FASERν -- Neutrinos at the LHC

FASER

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On behalf of the FASER Collaboration

LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN

UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

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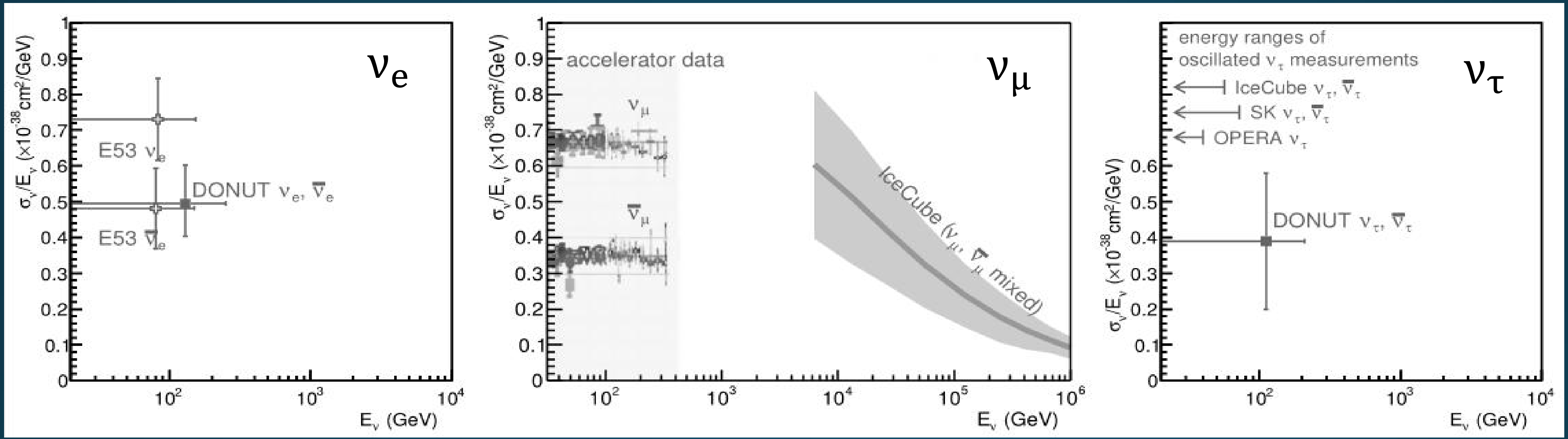
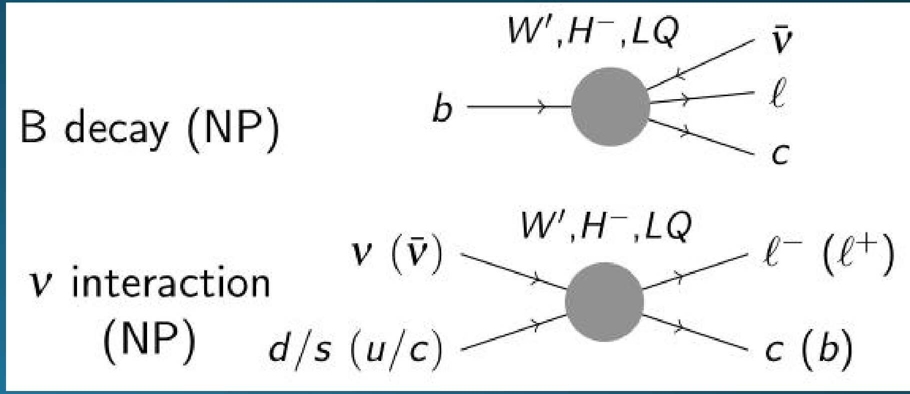
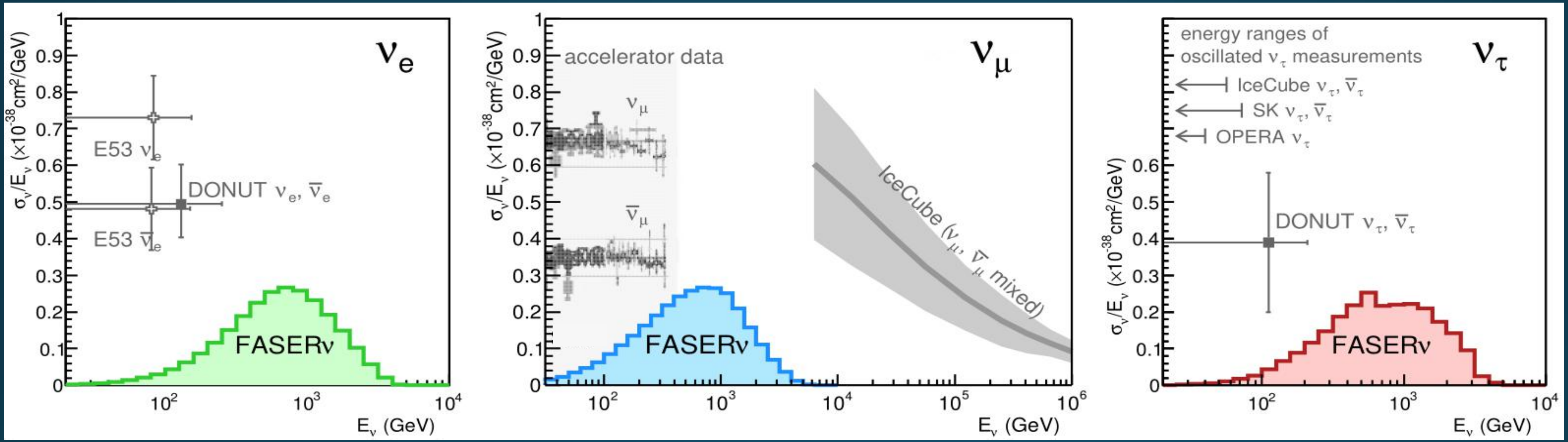
Motivations for high energy neutrinos



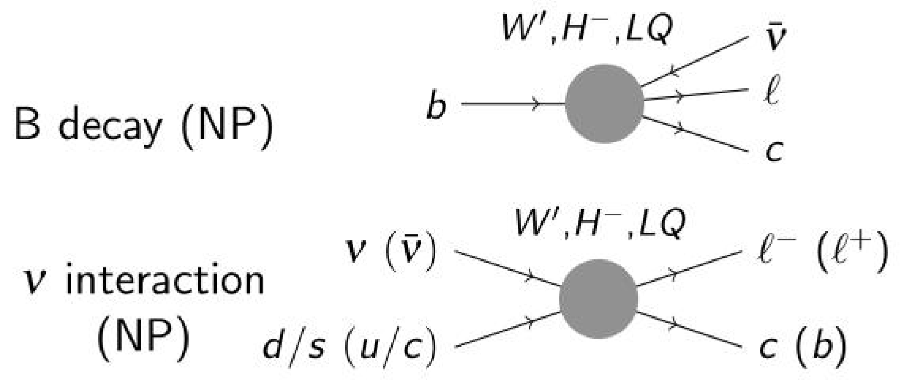
- Behavior of neutrinos at TeV energies?
- Lepton Universality in neutrino scattering?
  - ν_τ and heavy quarks → Flavor anomaly e.g. R_D
- Any new physics effects at high energy?



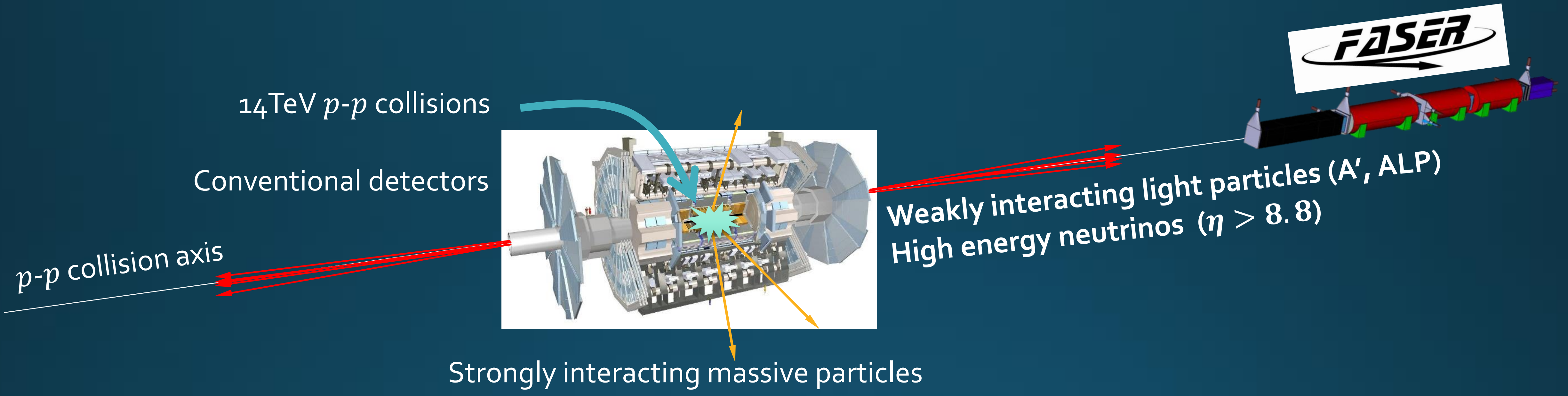
Motivations for high energy neutrinos



- Behavior of neutrinos at TeV energies?
- Lepton Universality in neutrino scattering?
  - ν_τ and heavy quarks → Flavor anomaly e.g. R_D
- Any new physics effects at high energy?
- →High energy neutrinos from the LHC!



FASER experiment: LLPs and neutrinos



No neutrino has ever been detected at the LHC, nor at any colliders

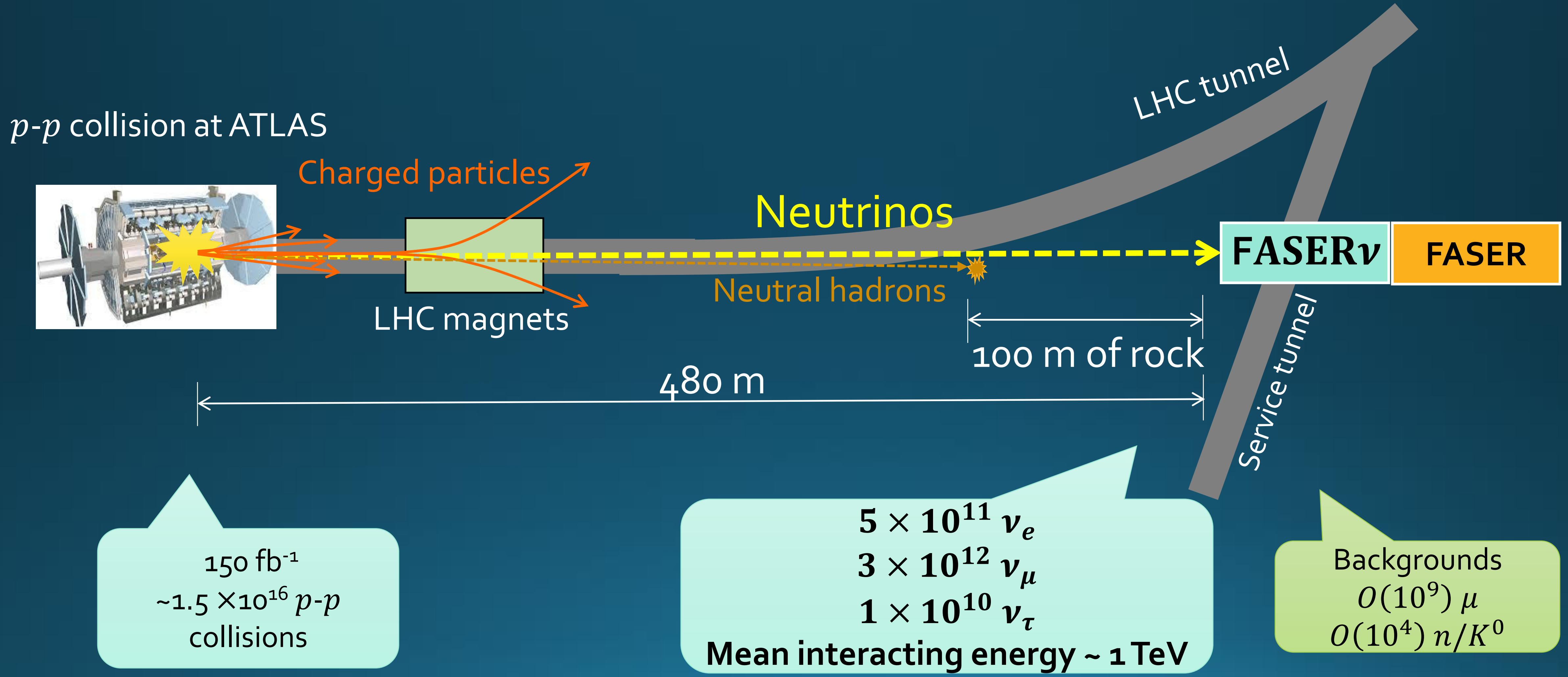
FASER (new particle searches) was approved by CERN in Mar 2019 [arXiv:1812.09139]

FASERν (neutrino program) was approved in Dec 2019 [Eur. Phys. J. C (2020) **80**: 61]

Data taking is starting in 2022!

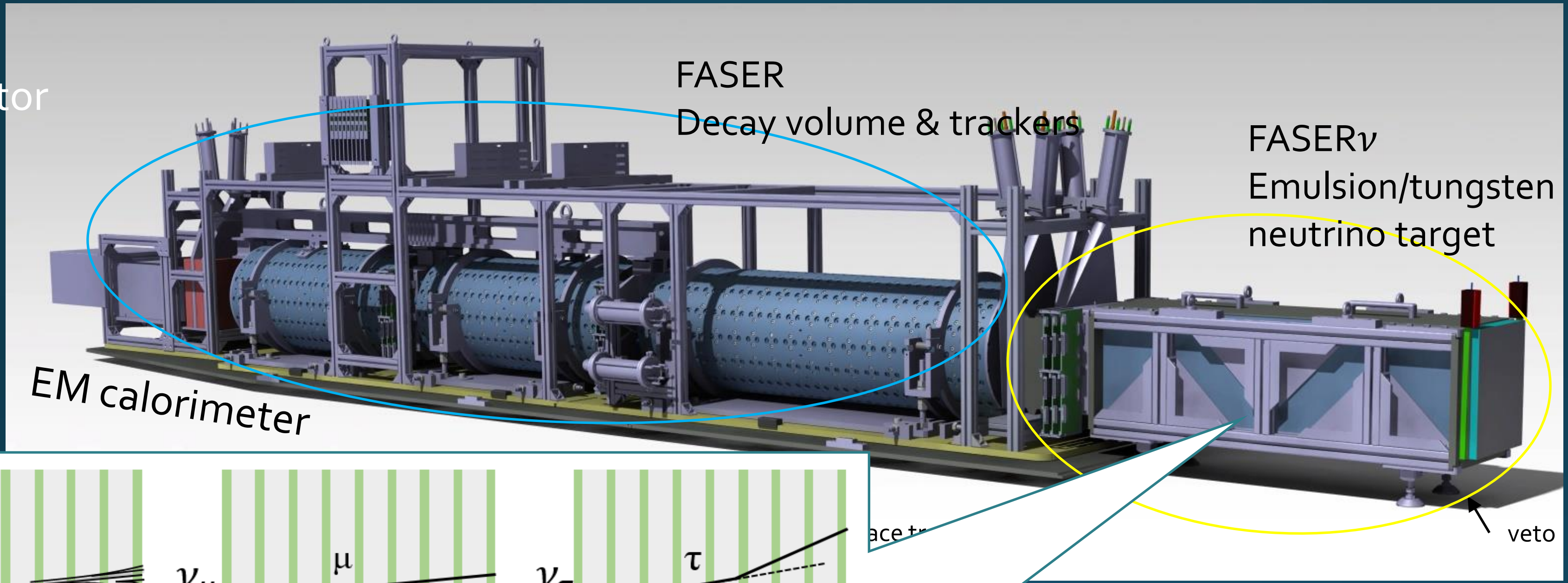
More → FASER web page: https://faser.web.cern.ch/

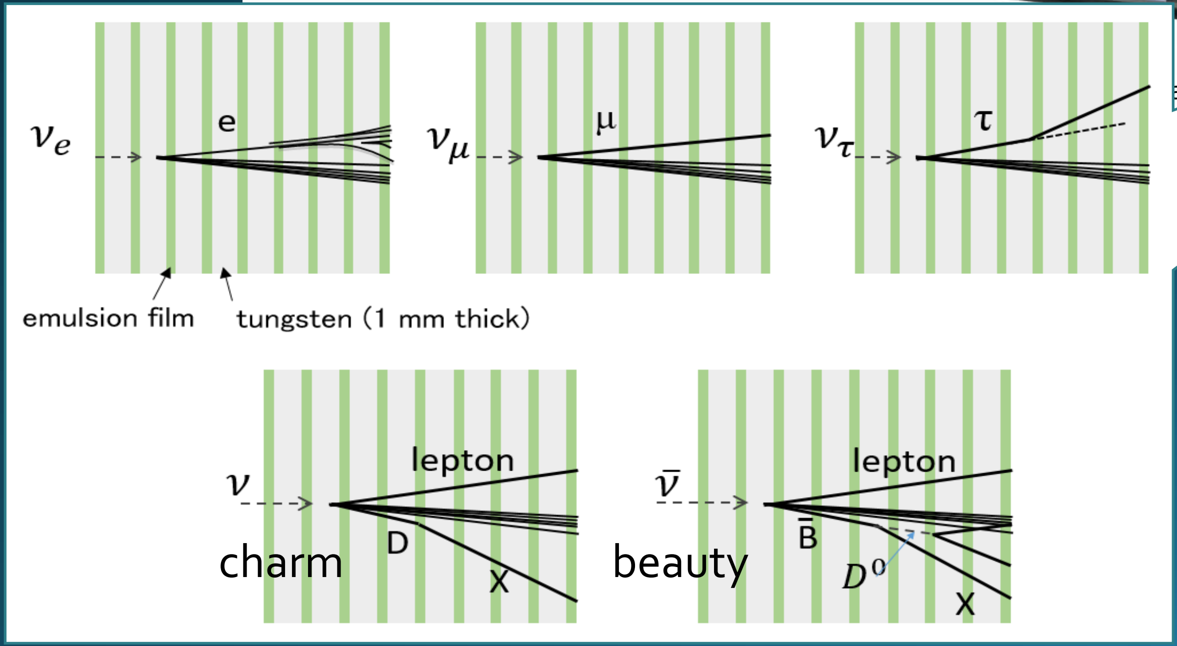
LHC's "neutrino beamline"



FASER/FASERν detector in Run3 (2022-2025)

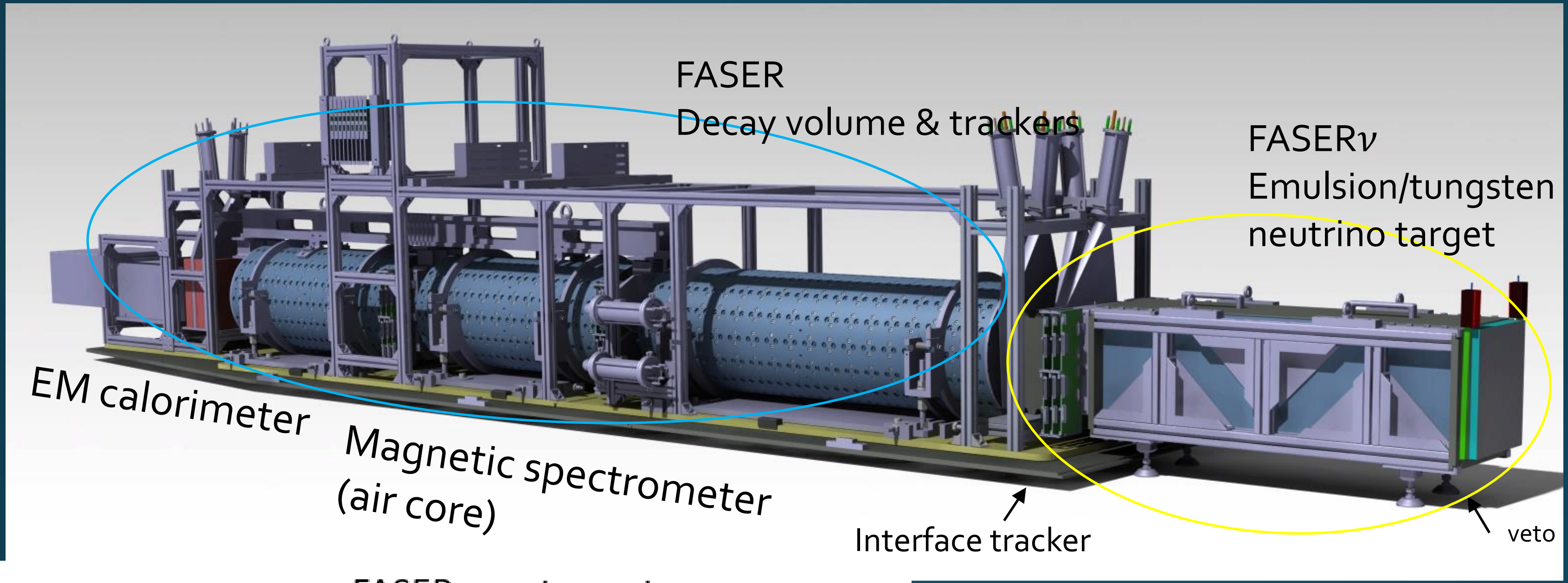
5m long detector

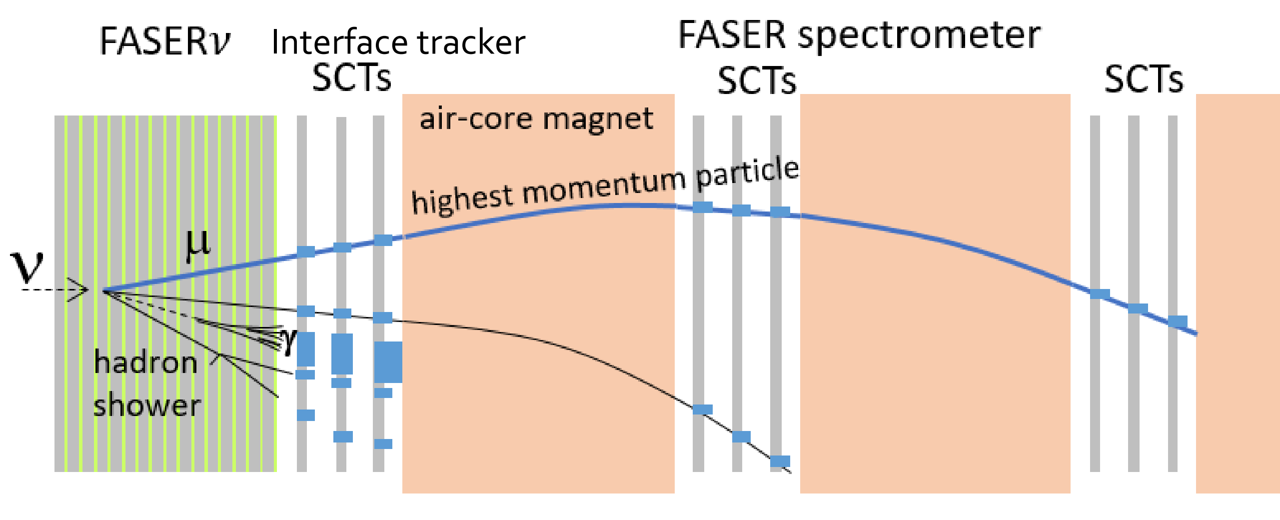




- Emulsion films = trackers with sub-micron spatial resolution, $\sigma_{intrinsic} \simeq 50\ nm$, $\sigma_{practical} \simeq 0.4\ \mu m$
- 770 1-mm-thick tungsten target and emulsion films
- 25x30 cm^2, 1.1 m, 1.1 tons (8 λ_{int}, 220X_0)
- Sensitive to 3 flavor neutrinos
- Muon ID in track length in tungsten
- Replace emulsions 3 times a year

FASER/FASERν detector in Run3 (2022-2025)





- Global reconstruction with FASER spectrometer
  → muon charge identification
  → $\nu_\mu/\bar{\nu}_\mu$ separation
- Improve energy resolution

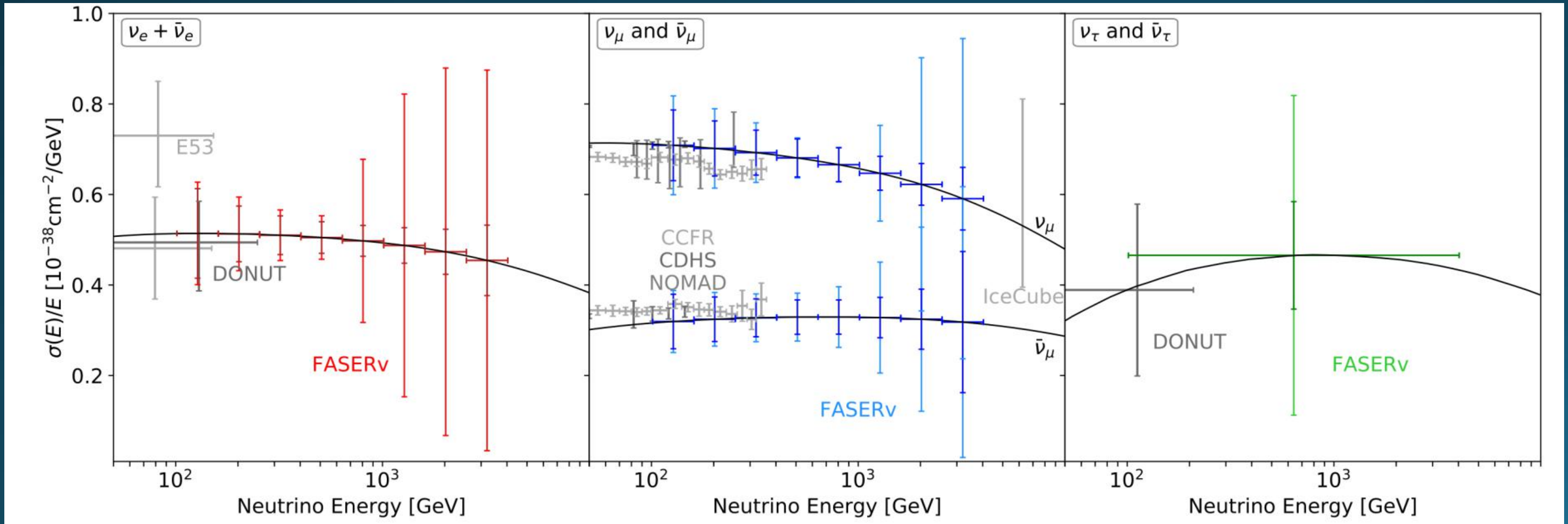
Physics studies in the LHC Run 3 (1):
Cross sections

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	901	4783	14.7
DPMJET	DPMJET	3457	7088	97
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2
QGSJET	Pythia8 (Soft)	970	5351	16.1
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$

Expected CC interactions with 150 fb^{-1}

- Three flavors neutrino cross section measurements at unexplored energies
- ~10,000 ν interactions expected in LHC Run 3
- NC interaction studies

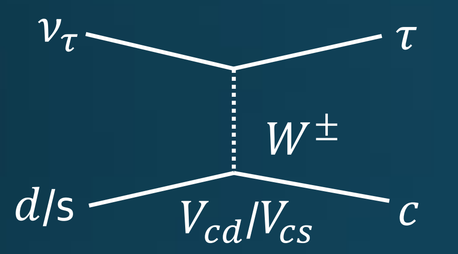


Projected cross section sensitivities

Physics studies in the LHC Run 3 (2):

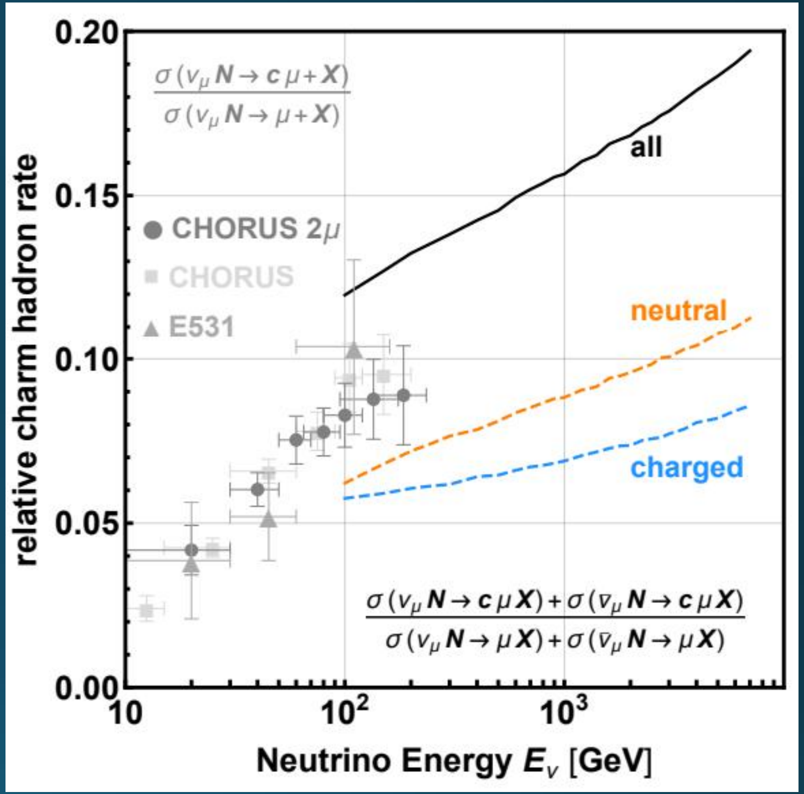
Heavy-flavor-associated channels

- Measure charm production channels
  - Large rate ~ 15% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.

