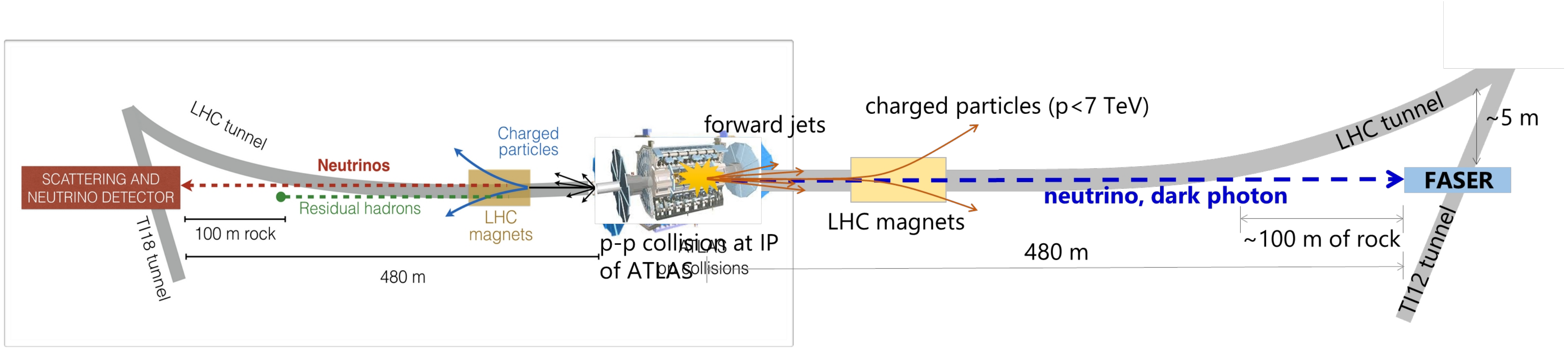
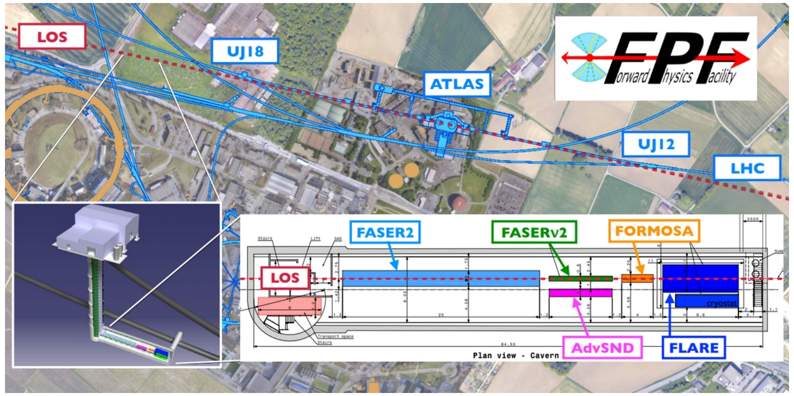
STATUS AND PERSPECTIVES FOR NEUTRINO STUDIES AT THE LHC





Mario Campanelli
University College London
On behalf of the SND@LHC collbaboration
With help from FASERv

FPCP May 2022

MOTIVATION

With the highest energy proton beams ever, the LHC can provide the world's highest energy accelerator neutrinos, and fill the gap between previous experiments and neutrino from UHE cosmic rays

- First observation of collider neutrinos
- Measure pp →X in an unexplored range
- Test lepton universality
- Study c/b production in CC interactions

Proposals for neutrino physics at the LHC have a long history

Klaus Winter, 1990, observing tau neutrinos at the LHC

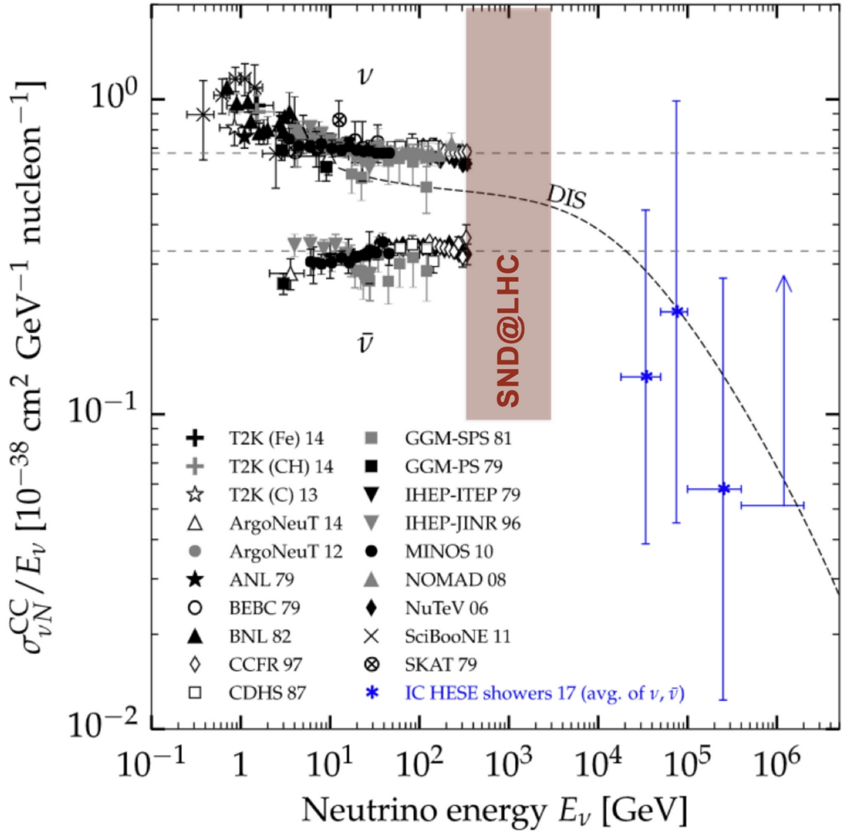
A. De Rùjula, E. Fernandez and J. J. Gòmez-Cadenas, 1993, Neutrino fluxes at LHC

F. Vannucci, 1993, neutrino physics at the LHC

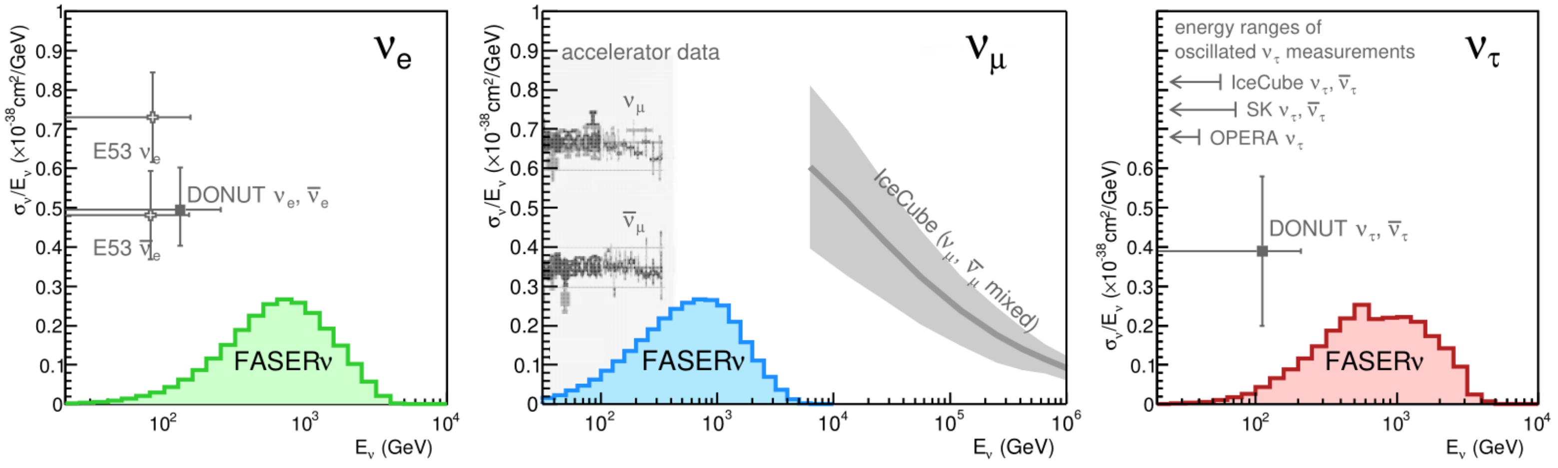
http://arxiv.org/abs/1804.04413 April 12th 2018
Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310
J. Phys. G Nucl. Part. Phys 46 (2019) 15008 (19 pp)
J.Phys. G Nucl. Part. Phys. 47 (2020) 125004 (18 pp)
CERN-LHCC 2021-003 https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf

