Detecting and studying high-energy collider neutrinos
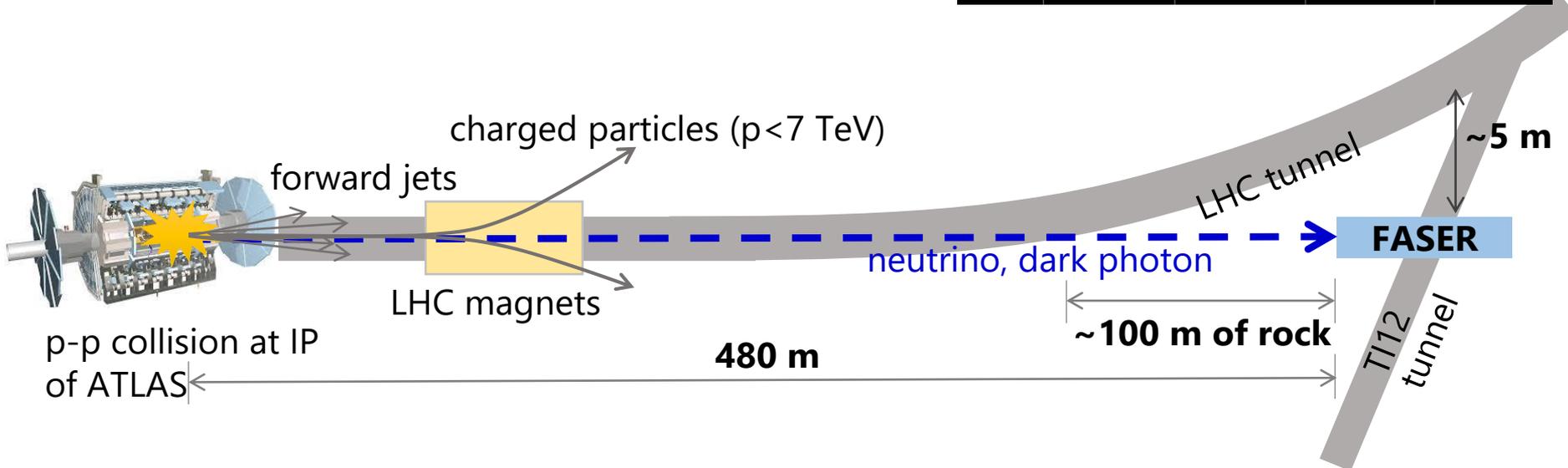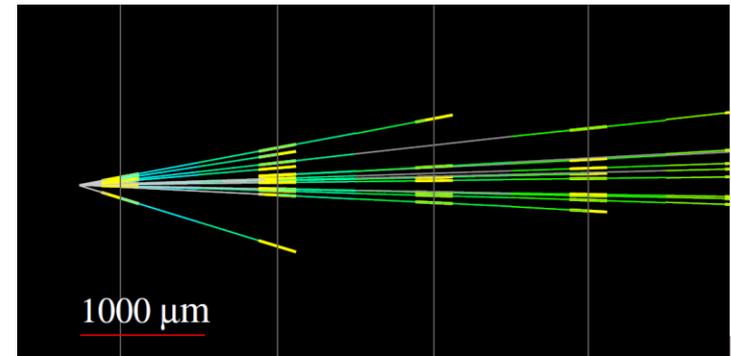
FASERν
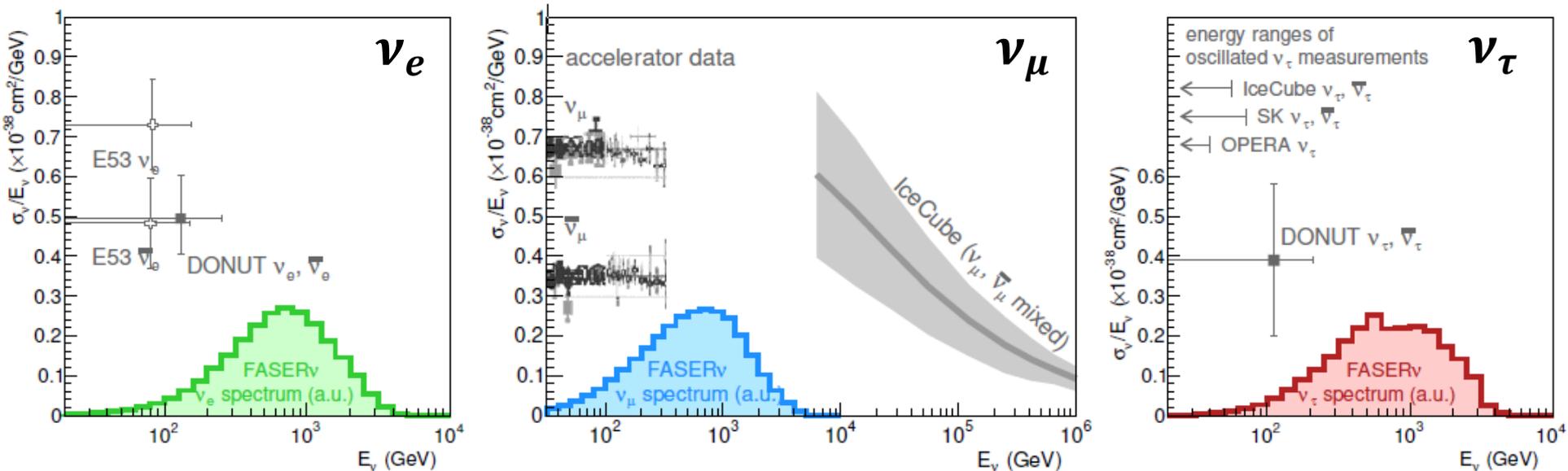
Tomoko Ariga (Kyushu University)
on behalf of the FASER Collaboration

1000 μm

charged particles (p<7 TeV)

forward jets

LHC tunnel

~5 m

FASER

neutrino, dark photon

LHC magnets

~100 m of rock

p-p collision at IP
of ATLAS

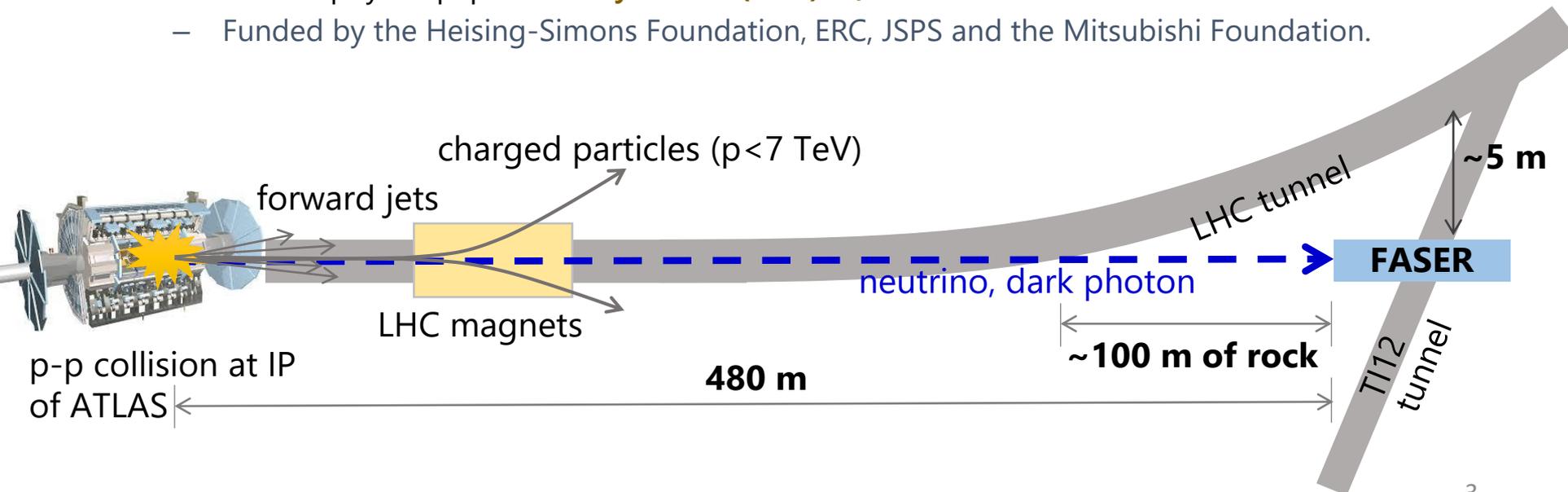480 m

Tl12 tunnel

Physics motivations

- **Studying neutrinos in unexplored energy regime (TeV energies)**
  - Use 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 neutrino production via heavy meson decays → a key input for neutrino telescopes

