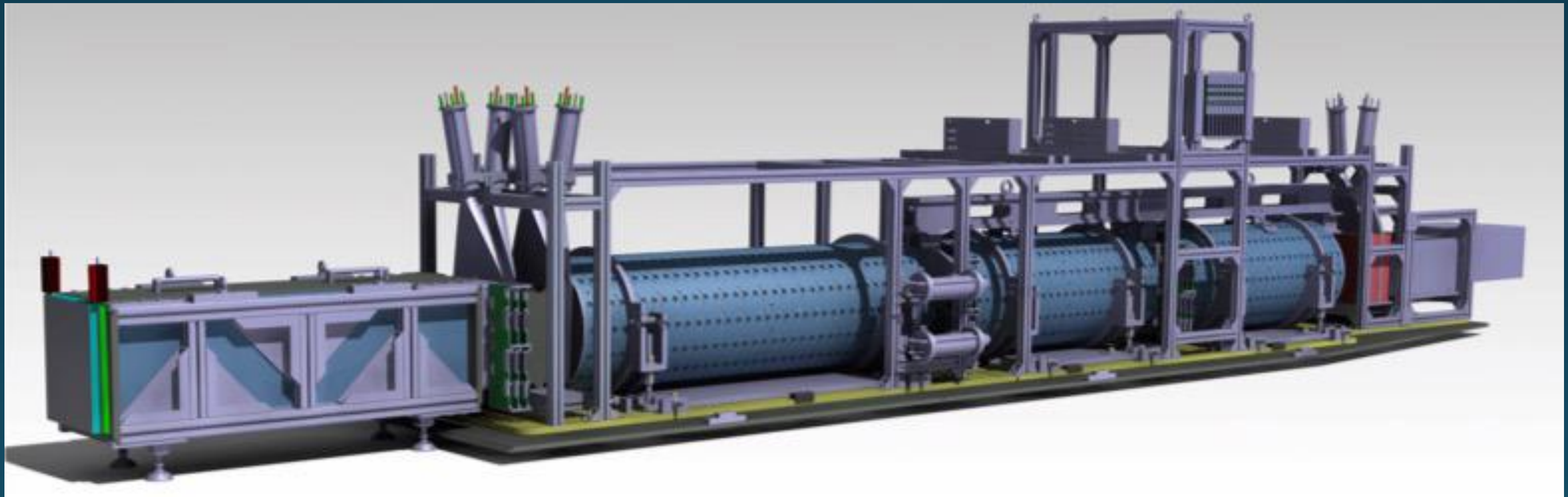
Akitaka Ariga
University of Bern / Chiba University

FASERν / FASERν2



FASERν
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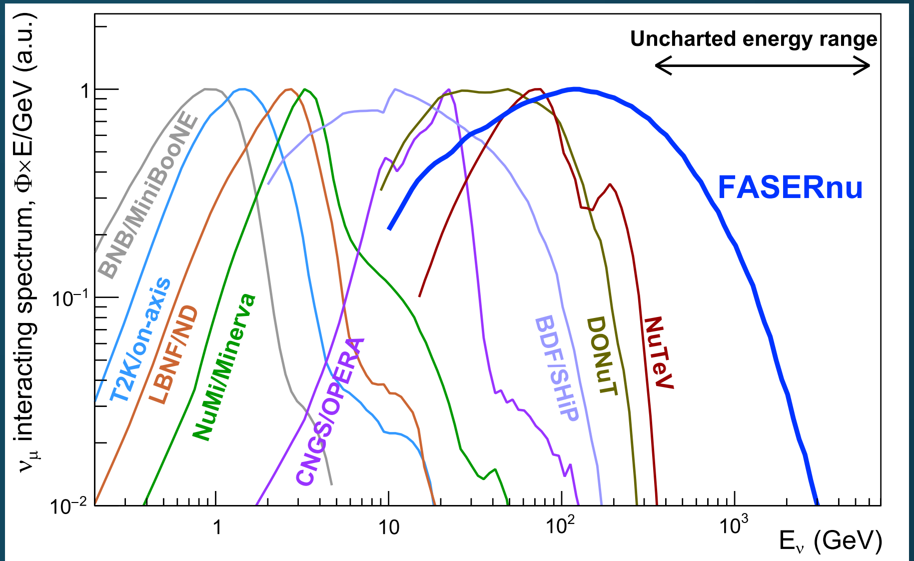
Neutrinos at the LHC: New domain of neutrino research!



- Neutrinos by collider method
- High energy frontier ~ TeV
- Study of production, propagation and interactions of high energy neutrinos

Production

Prompt neutrino production → Input for neutrino telescopes

Pion/Kaon/D ratio

QCD (charm/gluon PDF, intrinsic charm)

Propagation

Unique energy and baseline, $L/E \sim 10^{-3}$ m/MeV

Neutrino oscillation at $\Delta m^2 \sim 1000\ \mathrm{eV}^2$

Interaction

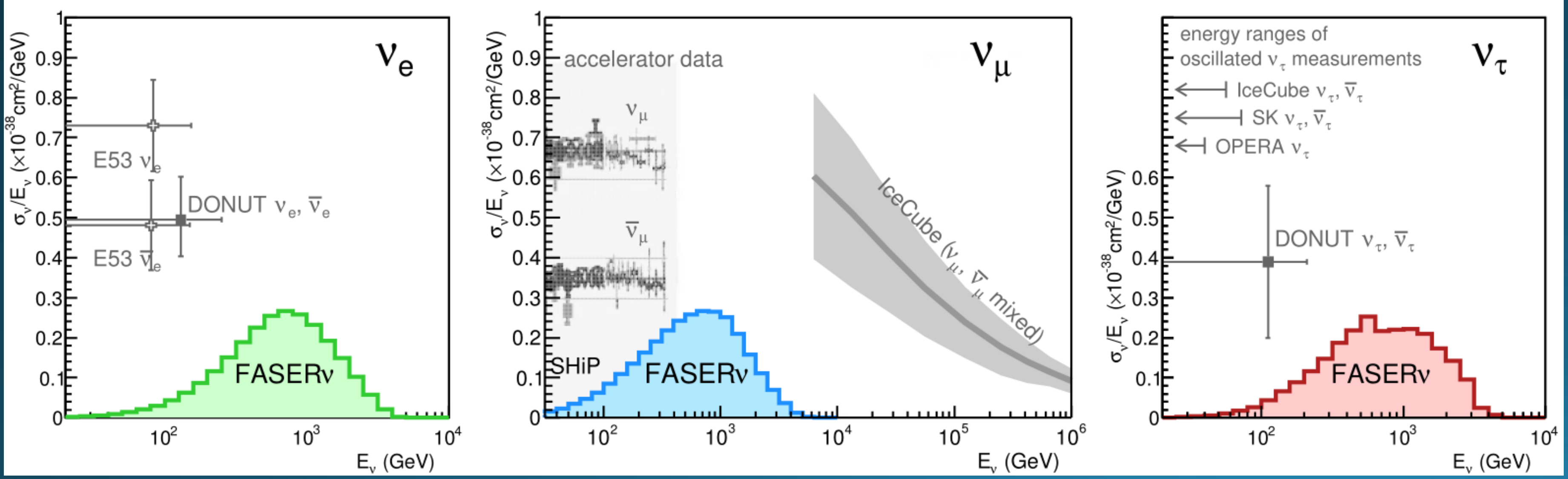
3-flavor neutrino cross sections in unexplored energy range

Neutrino induced heavy quark productions

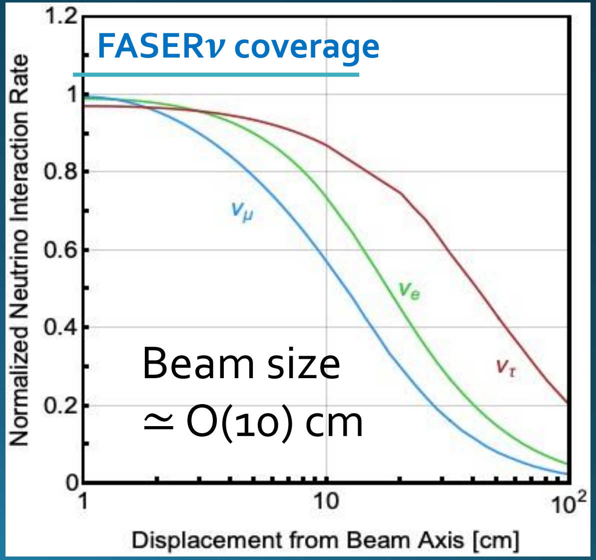
New physics effects

Forward neutrino beamline

Unexplored energy regime for all three flavors



Collimated beam

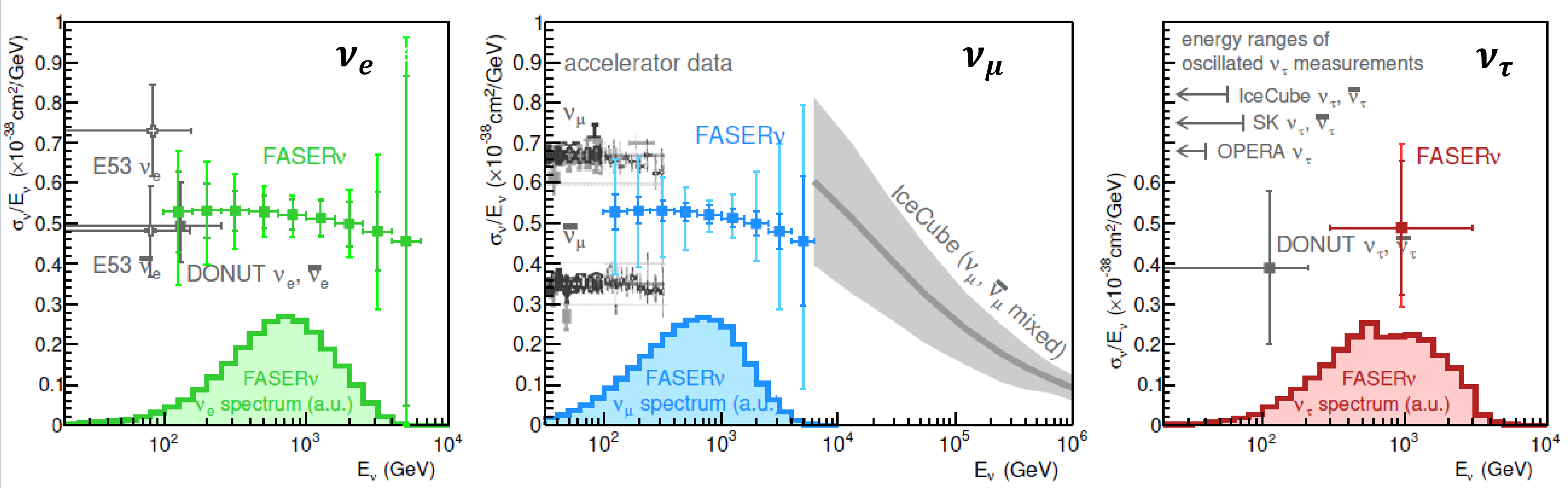


Physics studies in the LHC Run 3 (1): Cross sections

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

- Neutrino cross section measurement at unexplored energy range
  - ν_e, ν_τ at the highest energy
  - Fill the gap between accelerator and cosmic data for ν_μ

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

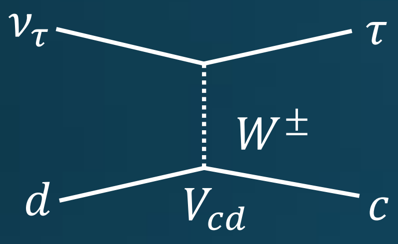


inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.