The accessible energy range

PRL 122 (2019) 041101

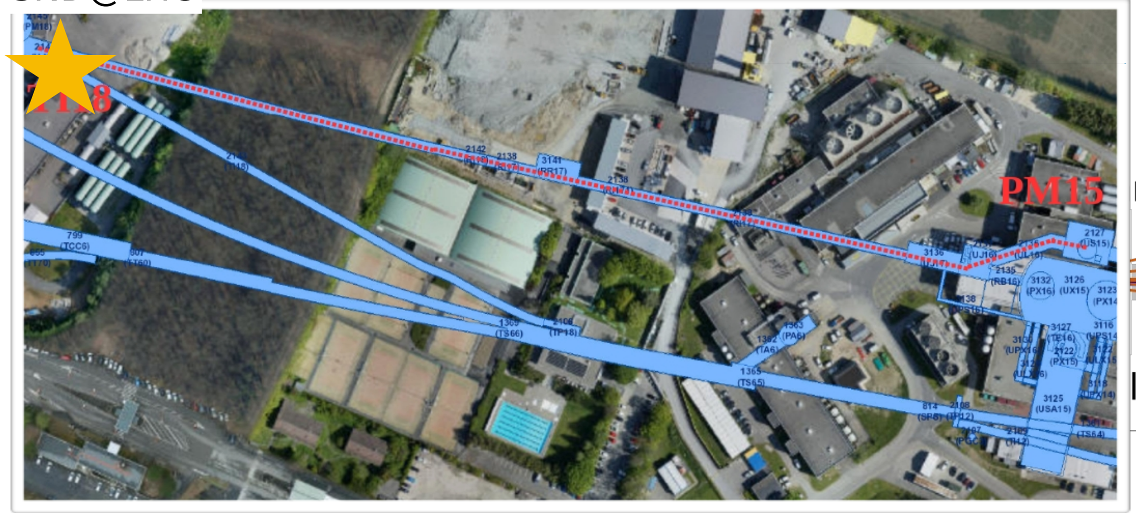


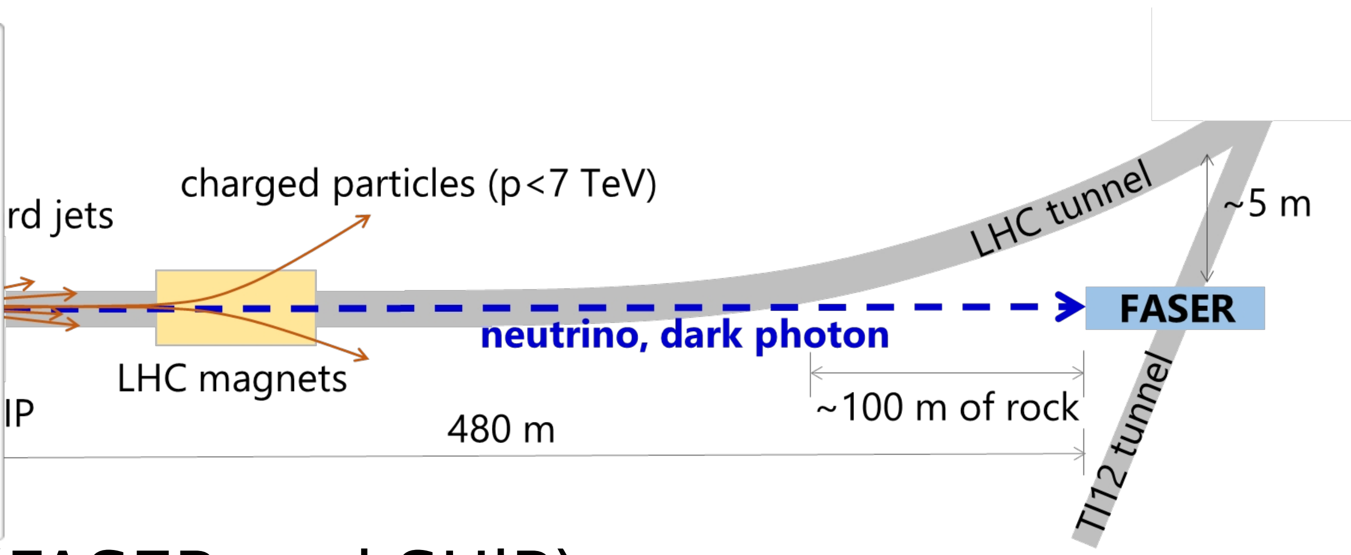
Eur. Phys. J. C 80 (2020) 61



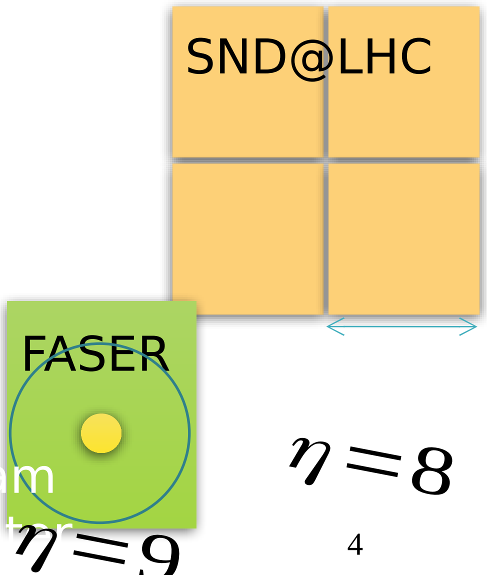
Two approved experiments: FASERν and SND@LHC

SND@LHC https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf





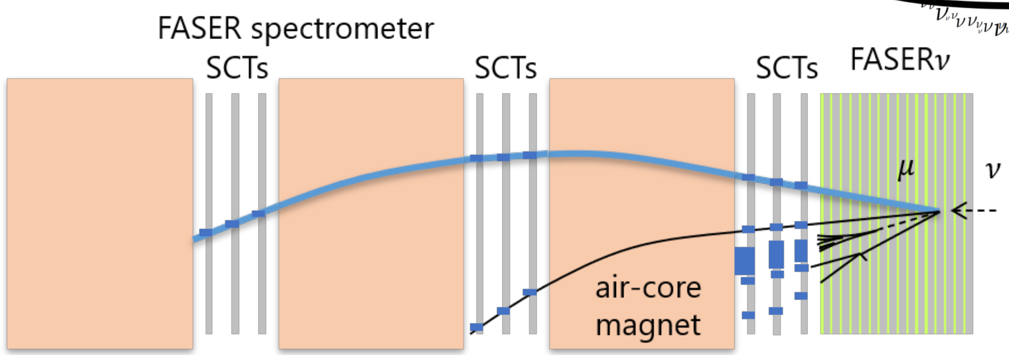
- Both “spinoffs” of LLP searches (FASER and SHiP)
- Located in symmetric locations in service tunnels ~480 m from ATLAS IP, with charged particles deflected by magnets, neutals absorbed by 100 m rock
- Aim at 150 (290)/fb, from 1.5 E16 pp collisions in Run3
- FASERν is on axis (η>8.8), SND@LHC covers 7.2<η< 8.4
- Expected yield: 5E11 ν_e, 3E12 ν_μ, 1E10 ν_τ

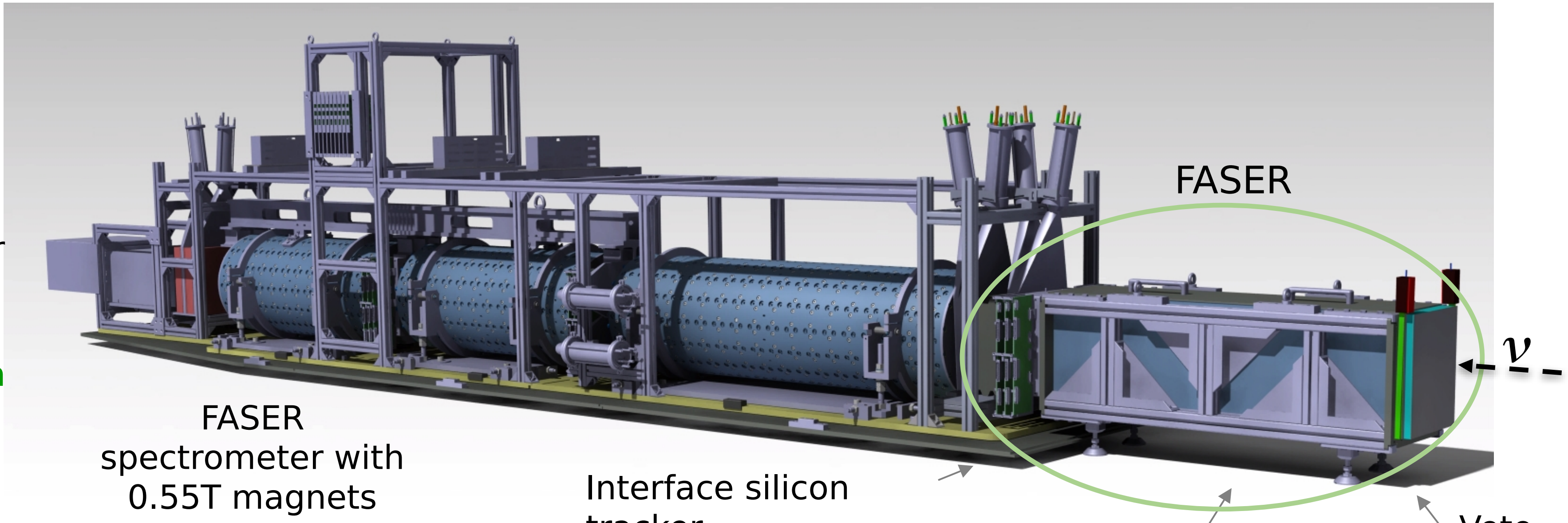


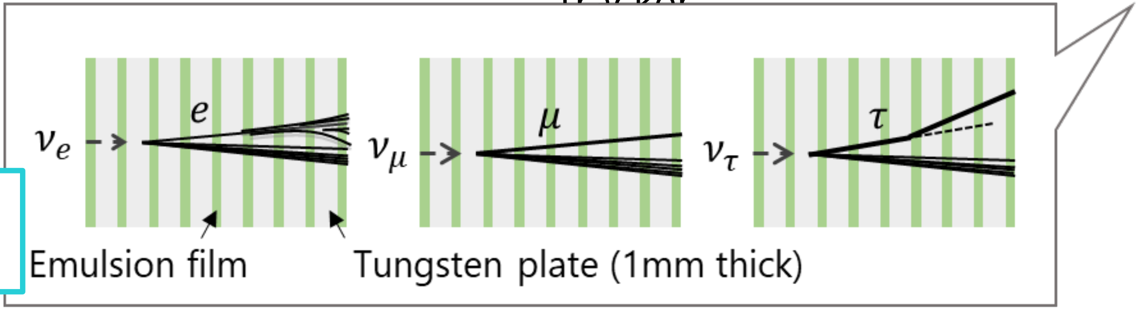
The FASER detector

- **Emulsion/tungsten detector, interface silicon tracker, and veto station** will be placed in front of the FASER main detector.
- Allow to distinguish **all flavor of neutrino interactions**.
  - **Muon identification** by their track length in the detector (8)
  - **Muon charge identification** with hybrid configuration ☾ distinguishing and
  - **Neutrino energy** measurement with ANN by combining topological and kinematical variables