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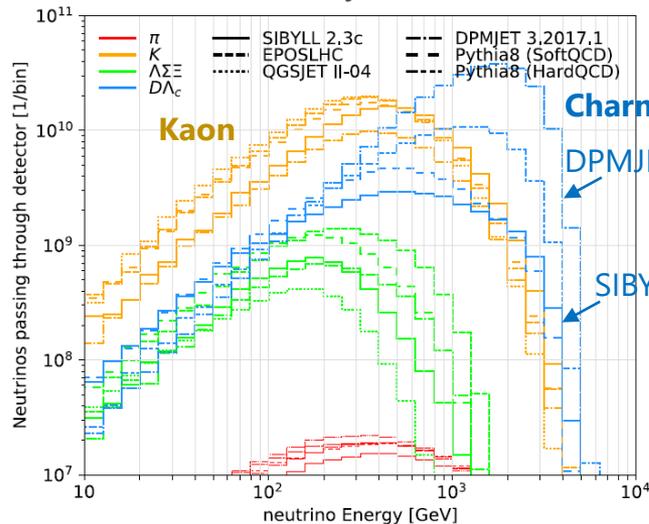
The FASER experiment

- FASER is a small and fast experiment to be installed in the LHC to take data in 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.**
  - Will perform first measurements of neutrinos from a collider and in unexplored energy regime.
  - FASERν physics paper: **Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310**
  - Funded by the Heising-Simons Foundation, ERC, JSPS and the Mitsubishi Foundation.

charged particles (p<7 TeV)

forward jets

LHC magnets

LHC tunnel

~5 m

neutrino, dark photon

FASER

TI12 tunnel

p-p collision at IP of ATLAS
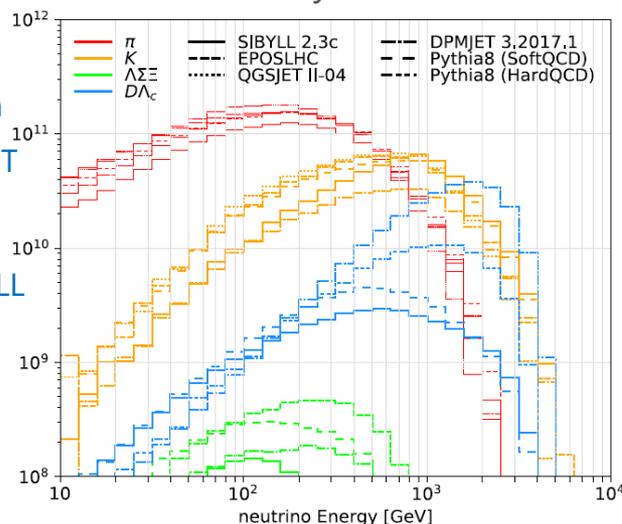
480 m

~100 m of rock

Neutrino flux estimates (1)

- Checking three simulations.
  - FLUKA (by F. Cerruti's group)
  - BDSIM (by H. Lefebvre, L. Nevay)
  - RIVET-module (by F. Kling)

- **Differences between generators** have been checked with the same propagation model (RIVET-module)
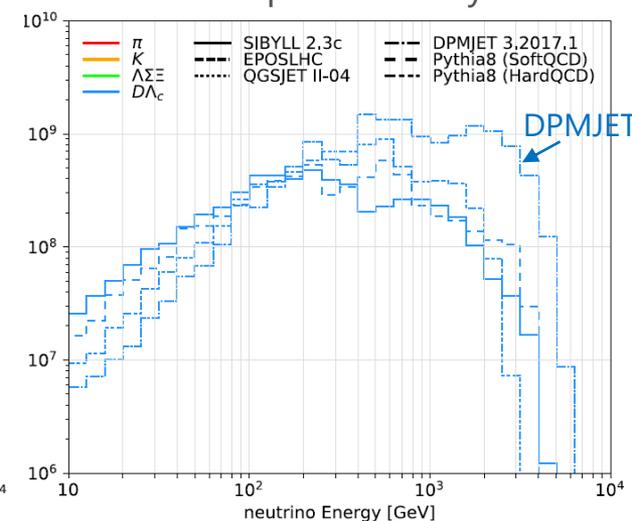
ν_e mainly from kaon and charm decays
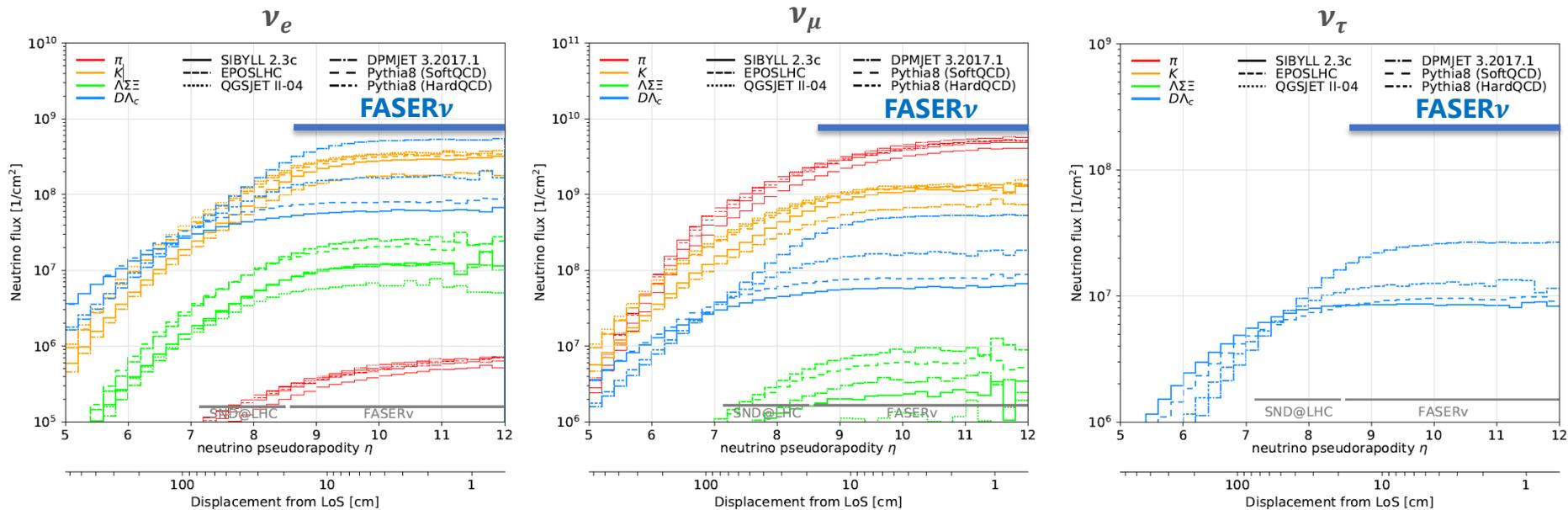
ν_μ mainly from pion and kaon decays

ν_τ mainly from D_s and subsequent τ decays

Neutrino flux estimates (2)

- Radial spectrum
  - FASERν will be centered on the LOS (in the FASER trench) to maximizes fluxes of all neutrino flavors.

- Work in progress for quantifying and reducing the uncertainties.
  - Creating a dedicated forward physics tune with Pythia8 using forward data.
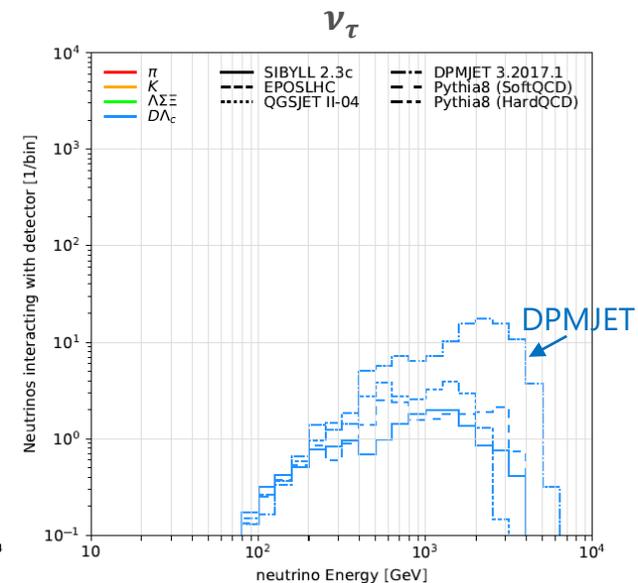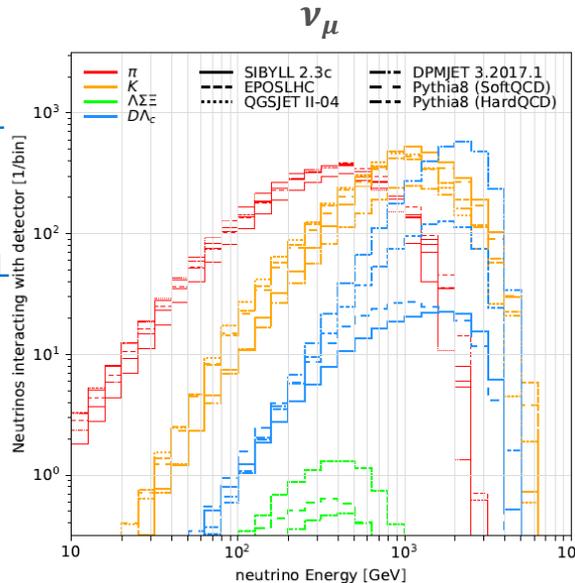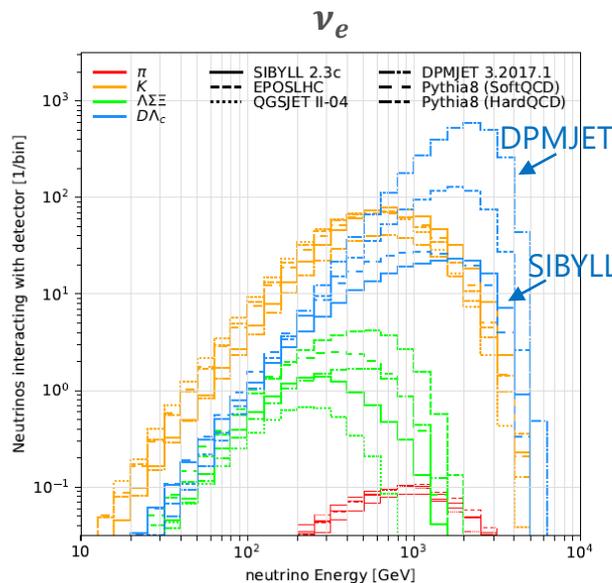 - Including tuning uncertainties.

