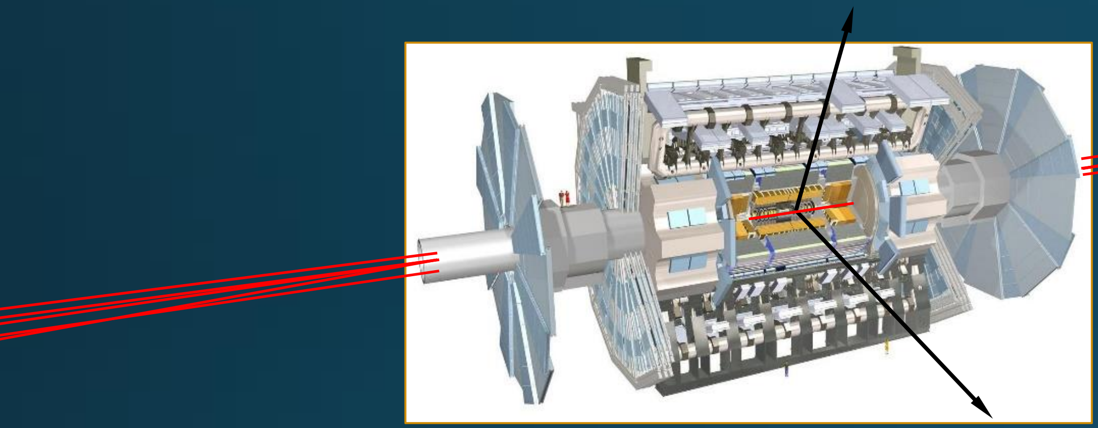
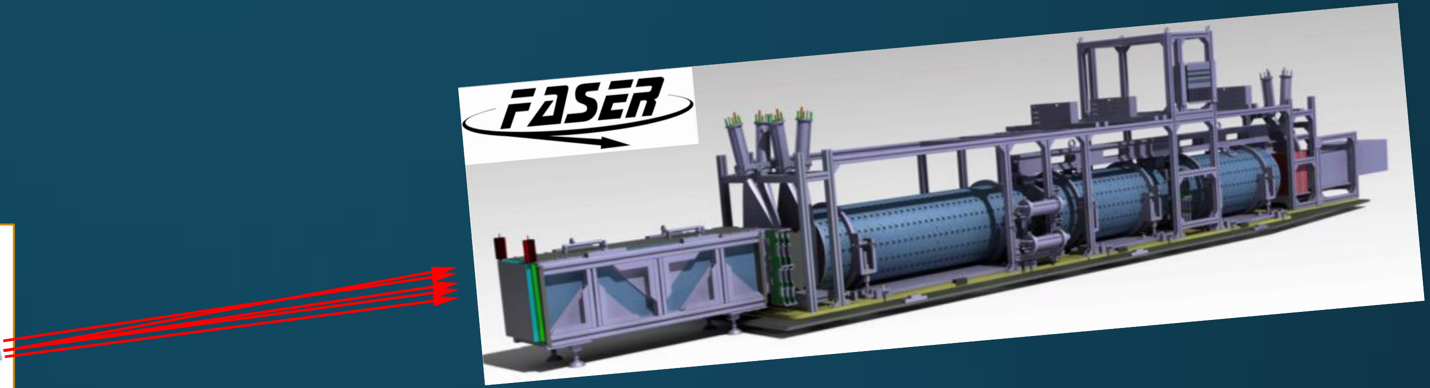




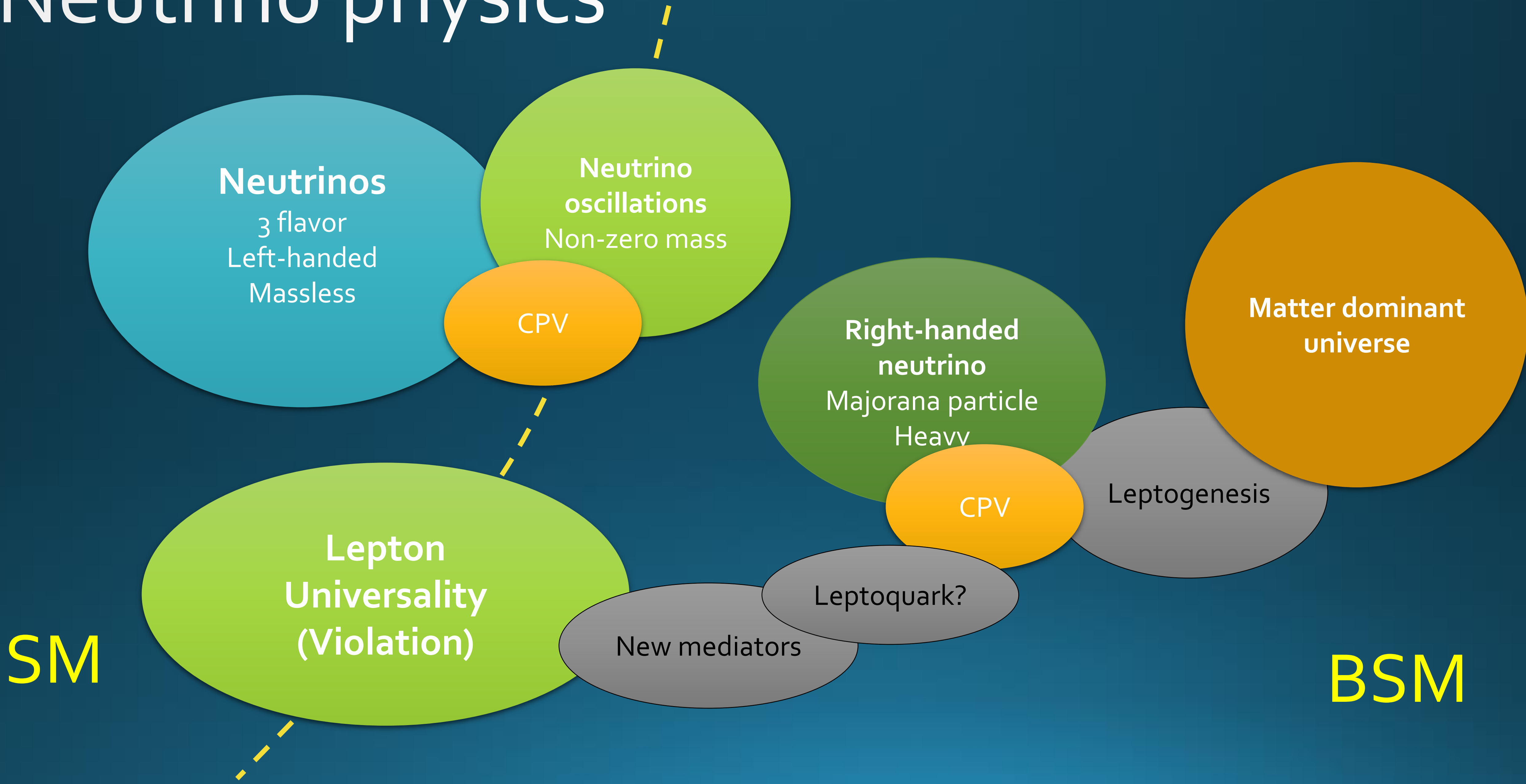
Akitaka Ariga
University of Bern & Chiba University
On behalf of FASER collaboration

FASERν

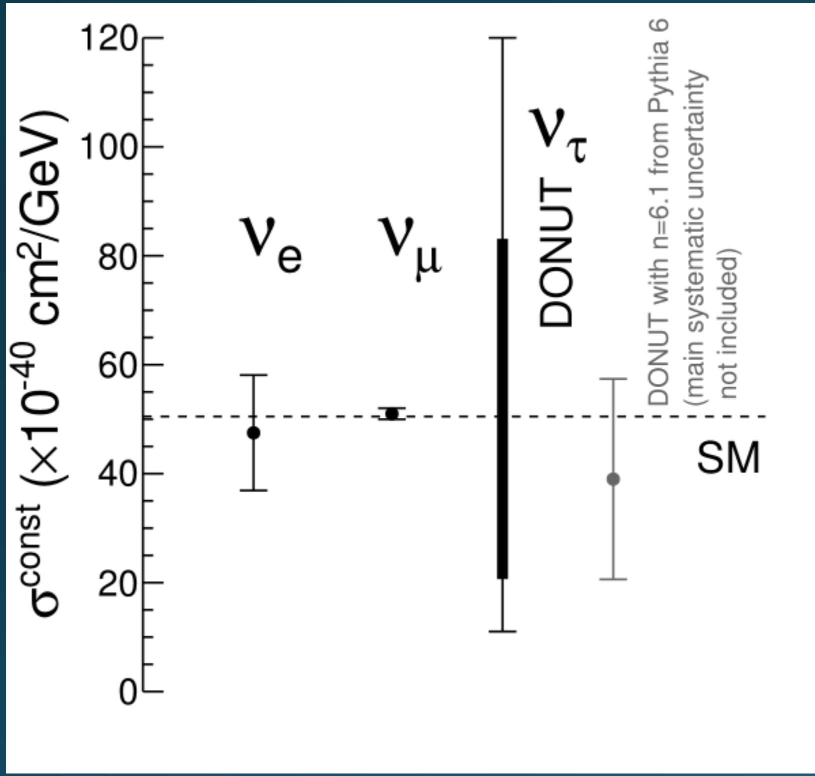
TeV neutrinos at the LHC

Supported by: HEISING-SIMONS FOUNDATION, SIMONS FOUNDATION, 科研費 KAKENHI, erc

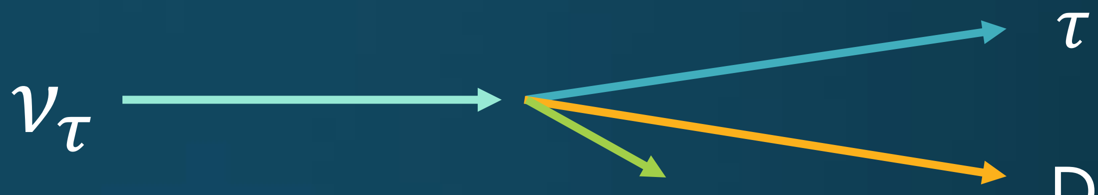
Neutrino physics



Status of Lepton Universality testing in neutrino scattering



Poor constraint for ν_τ



High energy neutrinos is required to access heavy flavor channels

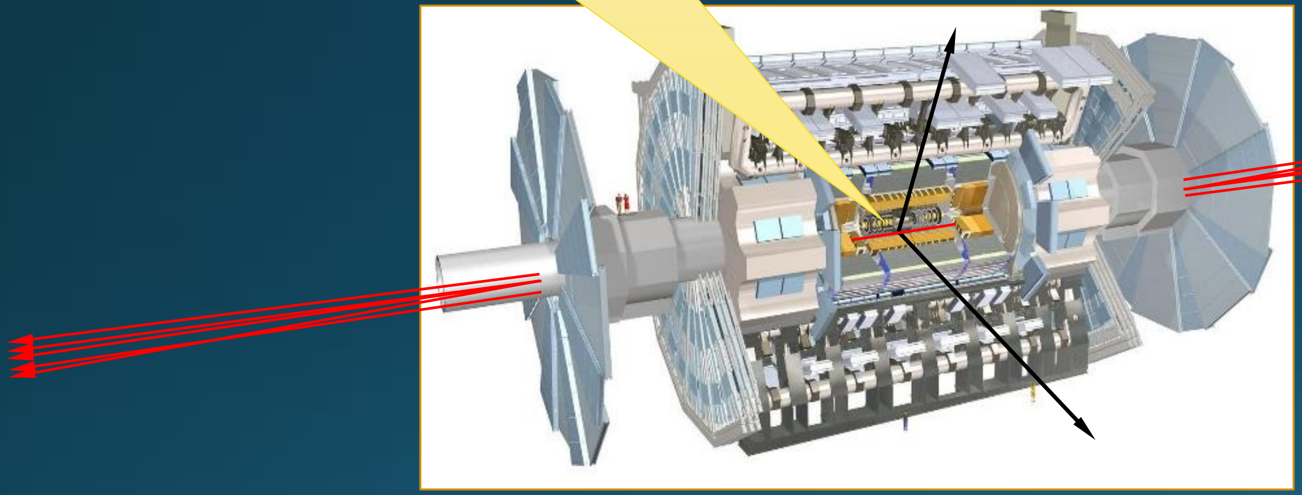
→ Need high statistics and high energy beam experiment!

LHC as a neutrino source

No experiment has sought neutrinos at the LHC so far!

14 TeV p-p collision

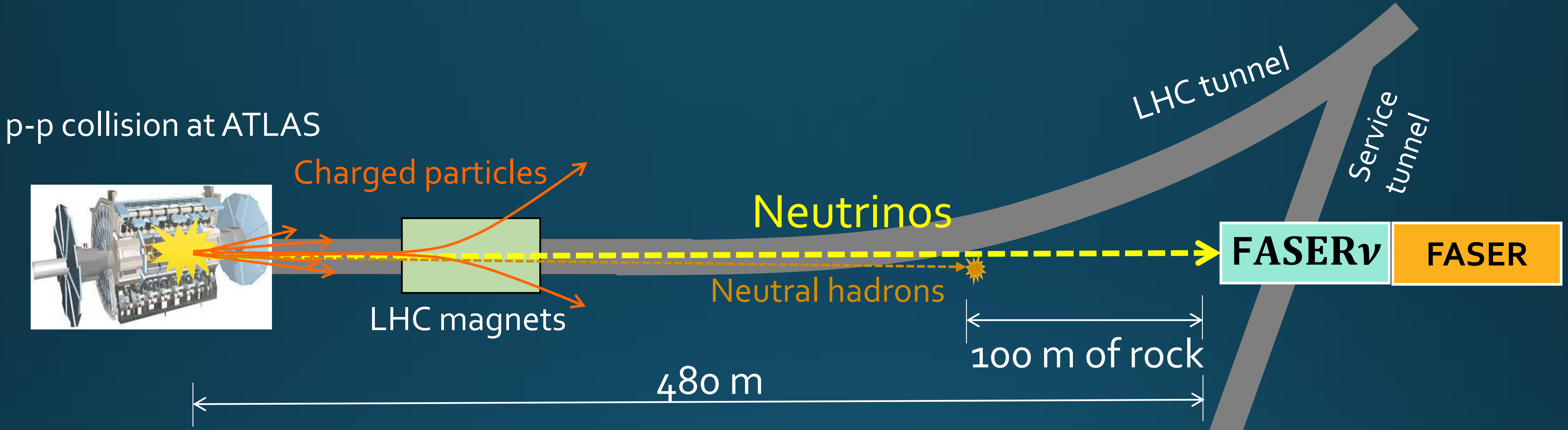
Intense neutrino beam (+ long lived particles, LLPs) here!



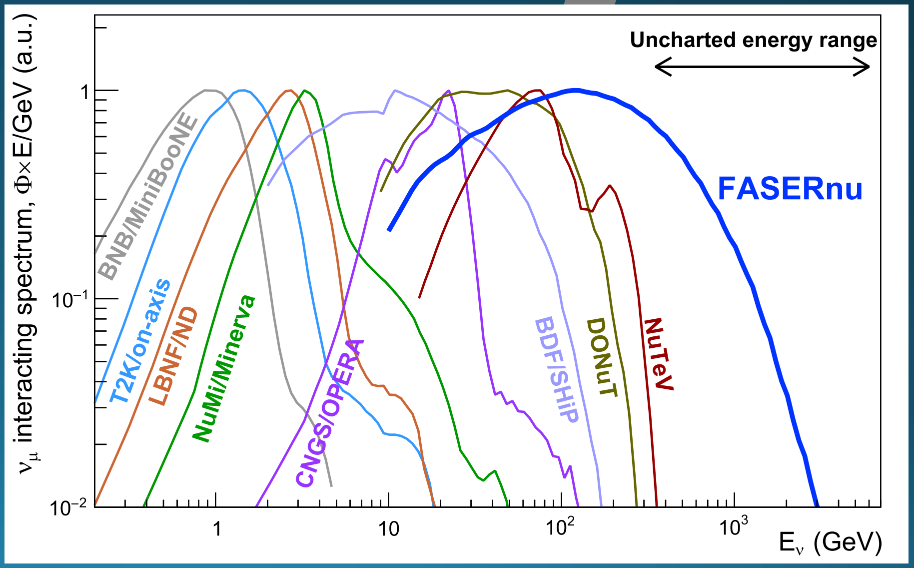
FASER, new particle searches, TP 1812.09139, approved in Mar 2019

FASERν, neutrinos, TP 2001.03073, approved in Dec 2019

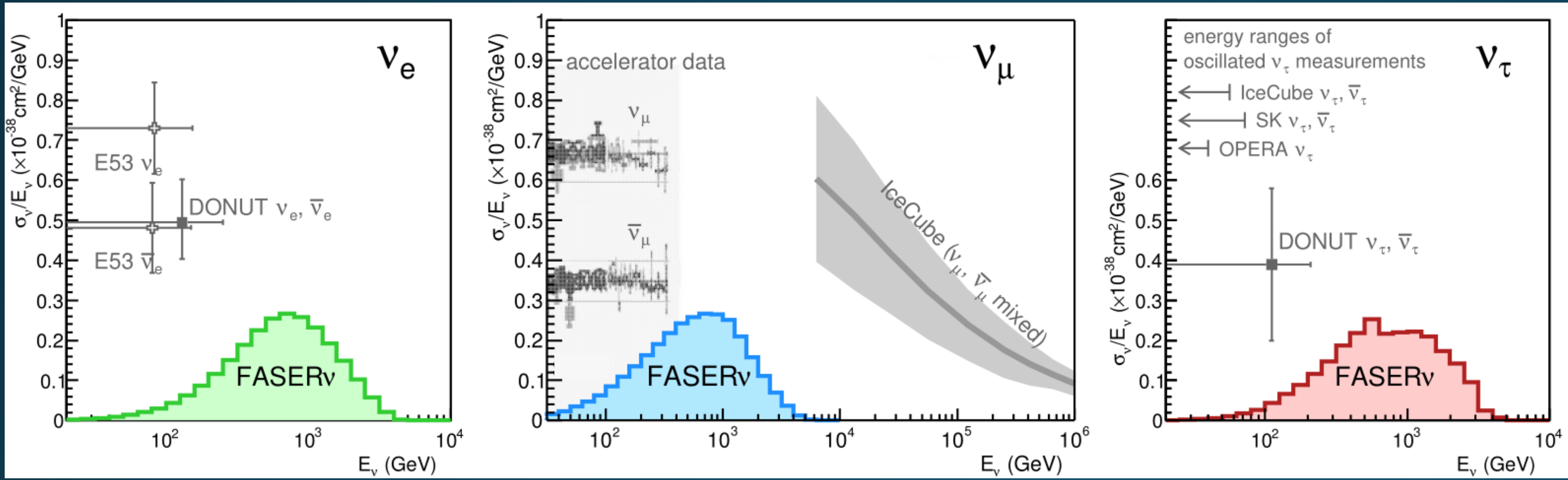
"Neutrino beamline"



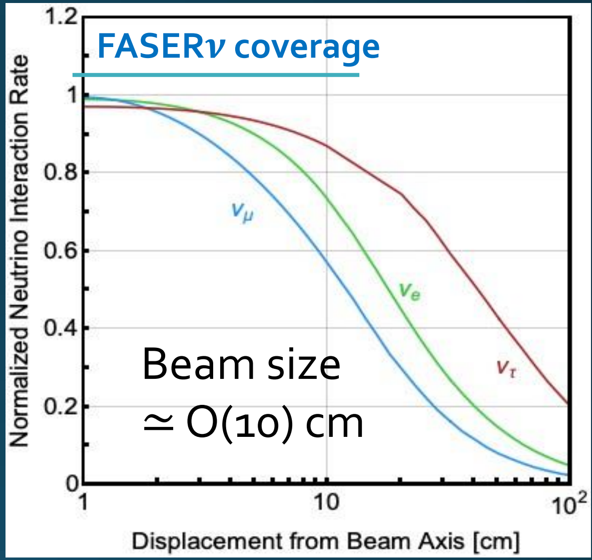
Negligible cost for infrastructure!



