Detecting and studying high-energy neutrinos with FASERν at the LHC

Xin Chen

Tsinghua University

On behalf of FASER collaboration

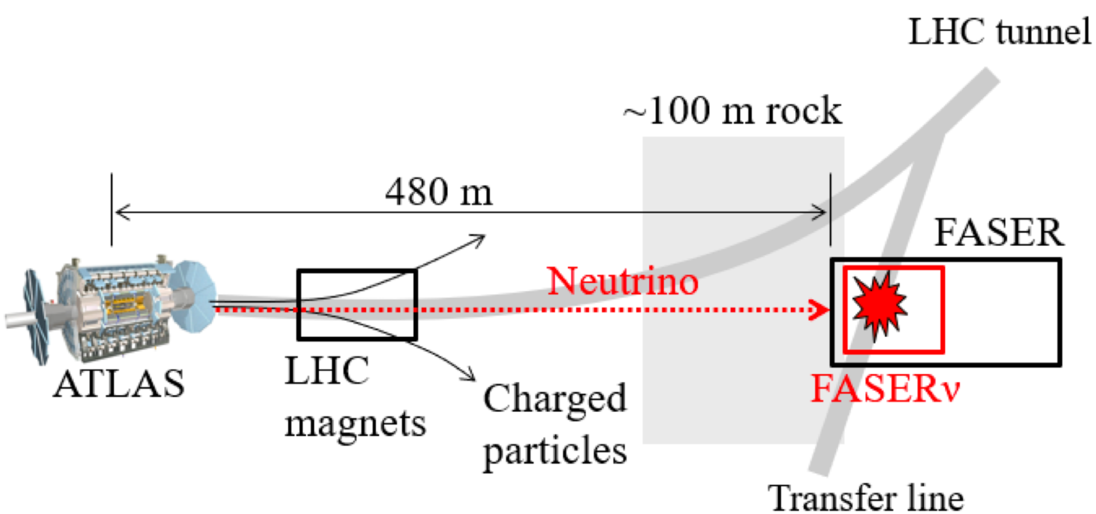
NuFact 2021

2021/09/6-11, Cagliari, Italy

FASER and FASERν

- FASER is a new detector to search for light, weakly coupled long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022 together with ATLAS Run-3.

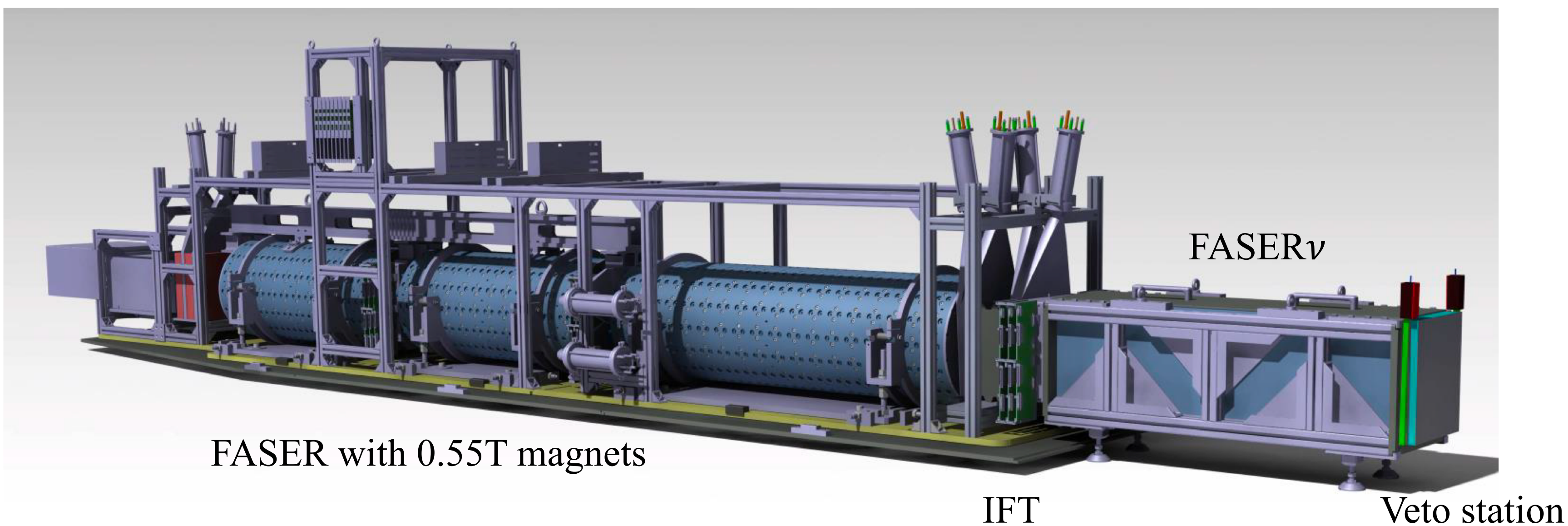
- FASERν is a detector (part of FASER) for neutrino measurements. Will make the first measurements of neutrinos from a collider and in unexplored energy regime.



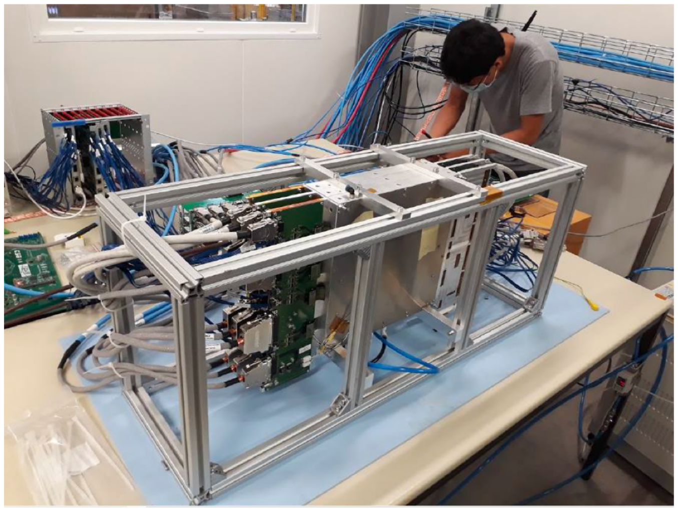
FASERν detector

- FASERν is a detector consisting of emulsion, tungsten, IFT and veto station
  - Composed of 770 1-mm-thick tungsten plates, interleaved with emulsion films
  - An area of 25×30 cm^2, 1.1 m long, 1.1 tons detector (220 $X0$)

- FASERν will be placed in front of the FASER main detector



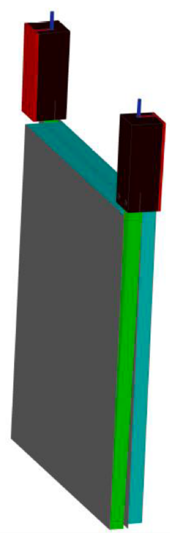
IFT and veto system



- **IFT** uses the same design as the tracker station in the FASER spectrometer. Important for track matching between FASER and FASERν