Neutrino event rate

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

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

	DPMJET	**SIBYLL**	**Pythia8**
ν_e , $\bar{\nu}_e$	3390 , 1024	800 , 452	826 , 477
ν_μ , $\bar{\nu}_\mu$	8270, 2391	6571 , 1653	7120 , 2178
ν_τ , $\bar{\nu}_\tau$	111 , 43	16 , 6	22 , 11

Comparison between FLUKA/BDSIM/RIVET
using the same generator (DPMJET)

	FLUKA	**BDSIM**	**RIVET**
ν_e , $\bar{\nu}_e$	2986 , 1261	4495 , 1265	3390 , 1024
ν_μ , $\bar{\nu}_\mu$	8437 , 2737	14190 , 3244	8270 , 2391
ν_τ , $\bar{\nu}_\tau$	110 , 55	(no estimate yet)	111 , 43

Detector for the LHC Run 3

- **Emulsion/tungsten detector** and **interface silicon tracker** will be placed in front of the main FASER detector.

- **Allows to distinguish all flavor of neutrino interactions.**
  - 770 1-mm-thick tungsten plates, interleaved with emulsion films
  - 25x30 cm^2, 1.1 m long, 1.1 tons detector ($220 X_0$)
  - Emulsion films will be replaced every 30-50 fb^{-1} during scheduled LHC technical stops (3 times per year)
  - **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

FASER spectrometer with 0.55T magnets

Interface silicon tracker and veto station (to be added in the figure)

FASERν

ν

Detection of neutrino interactions in emulsion detector

ν_e → e

ν_μ → μ

ν_τ → τ

Emulsion film   Tungsten plate (1mm thick)

CC heavy quark production

ν → lepton D X

$\bar{\nu}$ → lepton $\bar{B}$ X

ν
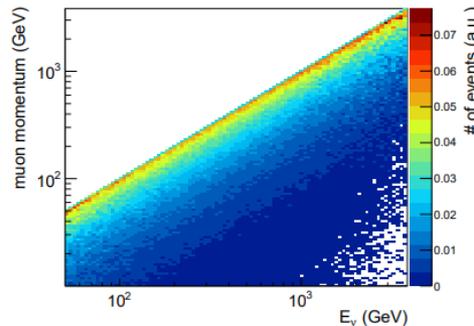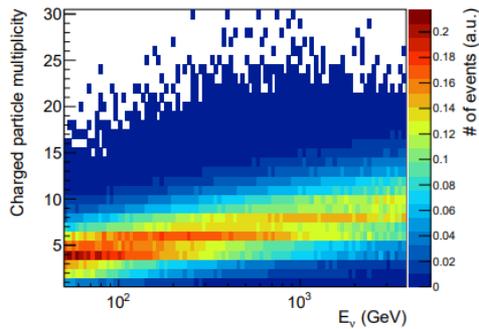
Neutrino energy reconstruction

- Neutrino energy will be reconstructed by combining topological and kinematical variables

An ANN algorithm was built with
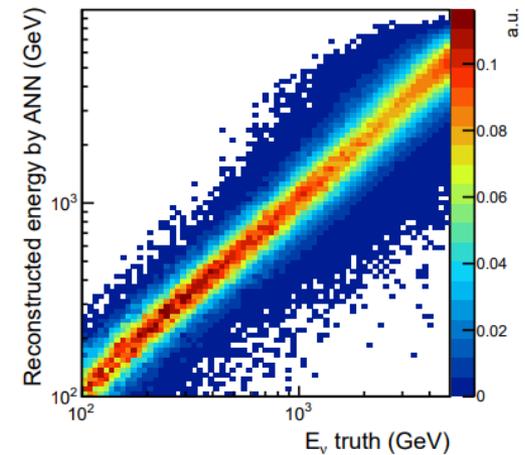**topological variables**
- # of charged tracks → E_h
- # of γ showers → E_h
- inverse of lepton angle → E_l
- sum of inverse of hadron track angles → E_h
- inverse of median of all track angles → E_h, E_l

kinematical info (smeared)
- lepton momentum → E_l
- sum of charged hadron momenta → E_h
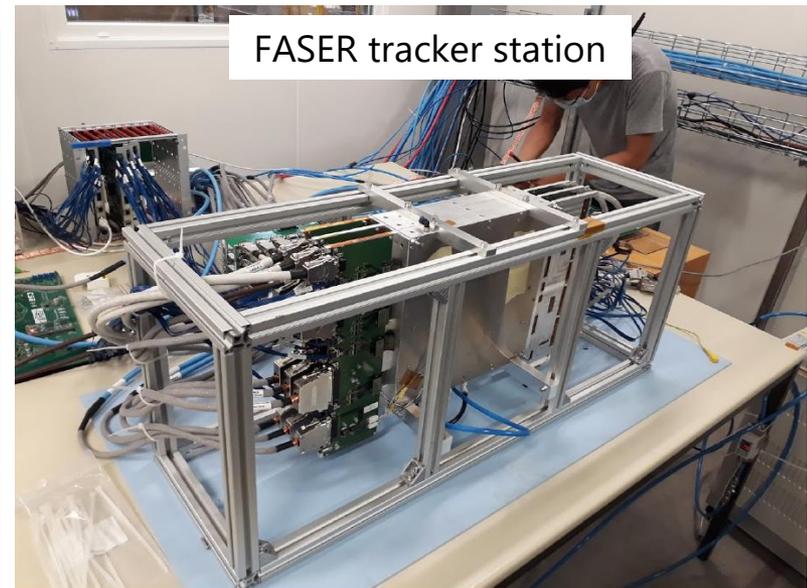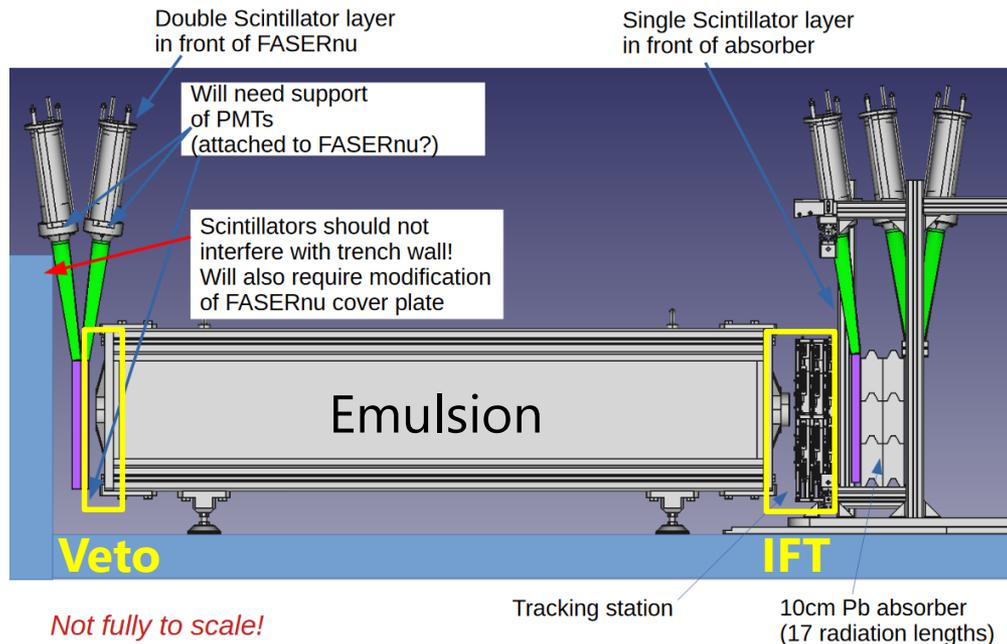- sum of energy of γ showers → E_h