Neutrino spectrum at FASERν



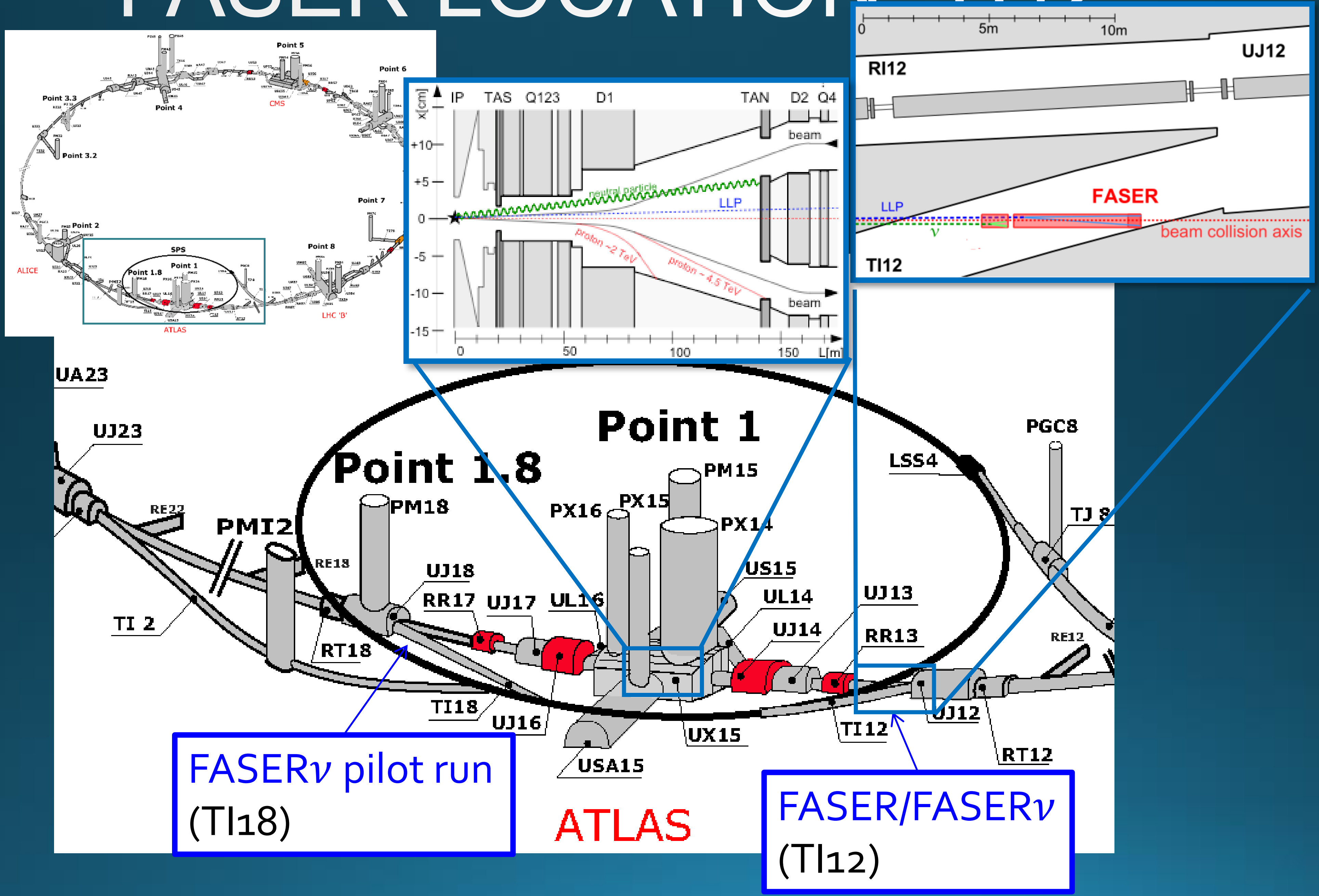
Unexplored energy regime for all three flavors



Collimated beam

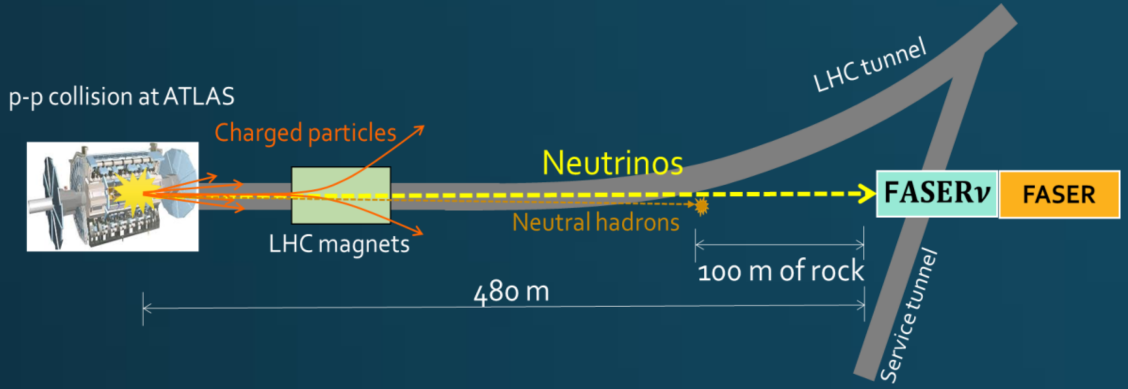
Study of <u>production</u>, <u>propagation</u> and <u>interactions</u> of high energy neutrinos

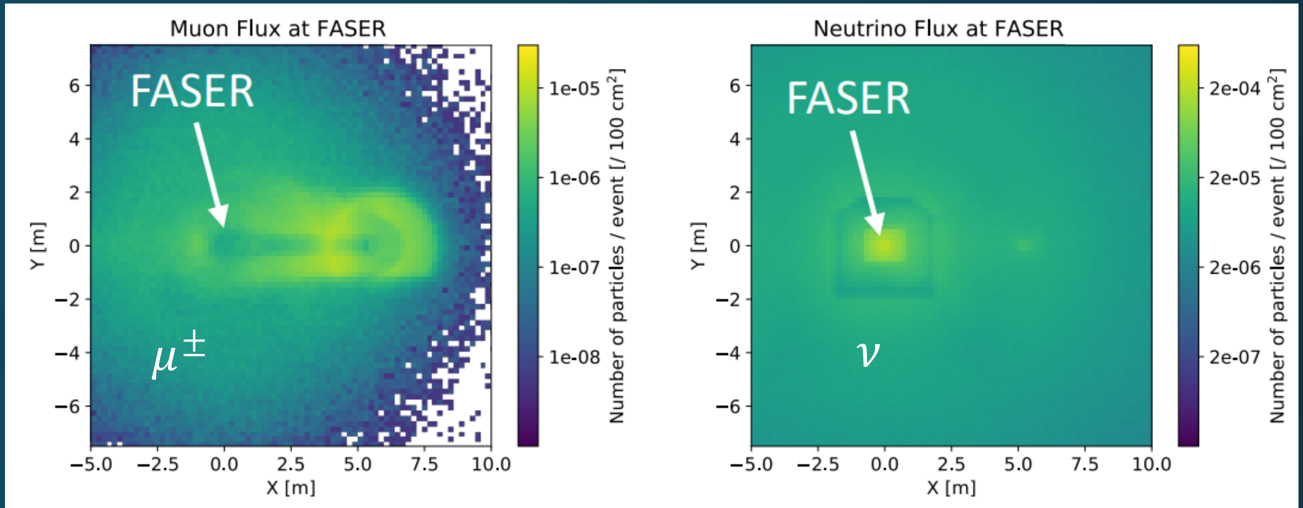
FASER LOCATION: TI12



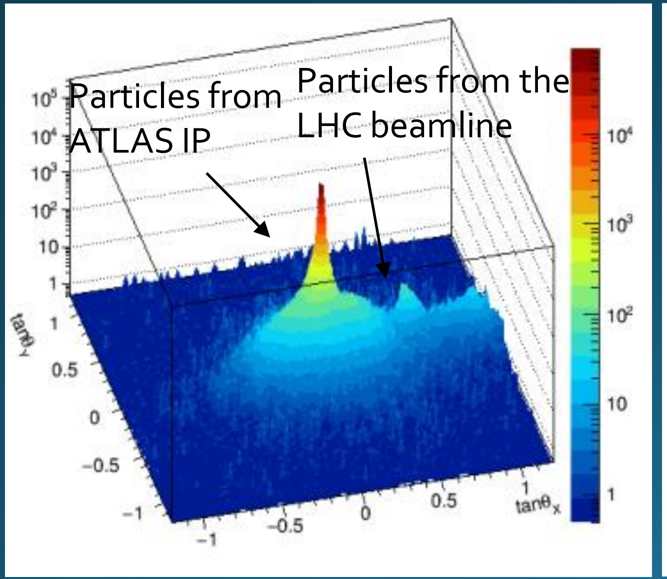
Particle fluence at the site

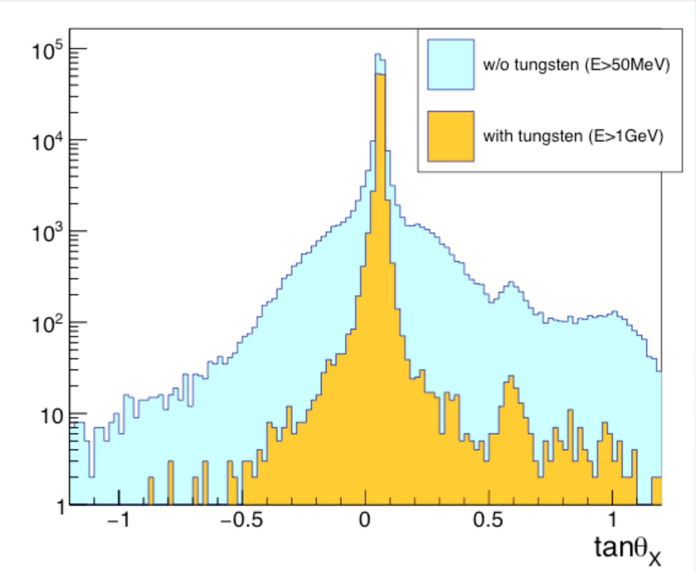
BDSim result for TI12, Lefebvre ICHEP2020





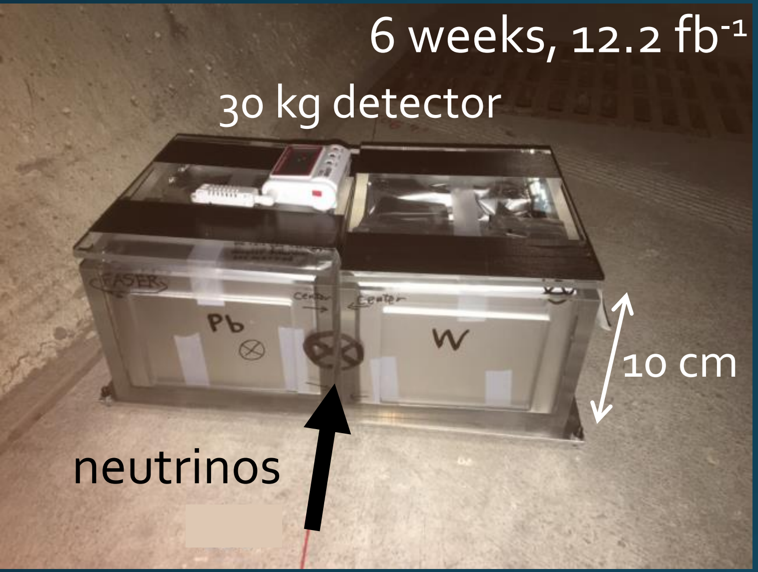
- On site measurement in 2018

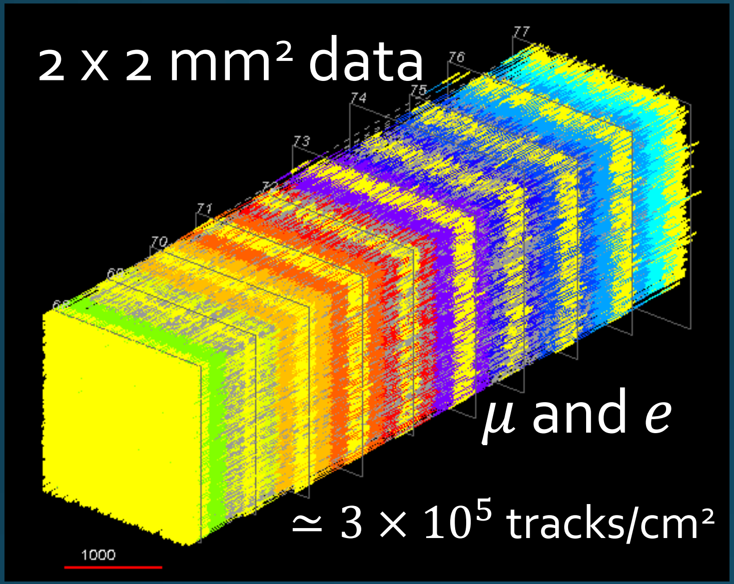


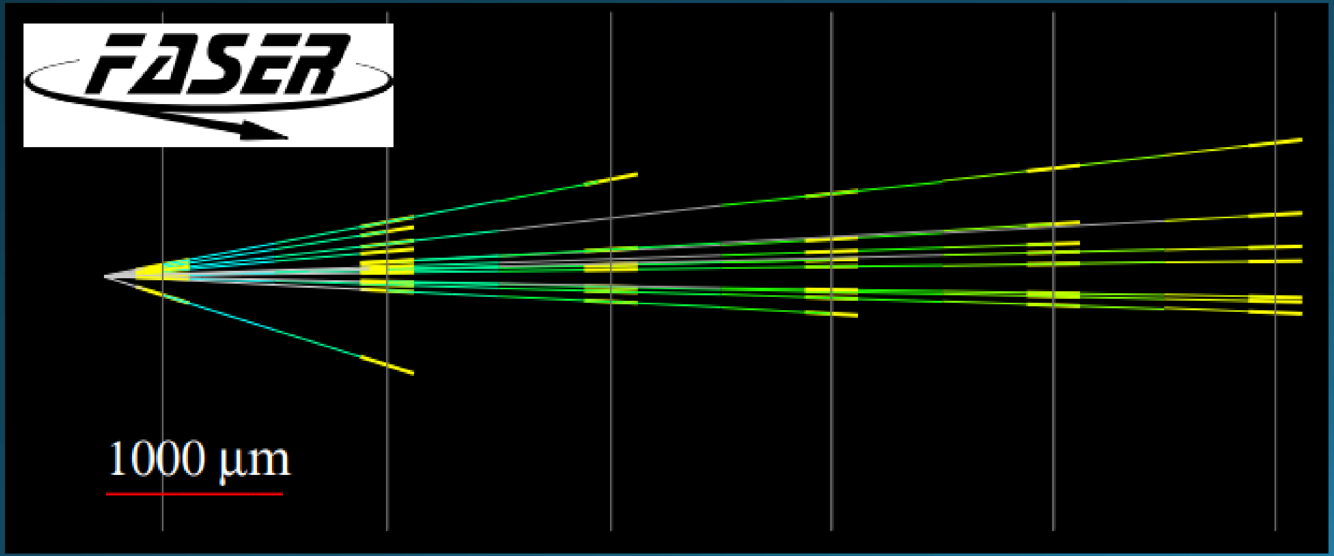


	Flux in main peak [fb/cm²]
TI18 pilot	$1.7 \pm 0.1 \times 10^4$
TI12 data	$1.9 \pm 0.2 \times 10^4$
FLUKA MC	2.5×10^4

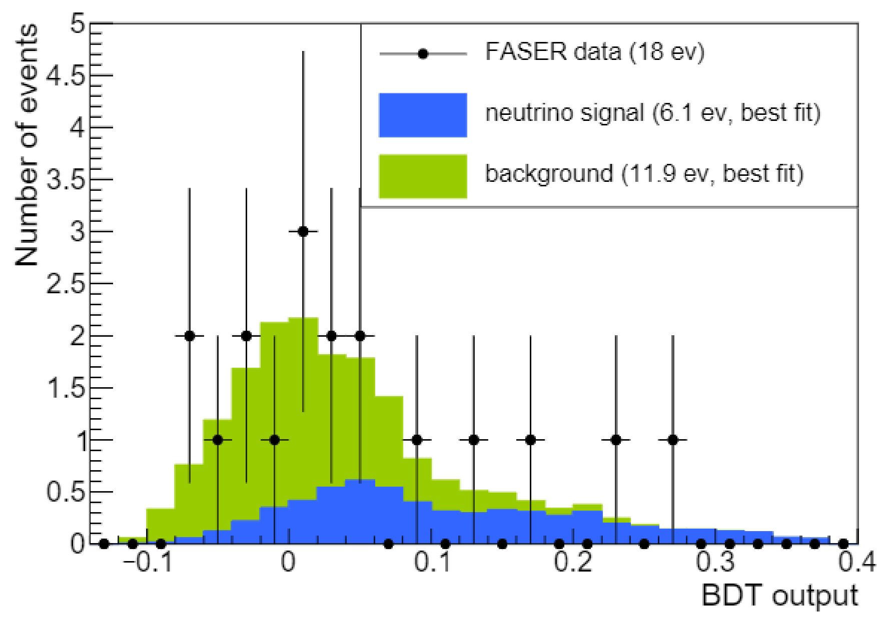
FASERν pilot run in 2018





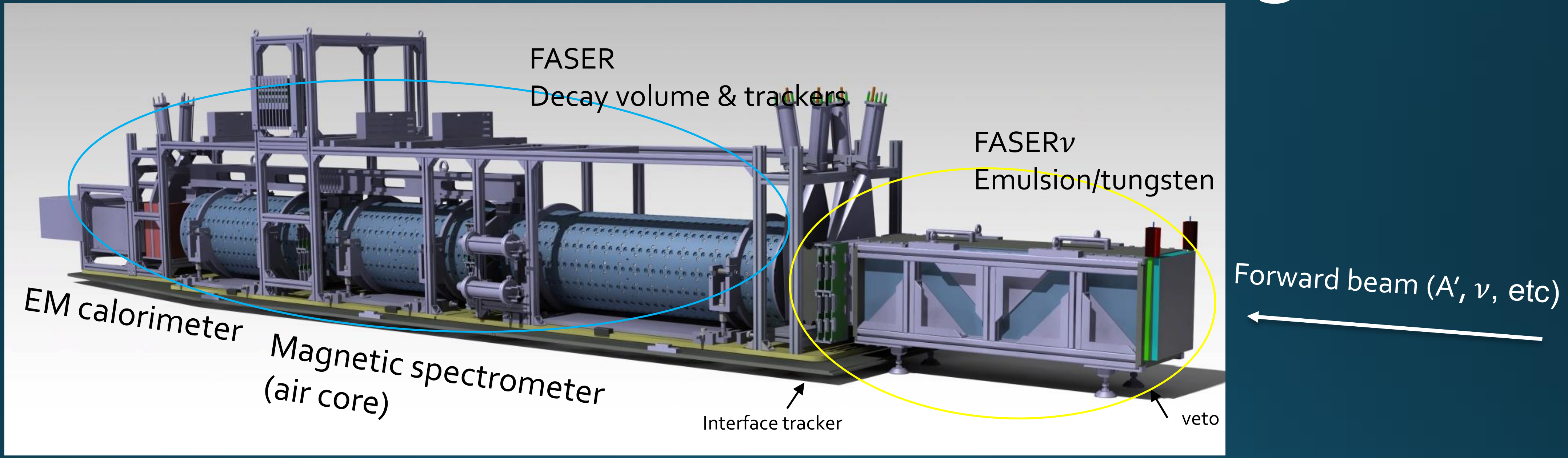


- Analyzed target mass of 11 kg and 12.2 fb^{-1}
- Pilot neutrino detector doesn't have lepton ID
- Expected signal = $3.3^{+1.7}_{-0.95}$ events, BG = 11.0 events
- In BDT analysis, an excess of neutrino signal is observed. Statistical significance = 2.7 sigma from null hypothesis