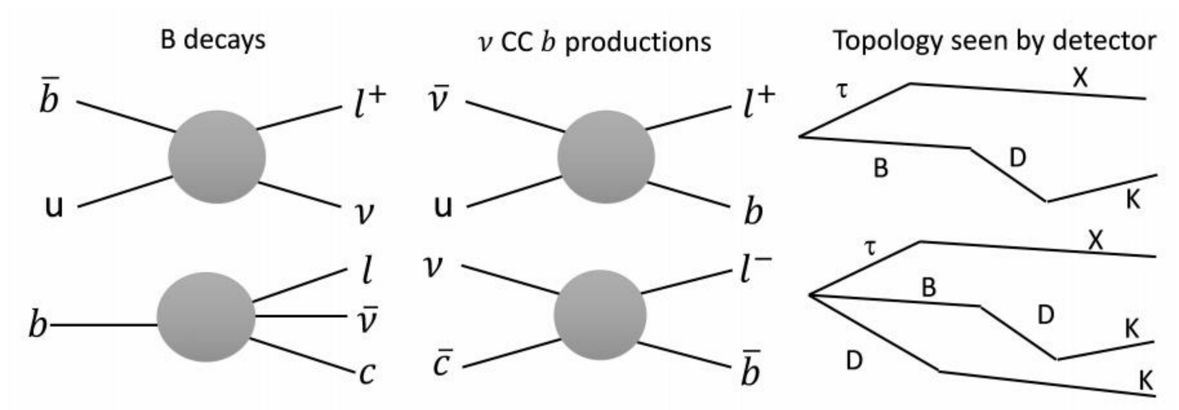


$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)}$$

$\ell = e, \mu, \tau$



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

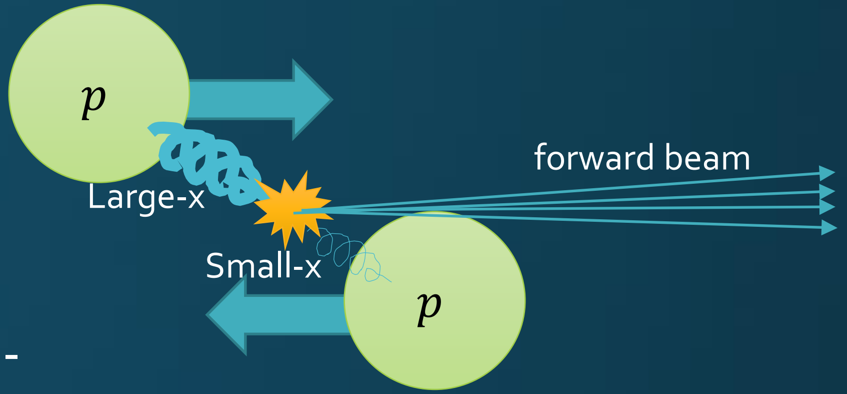


$\bar{\nu} N \to \ell \bar{B} X$

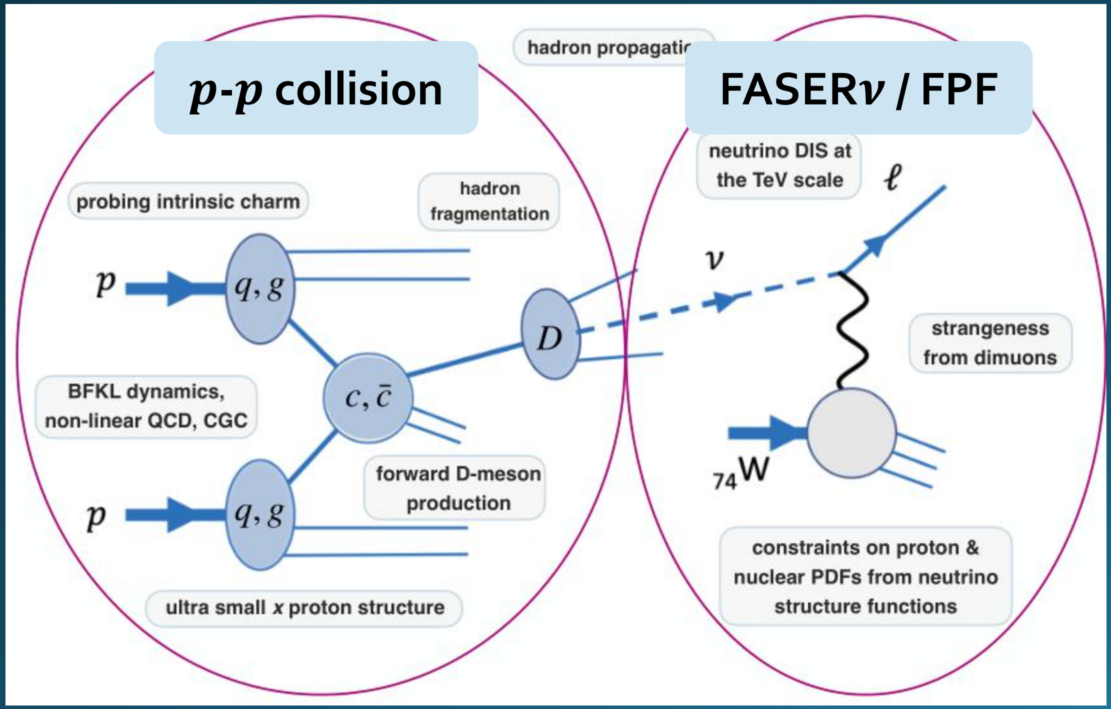
$\nu N \to \ell B D X$

Eur. Phys. J. C (2020) **80**: 61

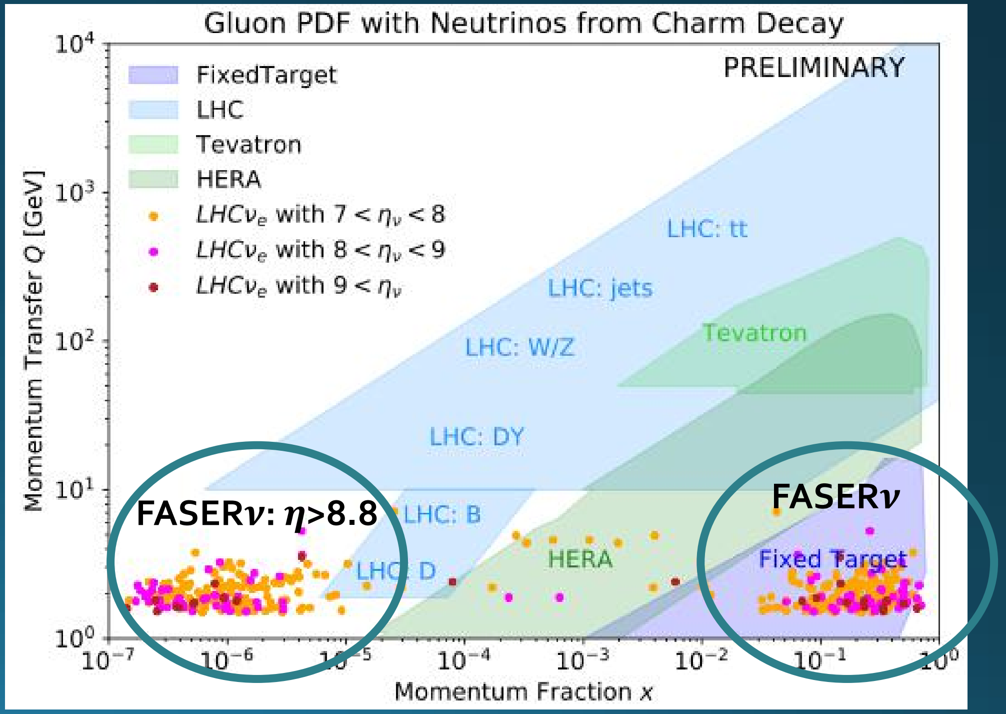
Physics studies in the LHC Run 3 (3):
Further insights on QCD



- Asymmetric gluon-gluon interaction, small-x × large-x
- Neutrinos from charm decay could allow to test transition to small-x factorization, probe intrinsic charm
- Deep understanding of neutrinos from charm decays (prompt neutrinos) is important for astrophysical neutrino observations

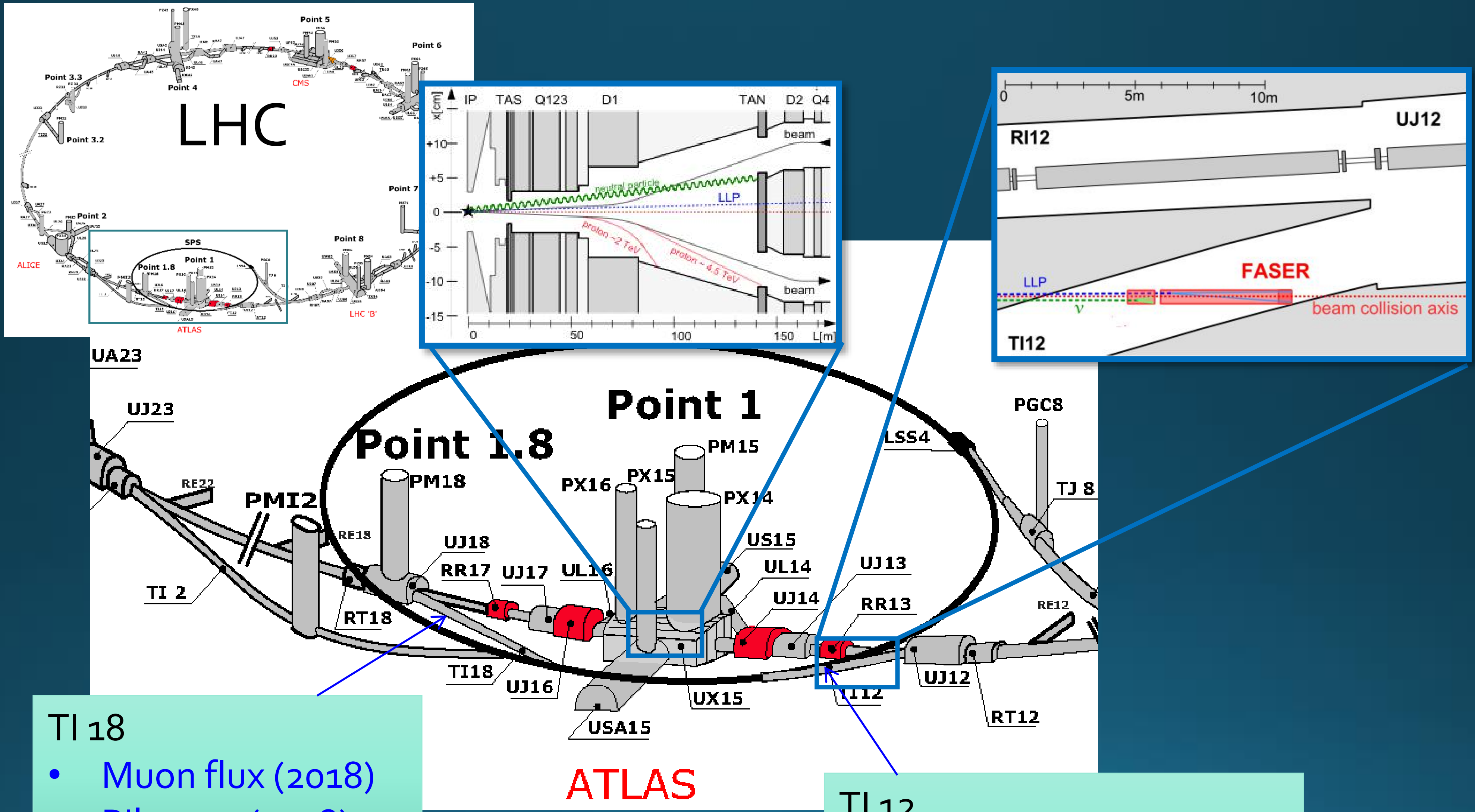


2203.05090



Results from 2018 run

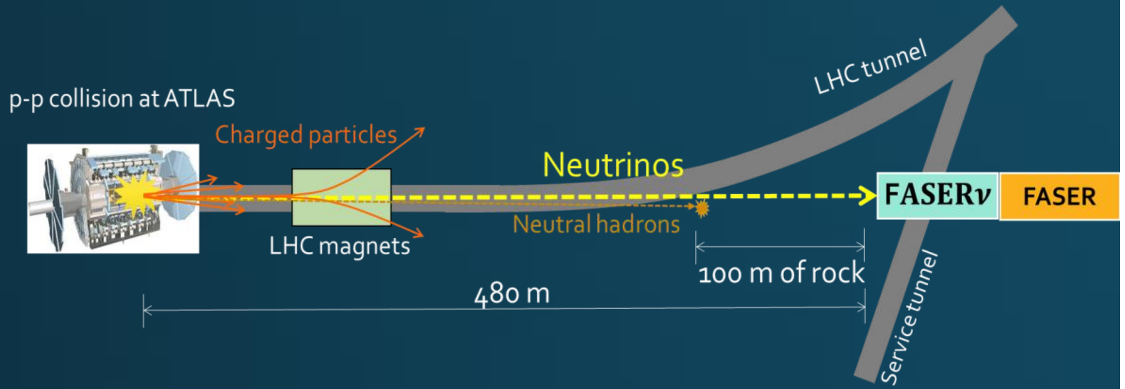
FASER locations



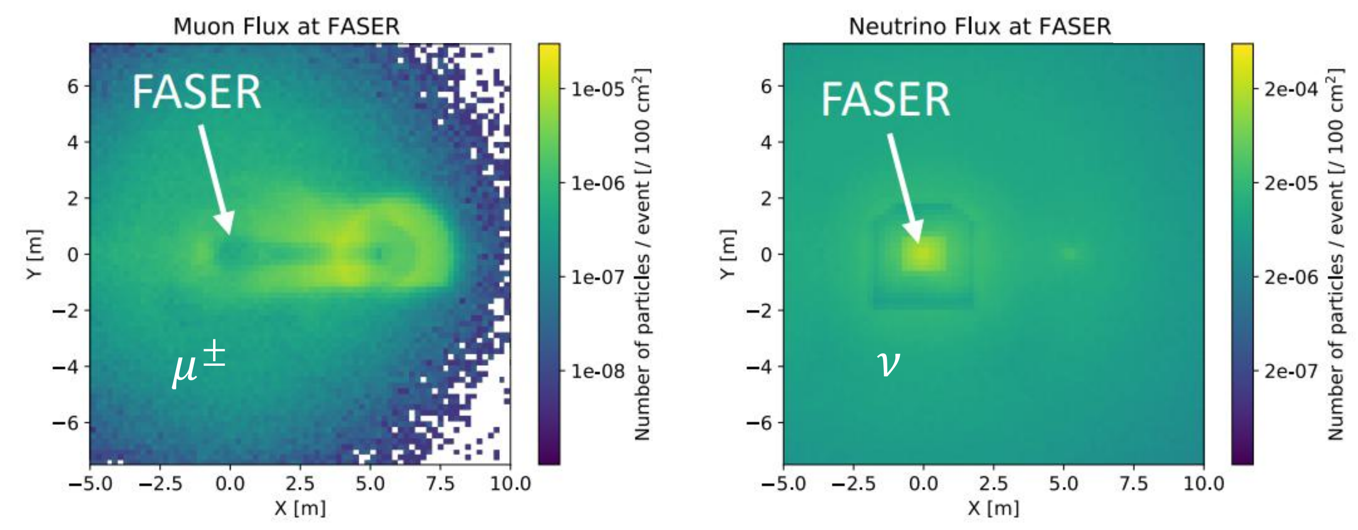
TI 18
- Muon flux (2018)
- Pilot run (2018)

TI 12
- Muon flux (2018)
- Physics run (2022-2025)

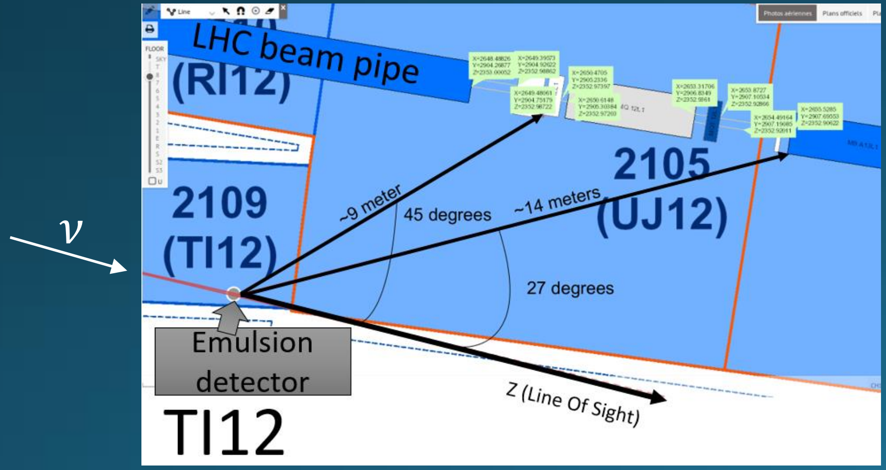
Particle fluence at the site

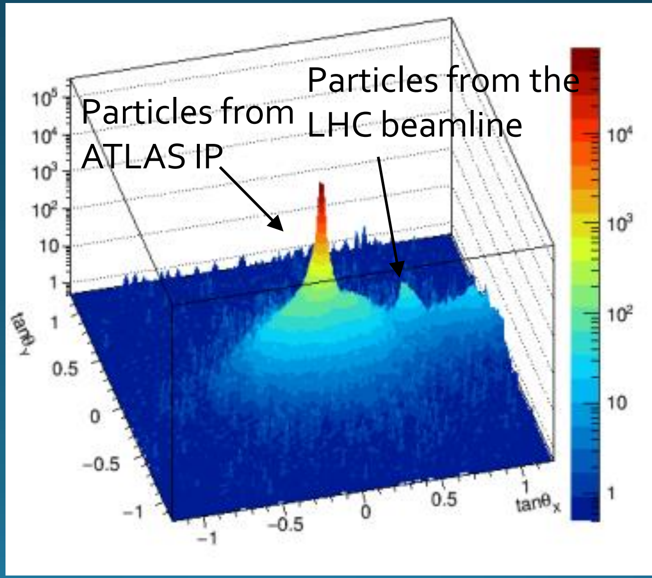


BDSim result for TI12, Lefebvre ICHEP2020



- *In-situ* measurements in 2018

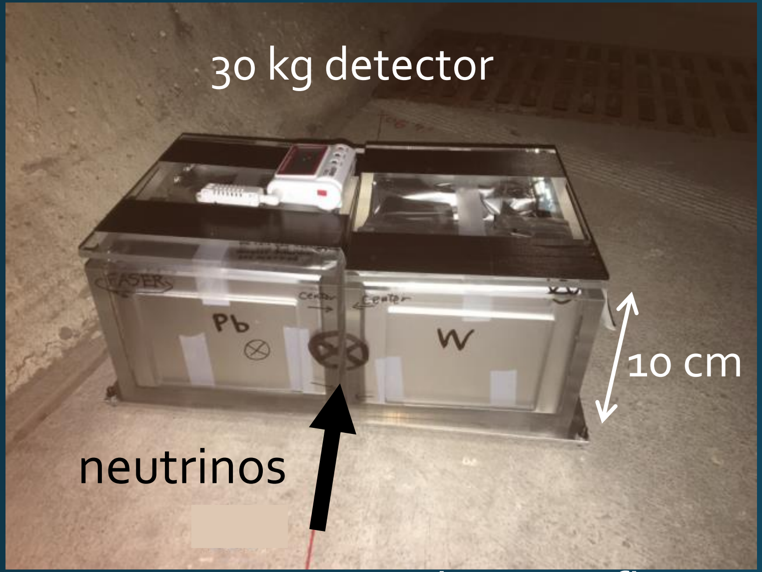




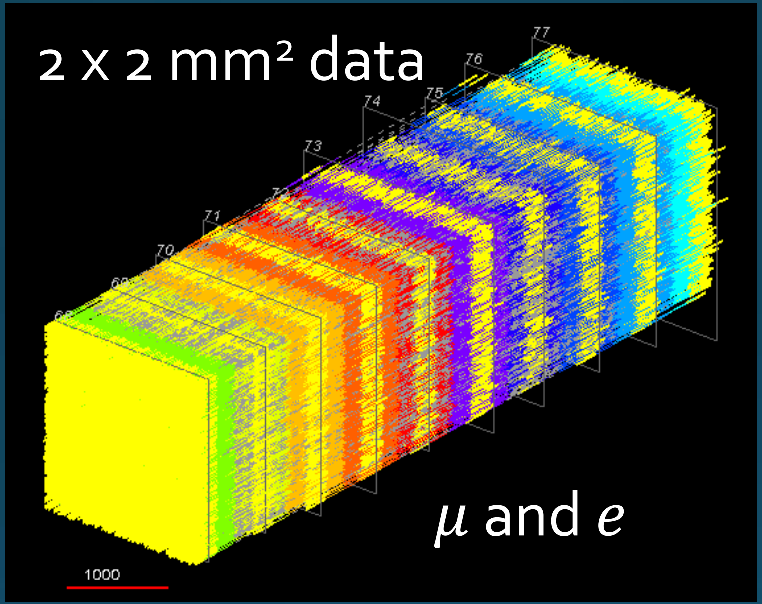
	Flux in main peak [fb/cm²]
TI18 data	$1.7 \pm 0.1 \times 10^4$
TI12 data	$1.9 \pm 0.2 \times 10^4$
FLUKA MC	2.5×10^4 (uncertainty 50%)

Pilot neutrino detector in 2018

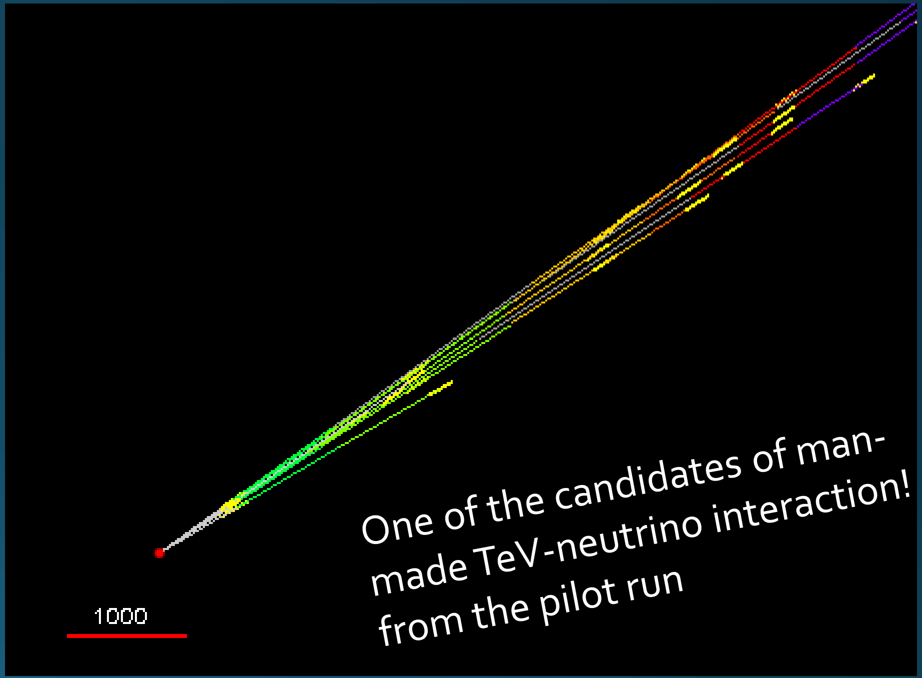
Proof of principle



6 weeks, 12.2 fb^{-1}



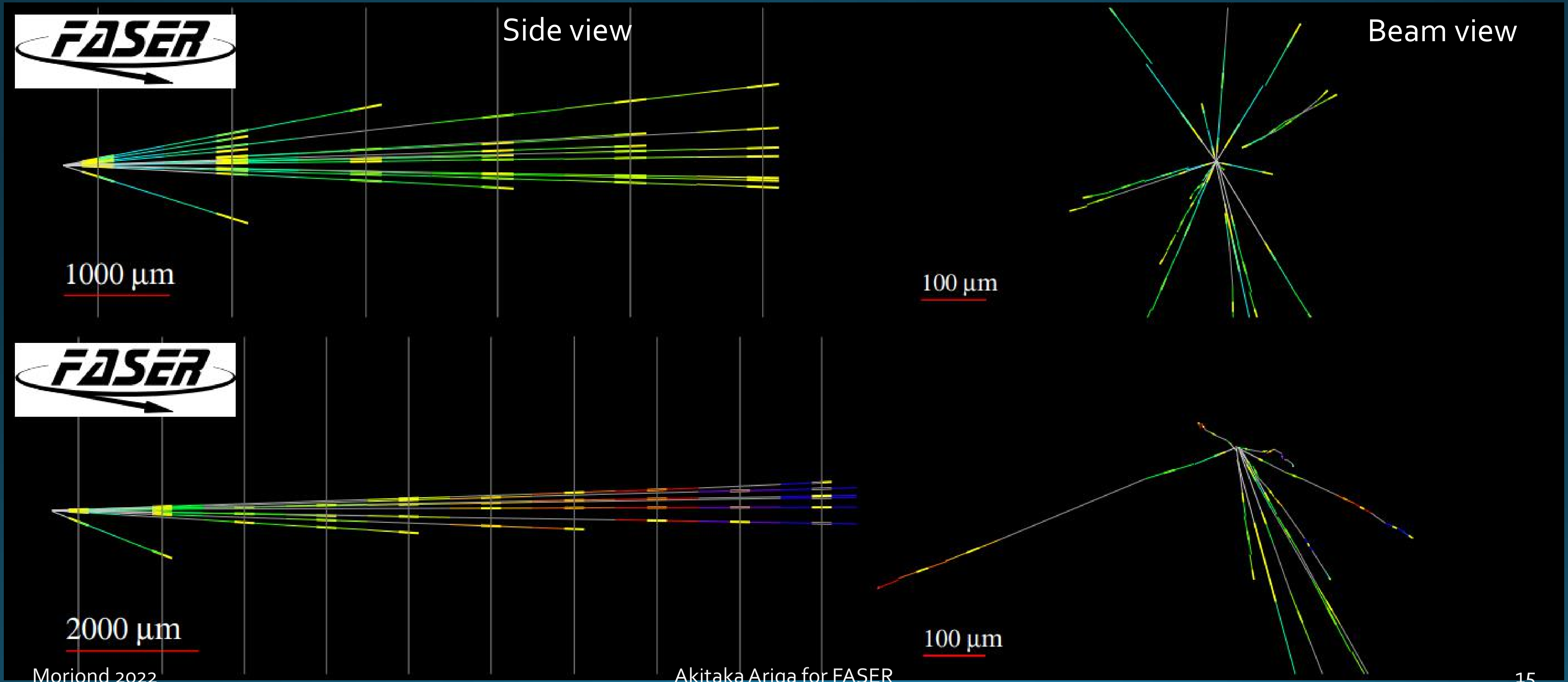
$\simeq 3 \times 10^5$ tracks/cm²



- 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)

Phys. Rev. D 104, L091101 (2021)

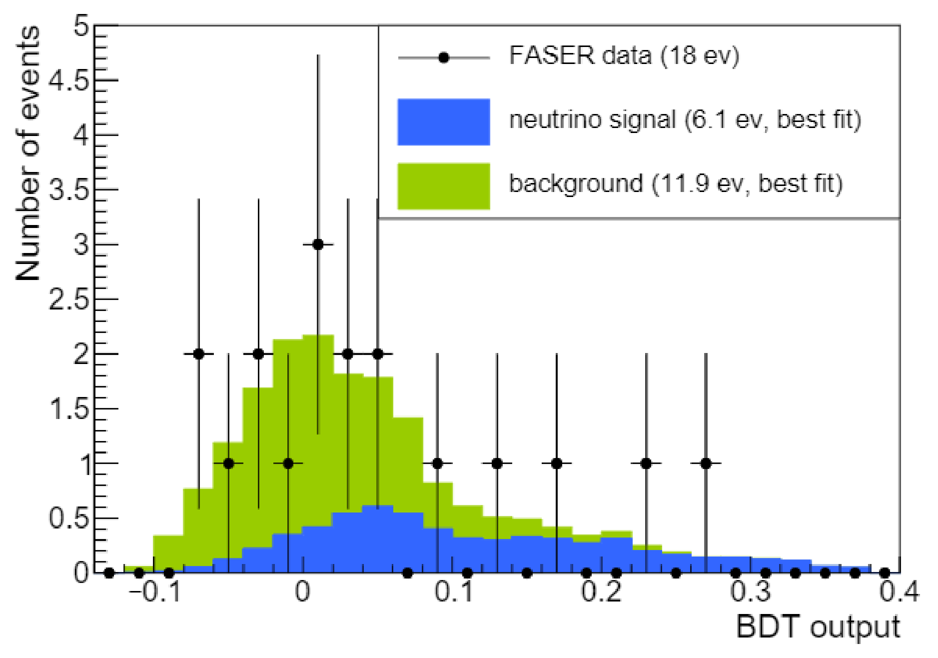
Neutrino interaction candidates



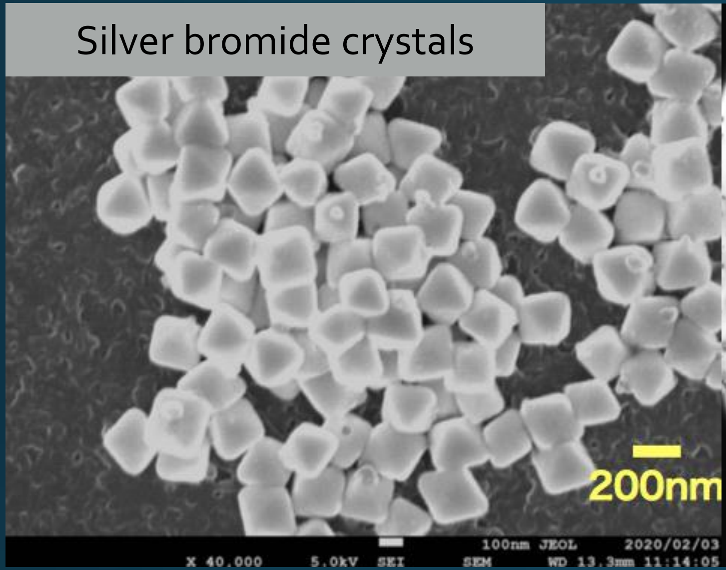
Phys. Rev. D 104, L091101 (2021)

