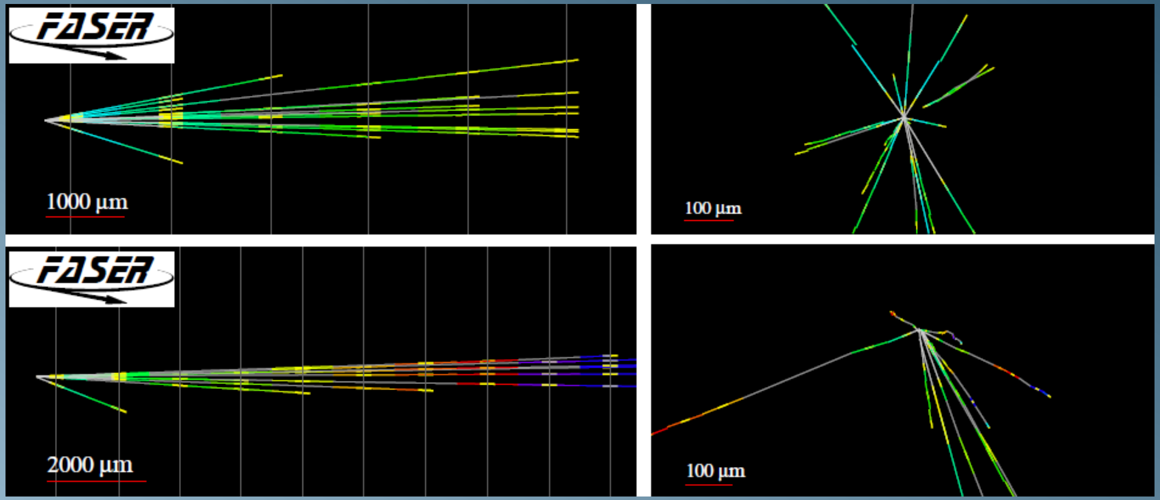
Measuring three-flavor neutrinos with FASERν at the LHC

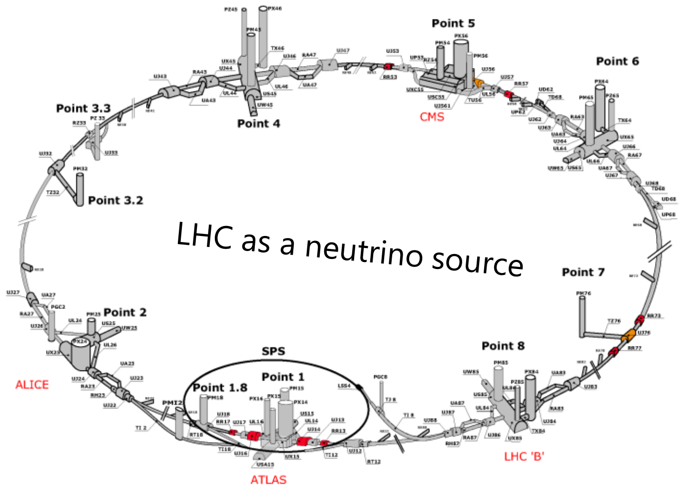
Tomoko Ariga (Kyushu University)
on behalf of the FASER Collaboration



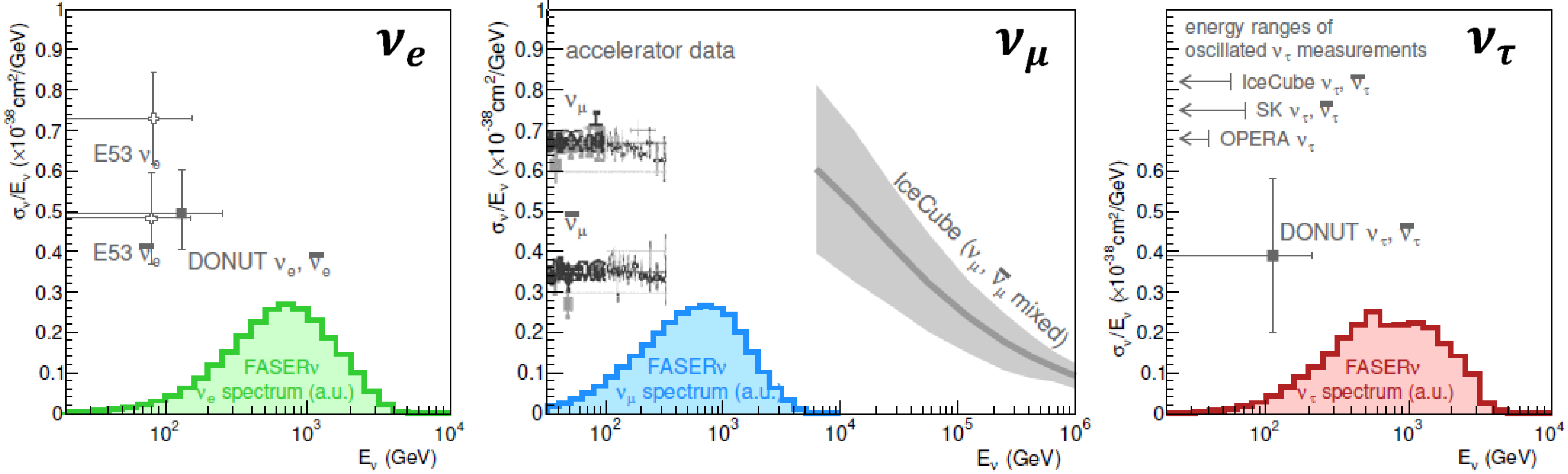
First neutrino interaction candidates at the LHC, arXiv:2105.06197

Physics motivations

- **Studying neutrinos in unexplored high-energy regime (TeV energies)**
  - Neutrinos from the LHC
    - Use of a collider as a neutrino source for the first time
    - High energy frontier of man-made neutrinos
  - Cross section measurements of different flavors at high energy
  - Probing neutrino-related models of new physics
  - From the other perspective, measurements of forward particle production



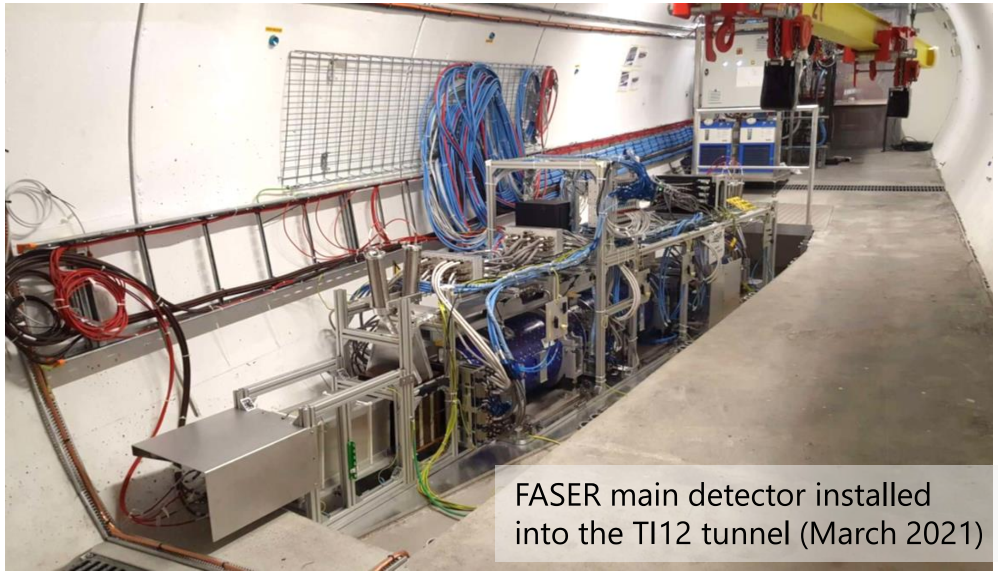
Existing measurements of νN CC cross sections and the expected energy spectra for FASERν