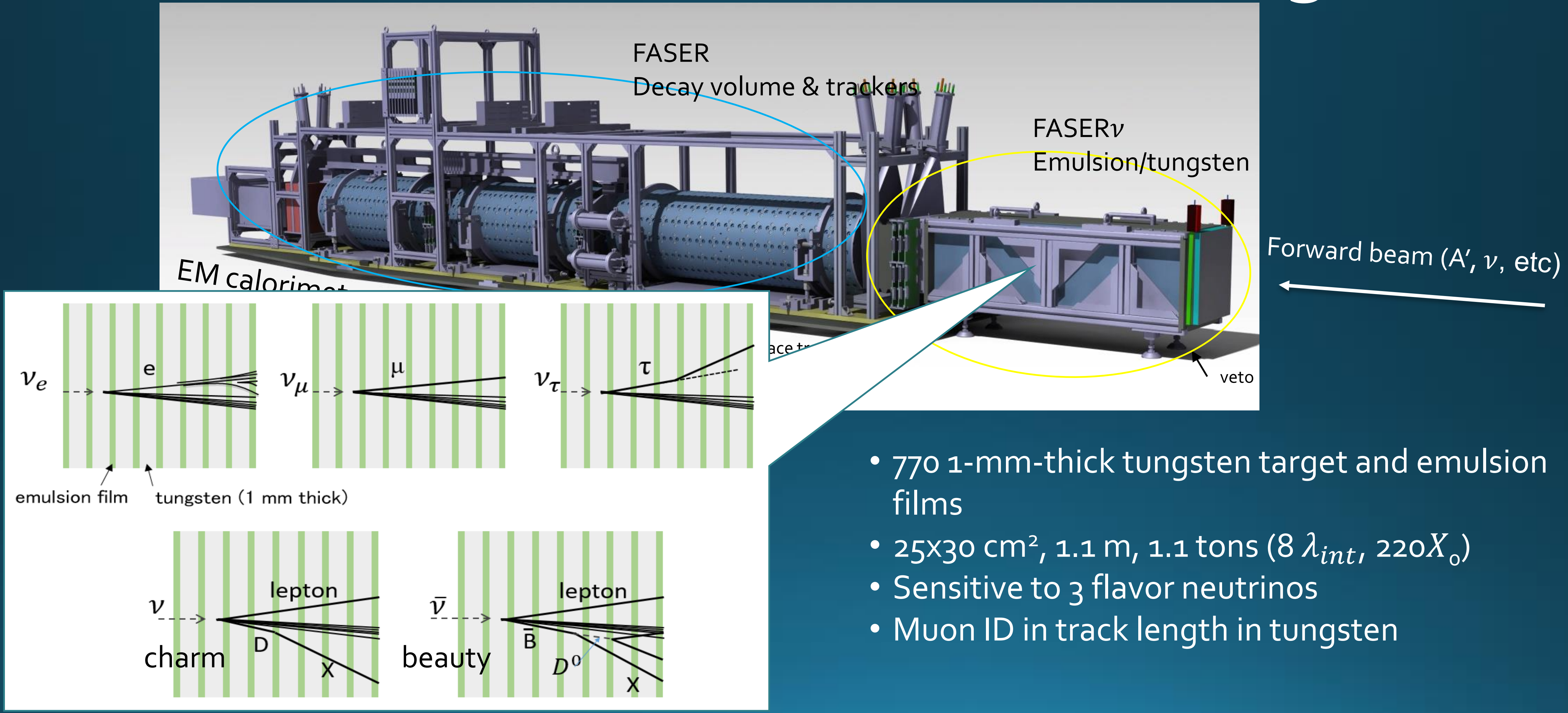


"First neutrino interaction candidates at the LHC, arXiv:2105.06197"

FASER/FASERν detector in Run3

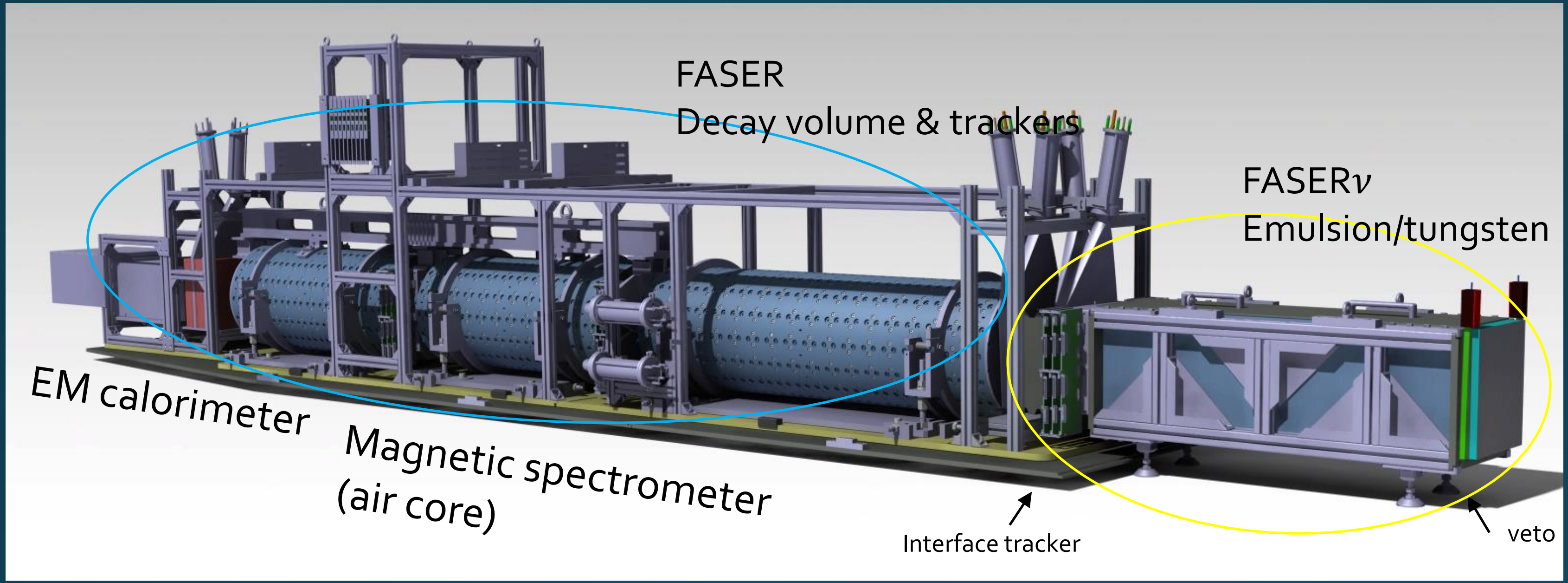


FASER/FASERν detector in Run3

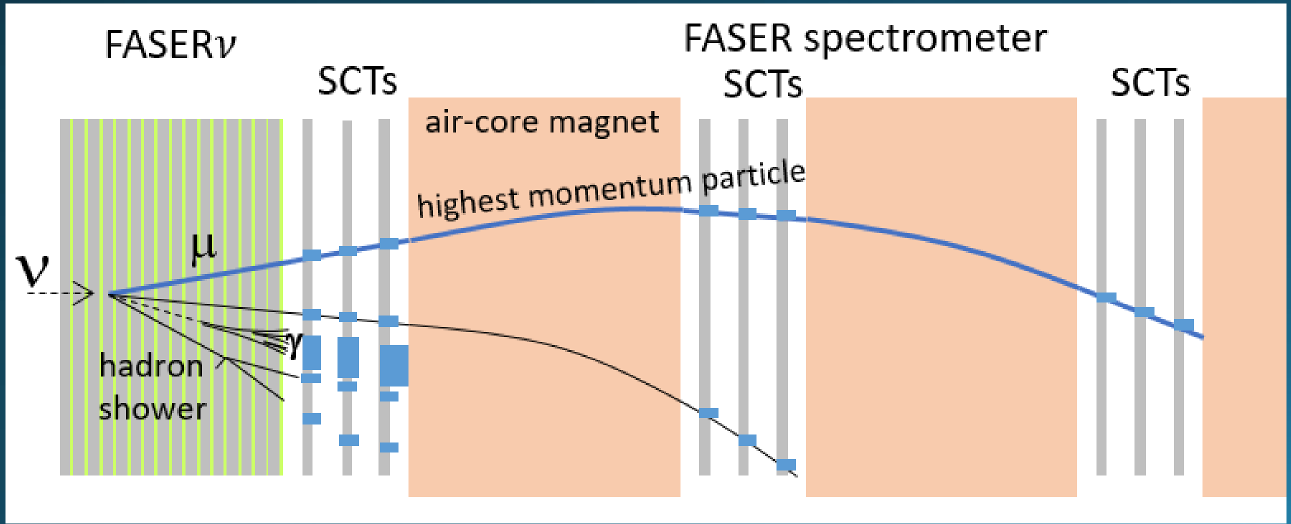


- 770 1-mm-thick tungsten target and emulsion films
- 25x30 cm², 1.1 m, 1.1 tons (8 λ_{int}, 220X_0)
- Sensitive to 3 flavor neutrinos
- Muon ID in track length in tungsten

FASER/FASERν detector in Run3



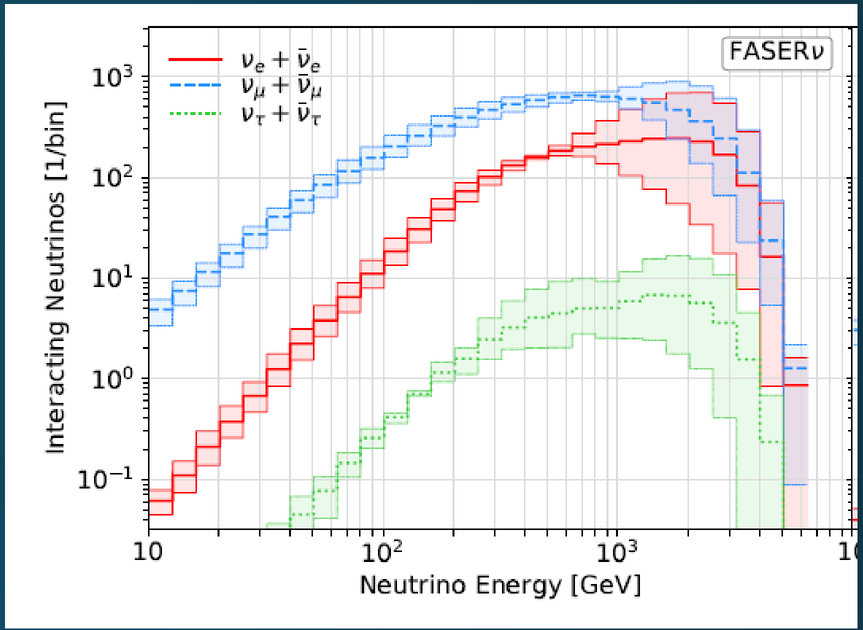
Forward beam (A′, ν, etc)



- Hybrid structure to have muon charge ID
- Distinguish ν_μ and $\bar{\nu}_\mu$ → Wider physics cases
- Improve energy resolution

Neutrino event rate (2021-2024)

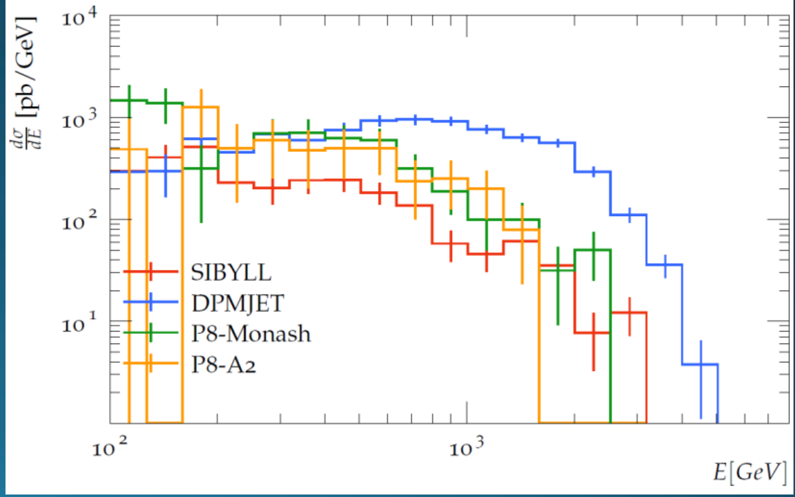
- **Small detector, but a lot of interactions ($\sim 10^4$ CC) are expected during Run3**
- Neutrino fluxes are being cross-checked among different simulations
  - Differences due to hadron generators and beamline infrastructure reproduction were identified. Currently, differences at hadron generators level is dominant



Expected number of CC interactions in FASERν in Run3 (14 TeV LHC, 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}	$31.5^{+17.3}_{-10.3}$

ν_e from charm decays (SYBYLL, DPMJET, Pythia8)



Large variation between different hadron production models (at p-p collision)

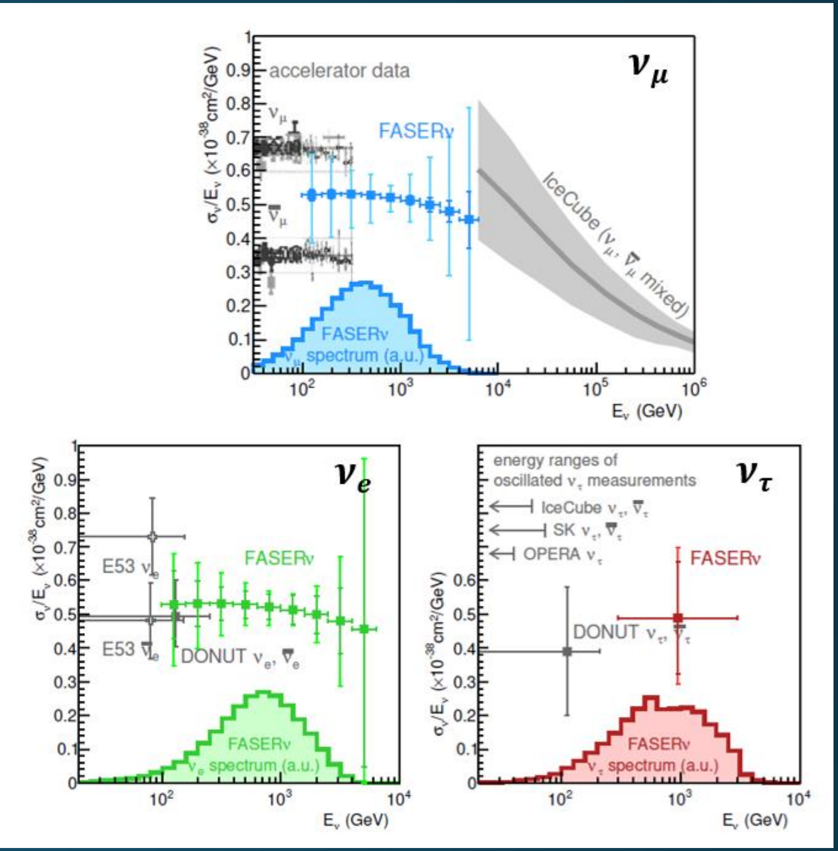
- Work in progress for quantifying and reducing these uncertainties
  - Creating a dedicated forward physics tune with Pythia8, using forward data (LHCf, FASER's muon measurements, etc.)