Physics run in LHC Run 3 (2022-2025), 12 emulsion replacements







Emulsion/tungsten detector
- 700 1.1-mm-thick tungsten plates, interleaved with emulsion films
- $25 \times 30\ cm^2$, 1.1 m long, 1.1 tons detector (220)

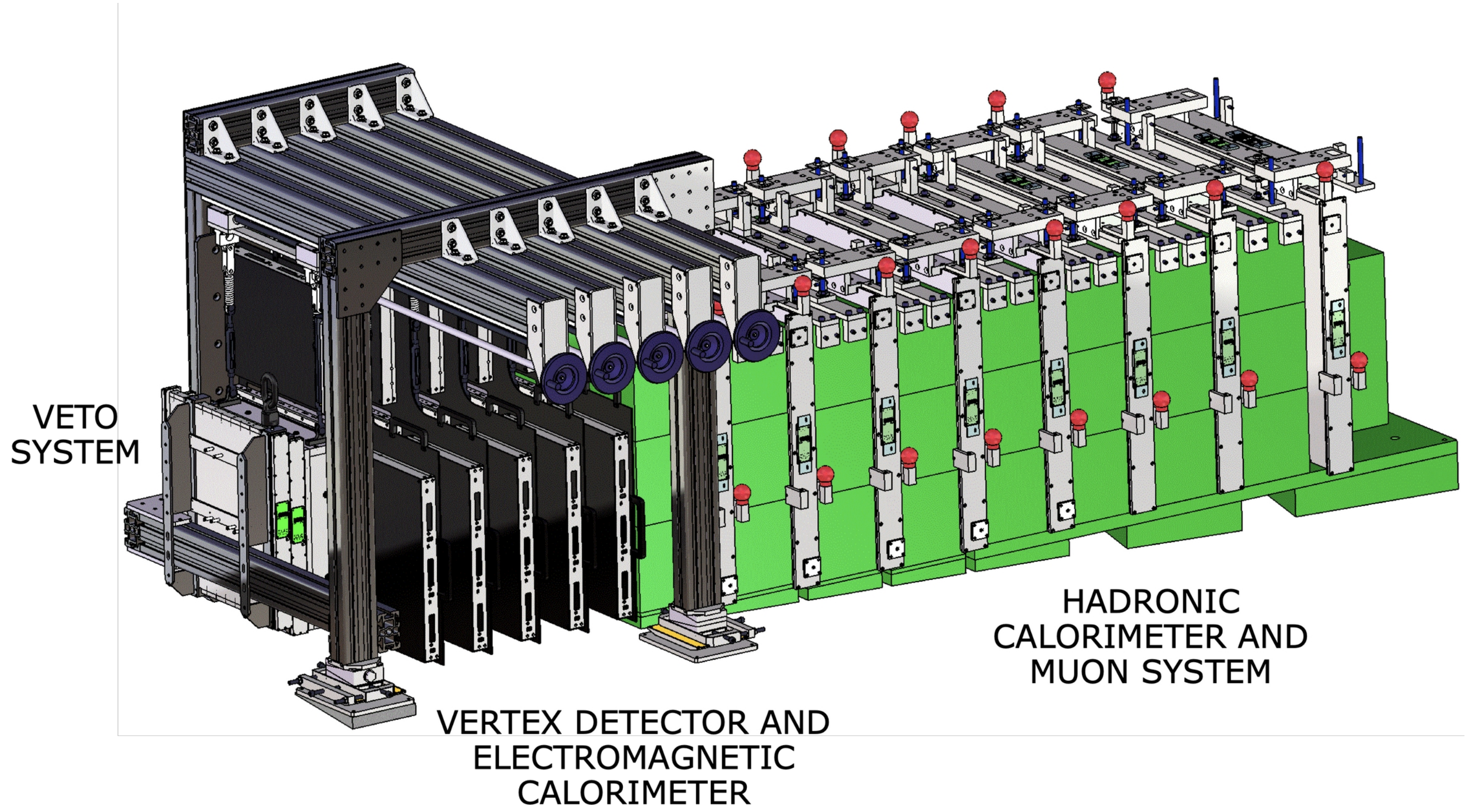
SND@LHC

Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles
Angular acceptance: 7.2< η < 8.4

VETO SYSTEM:
tag penetrating muons

VERTEX DETECTOR + EM CAL:
- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

HAD CAL + MUON SYSTEM:
iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement



Neutrino rapidity distributions
Phys Rev D 104, 113008 (2021)

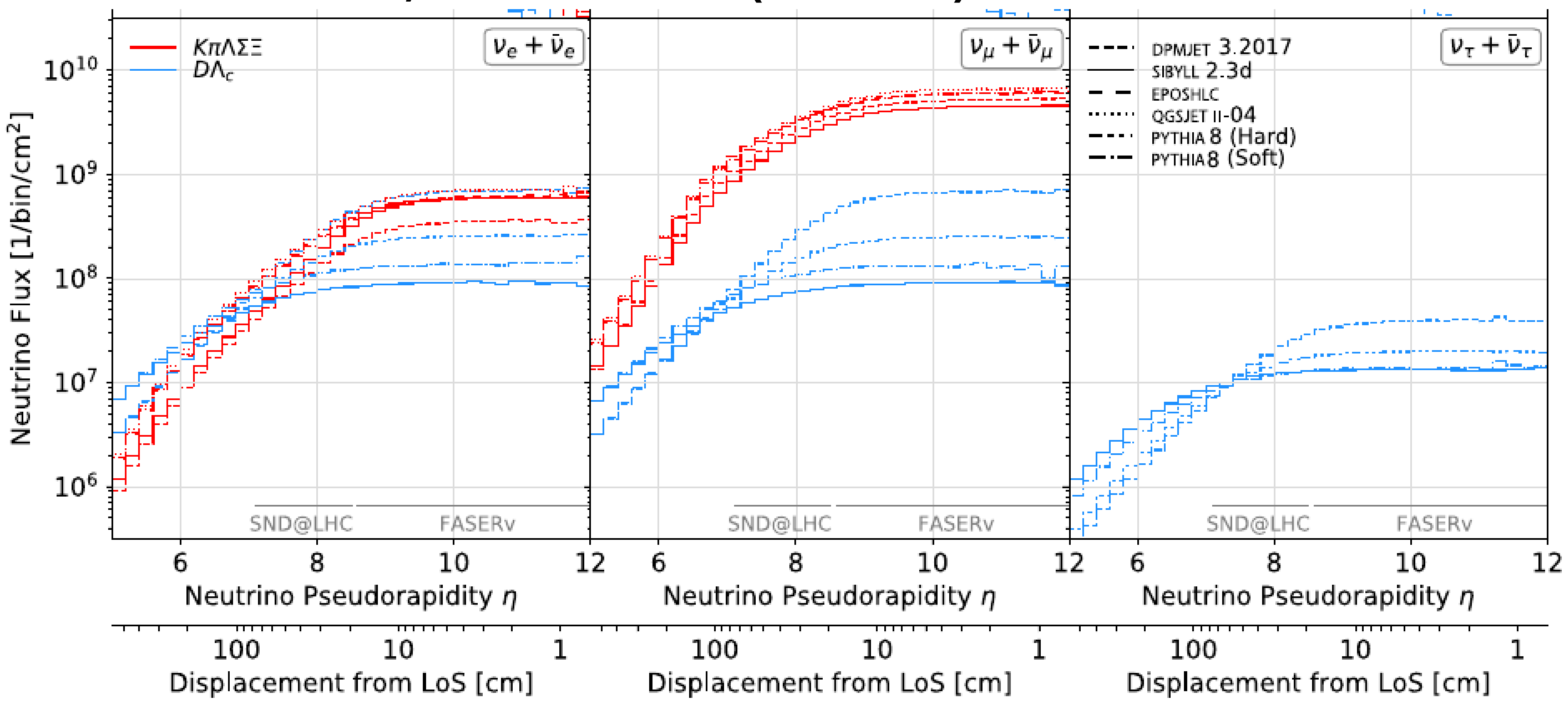
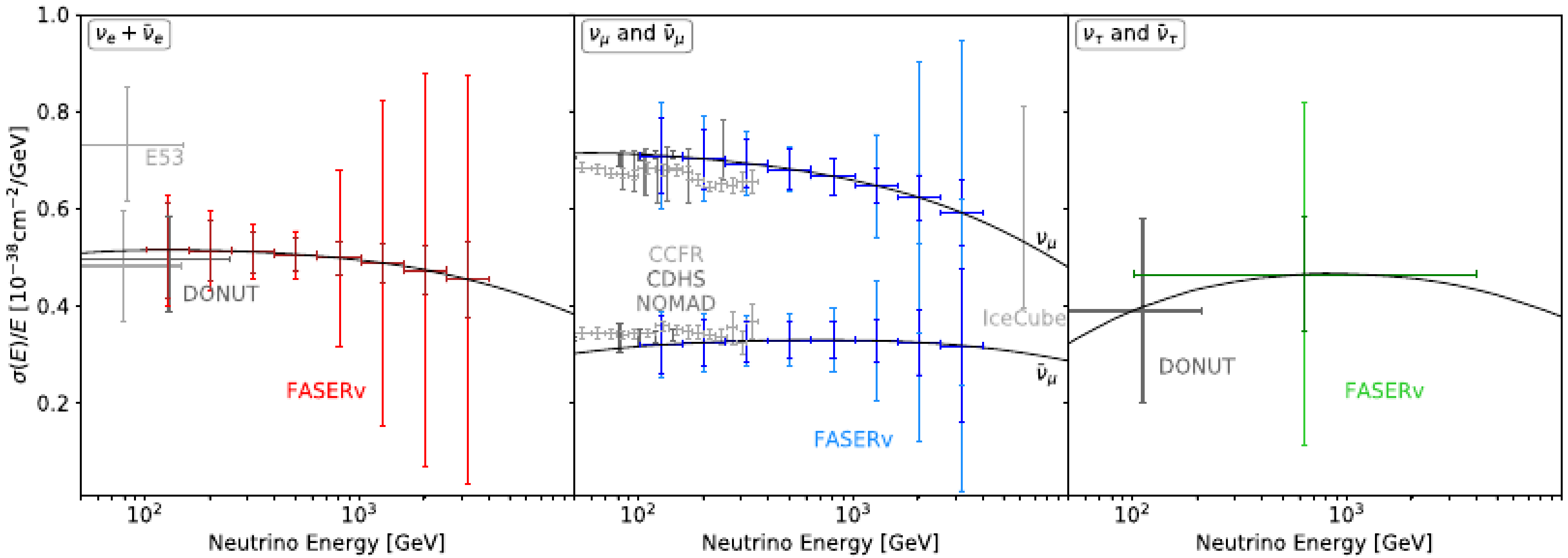