Physics studies in the LHC Run 3 (2):

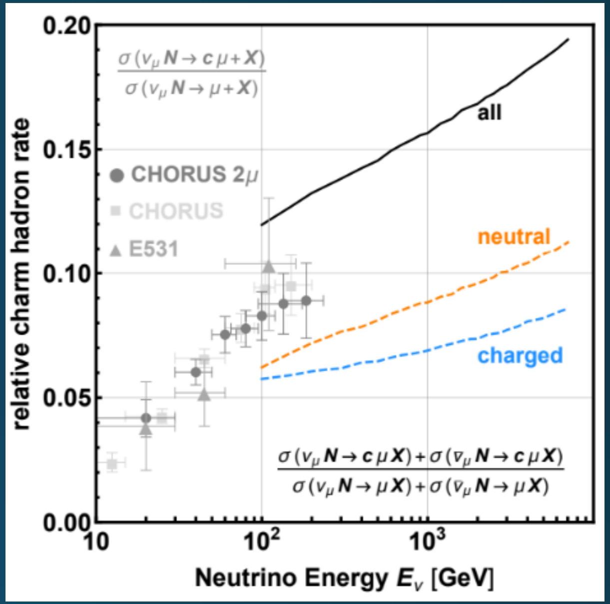
Heavy-flavor-associated channels

- Measure charm production channels
  - Large rate ~ 10% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.

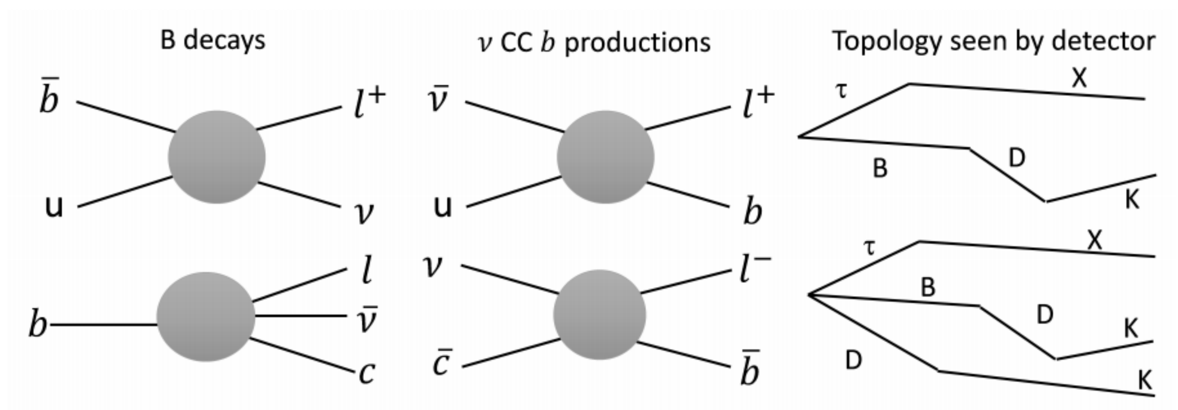


$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)}$$

$\ell = e, \mu$



- Search for Beauty production channels
  - Expected SM events (ν_μ CC b production) are $\mathcal{O}(0.1)$ events in Run 3, due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$



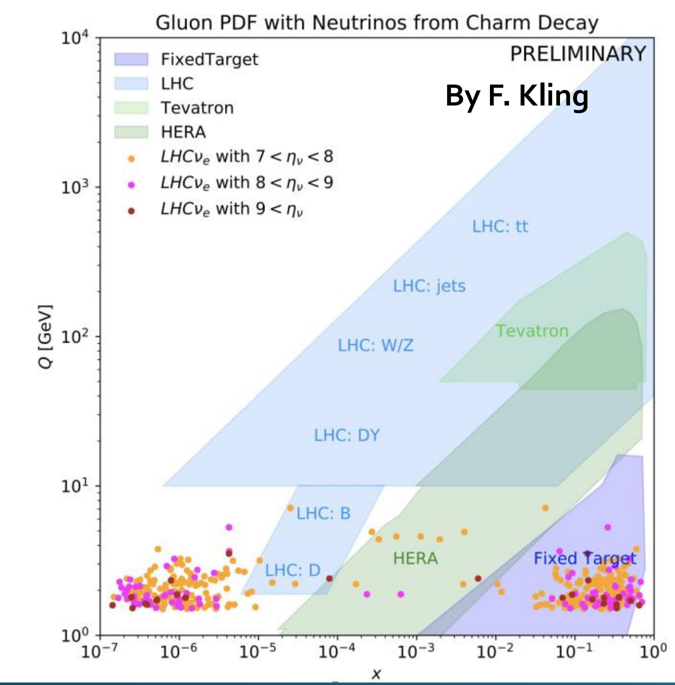
$\bar{\nu}N \to \ell \bar{B} X$

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

Physics studies in the LHC Run 3 (3): QCD

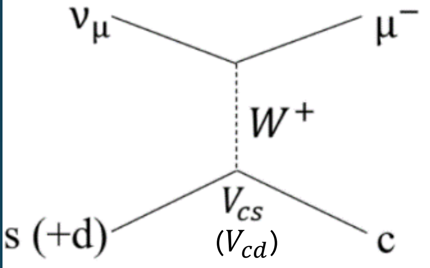
PDF in proton (neutrino production)

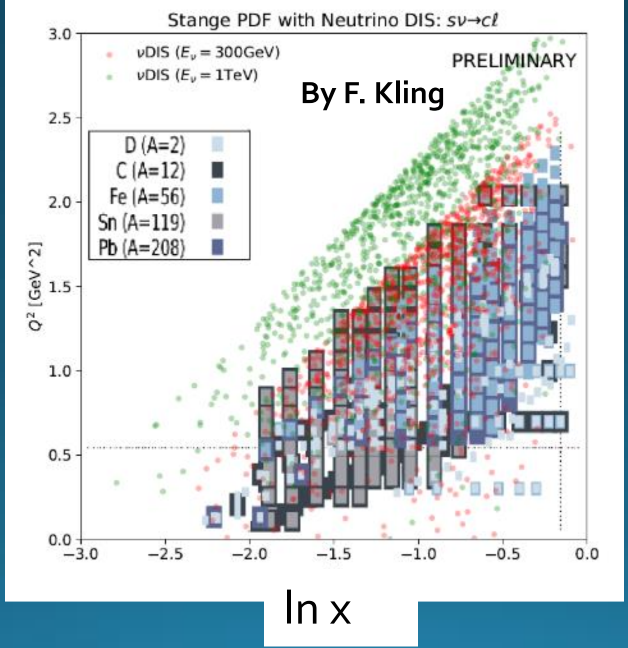
- Forward particle production is poorly constrained by other LHC experiments. FASERν's **neutrinos flux measurements** will provide novel complimentary constraints that can be used to validate/improve MC generators.
- Neutrinos from charm decay could allow to **test transition to small-x factorization, constrain low-x gluon PDF and probe intrinsic charm**.

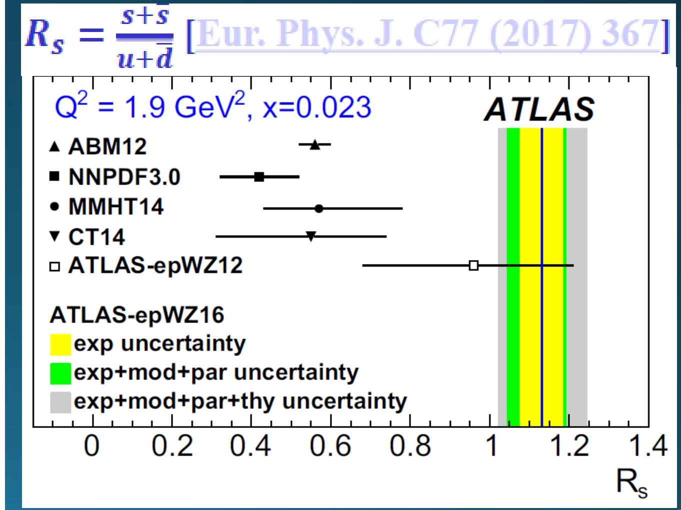


PDF in target (neutrino interaction)

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



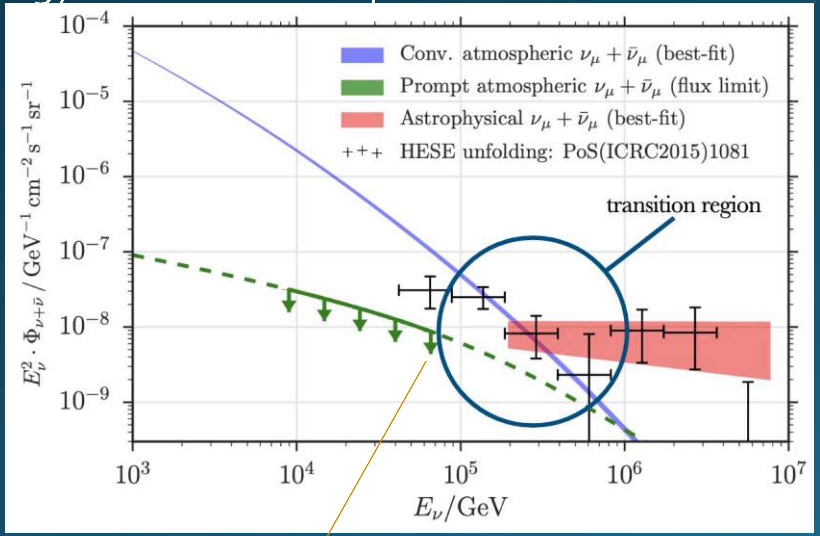




Physics studies in the LHC Run 3 (4):

Cosmic rays and neutrino

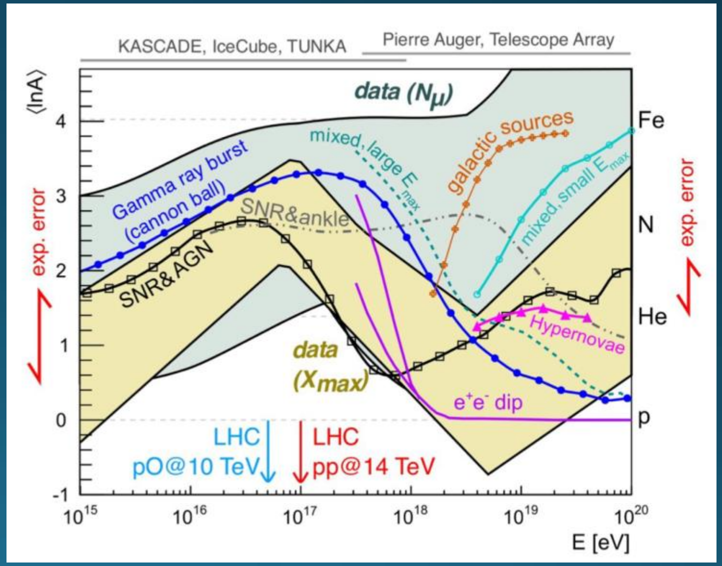
- In order for IceCube **to make precise measurements of the cosmic neutrino flux**, accelerator measurements of high energy and large rapidity charm production are needed.
- As 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode, a direct **measurement of the prompt neutrino production at FASERν** would provide important basic data for current and future high-energy neutrino telescopes.



prompt atmospheric neutrinos

IceCube Collaboration, Astrophys. J. 833 (2016)

- 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.

