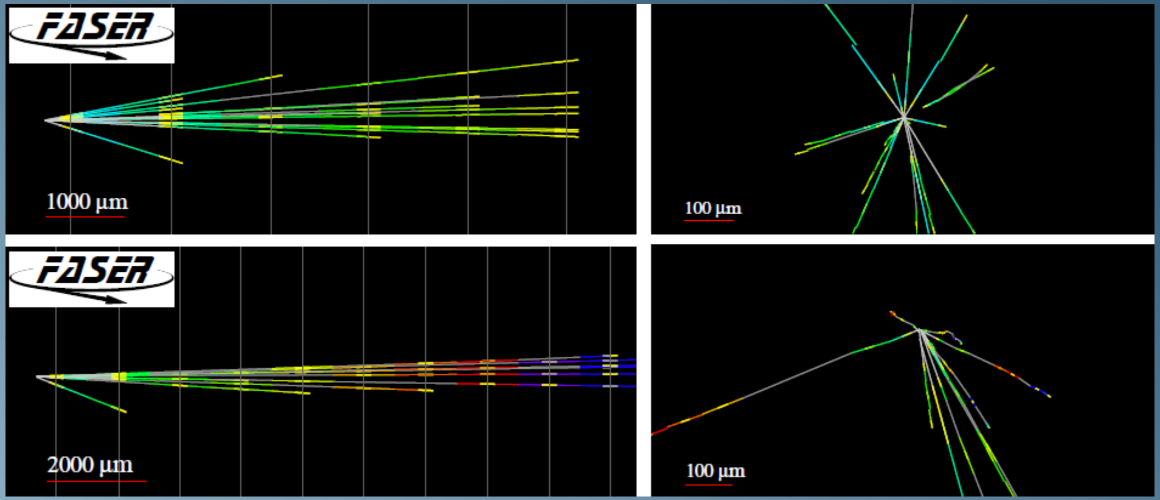
Measuring TeV neutrinos with FASERν in the LHC Run-3

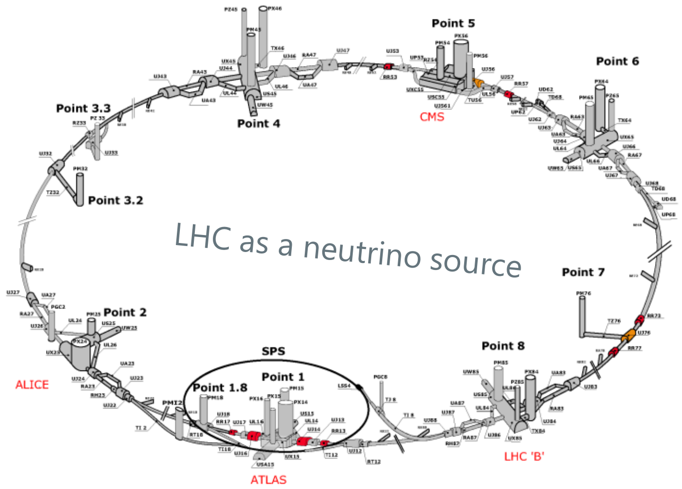
Tomoko Ariga (Kyushu University)
on behalf of the FASER Collaboration



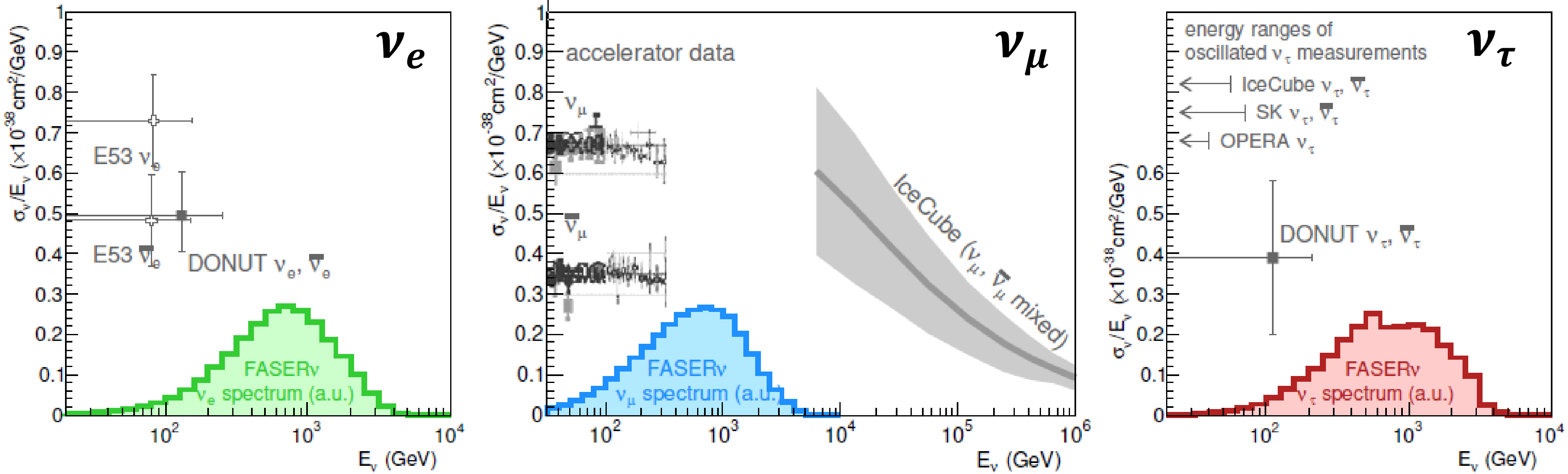
First neutrino interaction candidates at the LHC, arXiv:2105.06197

Physics motivations

- **Studying neutrinos in unexplored energy regime (TeV energies)**
  - Neutrinos from the LHC
    - First detection of collider neutrinos
    - 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



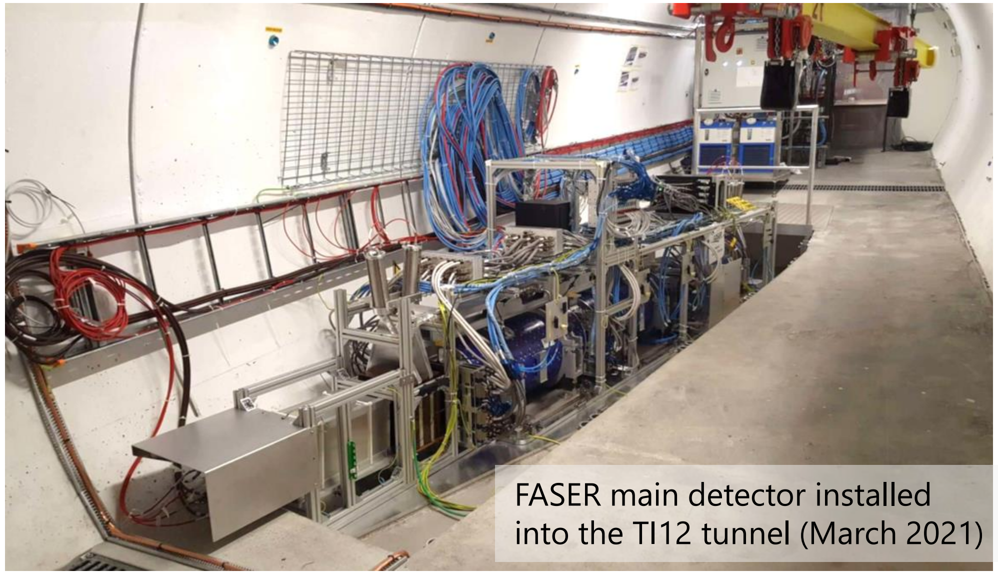
Existing measurements of νN CC cross sections and the expected energy spectra for FASERν



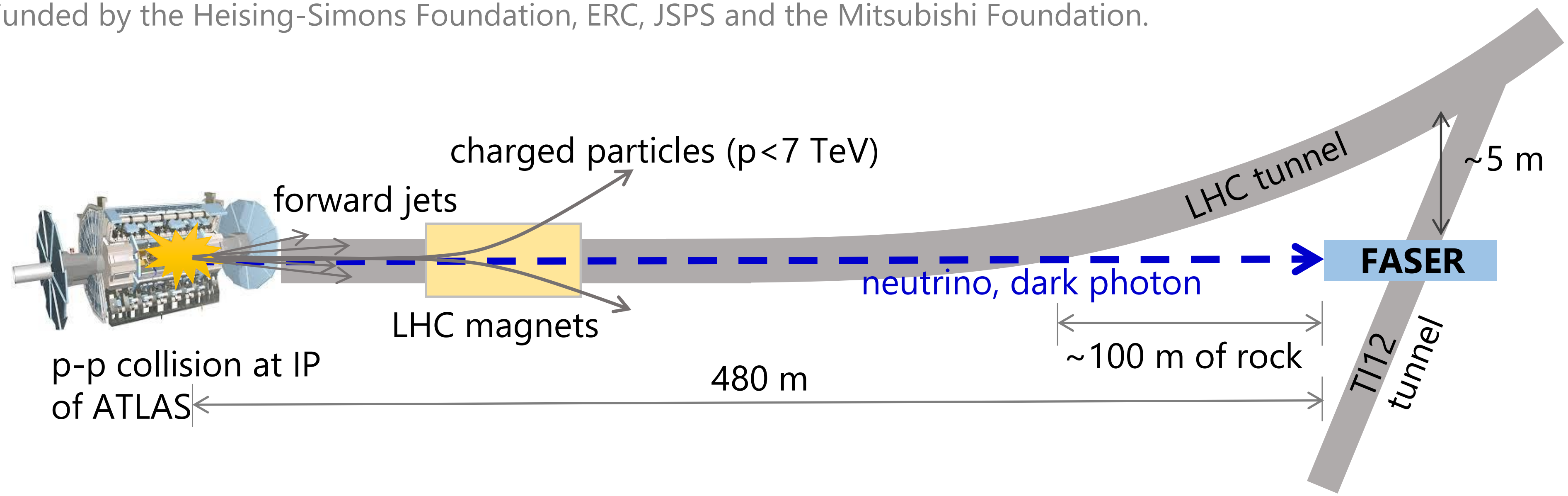
The FASER experiment

- 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.

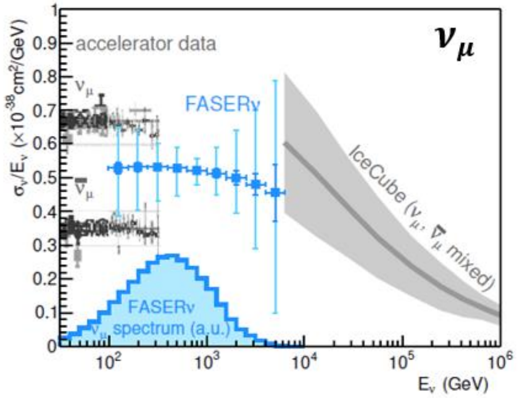

FASER main detector installed into the TI12 tunnel (March 2021)

FASER talk by Di Wang (on 29th, T10) and posters by Deion Fellers, Ondrej Theiner

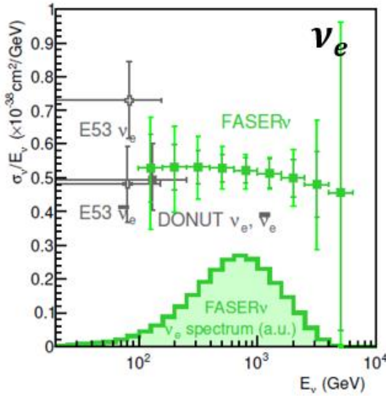


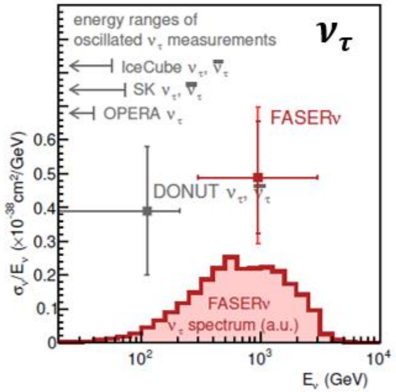
FASERν physics potential: high-energy neutrino interactions

- Primary goal: cross section measurements of different flavors at TeV energies
  - where no such measurements currently exist.
- NC measurements
  - could constrain neutrino non-standard interactions (NSI).
- 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].
- Neutrino CC interaction with beauty production
  - Has never been detected.