$E_\nu - E_{ANN}$

$$\frac{\Delta E}{E} \sim 30\%$$
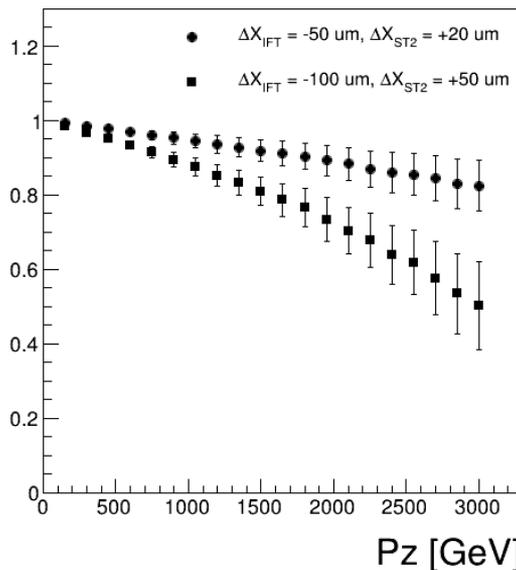
Interface to the FASER spectrometer

- **To connect muon tracks from $\nu_\mu/\overline{\nu}_\mu$ interactions for charge identification etc.**
  - **Interface tracker (IFT)** with 3 layers of silicon strip detector. A copy of FASER tracker station.
  - **Veto station** consists of 2 scintillator layers with 2 cm thickness. >99.99% veto efficiency for a charged particle coming from upstream of FASERν.
  - Construction of the IFT will start in January 2021. Installation at FASER site is planned in fall 2021.

Double Scintillator layer in front of FASERnu

Single Scintillator layer in front of absorber

Will need support of PMTs (attached to FASERnu?)

Scintillators should not interfere with trench wall! Will also require modification of FASERnu cover plate

Emulsion

Veto

IFT

Tracking station

10cm Pb absorber (17 radiation lengths)

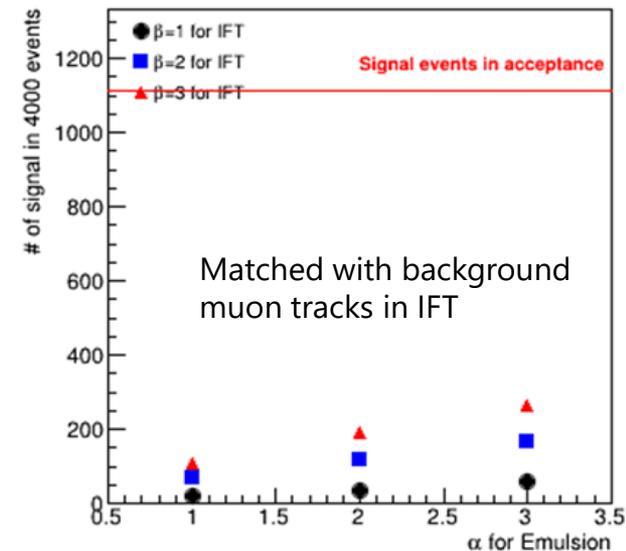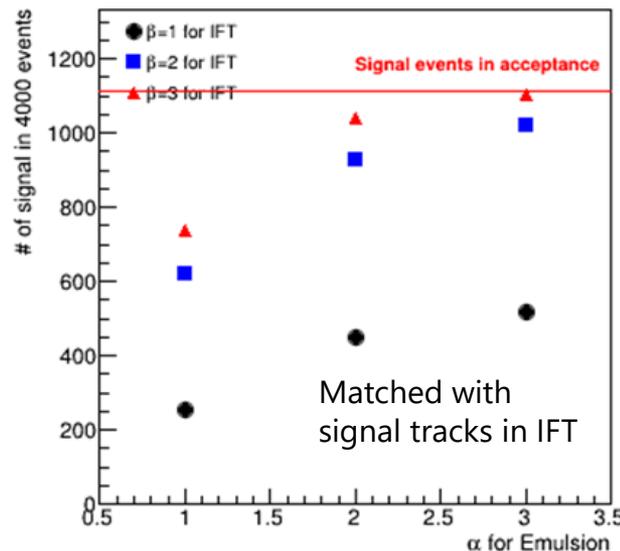*Not fully to scale!*

FASER tracker station

Expected performance of the interface detector

- Tracking performance with IFT/veto was evaluated with mathematical calculation, including alignment shifts of IFT and FASER tracker stations.

- Particle charge can be identified up to ~1.7 TeV with 3σ even with alignment shift of 200 μm in IFT and 100 μm in the second tracker station in FASER.

  - Uncertainty on q was checked when fixing x on each layer with q and r as $q(r - \sqrt{r^2 - z^2}) + \alpha z + \beta$

- Muon tracks from $\nu_\mu/\bar{\nu}_\mu$ interaction in emulsion can be connected with those in IFT with high efficiency and low probability of fake matching with background muons.

  - Track matching condition: $\Delta x/\Delta y < \sqrt{(\alpha \cdot \sigma_{x/y})^2_{Emulsion} + (\beta \cdot \sigma_{x/y})^2_{IFT}}$
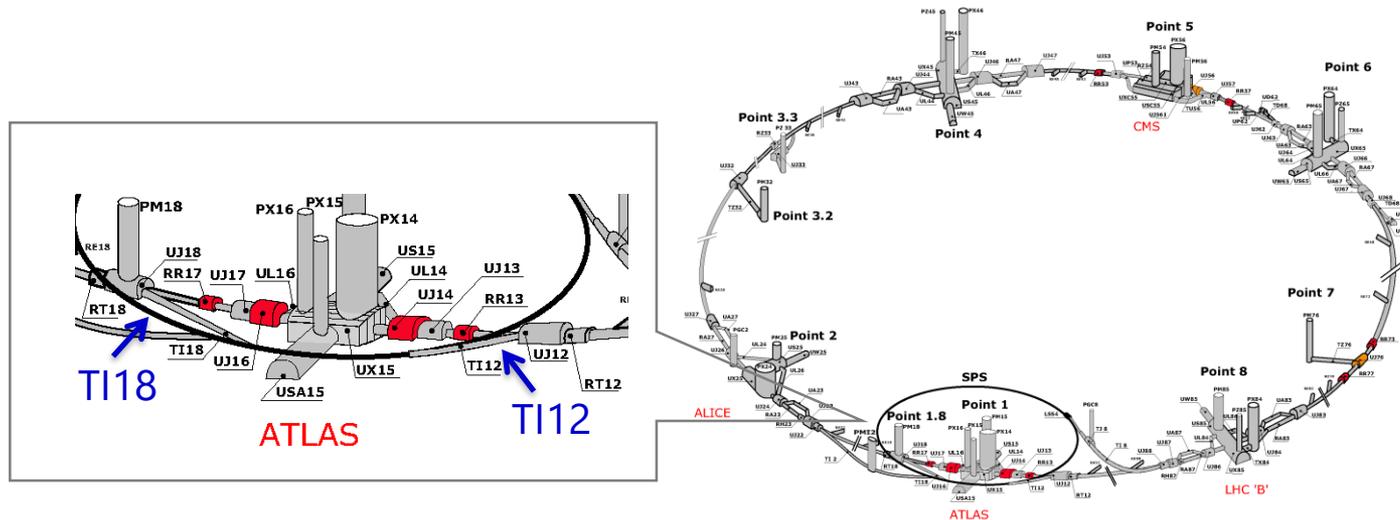
Charge ID capability $\qquad$ **# of μ tracks from ν interaction in Emulsion @30fb⁻¹**
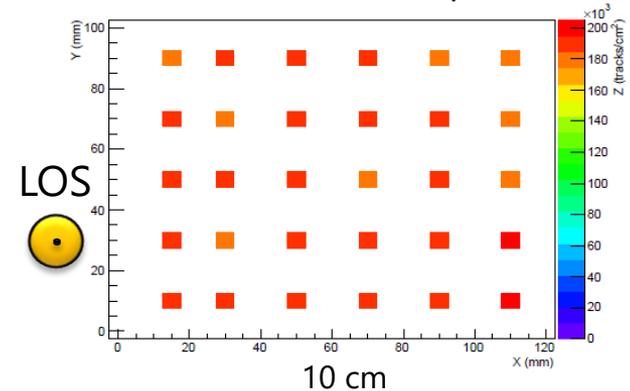
Pilot run in 2018

