First results from the FASER experiment and overview of Forward Physics Facility

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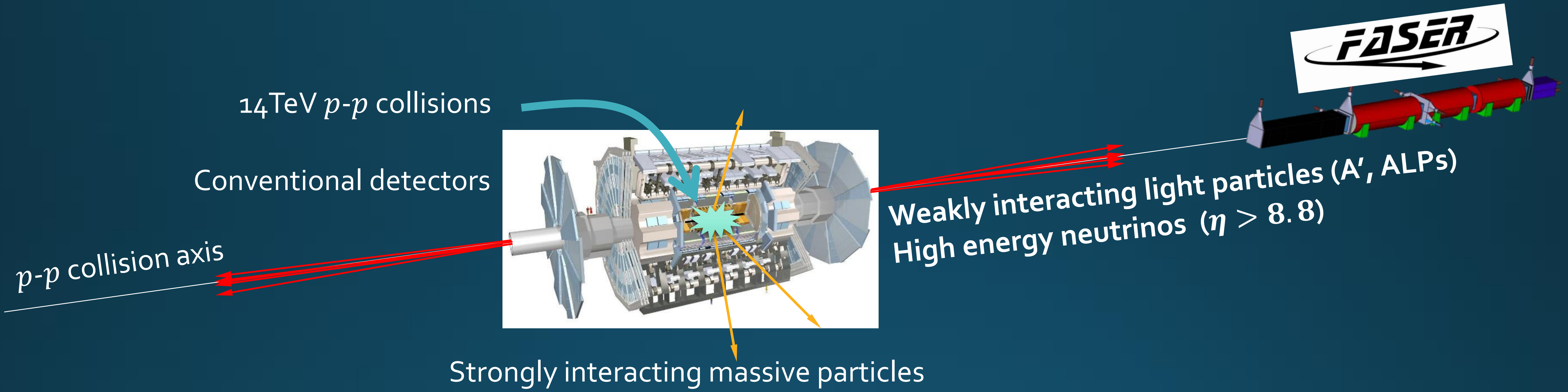
On behalf of the FASER Collaboration

FASER is supported by erc, HEISING-SIMONS FOUNDATION, SIMONS FOUNDATION, 科研費 KAKENHI, CERN

Forward beam for neutrino and LLPs



FASER (long-lived 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

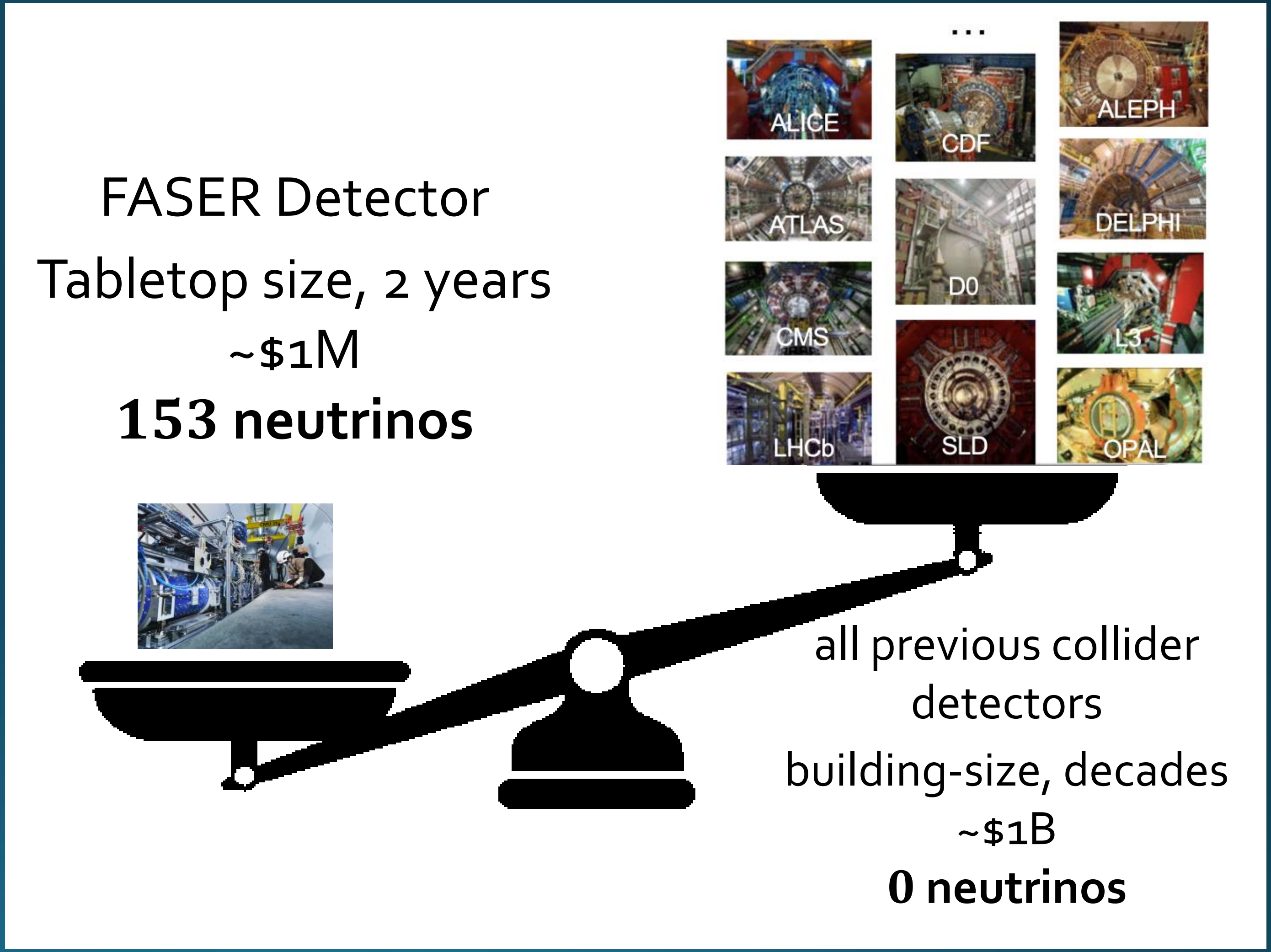
Data taking started in 2022! Continue in Run3

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

Forward Physics Facility (FPF) in HL-LHC era

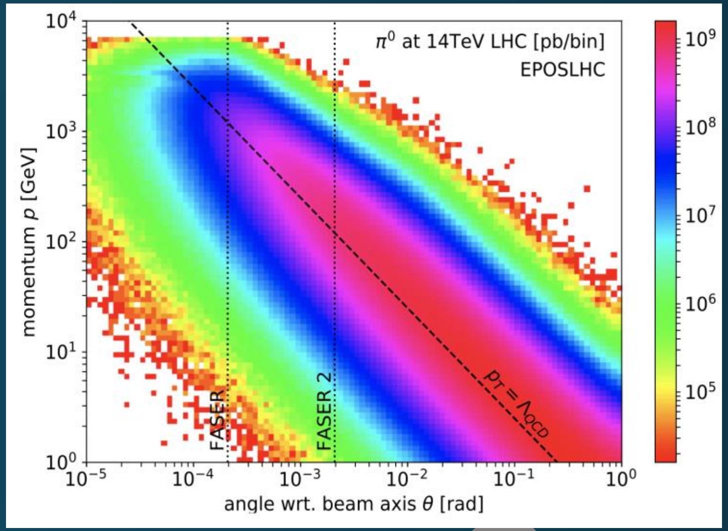
Consideration from "collider neutrinos"

- No neutrino detected by any collider experiments till recently
- In 2018, new initiatives have started
- → Collider neutrinos were detected in 2023
- Important to have a proper setup for a certain type of particles
- New opportunities for dark sector searches, as well as high energy neutrinos!