Physics potential:

High-energy neutrino interactions

- Primary goal: Cross section measurements of three flavors at the unexplored TeV energies
- NC measurements
  - Could constrain neutrino non-standard interactions (NSI).
- Neutrino CC interaction with charm production ($\nu s \rightarrow lc$)
  - Study the strange quark content.
  - Probe inconsistency between the predictions and the LHC data [Eur. Phys. J. C77 (2017) 367].
  - LU test
- Search for neutrino CC interaction with beauty production

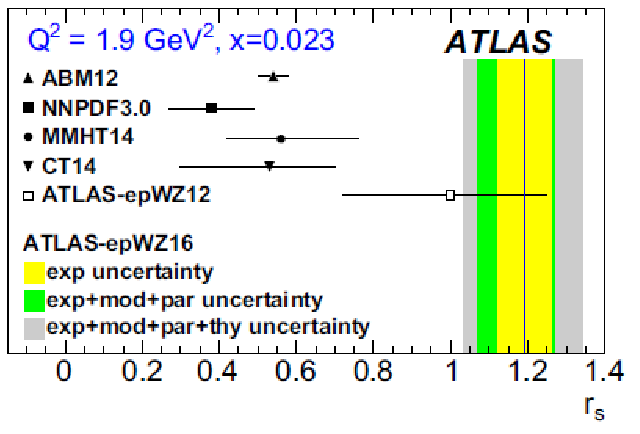
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

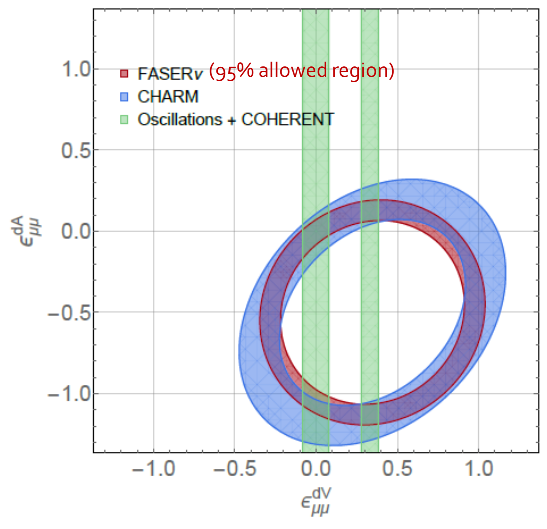


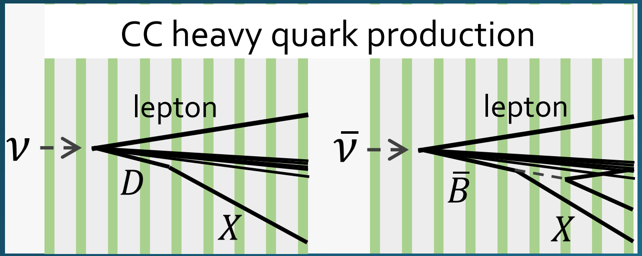
A. Ismail, R.M. Abraham, F. Kling, Phys. Rev. D 103, 056014 (2021), arXiv:2012.10500

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

Eur. Phys. J. C77 (2017) 367



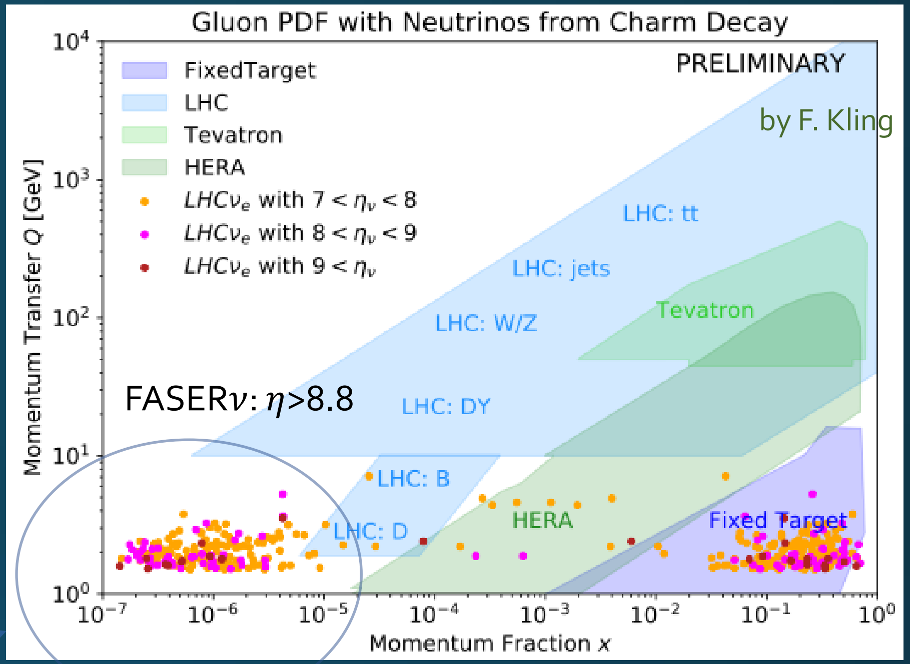




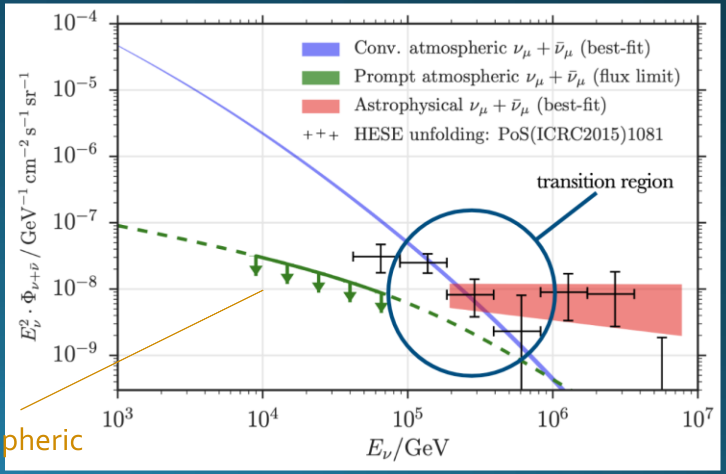
Physics potential:

Forward particle production

- Neutrinos are from the decay of hadrons, mainly pions, kaons, and charm particles. But, forward particle production is poorly constrained by other LHC experiments.
- FASERν provides 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, probe intrinsic charm.
- Relevant for neutrino telescopes (such as IceCube).
  - To make measurements of astrophysical neutrinos, a precise knowledge of prompt neutrinos is important
  - 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode → a direct measurement of PeV atmospheric (prompt) neutrino production. FASERν would provide important basic data for current and future high-energy neutrino telescopes.

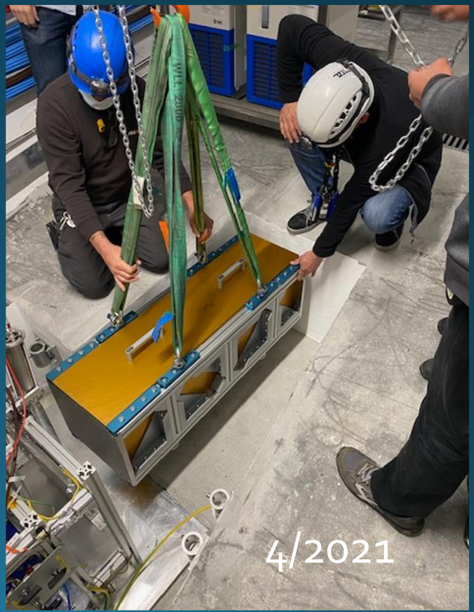


IceCube Collaboration, Astrophys. J. 833 (2016)



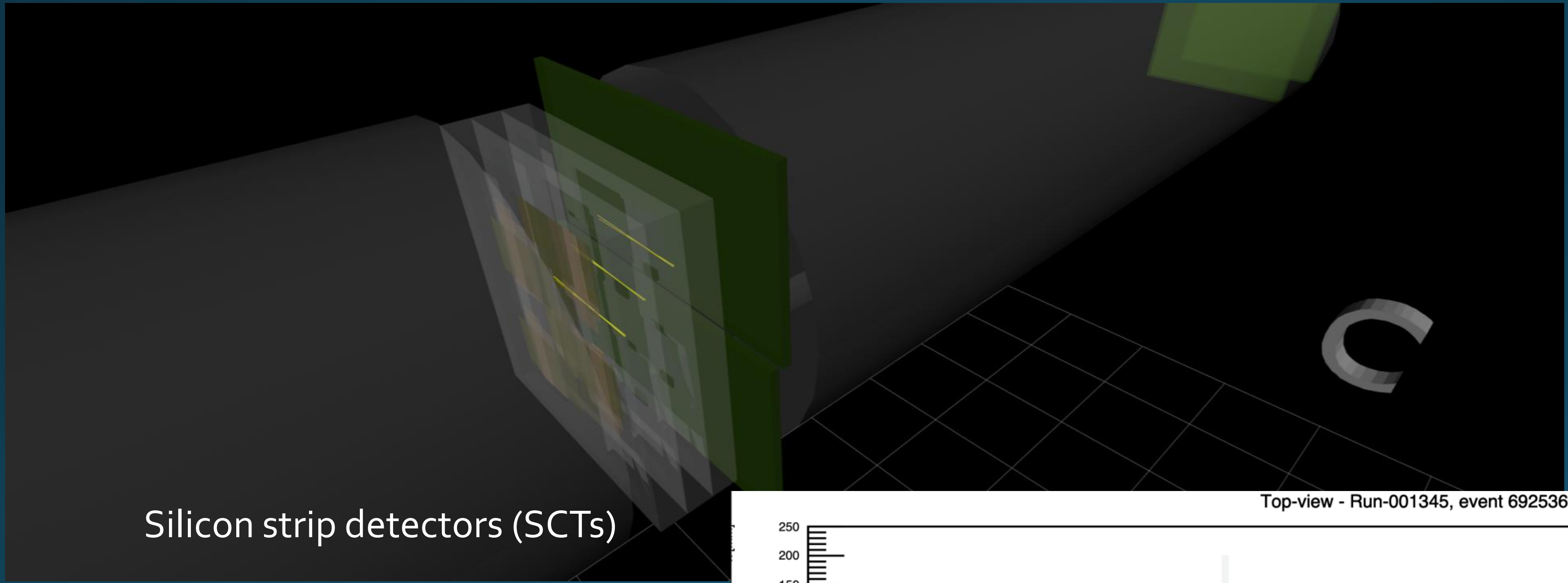
prompt atmospheric neutrinos

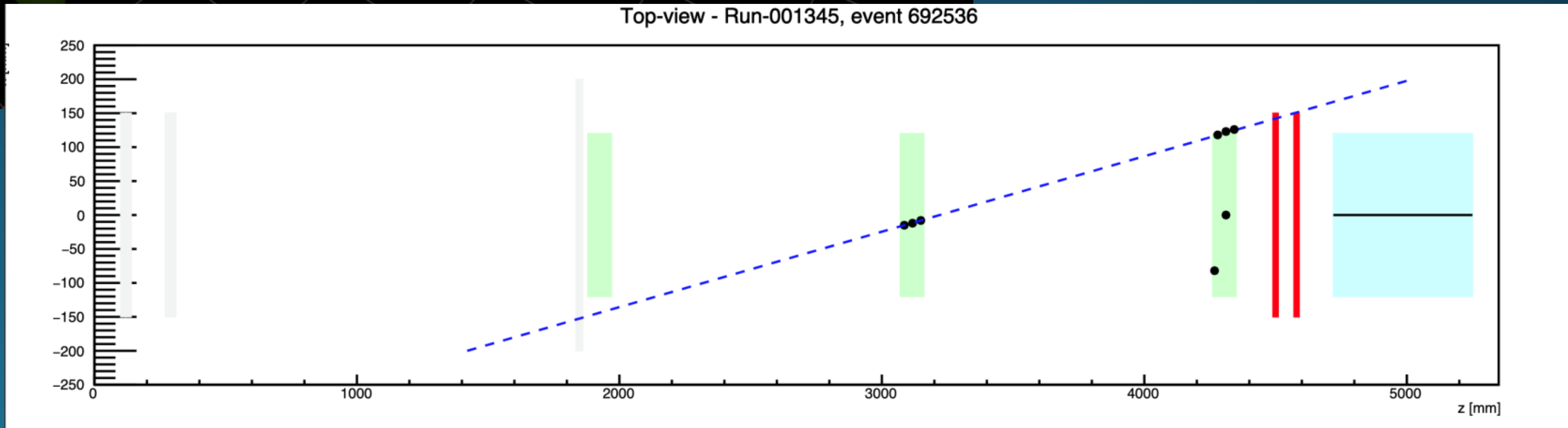
Evolution of TI12 tunnel for FASER installation



Commissioning of FASER trackers

Cosmic-ray tracks at the experimental site (TI12 tunnel).
Rate of such tracks is 1 every 2 minutes.





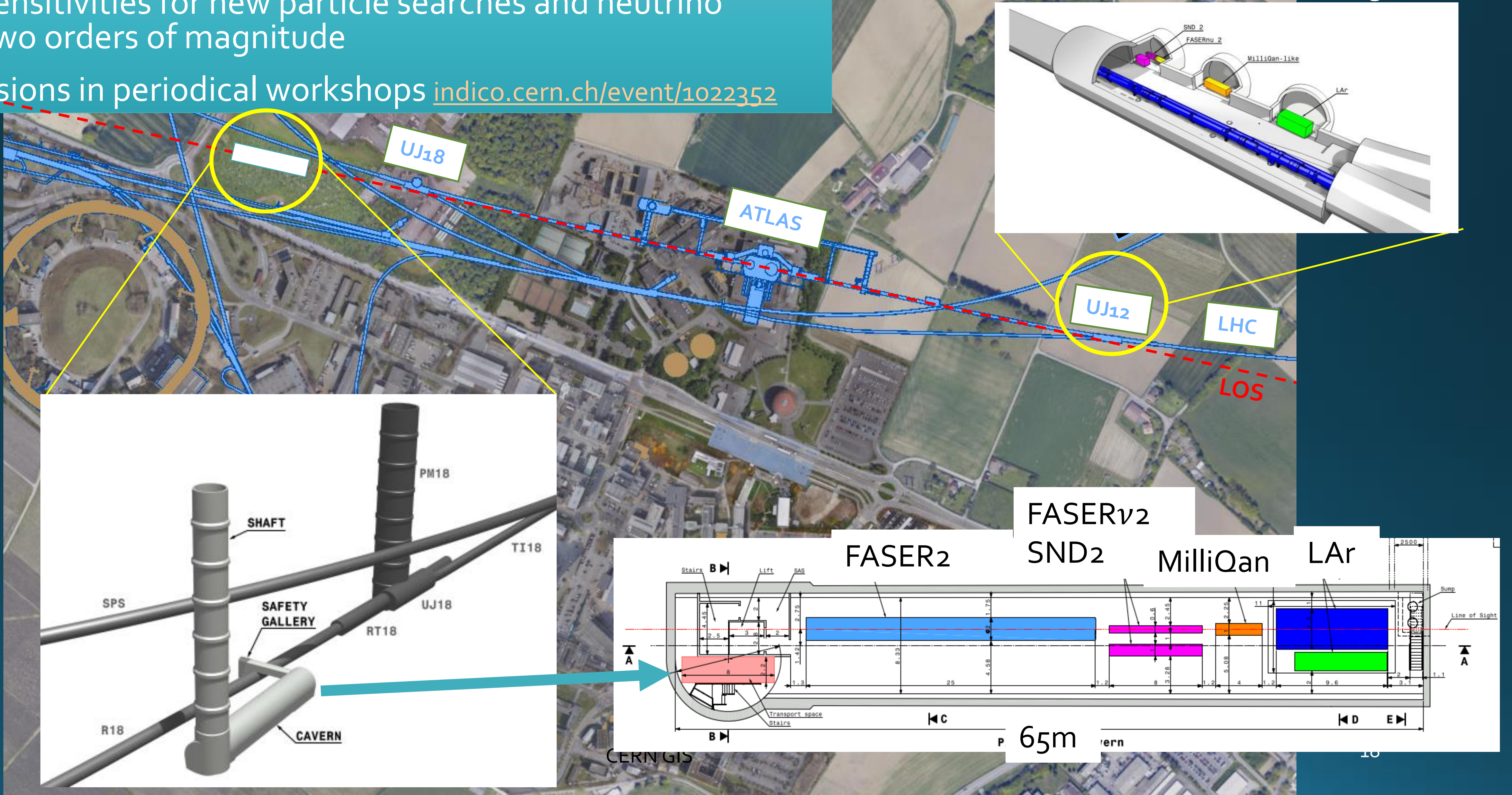
Forward Physics Facility at the HL-LHC

HL-LHC provides x20 proton collisions

Extending sensitivities for new particle searches and neutrino physics by two orders of magnitude

Wide discussions in periodical workshops indico.cern.ch/event/1022352

Option 1:
Extend existing tunnel



Option 2:
New shaft
and hall

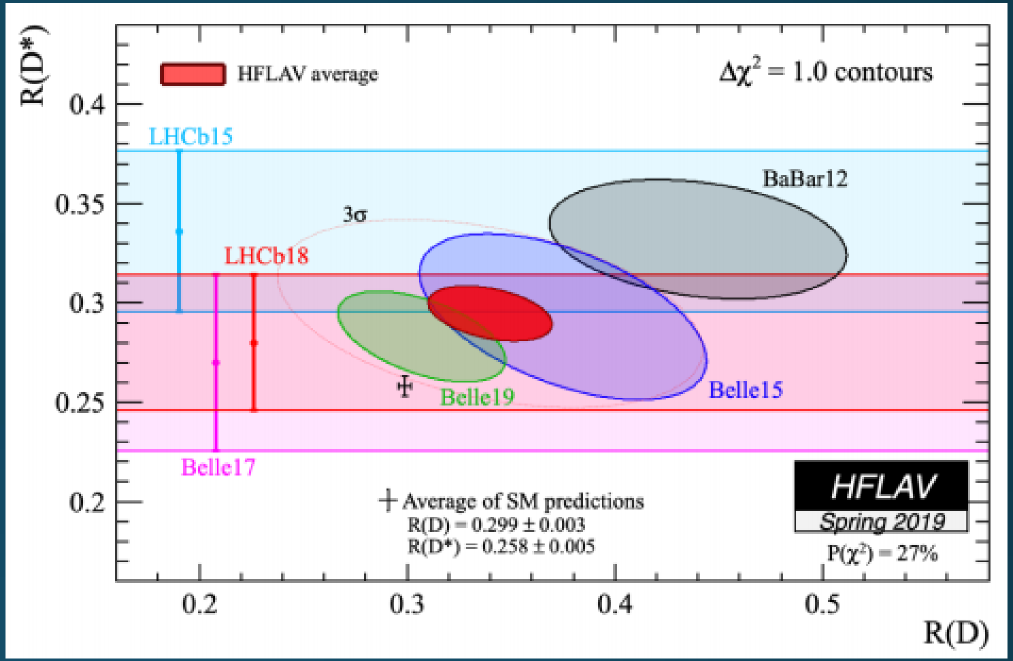
Summary

- New domain of research is opening at the far forward region of the LHC
- FASERν is going to study “Collider neutrinos” for the first time at the unexplored energy ranges, approved by CERN in Dec 2019
- First neutrino candidates from the LHC in 2018 run
- FASERν will take data in Run 3 (2022 – 2024), rich physics outcome.
- Discussion on the next stage experiments at the HL-LHC is ongoing

Backup

"Flavor anomaly"

$$R(D) = \frac{\mathcal{B}(B \to \tau\nu_\tau D)}{\mathcal{B}(B \to \mu\nu_\mu D)}$$

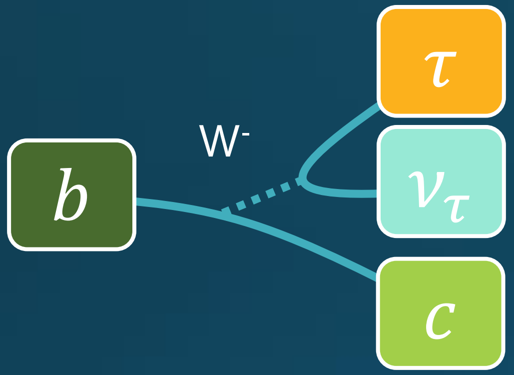


Possible contribution from new physics in heavy flavors!?