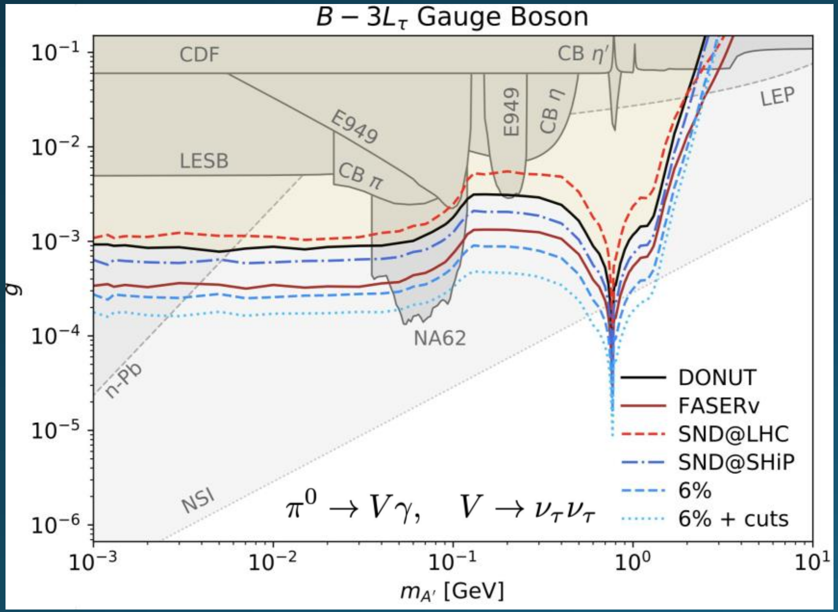


K.H. Kampert, M. Unger, Astropart. Phys. 35, 660 (2012),
H.P. Dembinski et al., EPJ Web Conf. 210, 02004 (2019)

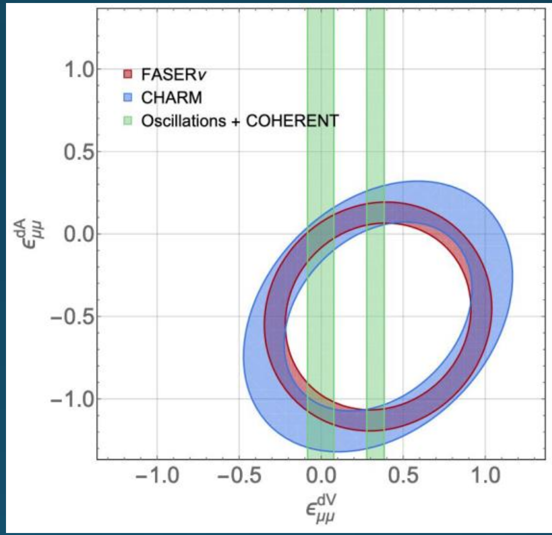
Physics studies in the LHC Run 3 (5):
BSM Physics

- 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



- 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.

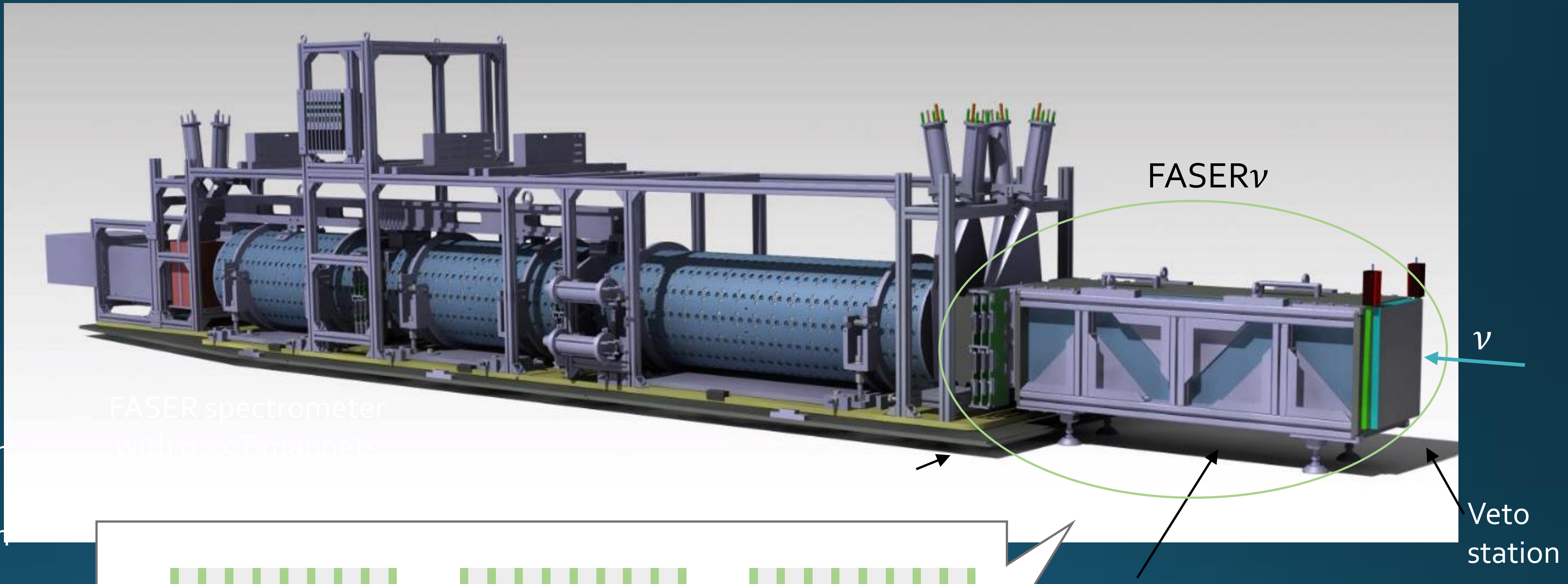
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

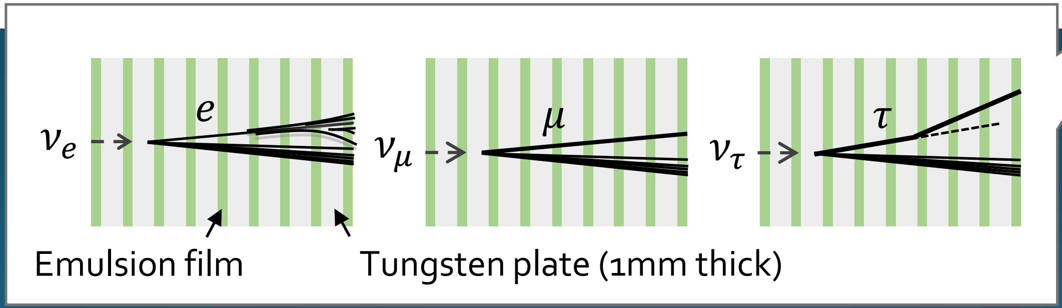
- If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERν could also search for **DM scattering**.

B. Batell, J. Feng, S. Trojanowski, 2020, in preparation

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 λ_{int}**)
  - **Muon charge identification** with hybrid configuration → distinguishin ν_μ and $\bar{\nu}_\mu$
  - **Neutrino energy** measurement with ANN by combining topological and kinematical variables
- Exchange emulsion films every 2-3 months



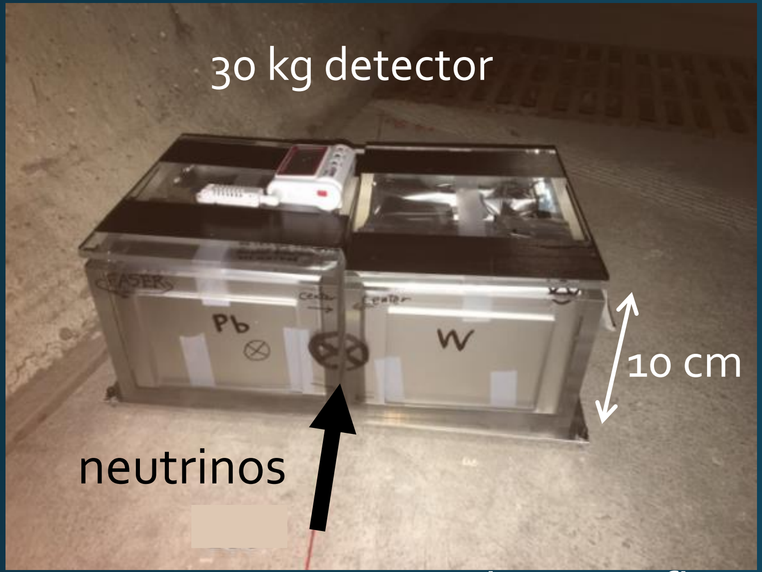


Emulsion/tungsten detector

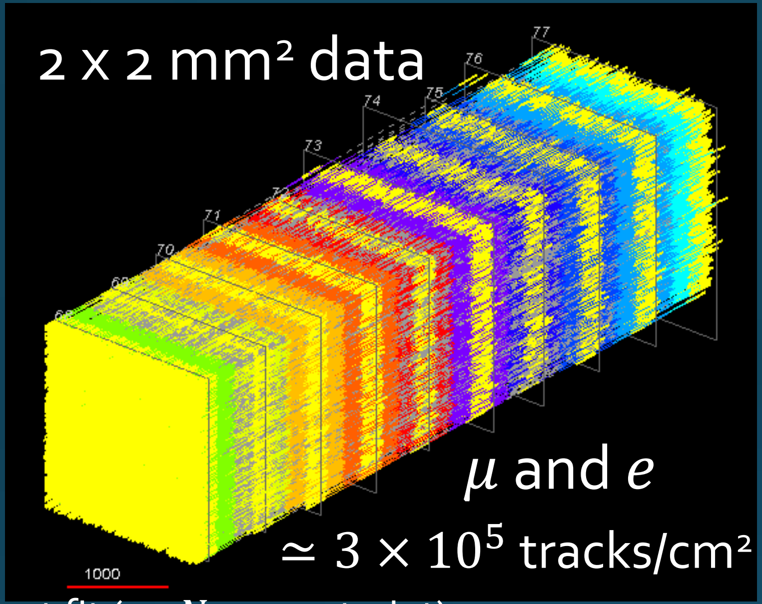
- 770 1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm², 1.1 m long, 1.1 tons detector ($220X_0$)