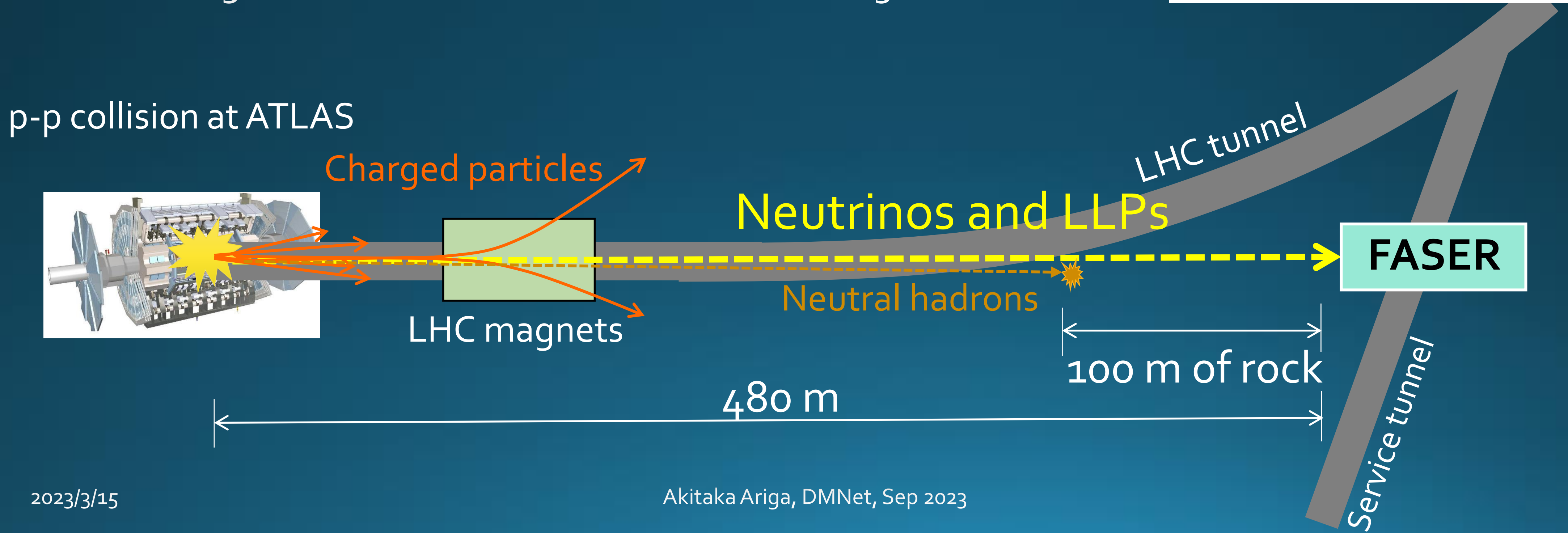


The FASER experiment

- FASER is a new forward LHC experiment
  - Targets long-lived BSM particles (e.g. A′, ALPs) and neutrinos
  - Exploiting large LHC collision rate + forward-peaked production
- Located 480 m downstream of ATLAS interaction point
  - LHC magnets and 100 m of rock shield most background



arXiv:1901.04468

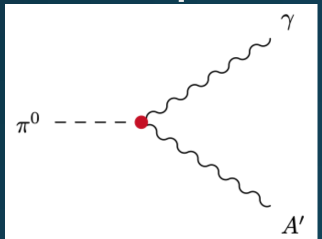


Dark Photon (A’) properties

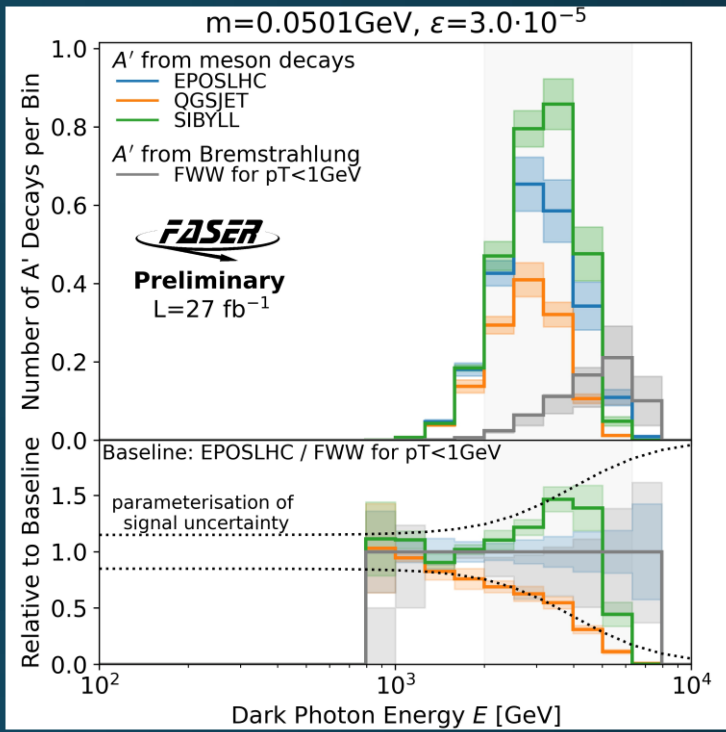
- Dark photon is a common feature of hidden sector models
  - Weakly coupling to SM via kinetic mixing (ε) with SM photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

- MeV A’s produced mainly in meson decays at LHC



$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

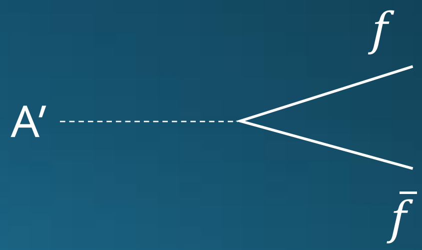


* arXiv:2105.07077

- Travels long distances through matter without interacting, decays to charged fermion pairs, e.g. $e^+e^-, \mu^+\mu^-, q\bar{q}$

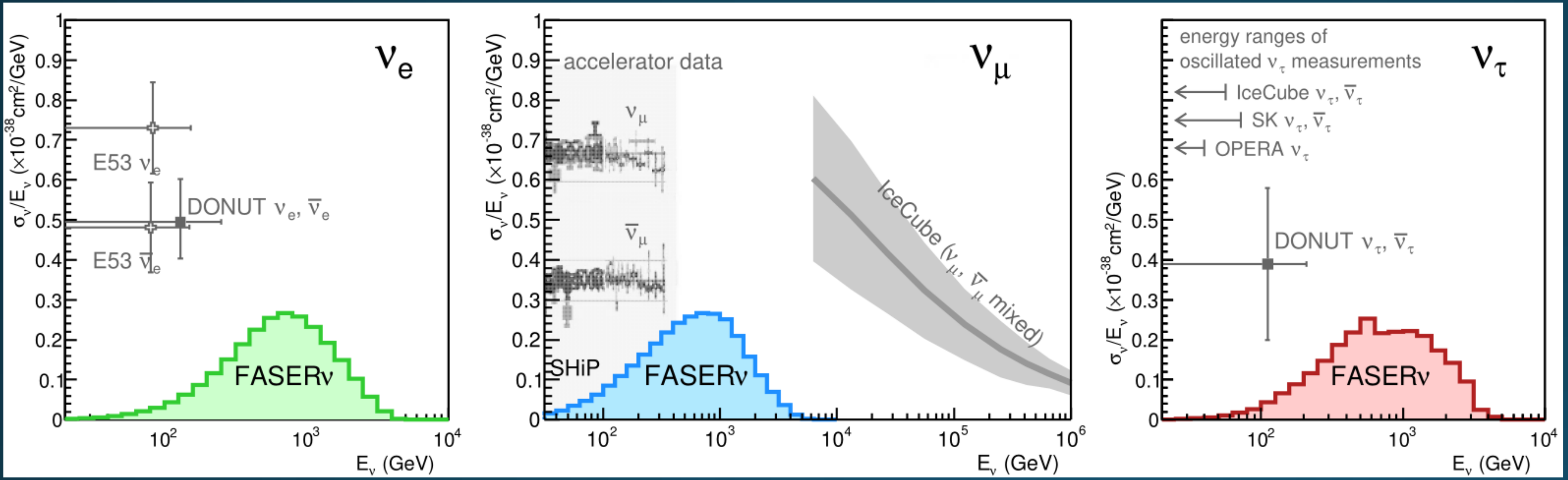
$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$