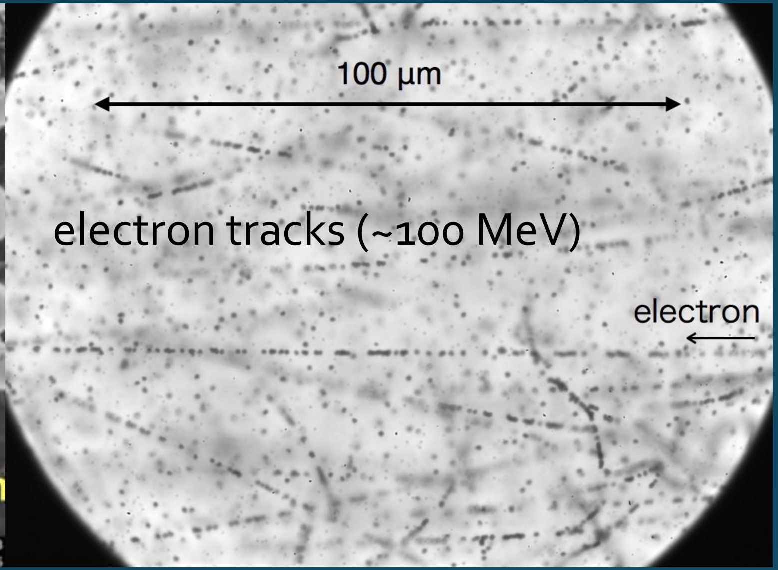
Pilot run event statistics

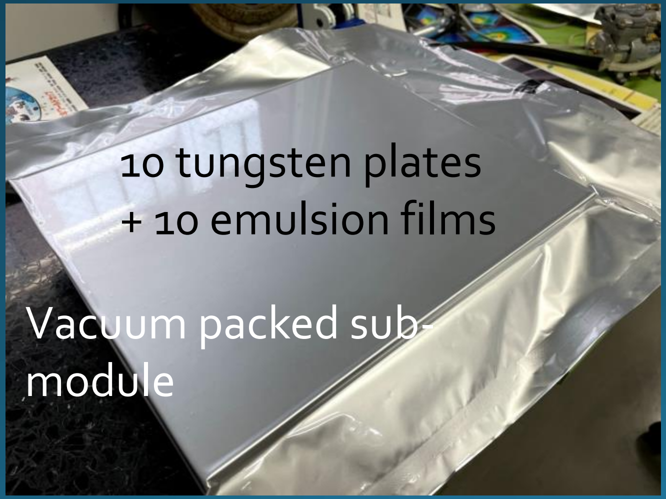
- Analyzed target mass of 11 kg and luminosity of 12.2 fb^{-1}
- 18 neutral vertices were selected
  - by applying # of charged particle ≥ 5, etc.
  - Expected signal = $3.3^{+1.7}_{-0.95}$ events, BG = 11.0 events
- Note: no lepton ID in the pilot run → High BG
- In BDT analysis, an excess of neutrino signal (6.1 events) is observed. Statistical significance = 2.7 σ from null hypothesis
- This result demonstrates the detection of neutrinos from the LHC

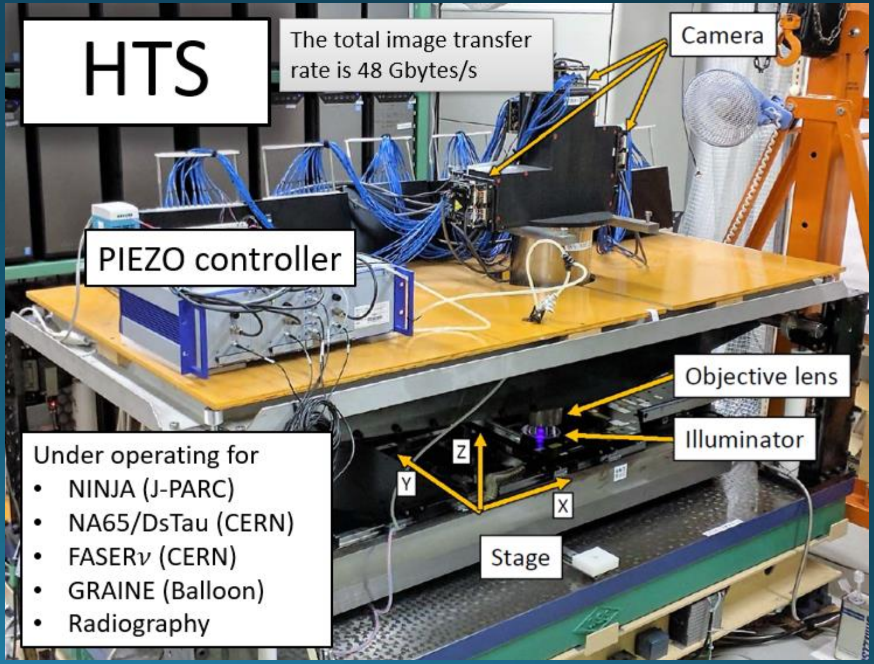


Preparation for Run 3: FASERν detector



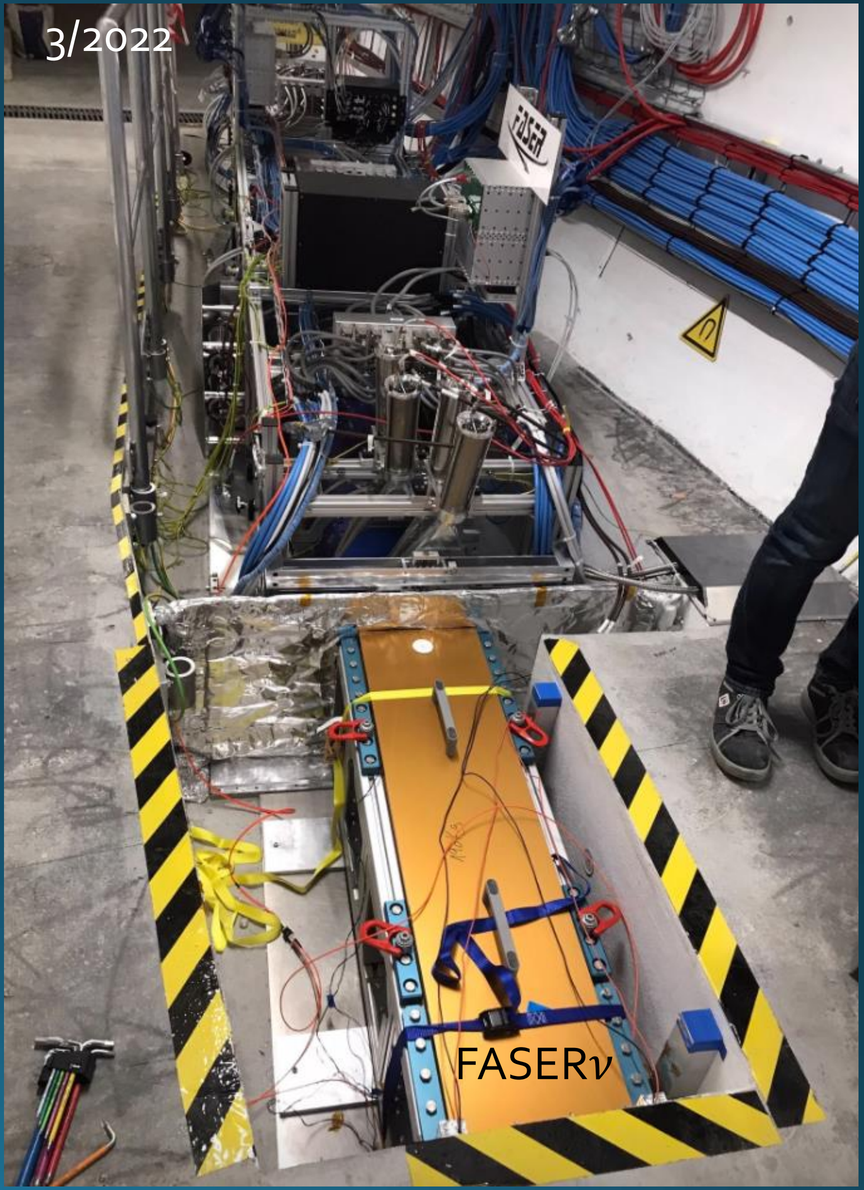


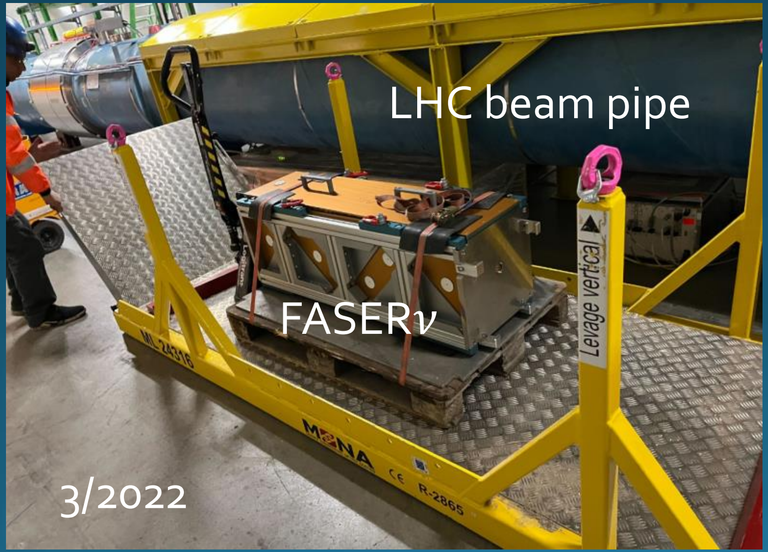




Preparation for Run 3 at site

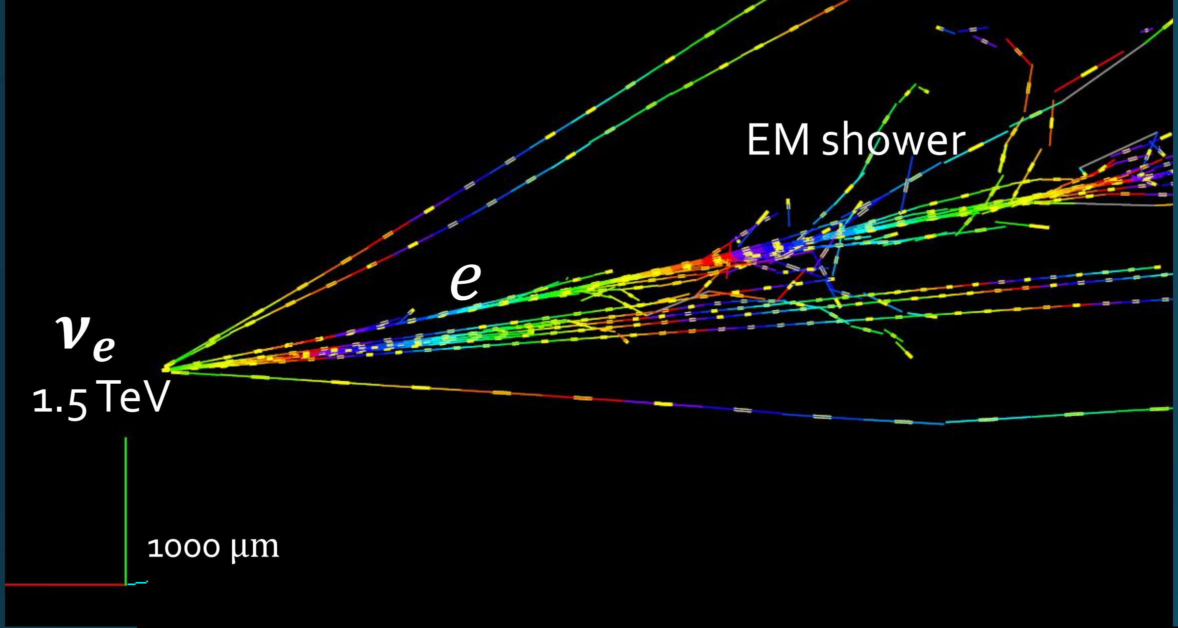
First emulsion detector installed this week!

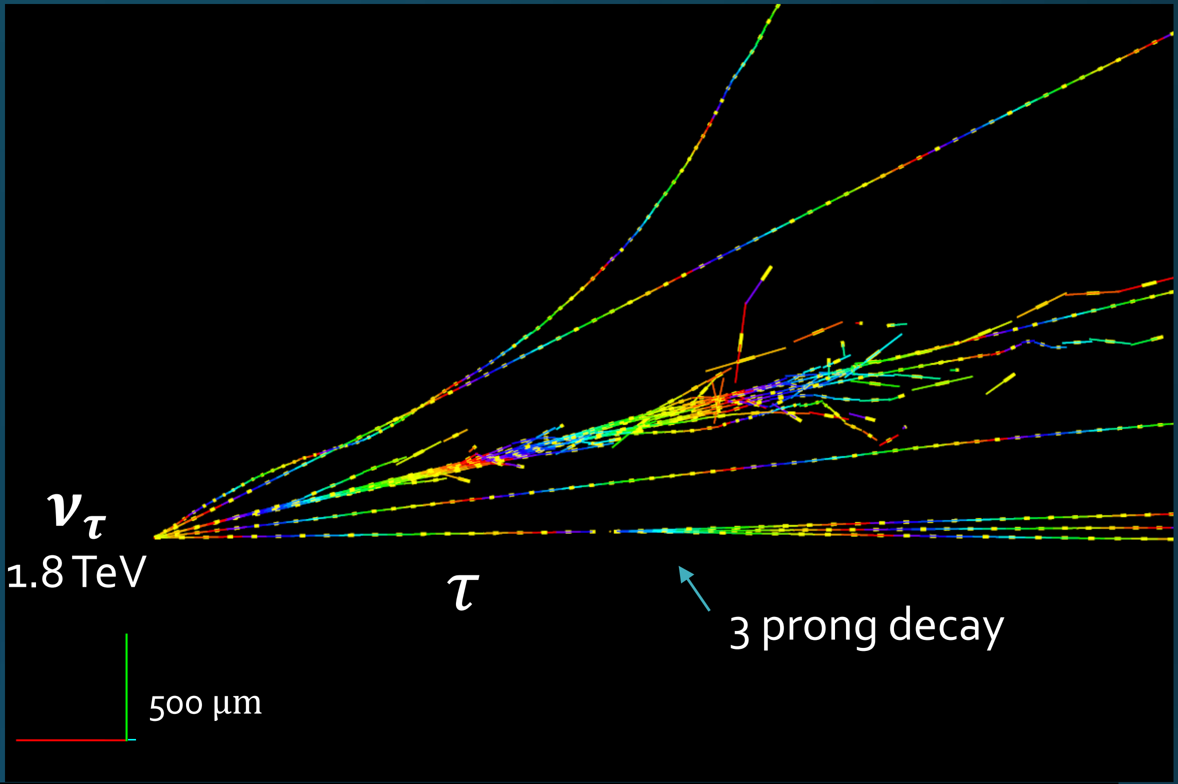


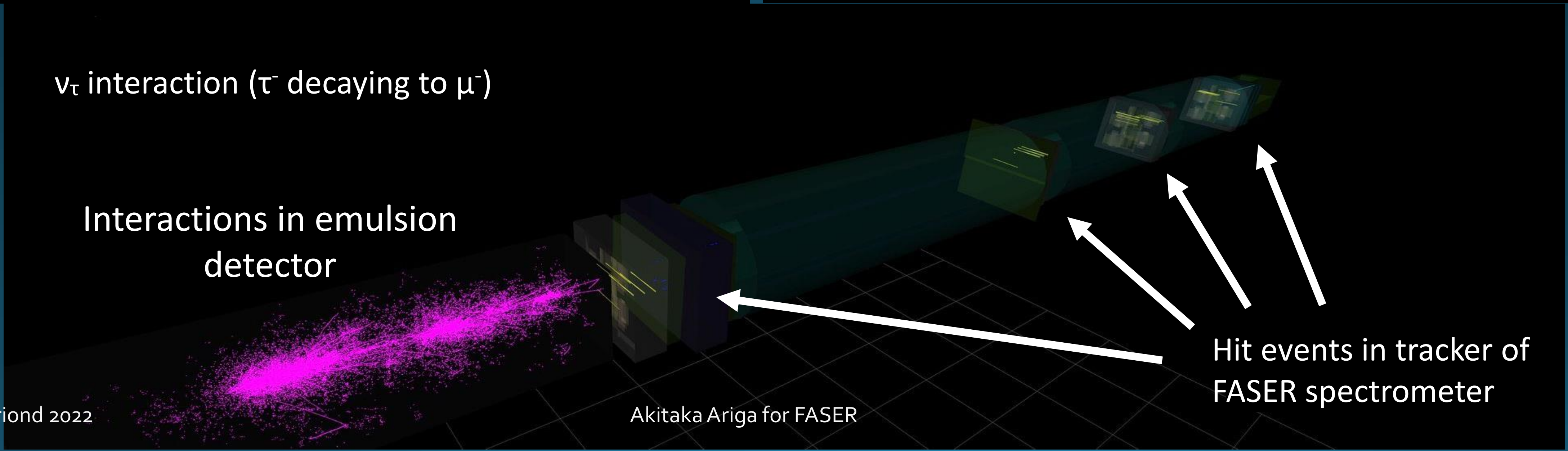


ν

Simulated ν_e and ν_τ events

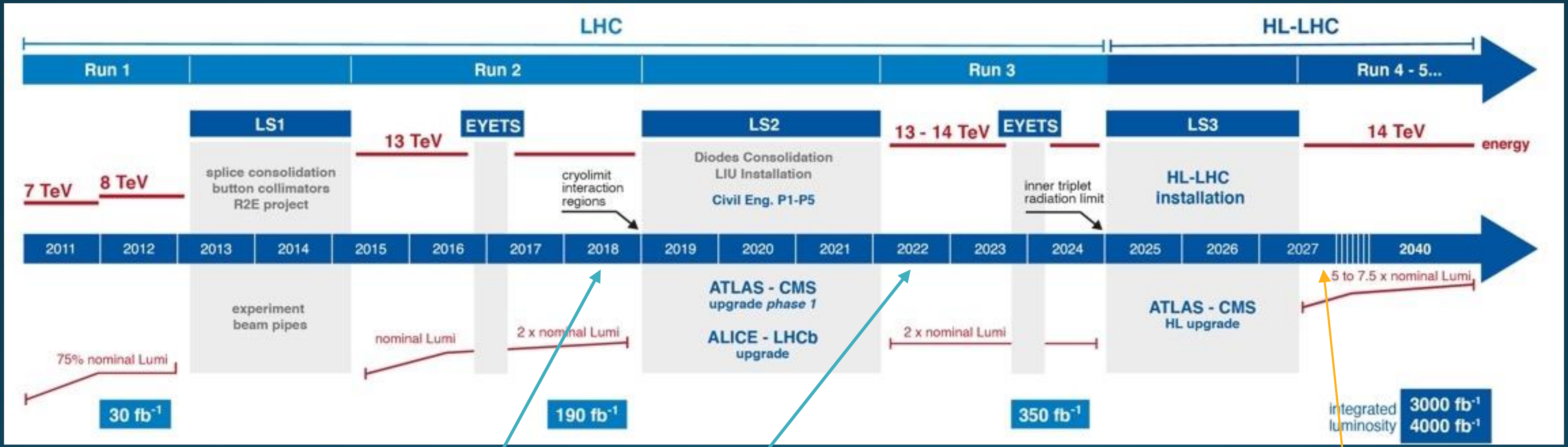






FASERν/FASERν2 schedule

- LHC Run-3 will start in 2022, FASERν.
- HL-LHC, starting in 2028, will deliver 10 times more integrated luminosity → FASERν2



Pilot run & background measurements in 2018

FASER's physics run ($\sim$150 fb^{-1} or more)

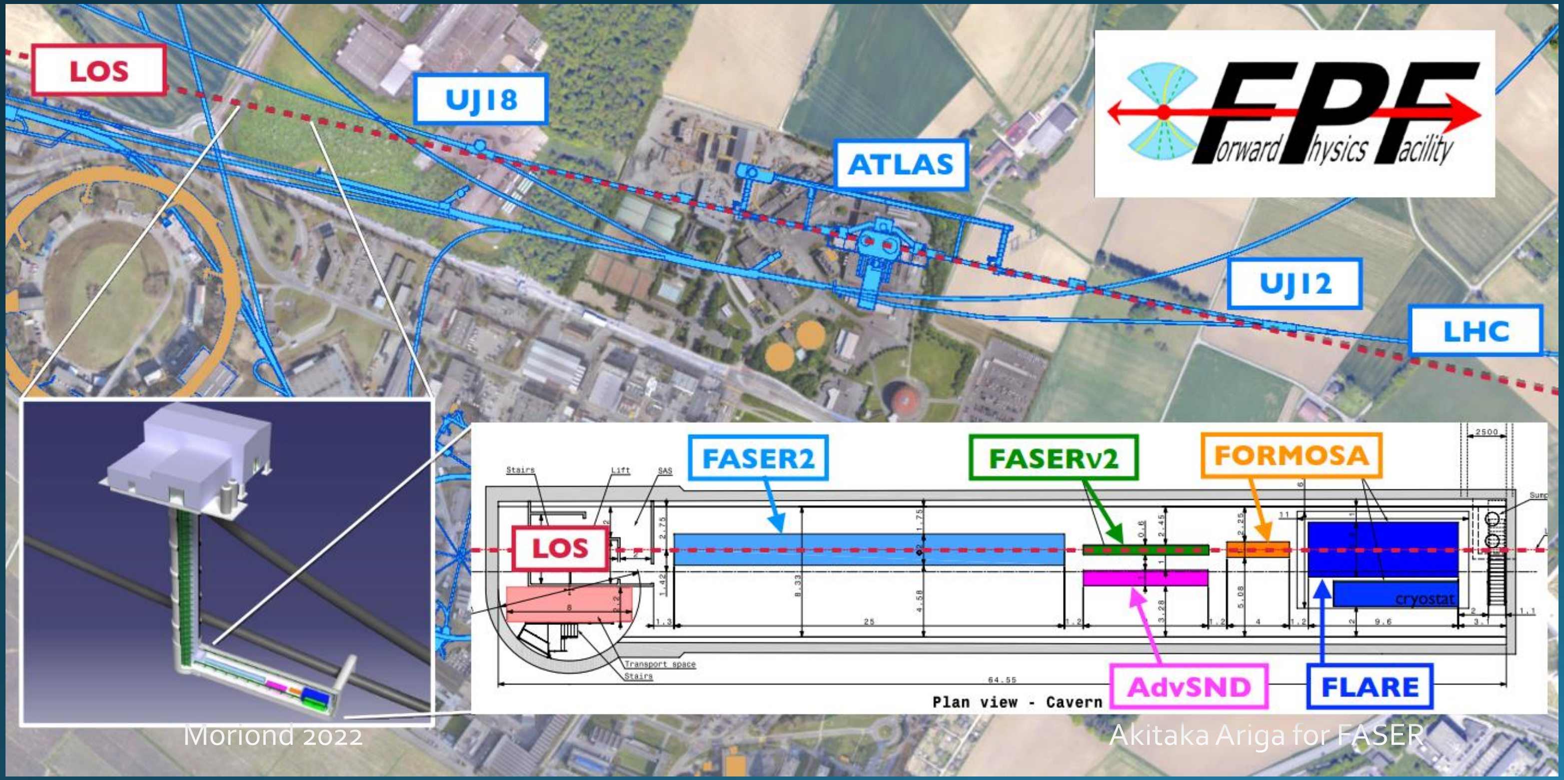
Forward experiment in HL-LHC

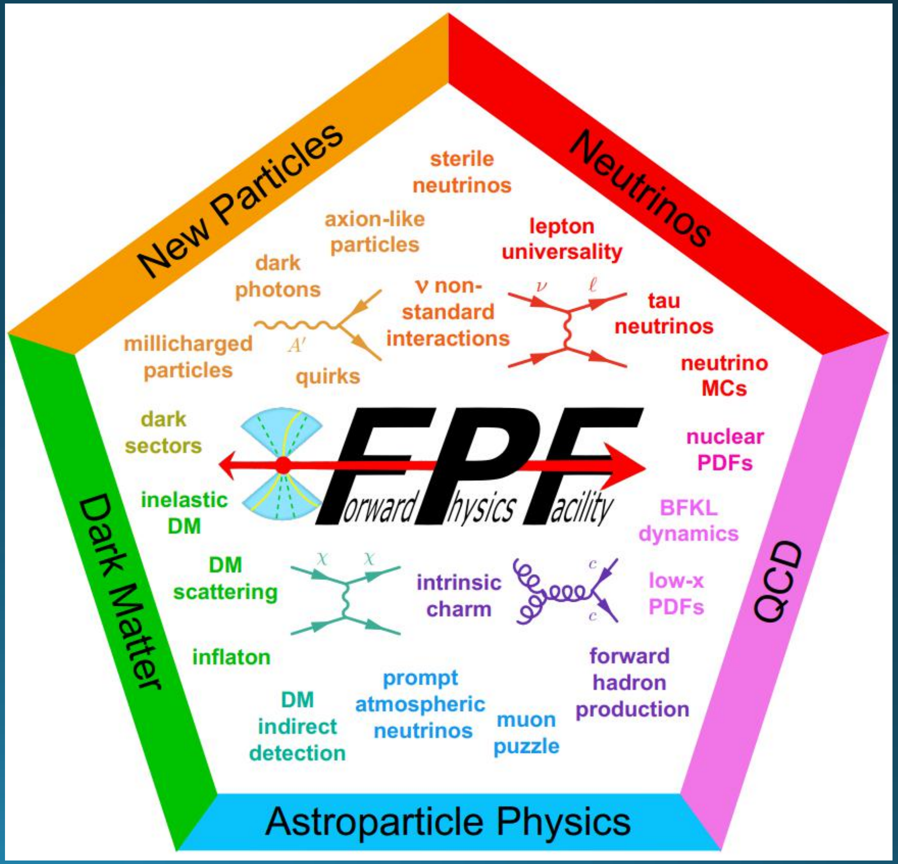
2022-25 physics run in LHC RUN3, 1.1 tons, a total area of film 720 m^2

2028- FASERν2@FPF in HL-LHC, 10-20 tons

Forward Physics Facility (*FPF*) at the HL-LHC

- HL-LHC ×20 proton collisions, and new experimental hall
- Extending sensitivities for new particle searches and neutrino physics by two orders of magnitude → FASER2, FASERν2, … much more
- FPF White Paper (429 pages, 236 authors, 156 endorsers) http://arxiv.org/abs/2203.05090





Summary

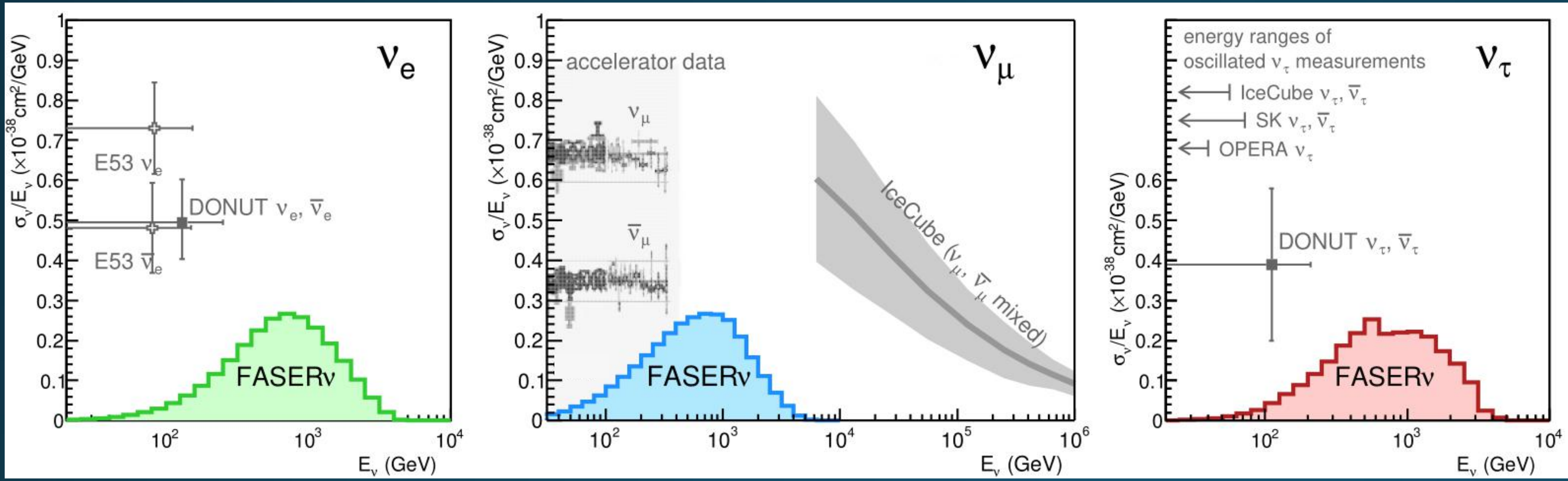
- Neutrinos at the LHC, a new domain of particle physics research!
- The FASER experiment at the LHC: neutrinos and LLPs
- FASERν is the first neutrino experiment with a collider
  - Beam at new kinematical regime, including 3 flavors
  - Detector with flavor sensitivity
  - Data taking in 2022-2025
- Comprehensive site studies during 2018
- Detection of neutrinos from the LHC was demonstrated with pilot detector
  - 2.7 σ from no neutrino hypothesis
- FASER is starting data taking in next months! (Collisions in June)
- Future projects (FPF) at the HL-LHC are under discussion