  – Silicon strip detector with ATLAS SCT barrel modules
  – Test beam data obtained with CERN SPS facility

PMT (H11934-300)

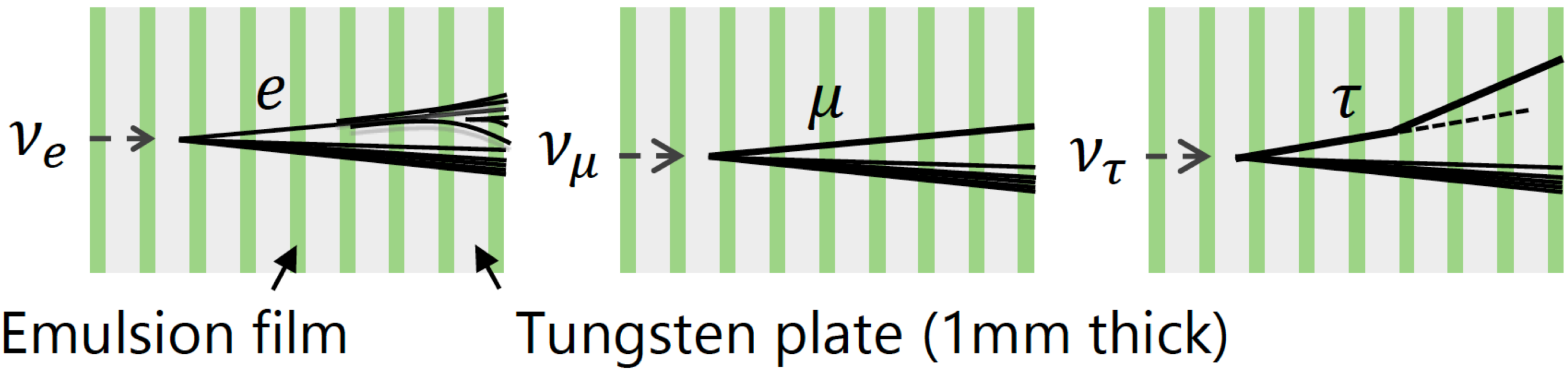


30×35 cm^2

- **Veto station** consists of two 2-cm scintillators and WLS (Wave Length Shifting) bars with two PMTs. Rejects upstream charged particles

  – The PMTs were tested
  – The scintillators have been assembled and are under test with cosmic rays

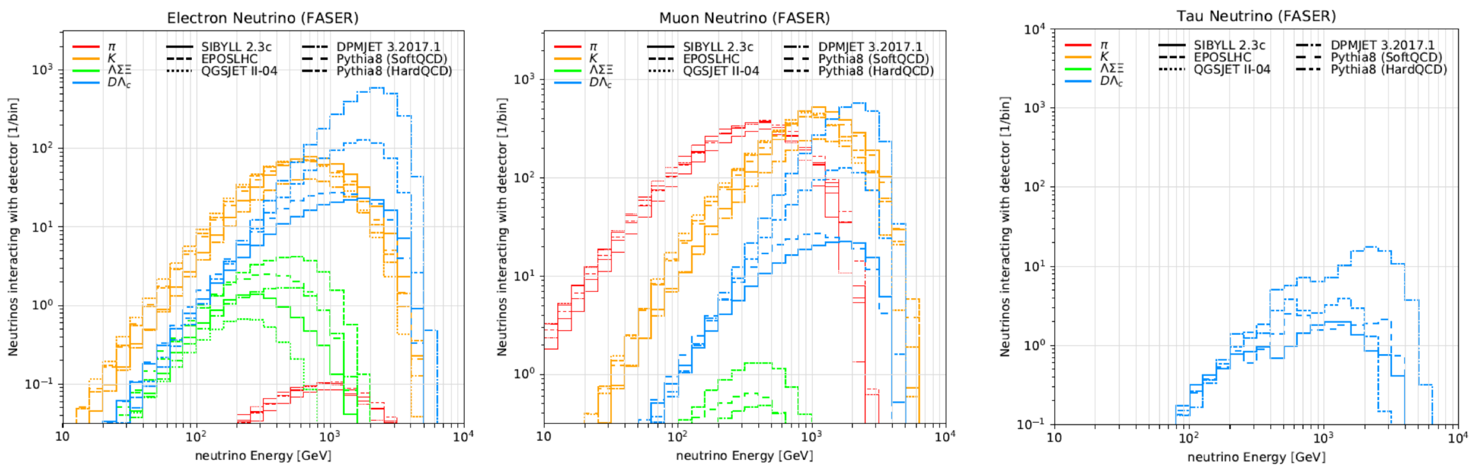
Neutrino detection



- All flavors of neutrino interactions can be detected and distinguished from each other
  - ✓ Muon identification by its track length in the detector (8 λ_{int})
  - ✓ Muon charge identification with tracking stations - distinguishing ν_μ and $\bar{\nu}_\mu$
  - ✓ Neutrino energy measurement with ANN by combining topological and kinematical variables

Expected Neutrino event rates at Run-3

[F. Kling, arXiv:2105.08270]



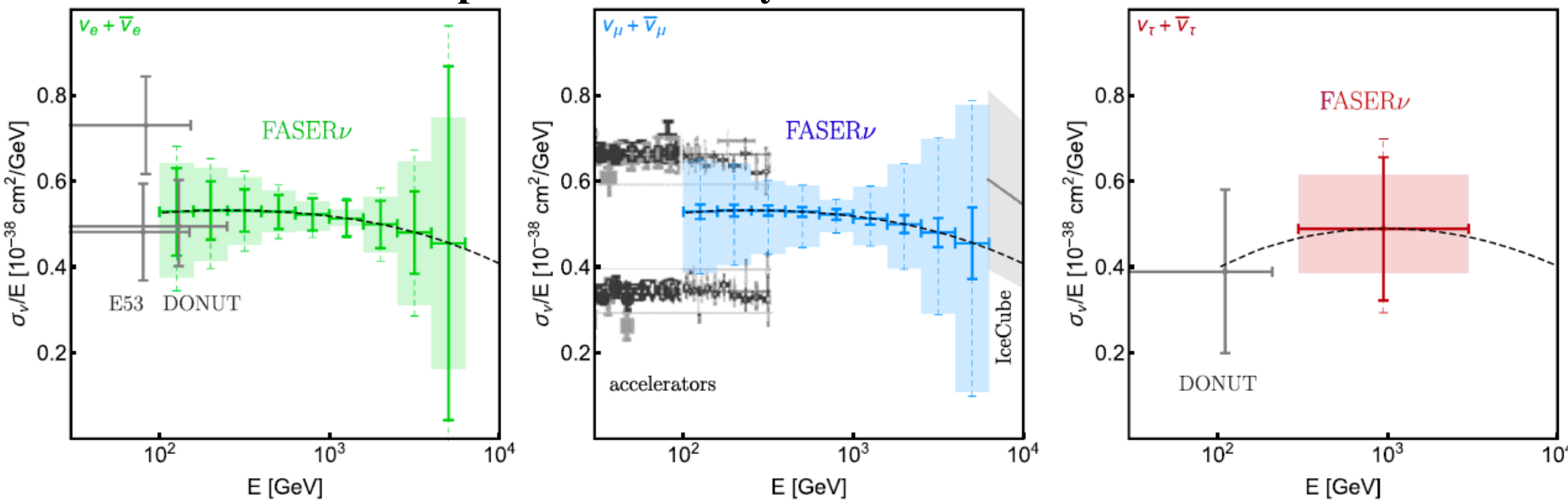
Expected number of CC interactions in FASERν during Run-3