FIG. 5. Neutrino angular distribution: neutrino pseudorapidity distribution for electron (left), muon (center), and tau (right) neutrinos, as a function of pseudorapidity η or equivalently the radial displacement from the LoS at $z = 480$ m for LHC Run 3 with an integrated luminosity of 150 fb^{-1}. In the top panel, we show the number of neutrinos, in units of particles per bin, while the bottom panels show the neutrino flux, in units of particles per area per bin. The flux components from light hadron decays and charmed hadron decays are shown in red and blue, respectively. The line styles denote the different event generators. All energies $E_\nu > 10$ GeV are included. Shown at the bottom of each panel is the angular coverage of FASERν and SND@LHC.

Neutrino cross sections



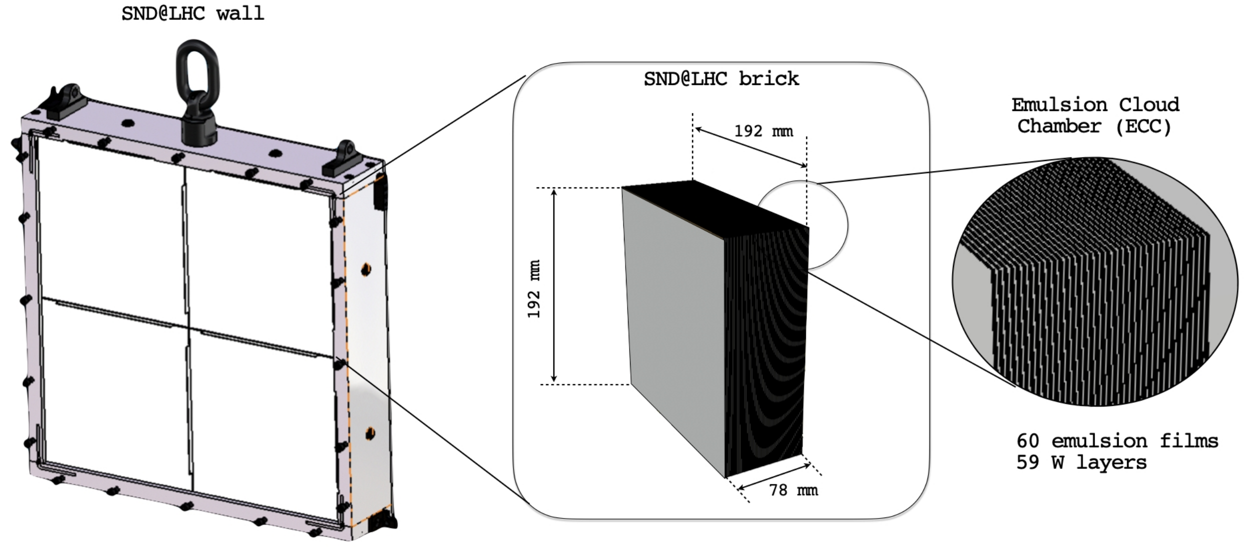
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7
DPMJET	DPMJET	3457	7088	97
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2
QGSJET	Pythia8 (Soft)	970	5351	16.1
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$

FASERv (150/fb)

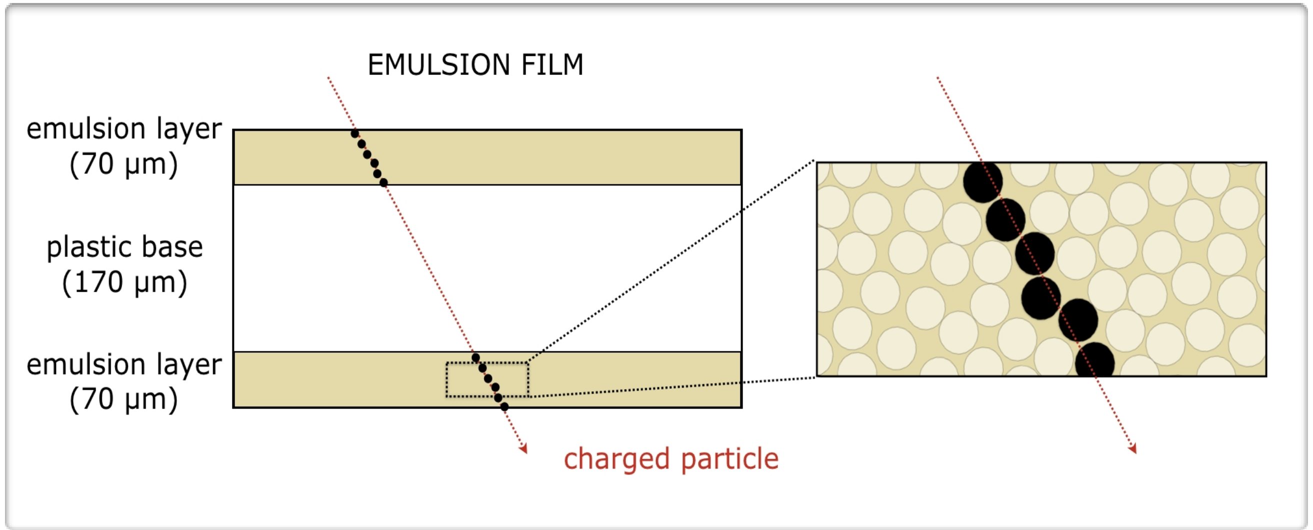
Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Yield	CC neutrino interactions ⟨E⟩ [GeV]	Yield	NC neutrino interactions ⟨E⟩ [GeV]	Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157
ν_e	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58
ν_τ	400	2.8×10^{10}	740	23	740	8
$\bar{\nu}_\tau$	380	3.1×10^{10}	740	11	740	5
TOT		7.3×10^{12}		1930		625

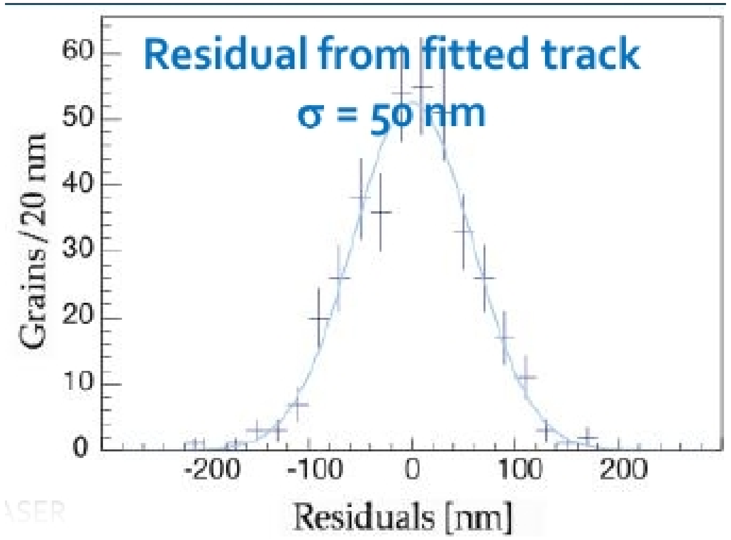
SND@LHC (290/fb)