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

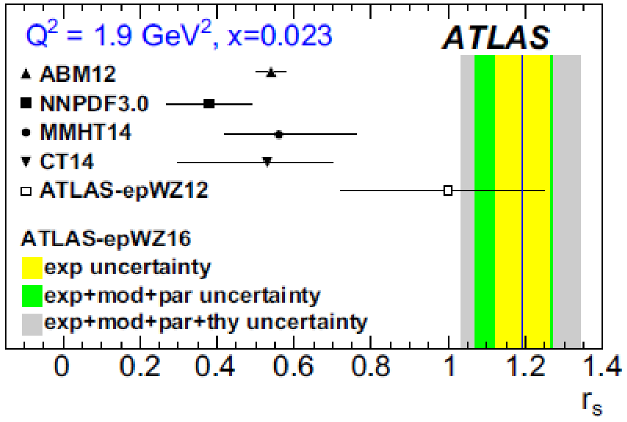


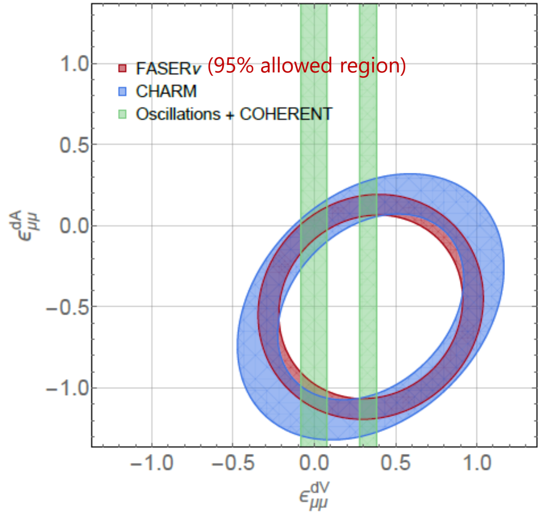


A. Ismail, R.M. Abraham, F. Kling,
Phys. Rev. D 103, 056014 (2021),
arXiv:2012.10500

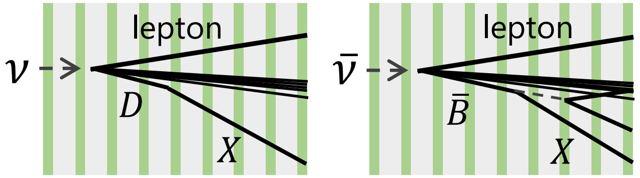
Eur. Phys. J. C77 (2017) 367

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





CC heavy quark production

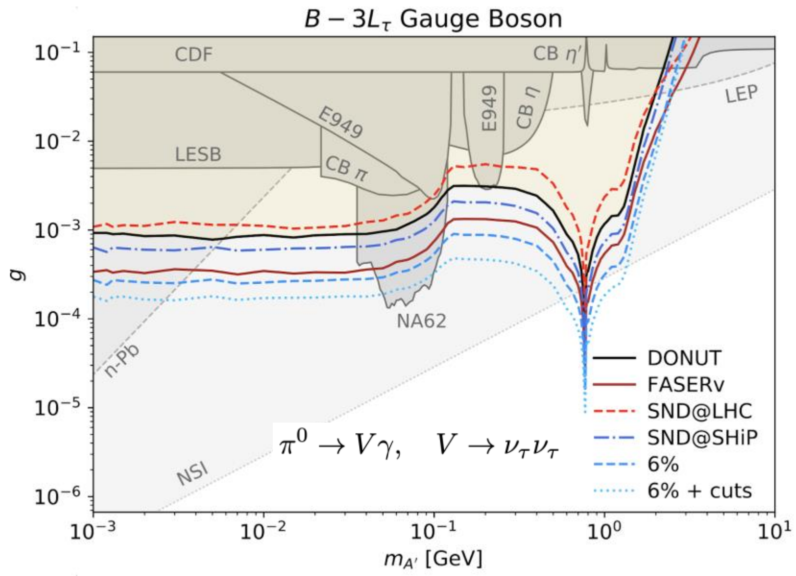


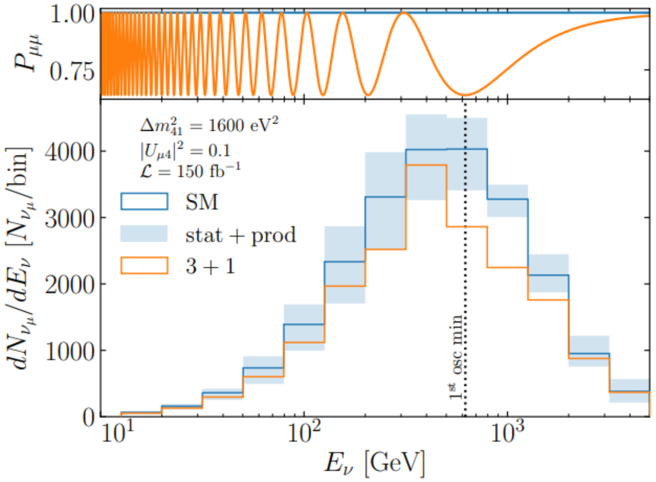
FASERν physics potential: BSM physics

- If SM uncertainties are under control, there is additional potential for BSM physics searches.

- The tau neutrino flux is small in SM.
  A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux.
  - F. Kling, Phys. Rev. D 102, 015007 (2020), arXiv:2005.03594

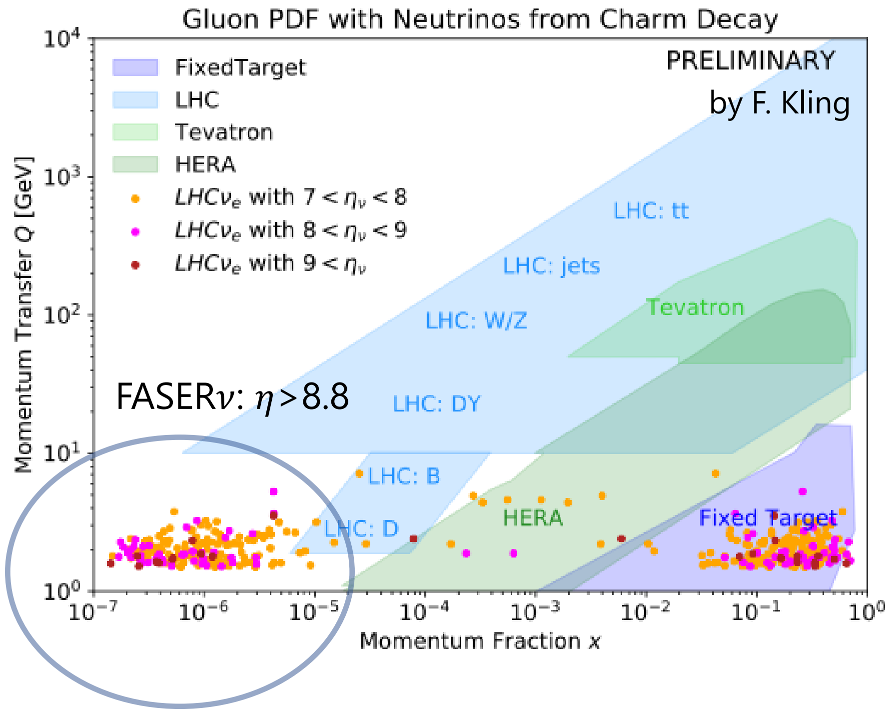
- SM neutrino oscillations are expected to be negligible at FASERν.
  However, sterile neutrinos with mass ~40 eV can cause oscillations.
  FASERν could act as a short-baseline neutrino experiment.
  - FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310



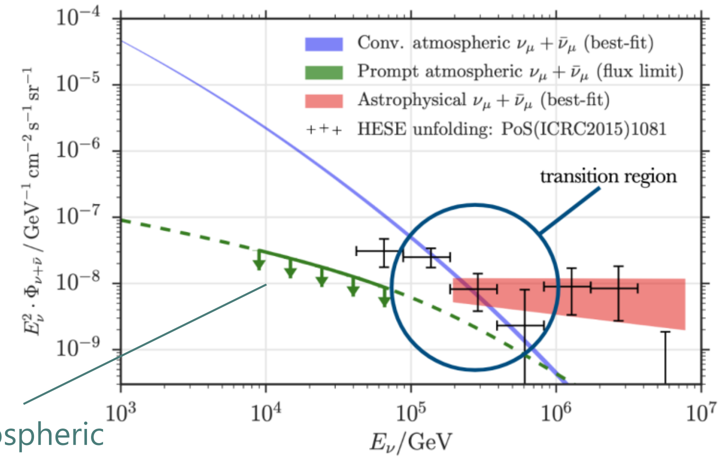


FASERν physics potential: forward particle production

- Neutrinos produced in the forward direction at the LHC originate from the decay of hadrons, mainly pions, kaons, and charm particles.
- Forward particle production is poorly constrained by other LHC experiments.
- FASERν's measurements provide novel input to validate/improve generators.
  - First data on forward kaon, hyperon, charm
- Neutrinos from charm decay could allow to
  - test transition to small-x factorization, see effects of gluon saturation, constrain low-x gluon PDF, probe intrinsic charm.
- 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.