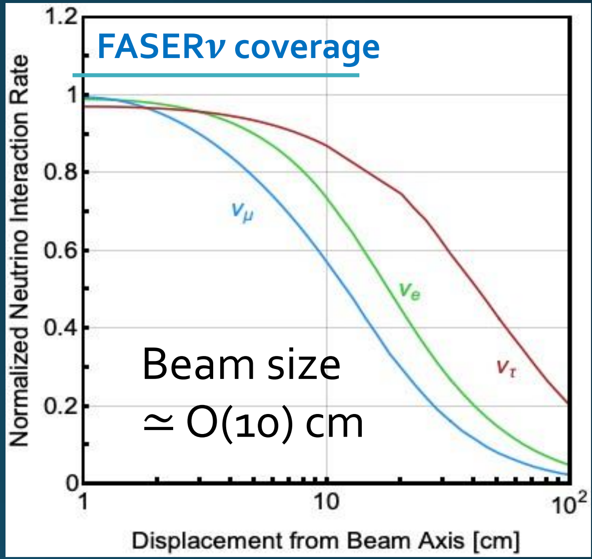
$$E_{A'} \gg m_{A'} \gg m_e$$



  - If $m_A' < 2m_\mu$, A’ has 100% decay to e⁺e⁻ pair. Typically $E_A' \sim 1\ \mathrm{TeV}$

Neutrino studies at FASER





Unexplored energy regime for all three flavors

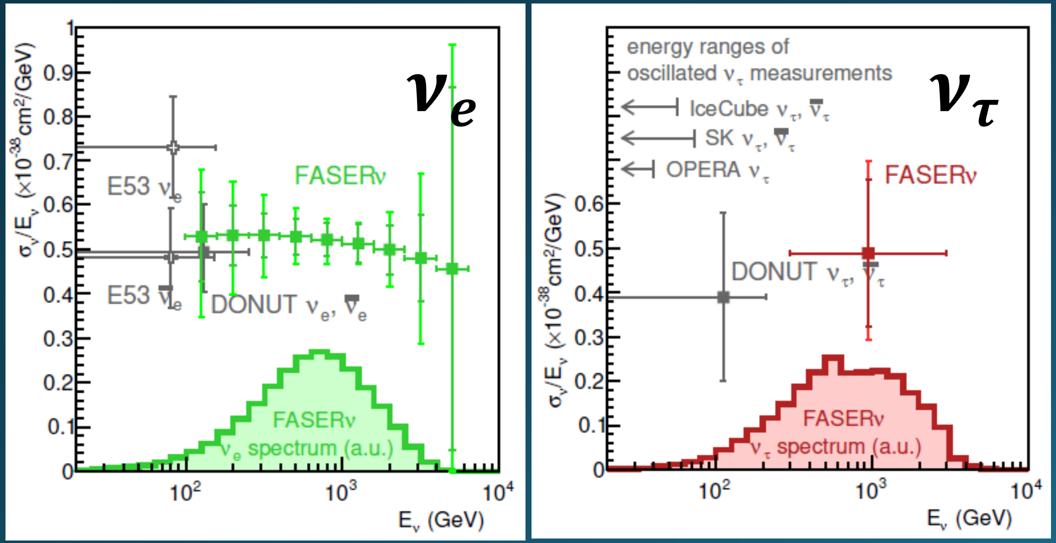
Collimated beam

- Neutrinos by collider method = High energy frontier ~ TeV
- Study of <u>production</u>, <u>propagation</u> and <u>interactions</u> of high energy neutrinos
- Dominant BG for dark photon search

FASERν physics potential

(1) Study high-energy neutrino interactions

- **Cross sections of different flavors** at TeV energies: FASER probes unexplored energy range.
- Neutrino CC interactions with charm production ($\nu N \rightarrow l N' c$)
- Lepton Universality test in neutrino scattering

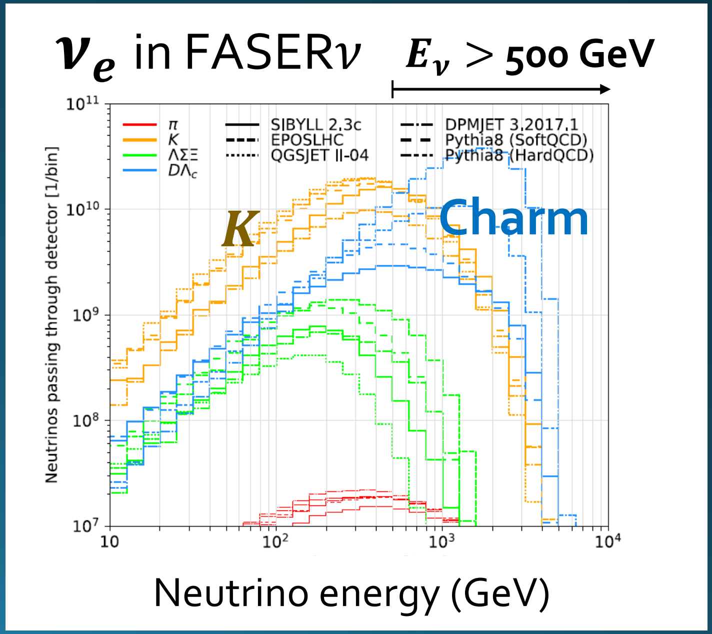


Projected cross section sensitivities

(2) Use neutrinos as probe of forward hadron production

- Neutrinos produced by the forward meson decays; pions, kaons, and charm particles.
- FASERν's measurements provide novel input to QCD (low-x PDFs, intrinsic charm, saturation) and astroparticle physics (prompt atmospheric neutrinos, cosmic ray muon puzzle)
- First data on forward charm, hyperon, and kaon

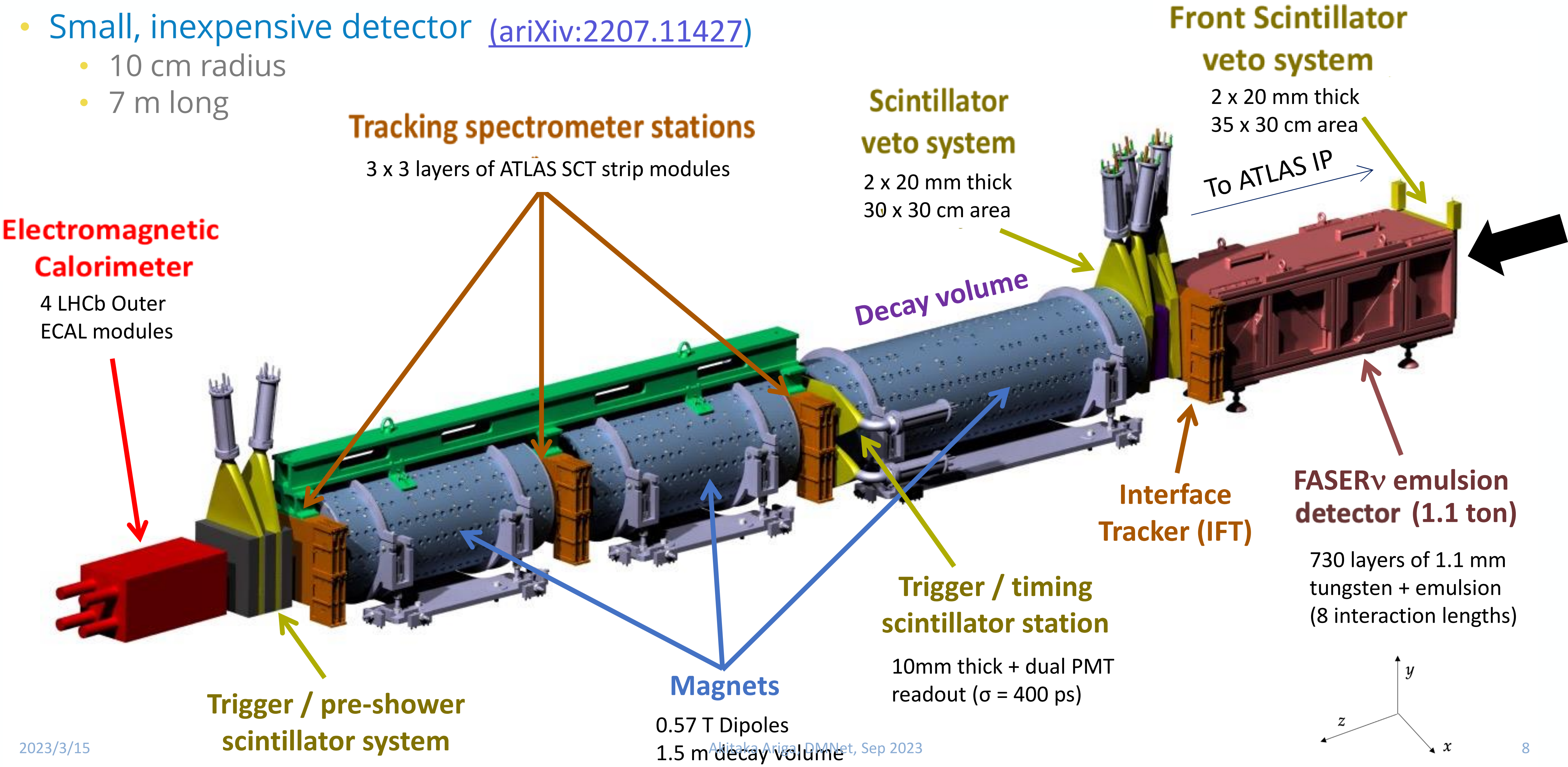
Neutrinos from charm decay dominates above 1 TeV for ν_e and ν_τ