FASER Collaboration

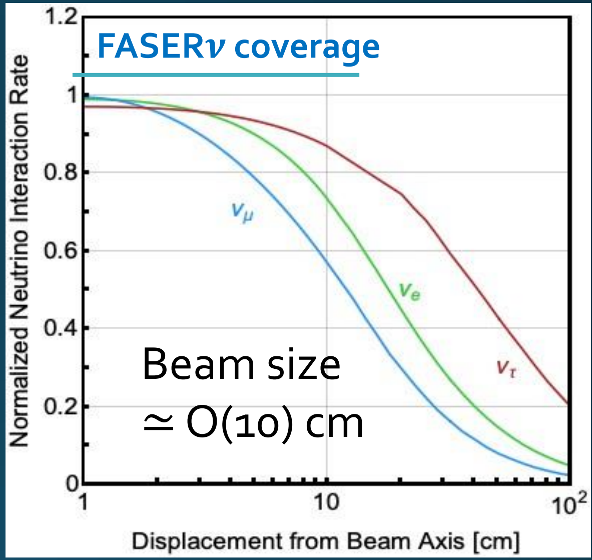
74 collaborators, 21 institutions, 9 countries (as of Jan. 2022)

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON
UNIVERSITÄT BONN
INFN
清華大学 Tsinghua University
SLAC NATIONAL ACCELERATOR LABORATORY
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX
JINR

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

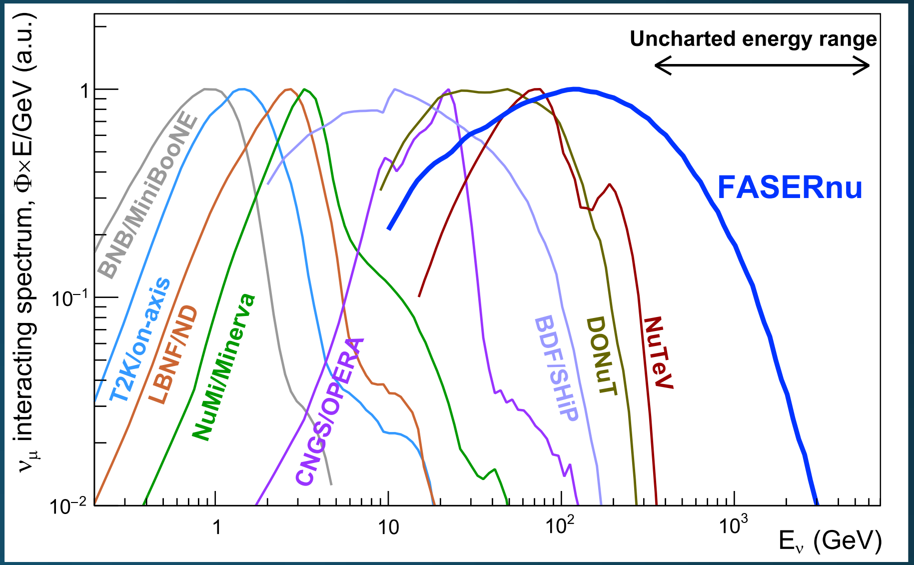
High energy frontier

Neutrino energy

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

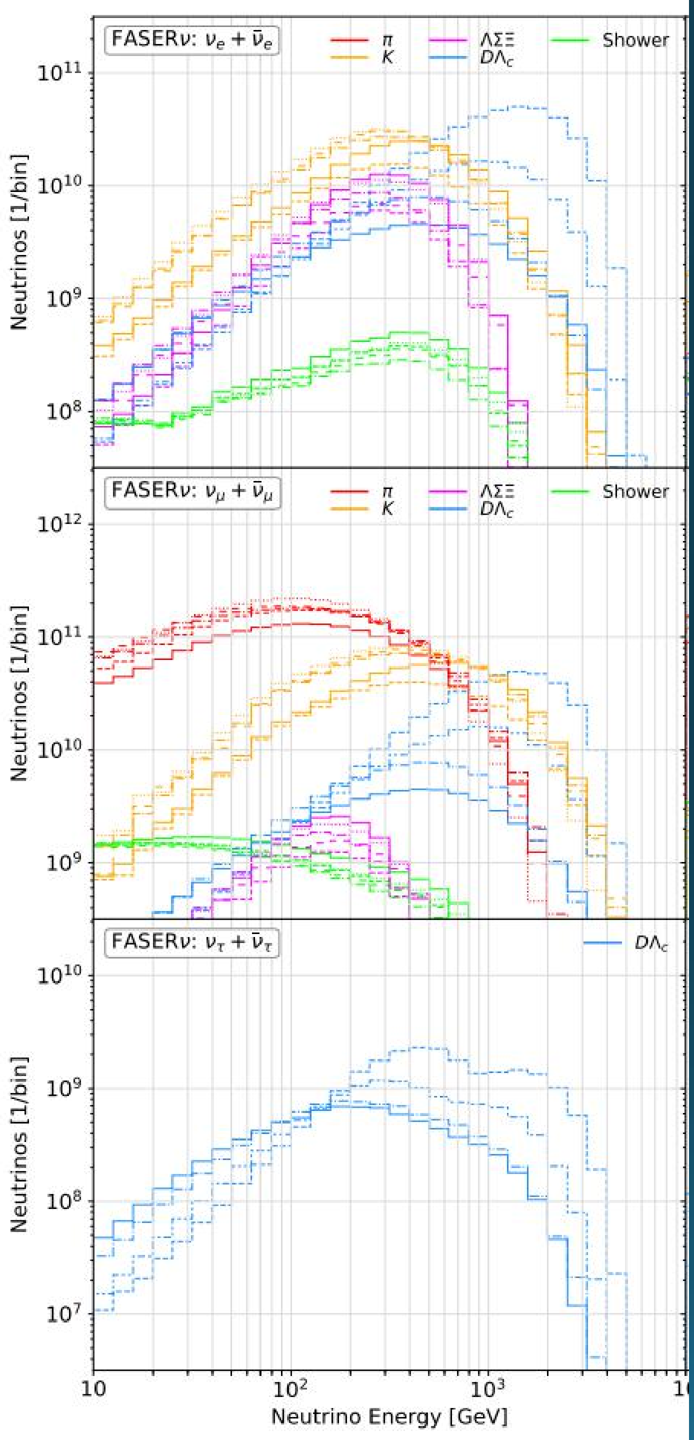
FASERν Up to ~5 TeV $(\nu_e, \nu_\mu, \nu_\tau)$

Unexplored energy range



Neutrino flux

- Contributions from different 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

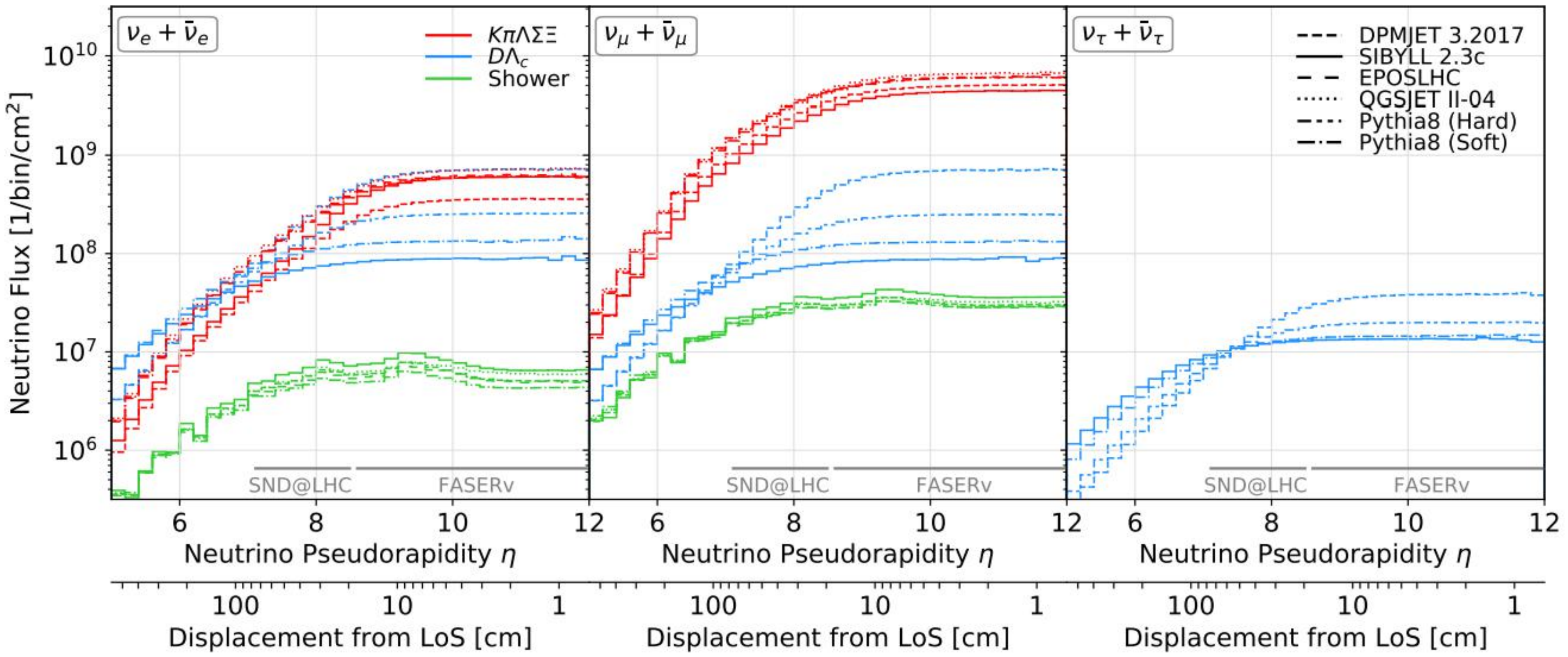
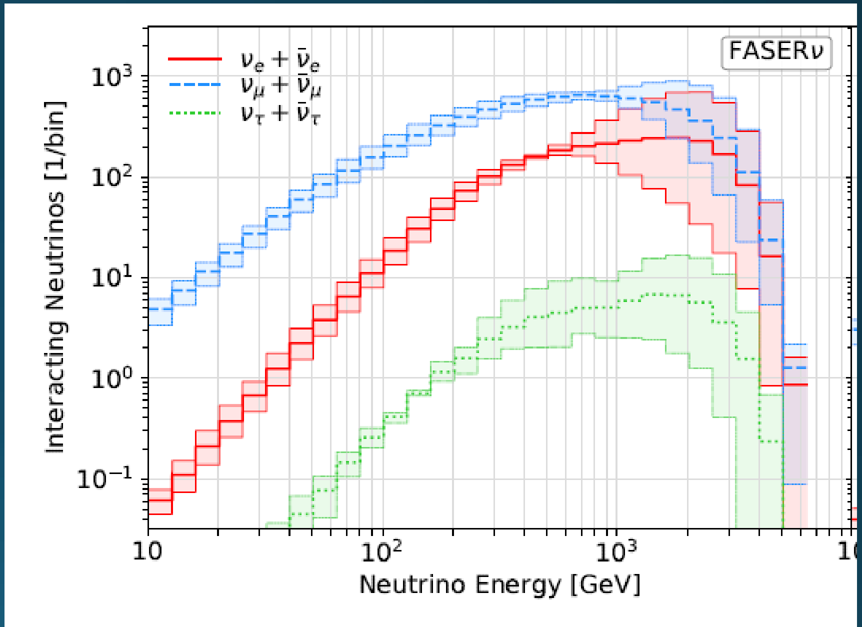


FIG. 3. **Neutrino Angular Distribution:** The panels show the flux for electron (left), muon (center) and tau (right) neutrinos, in units of particles per area per bin, as function of pseudorapidity η, or equivalently the radial displacement from the line of sight (LoS) at $z = 480$ m. The flux components 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.

Neutrino event rates (2022-2024)

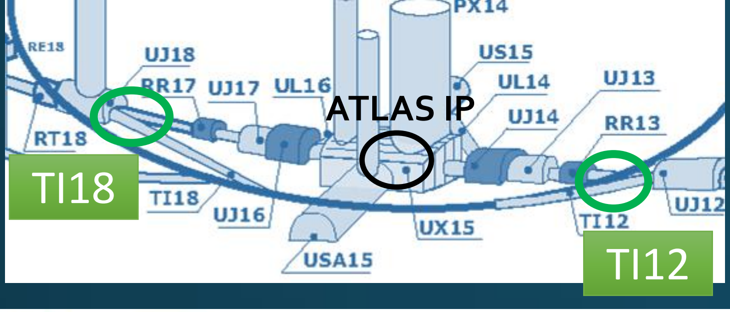
- **Small detector, but a lot of interactions ($\sim 10^4$ CC) are expected during Run3**
- **Neutrino fluxes are being cross-checked among different simulations**
  - Differences due to hadron generators and beamline infrastructure reproduction were identified. Currently, differences at hadron generators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



Expected number of CC interactions in FASERν in Run3 (14 TeV LHC, 150 fb^{-1})

	SIBYLL	Pythia 8	DPMJET (used in FLUKA)
ν_e , $\bar{\nu}_e$	800, 452	826, 477	3390, 1024
ν_μ , $\bar{\nu}_\mu$	6571, 1653	7120, 2178	8437 , 2737
ν_τ , $\bar{\nu}_\tau$	16, 6	22, 11	111 , 43

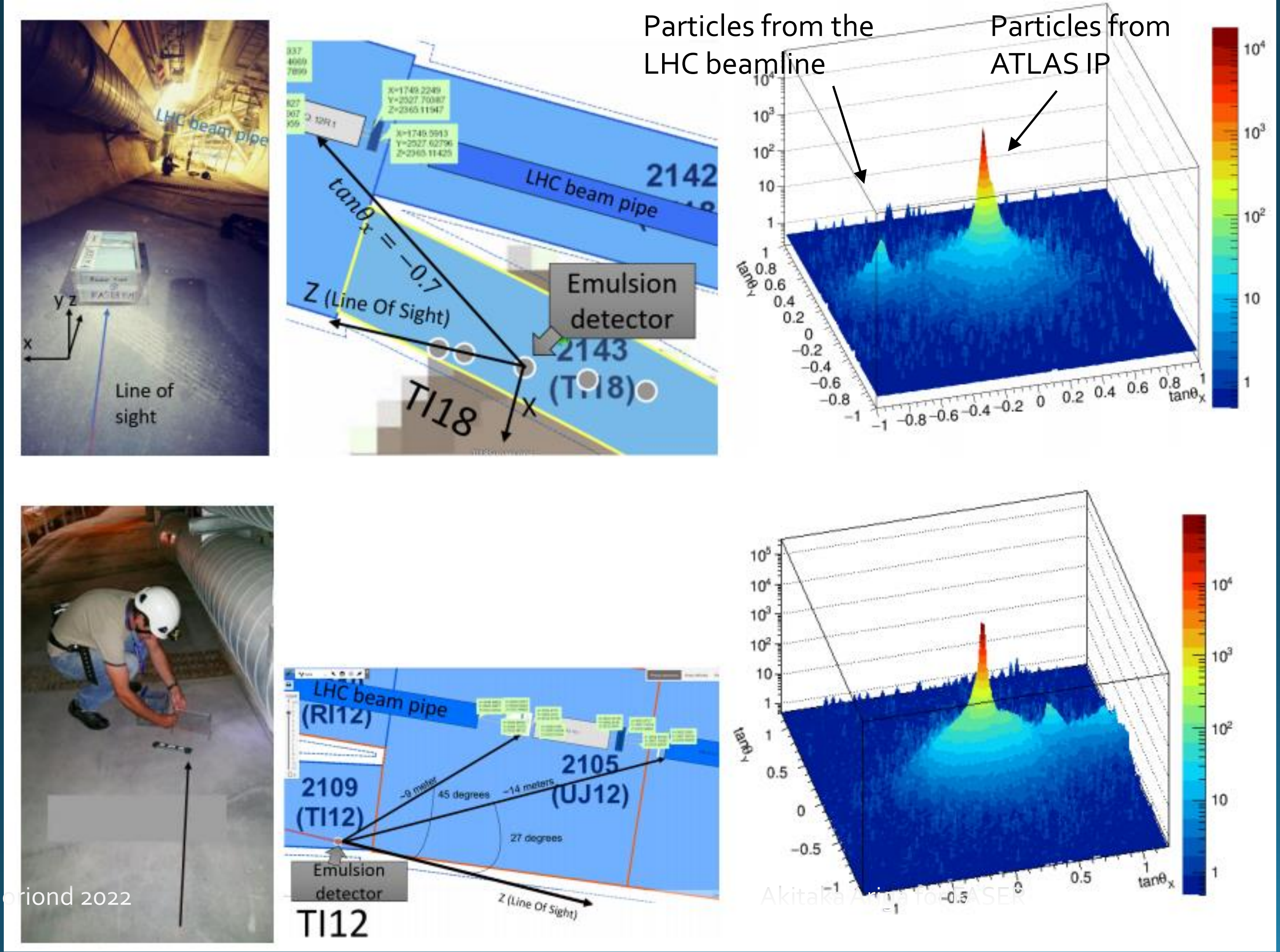
- **Work in progress for quantifying and reducing these uncertainties**
  - Creating a dedicated forward physics tune with Pythia8, using forward data (LHCf, FASER's muon measurements, etc.)



In situ measurements in 2018: Charged particle background

TI18

TI12

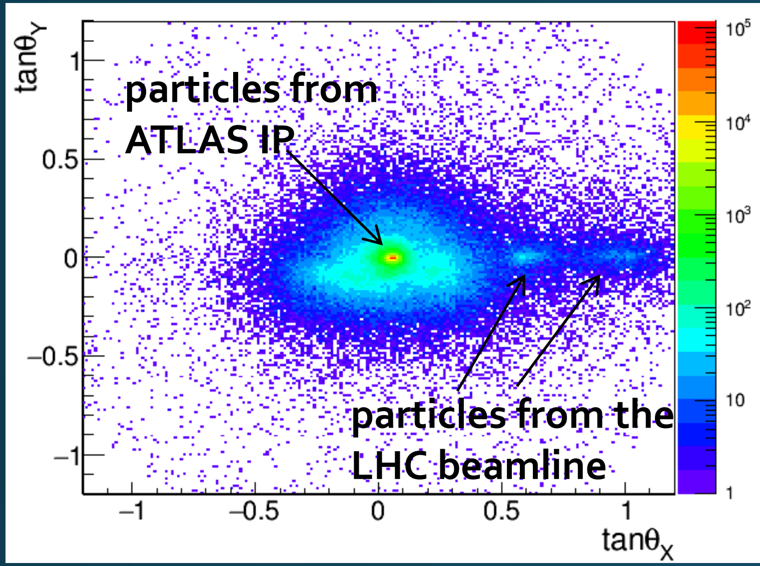


- Emulsion detectors were installed to investigate TI18 and TI12.
- **Low background was confirmed.**
- Few hadron tracks
- Consistent with the FLUKA prediction.

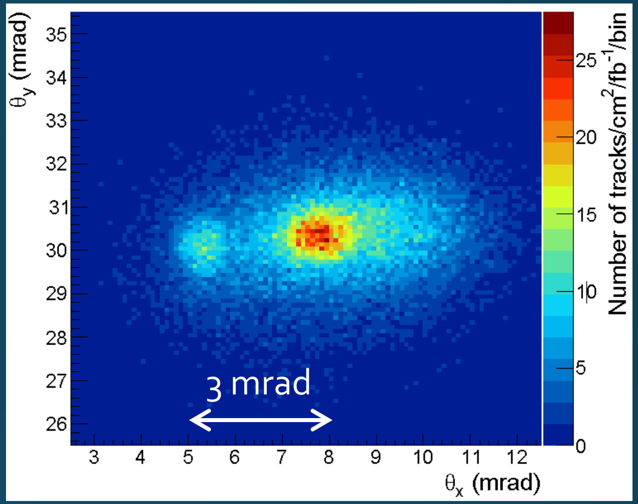
	Normalized flux (tracks/fb^{-1}/cm^2)
TI18	$(2.6 \pm 0.7) \times 10^4$
TI12	$(3.0 \pm 0.3) \times 10^4$

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



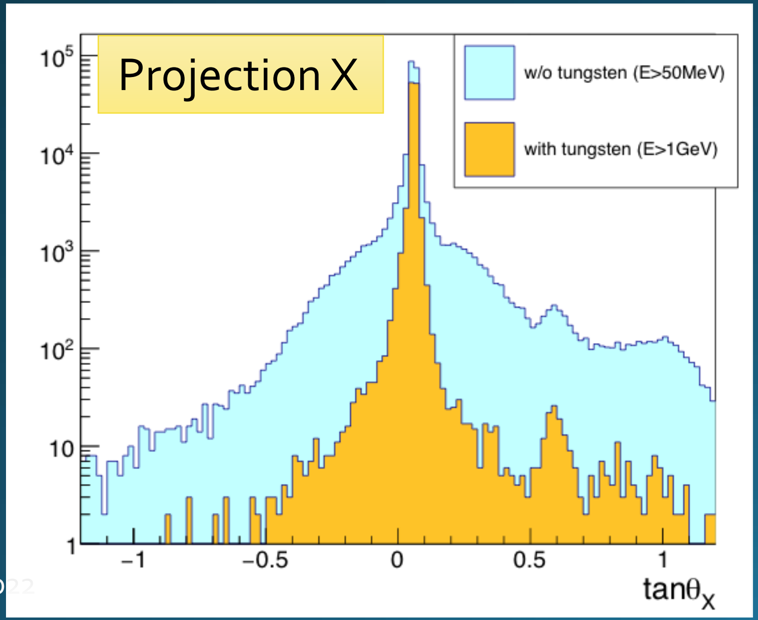
Close up to the main peak (TI-18)



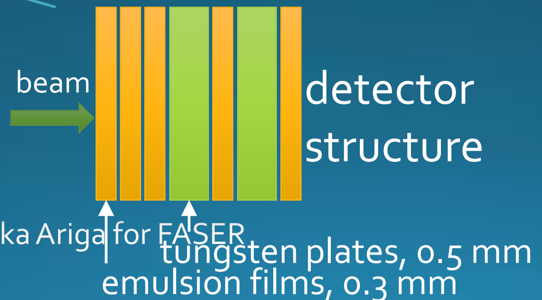
2 peak structure

$\sigma = 0.6\ mrad$

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



	Flux in main peak [fb/cm²]
TI18 data	$1.7 \pm 0.1 \times 10^4$
TI12 data	$1.9 \pm 0.2 \ \times 10^4$
FLUKA MC	$2.5 \ \times 10^4$ (uncertainty 50%)

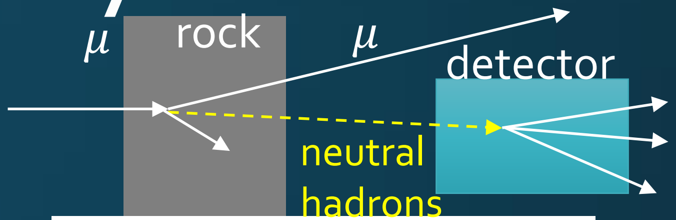


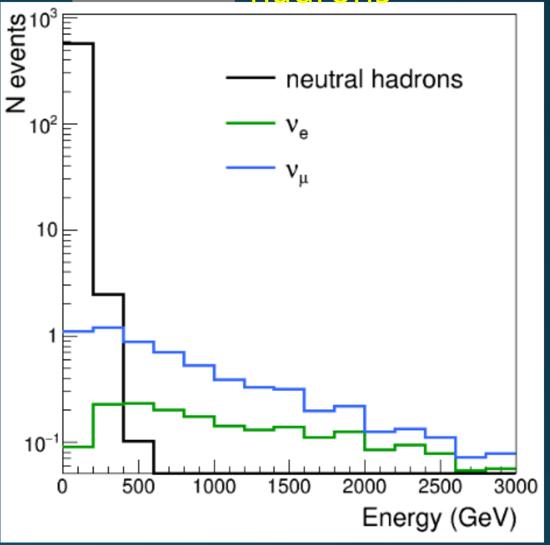
Data and the FLUKA prediction agrees within their uncertainties.

Phys. Rev. D 104, L091101 (2021)

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})
- Pilot neutrino detector doesn't have lepton ID
  - → Separation from neutral hadron BG (produced by muons) is challenging → tighter cuts
- The produced neutral hadrons are low energy → Discriminate by event topology





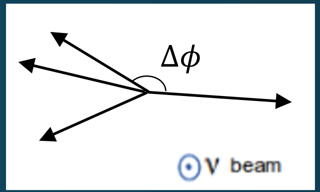
	Negative Muons	Positive Muons
K_L	3.3×10^{-5}	9.4×10^{-6}
K_S	8.0×10^{-6}	2.3×10^{-6}
n	2.6×10^{-5}	7.7×10^{-6}
$\bar{n}$	1.1×10^{-5}	3.2×10^{-6}
Λ	3.5×10^{-6}	1.8×10^{-6}
$\bar{\Lambda}$	2.8×10^{-6}	8.7×10^{-7}

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

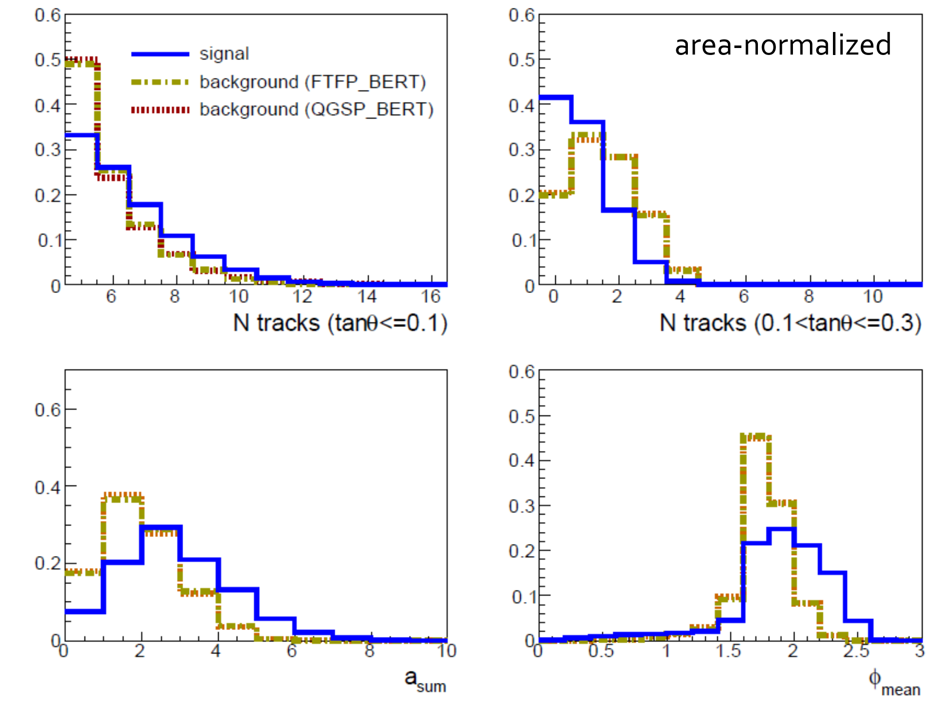
Vertex detection efficiency

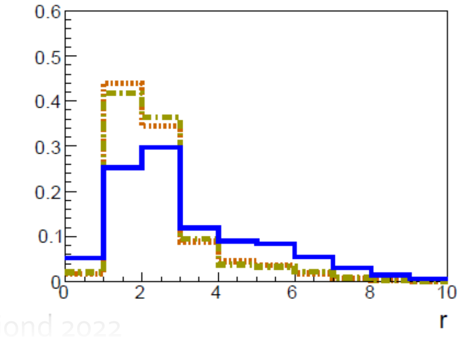
Signal		Background		
			FTFP_BERT	QGSP_BERT
ν_e	0.490	K_L	0.017	0.015
$\bar{\nu_e}$	0.343	K_S	0.037	0.031
ν_μ	0.377	n	0.011	0.012
$\bar{\nu_\mu}$	0.266	$\bar{n}$	0.013	0.013
ν_τ	0.454	Λ	0.020	0.021
$\bar{\nu_\tau}$	0.368	$\bar{\Lambda}$	0.018	0.018

Variables for MVA



Expected distributions of the variables





5 variables used in the analysis

1. the number of tracks with tanθ<=0.1 with respect to the beam direction
2. the number of tracks with 0.1<tanθ<=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).

Multiplicity and Pseud rapidity distribution

Momentum balance

Back-to-back kinematics at vertex

Conceptually why these variables are good:

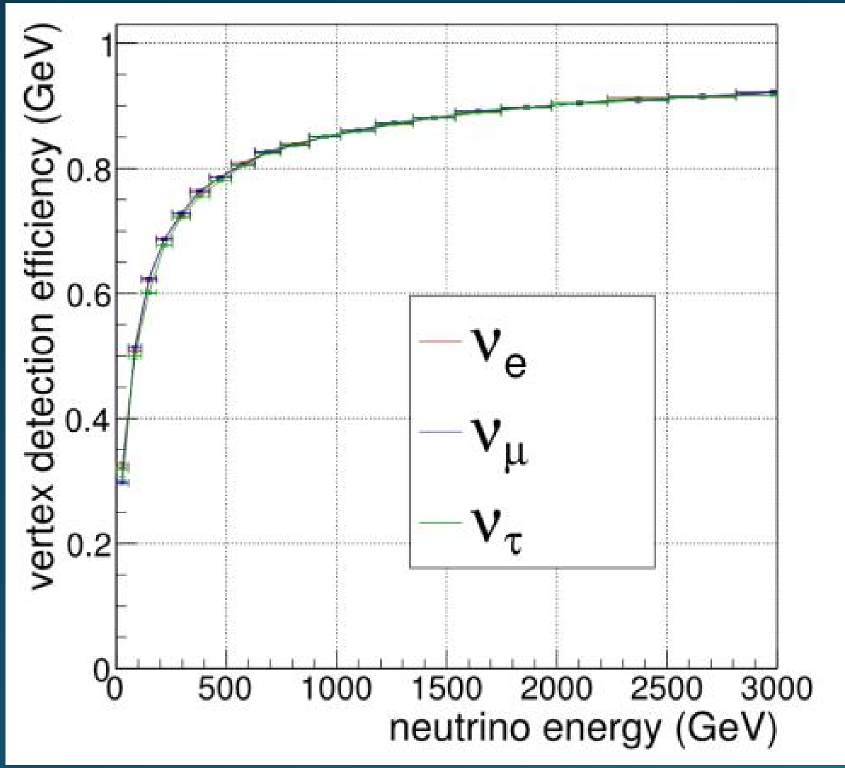
Variable 1, 2: The neutrino energy is higher than the neutral hadron energy. Higher energy, more particles are produced in forward direction, i.e. tan(theta)<0.1 (var 1), and higher ratio of var1/var2.