EMULSION TARGETS

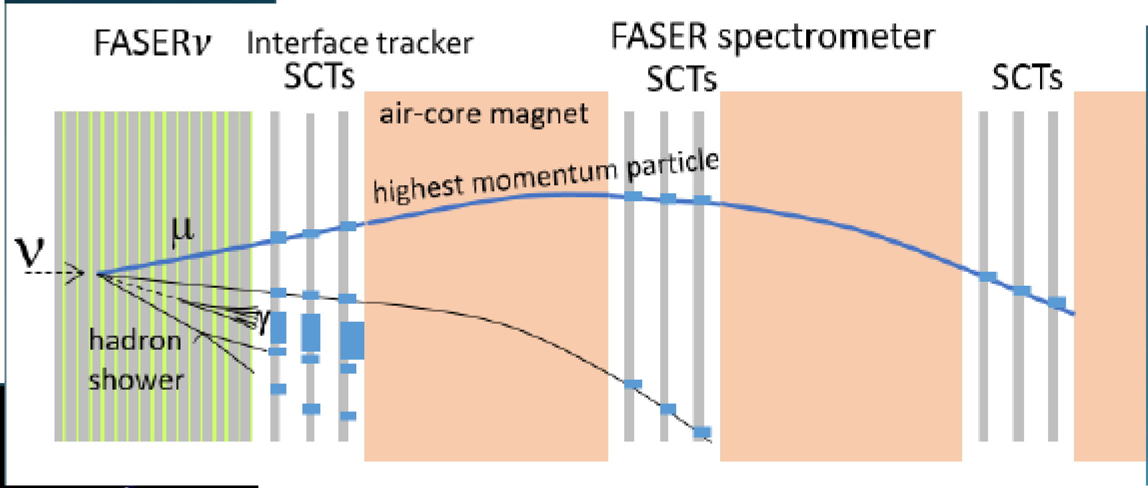


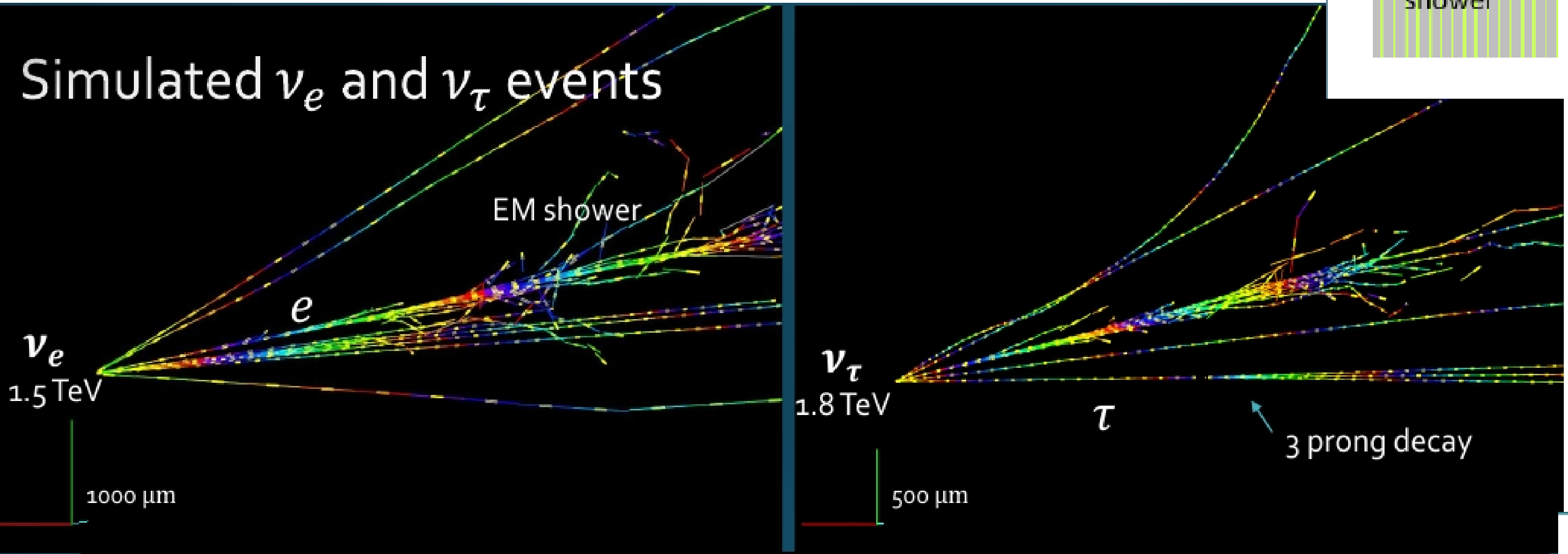
Target assembled according to the Emulsion Cloud Chamber (ECC) technique:
Tungsten layers (1mm-thick) alternated to nuclear emulsion films