- 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 12.5 fb^{-1} data collected.
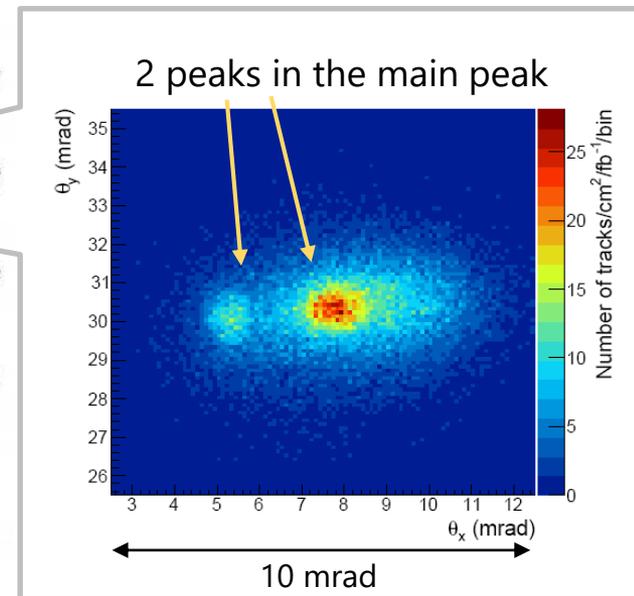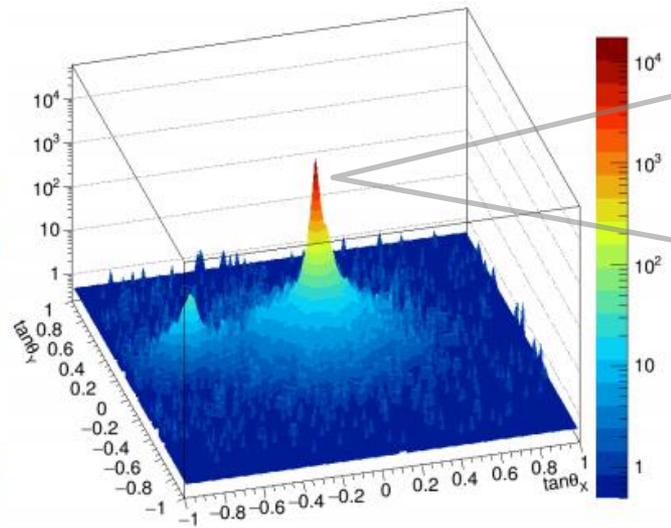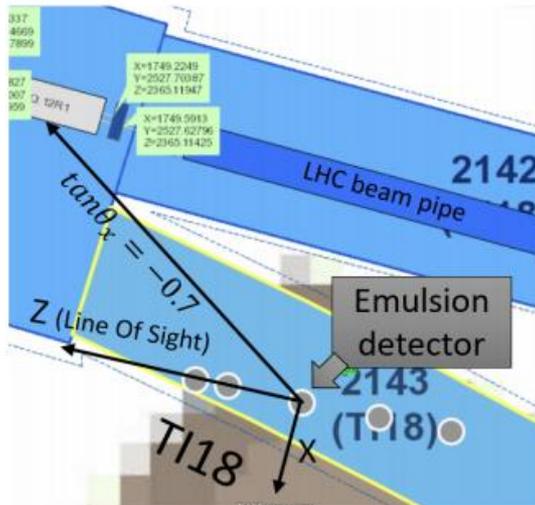
Pilot run: measurement of charged particles

- # of tracks within 10 mrad = dominated by muons
  - A flat distribution within the detector (10 cm scale)
  - Average 2.11×10^5 tracks/12.5 fb^{-1}/cm^2
  - → 1.69×10^4 /fb^{-1}/cm^2 (corrected by the efficiency)

The measured muon profile

LOS

10 cm

Angular distribution

2 peaks in the main peak

10 mrad
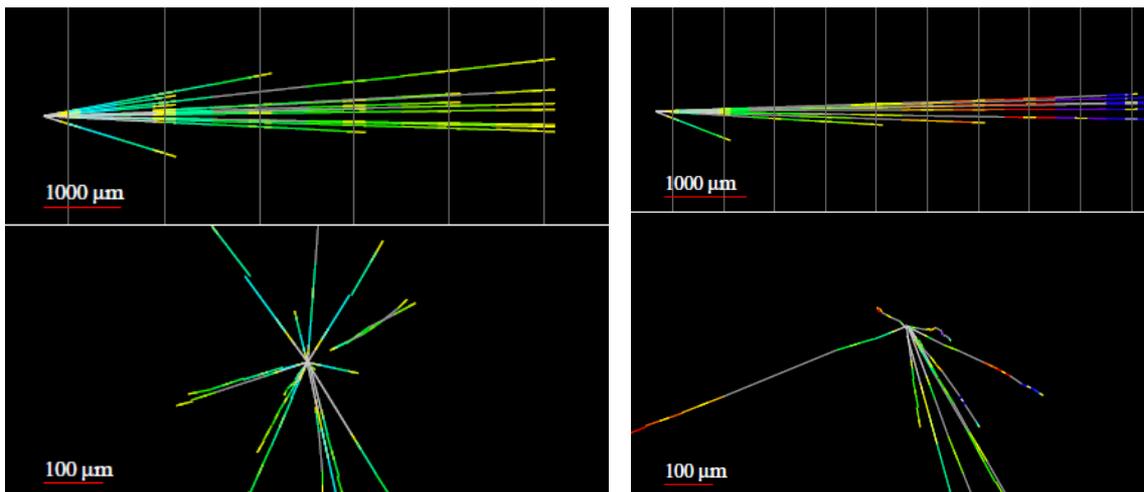
Pilot run: detection of neutrino interactions

- The analysis was conducted aiming to report first observation of neutrino interactions at the LHC.
  - We applied tight cuts in the vertex detection since the pilot detector was small and there was no muon ID, there is more background from neutral hadron interactions than the physics run.
    - N tracks ($\tan\theta < 0.1$) >= 5 & N tracks ($\tan\theta > 0.1$) <= 4
    - In the data analysis, detected several neutral vertices.
  - Then used multivariate analysis to separate neutrino interactions from hadronic interactions.

Event displays of detected events

Preparing for publication with the final result.

1000 μm

100 μm

1000 μm

100 μm

Status of the TI12 area

Before

Need digging to center FASER/FASERν on the LOS

After digging

Trench to install the detectors

Now

The handling equipment (cranes) for installing/removing FASERν is already installed in UJ12 and TI12 and has been tested (including a protection over the LHC in UJ12).
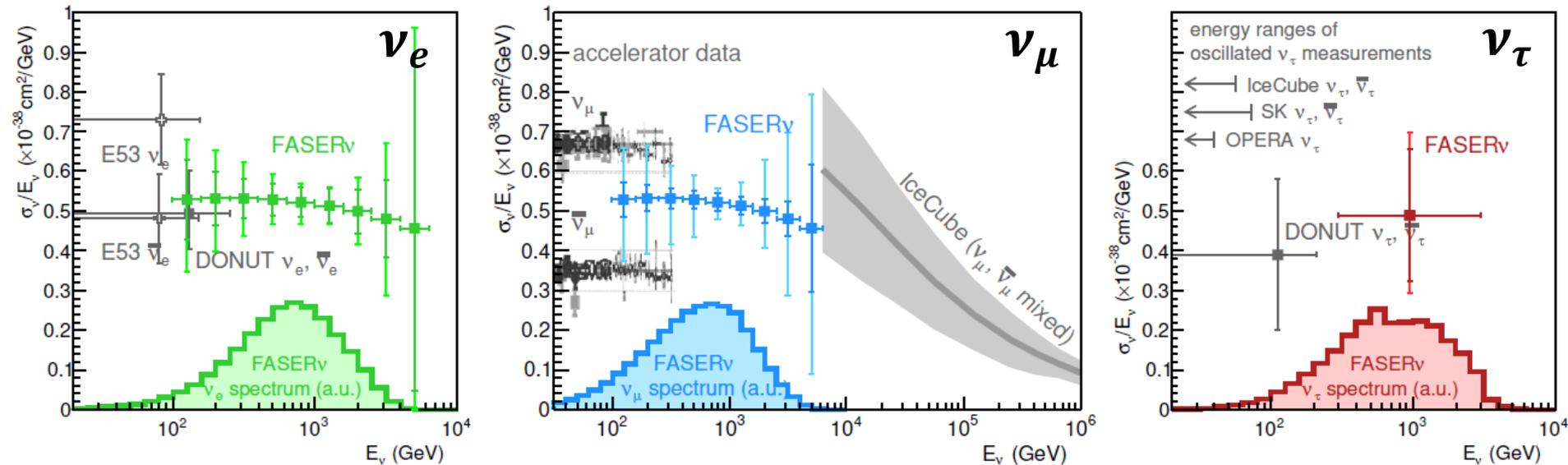
Acknowledge great support from many CERN teams: SMB-FS, EN-ACE, EN-EA, EN-EL, EN-HE, EN-CV, HSE – with support from PBC

Physics studies in the LHC Run 3 (1)

- **Neutrino detection and cross section measurement at high energy**
  - Measure three flavors in an energy range where cross sections are unconstrained.
  - Also study NC interactions. A. Ismail, R.M. Abraham, F. Kling, arXiv: 2012.10500
- Neutrino-induced charm/beauty production channels
  - Direct measurements for the charm production channel by CHORUS and E531 in E_ν < 200 GeV.
  - No data yet for the beauty production channel.

Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})
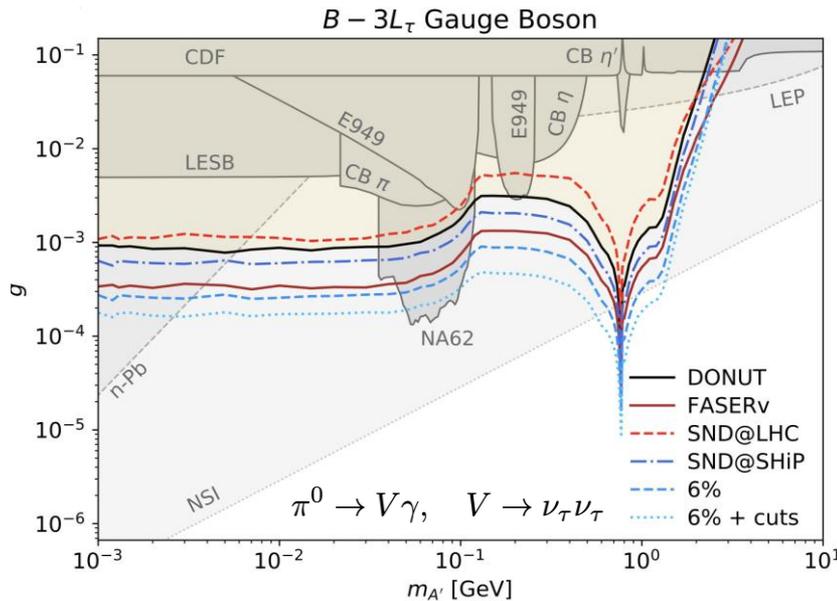

inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.
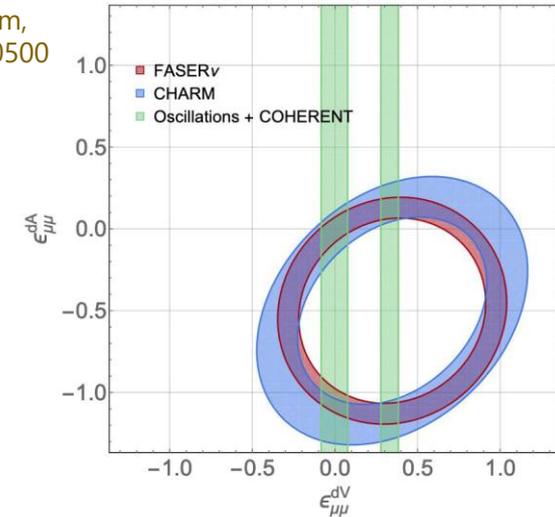
BSM physics

- 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, 015007 (2020), arXiv:2005.03594

$B - 3L_\tau$ Gauge Boson

$$\pi^0 \to V\gamma, \quad V \to \nu_\tau \nu_\tau$$

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

  A. Ismail, R.M. Abraham, F. Kling, arXiv: 2012.10500

- **Sterile neutrinos** with mass ~40 eV can cause oscillations at FASERν and the spectrum deformation may be seen.

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

- If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERν could also search for **DM scattering**.
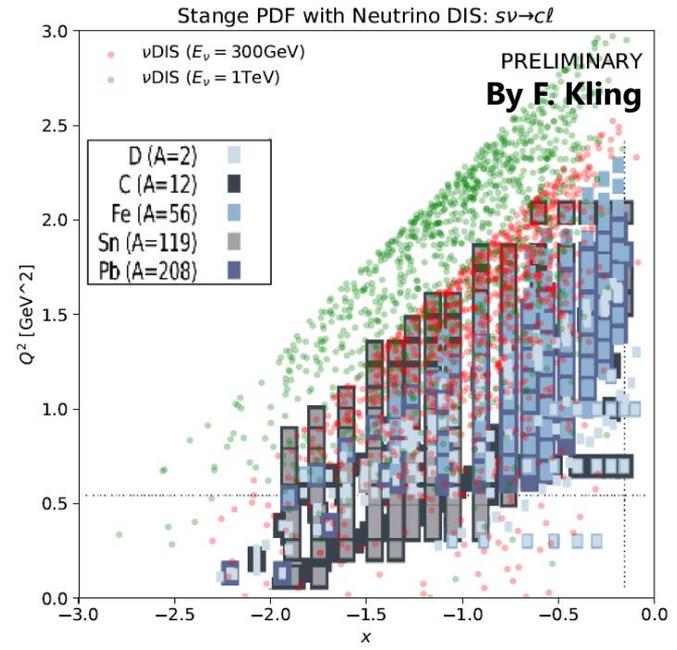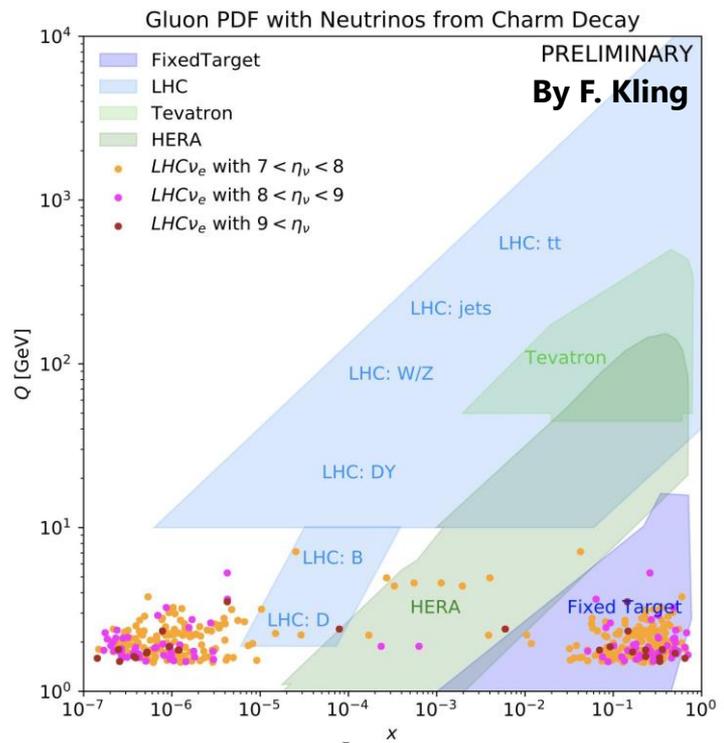
  B. Batell, J. Feng, S. Trojanowski, 2020, in preparation

16

Physics studies in the LHC Run 3 (3)
QCD

- Forward particle production is poorly constrained by other LHC experiments. FASERν's **neutrinos flux measurements** will provide novel complimentary constraints that can be used to validate/improve MC generators.

- Neutrinos from charm decay could allow to **test transition to small-x factorization, constrain low-x gluon PDF and probe intrinsic charm**.

- It might also be possible to probe (nuclear) PDFs via DIS neutrino scattering. In particular, charm associated neutrino events ($\nu s \to l c$) are sensitive to the poorly constrained strange quark PDF.
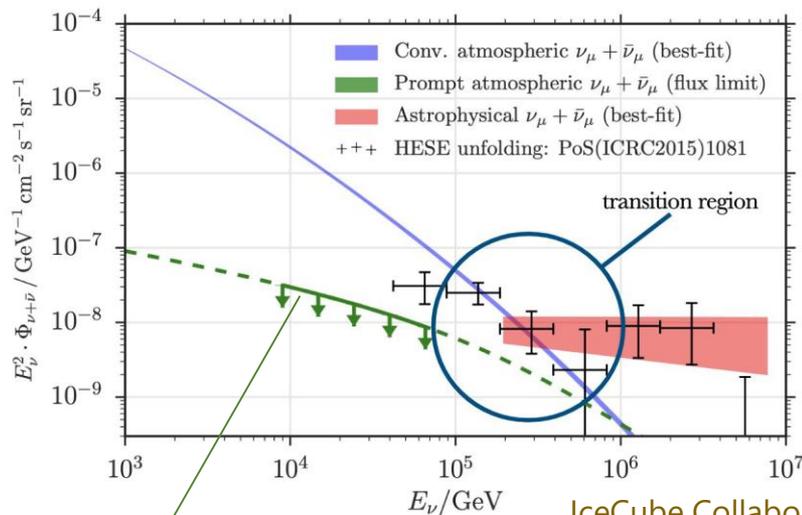

Gluon PDF with Neutrinos from Charm Decay
By F. Kling

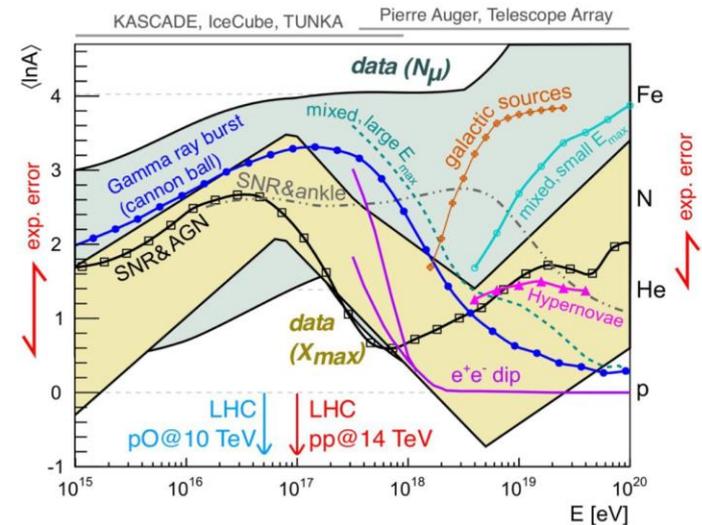Stange PDF with Neutrino DIS: $s\nu \to c\ell$
By F. Kling

- 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 at FASERν** would provide important basic data for current and future high-energy neutrino telescopes.