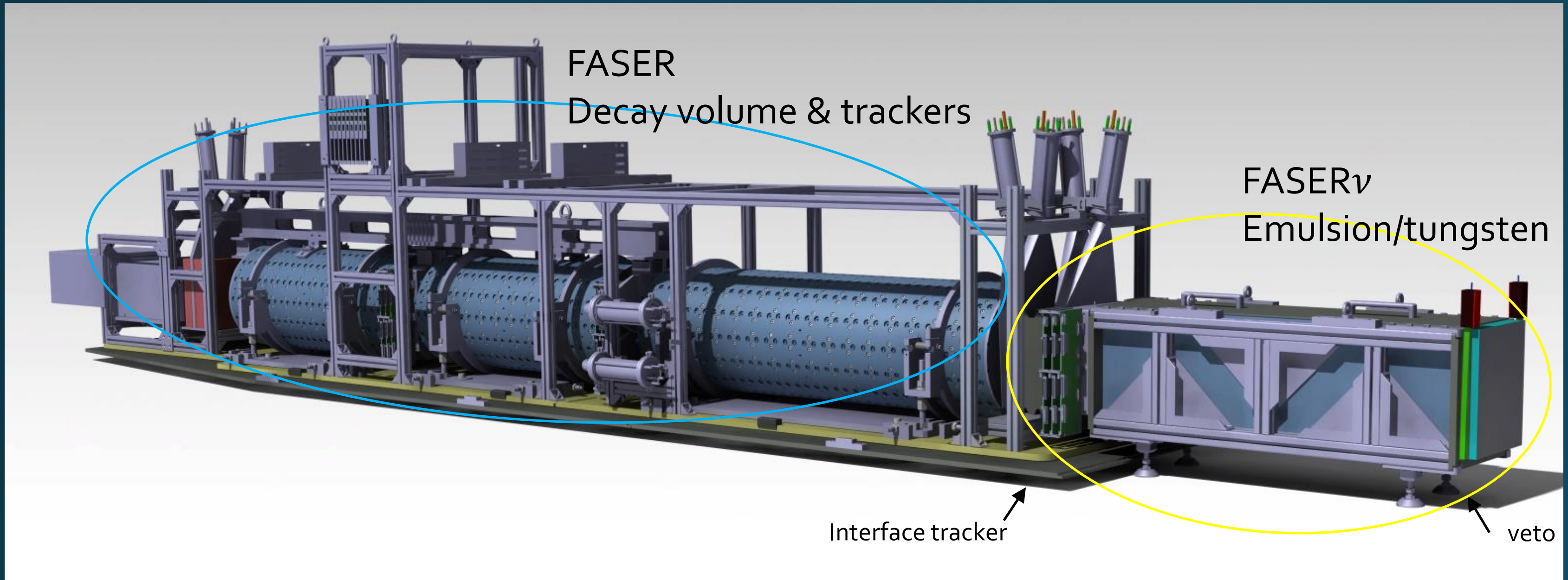
- (3)… more

FASER Detector

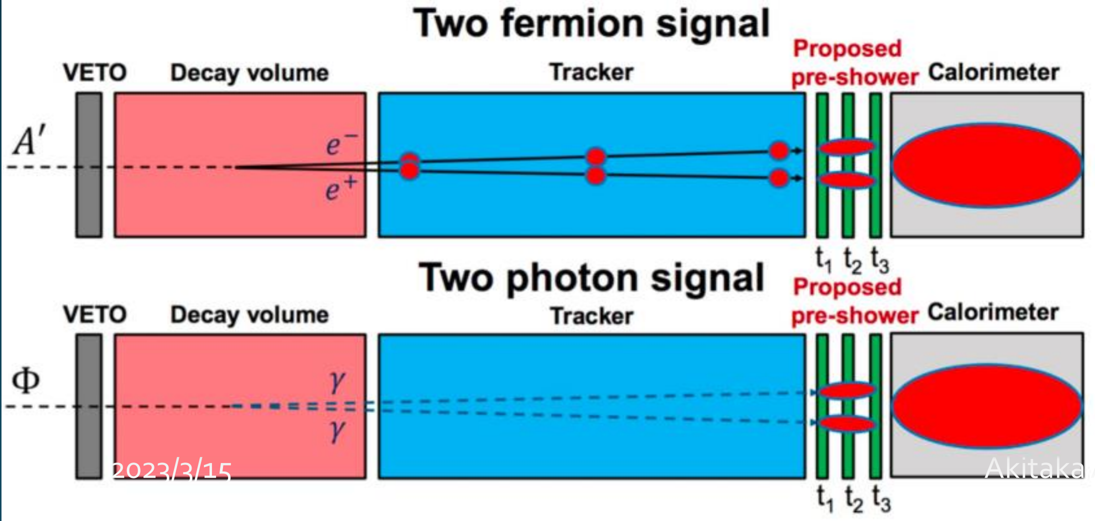
- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long



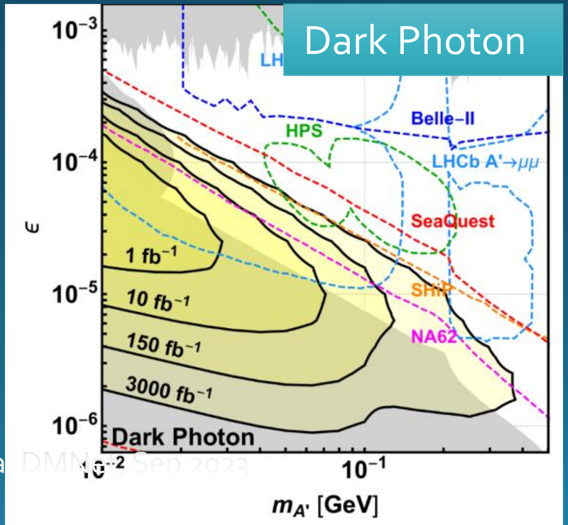
LLP signals with FASER detector

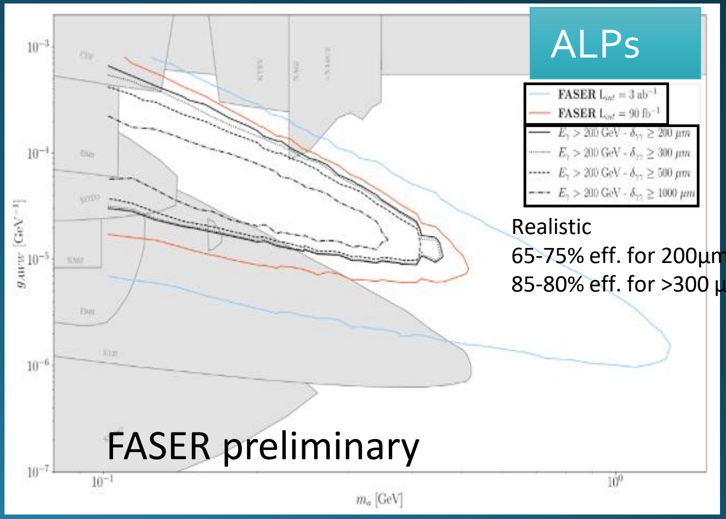


Forward beam (A′, ν, etc)