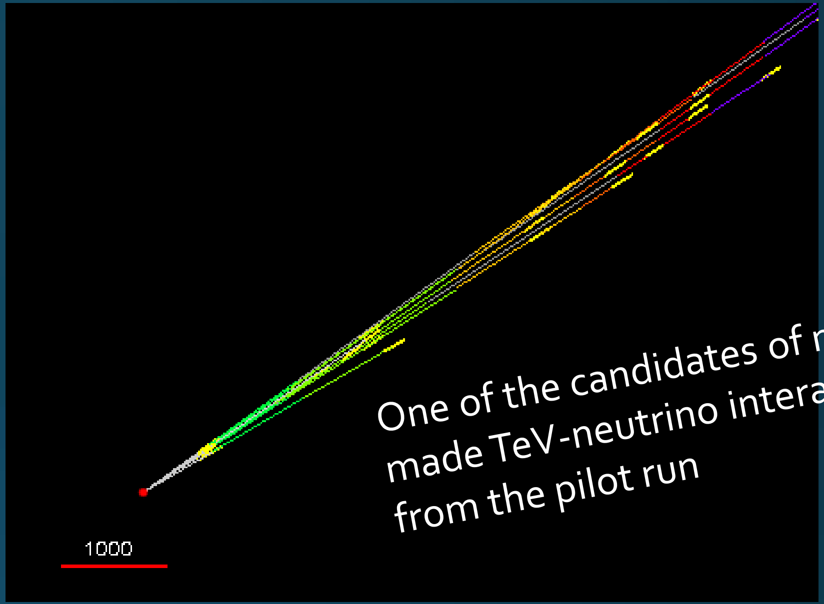
FASERν pilot run in 2018

Aiming to demonstrate the feasibility of detection of collider neutrinos

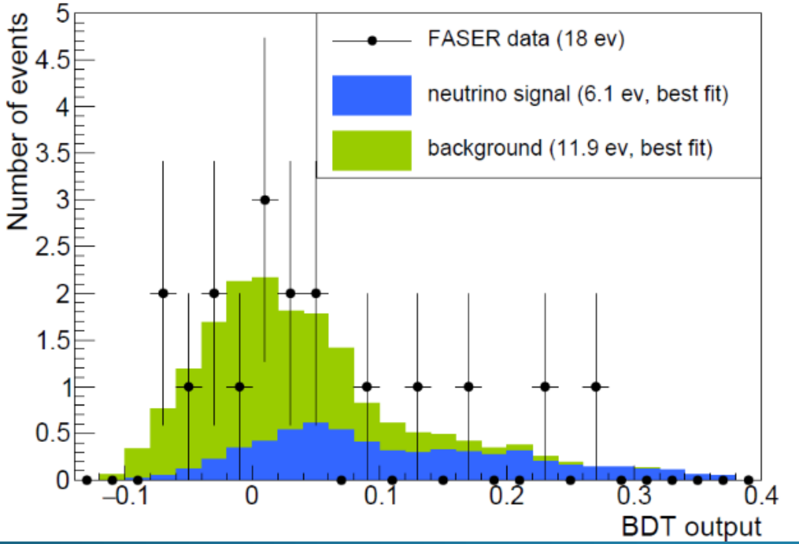


Sep-Oct 2018, 6 weeks, 12.2 fb^{-1}



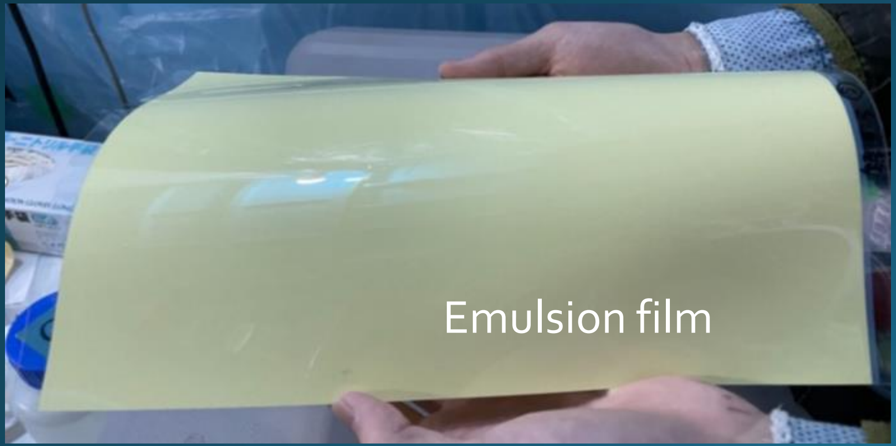


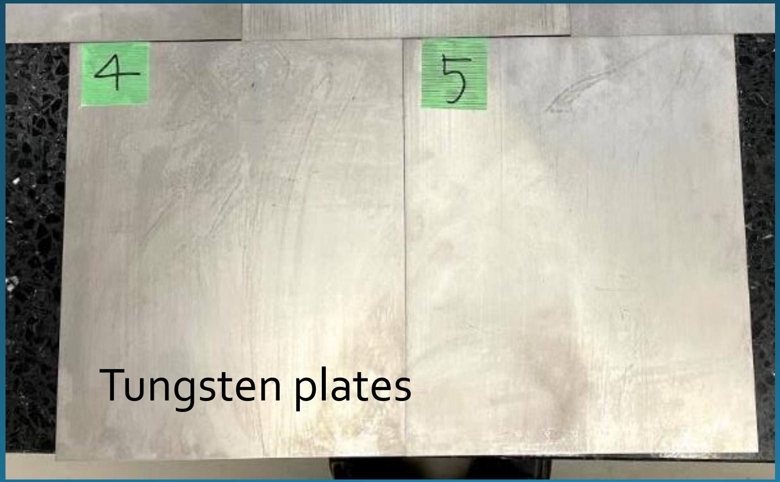
Best fit (no N_{BG} constraint)