Variable 3: 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.

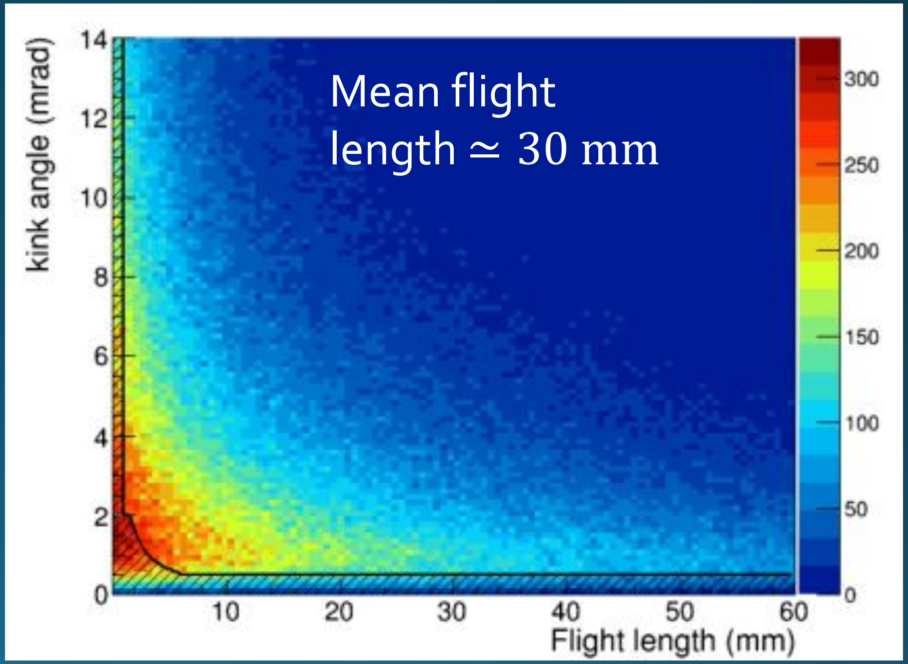
Variable 4, 5: For CC interactions, we expect the outgoing lepton and hadron system are back to back in the transverse plane.

Detection efficiency

Vertex detection efficiency
(charged multiplicity>=5)



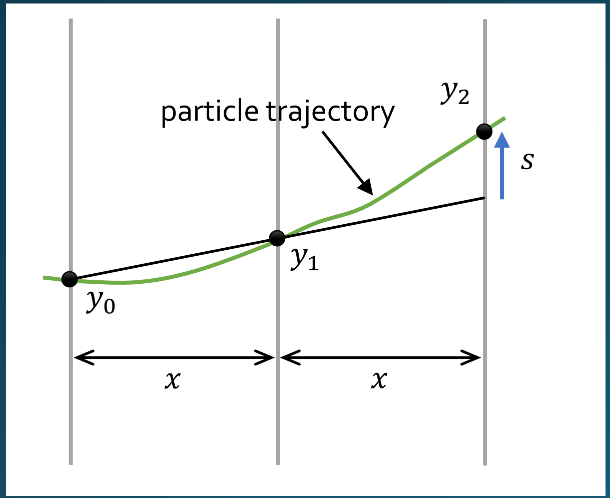
Tau decay detection efficiency
=75% ($\tau \rightarrow 1$ prong)



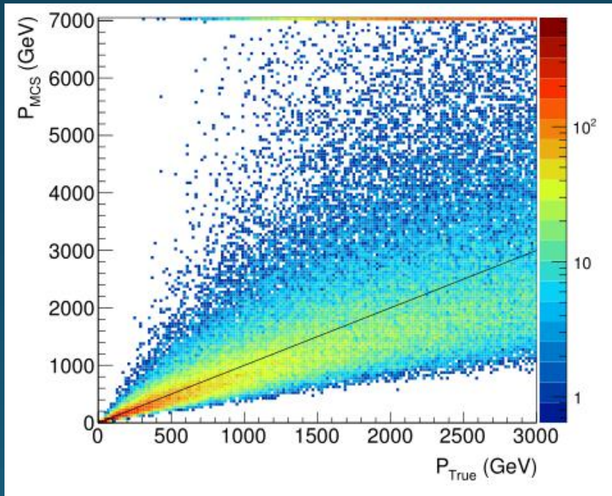
Particle momentum measurement

by multiple Coulomb scattering (MCS)

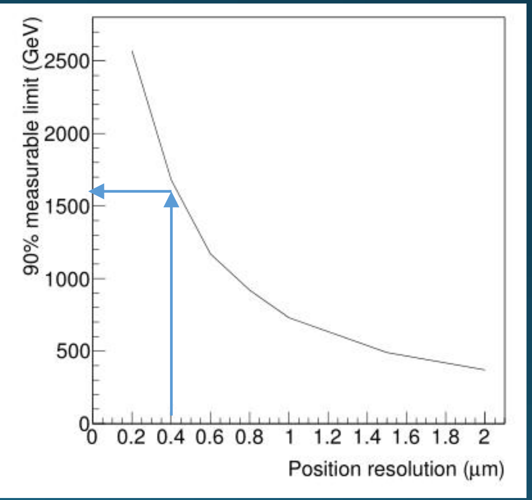
- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle momenta by MCS, even above 1 TeV.



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



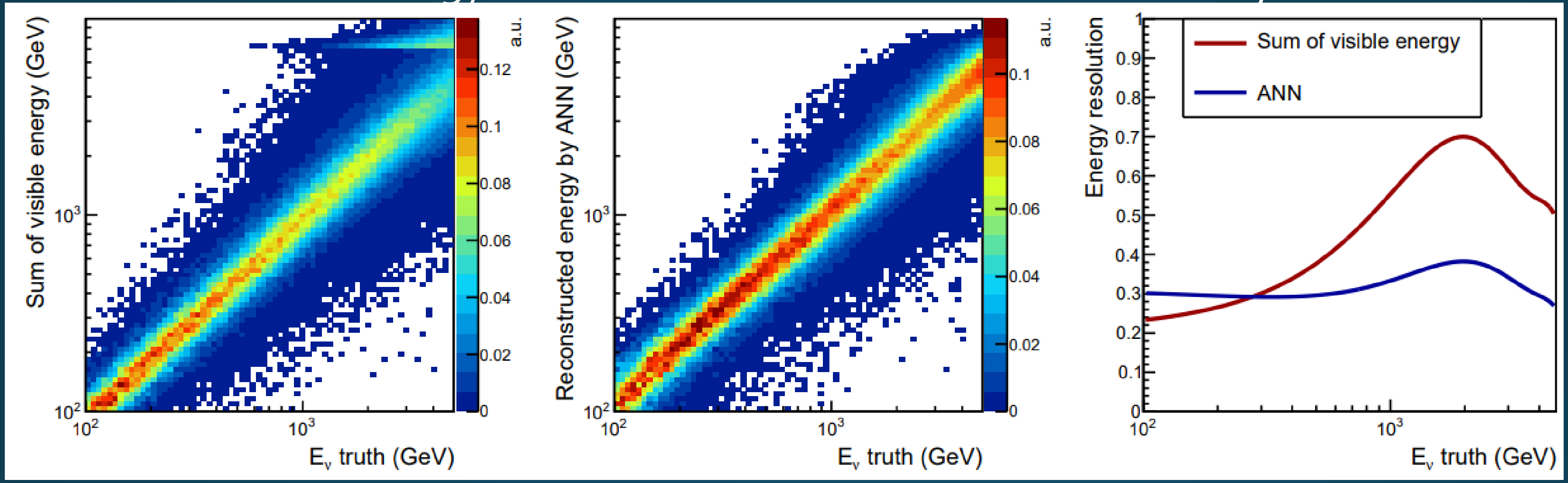
Performance with position resolution of 0.4 μm, in 100 tungsten plates (MC)



Measurable energy vs position resolution

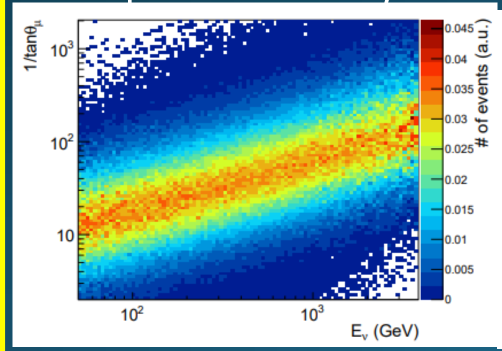
Energy reconstruction (ν_μ CC)

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

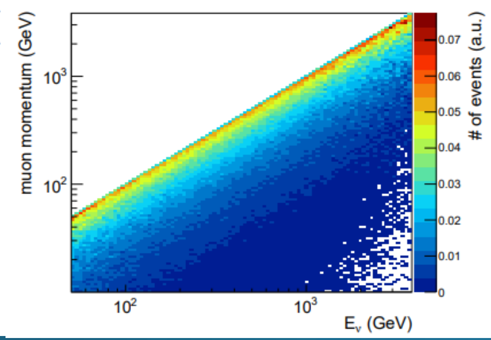


(smeared)

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.

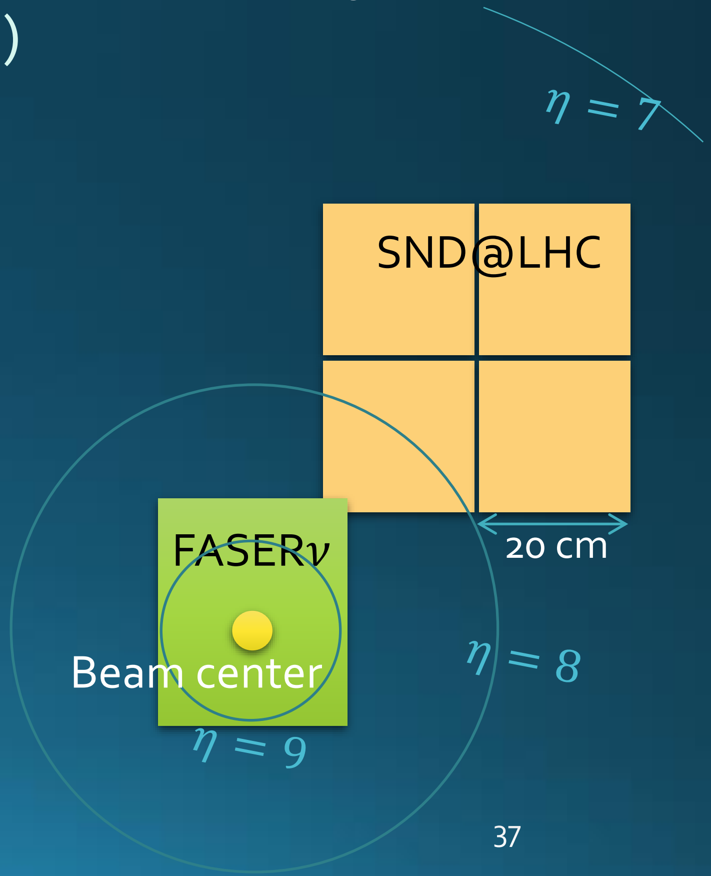
Neutrino physics

- Neutrino spectra at unexplored energy range
  - Study production / propagation / interaction
  - CC 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)

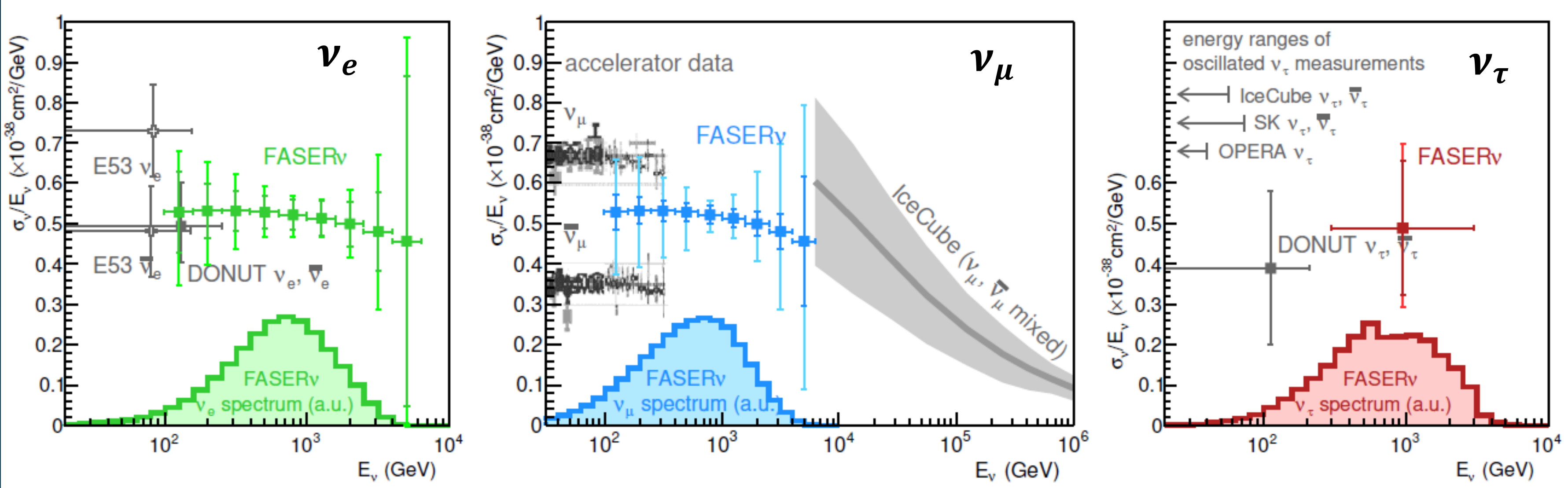
Expected CC event statistics

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

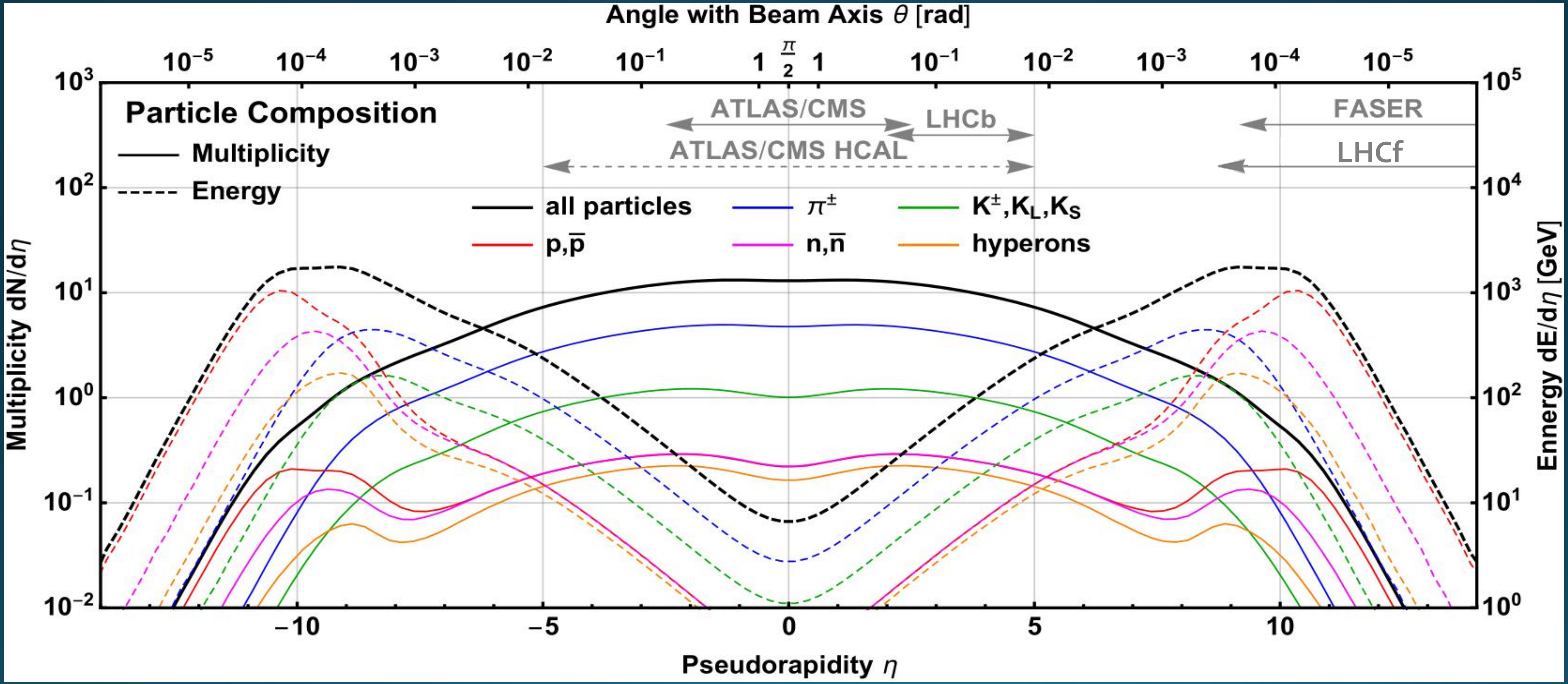


Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})

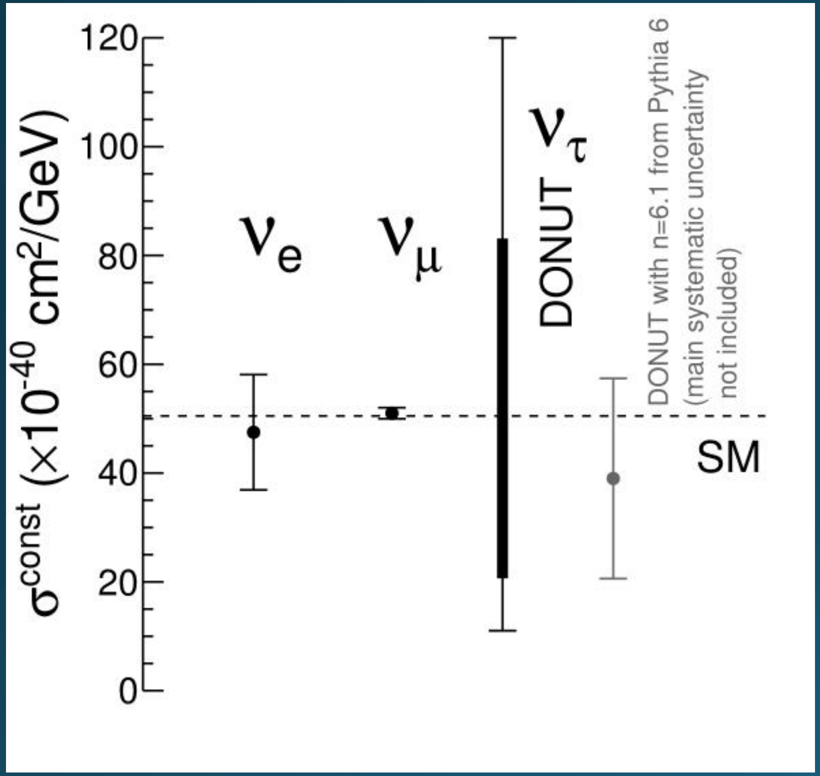


inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.

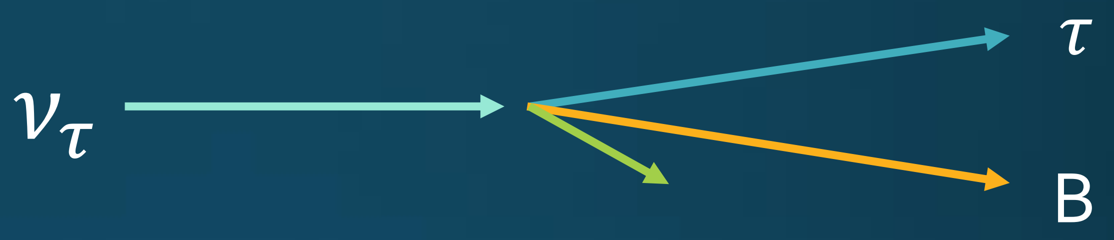
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310


Angle with Beam Axis θ [rad]
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 π/2 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵
Particle Composition
Multiplicity
Energy
ATLAS/CMS
LHCb
ATLAS/CMS HCAL
FASER
LHCf
all particles
π±
K±,KL,KS
p,p̄
n,n̄
hyperons
Multiplicity dN/dη
Ennergy dE/dη [GeV]
Pseudorapidity η

Status of Lepton Universality testing in neutrino scattering



Poor constraint for ν_τ

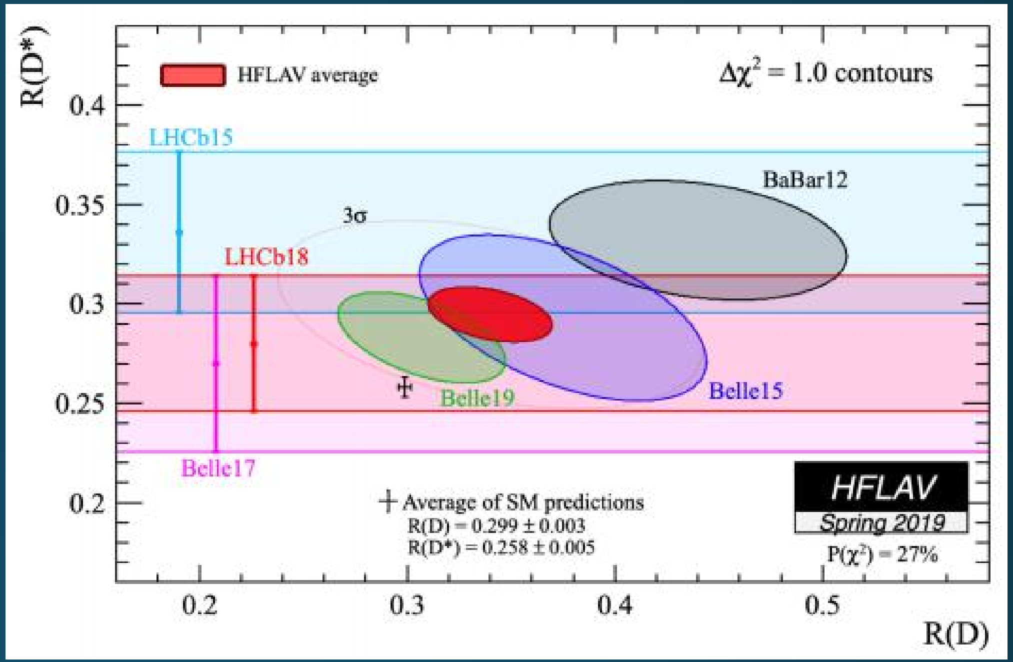


High energy neutrinos ($E_\nu > 100$ GeV) is required to access heavy flavor channels

→ Need high statistics and high energy beam experiment!

“Flavor anomaly”

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

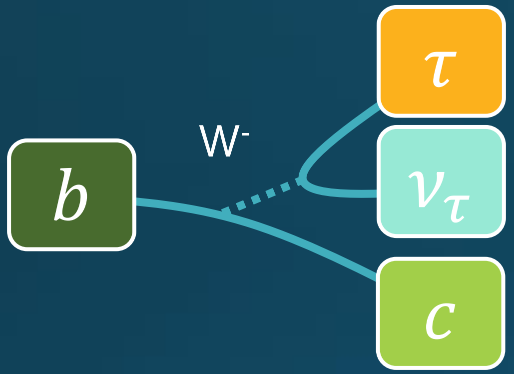


Possible contribution from new physics in heavy flavors!?

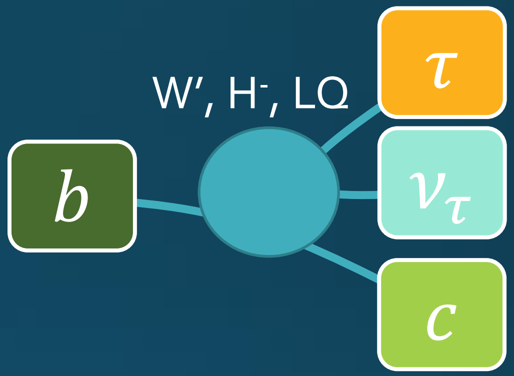
New physics effect?

B decays

SM



NP

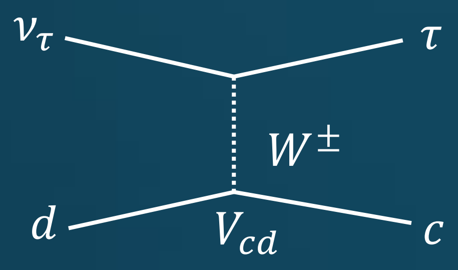


Neutrino CC beauty production

Why leptons are universal?
Why we have 3 generations?
Anything special for 3rd generation?

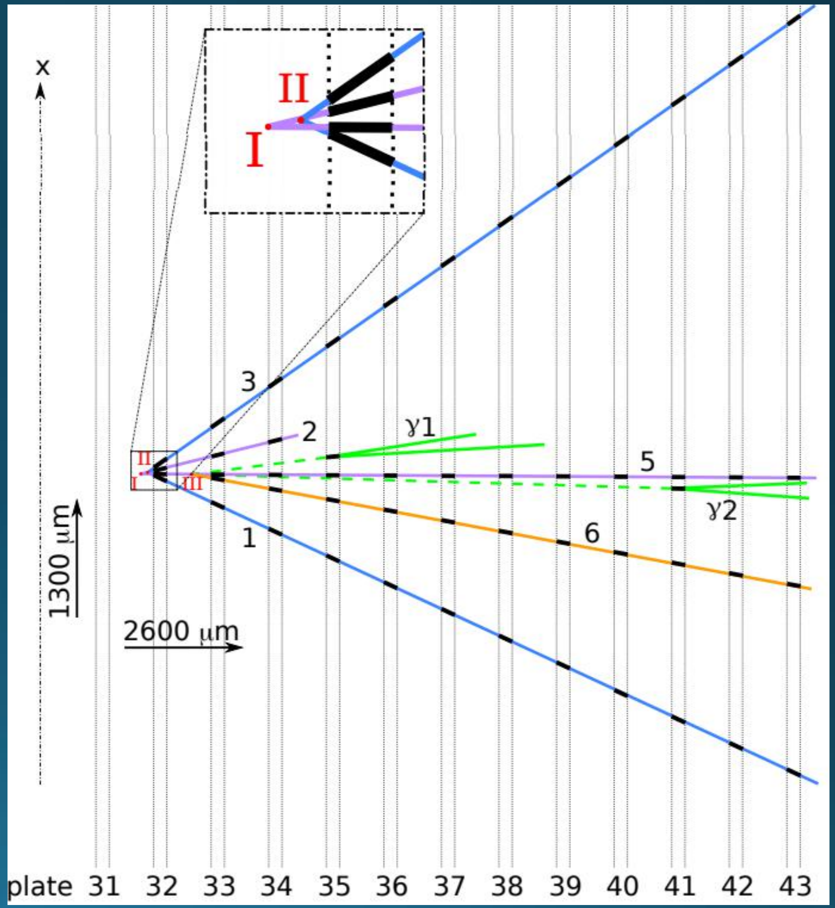
OPERA's ν_τ induced charm production event

SM process,
charm production
via mixing



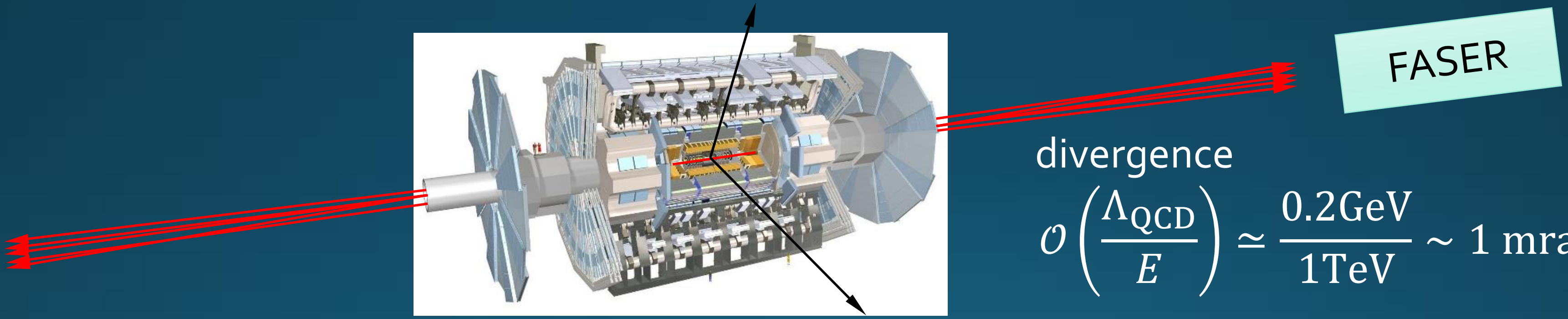
Well measured for ν_μ

- 1 event was observed <u>with surprise</u>
- Expectation:
  - Signal 0.04
  - Background <0.05
- Could also be a hint of new physics!?