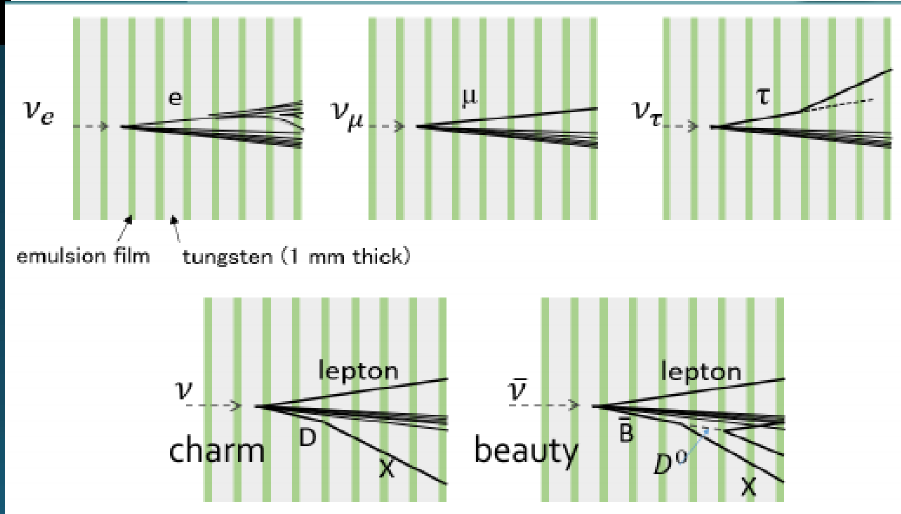




Events in FASER + FASERν

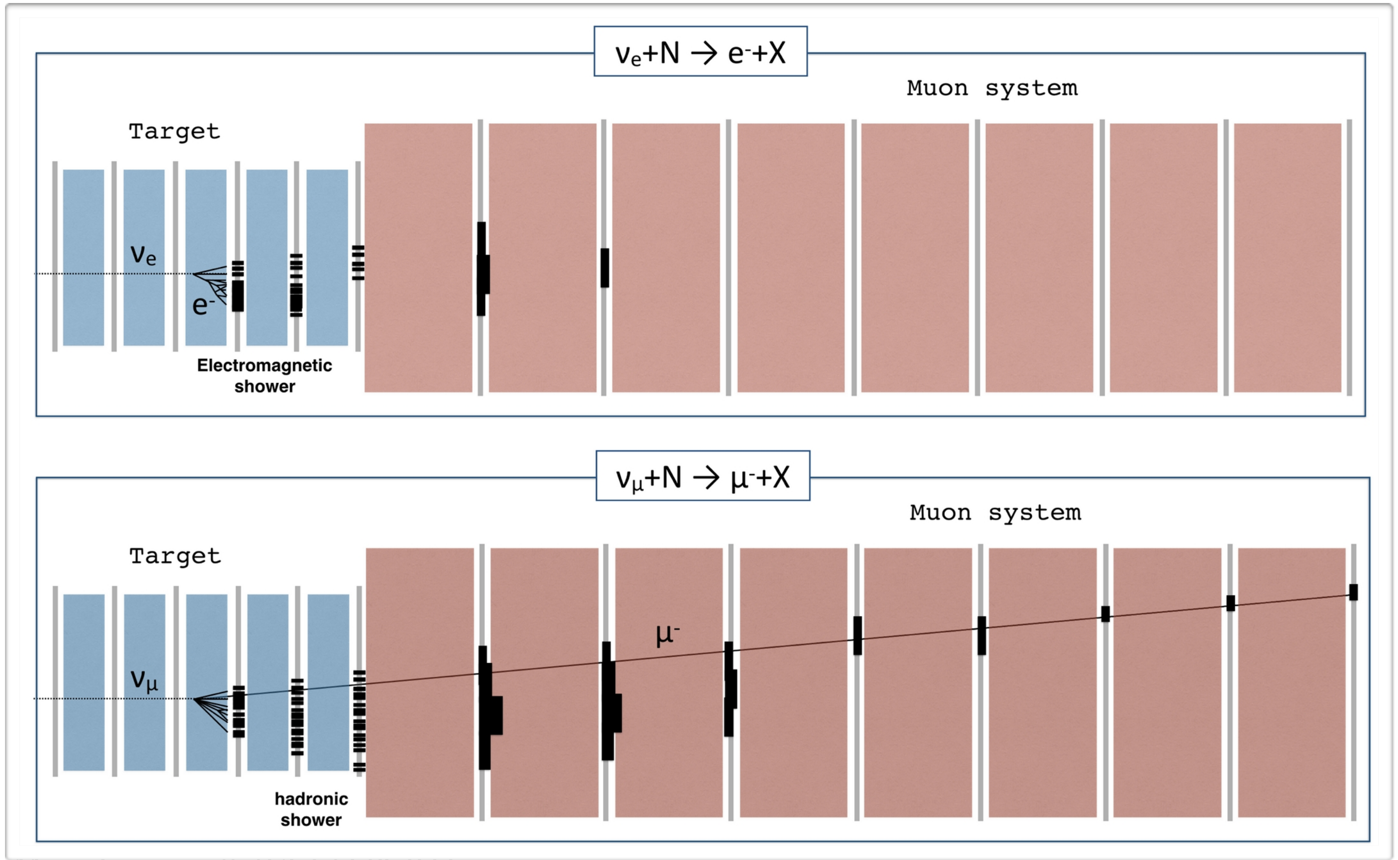




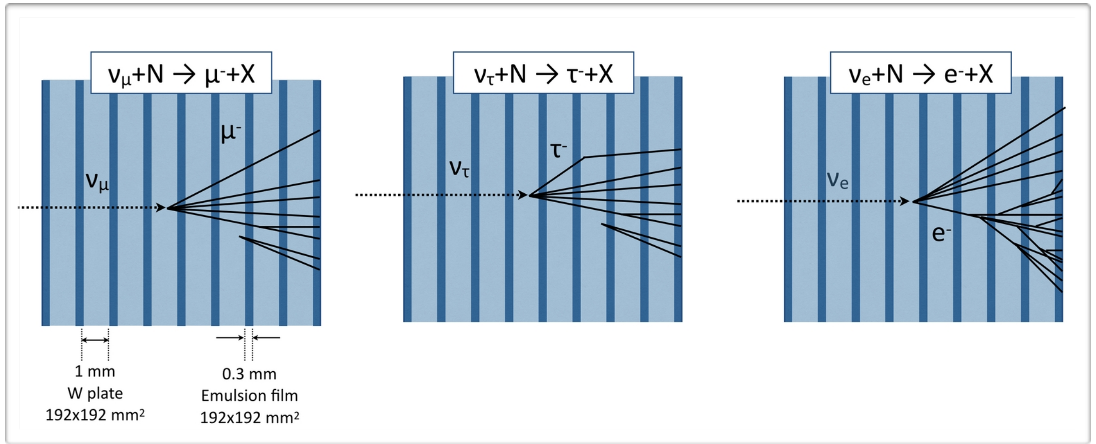


EVENT RECONSTRUCTION in SND

- **FIRST PHASE: electronic detectors**
- Event reconstruction based on Veto, Target Tracker and Muon system
  - Identify neutrino candidates
  - Identify muons in the final state
  - Reconstruction of electromagnetic showers (SciFi)
  - Measure neutrino energy (SciFi+Muon)

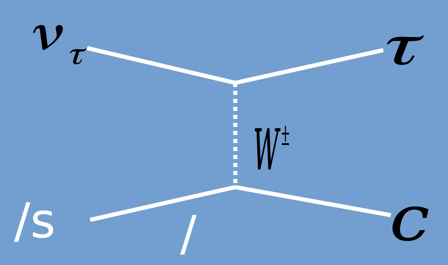


- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement



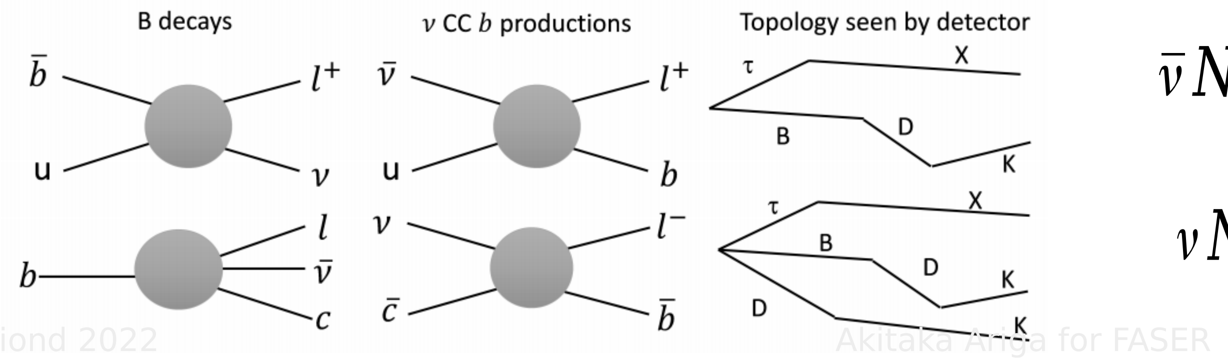
Heavy flavors with FASER

- Measure charm production channels
  - Large rate ~ 15% CC events, events
  - First measurement of induced charm prod.



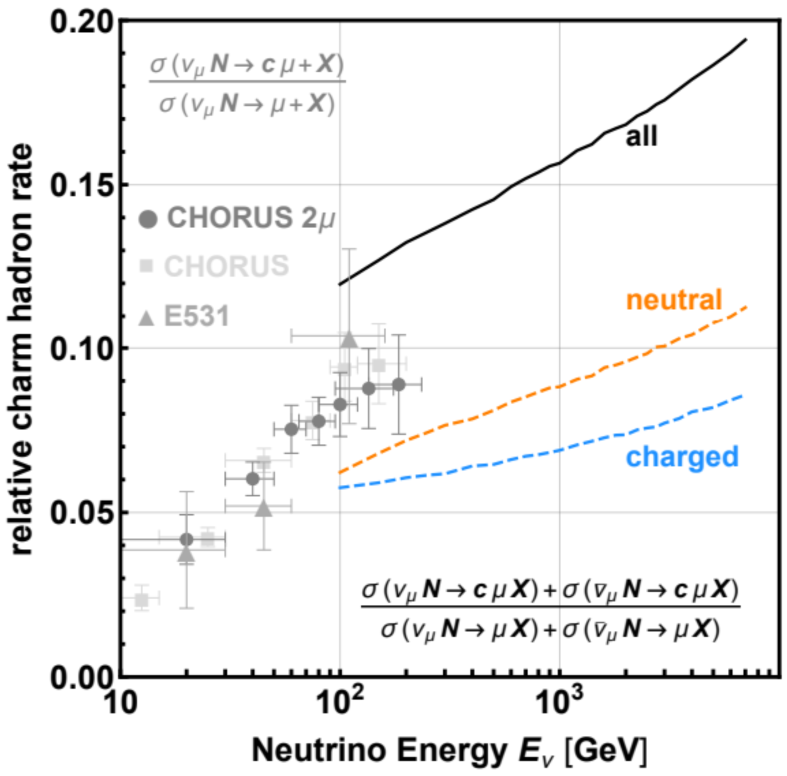
$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)}$$

- Search for Beauty production channels
  - Expected SM events (production) are events due to CKM suppression,