- Muon problem in CR physics: cosmic ray experiments have 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.

prompt atmospheric neutrinos

IceCube Collaboration, Astrophys. J. 833 (2016)

K.H. Kampert, M. Unger, Astropart. Phys. 35, 660 (2012),
H.P. Dembinski et al., EPJ Web Conf. 210, 02004 (2019)

Prospects for HL-LHC

- Discussing neutrino measurements in the HL-LHC era
  - Snowmass LOIs submitted on
  - <u>FASERν2: A Forward Neutrino Experiment at the HL LHC</u>
  - <u>Neutrino / Dark Particle Detectors for the HL-LHC Forward Beam</u>
  - <u>Forward Physics Facility (FPF)</u>

- A large detector for **precision tau-neutrino physics**
  - With the expected luminosity and ~10 tons of target, FASERν2 will detect 10^5 ν_e, 10^6 ν_μ, 10^3 ν_τ interactions at TeV energies, opening up many new opportunities.

Summary and prospects

- FASERν is a detector at the LHC to study high-energy neutrinos in unexplored energy regime (TeV energies).

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

- We will study neutrinos from a collider for the first time. ~10000 CC interactions (distinguishing the flavors) are expected in LHC-Run3 (2022-2024). Preparation for the data taking is in progress.
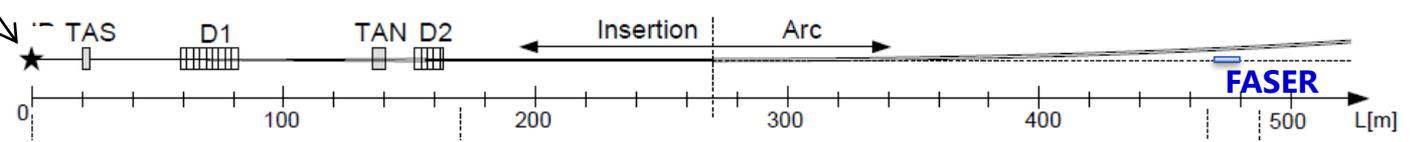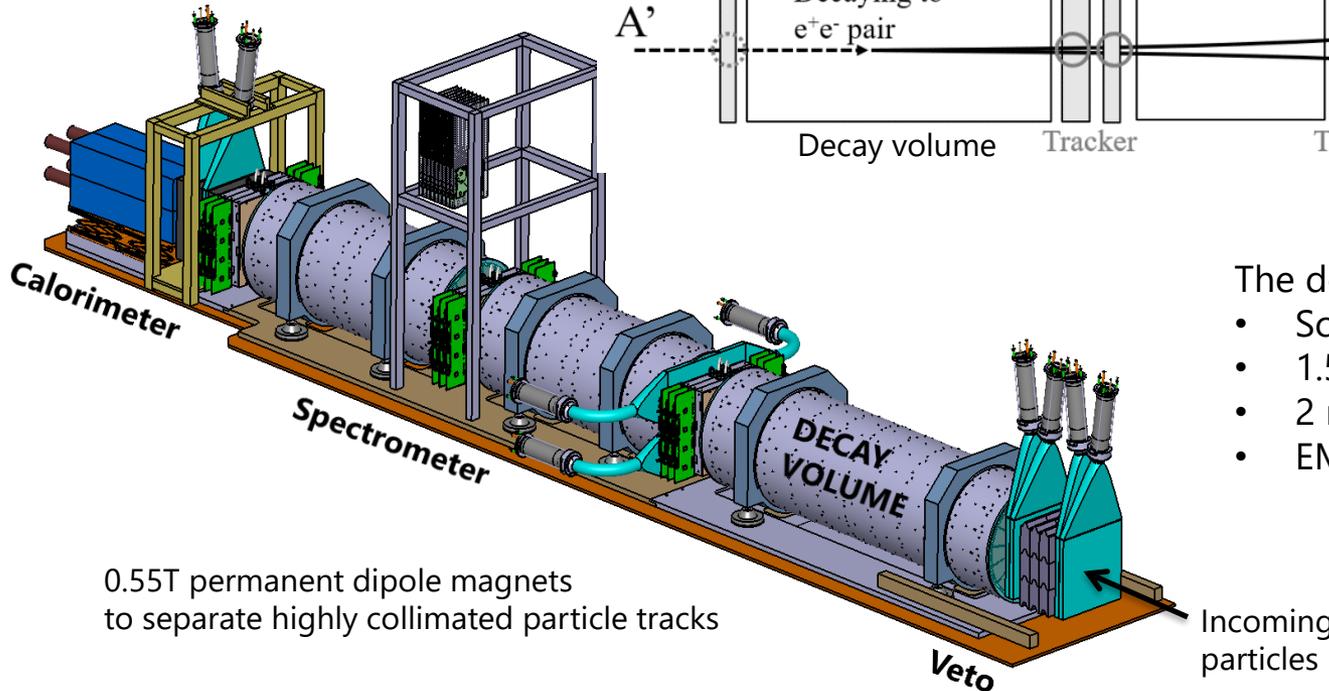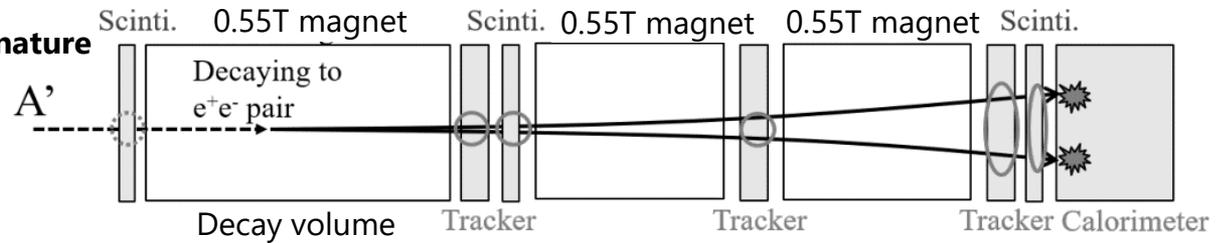
- Also discussing neutrino measurements in the HL-LHC era.

Backup

The FASER detector

ATLAS interaction point

pp → LLP + X, LLP travels ~480 m, LLP → e$^+$e$^-$, μ$^+$μ$^-$, …
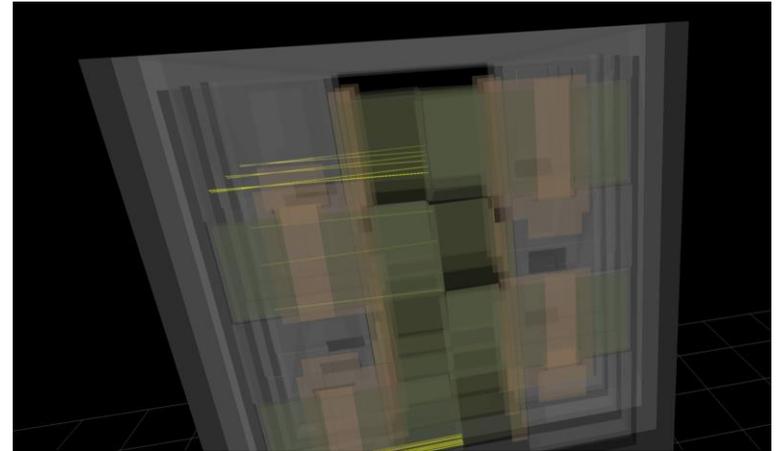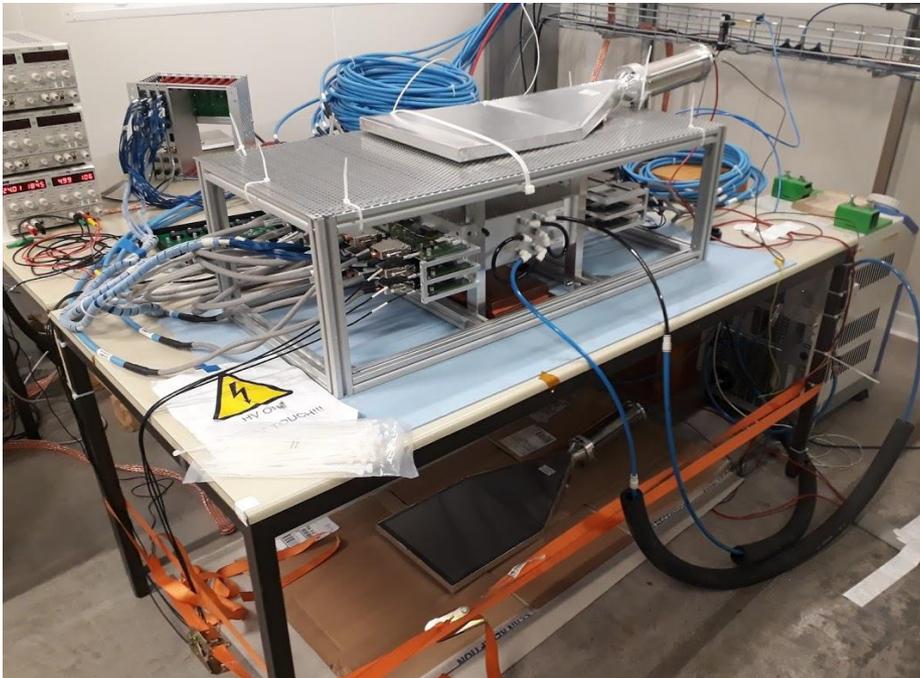