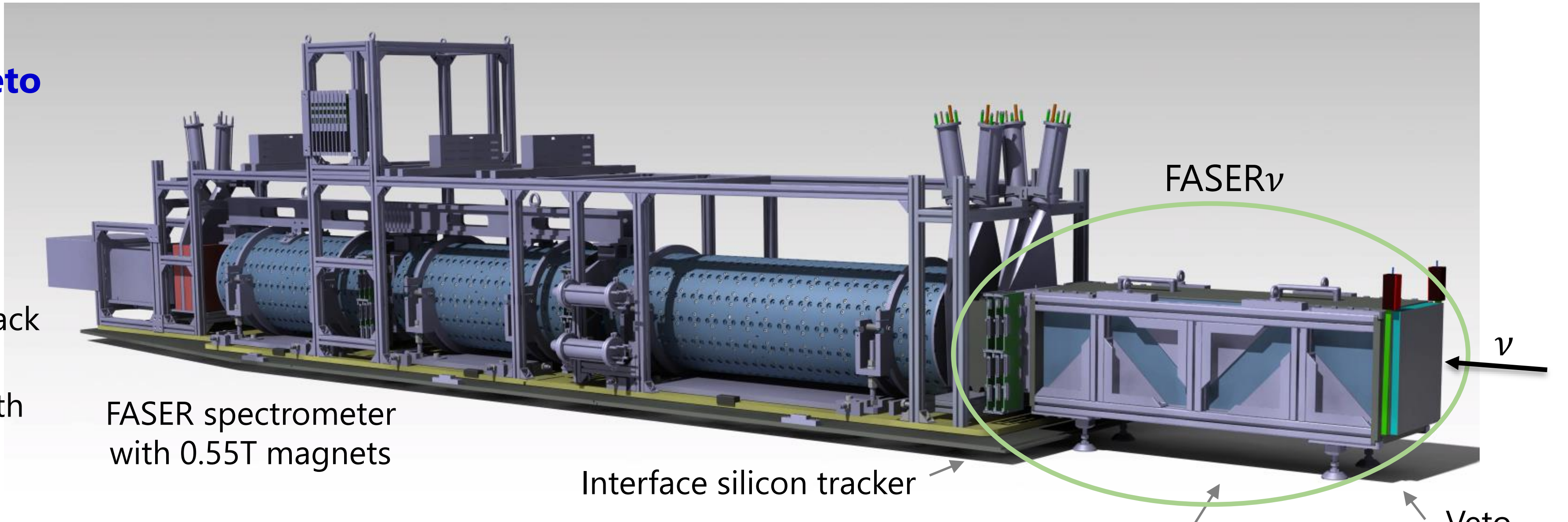
IceCube Collaboration, Astrophys. J. 833 (2016)

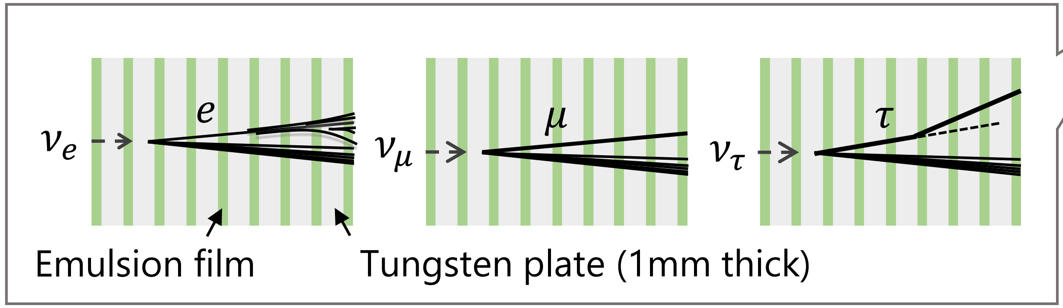


prompt atmospheric neutrinos

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

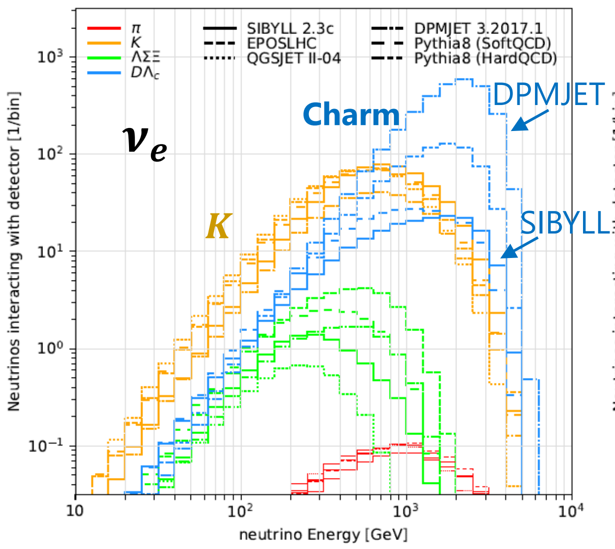
- A high-intensity beam of neutrinos will be produced in the far-forward direction.
- FASERν will be centered on the LOS (in the FASER trench) to maximizes fluxes of all neutrino flavors.

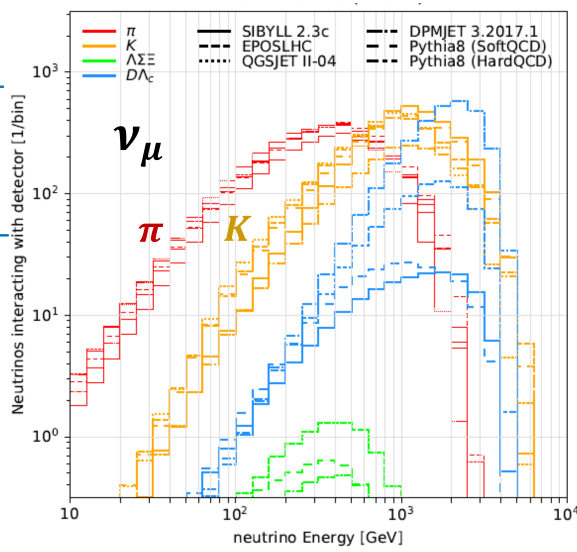
Expected number of CC interactions in FASERν during LHC Run-3 (150 fb^{-1})

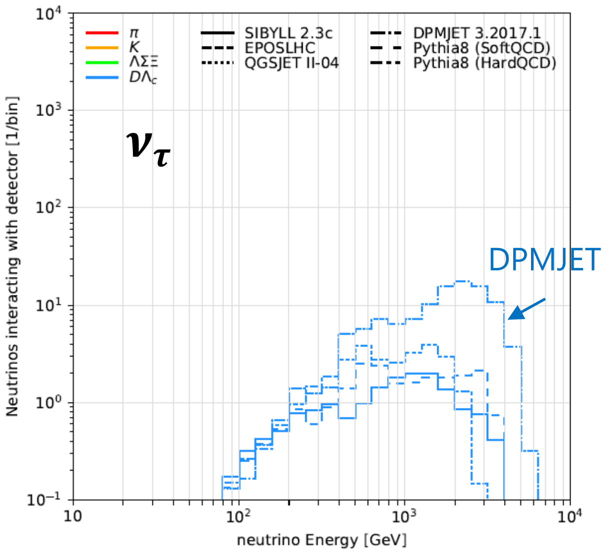
F. Kling, Forward Neutrino Fluxes at the LHC, arXiv:2105.08270

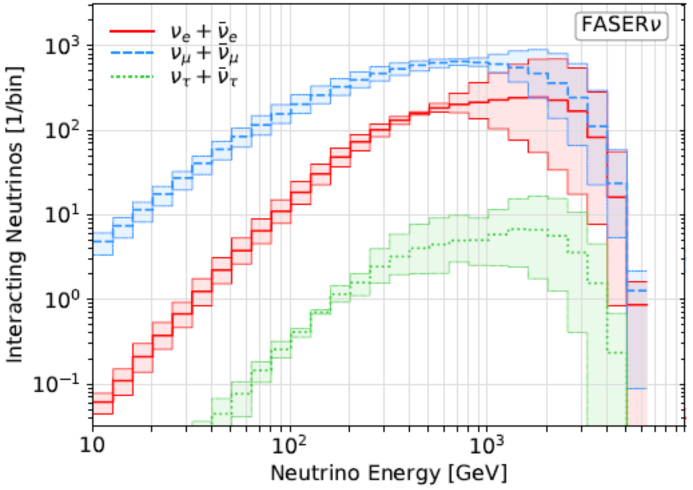
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2
DPMJET	DPMJET	4614	9198	131
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}	$56.4^{+74.5}_{-35.1}$
Combination (w/o DPMJET)		1630^{+479}_{-286}	7000^{+763}_{-926}	$31.5^{+17.3}_{-10.3}$

Differences between the generators checked with the same propagation model (RIVET-module)



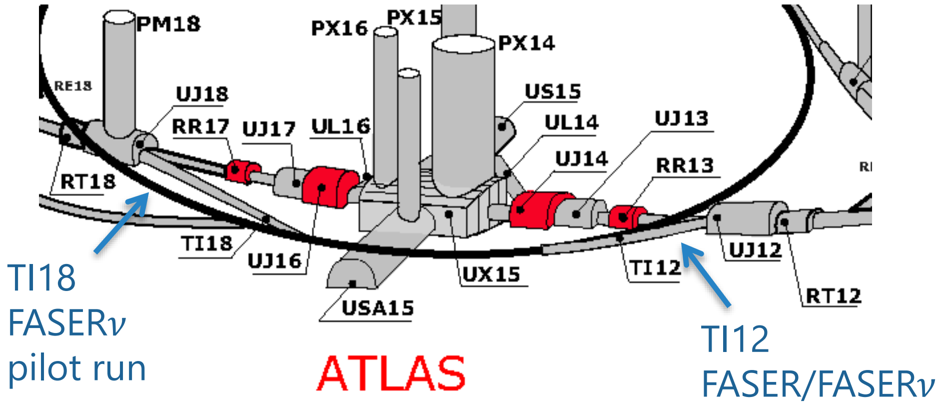


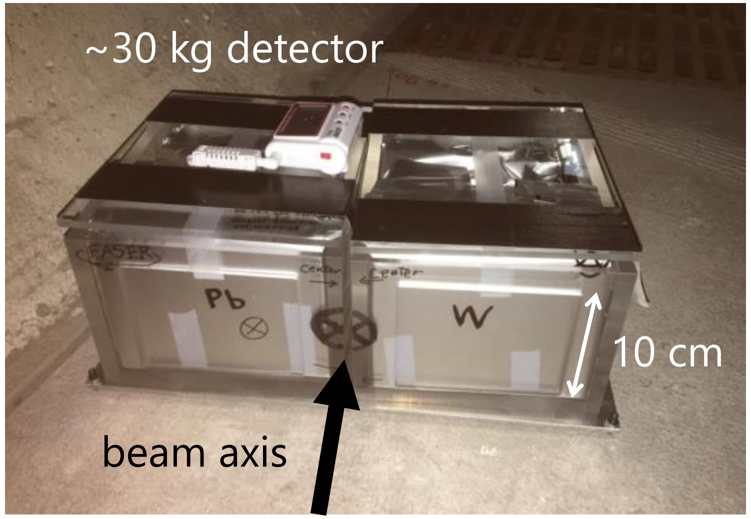


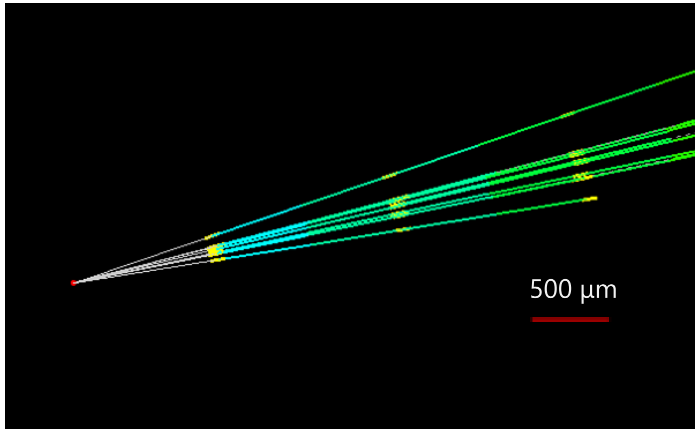


Pilot run in 2018 (LHC Run-2)