$$\bar{\nu} N \to \ell \bar{B} X$$

$$\nu N \to \ell B D X$$

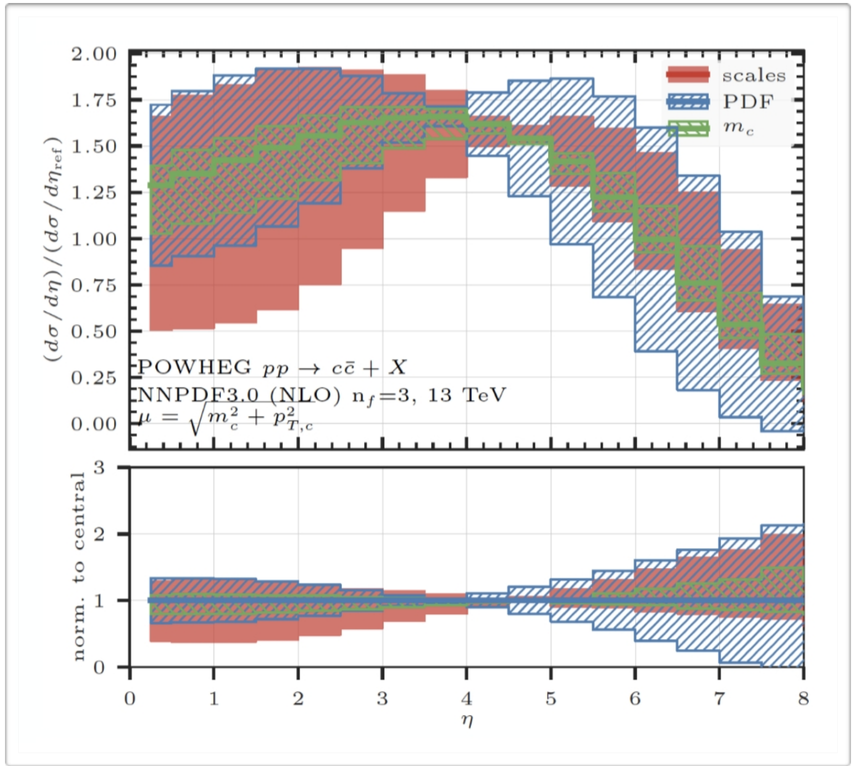


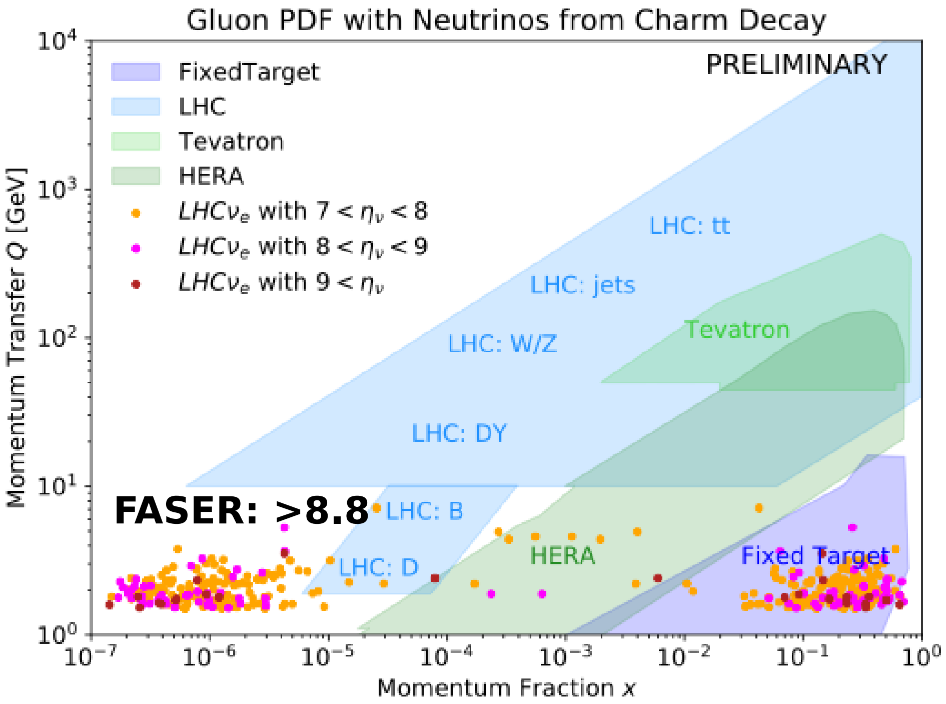
A.Ariga, Moriond 2022 talk

QCD MEASUREMENTS

The dominant partonic process for associated charm production at the LHC is gluon-gluon scattering
Average lowest momentum fraction: 10^{-6}

Extraction of gluon PDF in very small x-region relevant for Future Circular Colliders





Ratio between the cross-section measurements at different energies and pseudo-rapidities

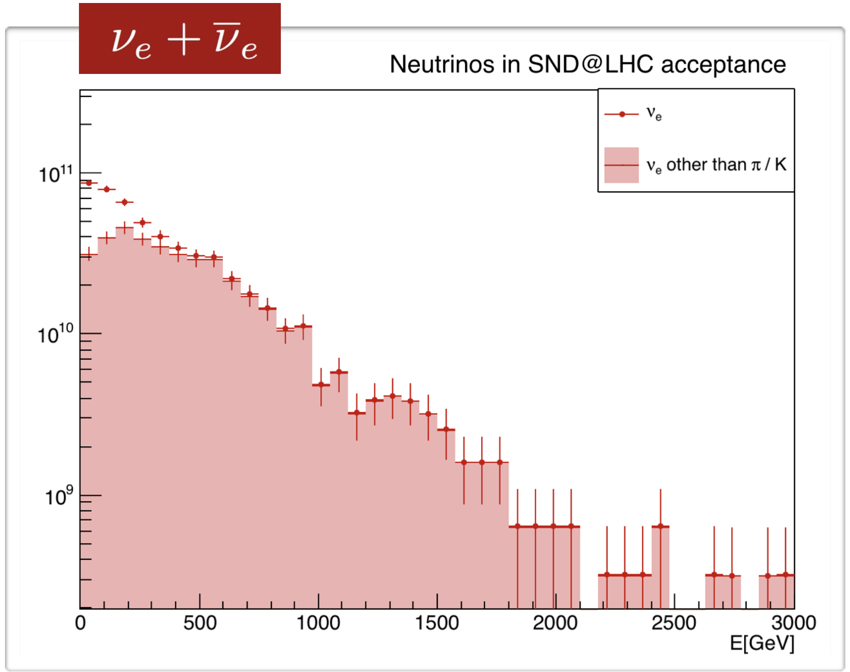
$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

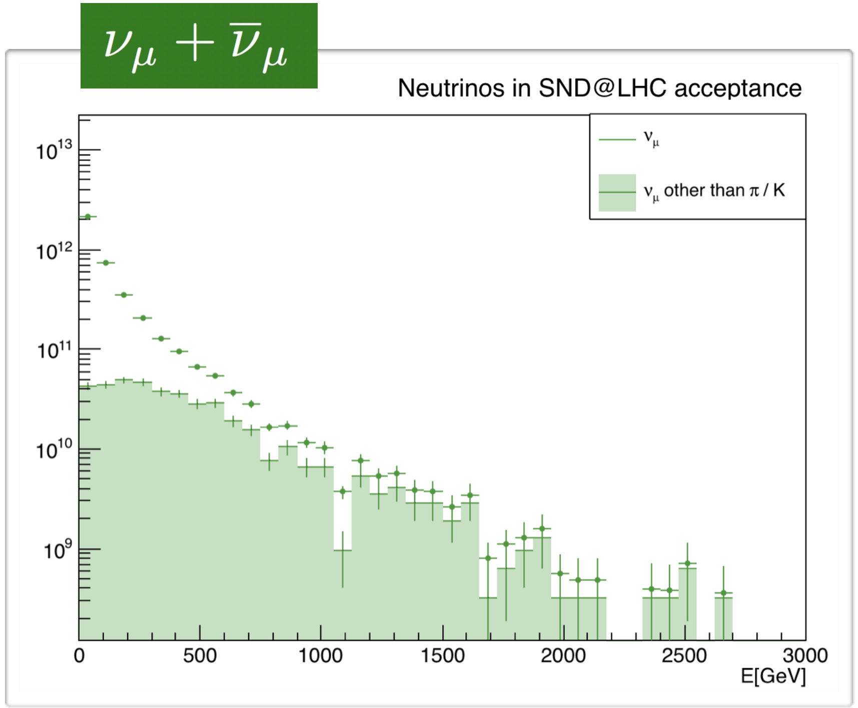
$$\eta_{ref} = 4.5$$

Reduction of scale uncertainties
Constraint the PDF with data

LEPTON FLAVOUR UNIVERSALITY TEST

- The identification of three neutrino flavours in the SND@LHC detector offers a unique possibility to test the Lepton Flavor Universality (LFU)





$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

- Sensitive to ν-nucleon interaction cross-section ratio of two neutrino species

$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

contamination from π/k

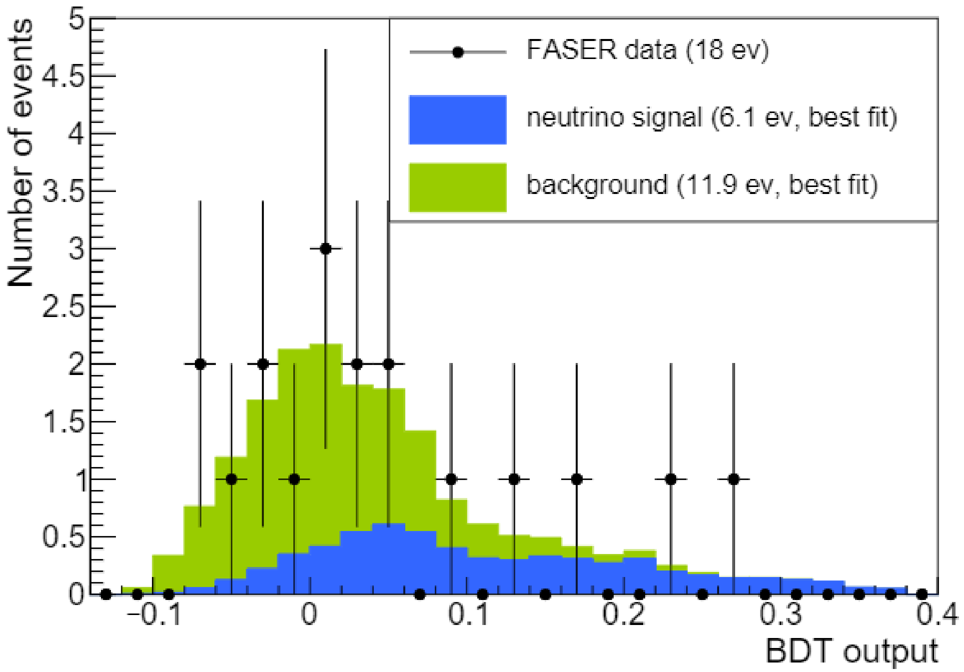
- The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU for E>600 GeV

SUMMARY OF NEUTRINO PHYSICS UNCERTAINTIES IN SND

Measurement	Uncertainty Stat.	Uncertainty Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	20%
ν_e/ν_μ ratio for LFU test	10%	10%
Measurement of NC/CC ratio	5%	10%