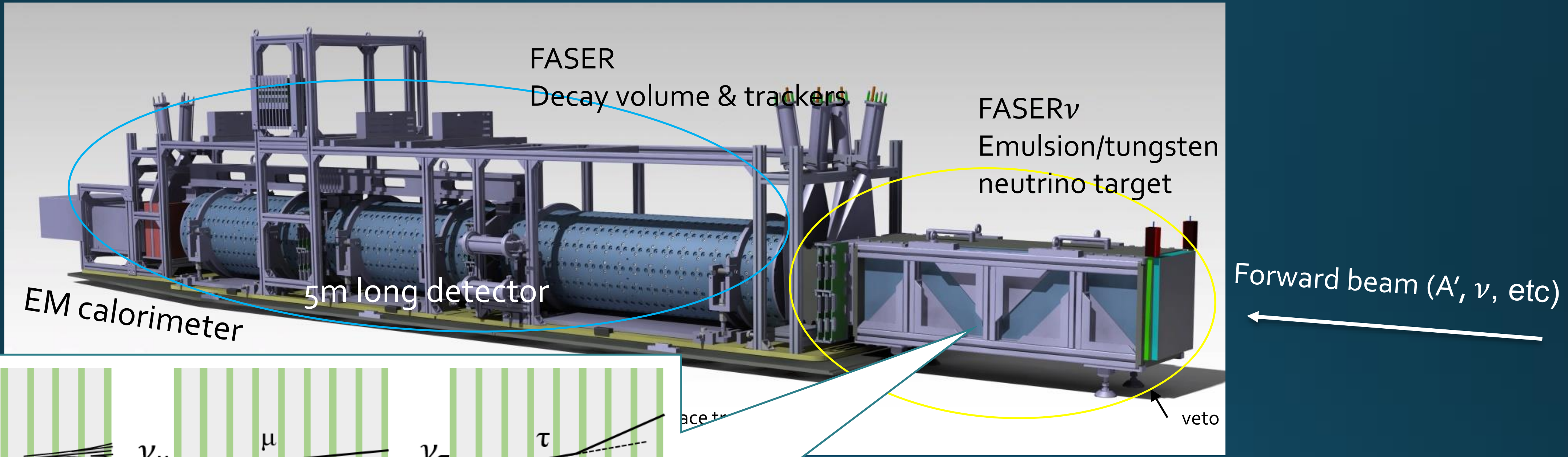


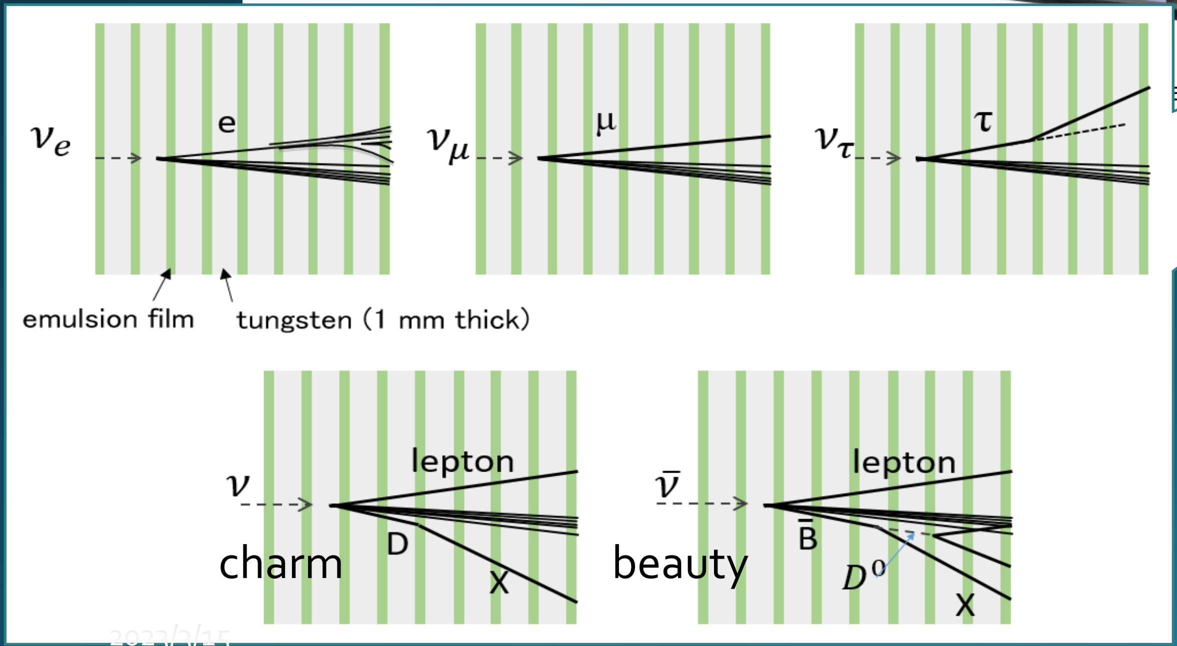
Sensitivities





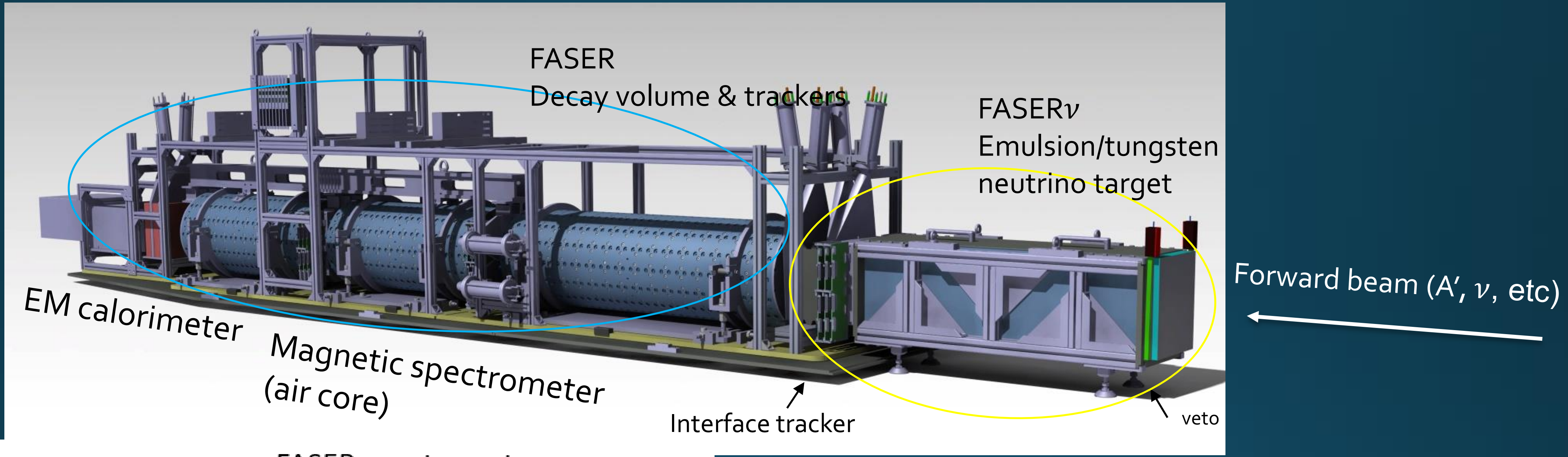
FASER+FASERν detector in Run3 (2022-2025)