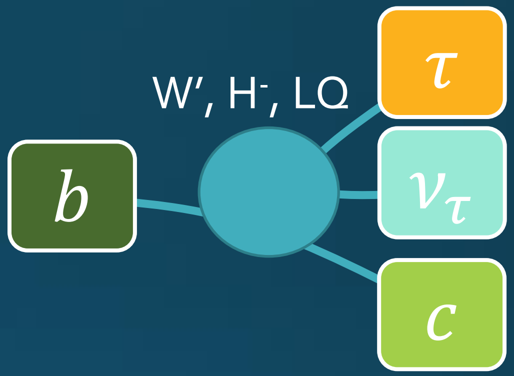
New physics effect?

B decays

SM



NP

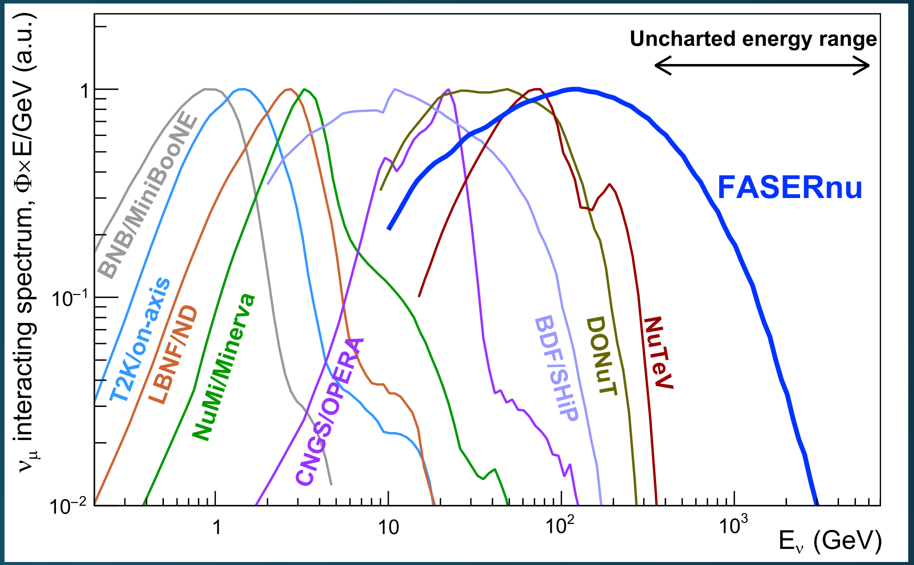


Neutrino CC beauty production

High energy frontier

Neutrino energy

Past	350 GeV	Tevatron (US)
Current	10 GeV	T2K (Japan)
	20 GeV	DUNE (US)
Future	150 GeV	SHiP (CERN)

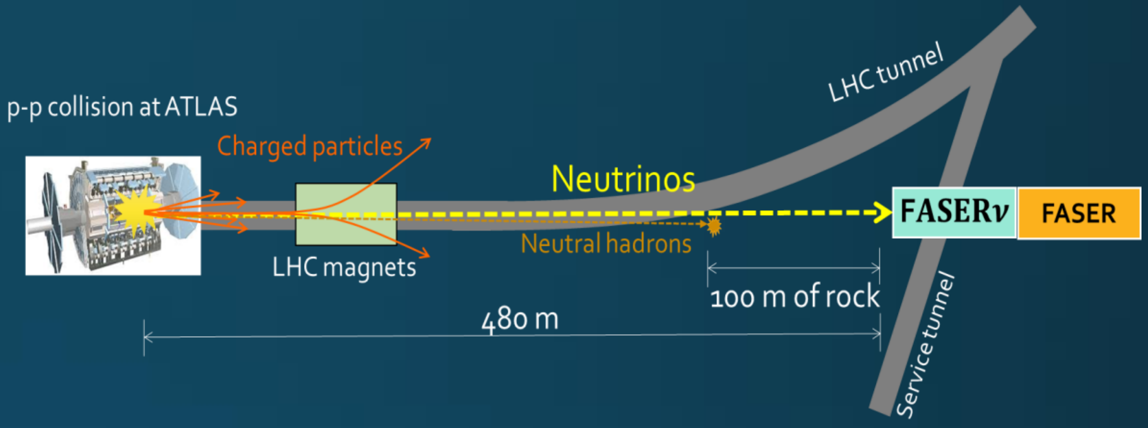


FASERν — Up to 6 TeV $(\nu_e, \nu_\mu, \nu_\tau)$

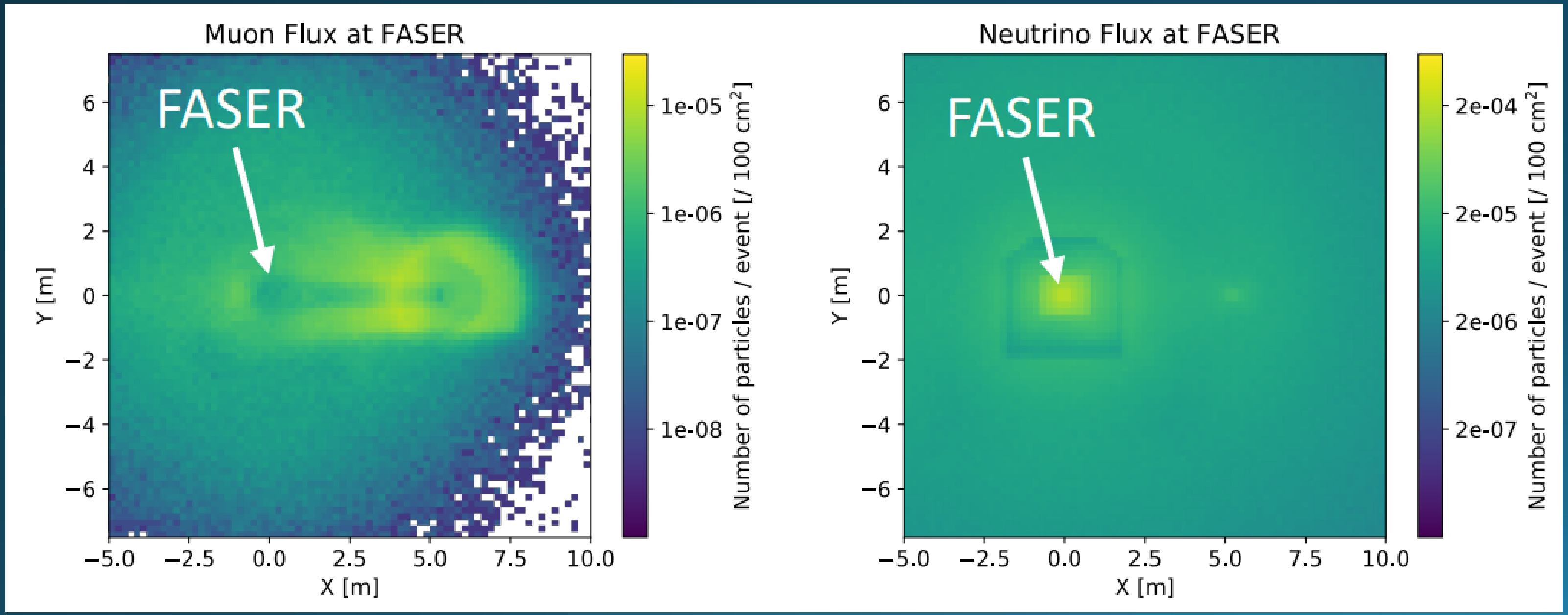
Unexplored energy range

Particle fluence at the site

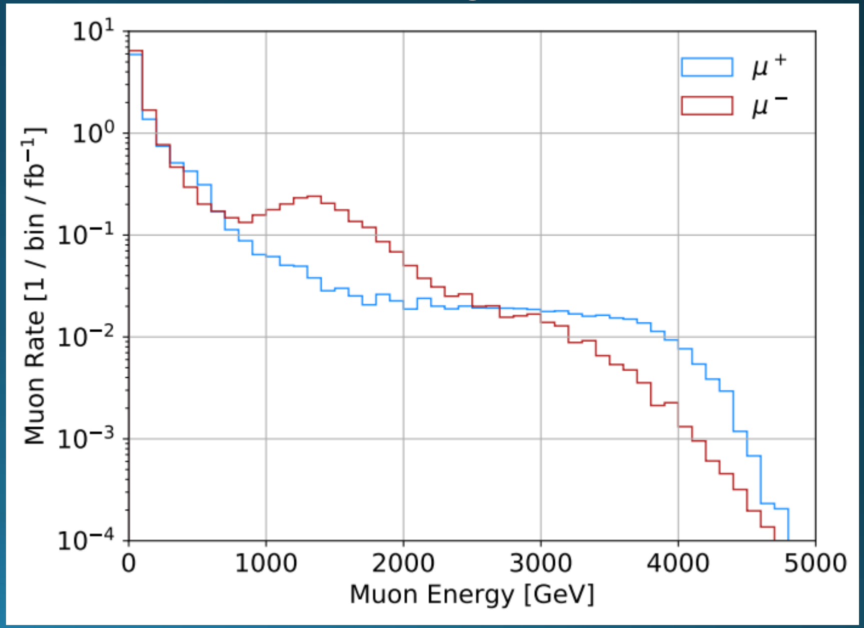
- Crucial for both neutrinos and LLP searches
- Simulation through the LHC infrastructures by FLUKA and BDSim
- Minimum muons, maximum neutrinos

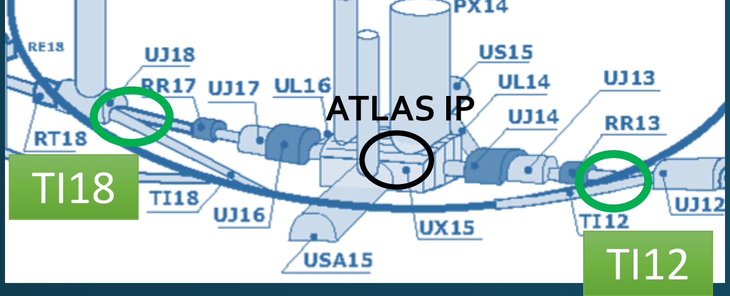


BDSim result for TI12, Lefebvre ICHEP2020



Muon energy (at 409m from IP, pilot run)
Simulated by CERN-STI group with FLUKA

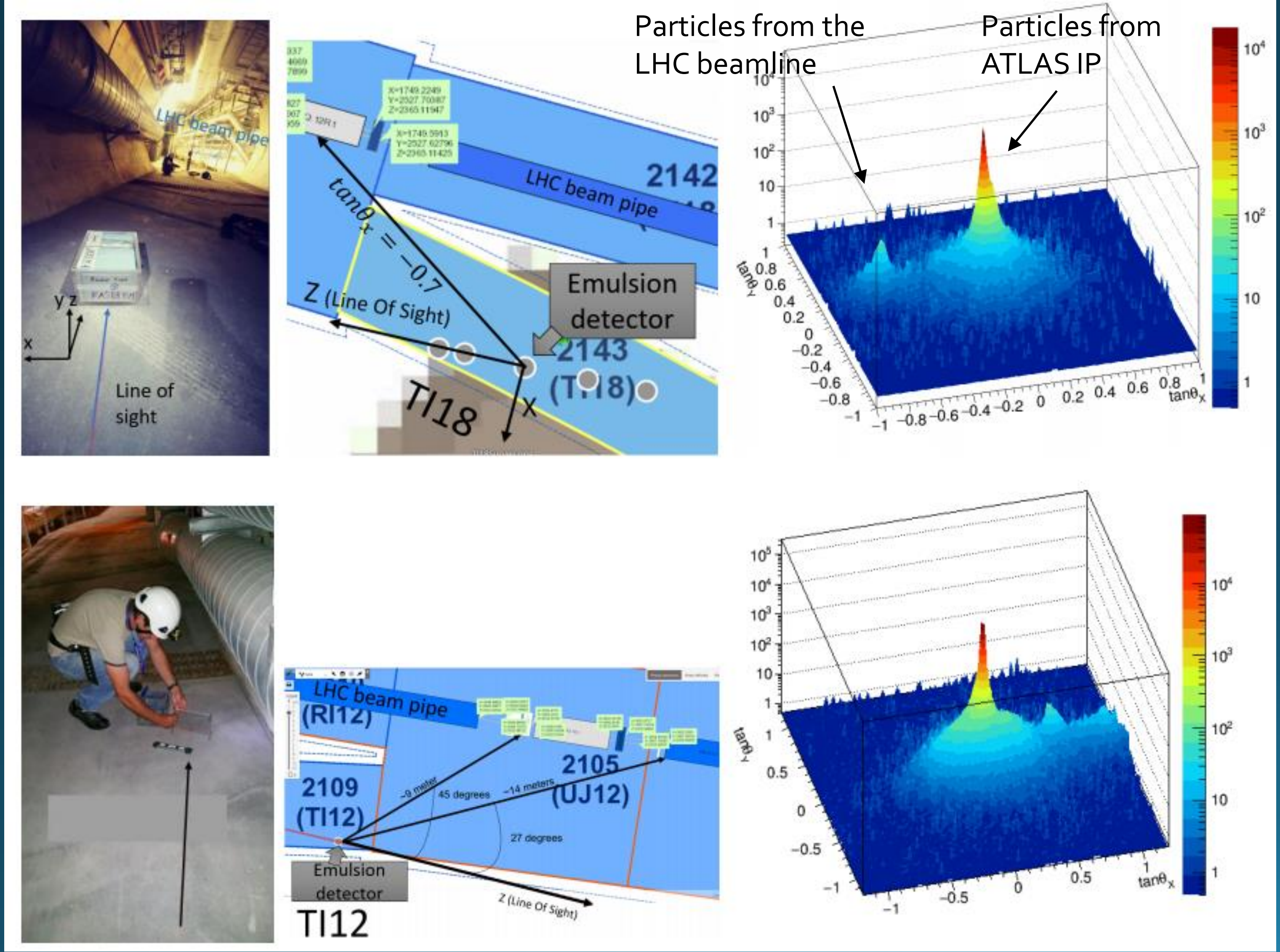




In situ measurements in 2018: Charged particle background

TI18

TI12

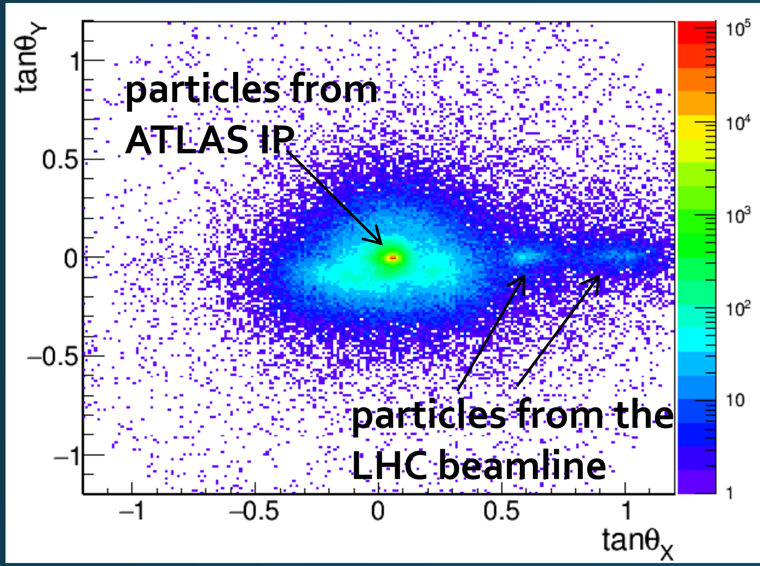


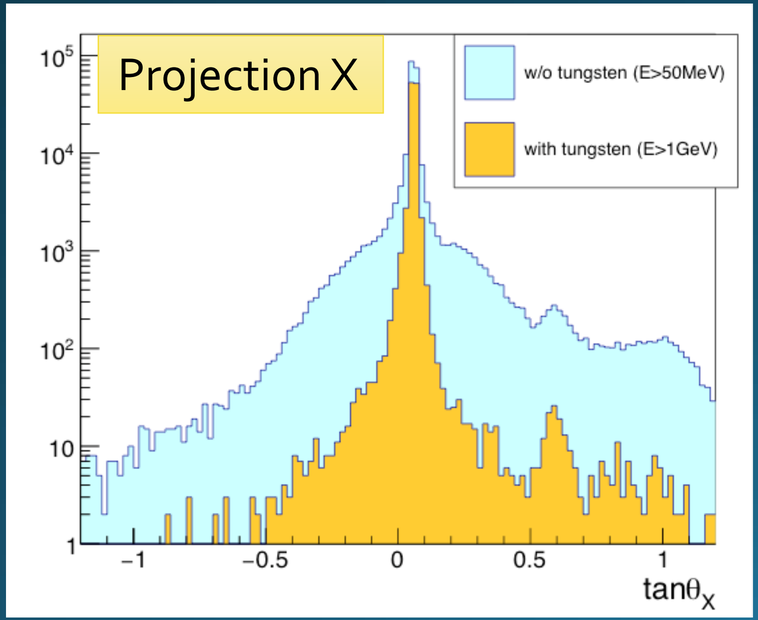
- Emulsion detectors were installed to investigate TI18 and TI12.
- **Low background was confirmed.**
- Few hadron tracks
- Consistent with the FLUKA prediction.