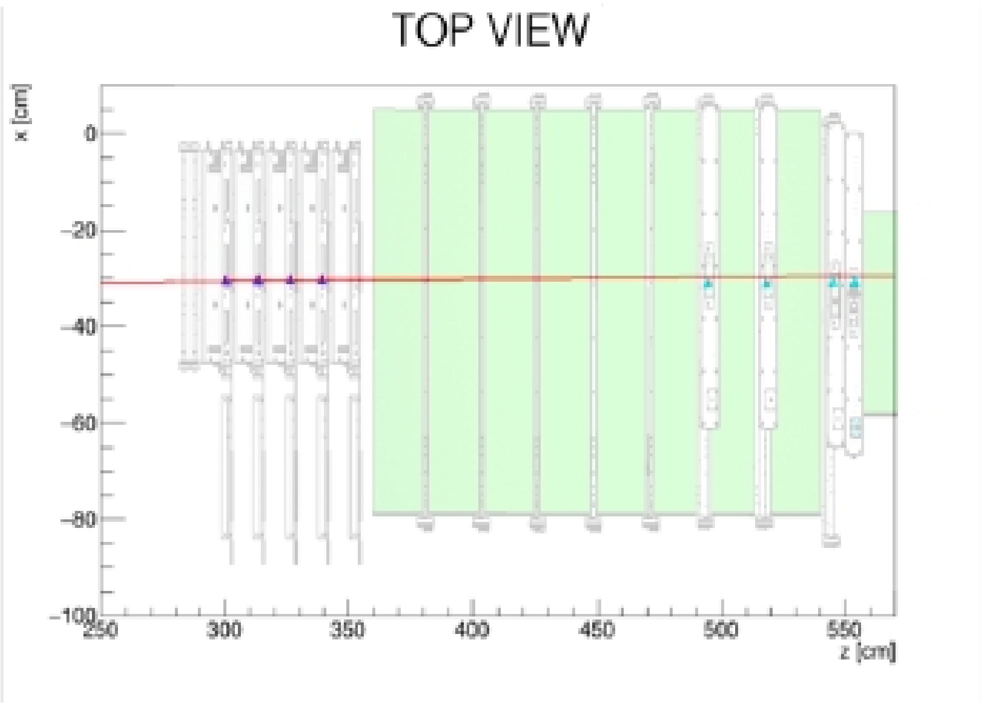
FASER RESULTS FROM 2018 TEST RUN
Phys. Rev. D 104, L091101 (2021)

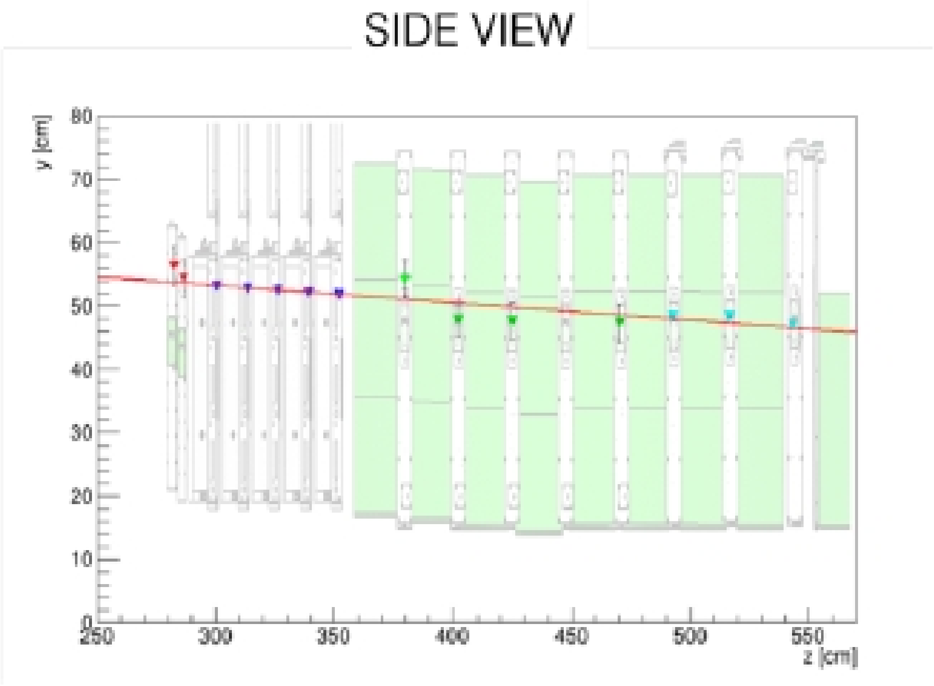
- Analyzed target mass of 11 kg and luminosity of 12.2 fb^{-1}
- 18 neutral vertices were selected
  - by applying # of charged particle 5, etc.
  - Expected signal = events, BG = 11.0 events
- Note: no lepton ID in the pilot run ☾ High BG
- In BDT analysis, an excess of neutrino signal (6.1 events) is observed. Statistical significance = 2.7 from null hypothesis
- This result demonstrates the detection of neutrinos from the LHC



2022 splashes in SND@LHC

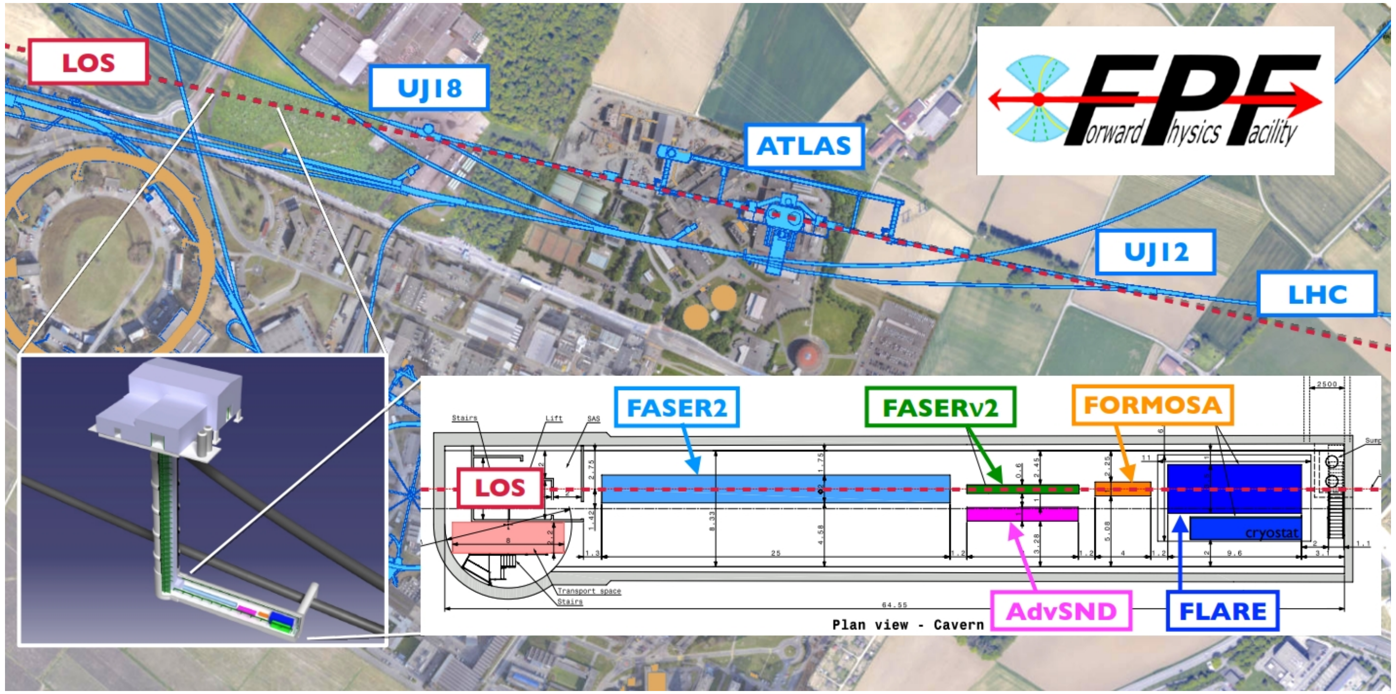
SND@LHC was not installed in 2018, but it observed its first signals on April 29, 2022, recording LHC splashes on the ATLAS collimators using its electronic detectors



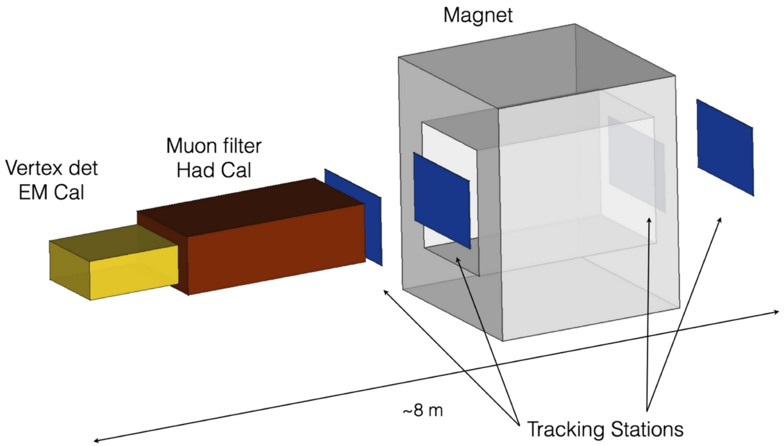


The new FPF facility, FASERv2 and advanced SND@LHC

- The Forward Physics Facility (https://arxiv.org/abs/2203.05090) for the HL-LHC is a proposed facility that could house a suite of experiments to **greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD**.
  - The background muon rate may be able to be reduced with a sweeper magnet (studies ongoing).
- **FASER2 is a much larger detector designed to increase sensitivity to LLP by two orders of magnitude. FASER v2 can carry out precision tau-neutrino measurements** and heavy flavor physics studies
  - **2300 (SIBYLL) / 20000 (DPMJET) tau-neutrino interactions are expected.**



	AdvSND - NEAR	AdvSND - FAR
η	[4.0, 5.0]	[7.2, 8.4]
mass (ton)	5	5
surface (cm^2)	120×120	100×55
distance (m)	55	630



CONCLUSIONS

- After many years of feasibility studies, neutrino experiments from colliders are becoming a reality with LHC RUN3
- FASER-ν and SND@LHC are located in symmetric positions 480 meters from the ATLAS interaction point, covering complementary rapidity intervals
- Neutrino physics programs covers cross section for the three flavours, HF production, NC/CC rations, lepton universality
- Both detectors foresee upgrades for the HL-LHC, possibly to be integrated in a future Forward Physics Facility