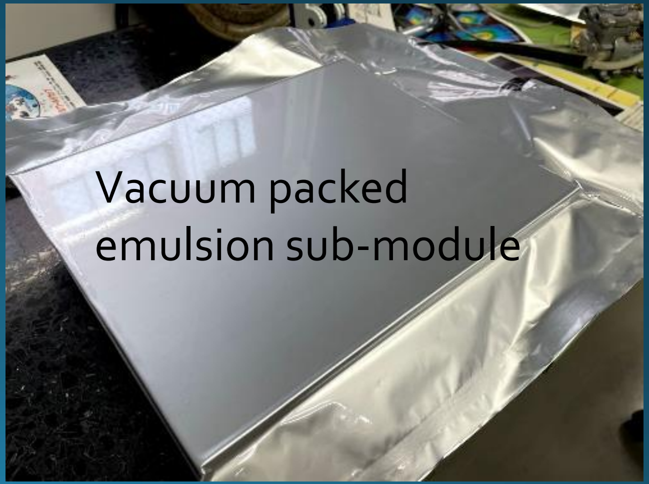


- First neutrino interaction candidates at the LHC, arXiv:2105.06197

Preparation for data taking in 2022

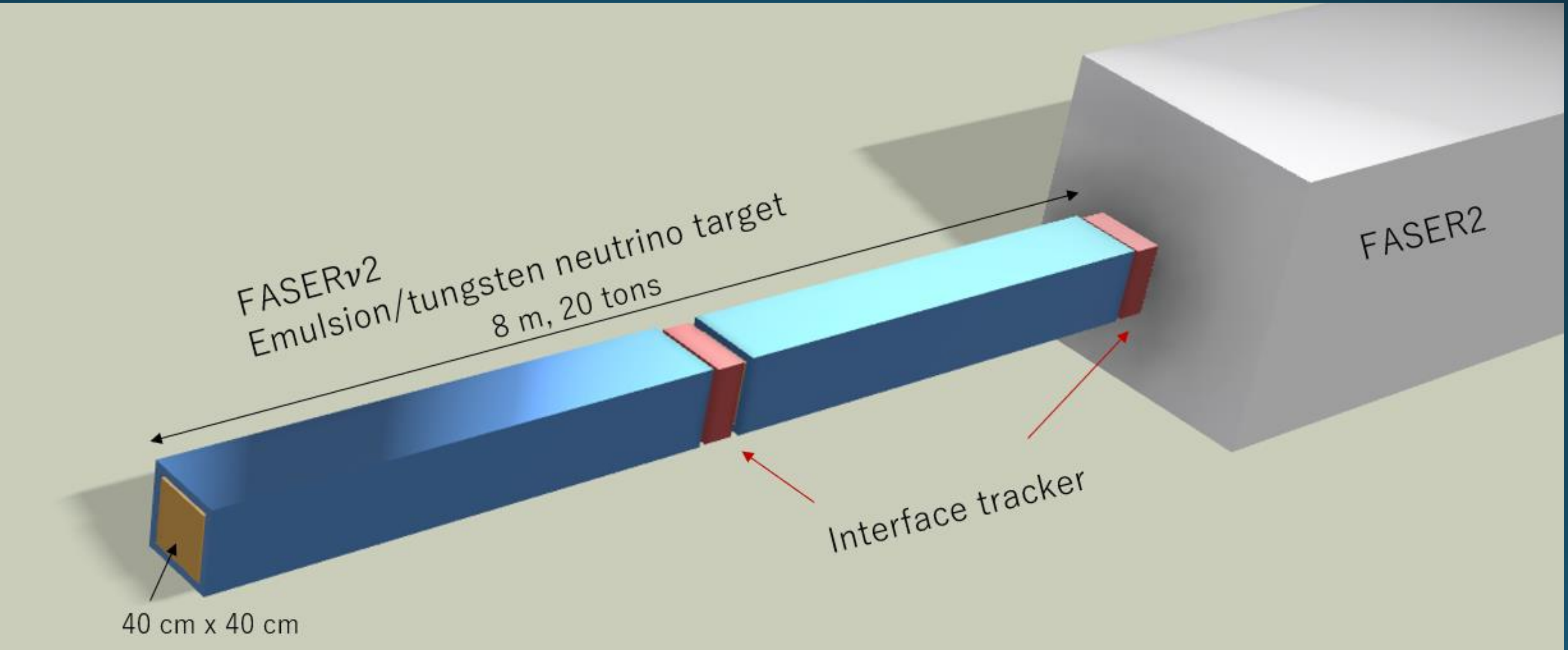




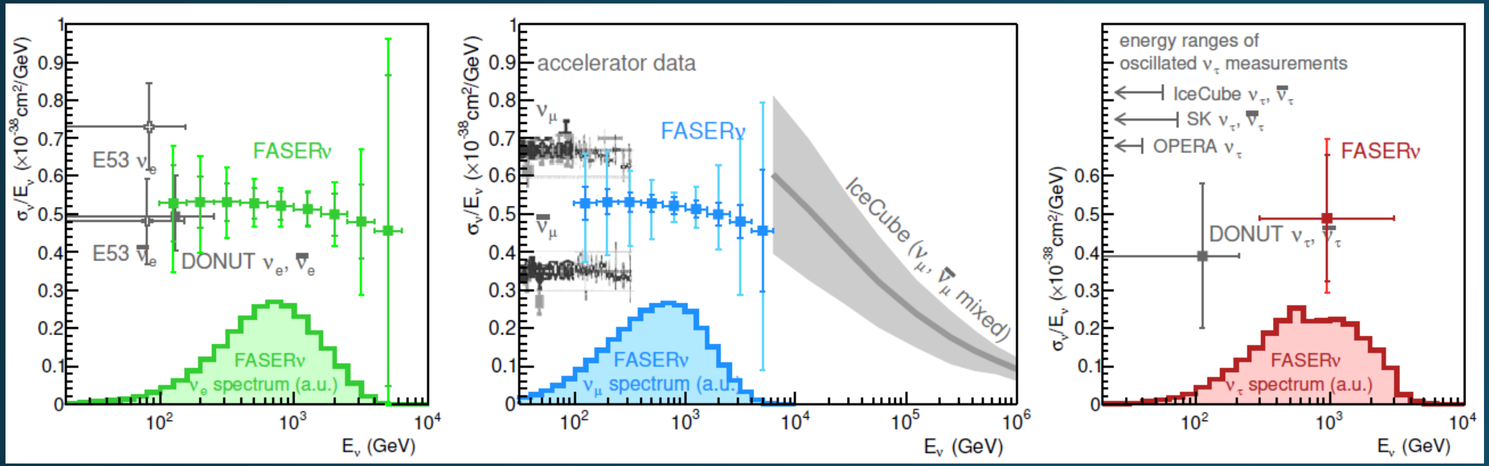


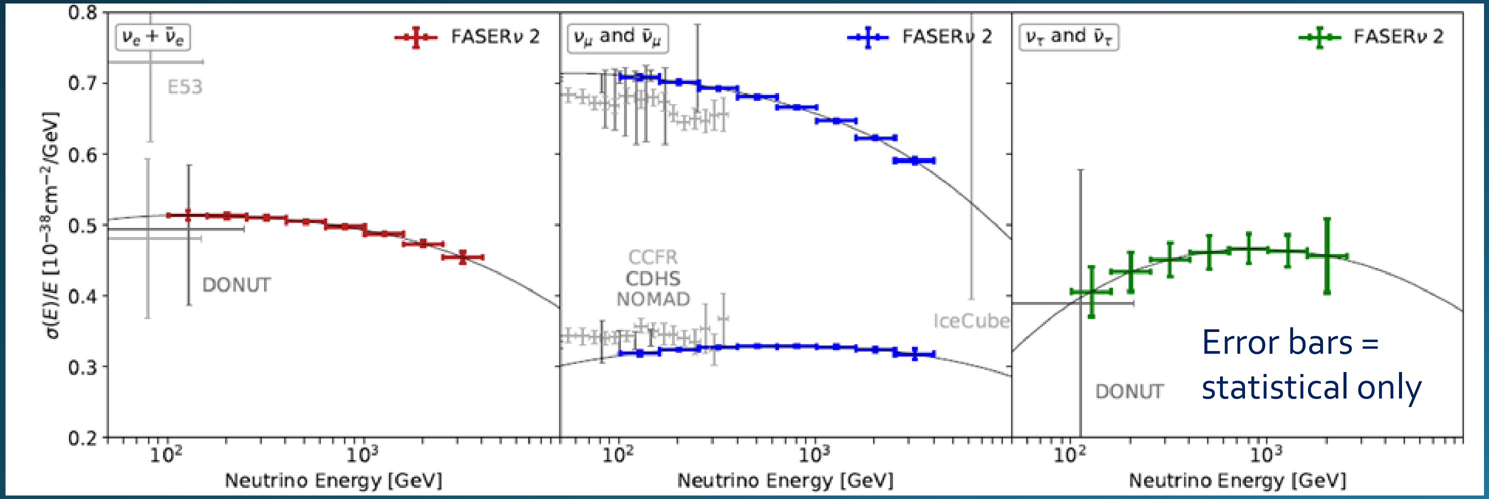
FASERν2

- Emulsion / tungsten detector combined with electric detectors
  - Flavor sensitivity, high interaction rates, muon identification, EM calorimeter
  - Target: 40 cm x 40 cm x (2 mm x 3300 tungsten plates), a total of 20 tons, divided into two big modules. ~$\times$ 20 of FASERν
  - $\times$ 20 mass and $\times$ 20 beam, 100-400 times statistics with respect to FASERν



FASERν → FASERν2





- Era of precision measurement of high energy neutrinos
- Study of tau neutrino and rare processes
  - Tau neutrino cross section and lepton universality in neutrino scattering
  - Tau neutrino magnetic moment
  - BSM physics in tau neutrino production
  - Neutrino-induced charm and beauty production → Flavor anomalies
  - Non-Standard Interaction
  - Neutrino oscillation at $\Delta m^2 \sim 1000\ eV^2$
  - Dark matter scattering

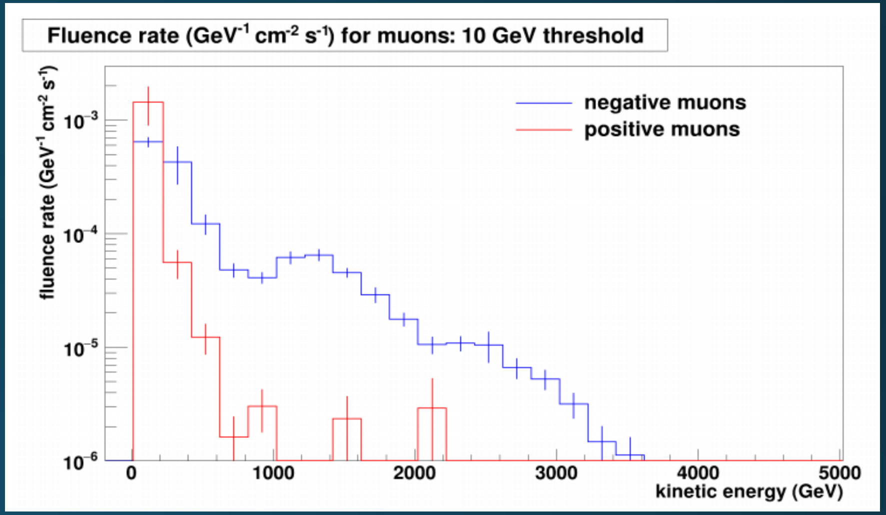
Expected number of CC interactions in FASERν2 during HL-LHC (3 ab^{-1}) using Sibyll 2.3d / DPMJET 3.2017

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

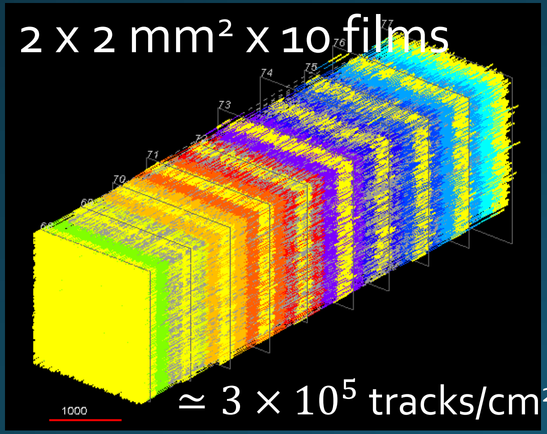
Key issue: Muon background

- Density of muons limits the duration of each data taking with emulsion detectors (we replace emulsion 3 times/year in Run 3!)
- HL-LHC would increase muon rate by a factor of 2.5 → Problem!!
- **Can we suppress 80-90% of muon background?**
- Let's sweep muons by a magnet upstream of the rock shielding
  - To bend 500 GeV particle by 4 mrad → 6.7 $T \cdot m$ is required

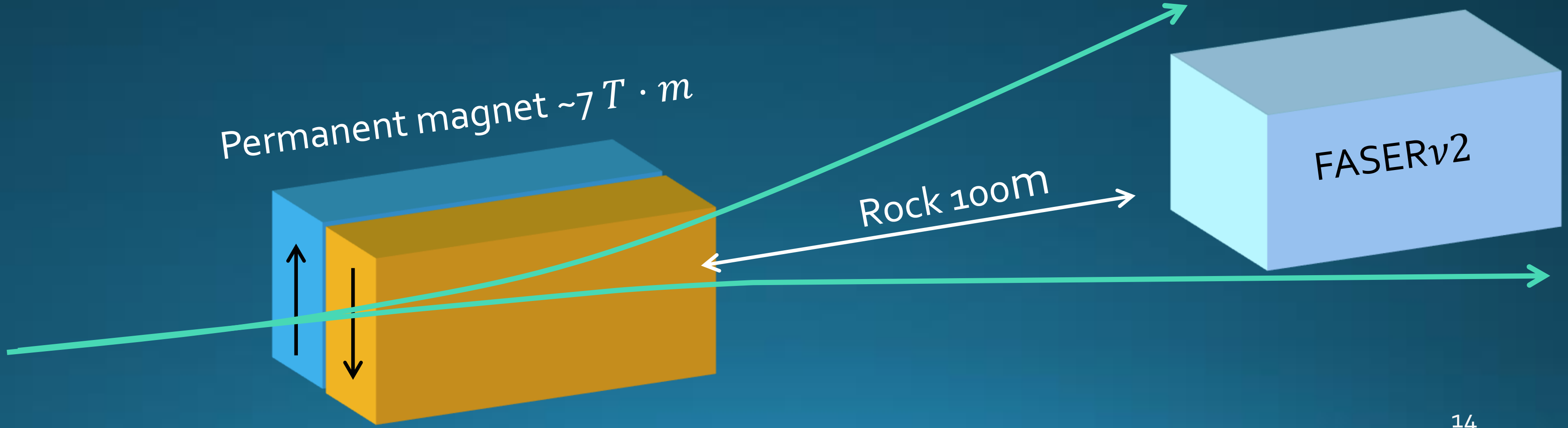
90% of muons are expected to be P<500 GeV



