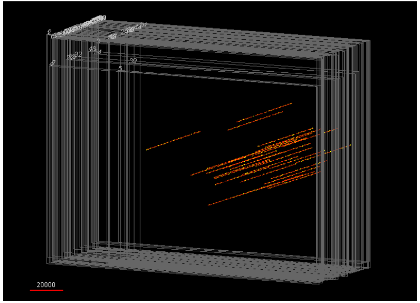


Early measurements (2022)

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
   - first result from emulsion scanning (5 days surface + 1 month cavern): 0.273 μ min^{-1} cm^{-2}
4. 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



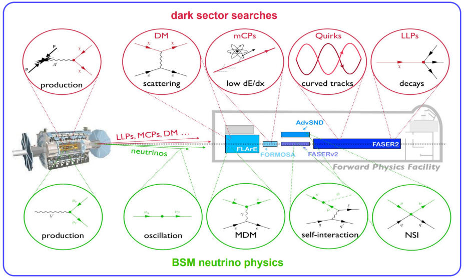
Simulated muons reconstructed in the emulsion target

Summary and plans

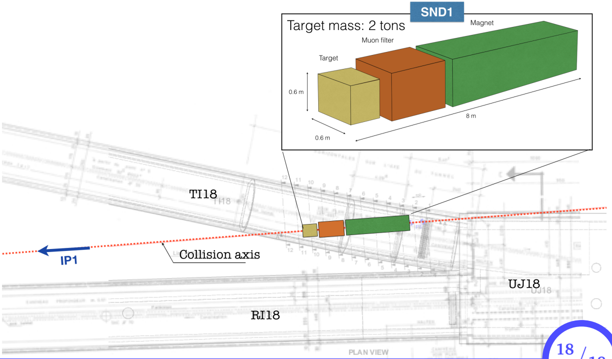
- first look at LHC neutrinos
  - ν cross-sections at uncharted energies
  - probe charm production
  - SM tests in the neutrino sector
- SND@LHC installation: ✔
- long commissioning runs
  - optimization of detector settings
  - measure background
- see next talk for first data!

What's next?

- AdvSND 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
  - possible FPF (**F**orward **P**hysics **F**acility) user if space constraints solved [hep-ph/2109.10905] [hep-ex/2203.05090]
- near detector to overlap with LHCb pseudora
  - meant to reduce systematic uncertainties
  - perform cross section measurements



[F. Kling, Neutrino 2022]



Spare slides

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