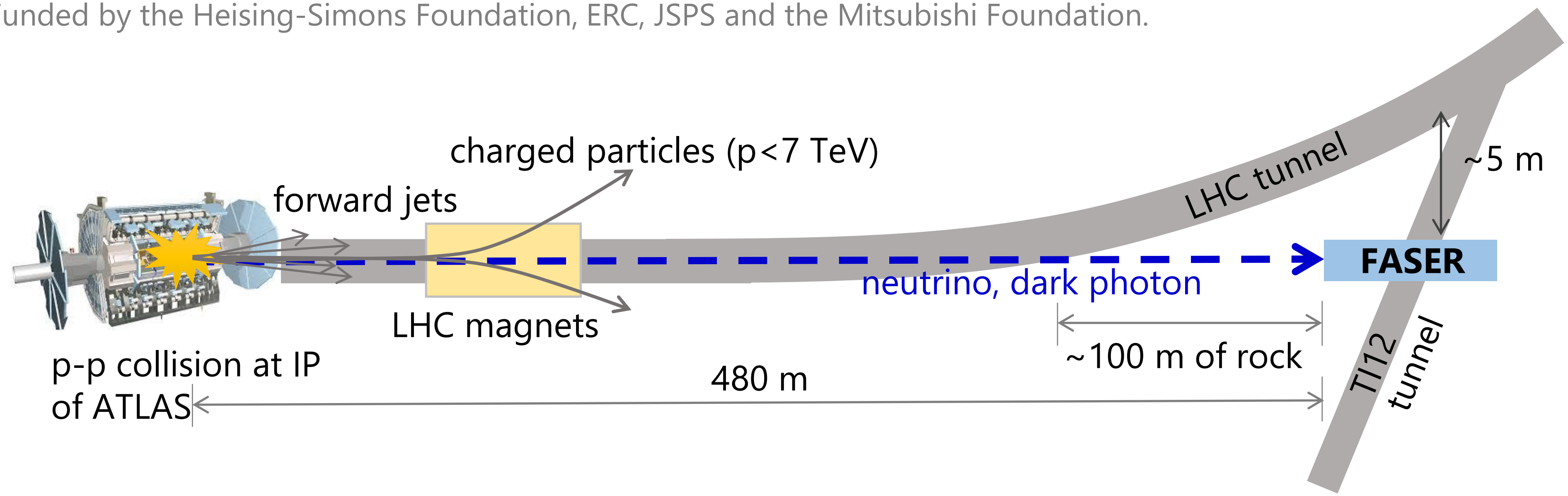


The FASER experiment

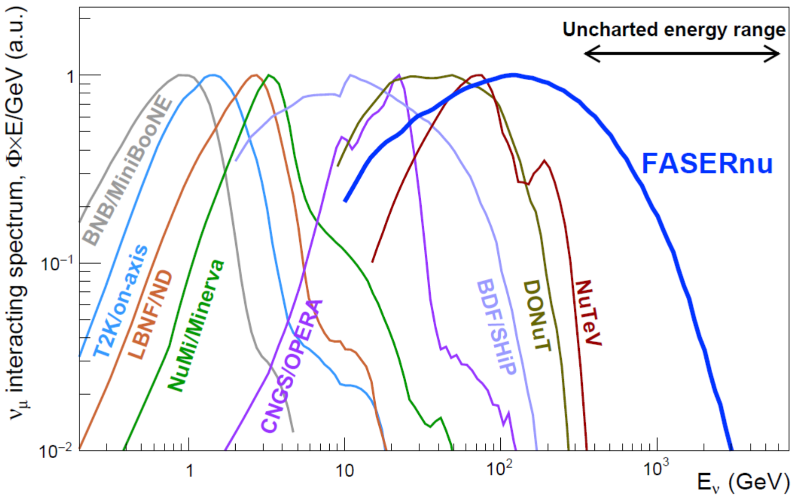
- FASER is a small and fast experiment at the LHC.
  - Will take data in the LHC Run-3 (2022-2024).

- **FASER (new particle searches)** approved by CERN in Mar. 2019.
  - Targeting light, weakly-coupled new particles at low p_T.
  - Funded by the Heising-Simons and Simons Foundations with support from CERN.
- **FASERν (neutrino measurements)** approved by CERN in Dec. 2019.
  - First measurements of neutrinos from a collider and in unexplored energy regime.
  - Funded by the Heising-Simons Foundation, ERC, JSPS and the Mitsubishi Foundation.


FASER main detector installed into the TI12 tunnel (March 2021)



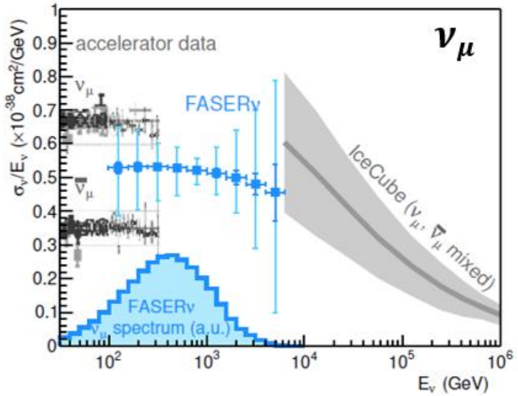
FASERν physics potential: high-energy neutrino interactions



- Primary goal: cross section measurements of **different flavors at TeV energies**
  - where no such measurements currently exist.

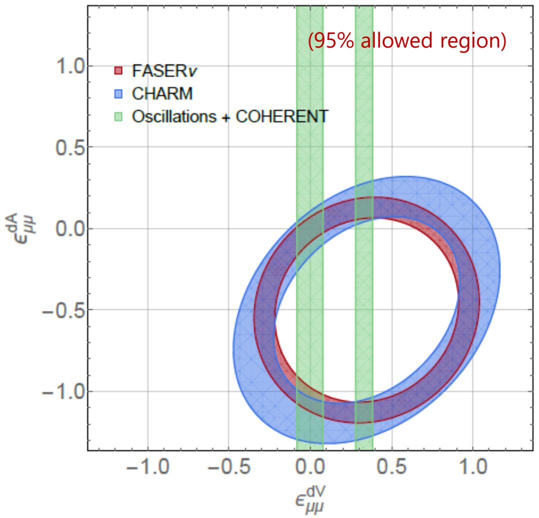
  Expected number of CC interactions in FASERν during LHC Run-3 (150 fb^{-1})
  $\sim 2000\ \nu_e, \sim 7000\ \nu_\mu, \sim 50\ \nu_\tau$ interactions

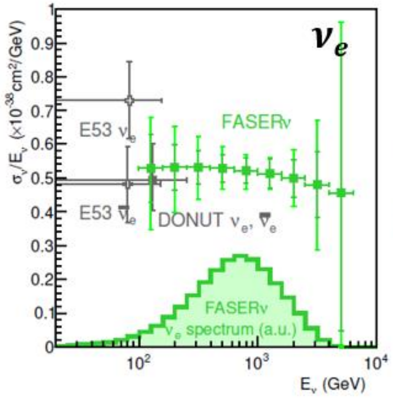
FASER Collaboration,
Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

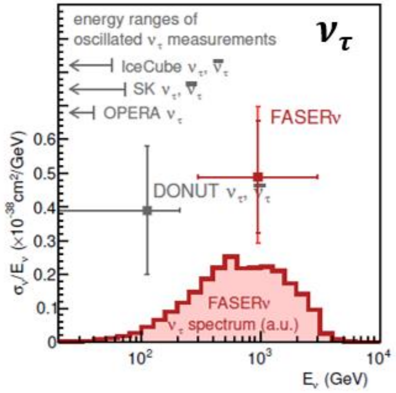


- NC measurements
  - could constrain neutrino non-standard interactions (NSI).

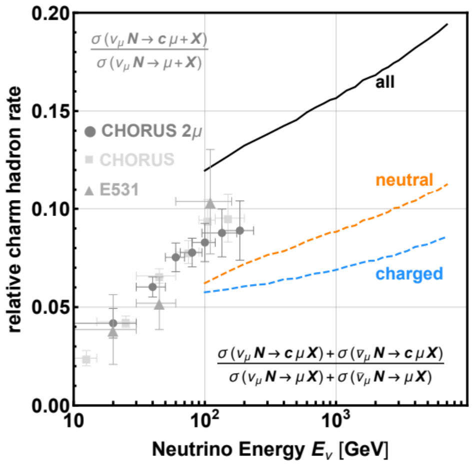
A. Ismail, R.M. Abraham, F. Kling,
Phys. Rev. D 103, 056014 (2021),
arXiv:2012.10500



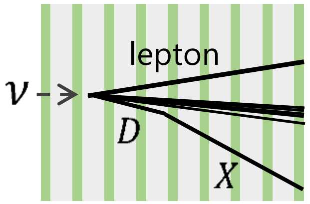




FASERν physics potential: heavy-flavor-associated channels

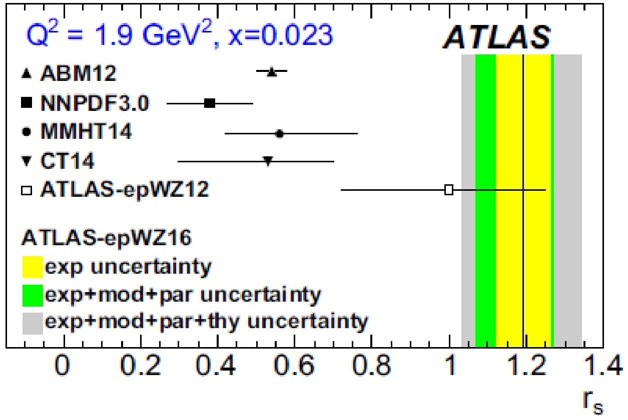


- Neutrino CC interaction with charm production ($\nu s \to lc$)
  - Study the strange quark content → Probe inconsistency between the predictions and the LHC data

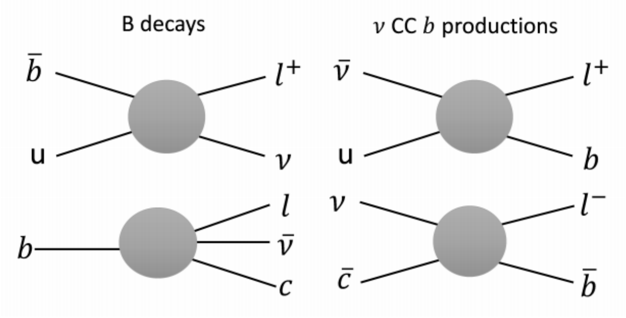


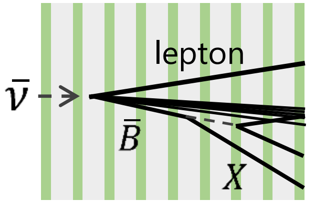
Eur. Phys. J. C77 (2017) 367

$$r_s = \frac{s+\bar{s}}{2\bar{d}}$$



- Neutrino CC interaction with beauty production
  - Has never been detected.