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}	$31.5^{+17.3}_{-10.3}$

- A high-intensity beam of neutrinos will be produced in the far-forward direction at ATLAS
- FASERν's LOS maximizes fluxes of all neutrino flavors. Most abundant is ν_μ

Charged Current interactions

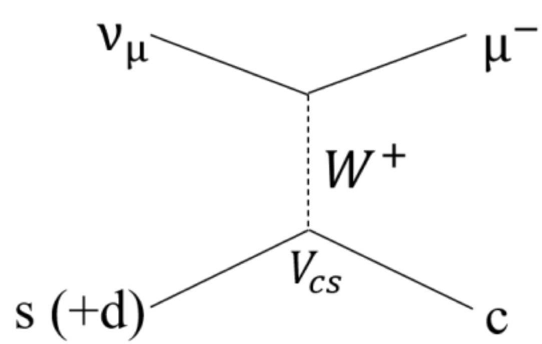
Expected sensitivity to neutrino cross-sections



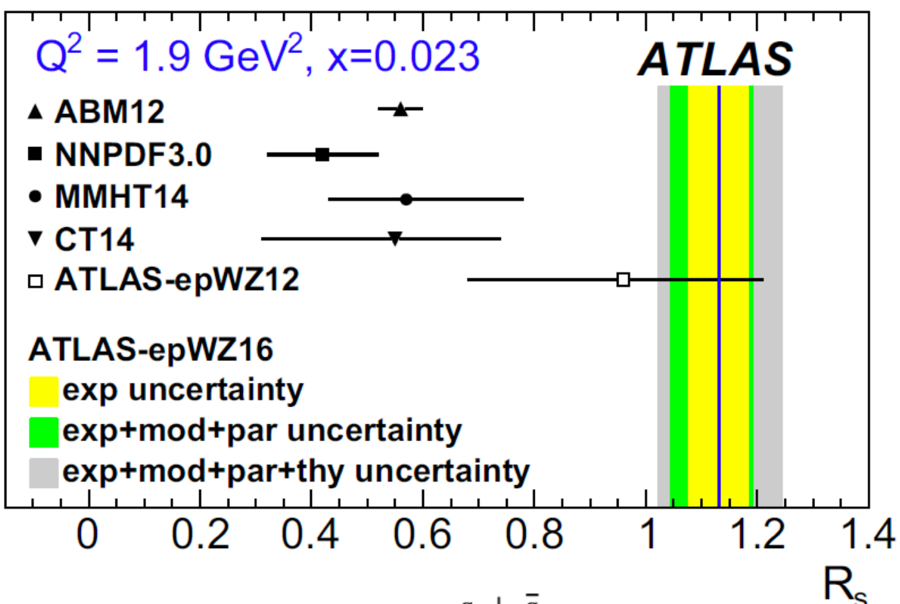
- FASERν will measure neutrino cross-sections at TeV scale which is uncovered by existing experiments
- Due to excellent position resolution of the emulsion detector, CC cross-sections will be measured for all neutrino flavors
- The charge measurement in FASER tracking stations behind FASERν to separate ν_μ and $\bar{\nu}_\mu$

Proton PDF

D meson production in CC ν_μ interaction is sensitive to strange PDF in a proton where tension exists between ATLAS and PDF predictions

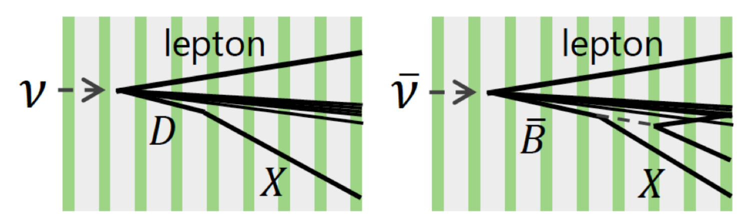


[Eur. Phys. J. C77 (2017) 367]

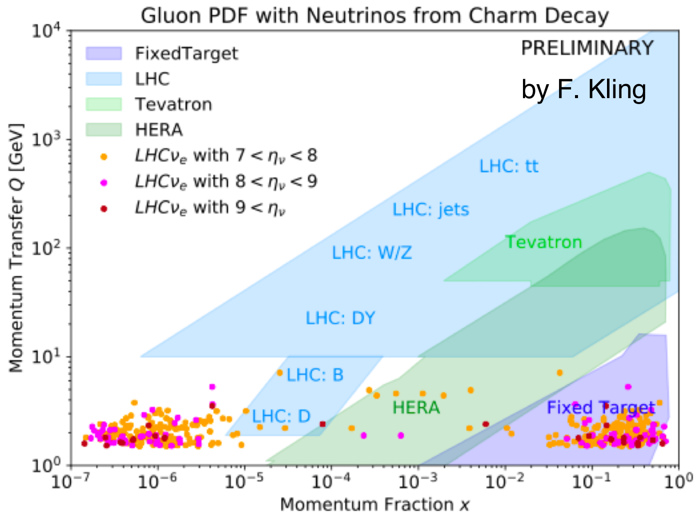


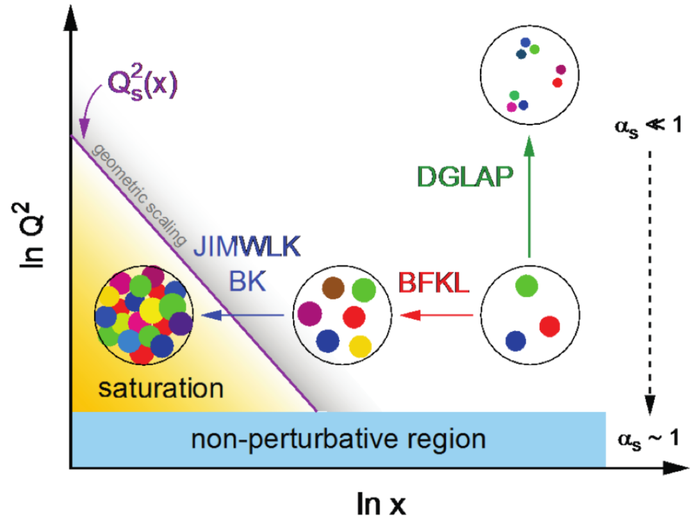
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