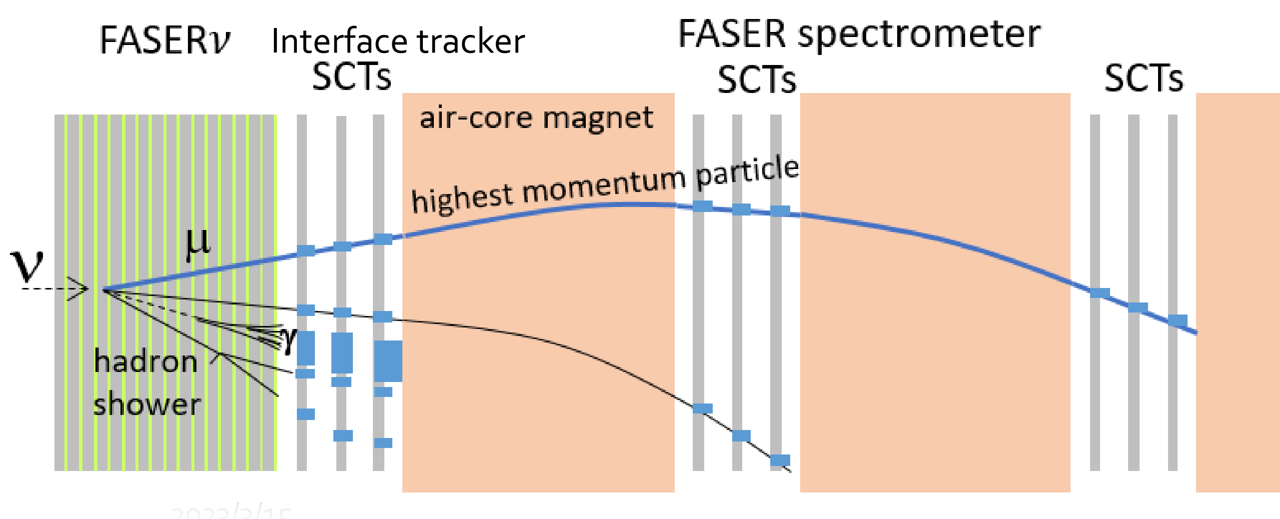




- Emulsion films = trackers with sub-micron spatial resolution, $\sigma_{intrinsic} \simeq 50\ nm$, $\sigma_{practical} \simeq 0.3\ \mu m$
- 730 1.1-mm-thick tungsten target and emulsion films
- 25x30 cm^2, 1.1 m, 1.1 tons (8 λ_{int}, 220X_0)
- Sensitive to 3 flavor neutrinos
- Muon ID in track length in tungsten
- Replace emulsions 3 times a year

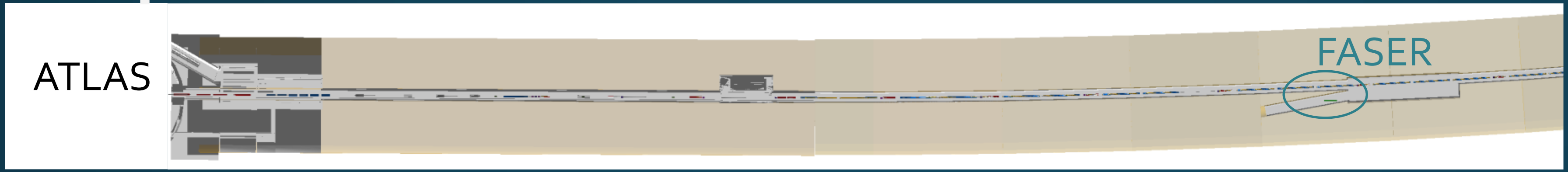
FASER+FASERν detector in Run3 (2022-2025)



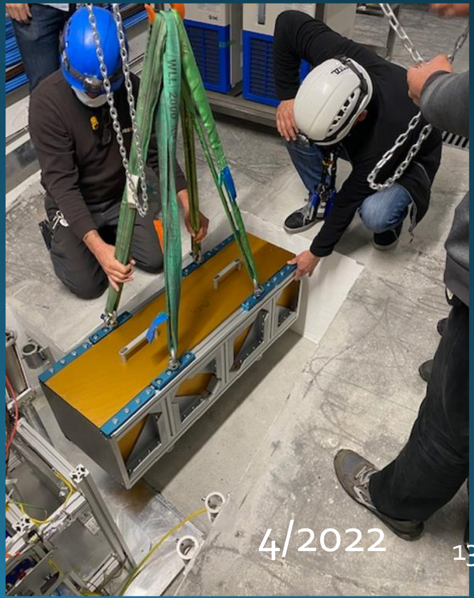


- Global reconstruction with FASER spectrometer
  → muon charge identification
  → $\nu_\mu/\bar{\nu}_\mu$ separation
- Improve energy resolution

Experimental site



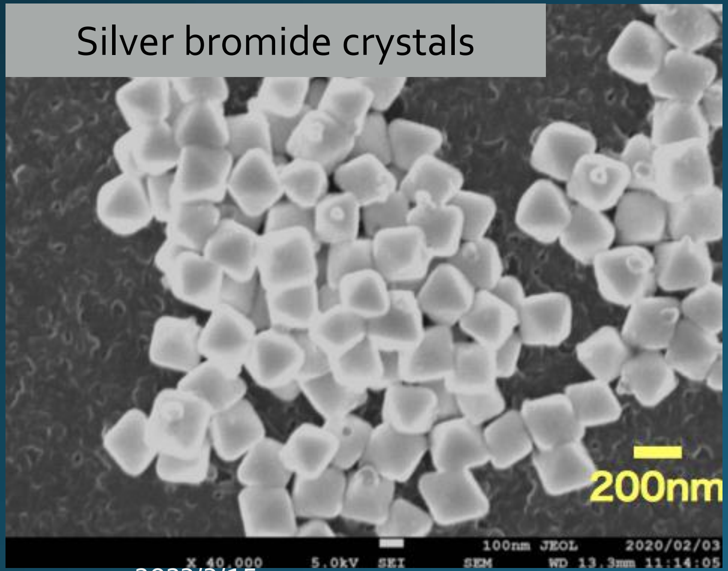
Evolution of TI12 tunnel for FASER installation




CMU 2t
CMU 2t
2t
FASER
To ATLAS
FASERν
IFT
Veto
Decay volume
Tracking spectrometer
Preshower
Calorimeter

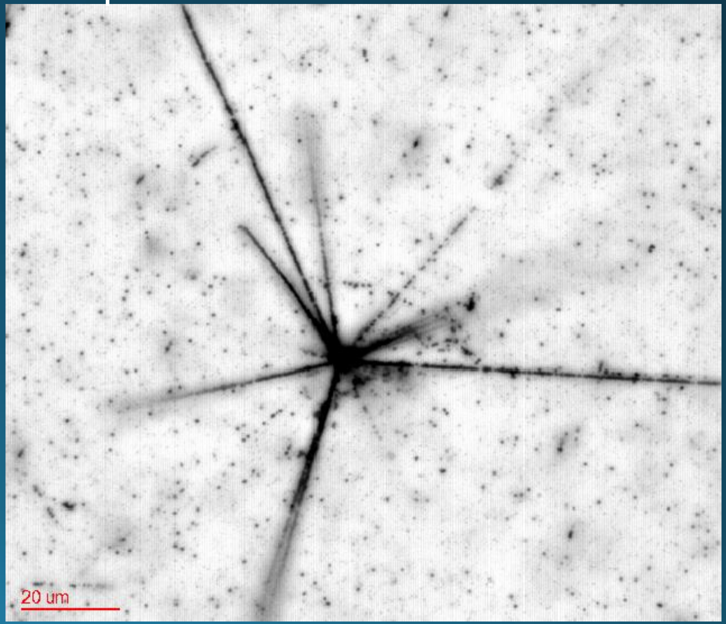
Emulsion-based neutrino target

- Super large number of detection channels ~ 8×10^{14} detection channels / film (30 x 25 cm²).
- 3D tracking device with 50 nm intrinsic resolution
- Coupled with tungsten target