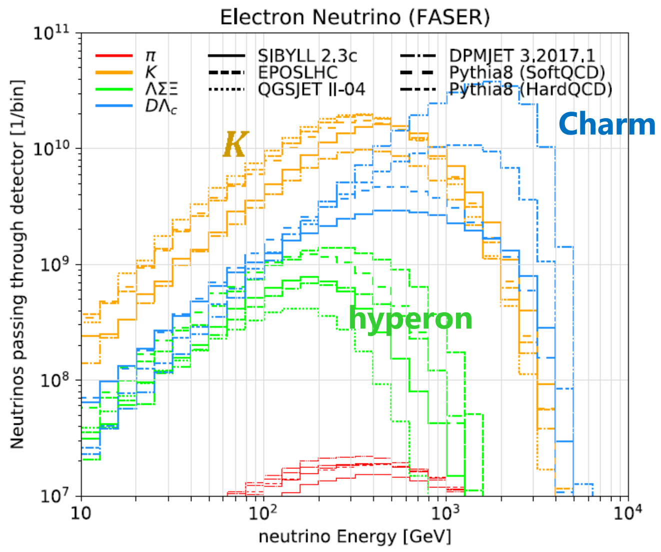


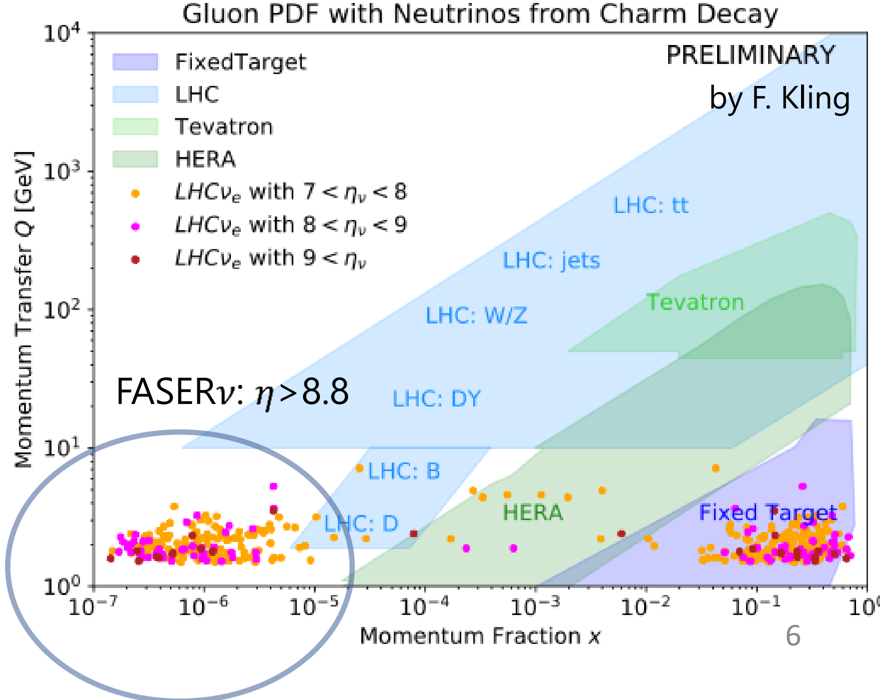


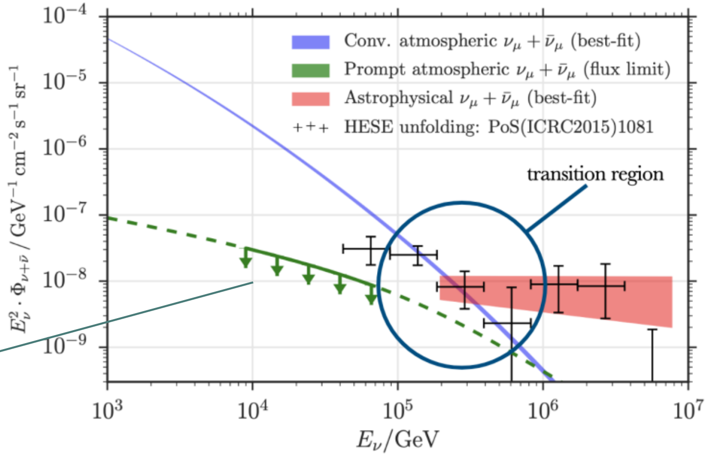
- Tests of lepton universality in the heavy-flavor-associated channels
  - ~100 ν_e CC charm, ~600 ν_μ CC charm, ~2 ν_τ CC charm, and ~0.1 ν_μ CC beauty production expected in FASERν
  - >100 more statistics in FASERν2

FASERν physics potential: forward particle production

- Neutrinos produced in the forward direction at the LHC originate from decays of hadrons, mainly pions, kaons, and charm particles.
- FASERν's measurements provide novel input to validate/improve generators.
  - Forward particle production is poorly constrained by other LHC experiments.
  - First data on forward charm
- Neutrinos from charm decay, relevant for neutrino telescopes (such as IceCube).
  - In order for IceCube to make precise measurements of the cosmic neutrino flux, accelerator measurements of high energy and large rapidity charm production are needed.
  - As 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode, a direct measurement of the prompt neutrino production would provide important basic data for current and future high-energy neutrino telescopes.



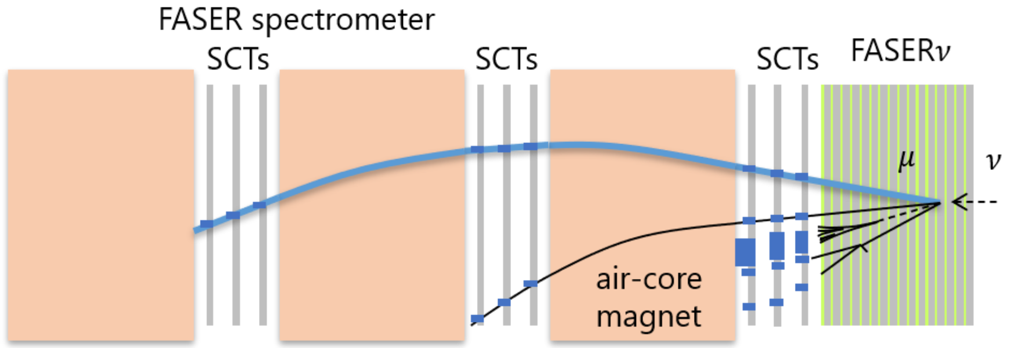




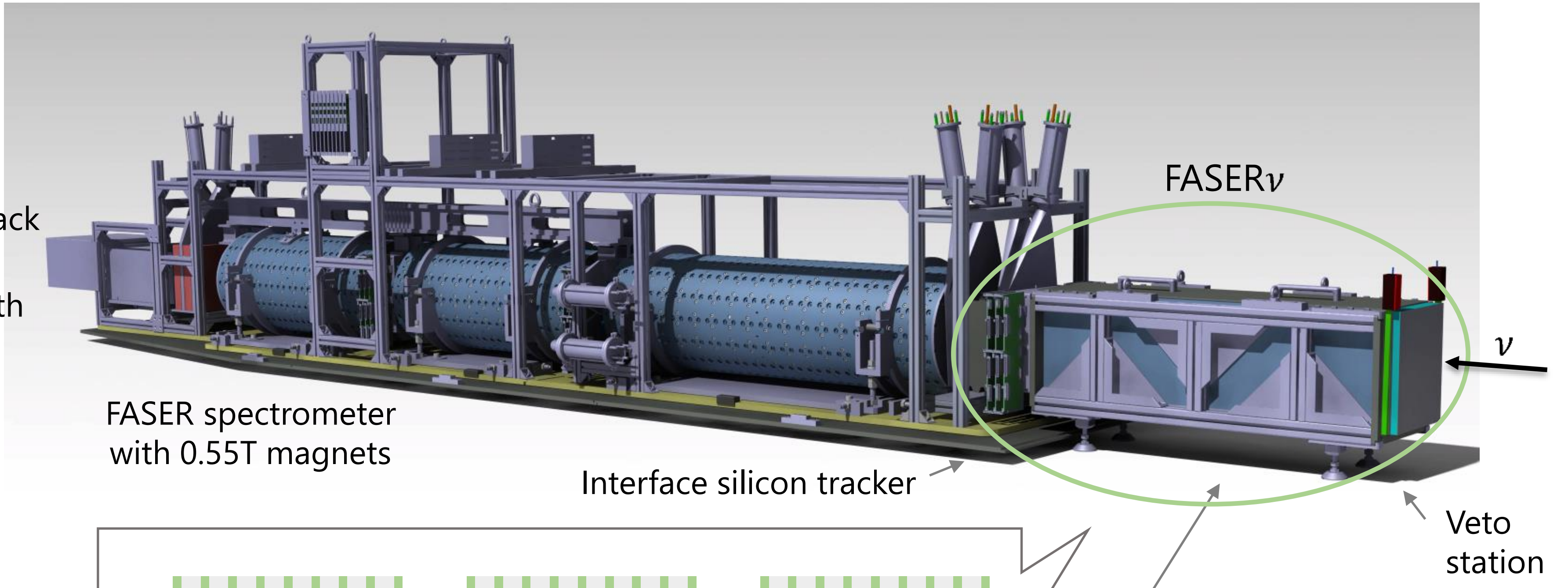
IceCube Collaboration, Astrophys. J. 833 (2016)