FASER: ForwArd Search ExpeRiment at the LHC

- ATLAS and CMS searches focus on high p_T → appropriate for heavy, strongly interacting particles
    - No evidence of new particles is detected so far.
- If new particles are light and weakly interacting to the SM particles (e.g. dark photon), they could be long-lived and collimated in the very forward region → FASER arXiv:1708.09389 , 1811.12522



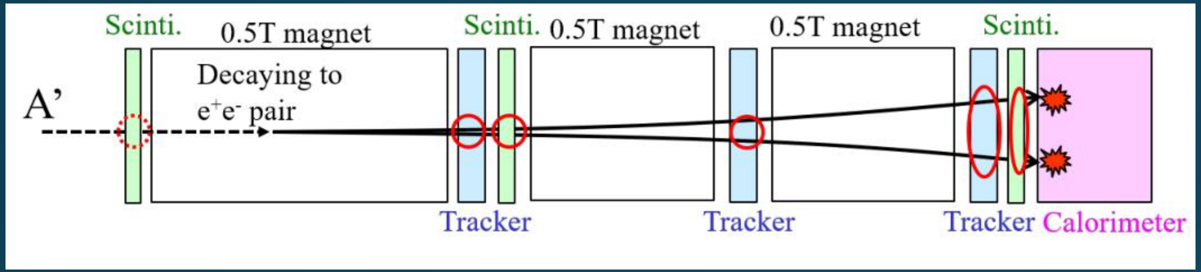
divergence

$$\mathcal{O}\left(\frac{\Lambda_{QCD}}{E}\right) \simeq \frac{0.2\mathrm{GeV}}{1\mathrm{TeV}} \sim 1\ \mathrm{mrad}$$

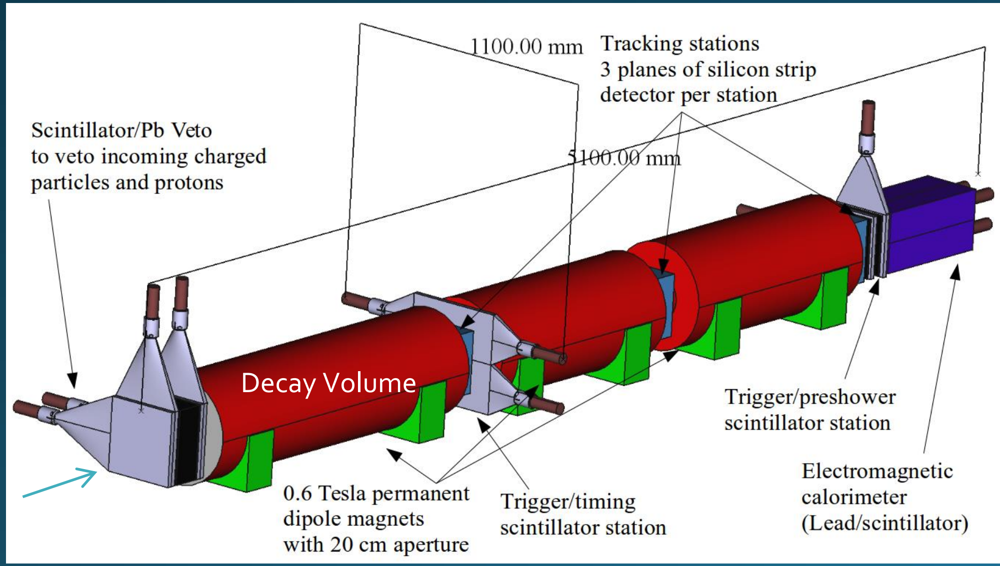
- The LOI (July 2018) and technical proposal (October 2018) were submitted. Approved by CERN in March 2019.
- Preparing for physics run in 2021 (Run3 of the LHC operation)

FASER detector & sensitivity

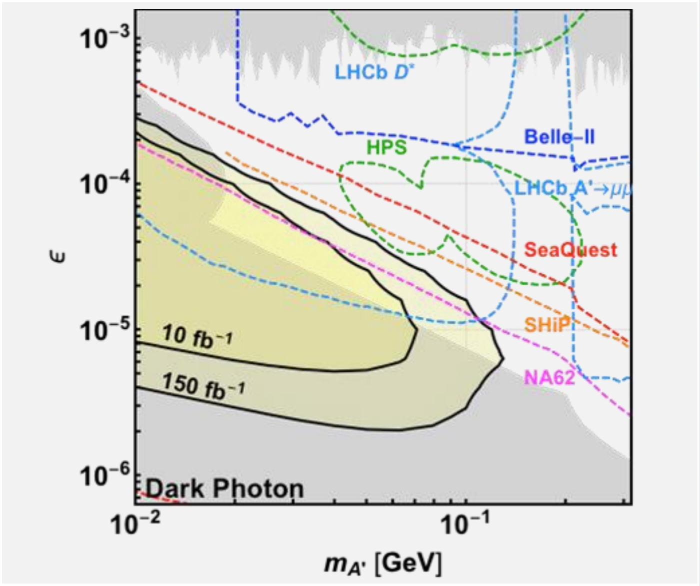
- Dark photon: Photon in dark sector, and it has mass
- Signal: Dark photon decay into e^+e^- pair



Detector schematic (original one without FASERnu)

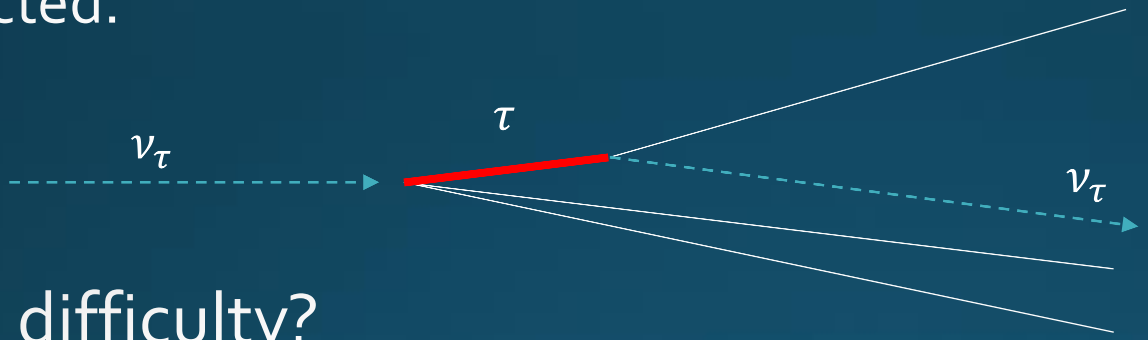


Sensitivity for dark photon search in Run 3



Detecting tau neutrino

- Tau neutrino is one of the most difficult particles to detect.
  - Only 9 events in DONUT (2001) and 10 events in OPERA (2015) were detected.



- What is difficulty?
  - It's neutrino! → Big target mass
  - Tau neutrino always escape measurement from tau decay → Difficult to reconstruct invariant mass
  - Tau is short-lived ($c\tau = 87\mu$m) → Need high precision detector <10 μm

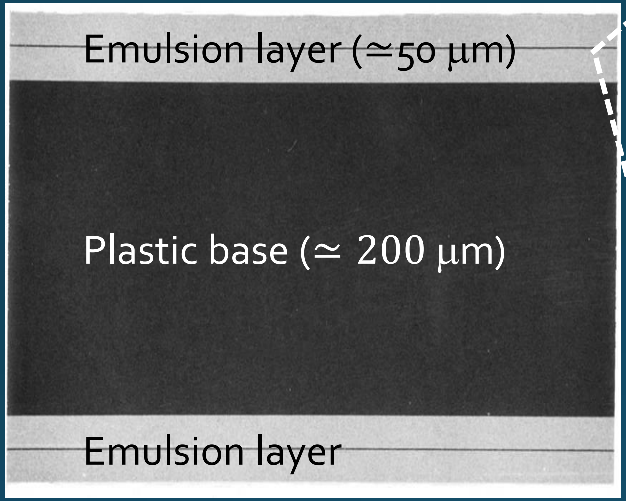
Tons of detector && micrometric precision → Emulsion detector!

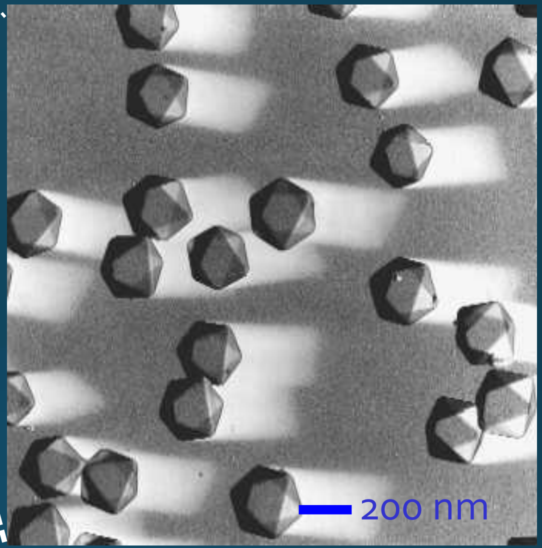
Emulsion detectors:
3D tracking device with 50 nm precision

AgBr crystal = detector
10^{14} channels/film or 10^{14} channels/cm^3

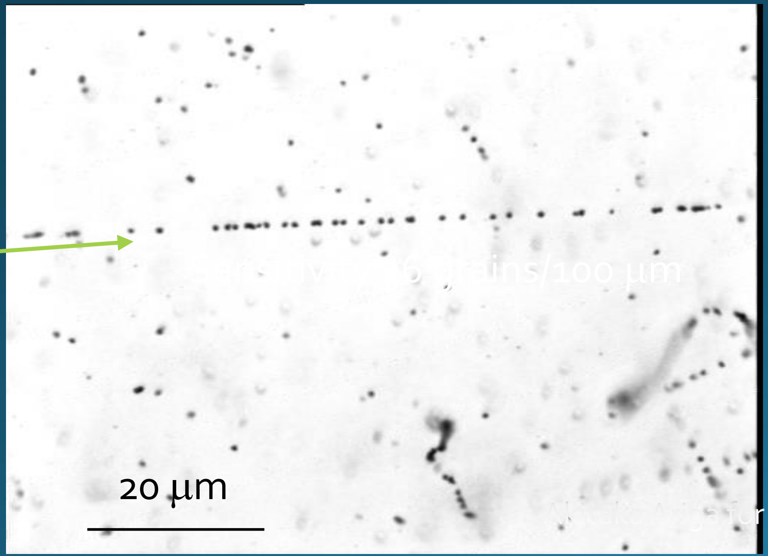
Emulsion film

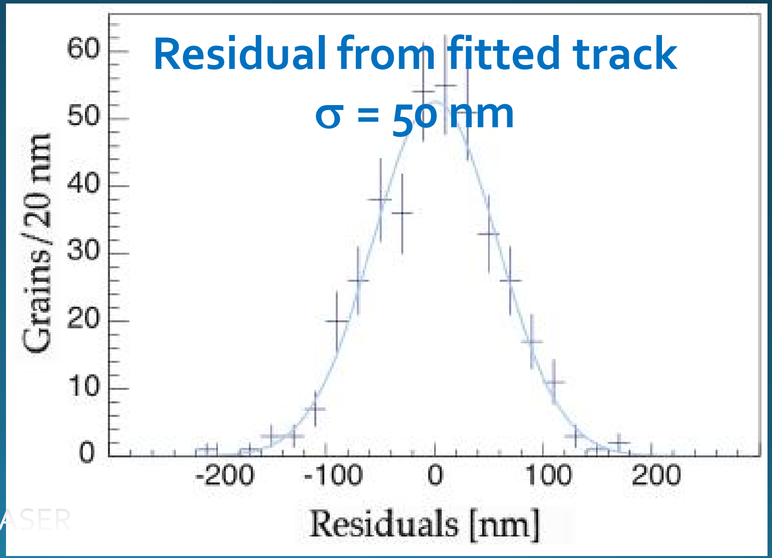
Cross-sectional view



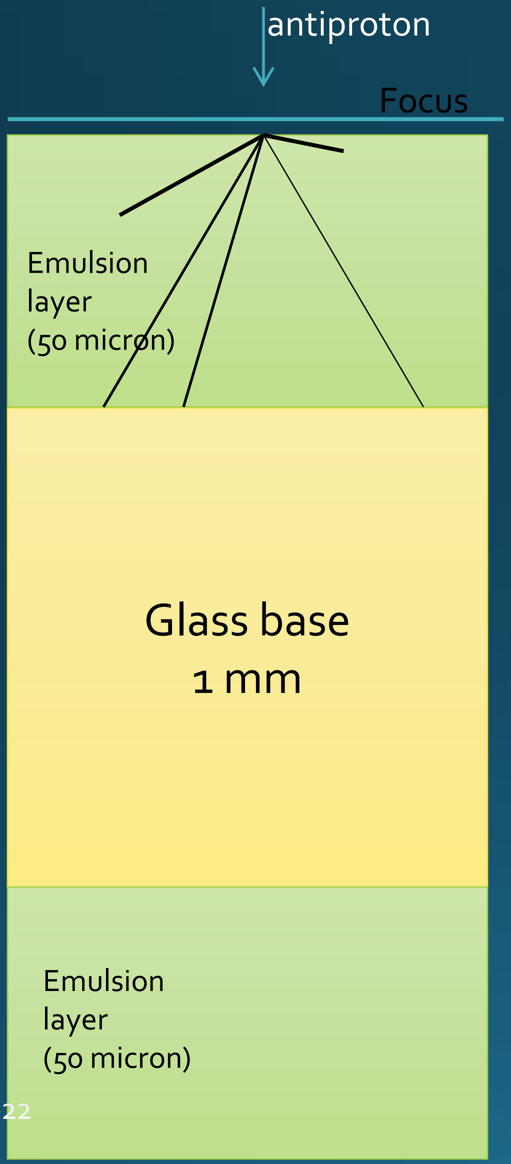


10 GeV/c π beam



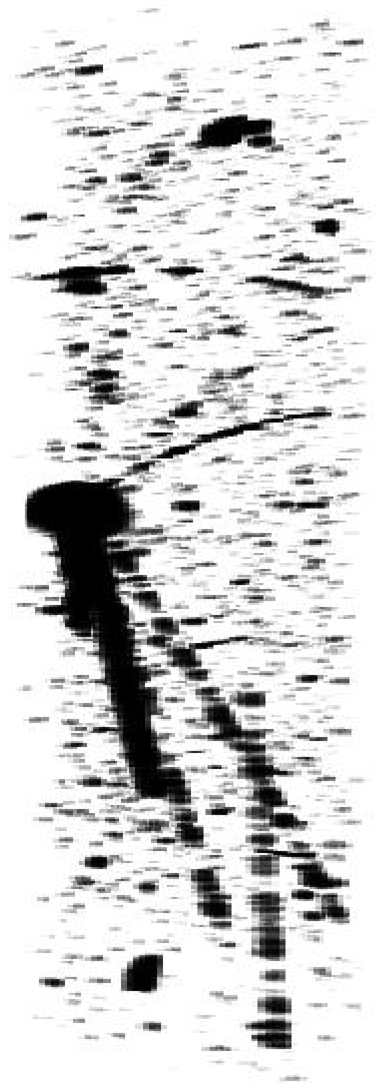


Antiproton annihilation in emulsion



Antiproton annihilation taken in AEgIS 2012

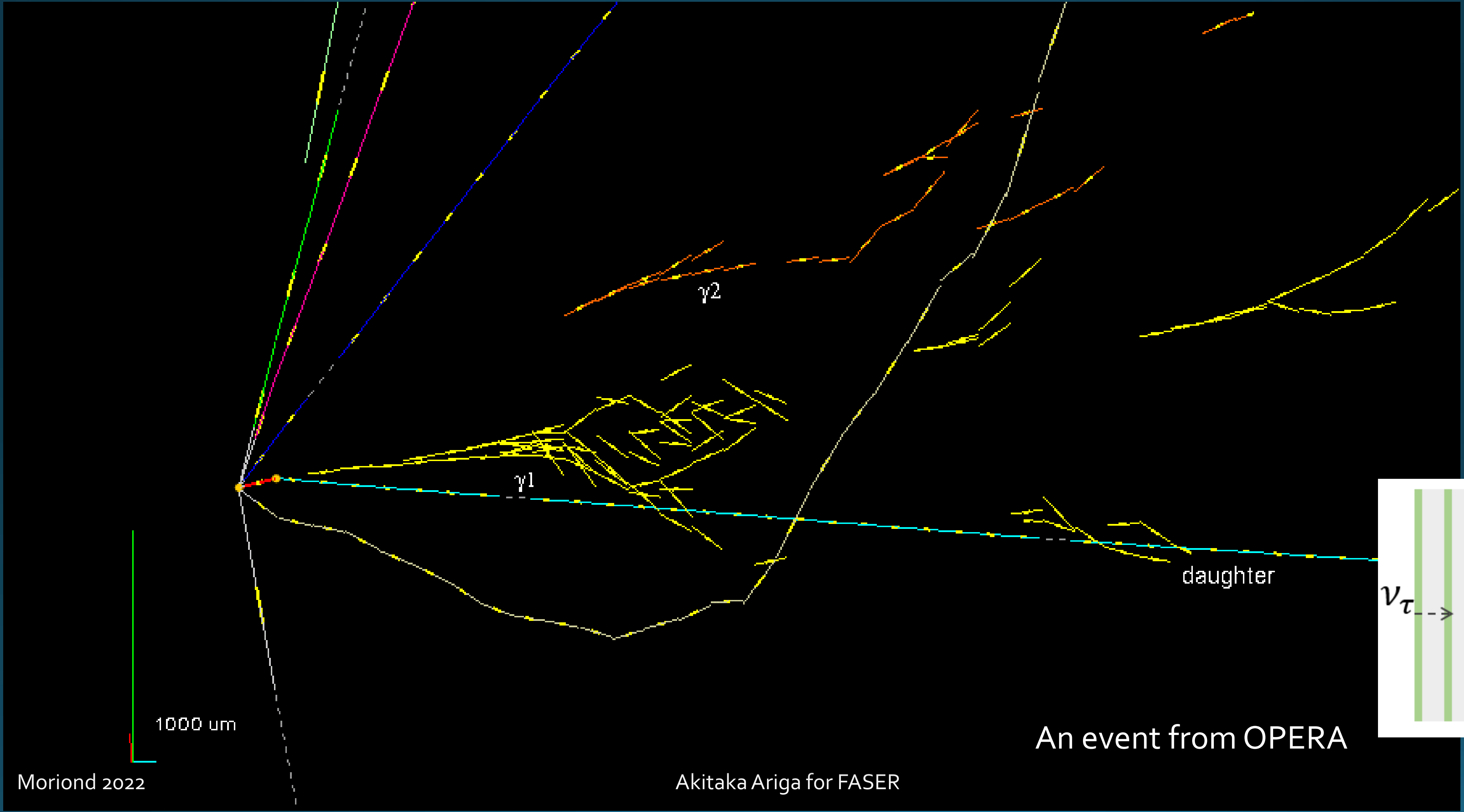
3D view of emulsion detector



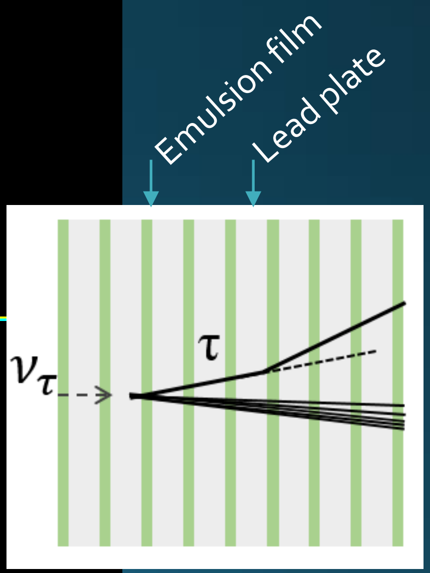
150 μm x 120 μm x 50 μm

- 3D high resolution hits
- Work as tracker
- dE/dx proportional to darkness (Number of grains)

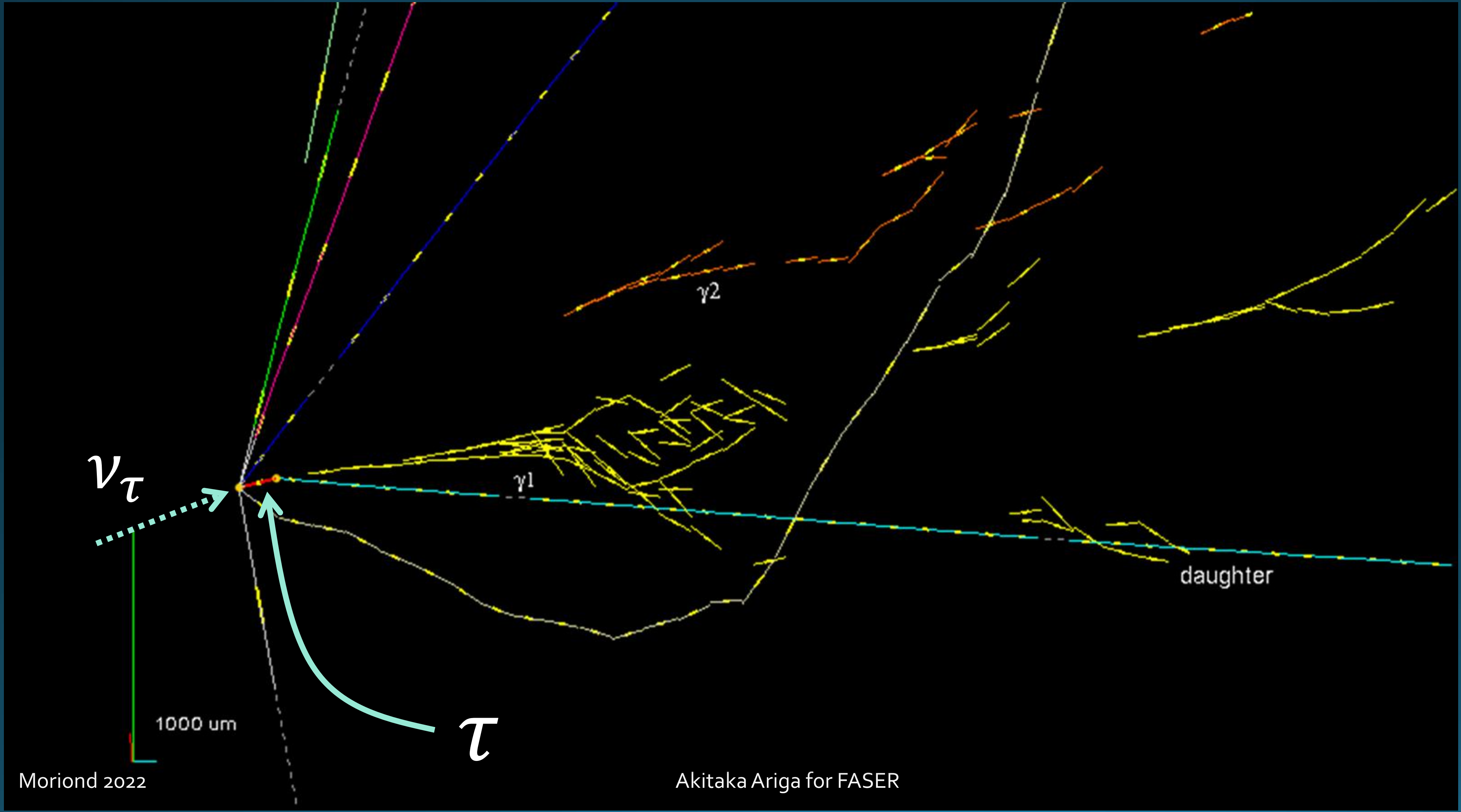
Emulsion-based neutrino detector



An event from OPERA

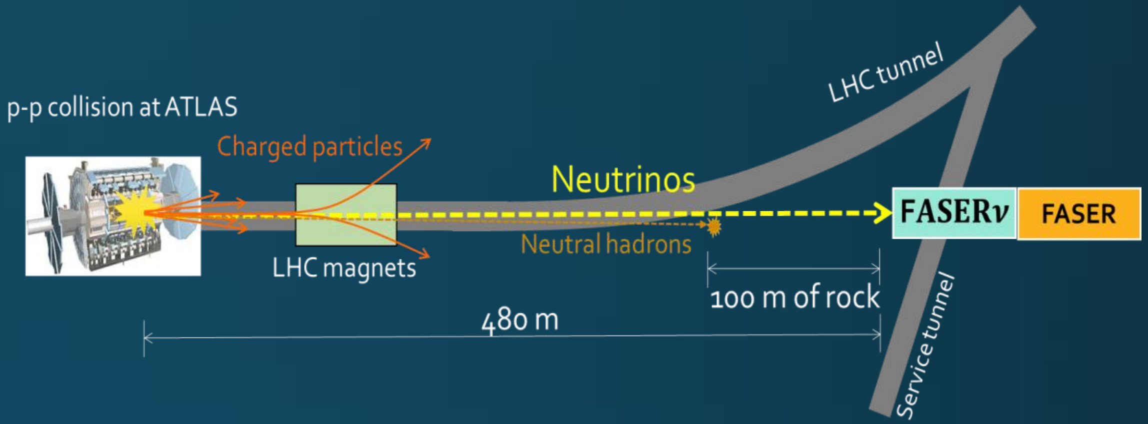


Emulsion-based neutrino detector

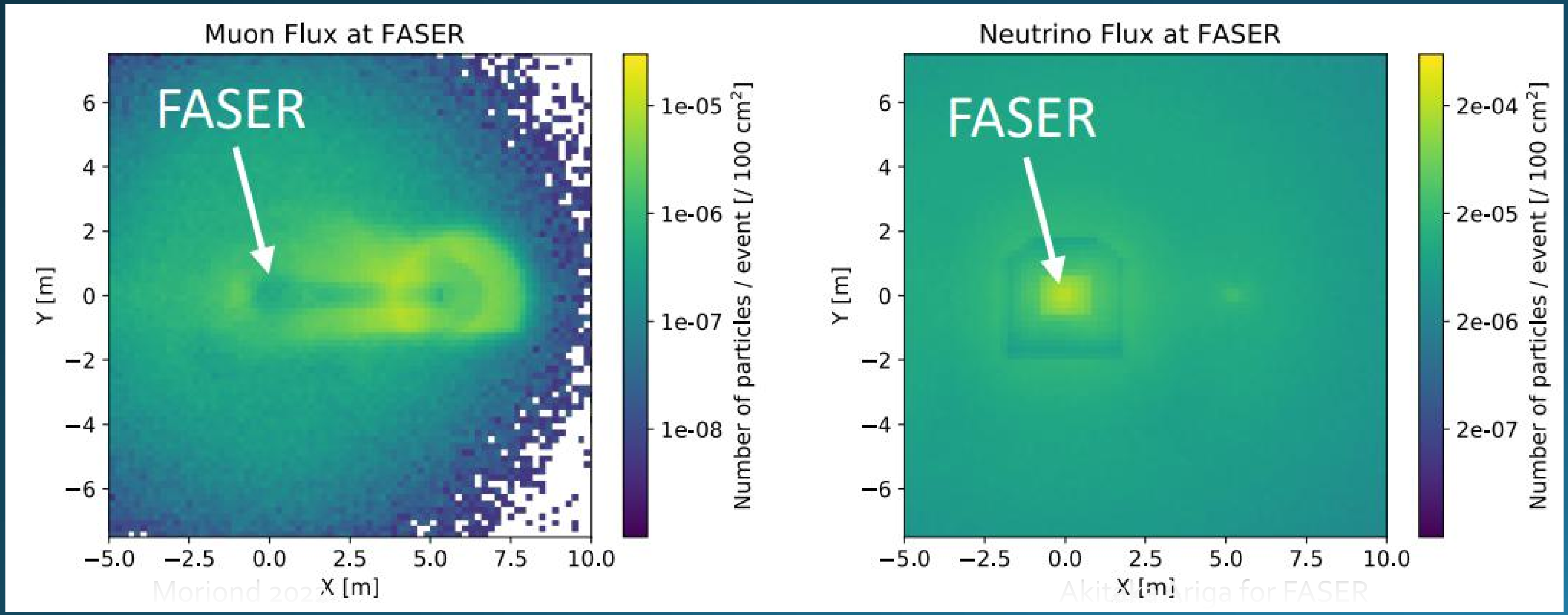


Particle fluence at the site

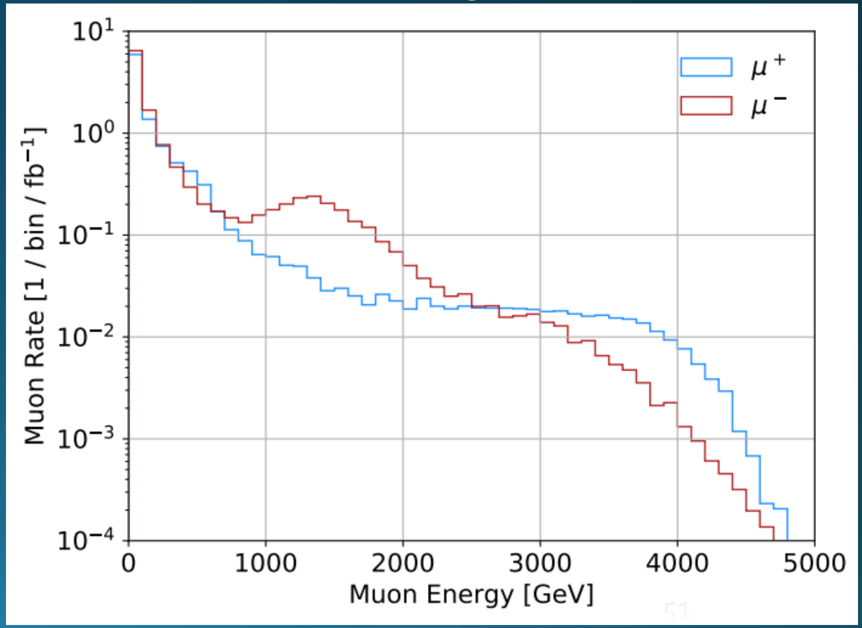
- Crucial for both neutrinos and LLP searches
- Simulation through the LHC infrastructures by FLUKA and BDSim
- Minimum muons, maximum neutrinos



BDSim result for TI12, Lefebvre ICHEP2020



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



FASERν history

2018, in Run 2 of LHC operation

- April, first discussion with FASER project
- June, install emulsion detectors for BG measurement
- July, Found that emulsions can work!
- Sep-Oct, install a pilot neutrino detector and data taking

- Nov, FASER TP

2019

- Jan, First neutral interactions
- Aug, FASERnu LOI
- Oct, FASERnu Technical proposal
- Dec, FASERnu Approval