Neutrino CC interaction with beauty production? – Has never been detected:



Forward physics

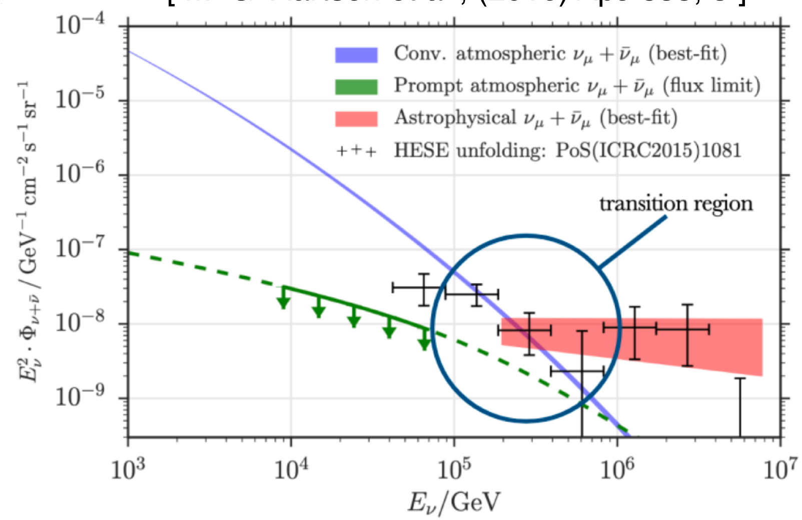




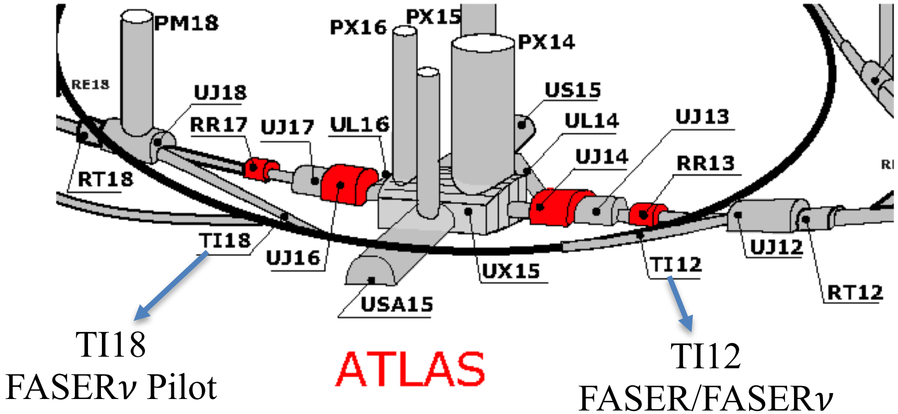
- Neutrino flux and its energy spectrum can allow to probe small-x PDF, effects of gluon saturation, and intrinsic charm

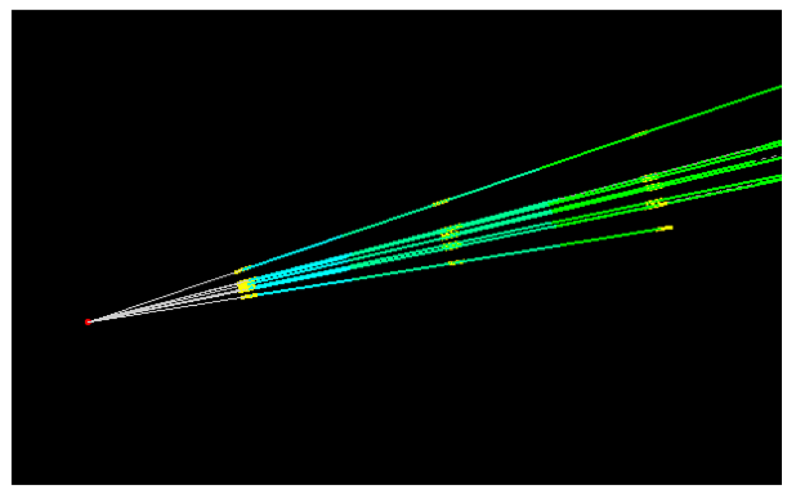
- Proton-proton collision at LHC corresponds to ~100 PeV proton interaction with fixed target. Cross-section of heavy mesons at LHC can provide constraint on the prompt atmospheric neutrino flux

[M. G. Aartsen et al., (2016) ApJ 833, 3]



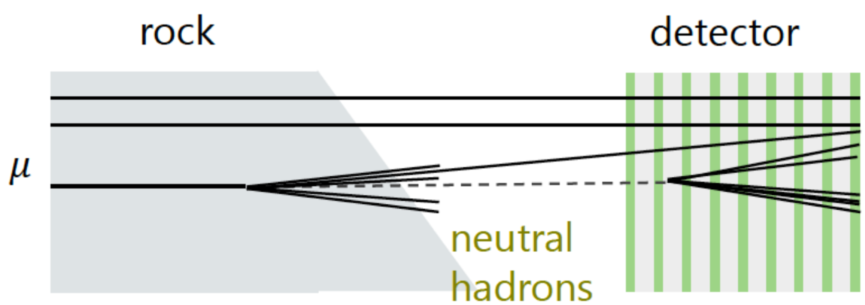
2018 FASERν pilot run





- The pilot runs were taken place for neutrino detection and flux measurement of charged particles at tunnels TI12 and TI18 in 2018
- TI18 is the tunnel at the same distance from ATLAS IP as TI12 but opposite side
- The neutrino detection was performed with a 30 kg emulsion detector installed at TI18, collecting 12.5 fb^{-1} of data

Pilot run background



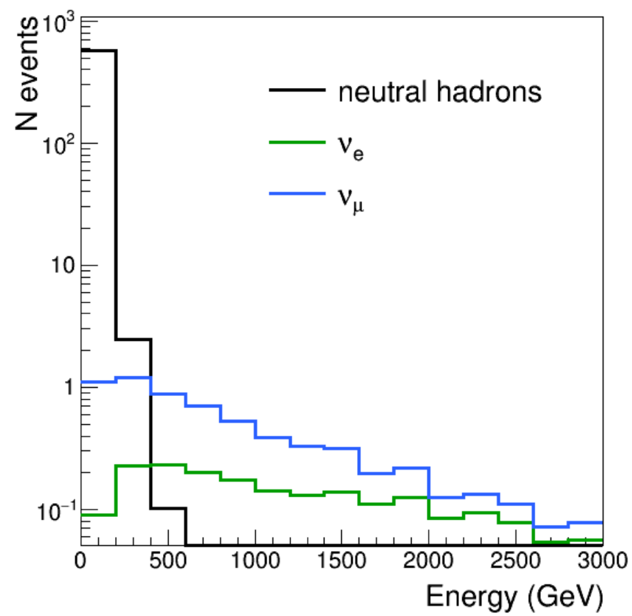
- The largest background are muons, which can be vetoed by emulsion vertices with a charged parent