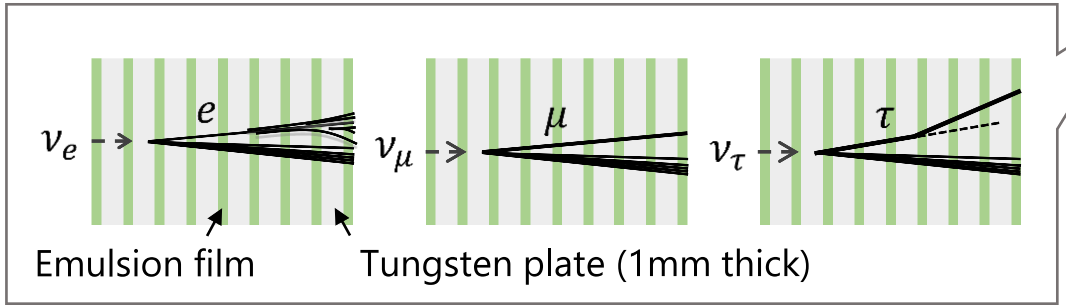
prompt atmospheric neutrinos

The FASERν detector for LHC Run-3



- **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 ($8\lambda_{int}$)
  - **Muon charge identification** with hybrid configuration → distinguishing ν_μ and $\bar{\nu}_\mu$
  - **Neutrino energy** measurement with ANN by combining topological and kinematical variables





Emulsion/tungsten detector
- 770 1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm^2, 1.1 m long, 1.1 tons detector ($220X_0$)

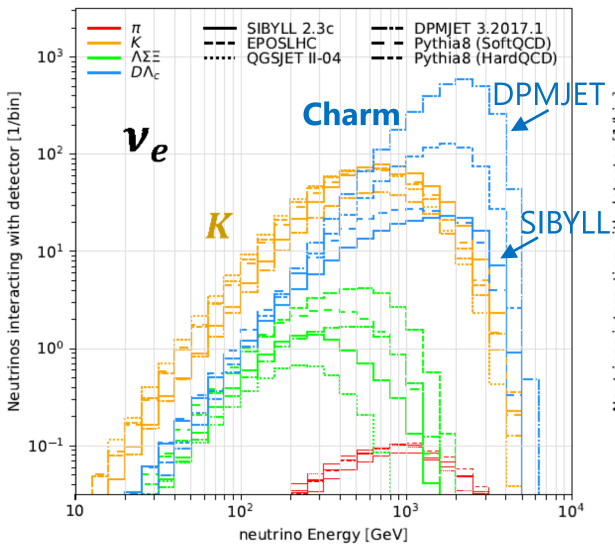
Expected neutrino event rate in LHC Run-3

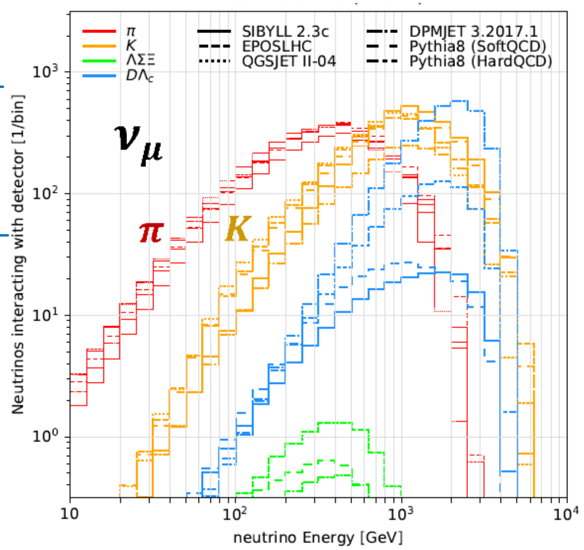
F. Kling, Forward Neutrino Fluxes at the LHC, arXiv:2105.08270

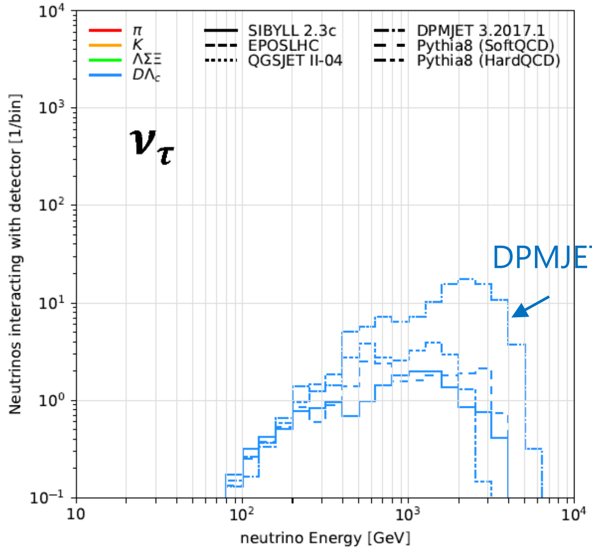
- A high-intensity beam of neutrinos will be produced in the far-forward direction.
- FASERν will be centered on the LOS (in the FASER trench) to maximizes fluxes of all neutrino flavors.
- Differences between the generators checked.

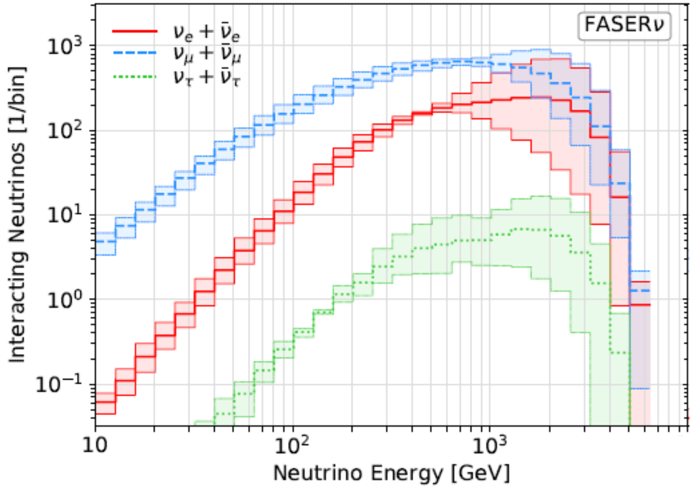
Expected number of CC interactions in FASERν during LHC Run-3 (150 fb^{-1})

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	1343	6072	21.2	184	965	10.1
DPMJET	DPMJET	4614	9198	131	547	1345	22.4
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9	367	1459	16.1
QGSJET	Pythia8 (Soft)	1437	7162	24.5	259	1328	10.7
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}	$56.4^{+74.5}_{-35.1}$	339^{+208}_{-155}	1274^{+184}_{-308}	$14.8^{+7.5}_{-4.7}$
Combination (w/o DPMJET)		1630^{+479}_{-286}	7000^{+763}_{-926}	$31.5^{+17.3}_{-10.3}$	270^{+96}_{-85}	1251^{+208}_{-285}	$12.3^{+3.8}_{-2.1}$