Silver bromide crystals

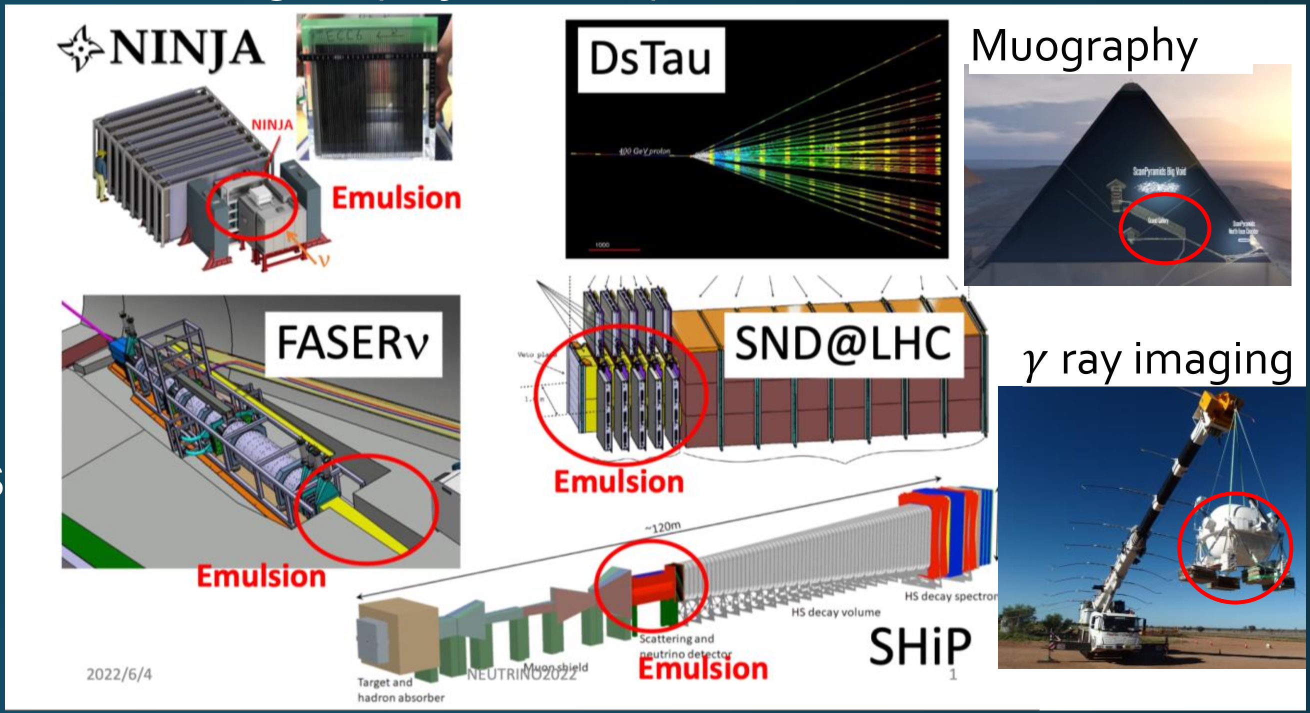

Emulsion films produced in Japan

Anti proton annihilation in emulsion


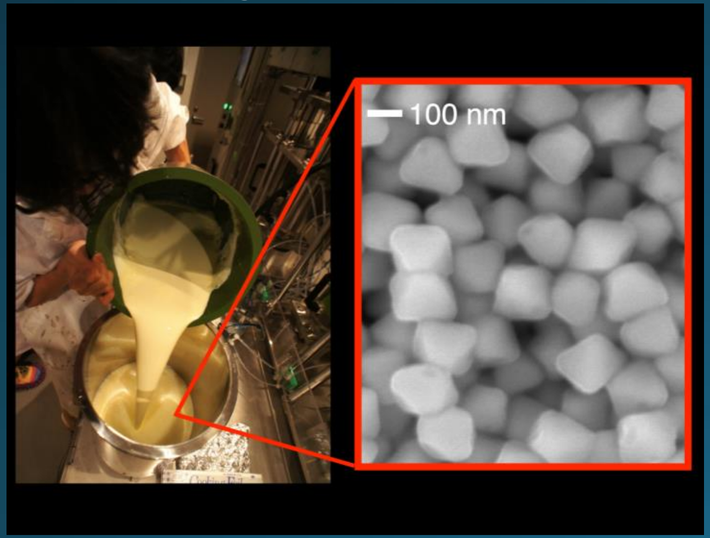
Nagoya's emulsion technology

- Long history: First charm, ν_τ observation (DONUT), $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (OPERA)
- Contributing to neutrino and hadron physics astroparticle, muography
- World-leading facilities

Wide range of projects, many more

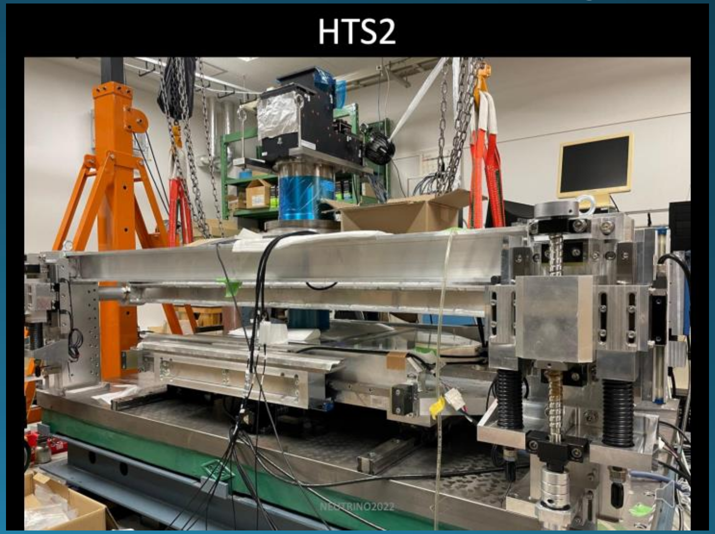


Emulsion gel production



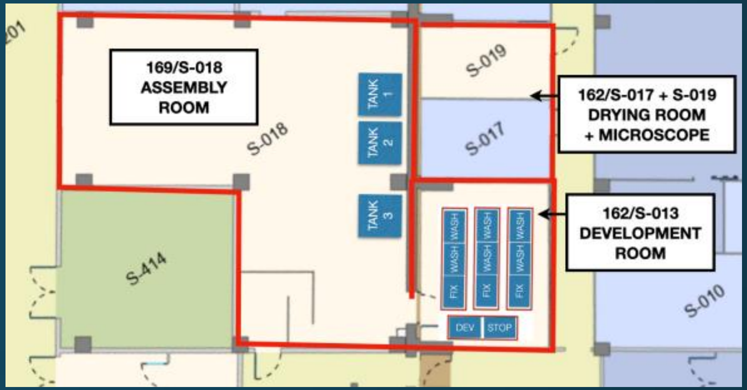
Film production

Emulsion read-out (scanning)



CERN Emulsion Facility

- A series of dark rooms at CERN, refurbished in 2022
- Emulsion experiments are increasing: NA65/DsTau, FASERν, SND@LHC, SHiP, test beams…
- Experiments share installation and equipment



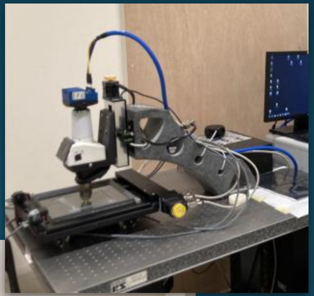

Dark room operation
Assembling of FASERν and SND@LHC

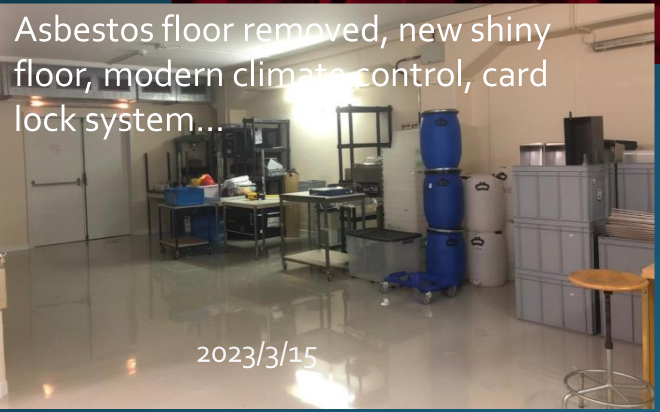
Temperature controlled developer bath

Development timer

Film drying

Microscope




Asbestos floor removed, new shiny floor, modern climate control, card lock system…