- Muons produce neutral hadrons in upstream rock, which can mimic neutrino interaction vertices – use Geant4 to simulate

The production rates of neutral hadrons per incident muon
[arXiv:2105.06197]

	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}

- Energy of upstream neutral hadrons are low $\longrightarrow$ can suppress them by vertex topology



Pilot data event reconstruction

Selection cuts are applied on the tracks to enhance signal and suppress backgrounds

- Reconstructed tracks passing through at least 3 plates
- Vertex reconstruction for tracks with a minimum distance within 5 μm
- Converging patterns with 5 or more tracks were then identified as vertices
- Collimation cuts on vertices:
  - The number of tracks with tan θ ≤ 0.1 with respect to the beam direction is required to be 5 or more
  - The number of tracks with tan θ > 0.1 with respect to the beam direction is required to be 4 or less

✓ Vertices are categorized as charged or neutral based on the presence or absence, respectively, of charged parent tracks

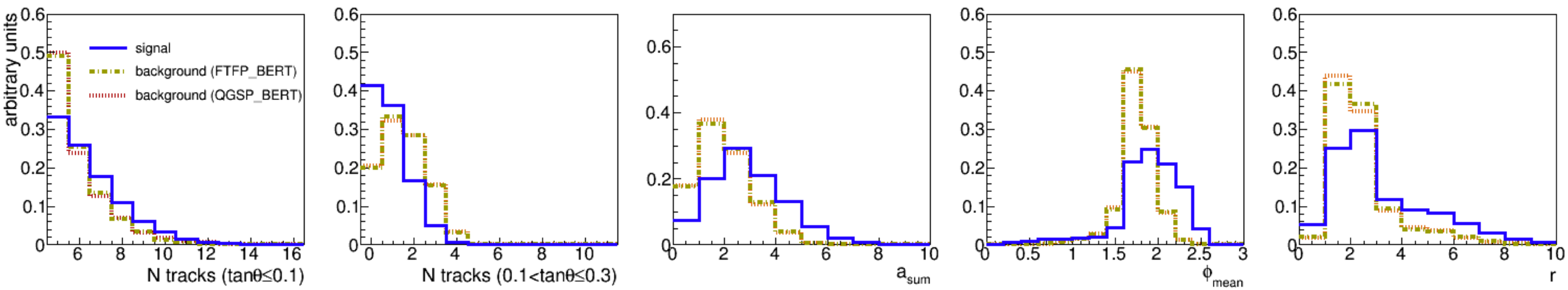
✓ In the signal, all neutrino flavors are combined

✓ 18 neutral vertices were selected

Selection efficiency cuts for signal and neutral hadron background (E > 10 GeV)

Signal		Background		
			FTFP_BERT	QGSP_BERT
ν_e	0.490	K_L	0.017	0.015
$\bar{\nu_e}$	0.343	K_S	0.037	0.031
ν_μ	0.377	n	0.011	0.012
$\bar{\nu_\mu}$	0.266	$\bar{n}$	0.013	0.013
ν_τ	0.454	Λ	0.020	0.021
$\bar{\nu_\tau}$	0.368	$\bar{\Lambda}$	0.018	0.018

Kinematic variables in pilot data

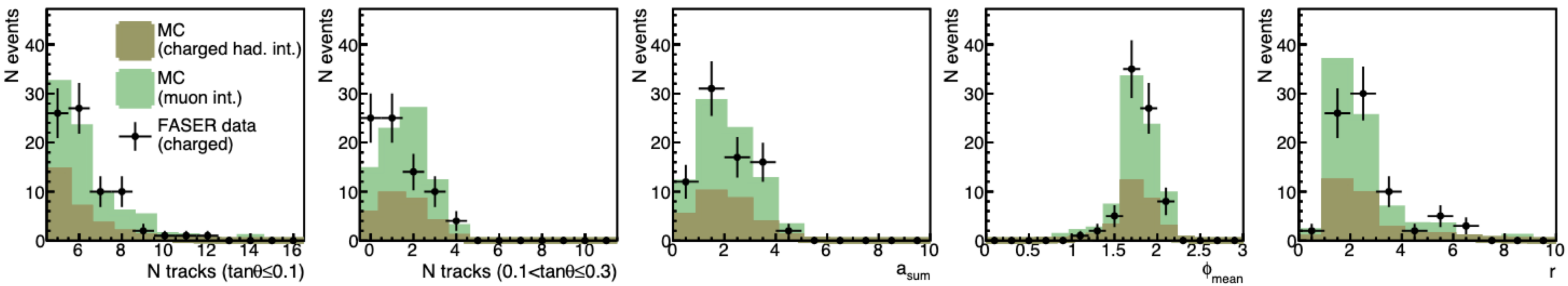


Five kinematic variables are used to separate signal and background

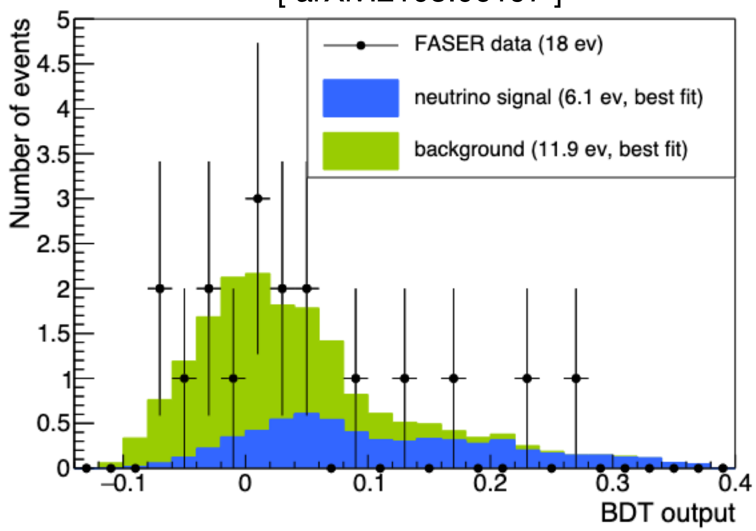
Variable	description
N_{trk} $(\tan\theta \le 0.1)$	The number of tracks with tanθ≤0.1 with respect to the beam direction
N_{trk} $(0.1 < \tan\theta \le 0.3)$	The number of tracks with 0.1<tanθ≤0.3 with respect to the beam direction
a_{sum}	The absolute value of vector sum of transverse angles calculated considering all the tracks as unit vectors in the plane transverse to the beam direction
ϕ_{mean}	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
r	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

Pilot data analysis

To validate the MC modeling of the BDT input variables, charged vertices from muons and hadrons are checked



[arXiv:2105.06197]