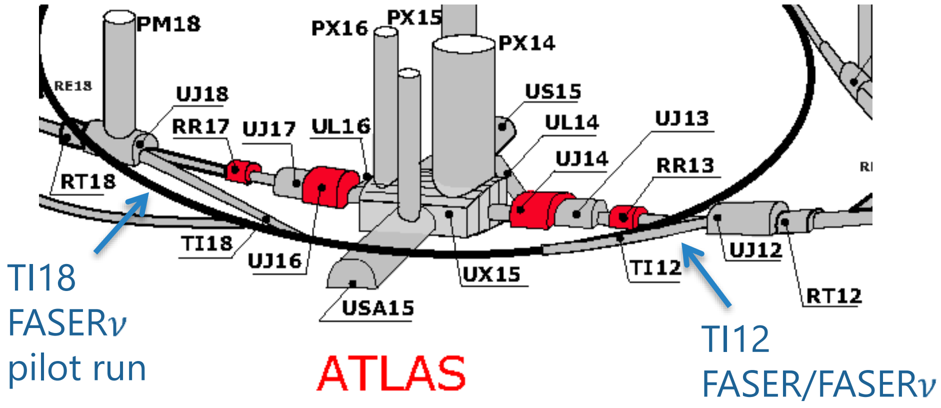


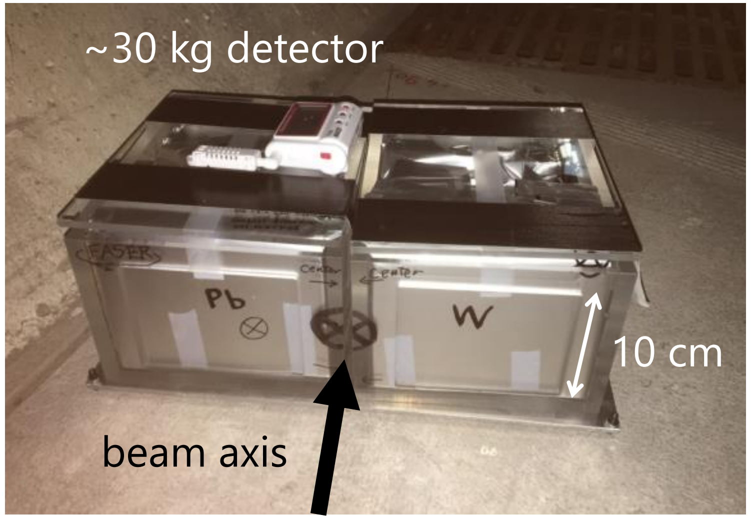


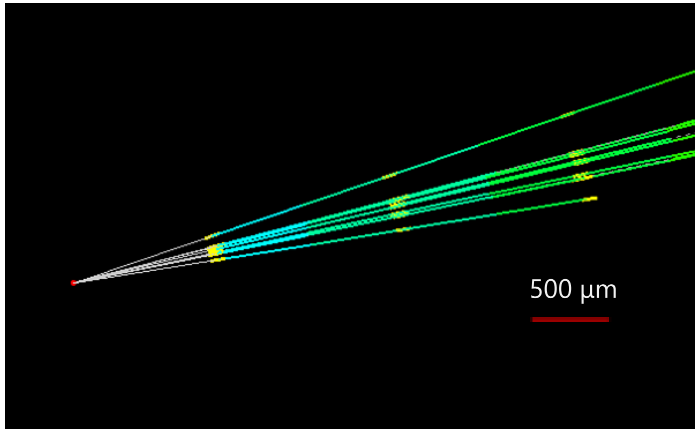


Pilot run in 2018 (LHC Run-2)

Aiming to demonstrate neutrino detection at the LHC for the first time

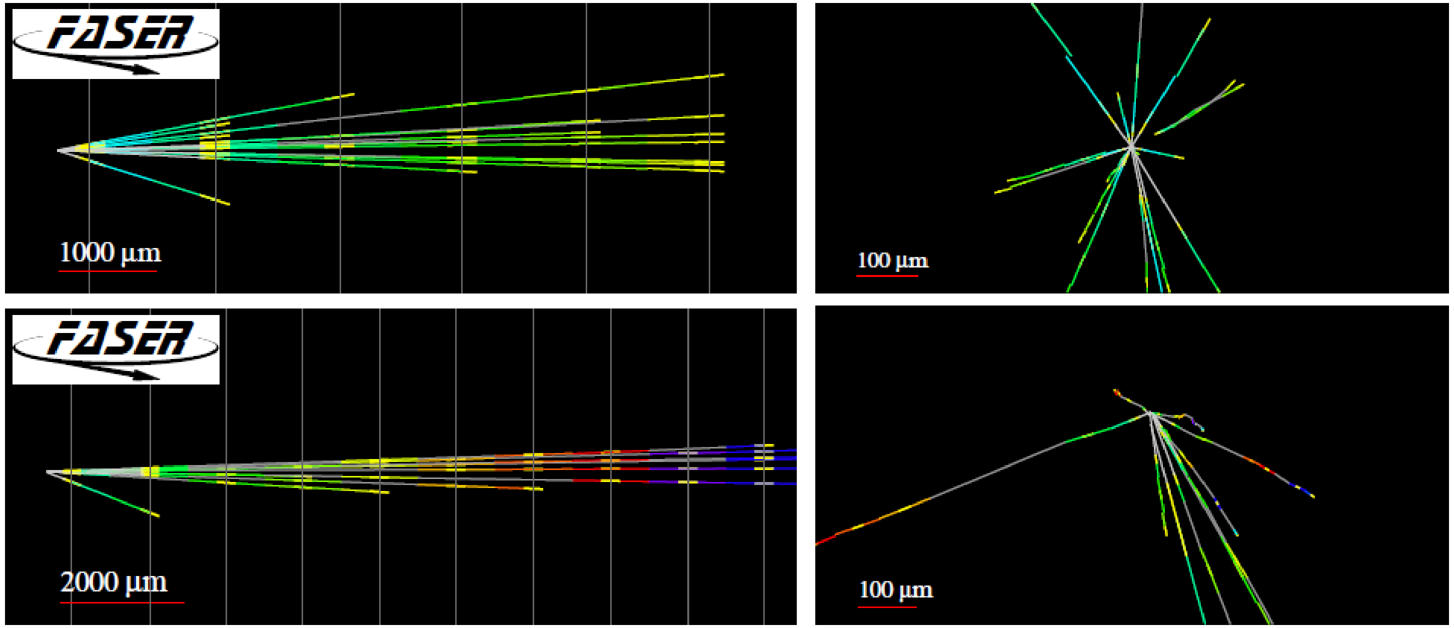






- Aims: charged particle flux measurement and neutrino detection
- We performed measurements in the tunnels TI18 and TI12, 480 m from the ATLAS IP.
- For neutrino detection, a 30 kg emulsion detector was installed in TI18 and 12.2 fb^{-1} data was collected.

Neutrino interaction candidates



First neutrino interaction candidates at the LHC, arXiv:2105.06197

UCI-TR-2021-04, KYUSHU-RCAPP-2020-04, CERN-EP-2021-087

First neutrino interaction candidates at the LHC

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(Dated: July 18, 2021)

FASERν at the CERN Large Hadron Collider (LHC) is designed to directly detect collider neutrinos for the first time and study their cross sections at TeV energies, where no such measurements currently exist. In 2018, a pilot detector employing emulsion films was installed in the far-forward region of ATLAS, 480 m from the interaction point, and collected 12.2 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV. We describe the analysis of this pilot run data and the observation of the first neutrino interaction candidates at the LHC. This milestone paves the way for high-energy neutrino measurements at current and future colliders.

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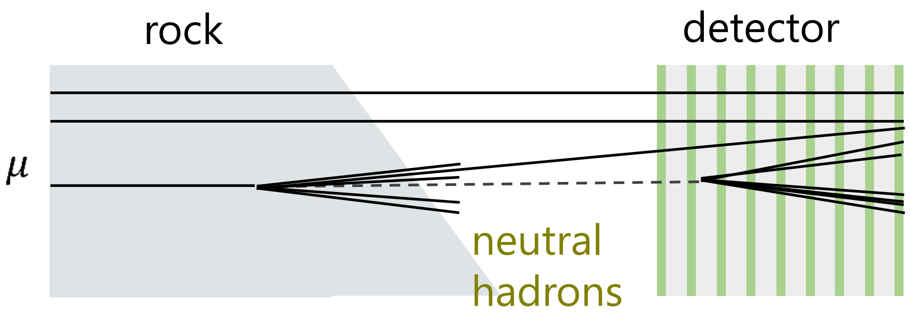
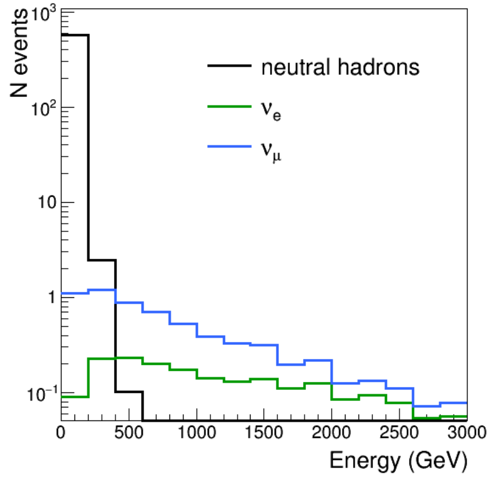
Pilot run in 2018 (LHC Run-2)

Background estimation and BDT analysis



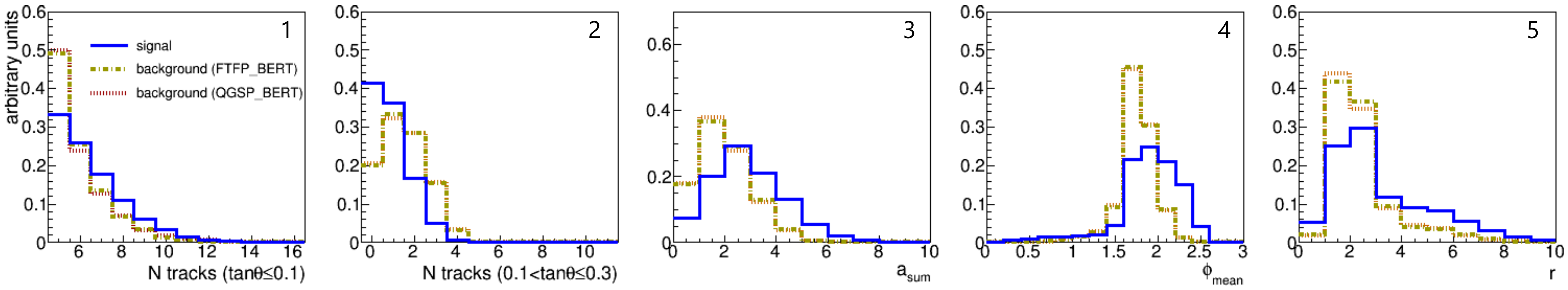


- The pilot detector lacked the ability to identify muons given its depth of only $0.6\lambda_{int}$, much shorter than the $8\lambda_{int}$ of the full FASERν detector.
- → Separation from neutral hadron BG (produced by muons) is much harder than the physics run.