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



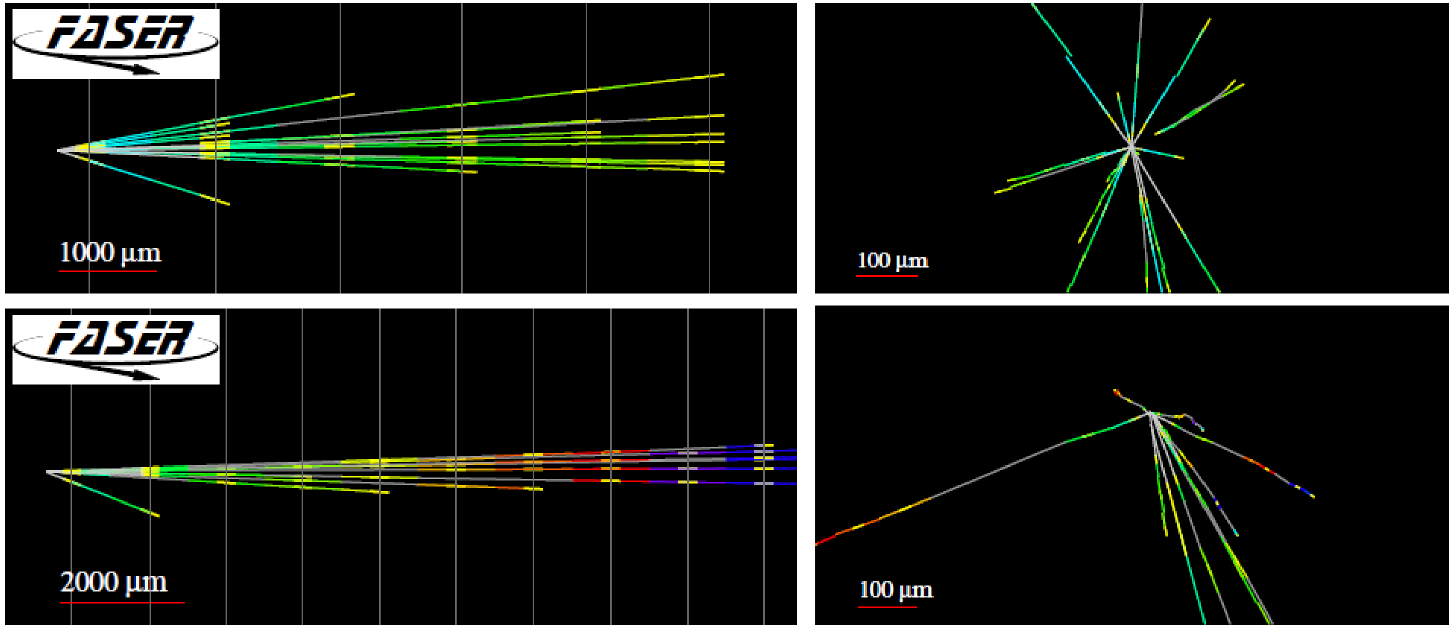




- Aims: charged particle flux measurement and neutrino detection
- We performed measurements in the tunnels TI18 and TI12, 480 m from the ATLAS IP.
- For neutrino detection, a 30 kg emulsion detector was installed in TI18 and 12.2 fb^{-1} data was collected.

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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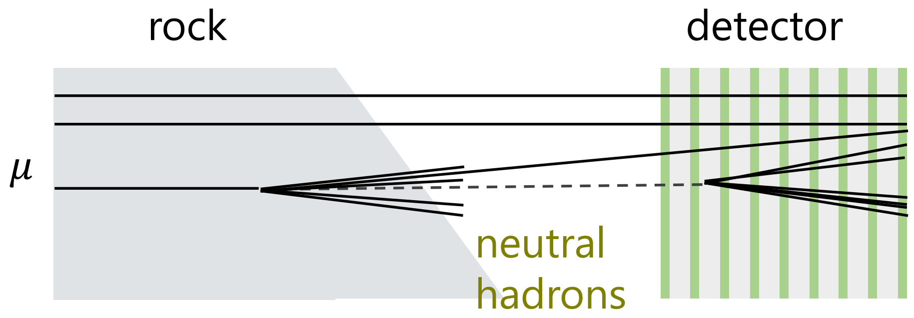
Background estimation

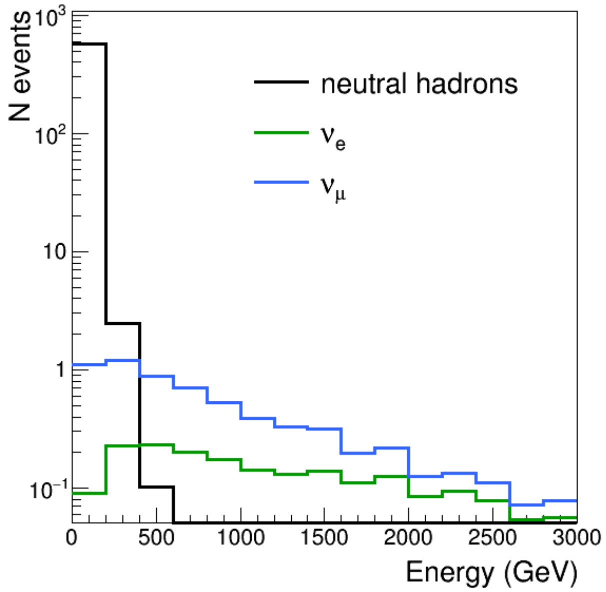
- The pilot detector lacked the ability to identify muons given its depth of only $0.6\lambda_{int}$, much shorter than the $8\lambda_{int}$ of the full FASERν detector.
- → Separation from neutral hadron BG (produced by muons) is much harder than the physics run.

- 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.



The production rates of neutral hadrons per incident muon

	Negative Muons	Positive Muons
K_L	3.3×10^{-5}	9.4×10^{-6}
K_S	8.0×10^{-6}	2.3×10^{-6}
n	2.6×10^{-5}	7.7×10^{-6}
$\bar{n}$	1.1×10^{-5}	3.2×10^{-6}
Λ	3.5×10^{-6}	1.8×10^{-6}
$\bar{\Lambda}$	2.8×10^{-6}	8.7×10^{-7}



First neutrino interaction candidates at the LHC, arXiv:2105.06197

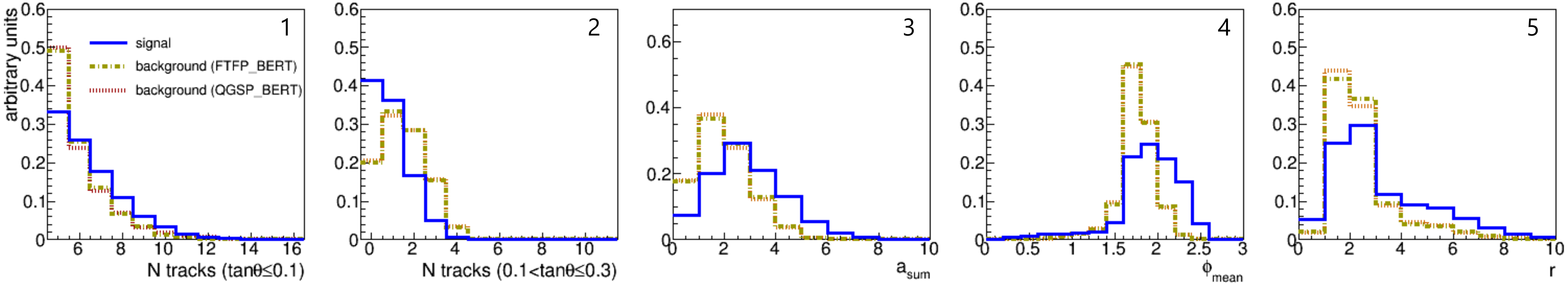
Variables for the BDT analysis

5 variables used in the analysis

1. the number of tracks with $\tan\theta$ <=0.1 with respect to the beam direction
2. the number of tracks with 0.1<$\tan\theta$<=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).

Concepts

- The neutrino energy is higher than the neutral hadron energy. Higher energy, more particles are produced in forward direction, i.e. tan(theta)<0.1. → variable 1, 2
- Momentum in the transverse plane is more balanced in hadron interactions than neutrino CC and NC interactions. Outgoing leptons in neutrino interactions take a major energy, which distorts this variable. → variable 3
- For CC interactions, we expect the outgoing lepton and hadron system are back to back in the transverse plane. → variable 4, 5

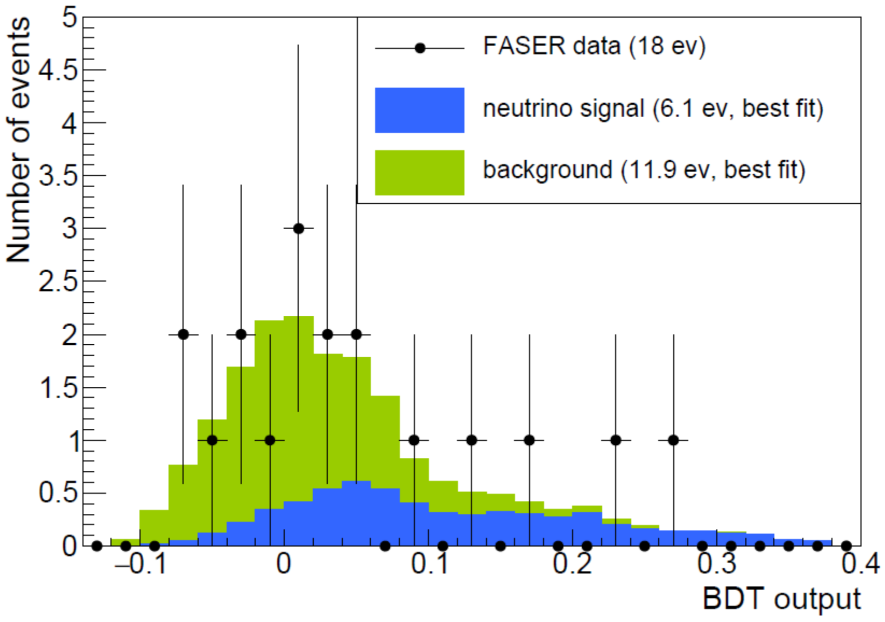


First neutrino interaction candidates at the LHC, arXiv:2105.06197

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 neutrinos 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