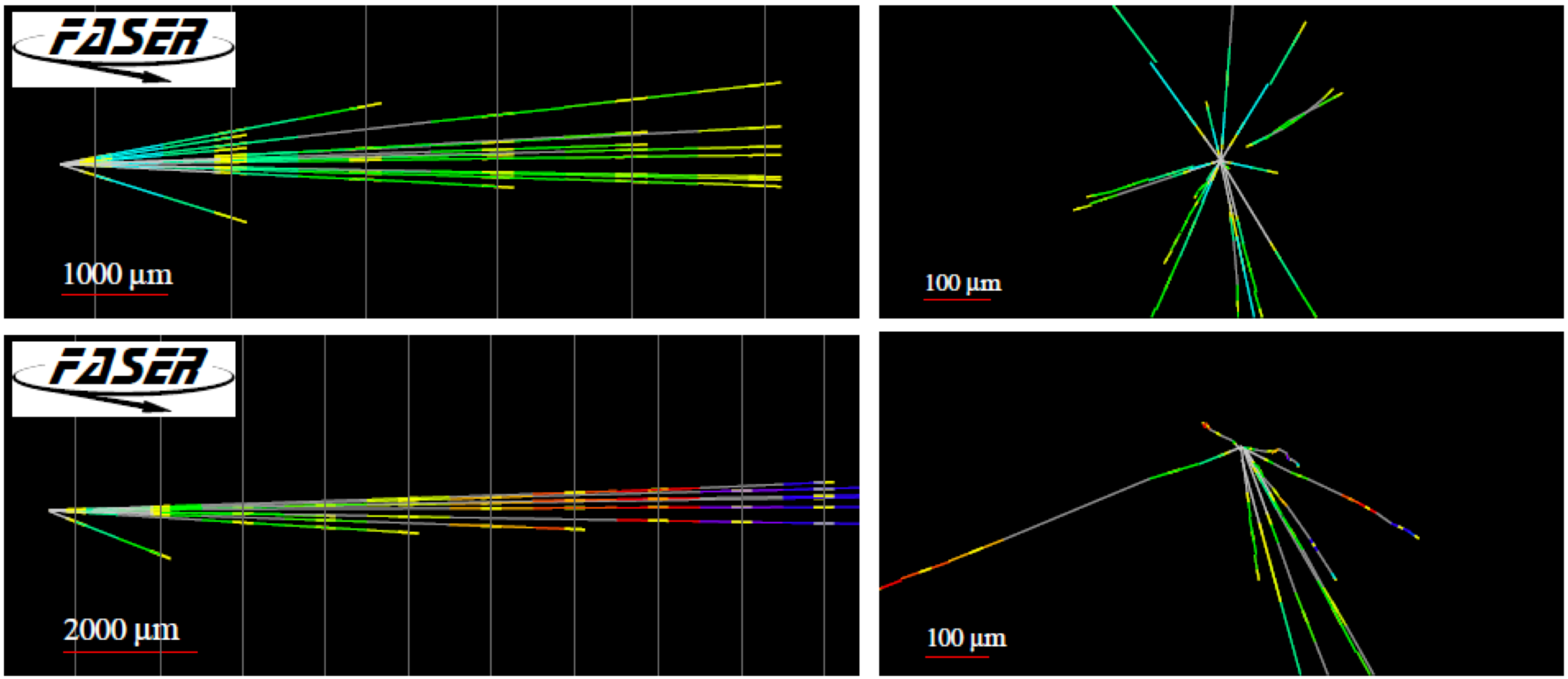


- Muon from the interactions of the true neutrino events can not be identified (λ_{int} too short compared to FASERν). Use BDT to discriminate signal and background with the 5 input variables
- Out of 18 neutral vertices, 6.1 signal events (2.7 σ) are obtained from the fit, while $3.3^{+1.7}_{-0.9}$ is expected. This result demonstrates **detection of neutrinos at the LHC**