- Muons rarely produce neutral hadrons in upstream rock, which can mimic neutrino interaction vertices.
  - The produced neutral hadrons are low energy → discriminate by vertex topology

5 variables used in the analysis

1. the number of tracks with tanθ<=0.1 with respect to the beam direction
2. the number of tracks with 0.1<tanθ<=0.3 with respect to the beam direction
3. the absolute value of vector sum of transverse angles calculated considering all the tracks as unit vectors in the plane transverse to the beam direction (a_{sum})
4. for each track in the event, calculate the mean value of opening angles between the track and the others in the plane transverse to the beam direction, and then take the maximum value in the event (ϕ_{mean})
5. for each track in the event, calculate the ratio of the number of tracks with opening angle <=90 degrees and >90 degrees in the plane transverse to the beam direction, and then take the maximum value in the event (r).



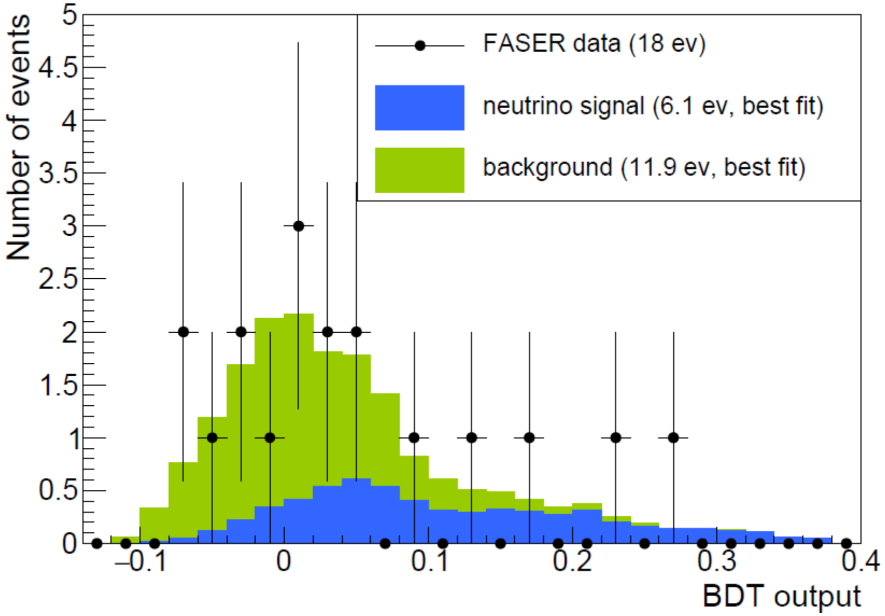
Pilot run in 2018 (LHC Run-2)

First neutrino interaction candidates at the LHC, arXiv:2105.06197

Results

- Analyzed target mass 11 kg
- 18 neutral vertices were selected
  - by applying # of charged particle ≥ 5, etc.
  - Expected signal $3.3^{+1.7}_{-0.9}$ events, BG 11.0 events
- In the BDT analysis, an excess of neutrino signal is observed. Statistical significance 2.7σ from null hypothesis
- This result demonstrates **detection of neutrino interaction candidates at the LHC.**

Best fit (no N_{BG} constraint)



We are currently preparing for data taking in LHC Run-3.
With a deeper detector and lepton identification capability, FASERν will perform better than this pilot detector.

FASERν/FASERν2 schedule

FASERν pilot run in 2018

FASERν physics run will start in 2022

FASERν2 in HL-LHC

First neutrino interaction candidates at the LHC, arXiv:2105.06197

Measuring neutrinos of different flavors at TeV energies

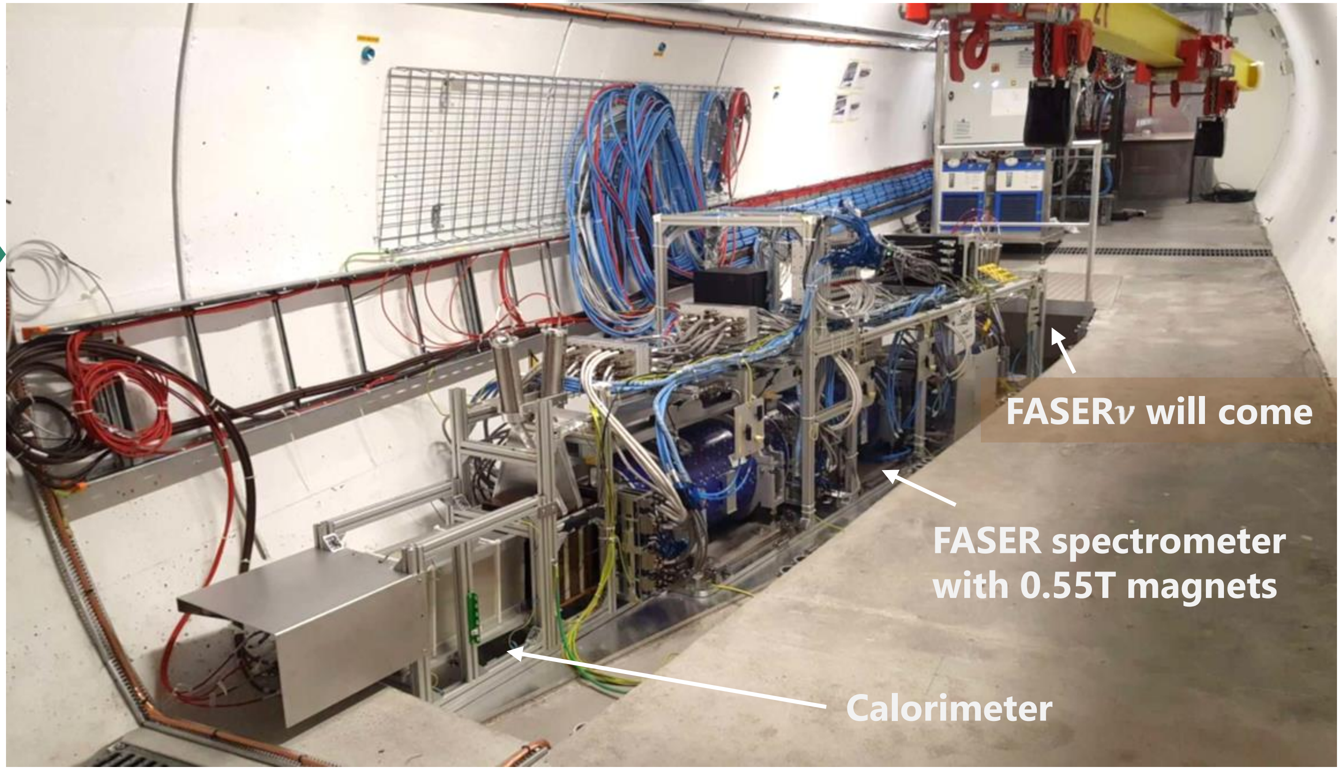
Preparation towards LHC Run-3

The TI12 area

2018

2020

2021



The FASER main detector was successfully installed into the TI12 tunnel in March 2021.
Acknowledge great support from many CERN teams involved in the work