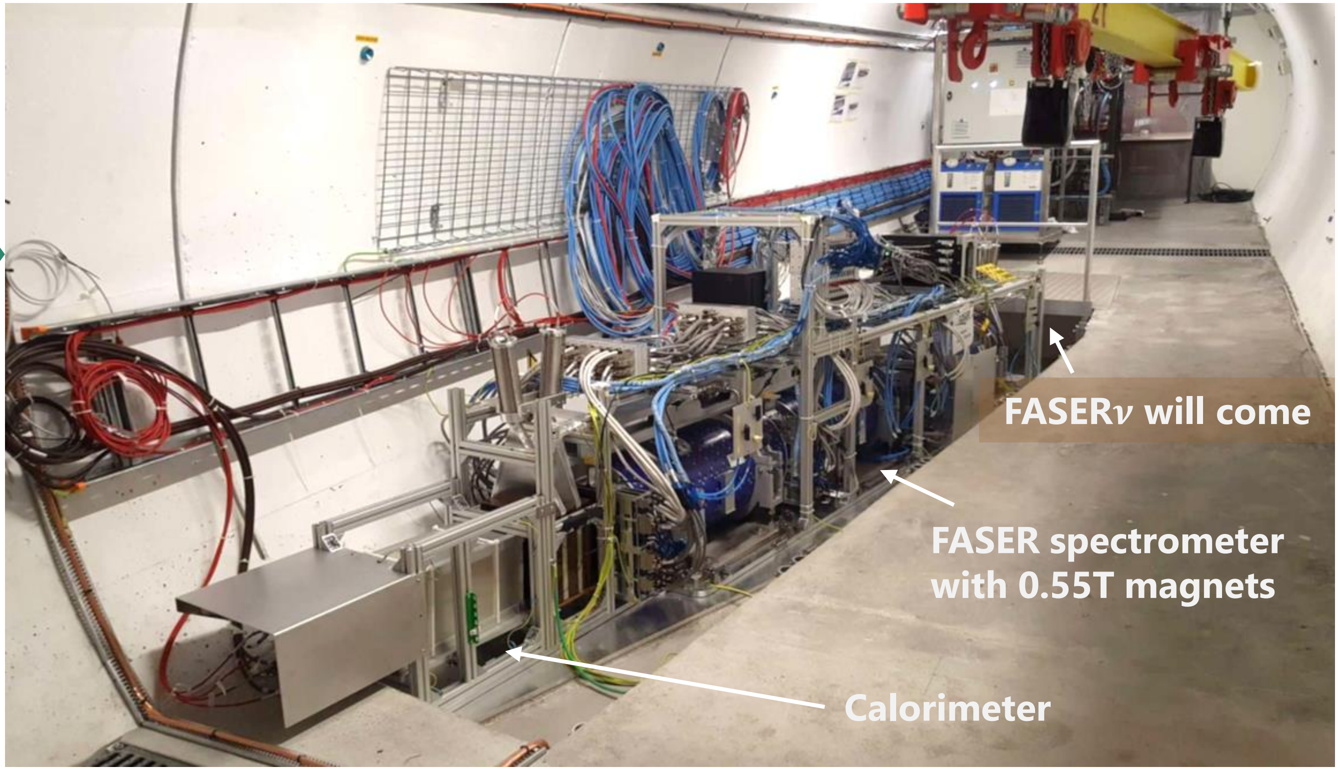
First neutrino interaction candidates at the LHC, arXiv:2105.06197

Cross section measurements of different flavors at TeV energies

Precision ν_τ measurements and heavy flavor physics studies

Preparation towards LHC Run-3

The TI12 area

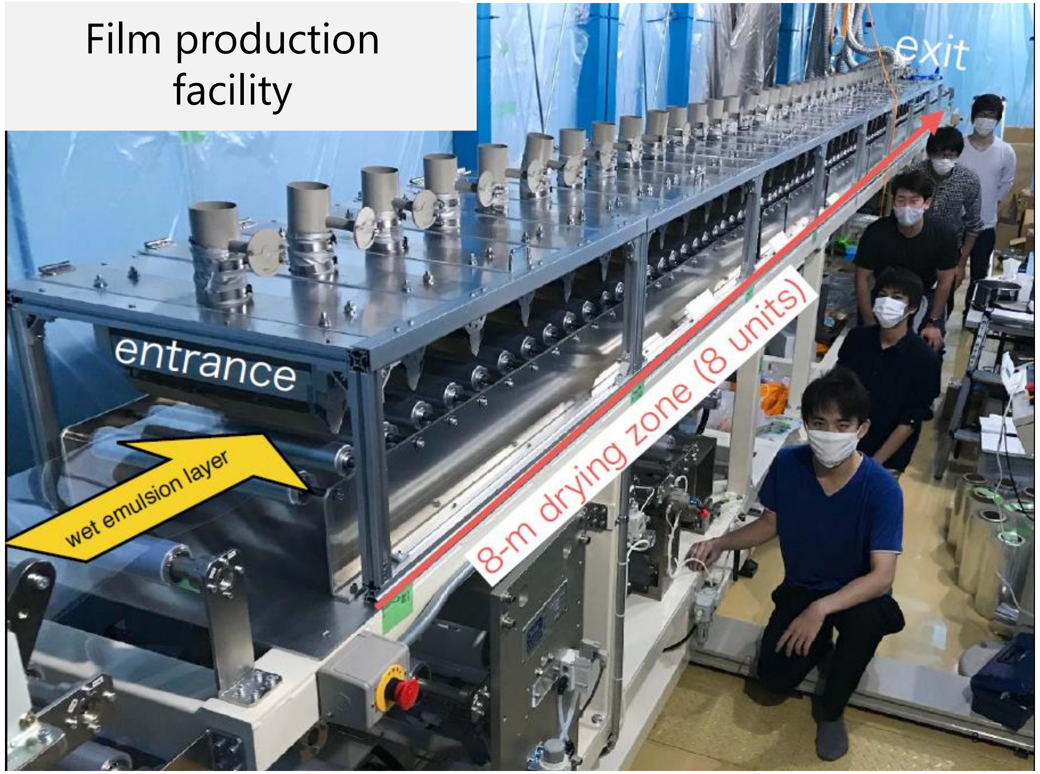


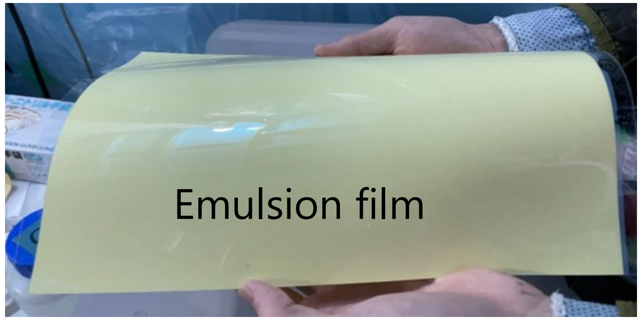
The FASER main detector was successfully installed into the TI12 tunnel in March 2021.
Acknowledge great support from many CERN teams involved in the work

FASERν installation test

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.

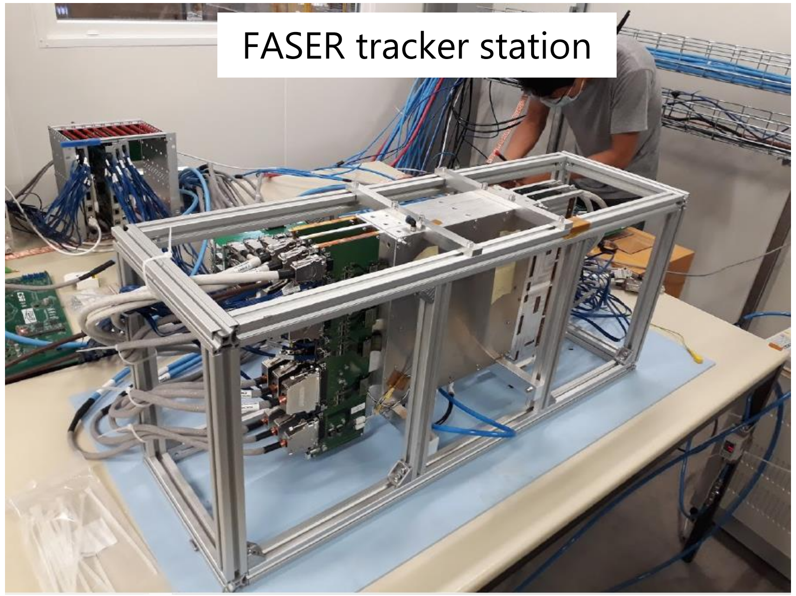


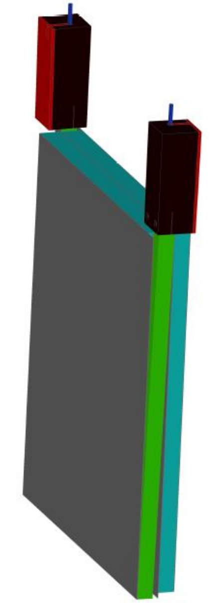


Interface tracker (IFT) and veto system

- **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.
  - The test beam is ongoing at the H2 beamline in the CERN SPS North Area.

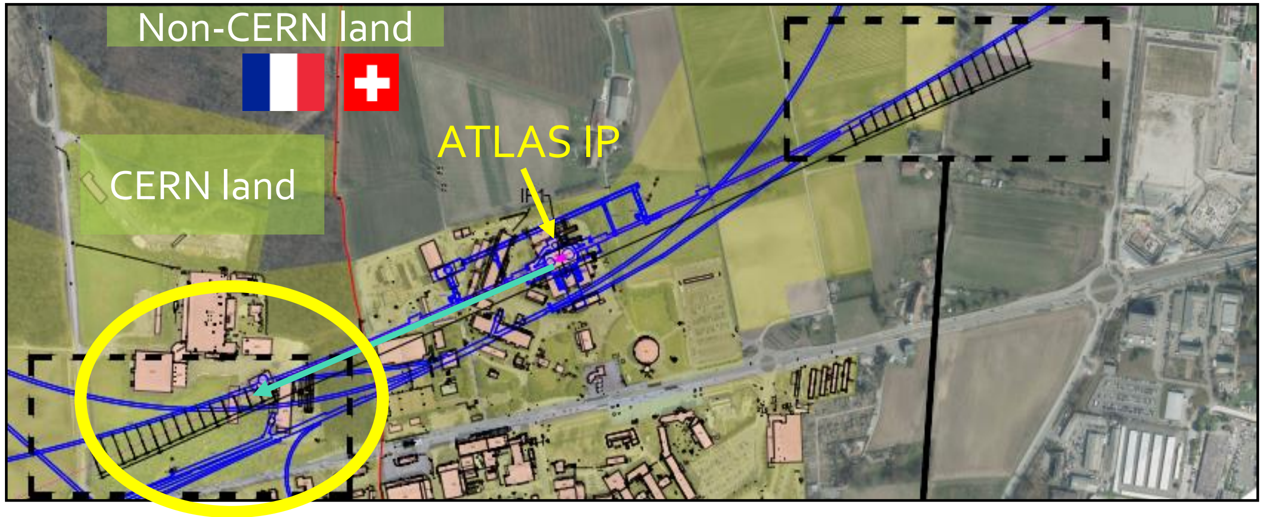
- **Veto station** consists of two 2-cm scintillators and WLS (Wave Length Shifting) bars with two PMTs.
  - The PMTs were tested.
  - The scintillators have been assembled and are under test with cosmic rays.