	Normalized flux (tracks/fb^{-1}/cm^2)
TI18	$(2.6 \pm 0.7) \times 10^4$
TI12	$(3.0 \pm 0.3) \times 10^4$

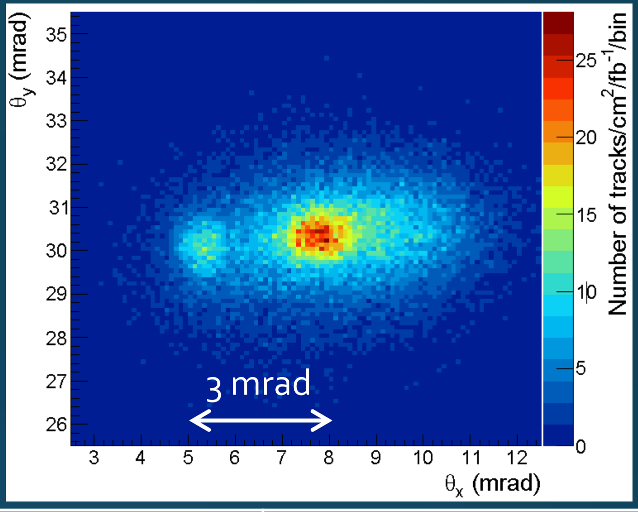
Emulsion detector can work at the actual environment!
(up to ~10^6/cm^2 $\simeq$ 30 fb^{-1} of data)

Angular distributions of beam backgrounds





Close up to the main peak

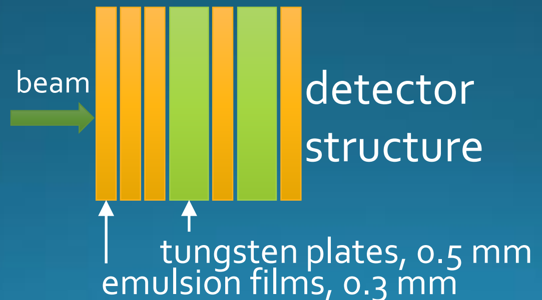


2 peak structure

$\sigma = 0.6\ mrad$

After 100 m of rock, it scatters only 0.6 mrad.
→ ~700 GeV

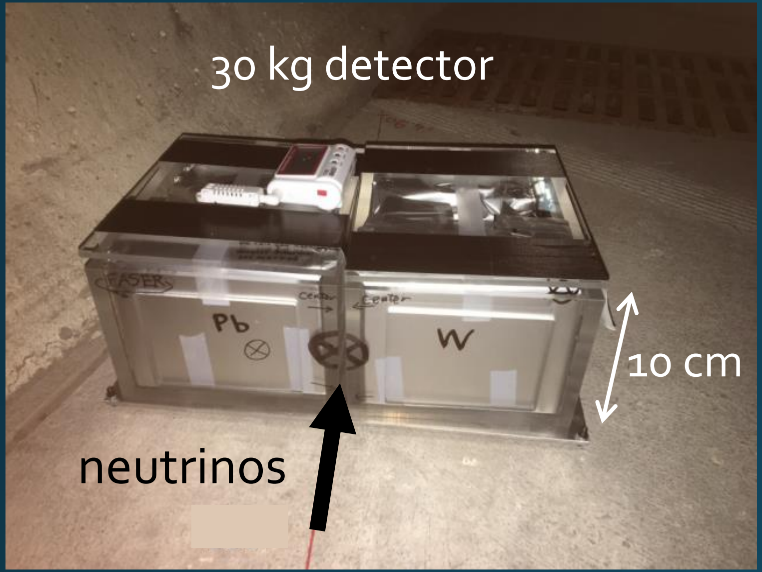
	Flux all [fb/cm²]	Flux in main peak [fb/cm²]
TI18 data	$2.6 \pm 0.7\ \times 10^4$	$1.2 \pm 0.4\ \times 10^4$
TI18 pilot		$1.7 \pm 0.1 \times 10^4$
TI12 data	$3.0 \pm 0.3\ \times 10^4$	$1.9 \pm 0.2\ \times 10^4$
FLUKA MC		$2.5\ \times 10^4$

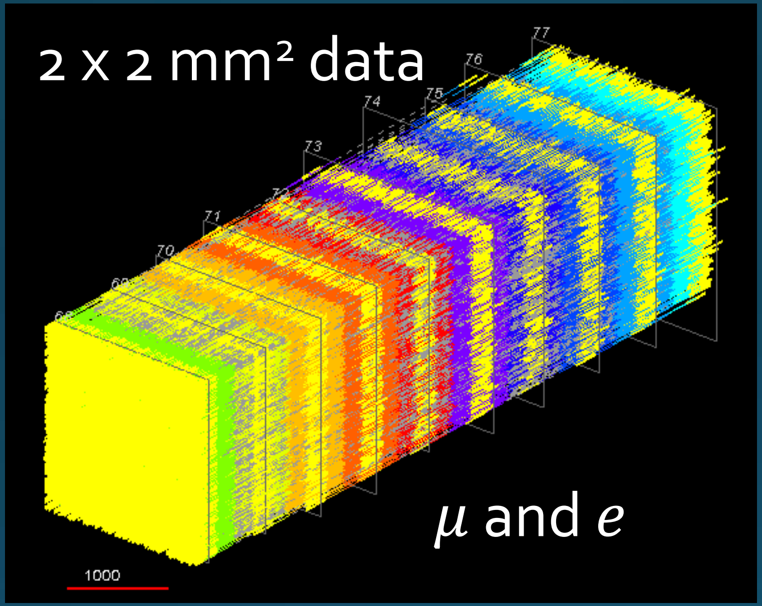


Data and the FLUKA (uncertainty 50%) prediction agrees within their uncertainties.

Pilot run in 2018

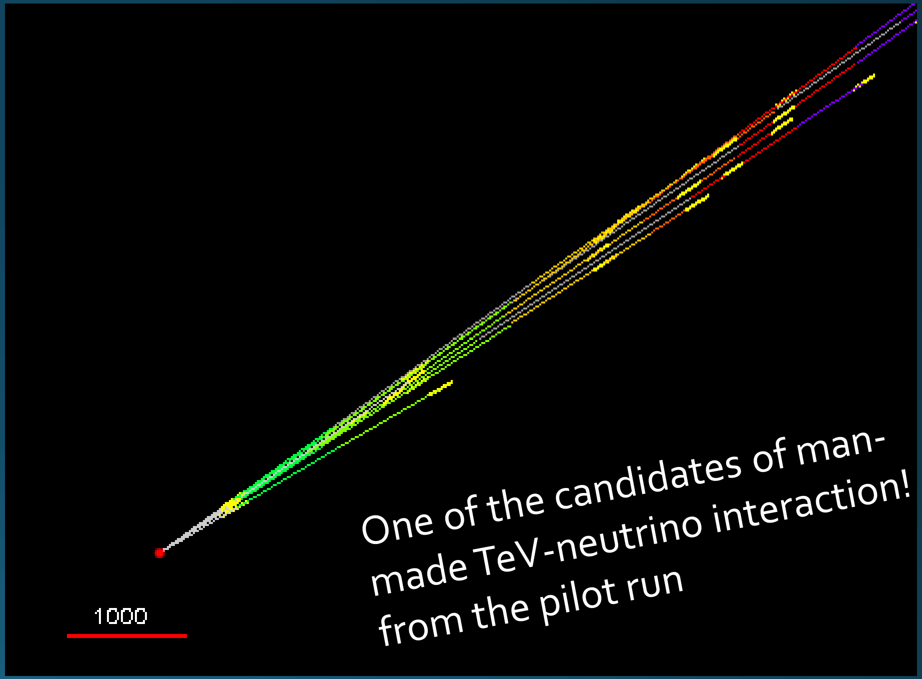
Aiming to demonstrate the feasibility of detection of collider neutrinos





6 weeks, 12.2 fb^{-1}

$\simeq 3 \times 10^5$ tracks/cm²



- A 30 kg emulsion based (lead, tungsten target) detector was installed on axis, 12.2 fb^{-1} of data was collected in Sep-Oct 2018 (6 weeks)

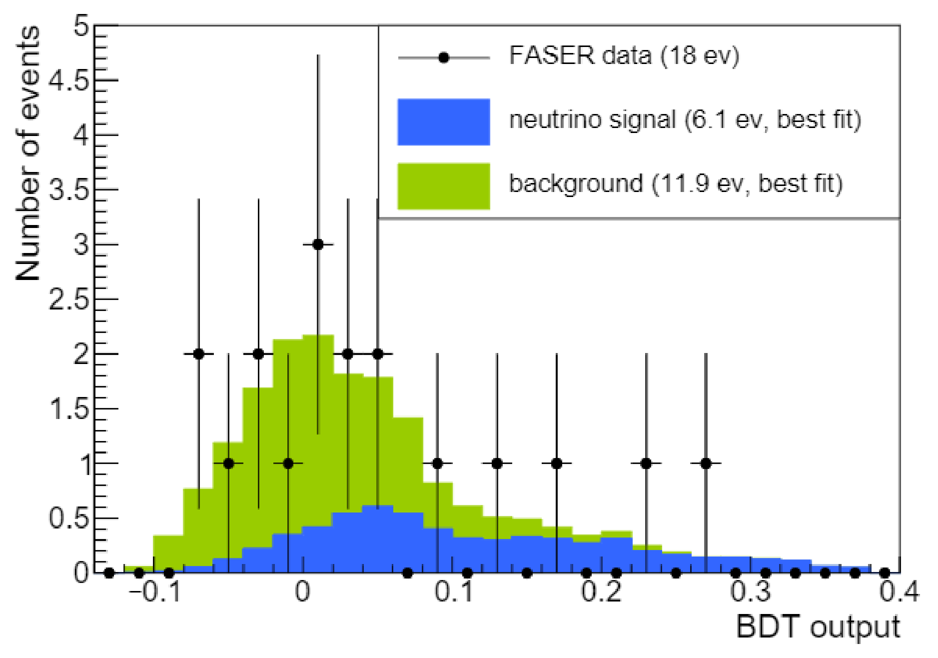
arXiv:2105.06197

Pilot run event statistics

- Analyzed target mass of 11 kg
- Pilot neutrino detector doesn't have lepton ID
  - → Separation from neutral hadron BG (produced by muons) is challenging → tighter cuts
- Expected signal = $3.3^{+1.7}_{-0.95}$ events, BG = 11.0 events
- 18 neutral vertices were selected
  - by applying # of charged particle ≥ 5, etc.
- In BDT analysis, an excess of neutrino signal is observed. Statistical significance = 2.7 sigma from null hypothesis
- This result demonstrates the detection of neutrinos from the LHC

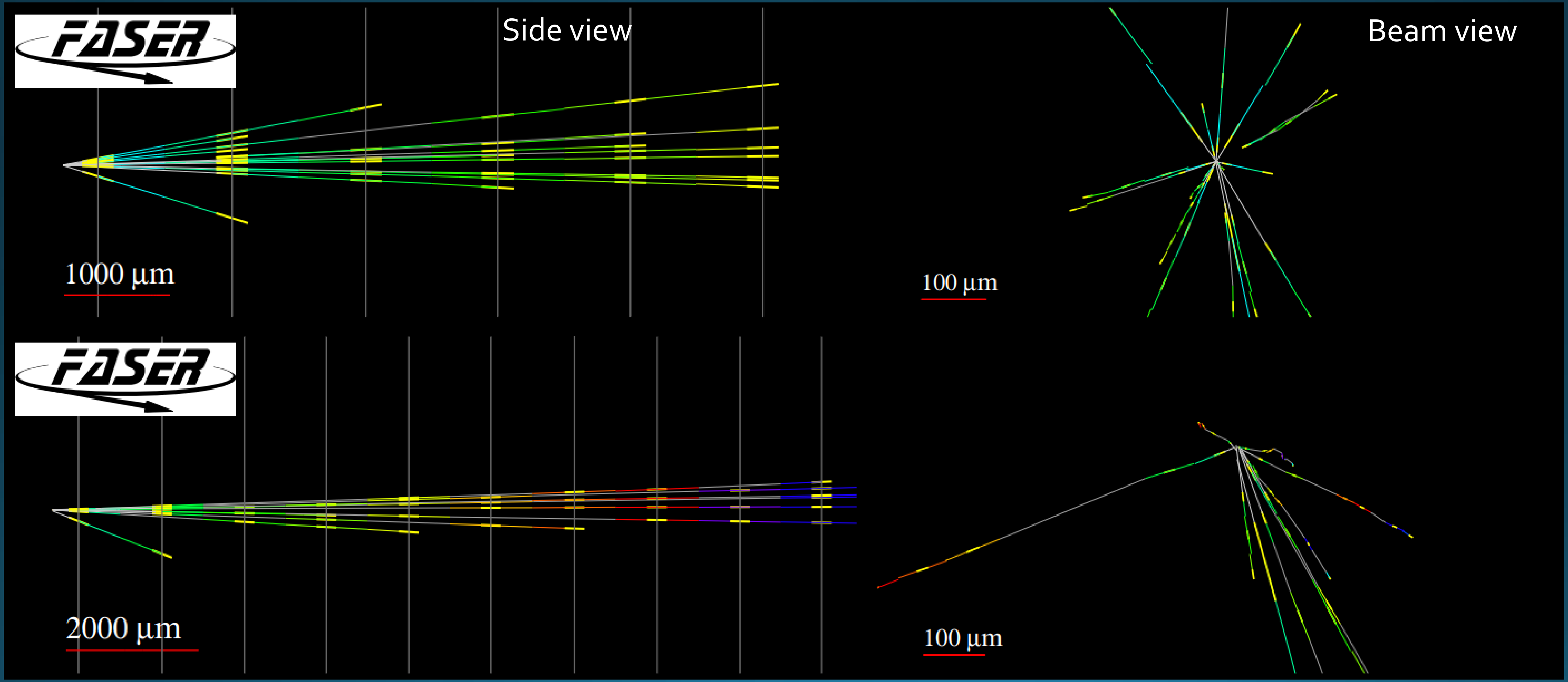
Vertex detection efficiency

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

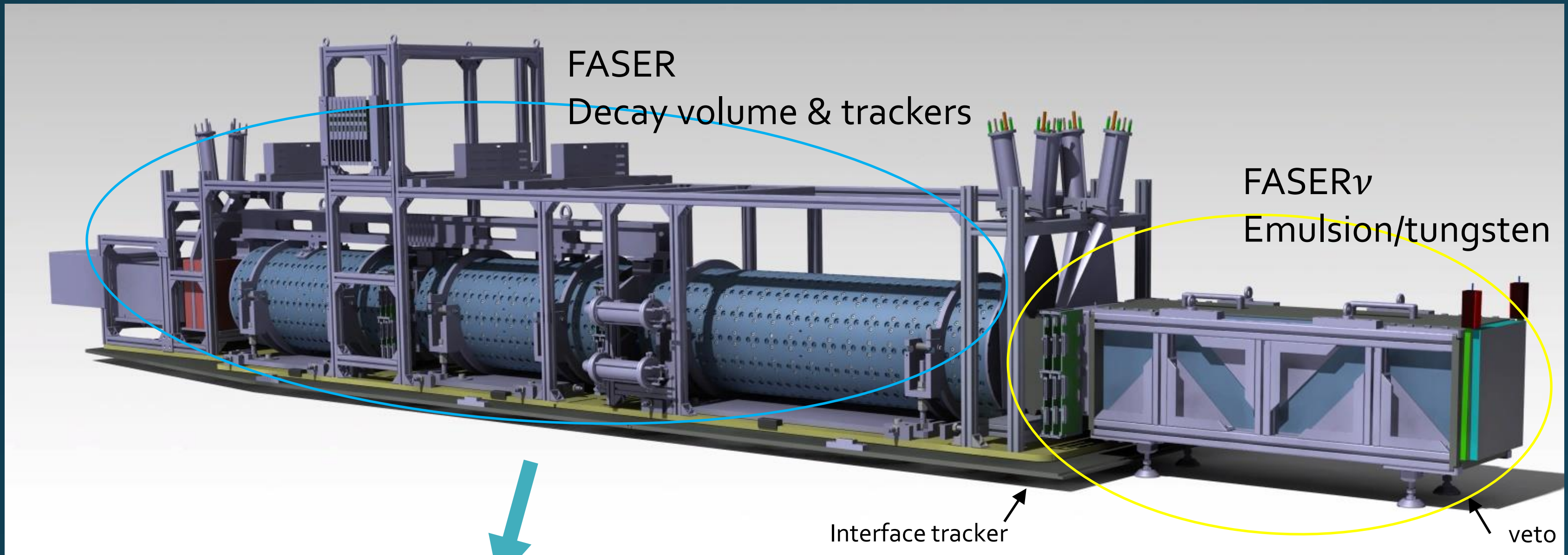


arXiv:2105.06197

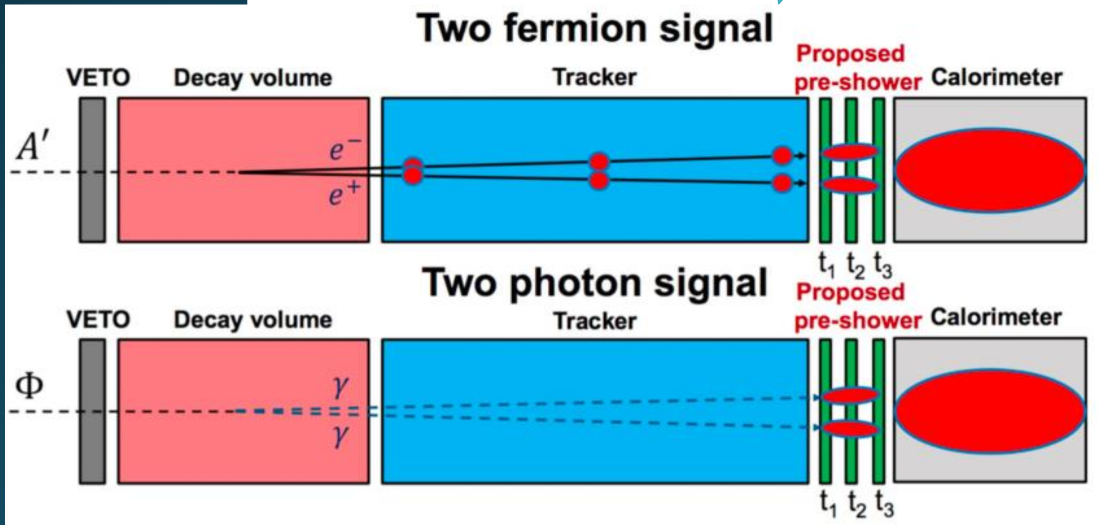
Neutrino interaction candidates

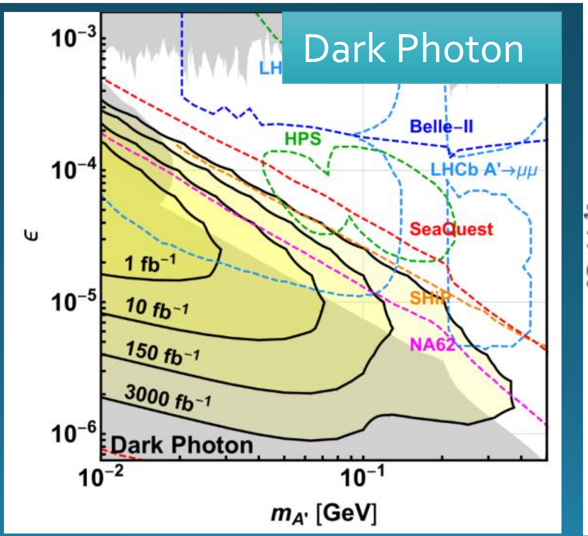


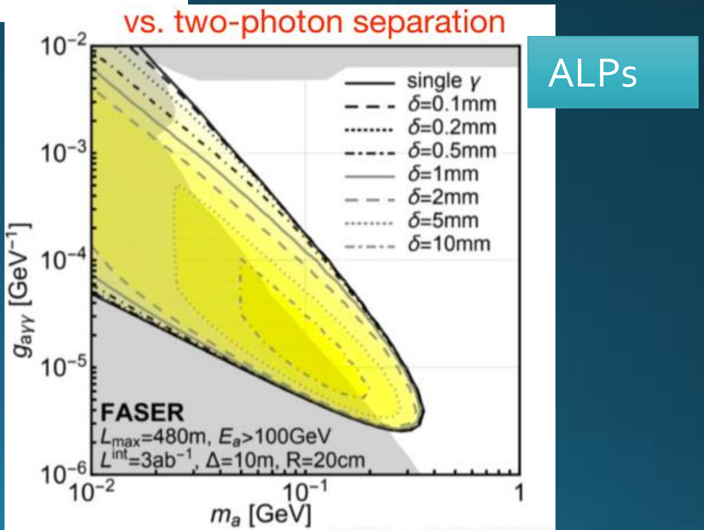
FASER/FASERν detector



Forward beam (A′, ν, etc)