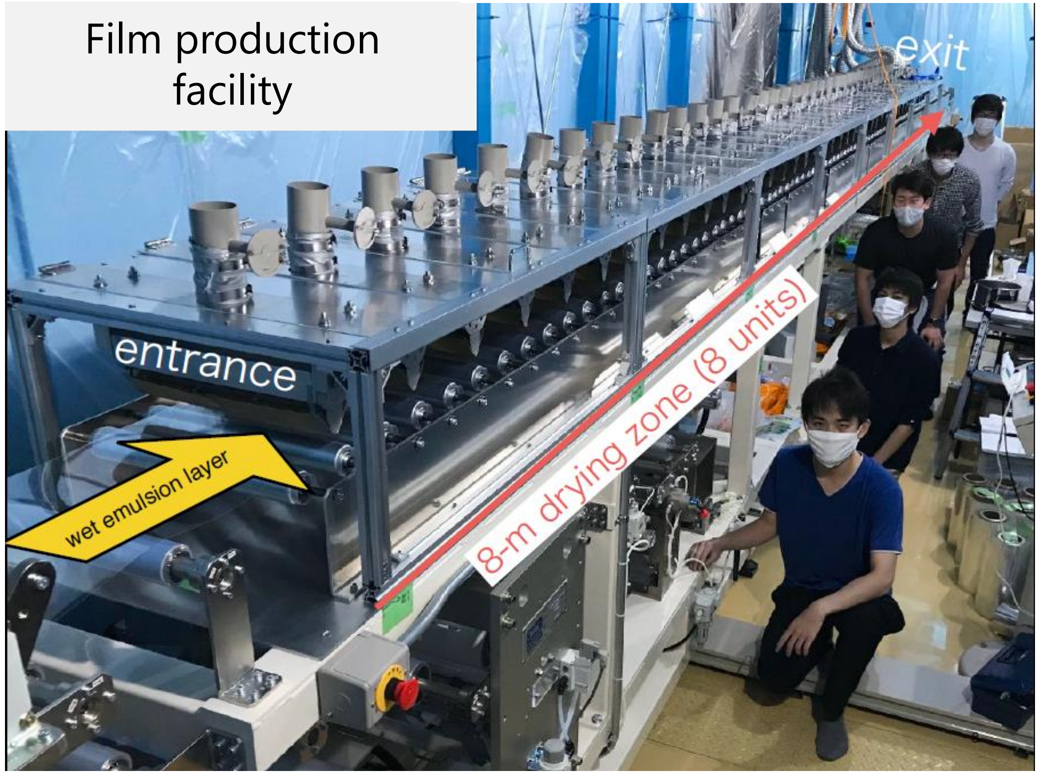
FASERν installation test

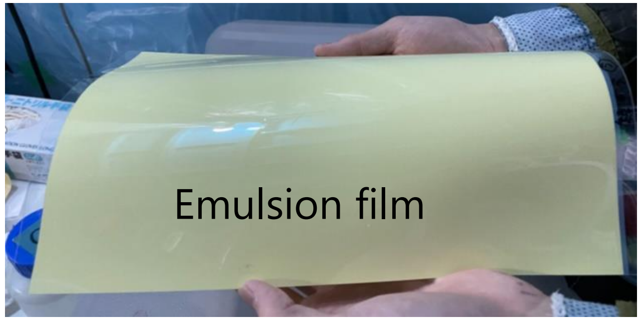
FASERν box


Transportation over the LHC beam pipe

Emulsion detector preparation

- Emulsion gel and film production facilities in Nagoya have been set up in 2020.
- We are testing mass production of the gel and films, and conducting tests of the produced films with cosmic rays.



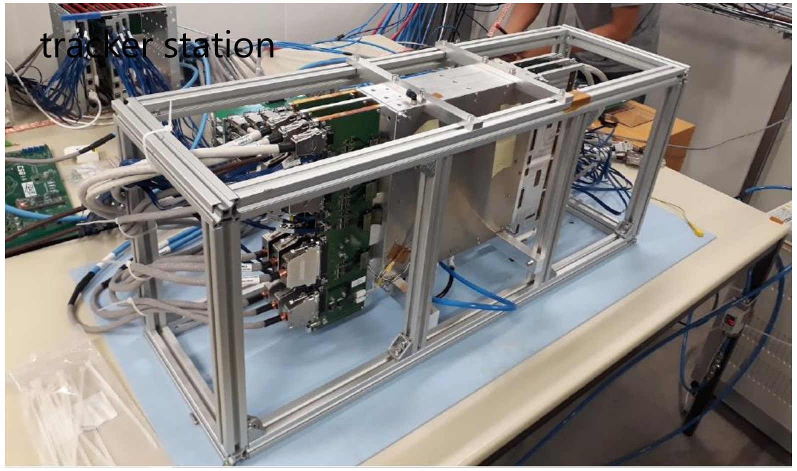


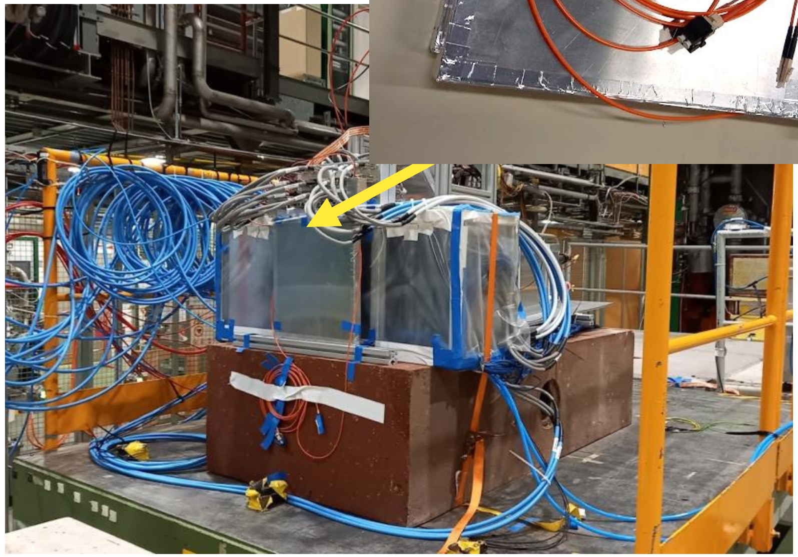
Interface tracker (IFT) and veto system

- **IFT** will use the same design as the tracker station in the FASER spectrometer.
  - Silicon strip detector with ATLAS SCT barrel modules
    - 80 μm strip pitch, 40 mrad stereo angle
    - Position resolutions are ~17 μm and ~ 580 μm in the 2 coordinates
  - The electrical qualification as well as assembly of the planes/station was completed.

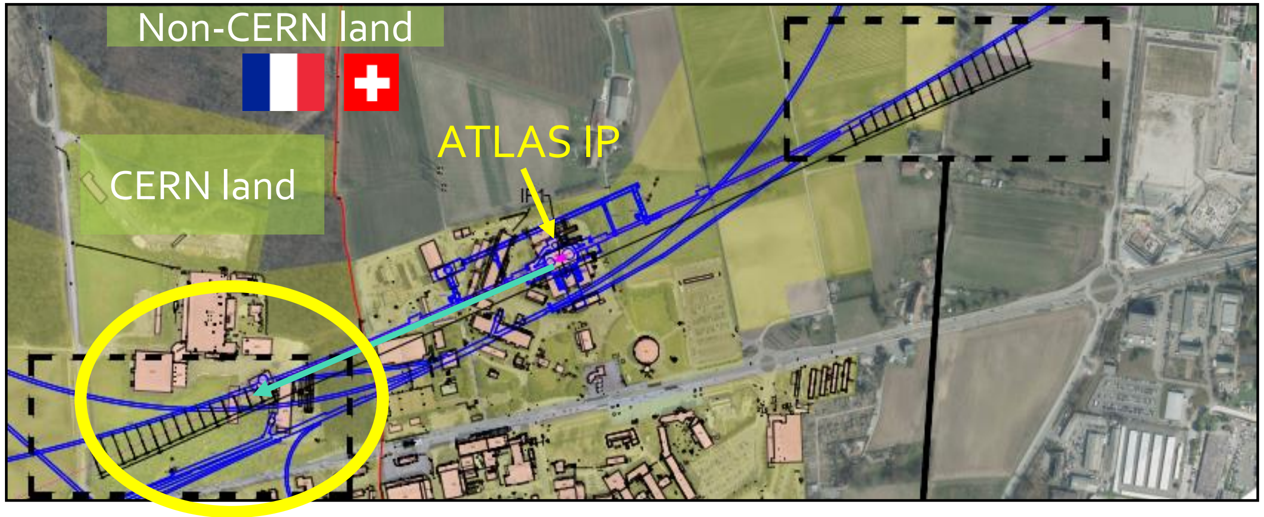
- **Veto station** consists of two 2-cm scintillators and WLS (Wave Length Shifting) bars with two PMTs (H11934-300).
  - The PMTs were tested and the scintillators were assembled.

- These detectors were used for the test beam at the H2 beamline in the CERN SPS North Area.
- Will be installed in TI12 in Nov. 2021.



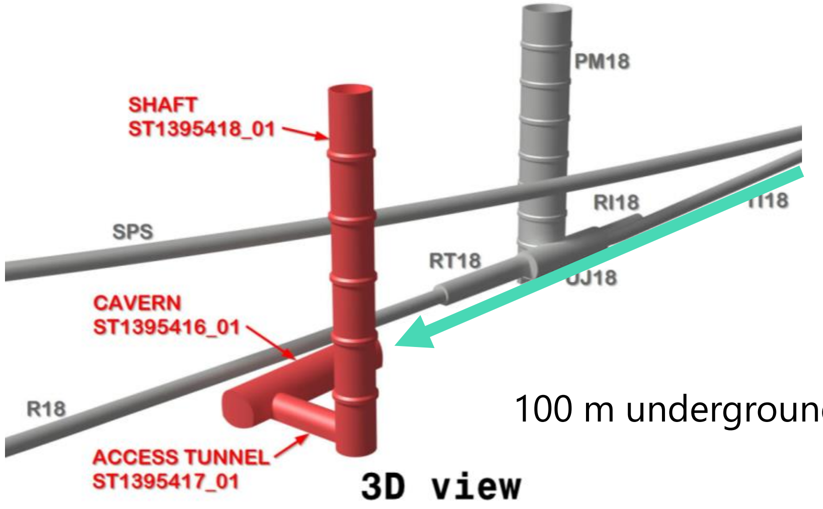


The new FPF facility and FASERν2

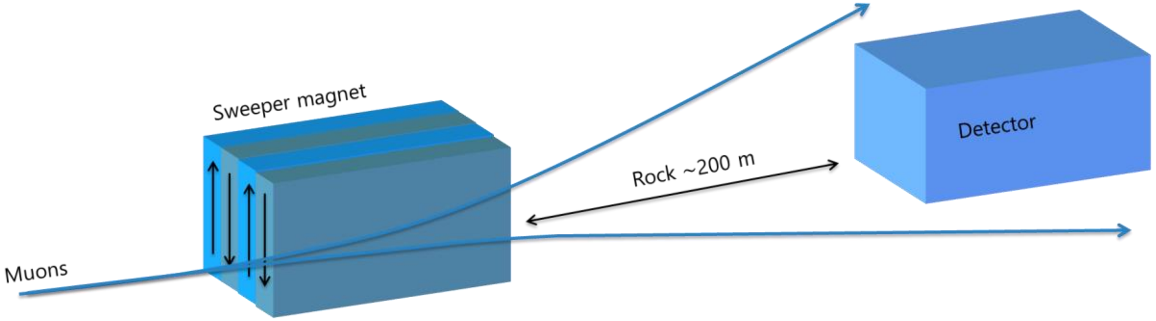


- The Forward Physics Facility (FPF) for the HL-LHC is a proposed facility that could house a suite of experiments to **greatly enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD**.