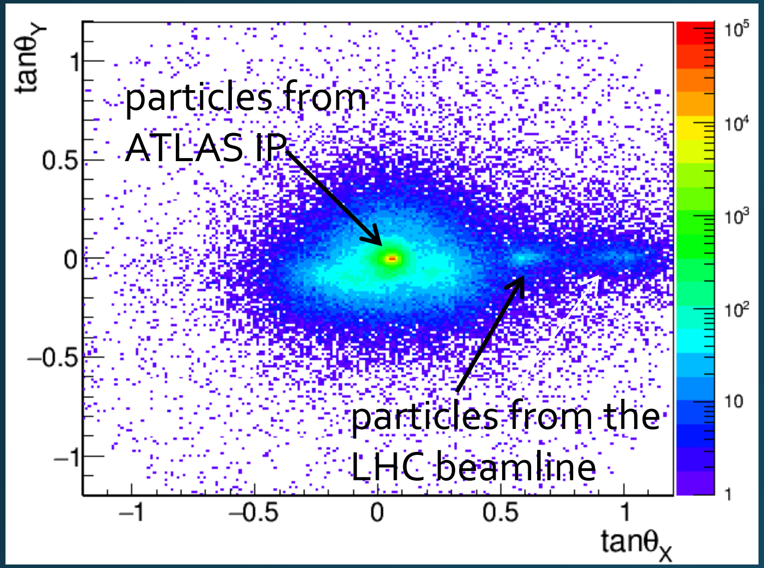
A piece of data from 2018 run

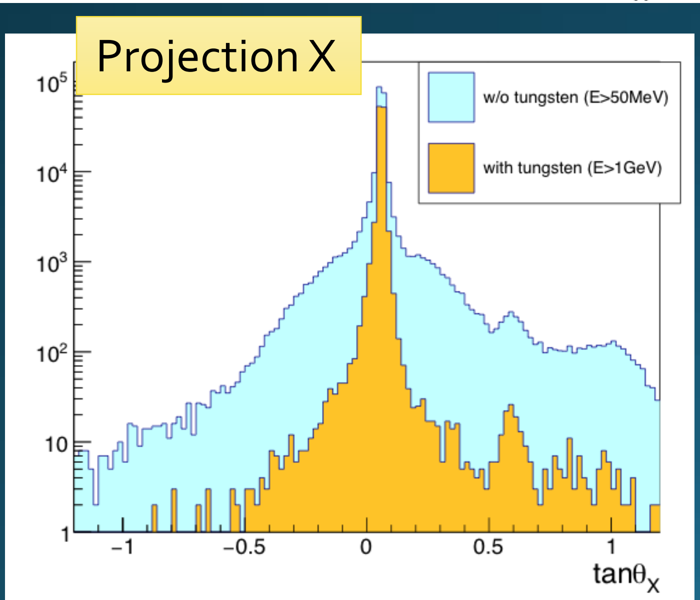


$\simeq 3 \times 10^5$ tracks/cm²
with 12.5 fb^{-1}

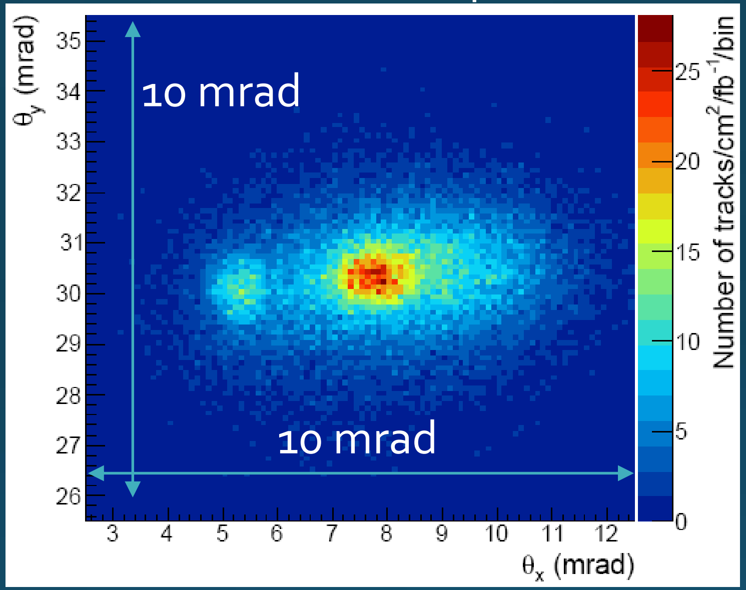


Muon background measurement in 2018

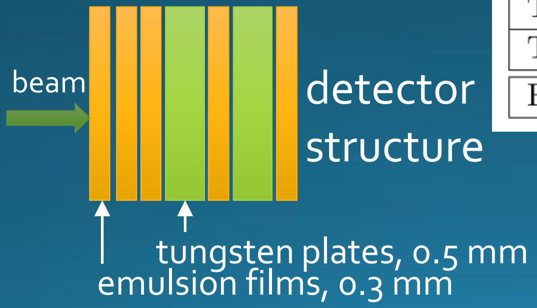




Zoom of the main peak



There are two peaks in the main peak. Particles traveled through 100 m of rock, nevertheless the angular spread is very small. The fitted sigma is less than 1 mrad, corresponding to P>500 GeV



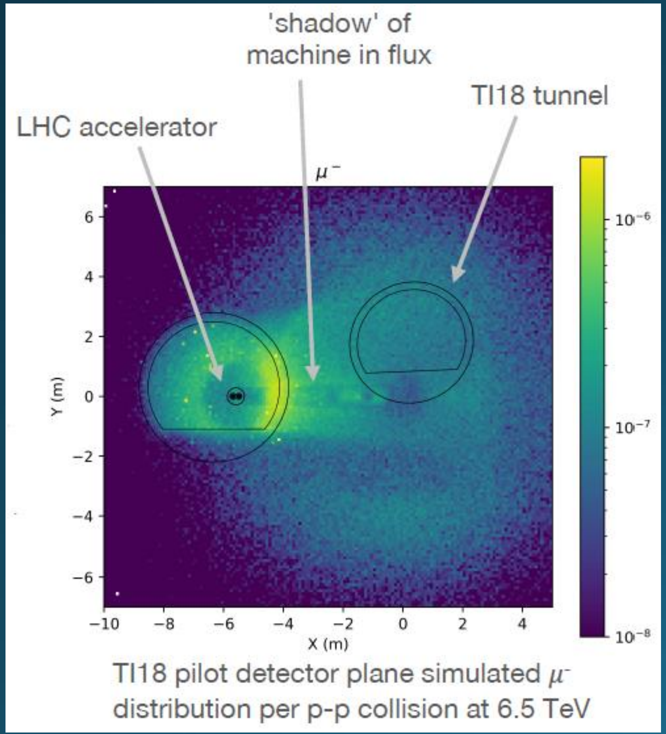
	beam [fb^{-1}]	normalized flux, all [fb cm^{-2}]	normalized flux, main peak [fb cm^{-2}]
TI18	2.86	$(2.6 \pm 0.7) \times 10^4$	$(1.2 \pm 0.4) \times 10^4$
TI12	7.07	$(3.0 \pm 0.3) \times 10^4$	$(1.9 \pm 0.2) \times 10^4$
FLUKA, E>10 GeV		2×10^4	

Data and the FLUKA prediction agrees within their uncertainty.

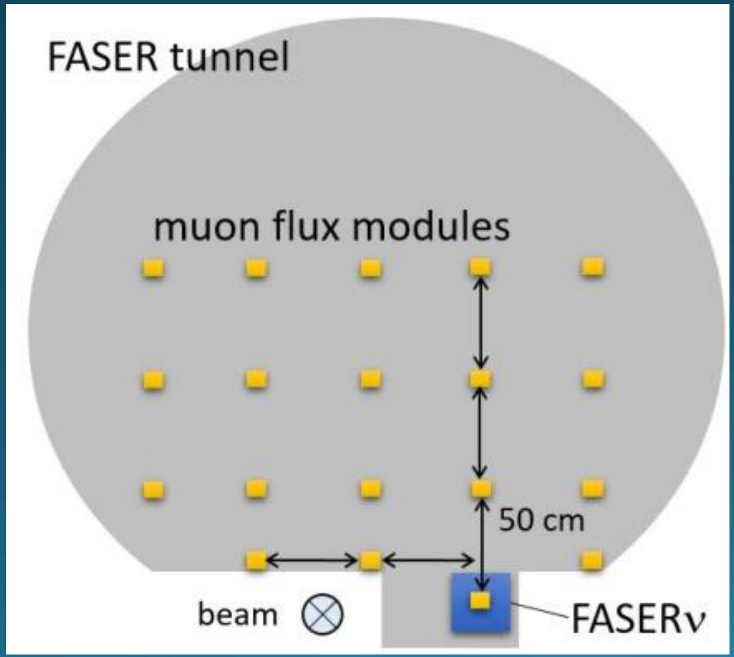
Muon flux mapping in Run 3

- There is a void of muon flux, where detectors would be placed
- Muon flux on-site is to be mapped during Run 3 to define the design of the FPF detectors
- Emulsion-based beam monitor, used in T2K and FASER, would be handy for this purpose [10.1093/ptep/ptv054, arXiv:1812.09139]

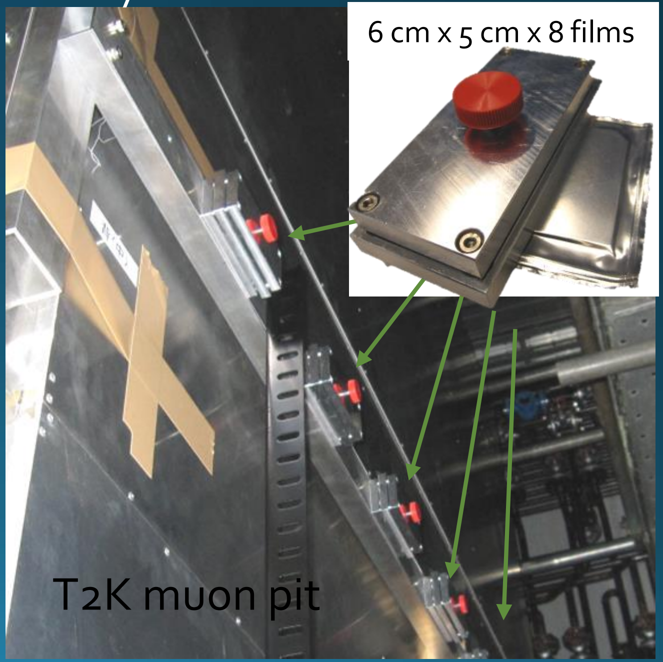
BDSim



TI18 pilot detector plane simulated μ^- distribution per p-p collision at 6.5 TeV