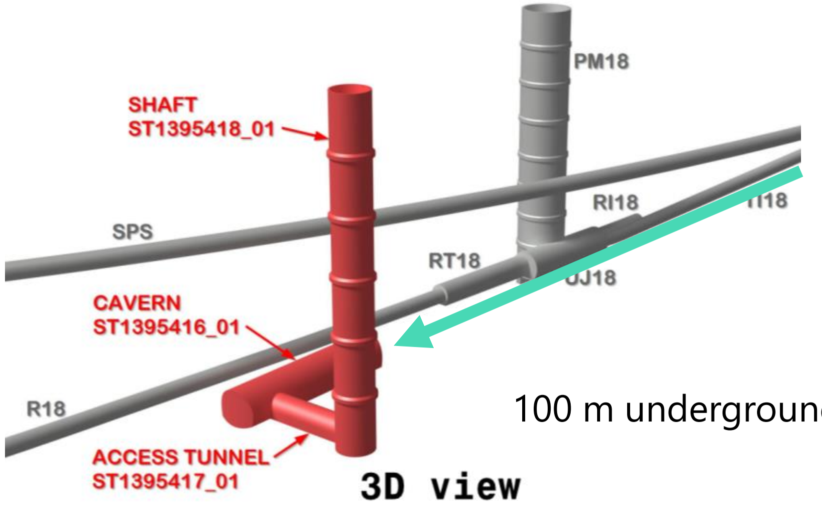


Veto dimension 30×35 cm^2

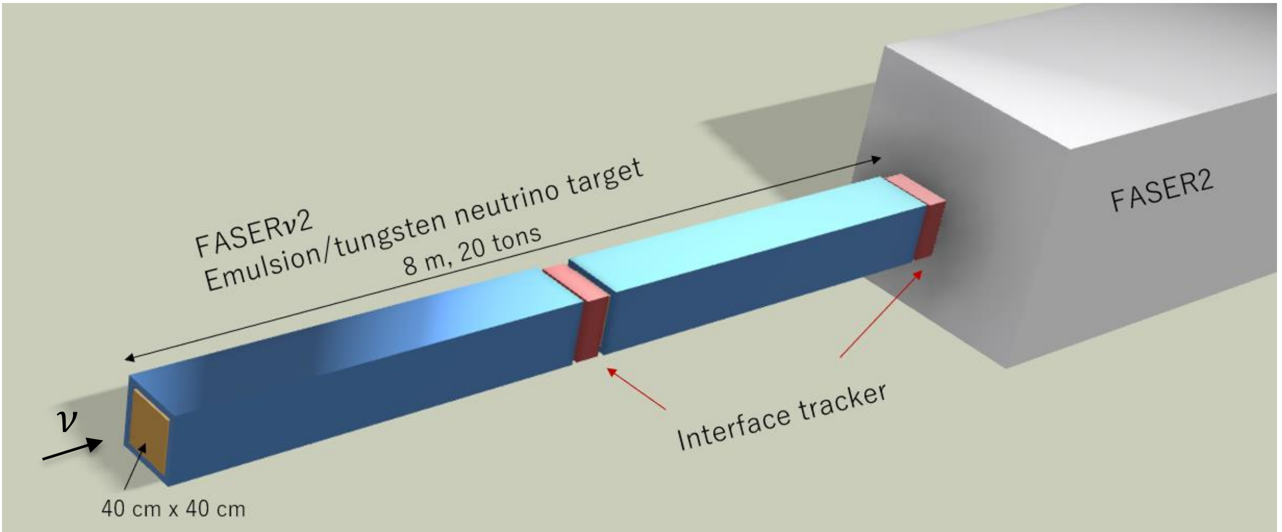
The new FPF facility and FASERν2



- 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).
- **FASERν2 is designed to carry out precision ν_τ measurements** and heavy flavor physics studies
  - ~2300 (SIBYLL) / ~20000 (DPMJET) ν_τ interactions are expected.



100 m underground



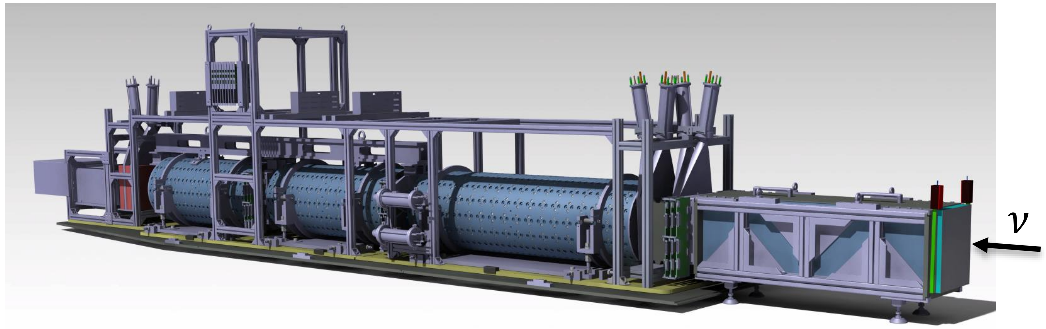
Summary and prospects

- 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.

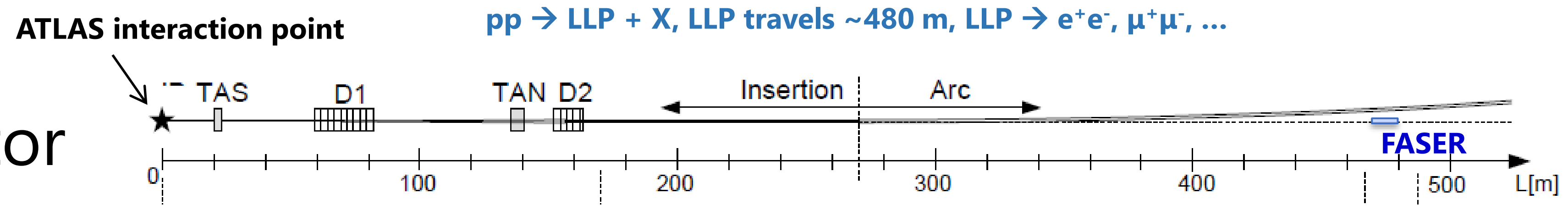
- Also planning neutrino measurements in the HL-LHC era.
  - A large detector for precision ν_τ physics with 20 tons of target



Thank you for your attention

Backup

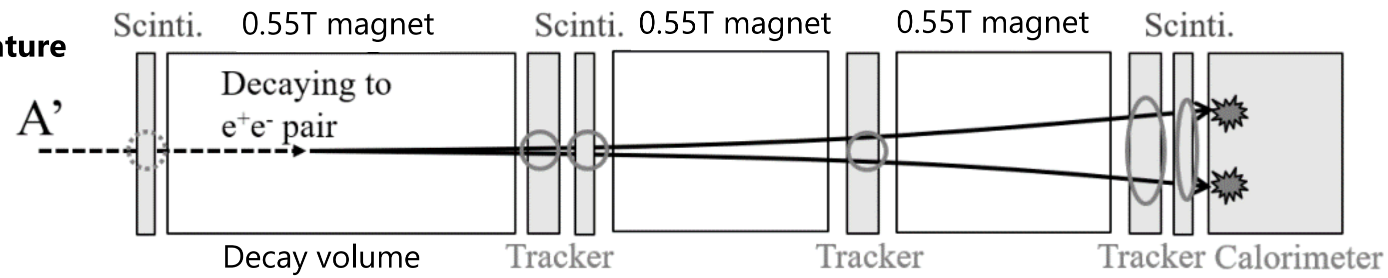
The FASER main detector

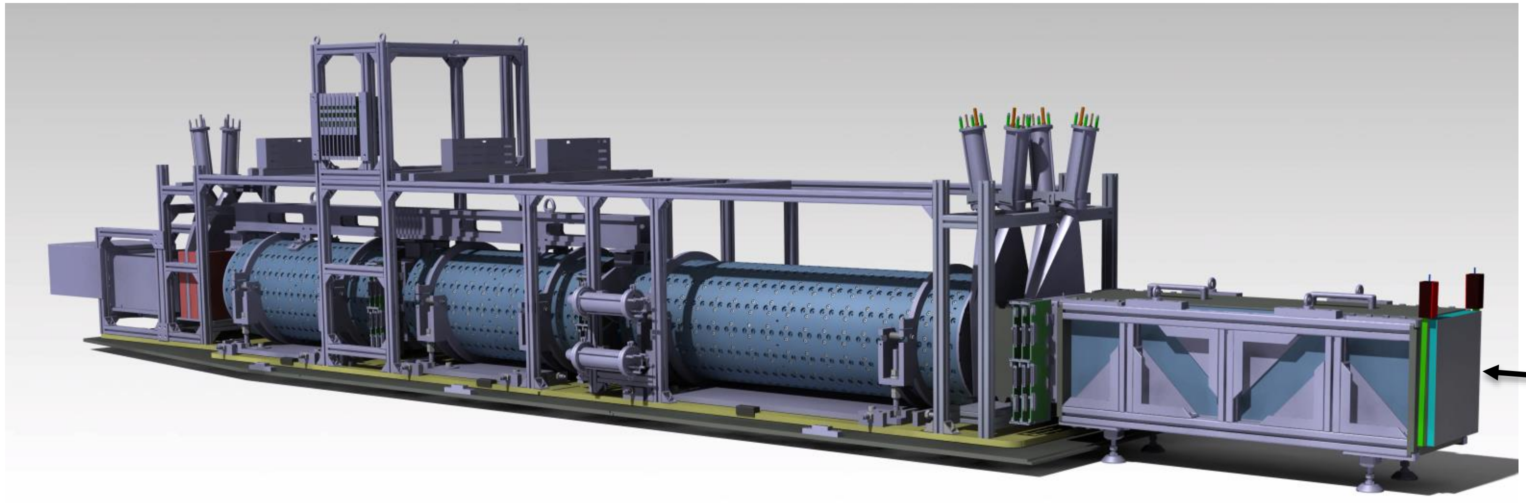


Technical proposal: FASER,
[CERN-LHCC-2018-036 ; LHCC-P-013]

FASER's physics reach for long-lived particles,
[Phys. Rev. D 99, 095011]

Signal signature





Incoming particles

The detector consists of:

- Scintillator veto
- 1.5 m long decay volume
- 2 m long spectrometer
- EM calorimeter