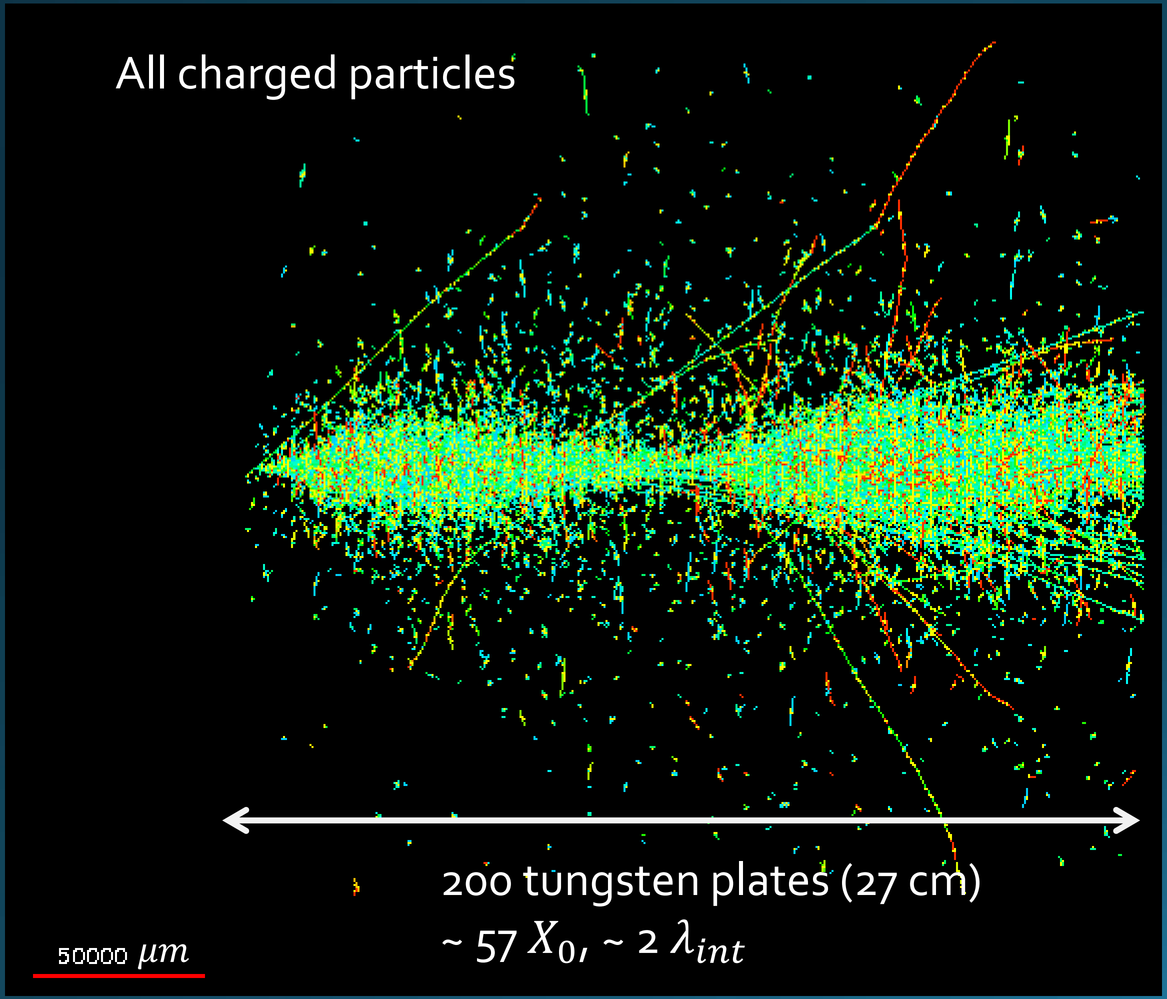


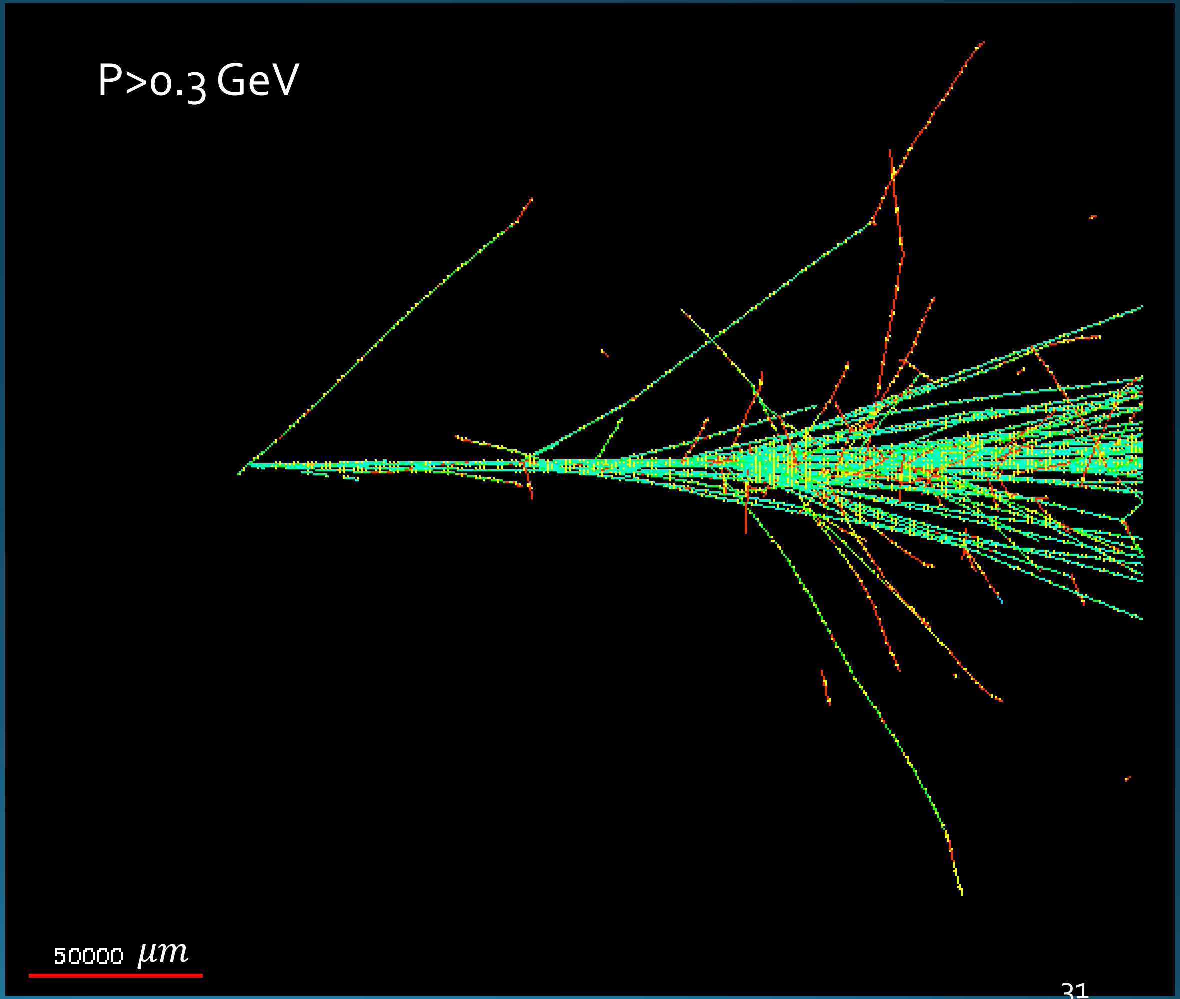




(arXiv.org 1806.02348)

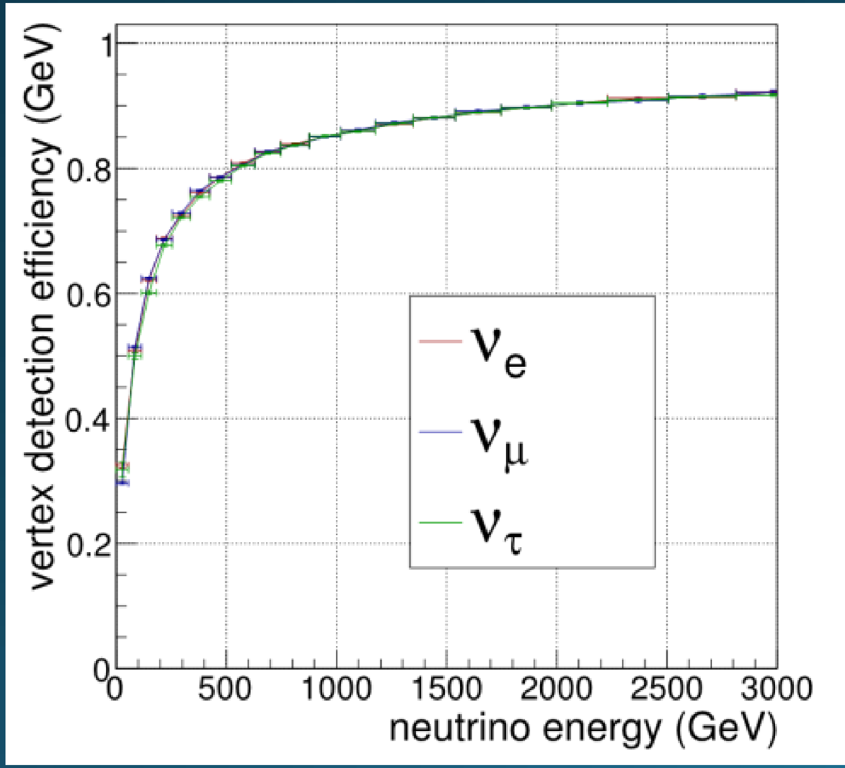
Simulated 1 TeV ν_μ CC interaction



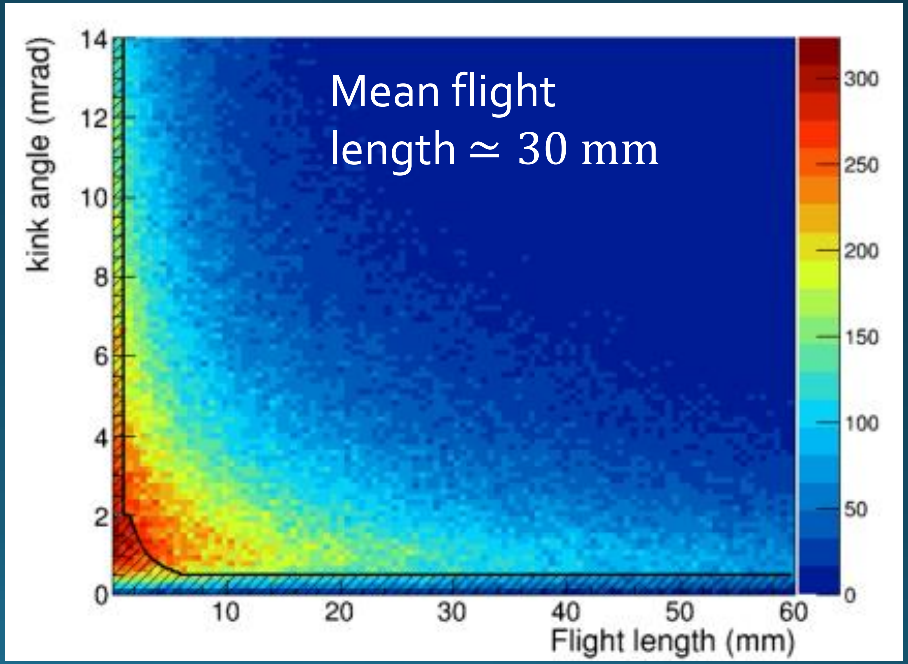


Detection efficiency

Vertex detection efficiency
(charged multiplicity>=5)



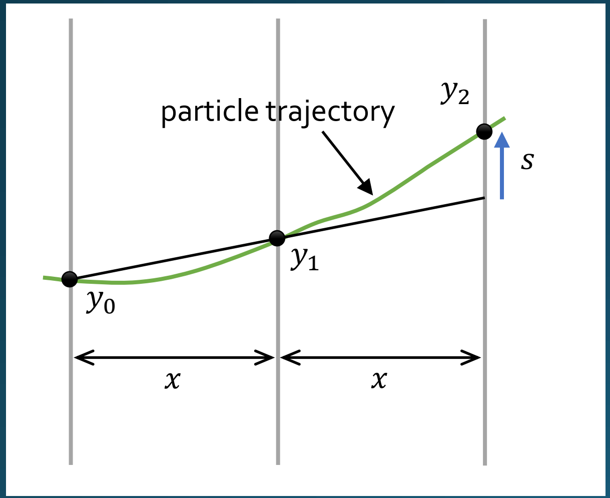
Tau decay detection efficiency
=75% ($\tau \rightarrow 1$ prong)



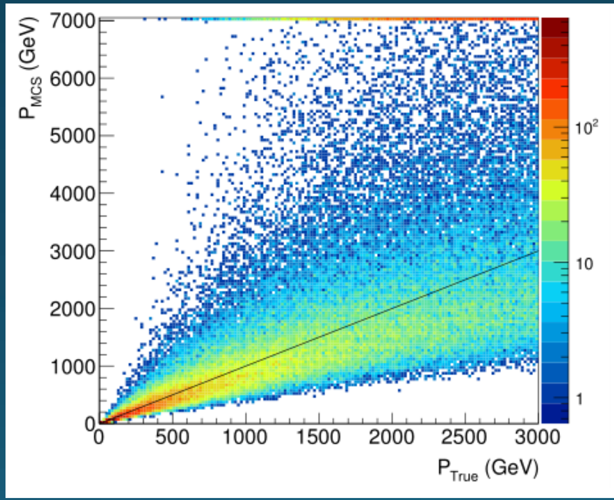
Particle momentum measurement

by multiple Coulomb scattering (MCS)

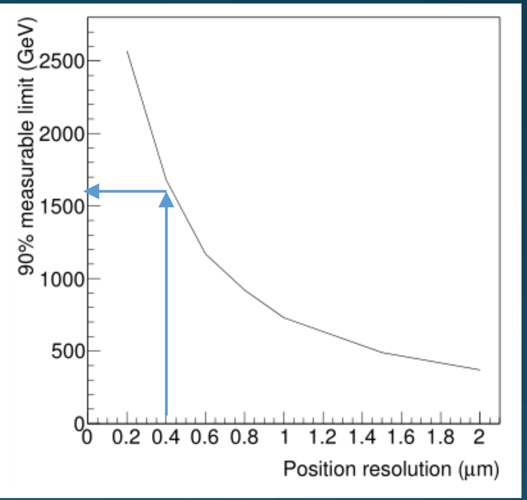
- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle momenta by MCS, even above 1 TeV.



$$(s^{\mathrm{RMS}})^2 = \left(\sqrt{\frac{2}{3}}\frac{13.6(\mathrm{MeV})}{\beta P}x\sqrt{\frac{x}{X_0}}\right)^2 + \left(\sqrt{6}\,\sigma_{\mathrm{pos}}\right)^2$$



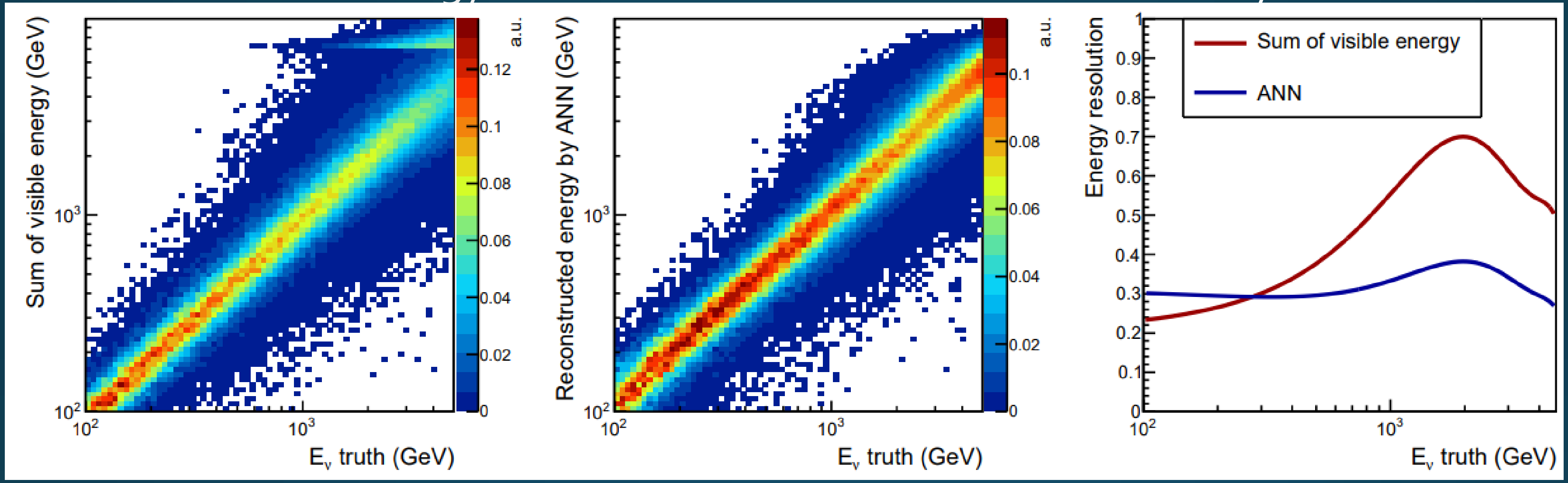
Performance with position resolution of 0.4 μm, in 100 tungsten plates (MC)



Measurable energy vs position resolution

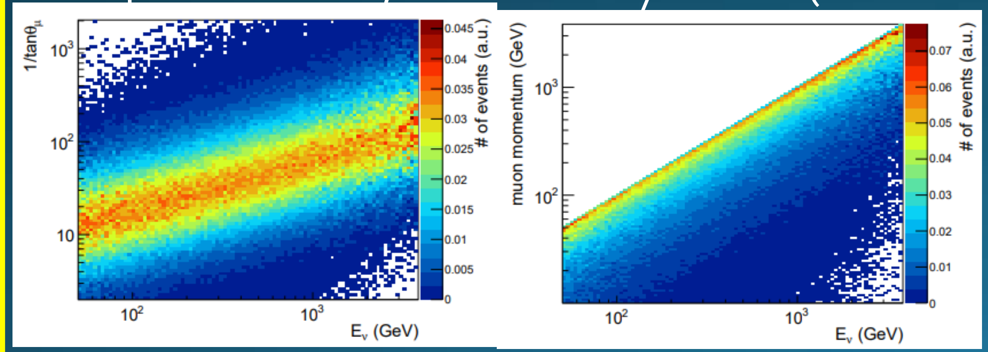
Energy reconstruction (ν_μ CC)

Sum of visible energy | ANN method | $\Delta E/E$



(smeared)

inputs for ANN, simulated by GENIE (MC truth)



Angular info | Momentum

…

- Sum of visible energy (model independent) already gives a reasonable resolution
- ANN can solve problem at high energy and gives about 30% resolution at relevant energy range.