an array of emulsion modules in T2K



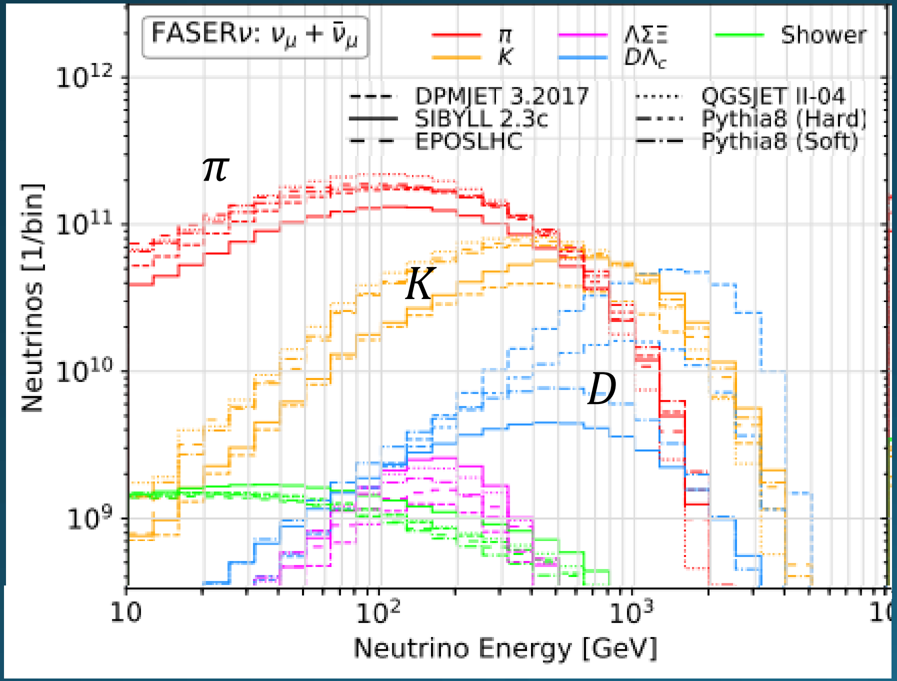
Summary

- Neutrino beam at the HL-LHC is a unique platform to study TeV neutrinos, in particular tau neutrinos and rare processes.
- FASERν2 in FPF, with x20 mass and x20 beam, 200-400 times more statistics can be obtained w.r.t. FASERν
- Key issue = muon background. On-site measurement + simulation is being planned.
- Conceptual design in https://arxiv.org/abs/2109.10905 .

Neutrinos = proxy of forward hadron production

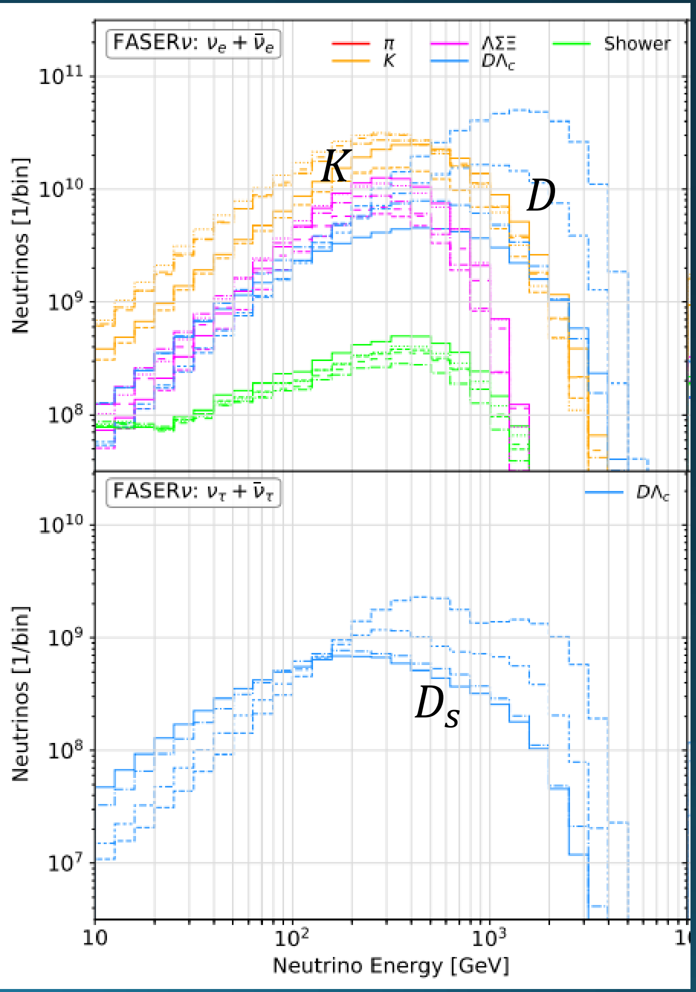
- Pion, Kaon, charm contribute to different part of energy spectra and flavor

ν_μ



ν_e

ν_τ



- FASERν provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

Expected neutrino event rate in LHC Run-3

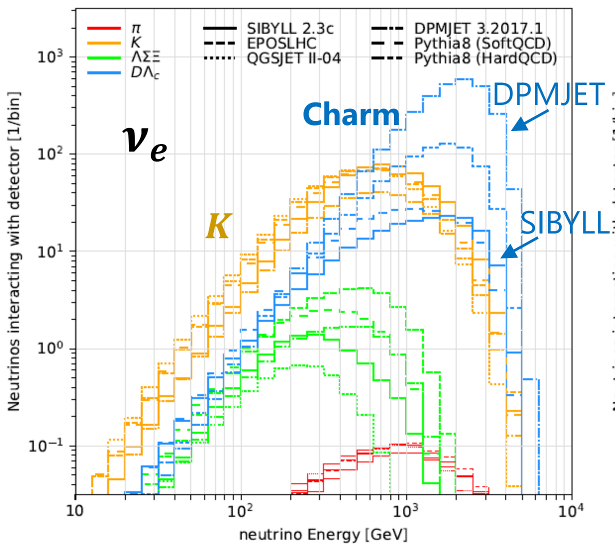
F. Kling, Forward Neutrino Fluxes at the LHC, arXiv:2105.08270

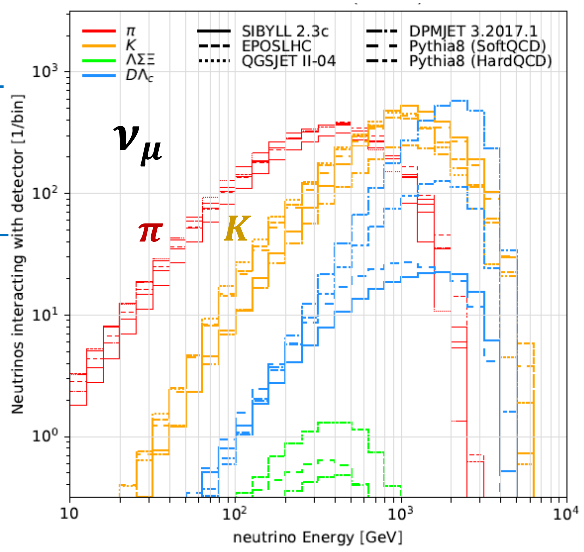
- A high-intensity beam of neutrinos will be produced in the far-forward direction.
- FASERν will be centered on the LOS (in the FASER trench) to maximizes fluxes of all neutrino flavors.

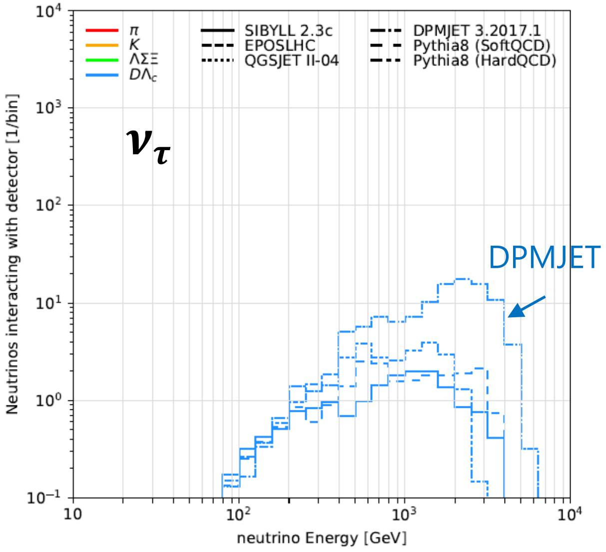
Expected number of CC interactions in FASERν during LHC Run-3 (150 fb^{-1})

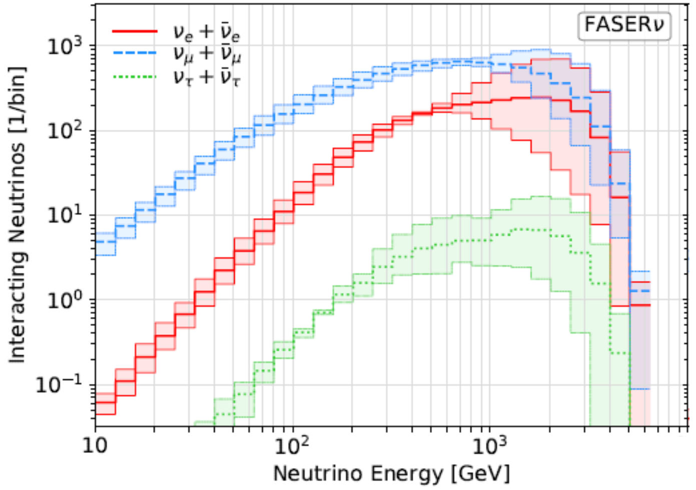
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2
DPMJET	DPMJET	4614	9198	131
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}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

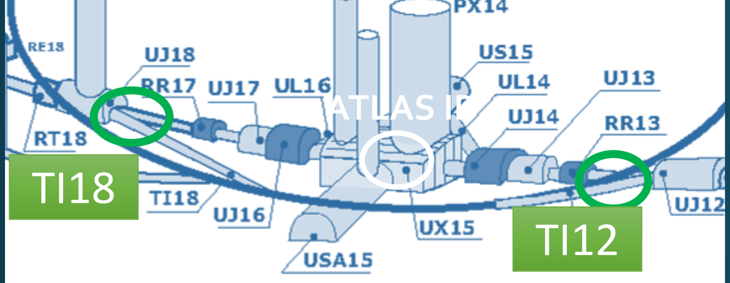
Differences between the generators checked with the same propagation model (RIVET-module)