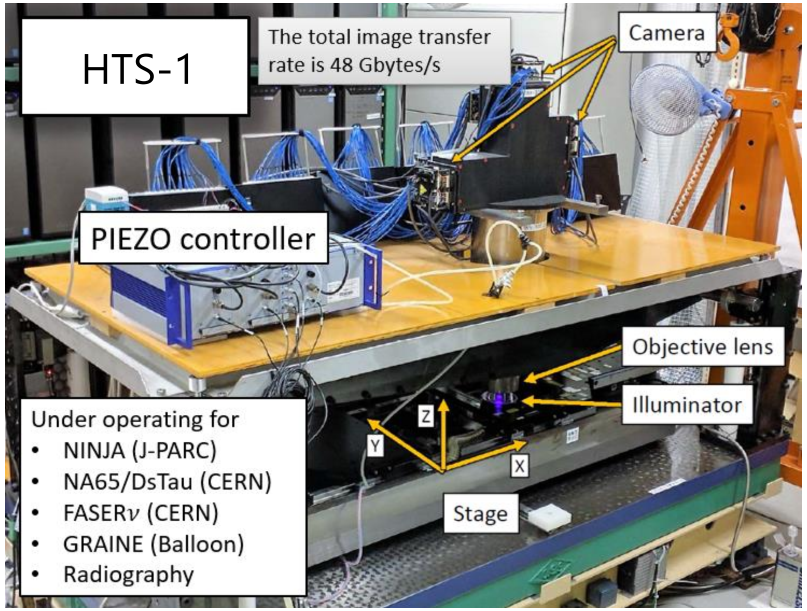
Emulsion readout systems

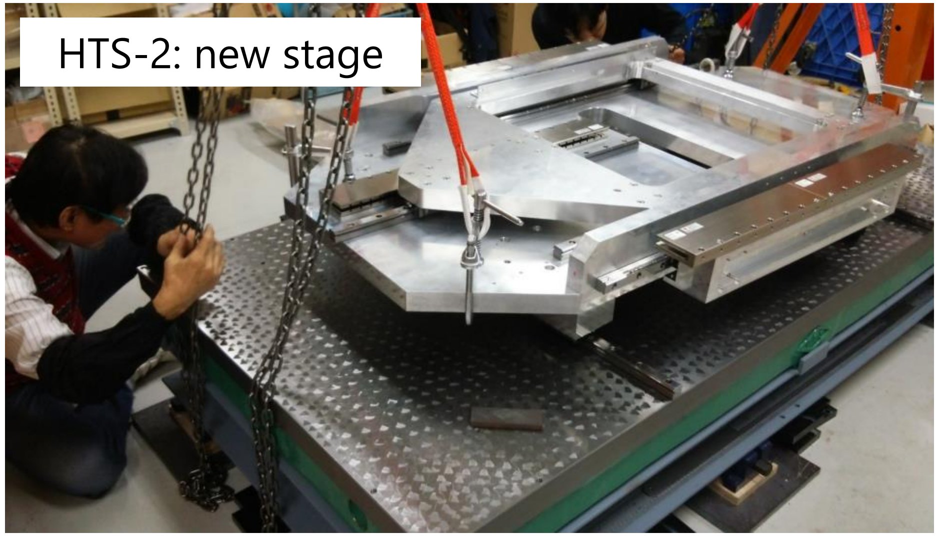
	Start year	Field of view (mm^2)	Readout speed (cm^2/h/layer)
S-UTS	2006	0.04	72
HTS-1	**2015**	**25**	**4500**
HTS-2	**2021**	**50**	**25000**

- **HTS-1** is under operation for several experiments.
- **HTS-2** is under development.
- **HTS-2** concept
  - Very large field of view: 9 x 5.5 mm2 (x2 cf. HTS-1)
  - Quick and continuous stage using the linear motors (good transfer characteristic) and counter stage.
  - GPGPU based image processing: <30 ms @tanθ<1.6 (total 72 Geforce RTX2080 will be used.)

Readout time for FASERν
(1 replacement = 50 m^2 x2layers)

~3 months with HTS-1 (using ~5 hours/day)
Would be faster with HTS-2





Physics potential: neutrino scattering

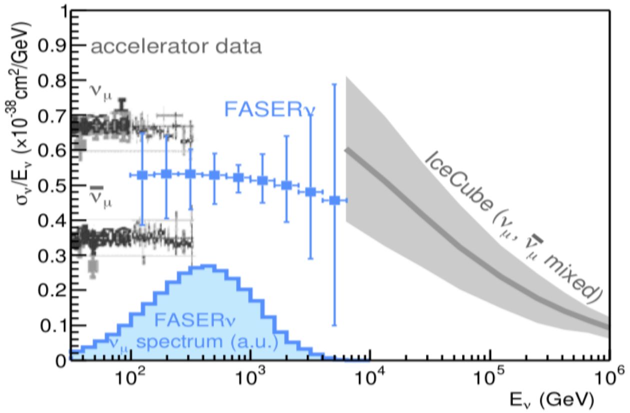
- Primary goal: measurement of the total DIS neutrino scattering cross section at TeV energies

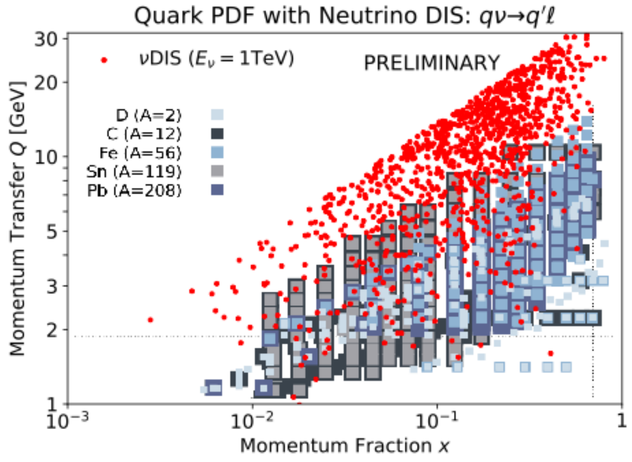
- FASERν can also measure differential distributions.
  - DIS variables: x, y, Q^2 and lepton charge

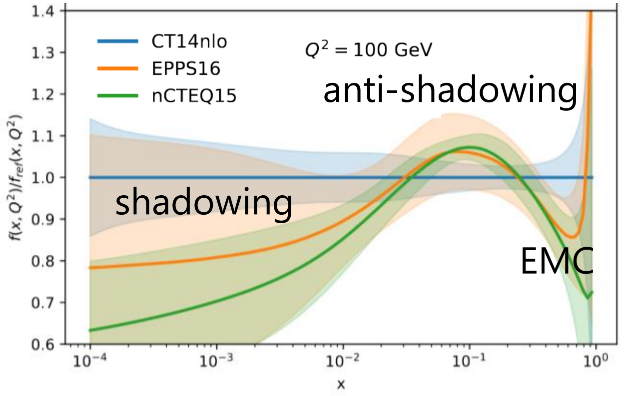
- This can be used to probe PDFs.
  - Similar to NuTeV and CHORUS measurements but extended to higher energy.
  - Allows to probe higher Q^2 and lower x.
  - The potential to measure PDF via neutrino scattering is currently being investigated. [Arakawa, Kling, Smith, Tait, Valli]

- Probe nuclear effects:
  - shadowing, anti-shadowing and EMC

- Strange quark content using $\nu\ s\ \rightarrow l\ c$
  - IFT allows to separate strange/anti-strange.
  - Probe inconsistency between DIS and LHC data. [ATLAS: 1612.03016]

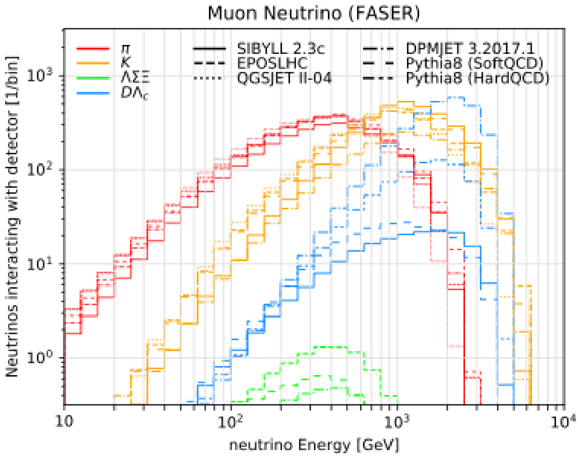


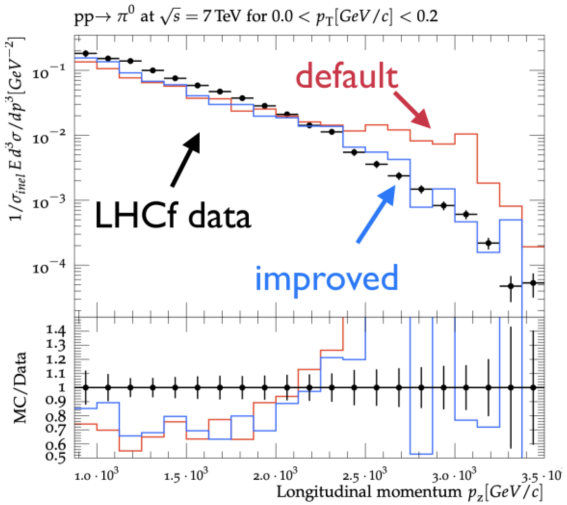




Physics potential: neutrino production

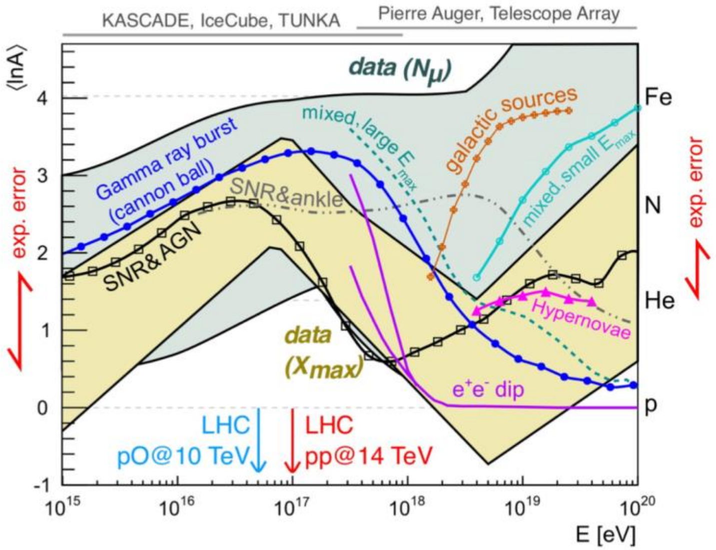
- Forward particle production is poorly constrained by other LHC experiments.
- FASERν's measurements provide novel input to validate/improve generators.
- First data on forward kaon, hyperon, charm
- A Pythia tune is currently being developed which includes all available forward data from LHCf, LHCb, TOTEM. [Fieg, Kling, Schulz]





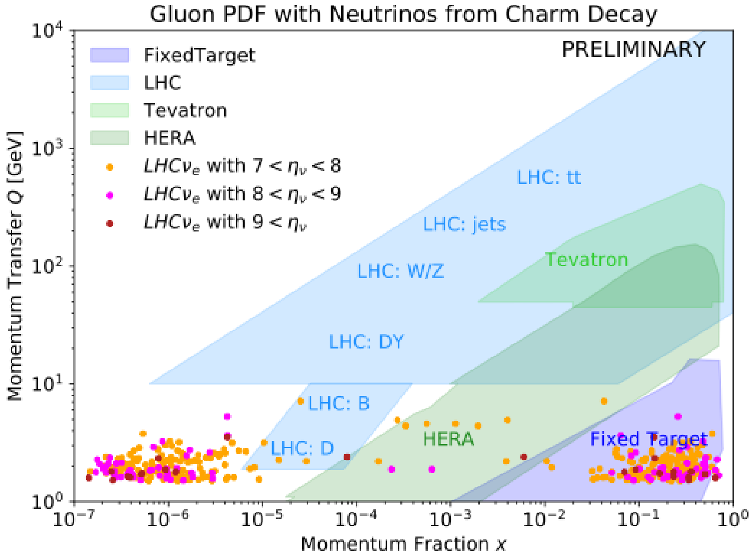
- Relevant for muon problem in CR physics:
  CR experiments reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level.