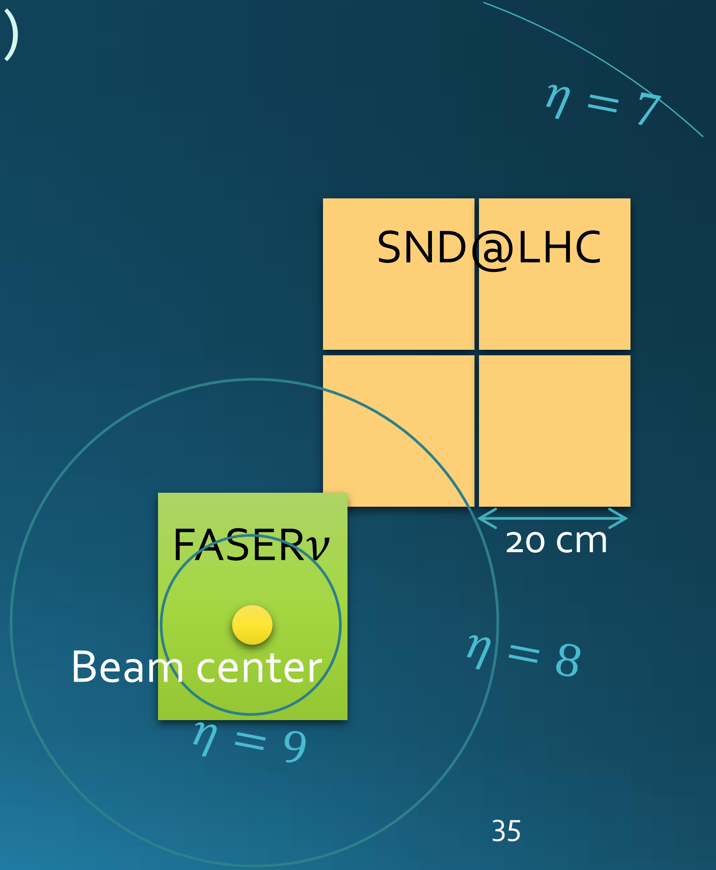
Neutrino physics

- Neutrino spectra at unexplored energy range
  - Study production / propagation / interaction
  - Cross section measurements of ν_e, ν_μ, ν_τ
  - Heavy flavor physics, NC, QCD, NSI, oscillations → see backup p18, 19
  - Complementarity between FASERν (on axis) and SND (off axis)

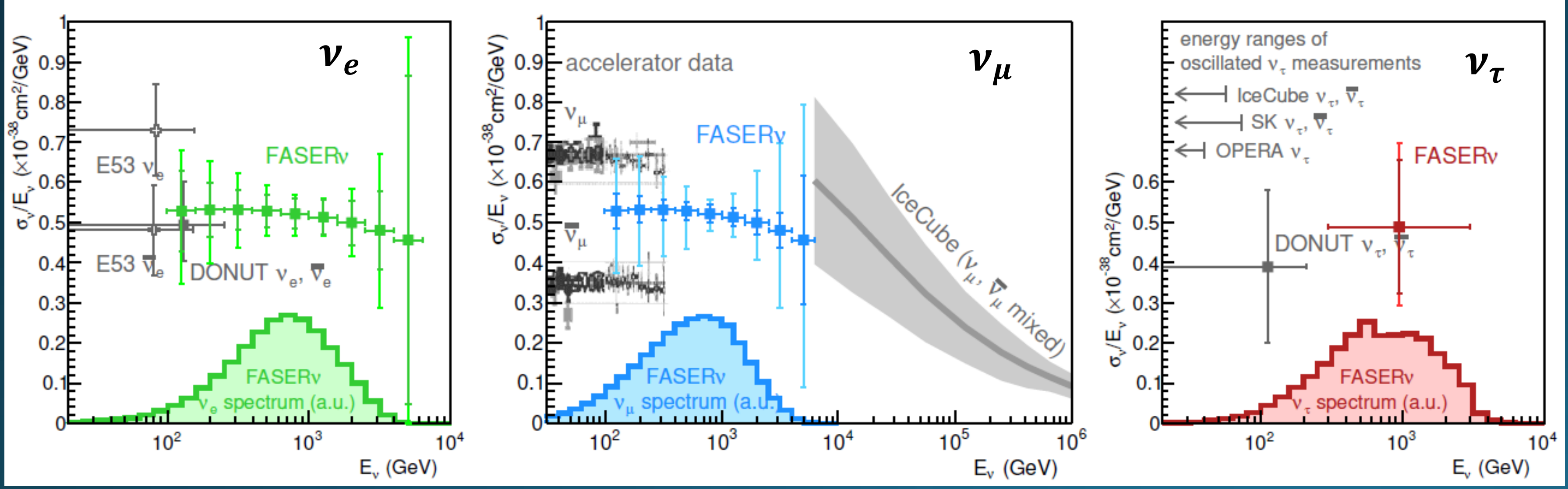
Expected CC event statistics

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

F. Kling, arXiv:2105.08270



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



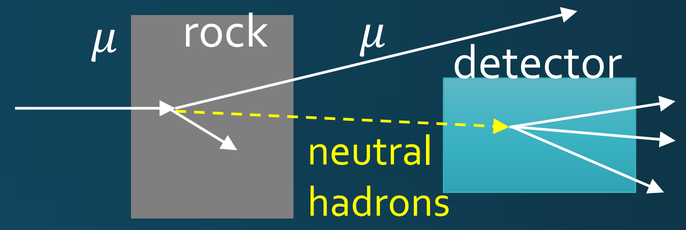
inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.

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

arXiv:2105.06197

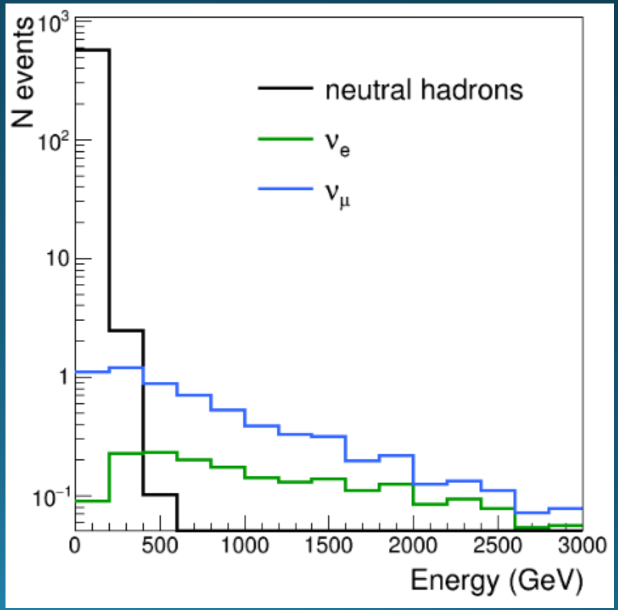
Background for neutrino analysis

- Muons rarely produce neutral hadrons in upstream rock or in detector, which can mimic neutrino interaction vertices
  - Probability of O(10^{-5})
- The produced neutral hadrons are low energy → Discriminate by vertex topology
- (For physics run, Lepton ID will kill most of background)



	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}

Production rate per muon (E_{had}>10 GeV)



FASERν / SND

Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2	184	965	10.1
DPMJET	DPMJET	4614	9198	131	547	1345	22.4
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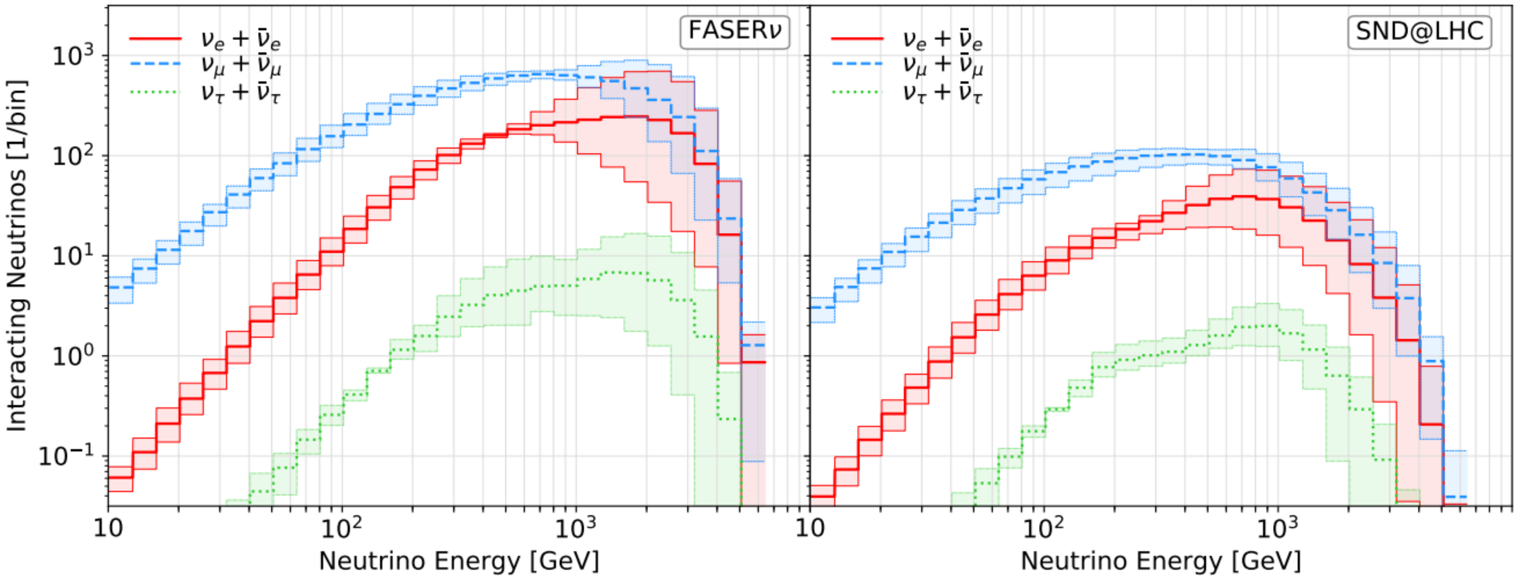
Combination (all)		2376^{+2238}_{-1032}	7549^{+1649}_{-1476}	$56.4^{+74.5}_{-35.1}$	339^{+208}_{-155}	1274^{+184}_{-308}	$14.8^{+7.5}_{-4.7}$
Combination (w/o DPMJET)		1630^{+479}_{-286}	7000^{+763}_{-926}	$31.5^{+17.3}_{-10.3}$	270^{+96}_{-85}	1251^{+208}_{-285}	$12.3^{+3.8}_{-2.1}$

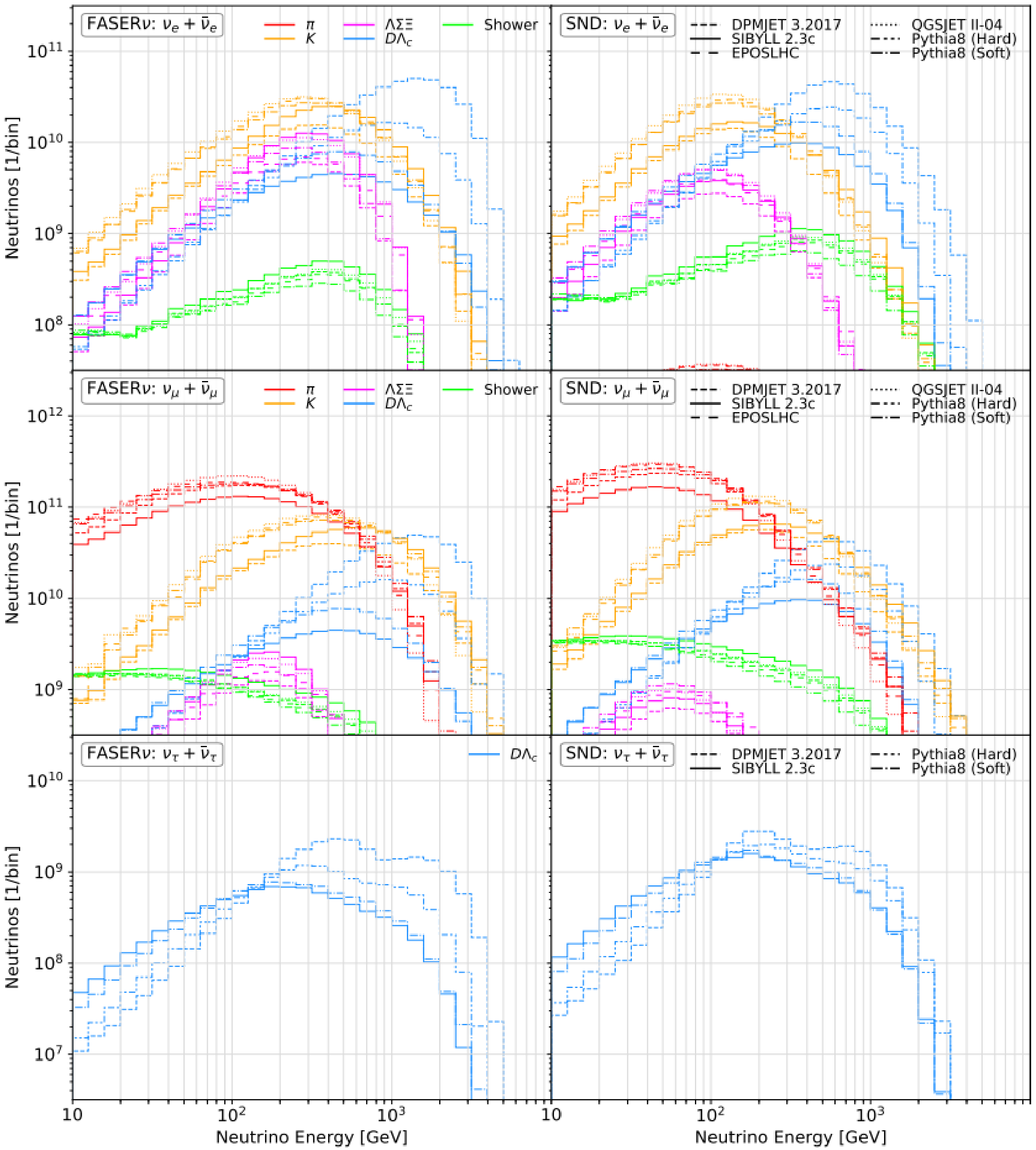
TABLE I. Expected number of neutrino interaction events occurring in FASERν and SND@LHC during LHC Run 3 with 150 fb^{-1} integrated luminosity. We provide predictions for `SIBYLL 2.3c`, `DPMJET III.2017.1`, `EPOSLHC/Pythia 8.2` with `HardQCD`, and `QGSJET II-04/Pythia 8.2` with `SoftQCD`. The two bottom rows provide a combined average, both including and excluding the `DPMJET` prediction, where the uncertainties correspond to the range of predictions obtained from different MC generators.

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



Neutrino flux

- Contributions from difference hadrons
- Currently large uncertainty exists
- Improving by creating a dedicated tune of hadron physics for forward region



Angular profile and acceptance of FASERnu and SND

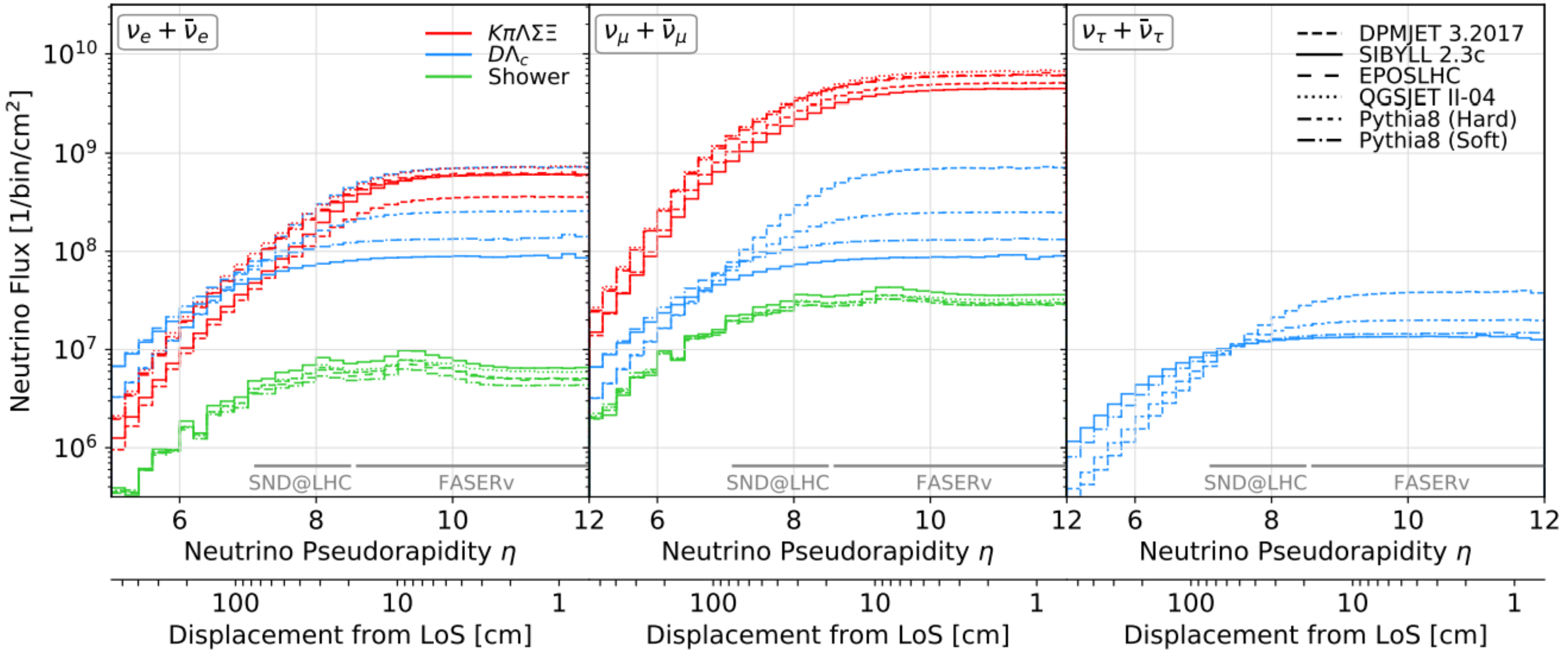


FIG. 3. **Neutrino Angular Distribution:** The panels show the flux for electron (left), muon (center) and tau (right) neutrinos, in units of particles per area per bin, as function of pseudorapidity η, or equivalently the radial displacement from the line of sight (LoS) at $z = 480$ m. The flux components from light hadron decays, charmed hadron decays and downstream hadronic showers are shown in red, blue and green, respectively. The line-styles denote the different event generators. All energies $E_\nu > 10$ GeV are included. Shown at the bottom of each panel is the angular coverage of FASERν and SND@LHC.