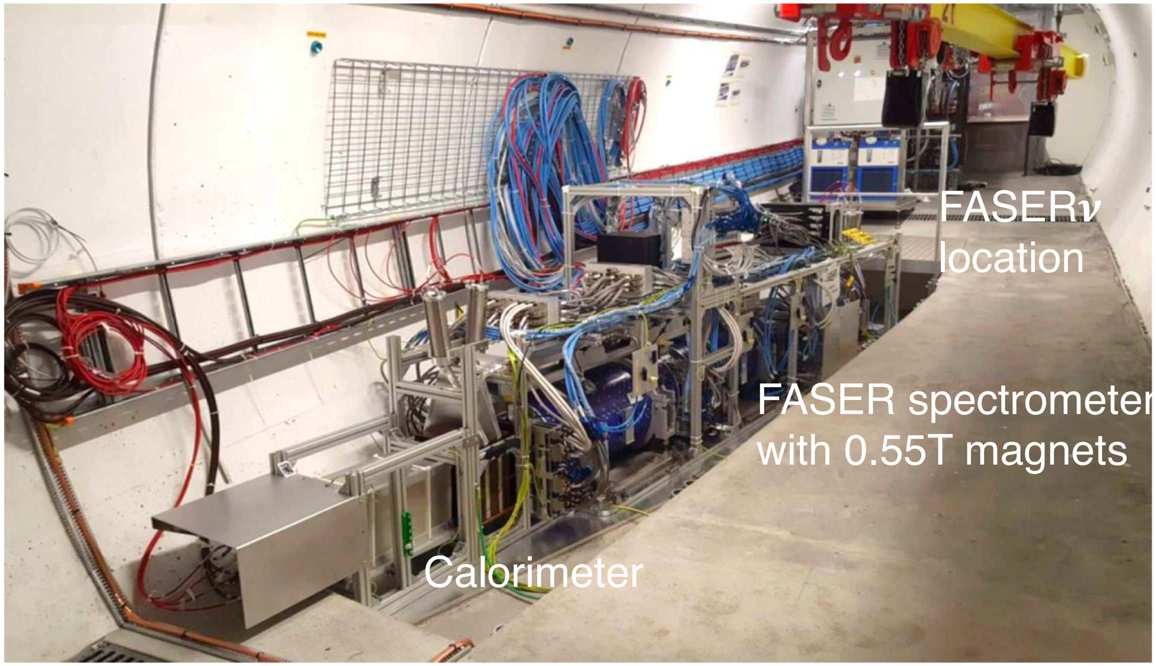
Neutrino candidates in pilot data

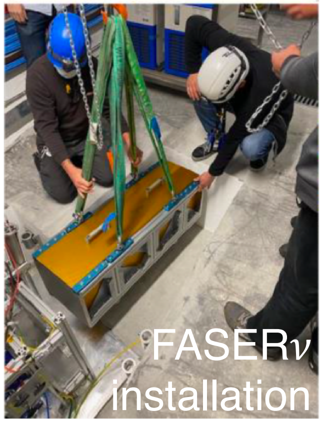
Longitudinal view

Transverse view

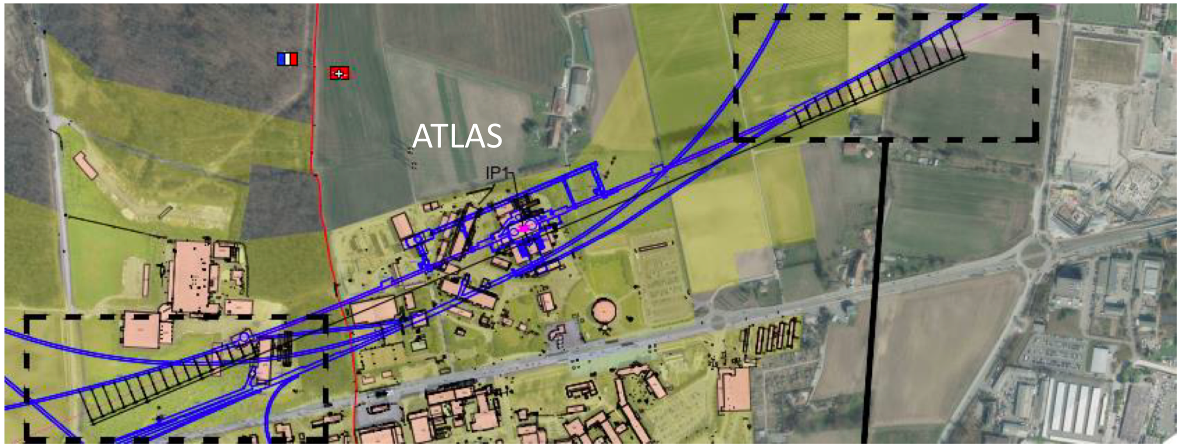


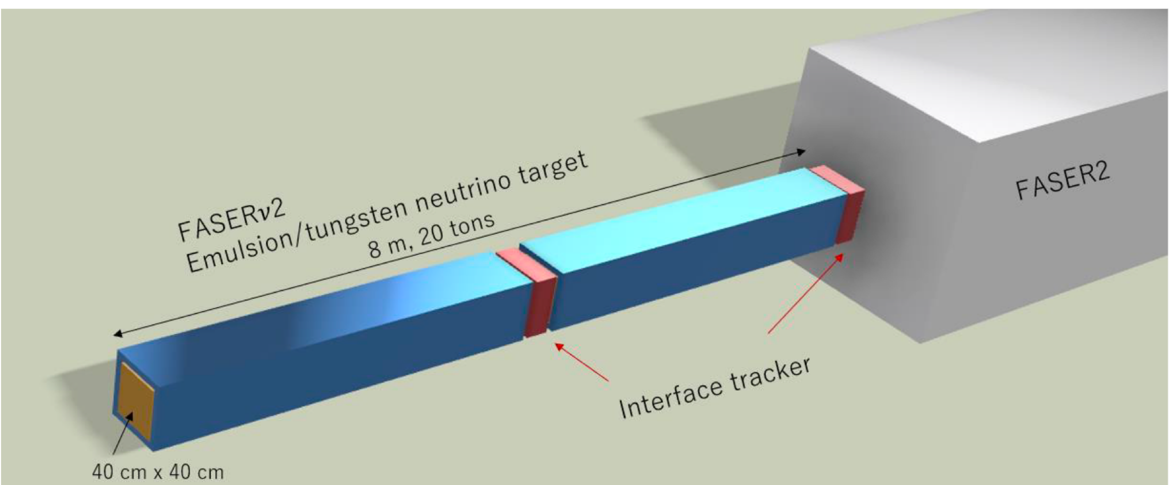
Preparation for Run-3





Detector upgrade





- The Forward Physics Facility (FPF) for the HL-LHC is a proposed facility that could house a suite of new forward experiments
  - – The background muon rate may be able to be reduced with a sweeper magnet (studies ongoing)
  - – Detector upgrade (FASERν2) is being discussed, with 10 times bigger target mass and 20 times larger luminosity
- FASER$\boldsymbol{\nu}$2 can have 200-fold increase in neutrino event rate
  - – e.g., ~3000 ν_τ interactions are expected

Summary

- FASERν is a detector in FASER experiment to measure cross-section of TeV neutrinos from proton-proton collisions at LHC - first experiment to measure neutrinos from colliders

- Cross-section for all neutrino flavors can be well separated from the backgrounds (muons and neutral hadrons), thanks to the excellent space resolution of the emulsion detector

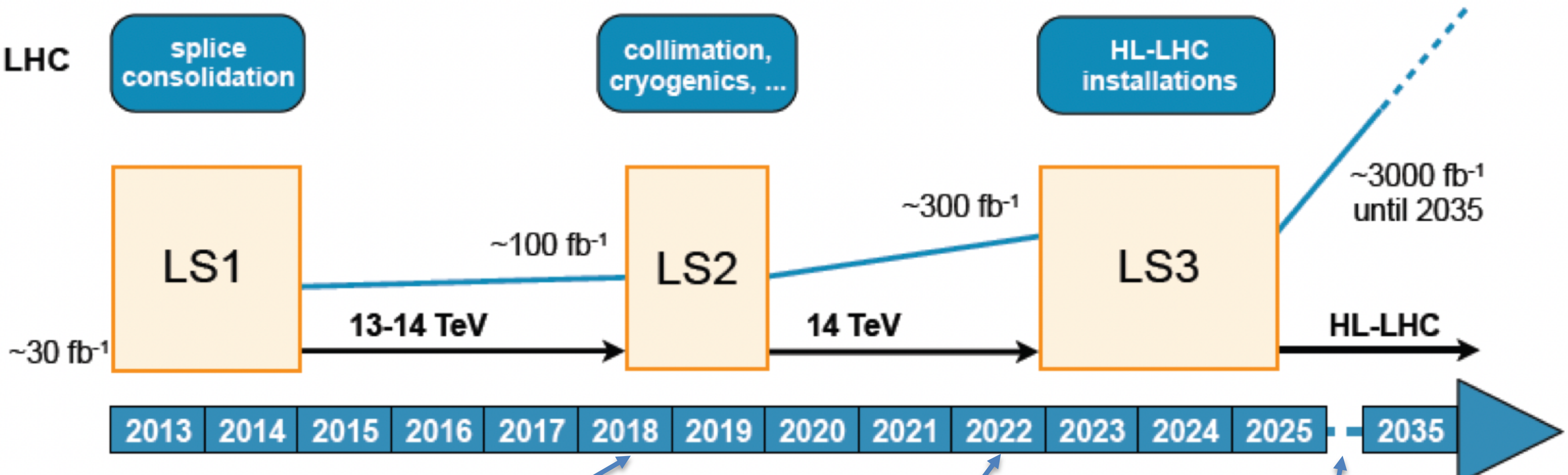
- FASERν is sensitive to charm/strange PDF, hadron production rates, and some BSM scenarios. Expect about 10,000 CC interactions in Run-3 (150 fb^{-1})