- Mar, FASER approval
- Aug, FASER LOI
- Nov, FASER TP

10.1140/epjc/s10052-020-7631-5

CERN-EP-2019-160, KYUSHU-RCAPP-2019-003, SLAC-PUB-17460, UCI-TR-2019-19

arXiv:1908.02310v1 [hep-ex] 6 Aug 2019

Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC

FASER Collaboration

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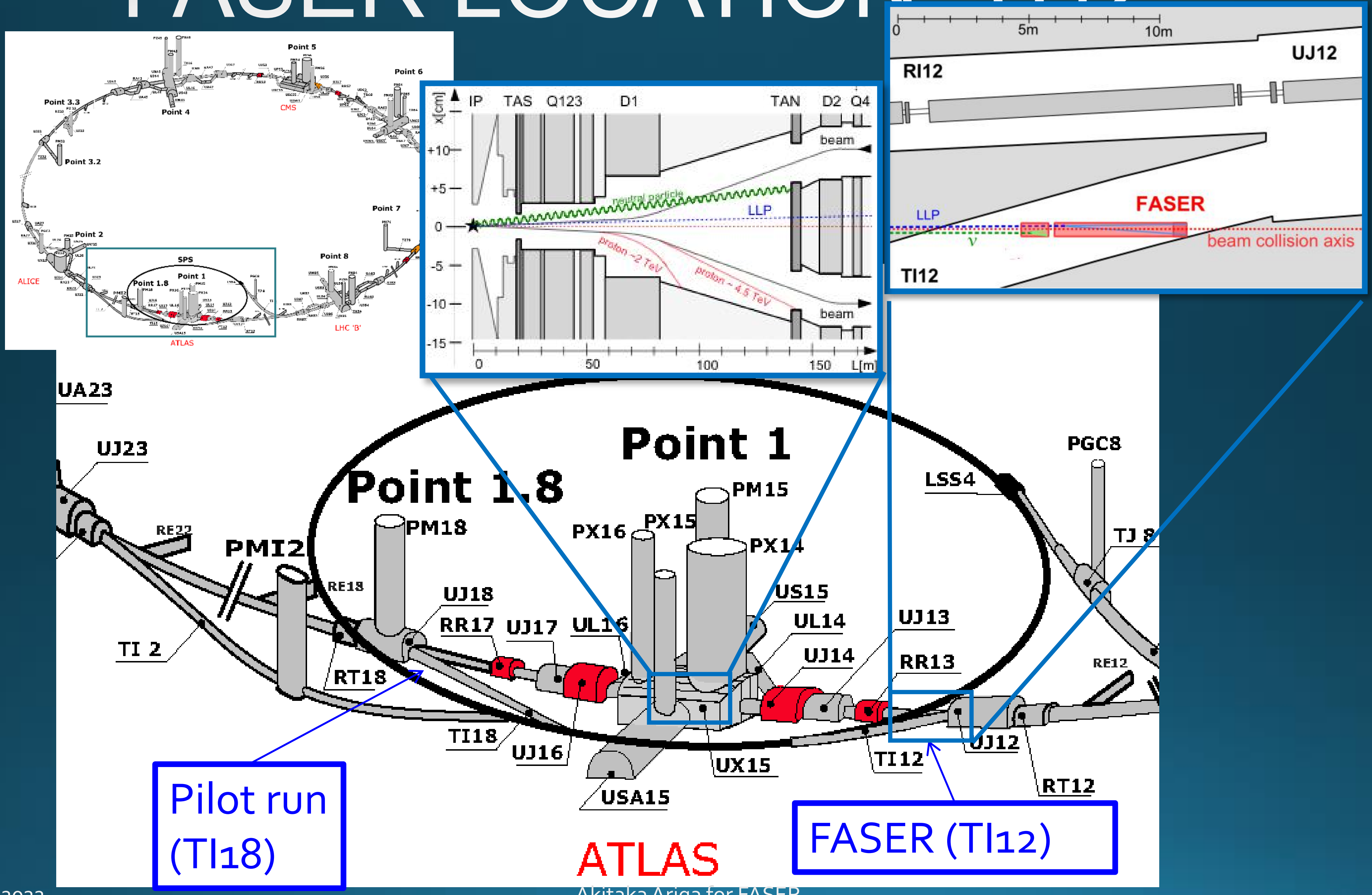
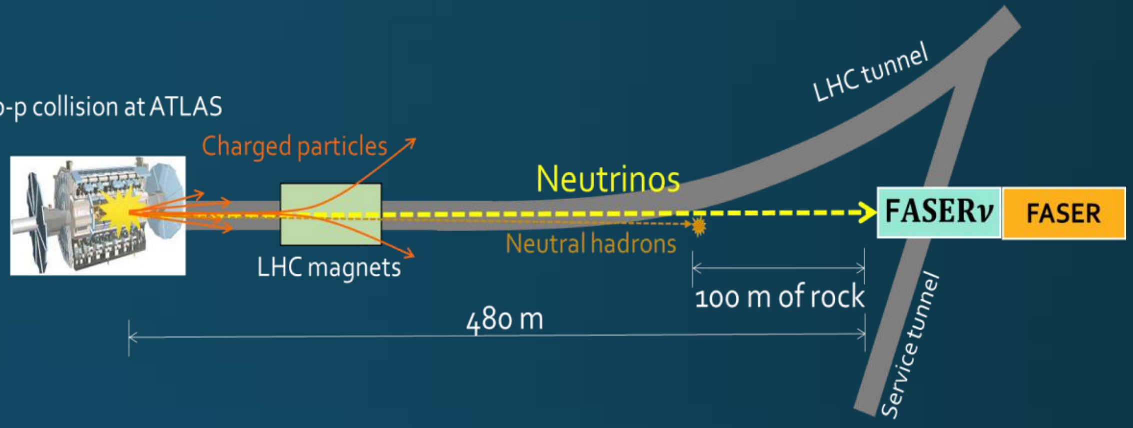
FASER LOCATION: TI12

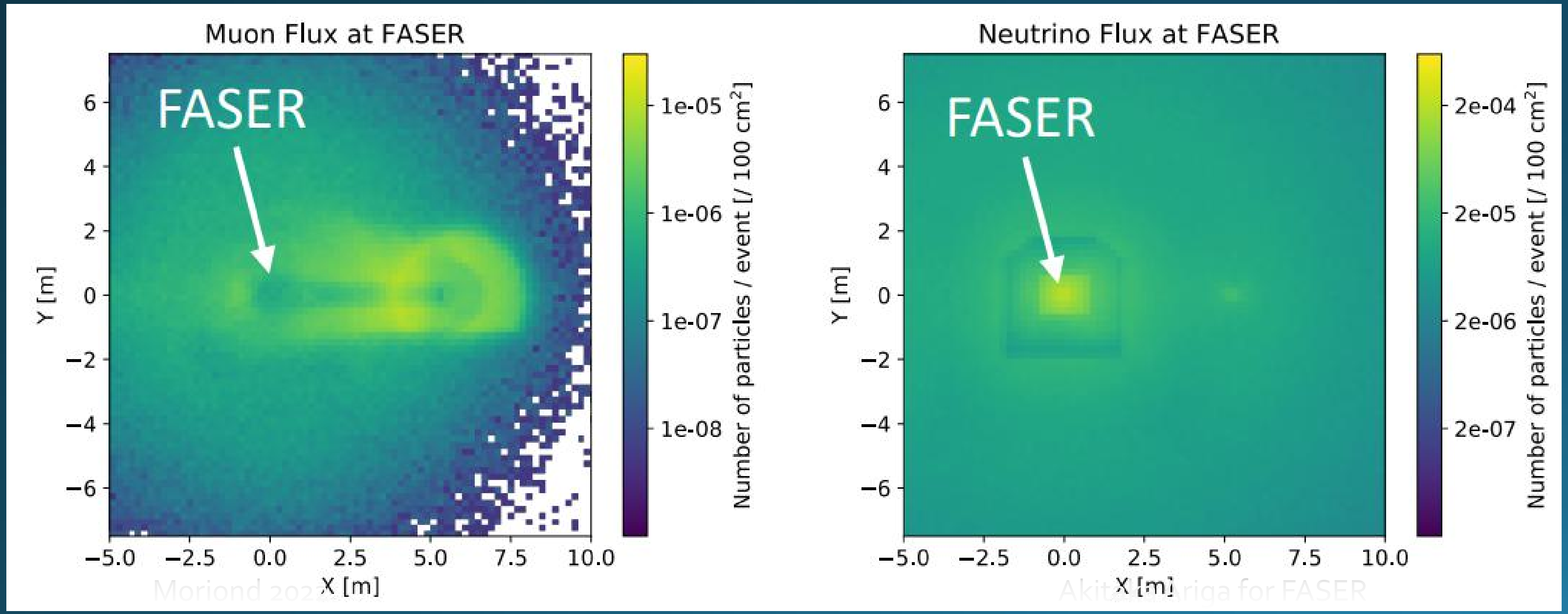


Particle fluence at the site

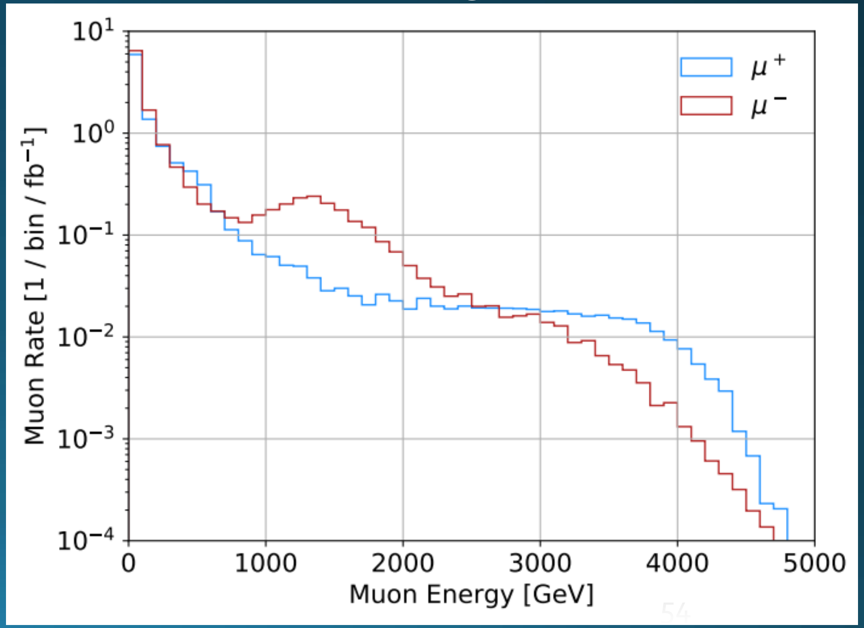
- Crucial for both neutrinos and LLP searches
- Simulation through the LHC infrastructures by FLUKA and BDSim
- Minimum muons, maximum neutrinos

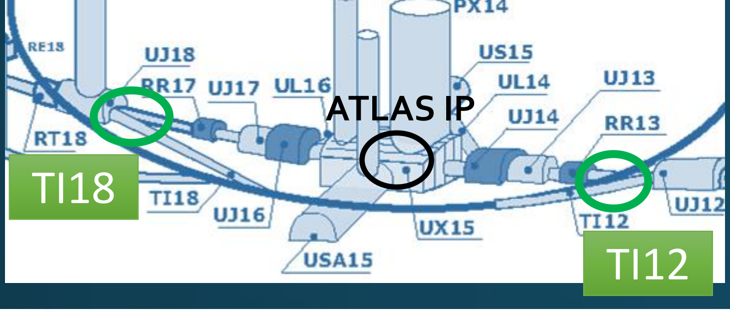


BDSim result for TI12, Lefebvre ICHEP2020



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

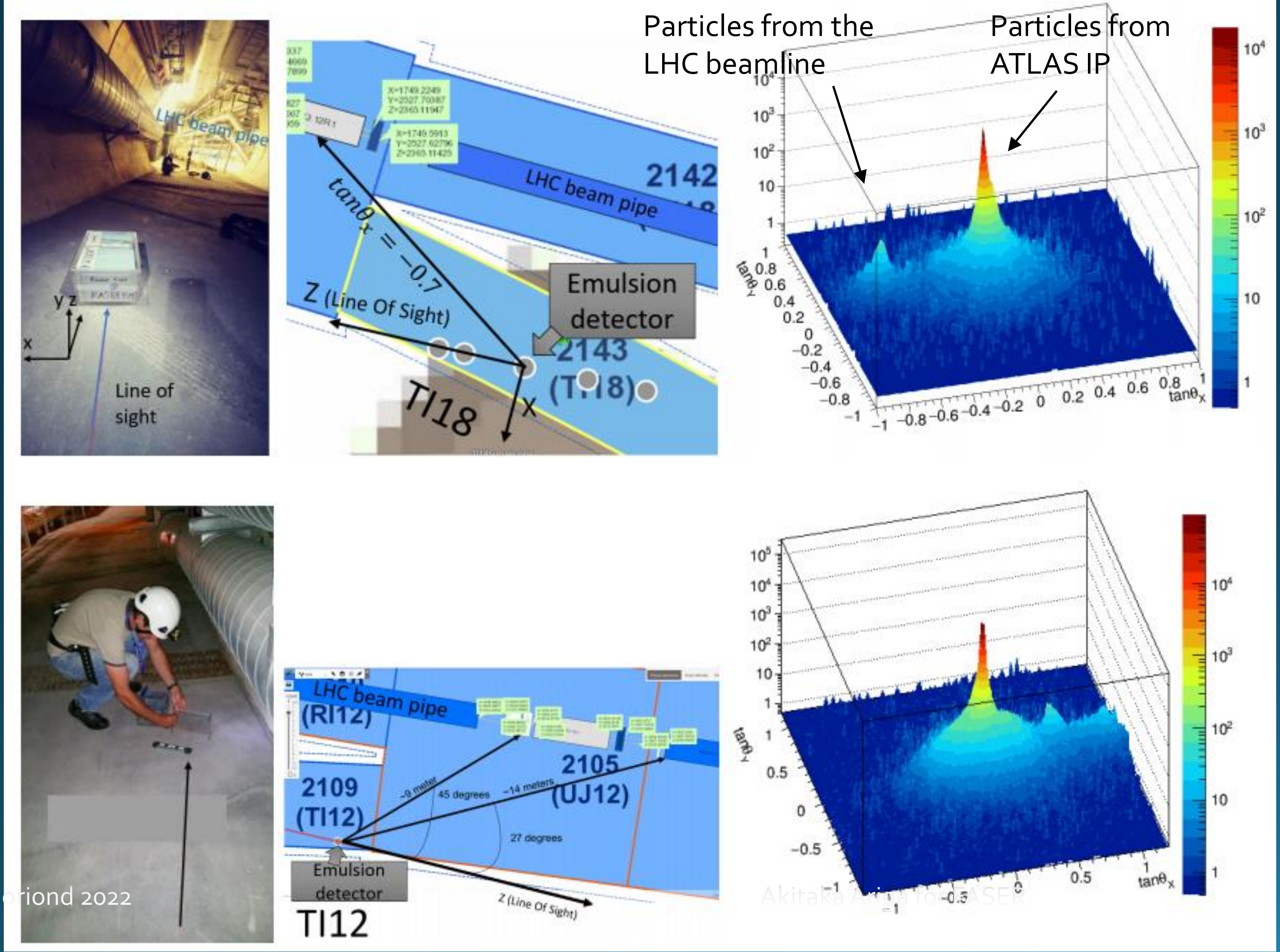




In situ measurements in 2018: Charged particle background

TI18

TI12

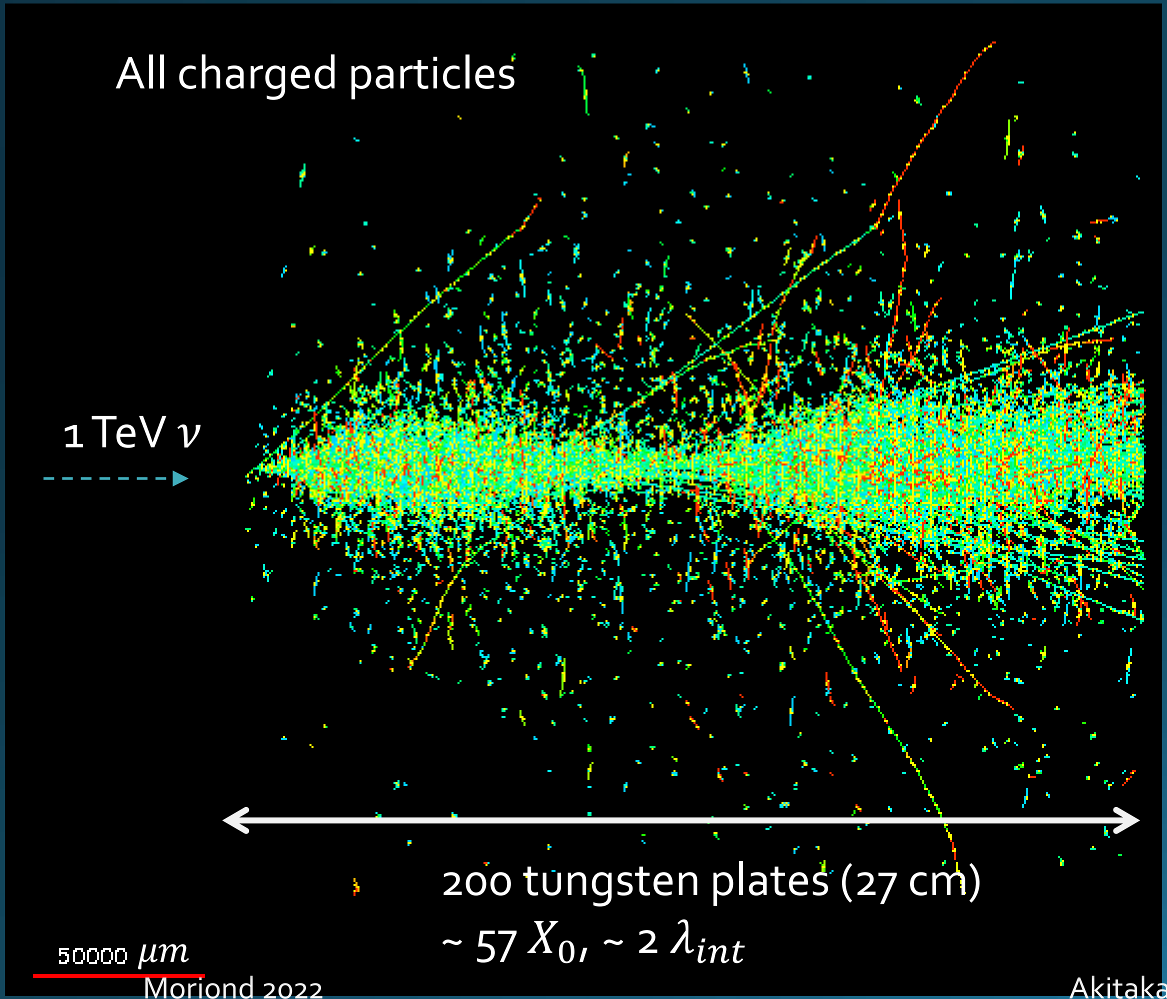


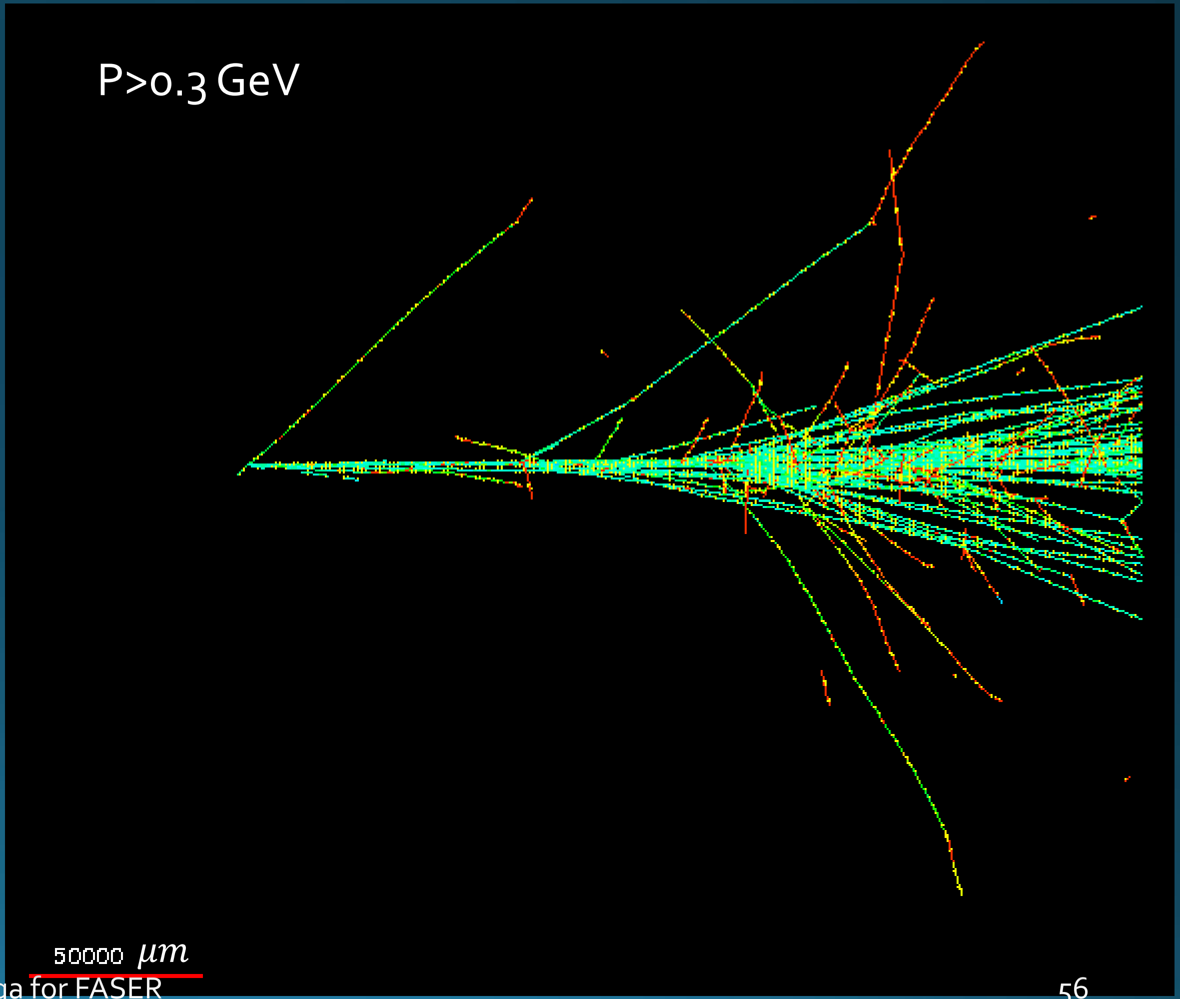
- Emulsion detectors were installed to investigate TI18 and TI12.
- **Low background was confirmed.**
- Few hadron tracks
- Consistent with the FLUKA prediction.

	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)

Simulated 1 TeV ν_μ CC interaction



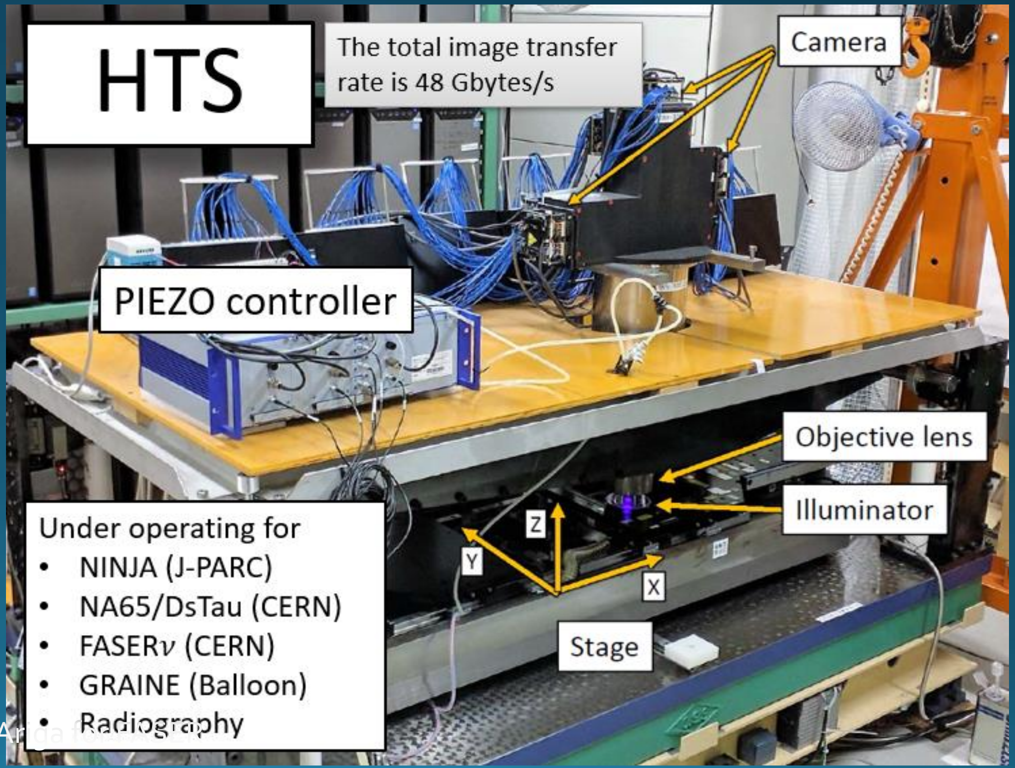


Emulsion detector technology

- **Fast readout of emulsion films**
  - Great progress in the readout speed, throughput of 48 GBytes/sec
  - ~100 times faster than OPERA
- Data readout for FASER will catch up with the irradiation at the LHC
  - 3 months irradiation at the LHC, followed by 3 months scanning for each module
  - 3 modules per year

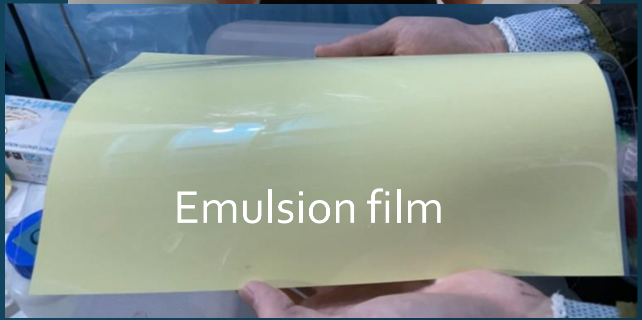
	Start year	Field of view (mm^2)	Readout speed (cm^2/h/layer)
S-UTS	2006	0.05	72
HTS-1	2015	25	4700
HTS-2	2021	50	25000

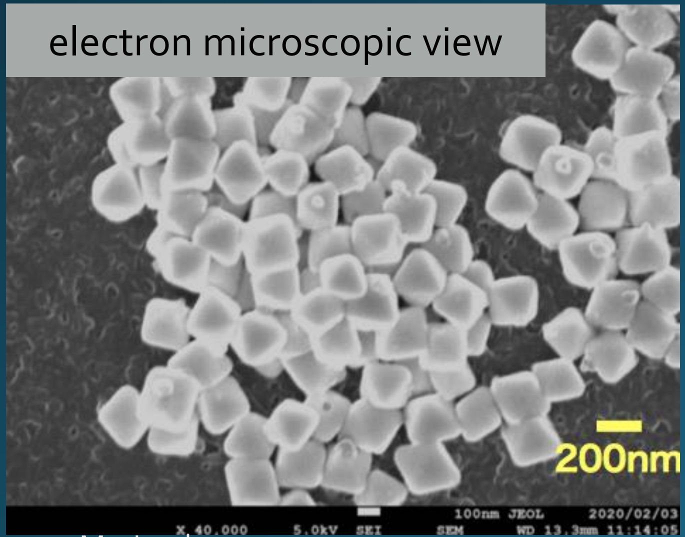
HTS paper: M. Yoshimoto, T. Nakano, R. Komatani, H. Kawahara, PTEP 10 (2017) 103H01.