Signal signature

The detector consists of:
- Scintillator veto
- 1.5 m long decay volume
- 2 m long spectrometer
- EM calorimeter

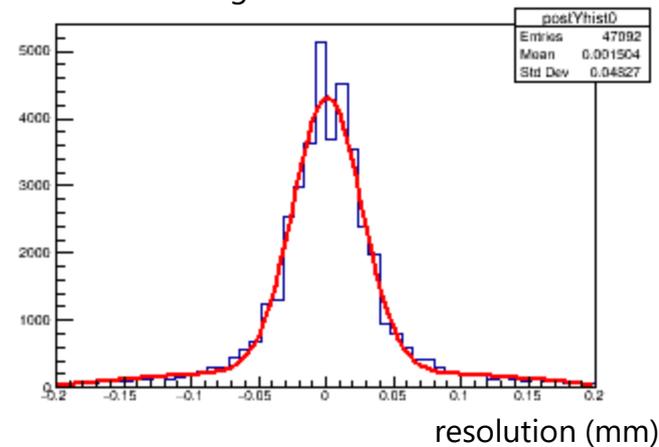0.55T permanent dipole magnets
to separate highly collimated particle tracks

Incoming particles

22

Tracker station commissioning

- We have been running long cosmic runs on the current tracking stations which have been used to test the performance - e.g. noise, efficiency and resolution are as expected.
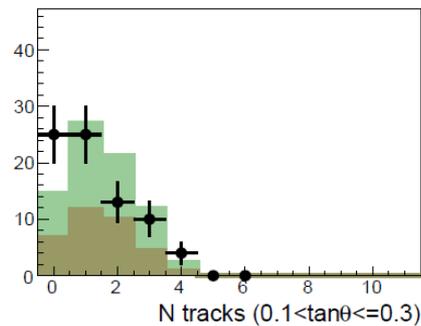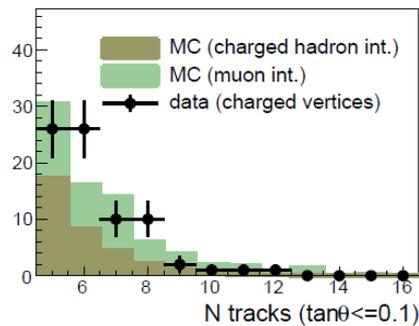

tracking station resolution

resolution (mm)

Timeline towards the first run

	FASERν offline	Emulsion detector	Interface detector / veto
			Design of IFT / veto
Sep 2020		Production of mechanical support	
Nov 2020	- neutrino flux - background flux - reconstruction in emulsion - interface to the FASER offline	Preparation of dark room at CERN	
Jan 2021		Procurement of tungsten plates	Production of IFT / veto
Mar 2021		Test of emulsion films (long-term stability etc.)	
May 2021			
July 2021			
Sep 2021		Emulsion production (1)	Installation
Nov 2021			
Jan 2022		Detector construction and installation (1)	

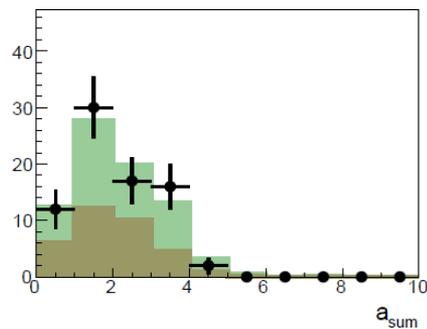Emulsion will be replaced ~9 times in 2022-2024.
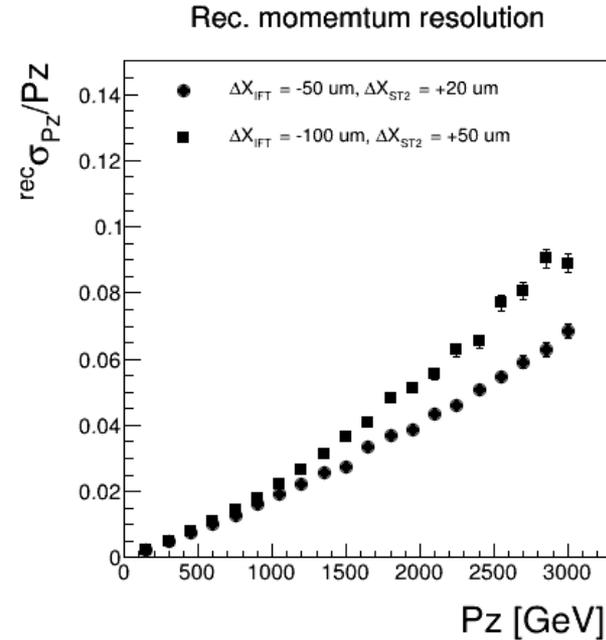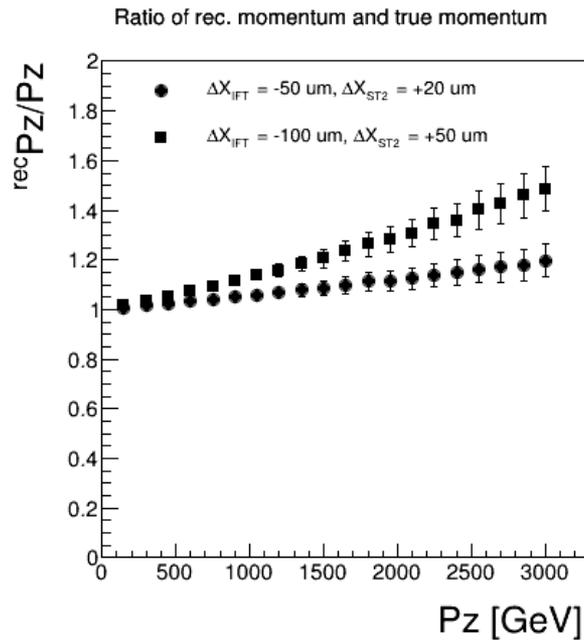
Mechanical support construction

Pilot run: cross checks with charged vertices

Fair agreement in the distributions

Particle momentum resolution by FASER+IFT
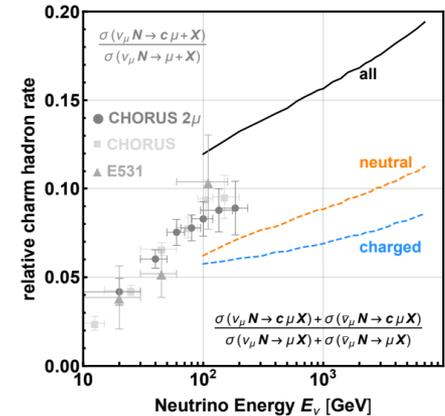

Ratio of rec. momentum and true momentum

ΔX_{IFT} = -50 um, ΔX_{ST2} = +20 um

ΔX_{IFT} = -100 um, ΔX_{ST2} = +50 um

Rec. momemtum resolution

ΔX_{IFT} = -50 um, ΔX_{ST2} = +20 um

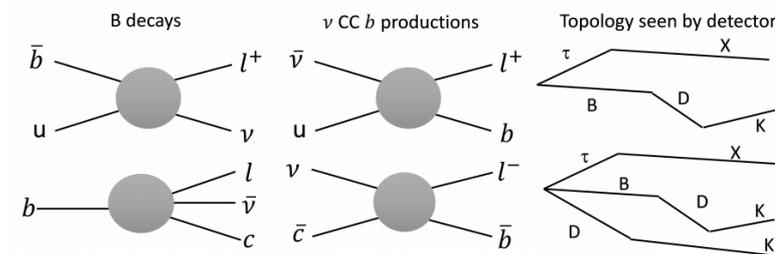ΔX_{IFT} = -100 um, ΔX_{ST2} = +50 um

Additional physics studies

- 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
  - Expected standard model events ($\nu_\mu\, CC\, b$ production) are $\mathcal{O}(0.1)$ events in Run 3, due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$

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

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

Additional physics studies

- Sterile neutrino oscillations
  - Due to unique energy and baseline (small L/E), FASERν is sensitive to large Δm^2.
  - If the effect is enough large, the spectrum deformation may be seen.

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

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