- The background muon rate may be able to be reduced with a sweeper magnet (studies ongoing).



100 m underground



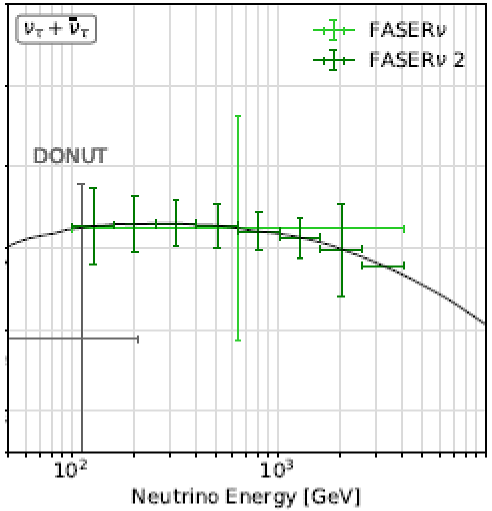
FASERν2

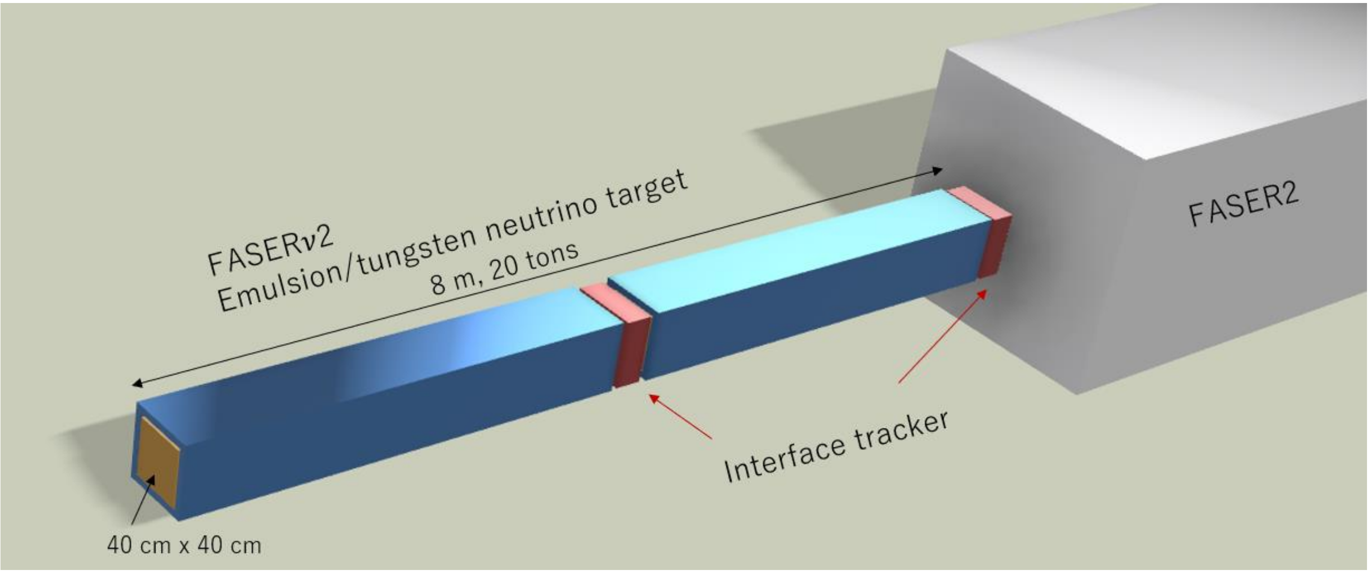
Expected number of CC interactions in FASERν2 during HL-LHC (3 ab^{-1}) using Sibyll 2.3d / DPMJET 3.2017

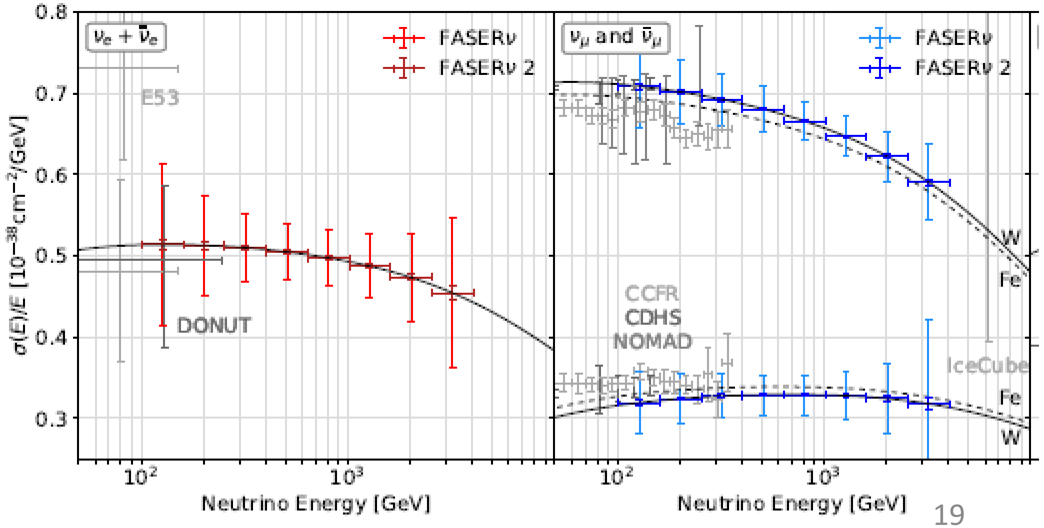
Detector			Interactions at FPF		
Name	Mass	Coverage	CC $\nu_e+\bar{\nu}_e$	CC $\nu_\mu+\bar{\nu}_\mu$	CC $\nu_\tau+\bar{\nu}_\tau$
FASERν2	20 tons	$\eta \gtrsim 8.5$	178k / 668k	943k / 1.4M	2.3k / 20k

- FASERν2 is designed to carry out precision measurements of high-energy neutrinos and heavy flavor physics studies
  - Emulsion-based detector
    - distinguishment of all flavor of neutrino interactions
    - identification of heavy flavor particles such as tau leptons, charm and beauty particles
  - and interface detectors to the FASER2 detector
    - muon charge identification → neutrino/anti-neutrino separation for muon neutrinos and for tau neutrinos in the muonic decay channel

2000–20000 ν_τ interactions are expected.







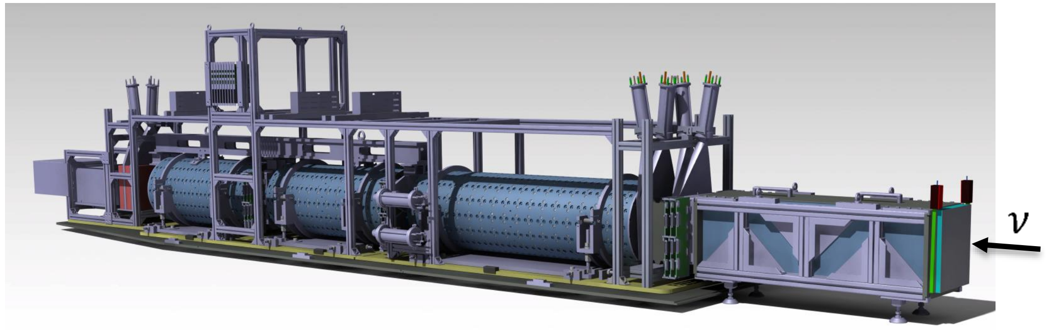
Summary and prospects

- FASERν at the CERN LHC is designed to **directly detect collider neutrinos for the first time and study their properties at TeV energies**.

- We have detected **first neutrino interaction candidates at the LHC** in the 2018 pilot run data.
  - arXiv:2105.06197

- We expect to collect ~10000 CC interactions (distinguishing the flavors) in LHC-Run3 (2022-2024). Preparation for the data taking is in progress.

- Also planning FASERν2 in the HL-LHC era.



Thank you for your attention