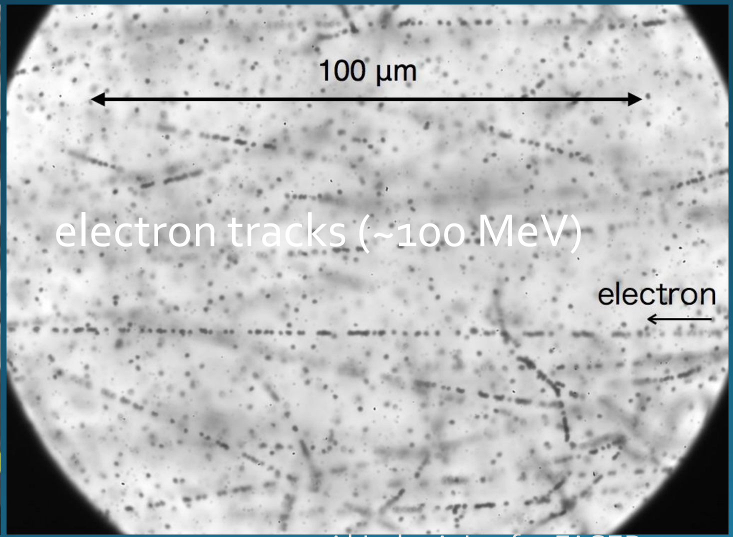


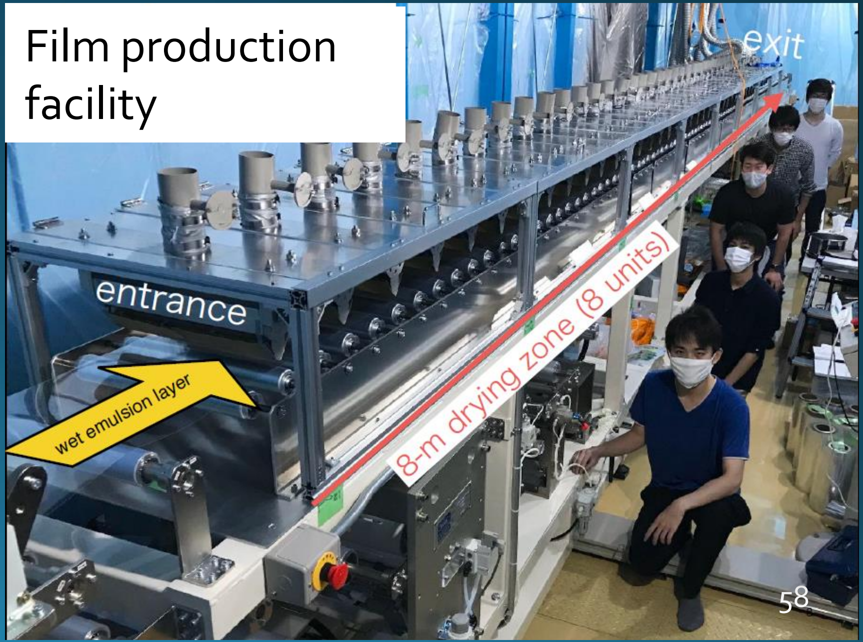
Emulsion detector preparation

- Emulsion gel and film production facilities in Nagoya have been set up in 2020. We are testing mass production
- Chemical compatibility of tungsten plates with emulsion film were tested







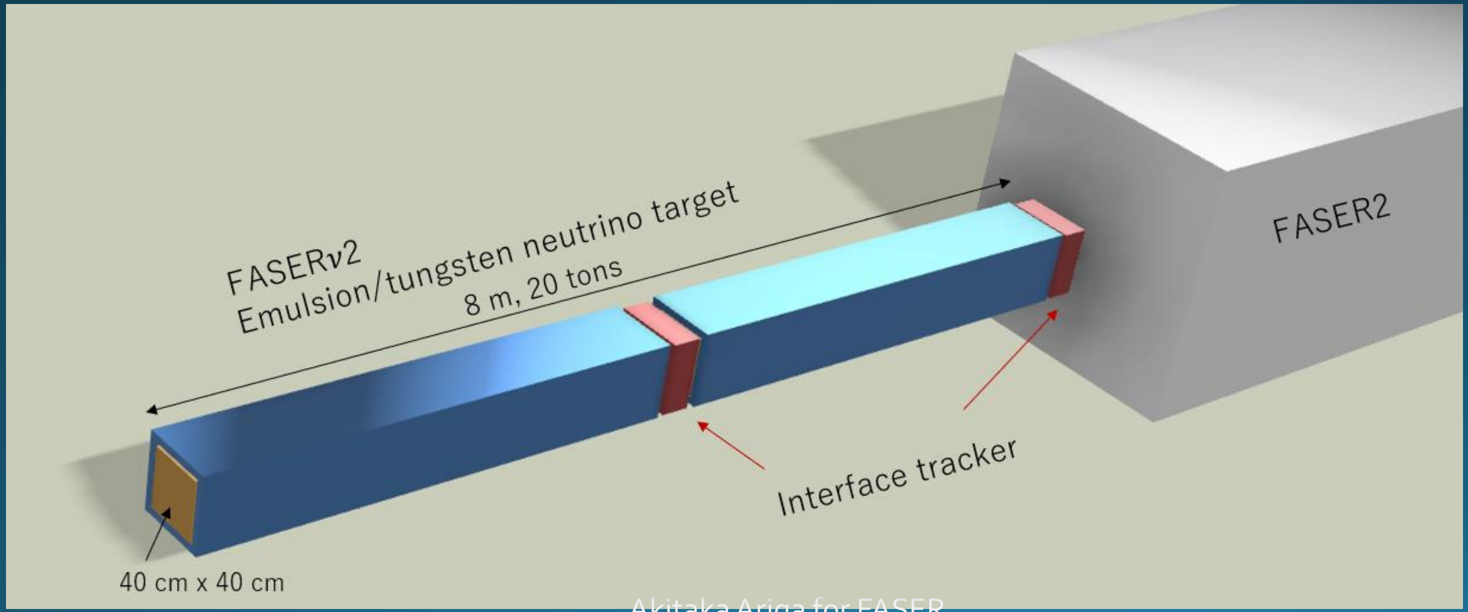


FASERν installation test in April 2021

Transportation over the LHC beam pipe

FASERν2 at the FPF

- **Tau neutrino physics, with >100 times statistics of FASERν**
  - FASERν2: Beam x 20, 20 tons mass
  - $\sim 10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^3\ \nu_\tau$ CC events
- **Rich physics programs in neutrino physics, flavor physics, QCD and cosmic-rays**



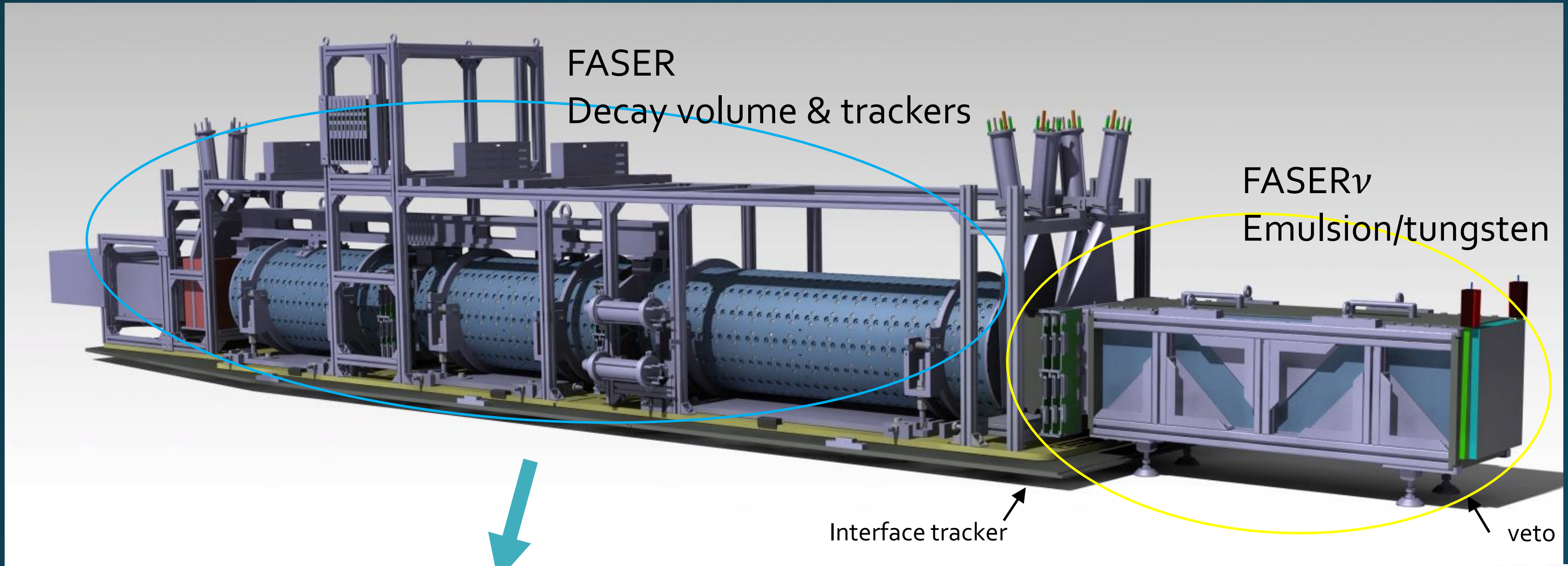
Publications on FASER/FASERnu

- Publications of the FASER Collaboration
  - FASER Letter of Intent at CERN document server and in arXiv
  - FASER Technical Proposal at CERN document server and in arXiv
  - FASER's Physics Reach for Long-Lived Particles in Physical Review D and in arXiv
  - Input to the European Strategy for Particle Physics Update in arXiv
  - Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC in European Physical Journal C and in arXiv
  - Technical Proposal of FASERν neutrino detector at CERN document server and in arXiv
  - First neutrino interaction candidates at the LHC in arXiv

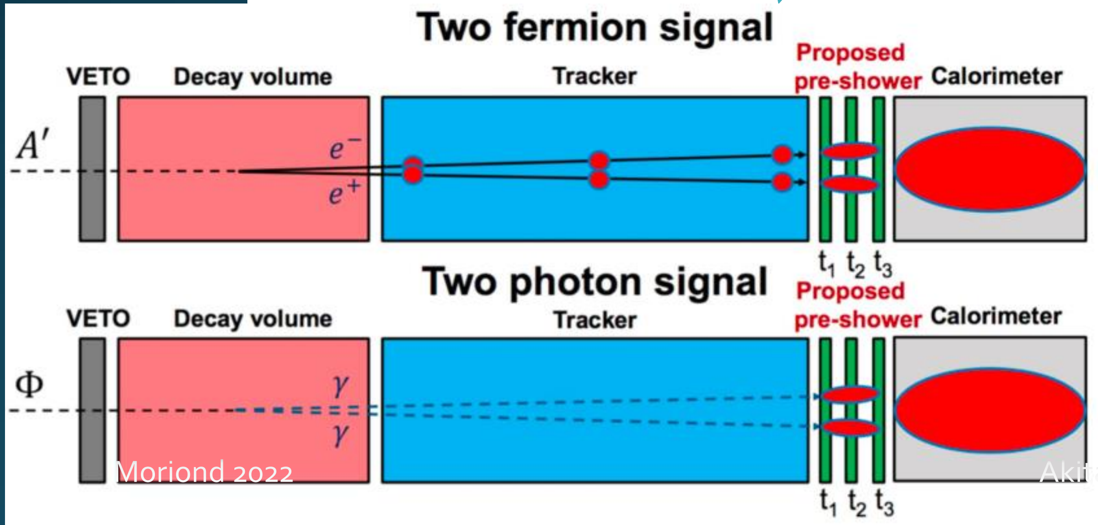
New since last week!

- Conference talks on FASERnu
  - Neutrinos at CERN, NEUTRINO 2020, 24 June 2020, Tomoko Ariga
  - FASERnu, ICHEP 2020, 28 July - 6 August, Akitaka Ariga

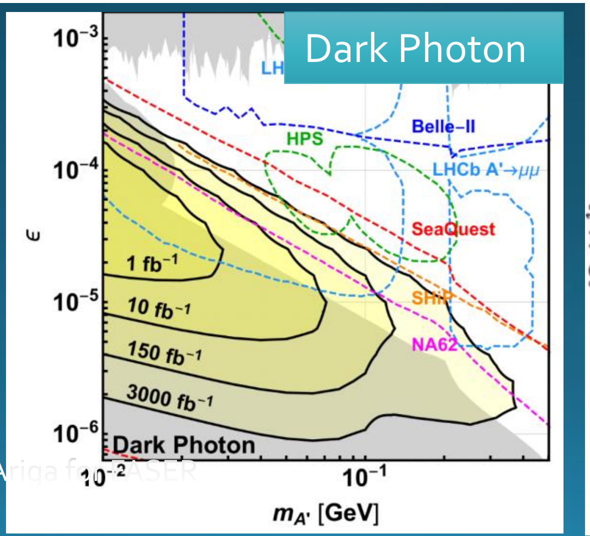
FASER/FASERν detector



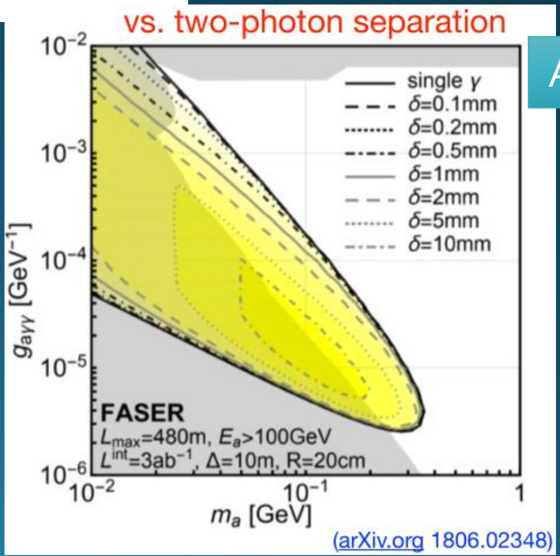
Forward beam (A′, ν, etc)



Dark Photon



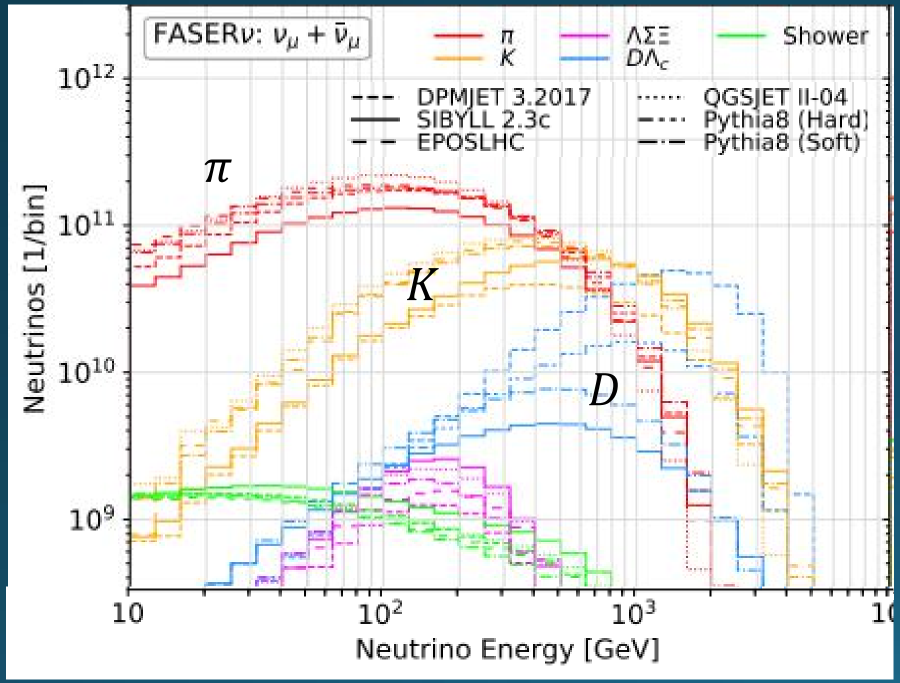
ALPs



Neutrinos = proxy of forward hadron production

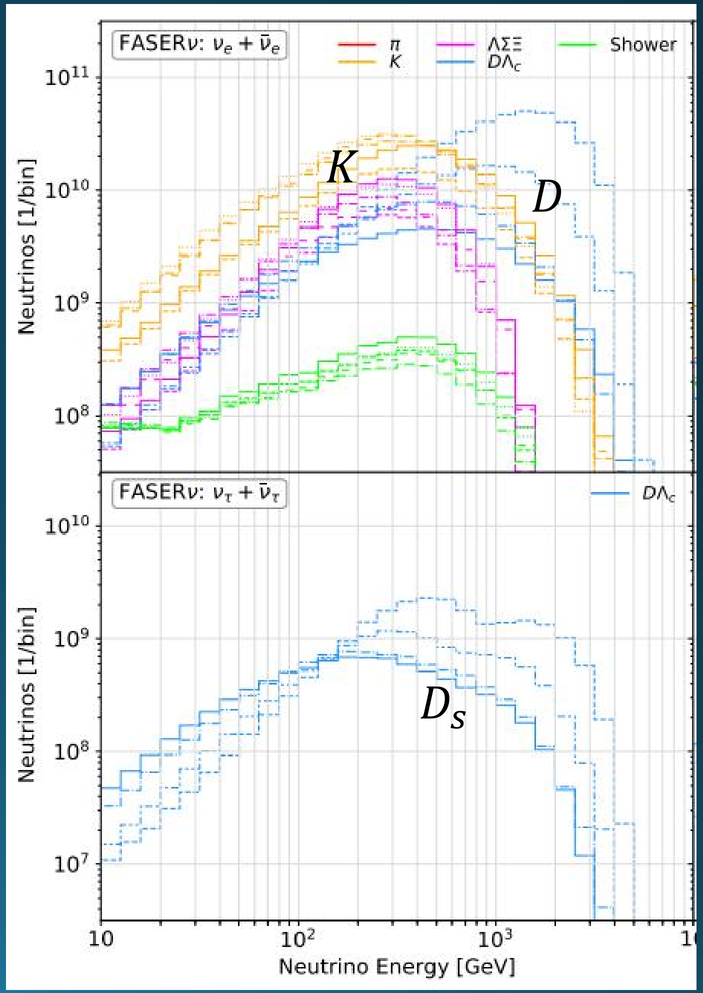
- Pion, Kaon, charm contribute to different part of energy spectra and flavor

ν_μ



ν_e

ν_τ

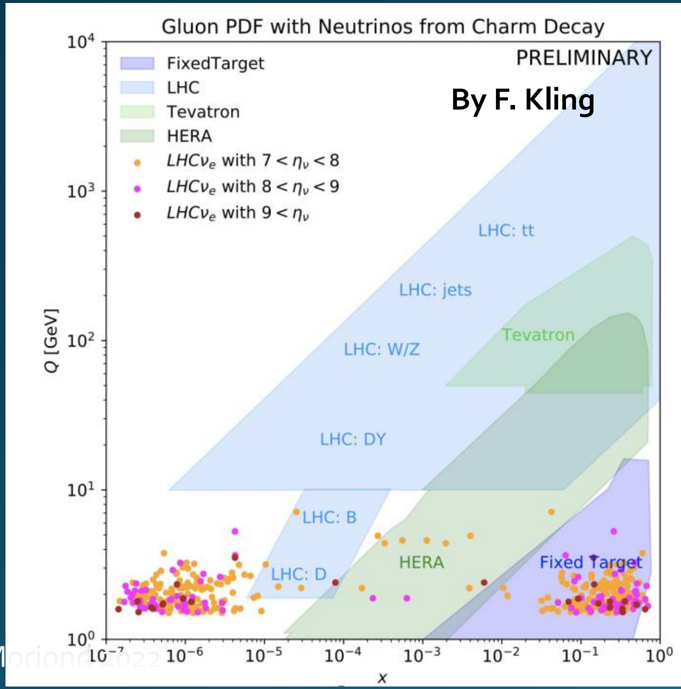


- FASERν provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

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

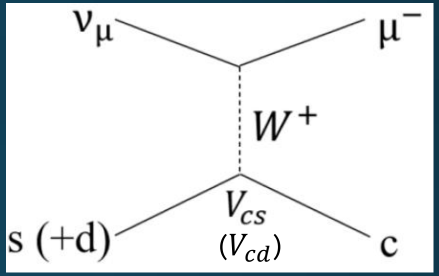
PDF in proton (neutrino production)

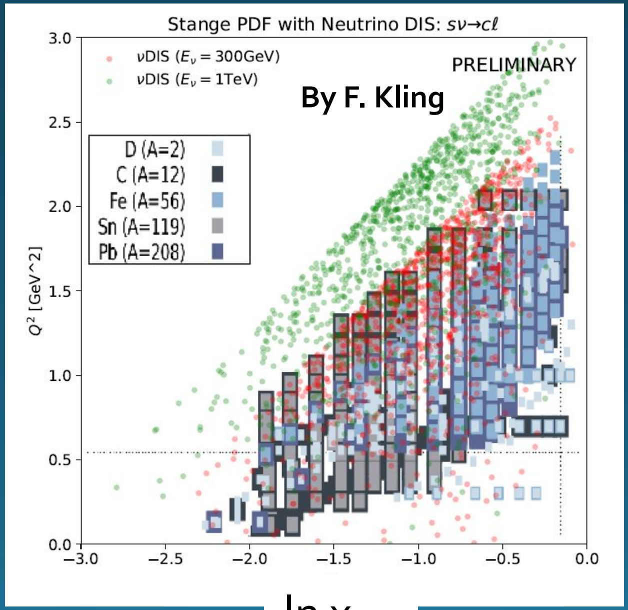
- Forward particle production is poorly constrained by other LHC experiments. FASERν's **neutrinos flux measurements** will provide novel complimentary constraints that can be used to validate/improve MC generators.
- Neutrinos from charm decay could allow to **test transition to small-x factorization,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



PDF in target (neutrino interaction)

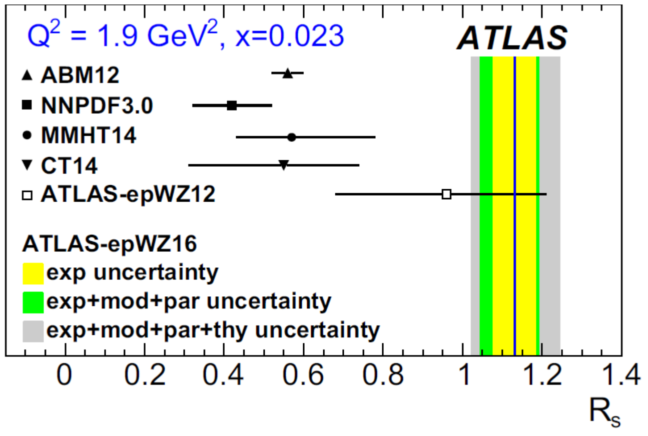
- It is also interesting to probe (nuclear) PDFs via DIS neutrino scattering. In particular, charm associated neutrino events ($\nu\ s \rightarrow l\ c$) are sensitive to the poorly constrained strange quark PDF.





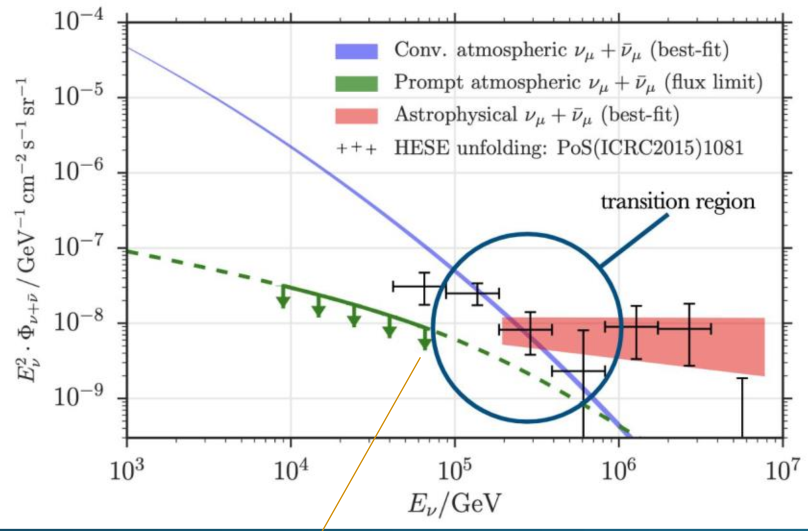
ln x

$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$ [Eur. Phys. J. C77 (2017) 367]



Physics studies in the LHC Run 3 (4):
Cosmic rays and neutrino

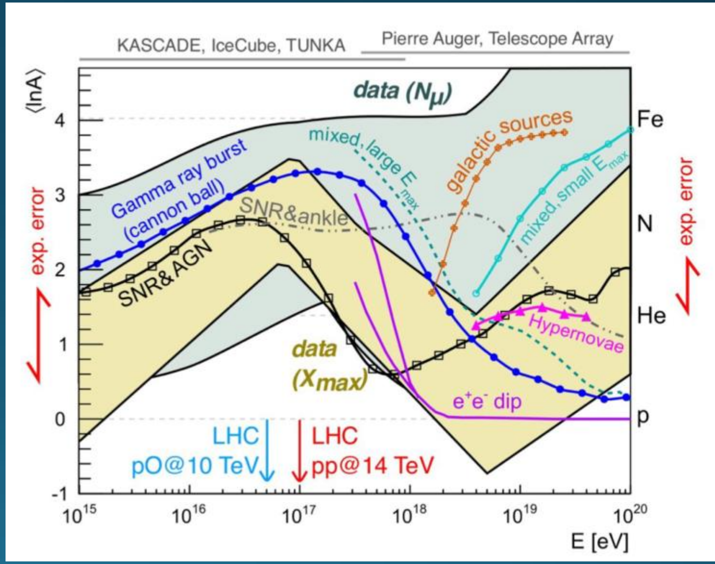
- In order for IceCube **to make precise measurements of the cosmic neutrino flux**, accelerator measurements of high energy and large rapidity charm production are needed.
- As 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode, a direct **measurement of the prompt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

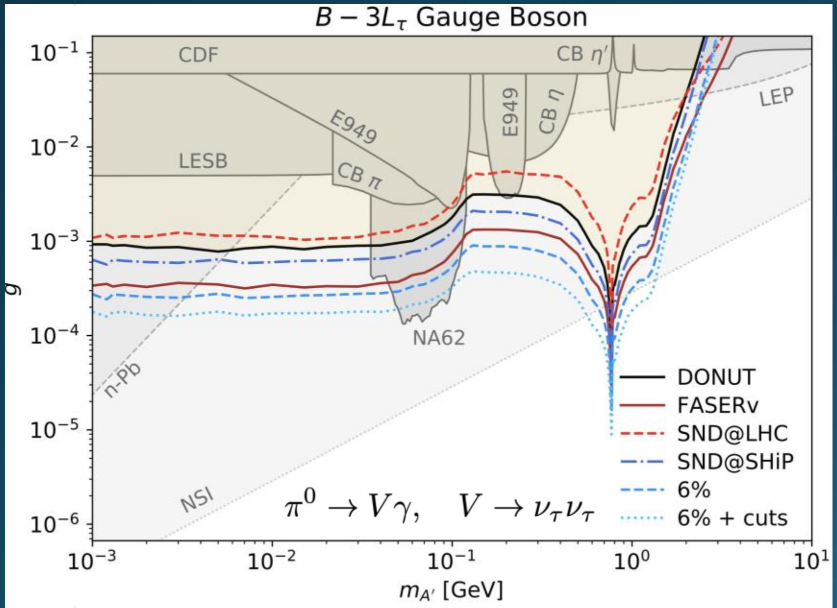


K.H. Kampert, M. Unger, Astropart. Phys. 35, 660 (2012),
H.P. Dembinski et al., EPJ Web Conf. 210, 02004 (2019)

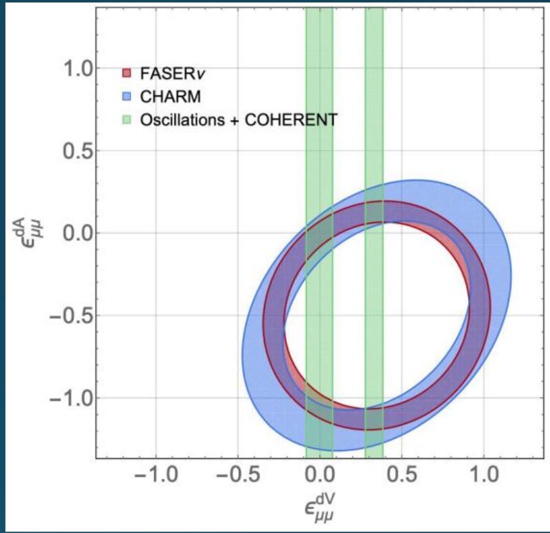
Physics studies in the LHC Run 3 (5):
BSM Physics

- 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.

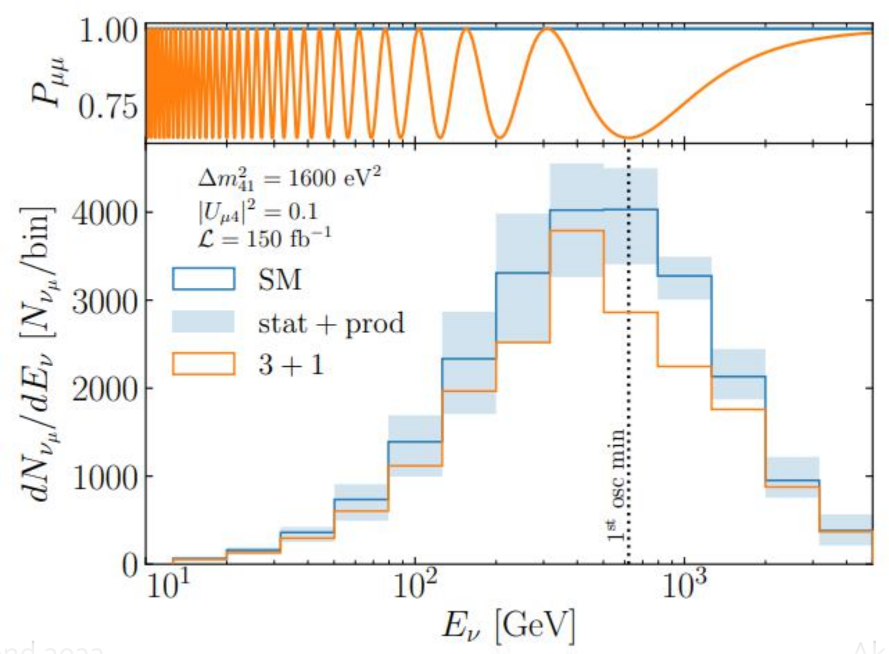
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

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

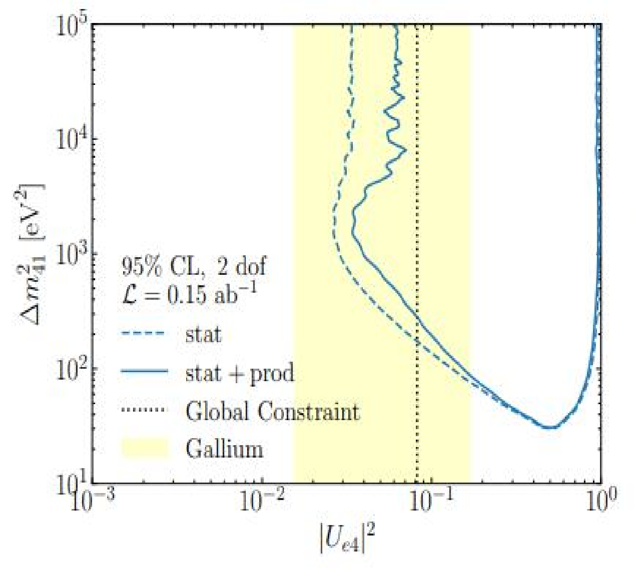
B. Batell, J. Feng, S. Trojanowski, 2020, in preparation

Sterile neutrino oscillation

- Due to unique energy and baseline ($L/E \sim 10^{-3}$ m/MeV), FASERν is sensitive to large $\Delta m^2 \sim 10^3$ eV².
- Neutrino spectrum deformation
- Competitive in disappearance channels.



ν_e disappearance



ν_μ disappearance