- New input from LHC is crucial to reproduce CR data consistently.
- Goal: understand composition/origin of CR

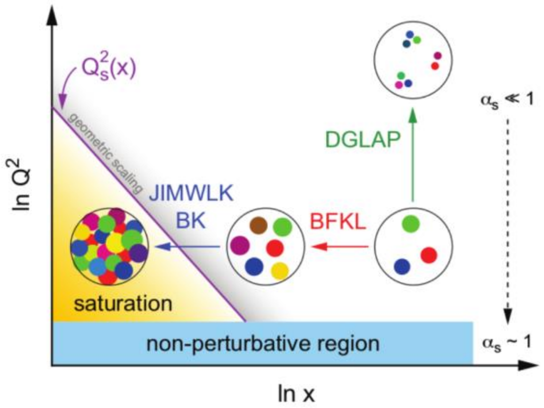


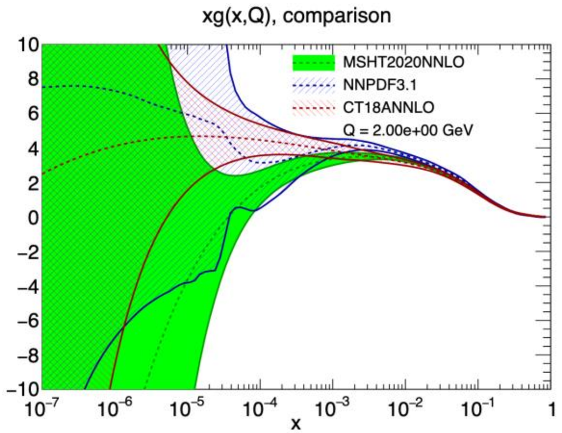
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

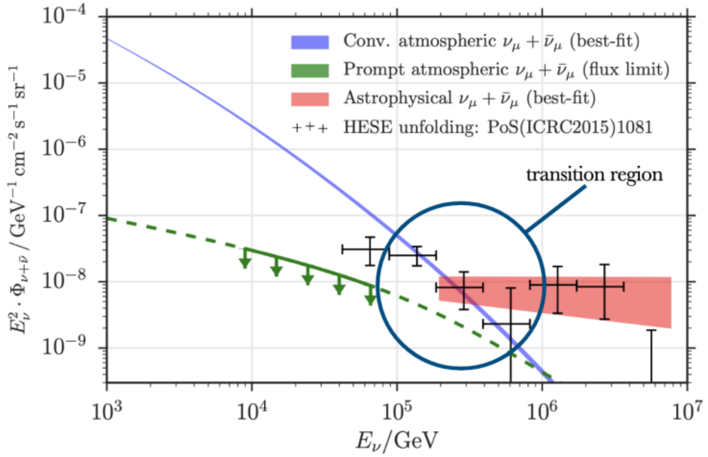
Physics potential: forward charm



- Electron neutrinos at high energy and tau neutrinos are mainly produced in charm decays.
- Neutrinos from charm decay could allow to
  - test transition to small-x factorization.
  - see effects of gluon saturation.
  - constrain low-x gluon PDF.
  - probe intrinsic charm.
- Relevant for neutrino telescopes (such as IceCube).
  - Direct measurements of forward charm production will also help to constrain the flux prompt atmospheric neutrinos at IceCube and improve cosmic neutrino measurements.
- A calculation of forward charm production at the LHC using BFKL resummation and including gluon saturation is currently being performed. [Bhattacharya, Kling, Sarcevic, Stasto]



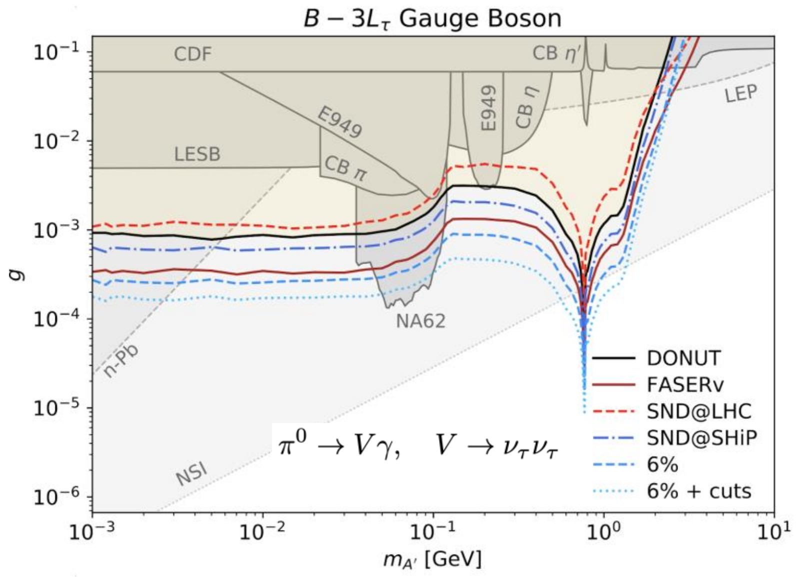


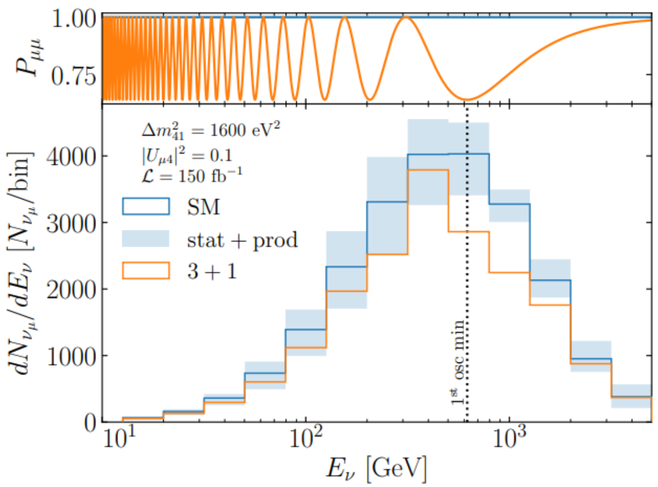


Physics potential: BSM physics (1)

- If SM uncertainties are under control, there is additional potential for BSM physics searches.

- The tau neutrino flux is small in SM.
  A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux.
  [Kling 2005.03594]





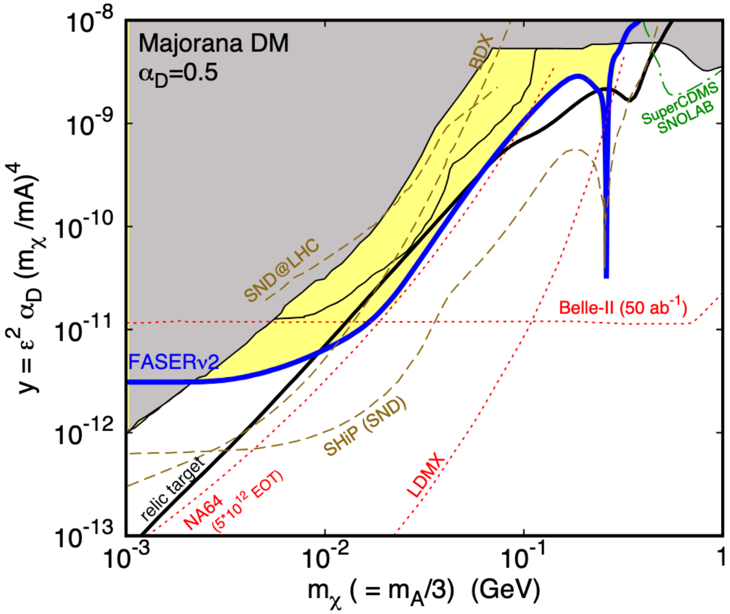
- SM neutrino oscillations are expected to be negligible at FASERν. However, sterile neutrinos with mass ~40 eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment. [FASER collaboration1908.02310]

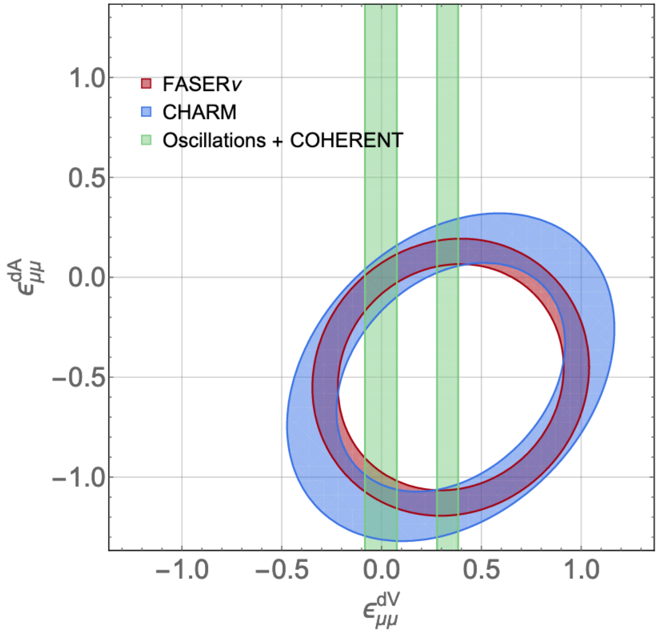
$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\sin^2\frac{\Delta m^2_{41} L}{4E},$$

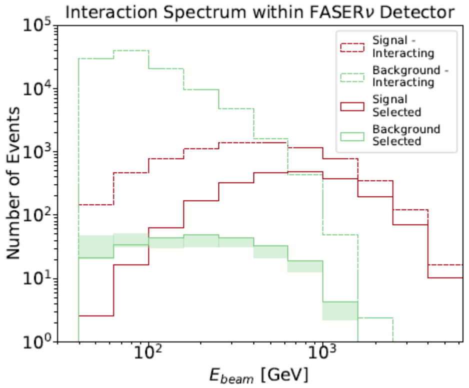
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2 \frac{\Delta m^2_{41} L}{4E}.$$

Physics potential: BSM physics (2)

- If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERν could therefore also search for DM scattering. [Batell, Feng, Trojanowski 2101.10338]





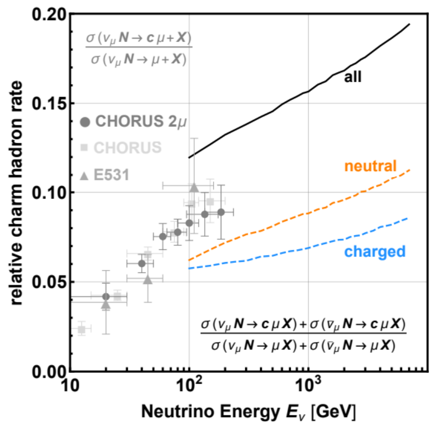


- NC measurements at FASERν could constrain neutrino non-standard interactions (NSI). [Abraham, Ismail, Kling 2012.10500]

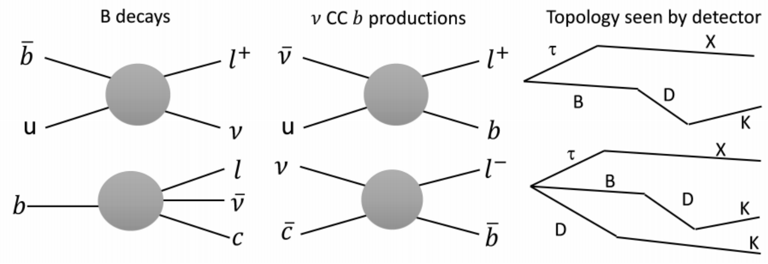
Heavy-flavor-associated channels

- Measure charm production channels
  - Study of quark mixing and QCD
  - Large rate ~10% of ν CC events

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



- Search for Beauty production channels
  - Probe "flavor anomaly" suggested by collider experiments
  - Expected standard model events ($\nu_\mu\ CC\ b$ production) are $\mathcal{O}(0.1)$ events in Run 3, due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$



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

$$\nu N \to \ell BDX$$