- We have detected first neutrino interaction candidates at the LHC in the 2018 pilot run data

- The detector upgrade towards HL-LHC era (FASERν2) is under discussion with a prospect to increasing neutrino statistics by one order of magnitude. We acknowledge the great support from CERN for FASER and its upgrade

Backup Slides

FASERν/FASERν2 schedule



FASERνpilot run in 2018

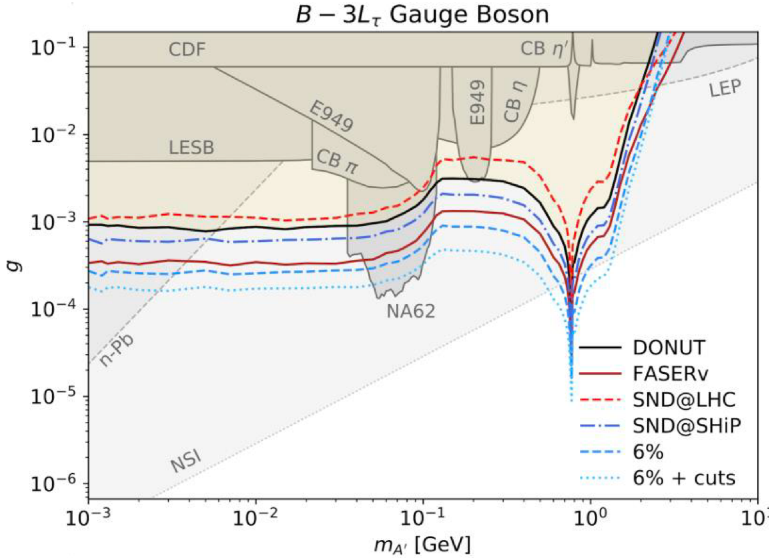
FASERν2 in HL-LHC

FASERνphysics run starts in 2022

FASERν2 for BSM physics

- 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 (2020) 015007]

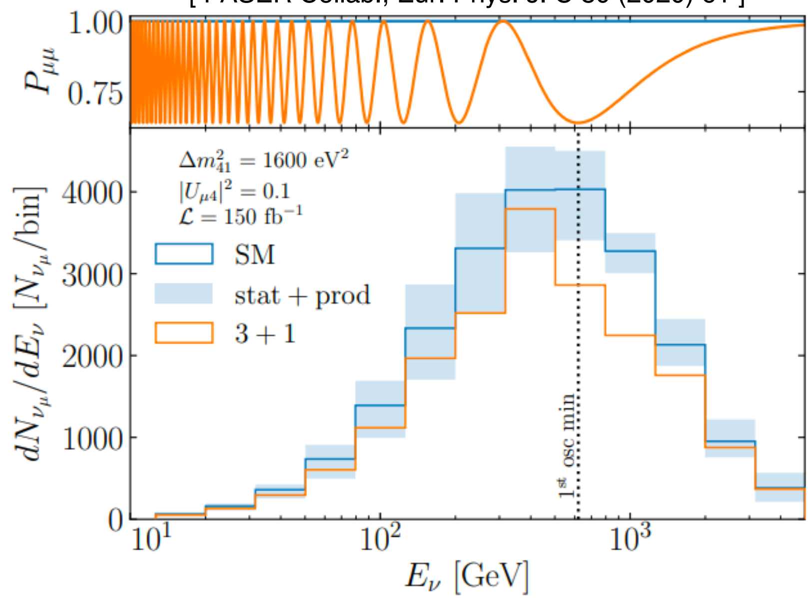


- SM neutrino oscillations are expected to be negligible at FASERν. However, sterile neutrinos with mass ~40 eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment

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

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

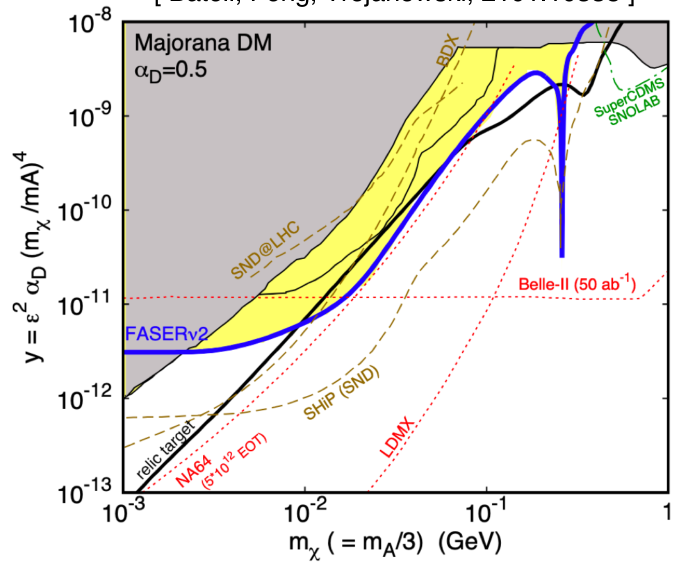
[FASER Collab., Eur. Phys. J. C 80 (2020) 61]



FASERν2 for BSM physics

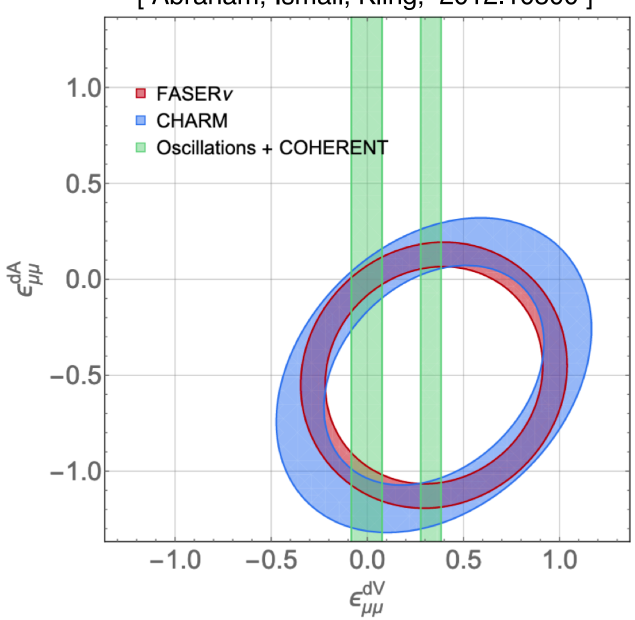
- If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERνcould therefore also search for DM scattering

[Batell, Feng, Trojanowski, 2101.10338]



- FASERνalso measures cross-section of Neutral Current (NC) neutrino interactions. Non-Standard Interaction (NSI) can be explored in conjunction with measurement of CC cross-section

[Abraham, Ismail, Kling, 2012.10500]



DIS cross-section of CC/NC interactions