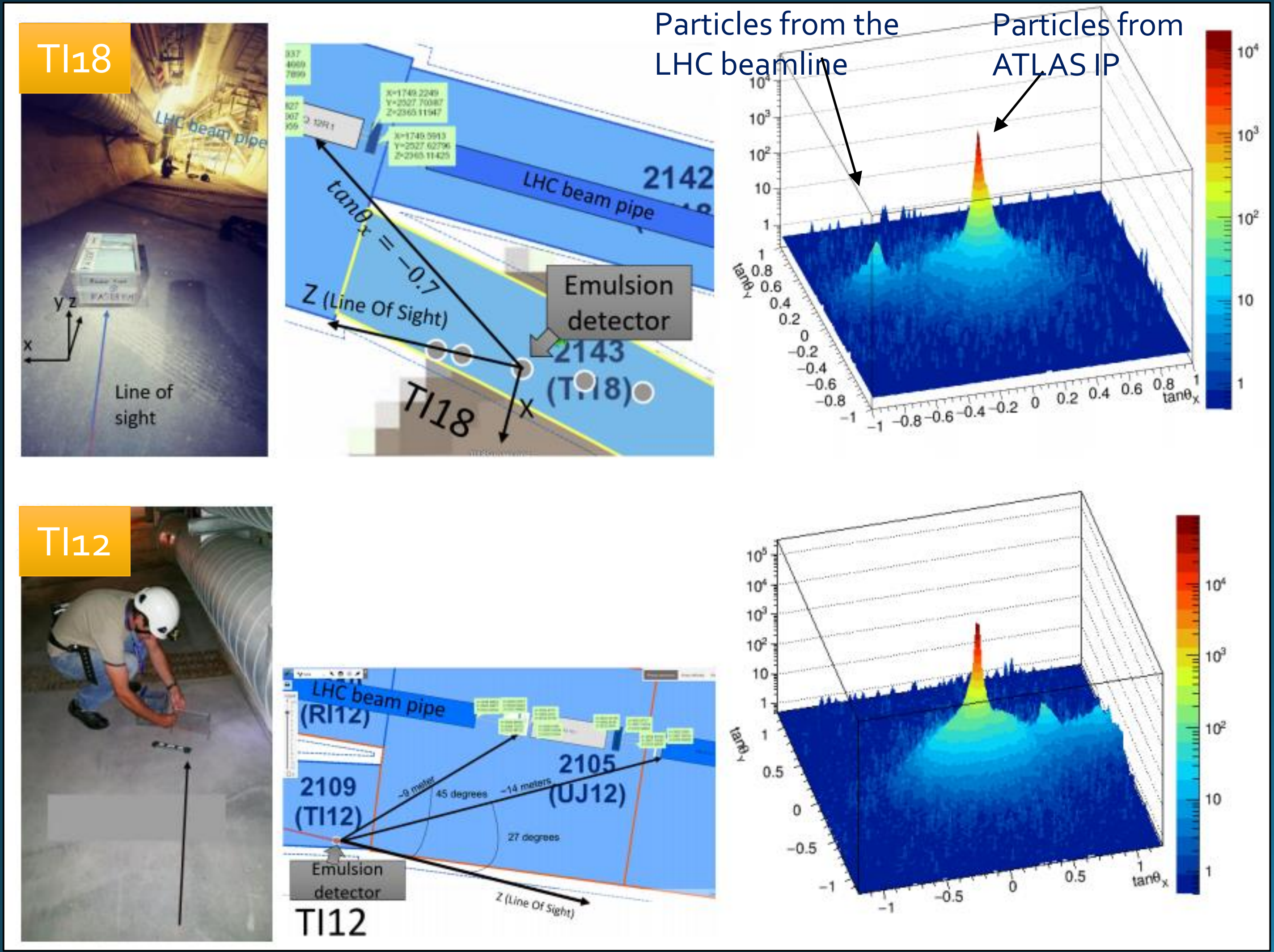








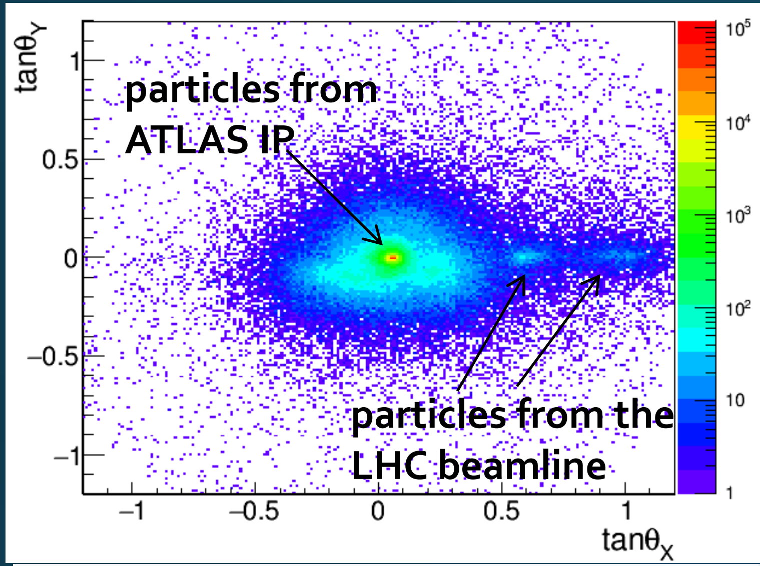
In-situ measurements
in 2018: Detector environment



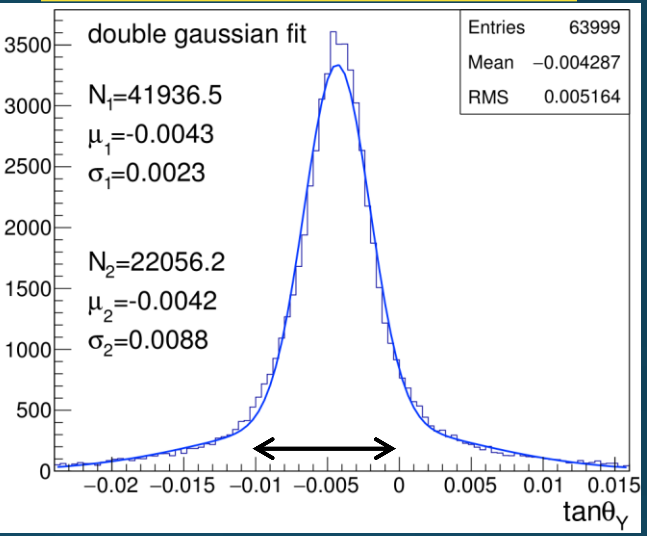
- Emulsion detectors were installed to investigate TI18 and TI12.
- The measured charged particle flux was low and consistent with the FLUKA prediction.
- The measurements also showed the radiation was low and not problematic.

Feasible to perform neutrino measurements!

Muon background measurement in 2018



Projection Y and zoomed

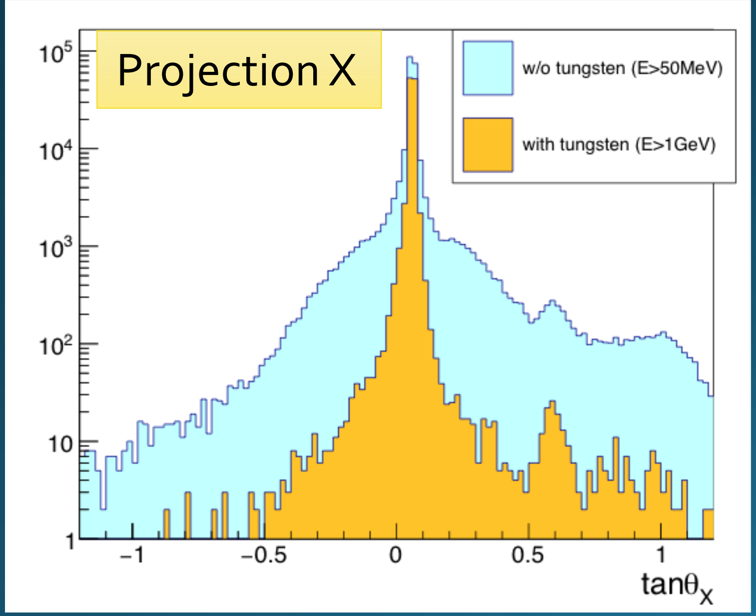


$\sigma = 2.3$ mrad

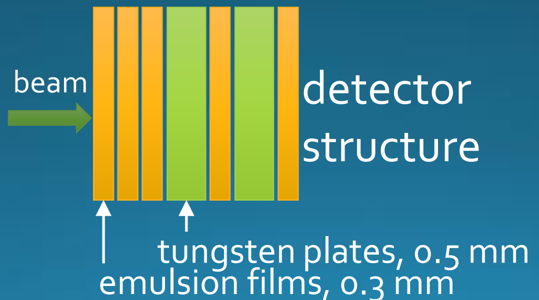
$\simeq$ measurement resolution

→ marginal multiple Coulomb scattering in 100 m of rock

→ the particles are very high momentum, P>300 GeV.



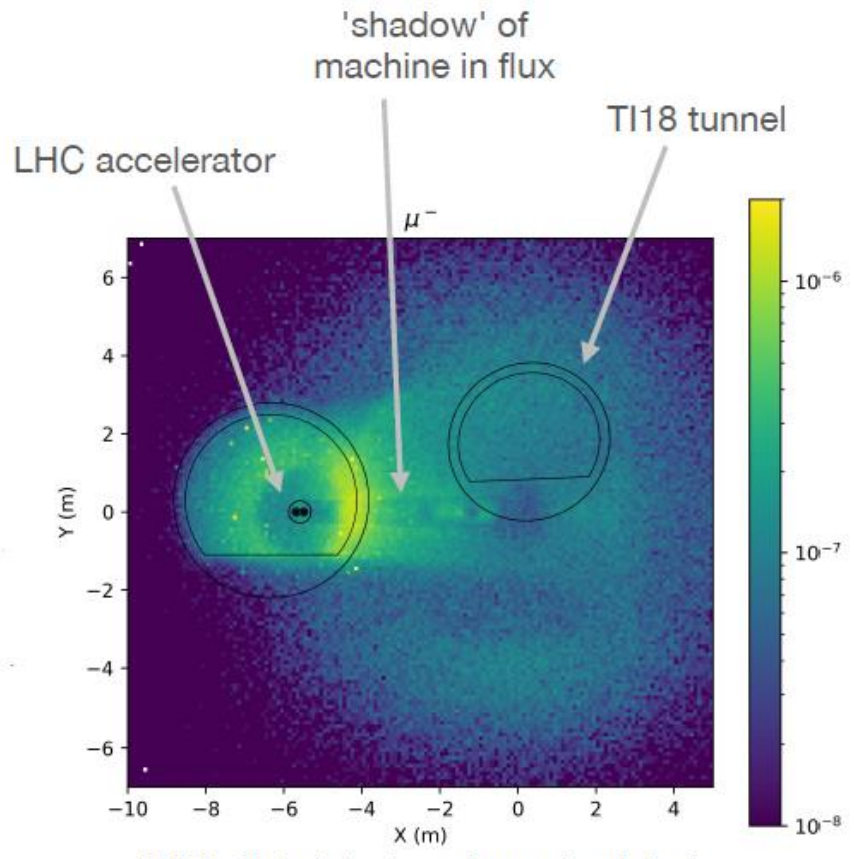
	Flux all [fb/cm²]	Flux in main peak [fb/cm²]
TI18 data	$2.6 \pm 0.7 \times 10^4$	$1.2 \pm 0.4 \times 10^4$
TI12 data	$\mathbf{3.0 \pm 0.3 \times 10^4}$	$\mathbf{1.9 \pm 0.2 \times 10^4}$
FLUKA MC		$\mathbf{2.0 \times 10^4}$



Data and the FLUKA (uncertainty 100%) prediction agrees within their uncertainties.

Muon background estimation

- Muon background simulation with BDSim
- On-site measurement being planned
- Magnet prototype design for FASERν, identification of location, simulation



TI18 pilot detector plane simulated μ^- distribution per p-p collision at 6.5 TeV