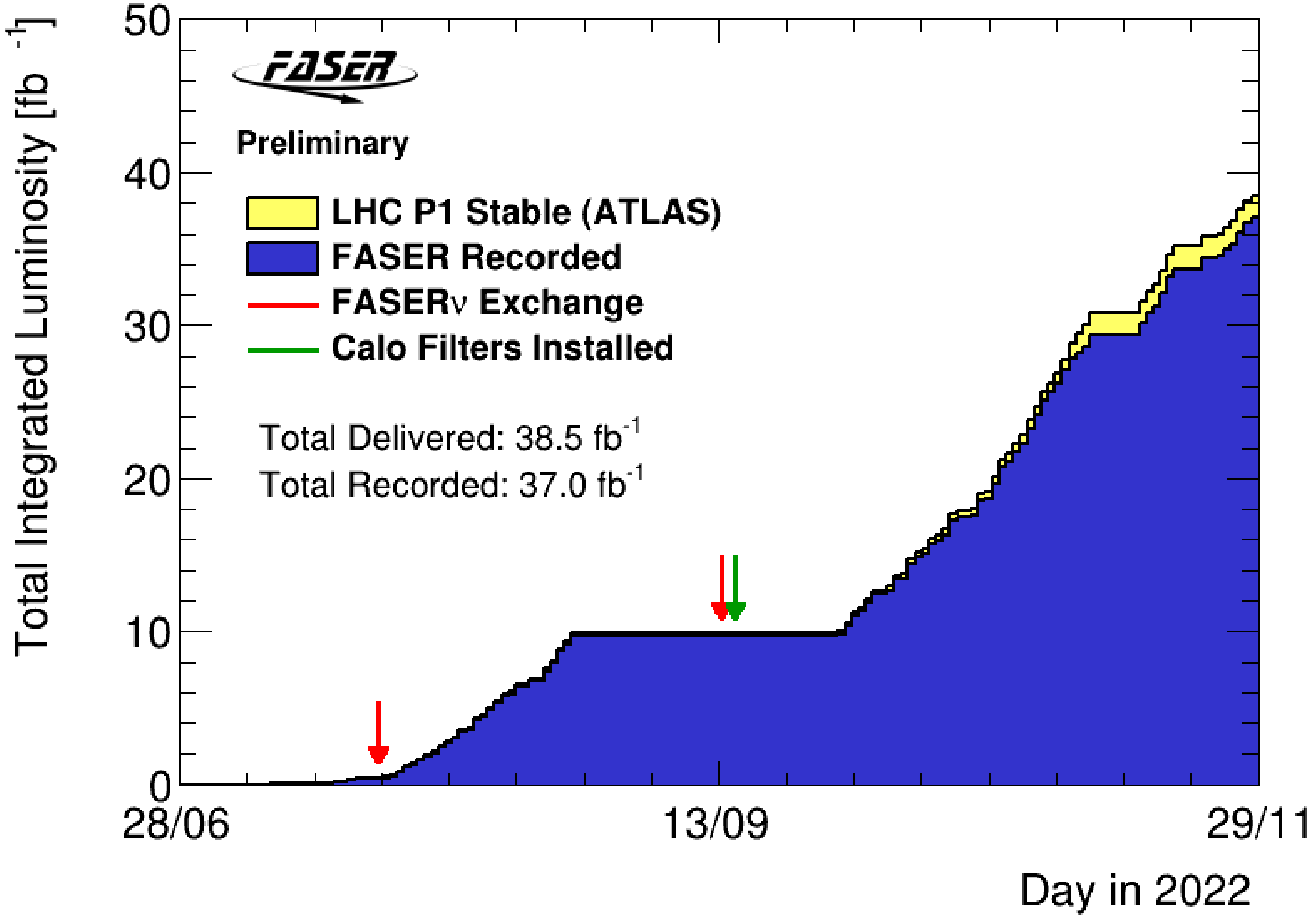
2023/3/15


Development room
13 x 100L tanks
Easy disposal system

Disposal

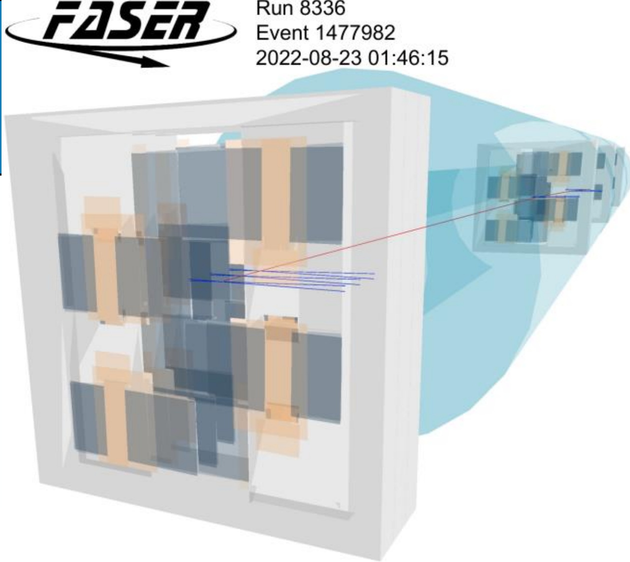
FASER 2022 Operations

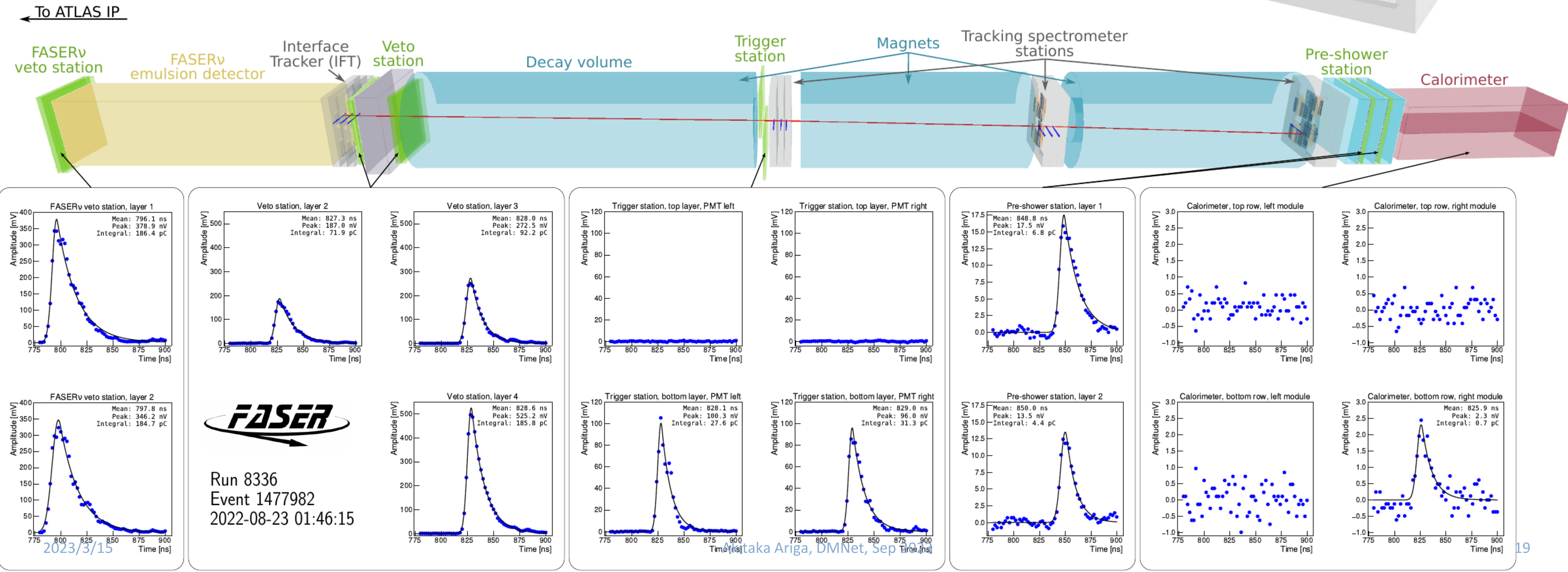
- Successfully operated throughout 2022
  - All detector components working as expected
  - Up to 1.3 kHz
- Recorded 37 fb^{-1} of data
  - Dead-time of 1.3%
- 3 emulsion detectors
  - Needed to manage occupancy
  - First box only partially filled



FASER 2022 Operations (2)

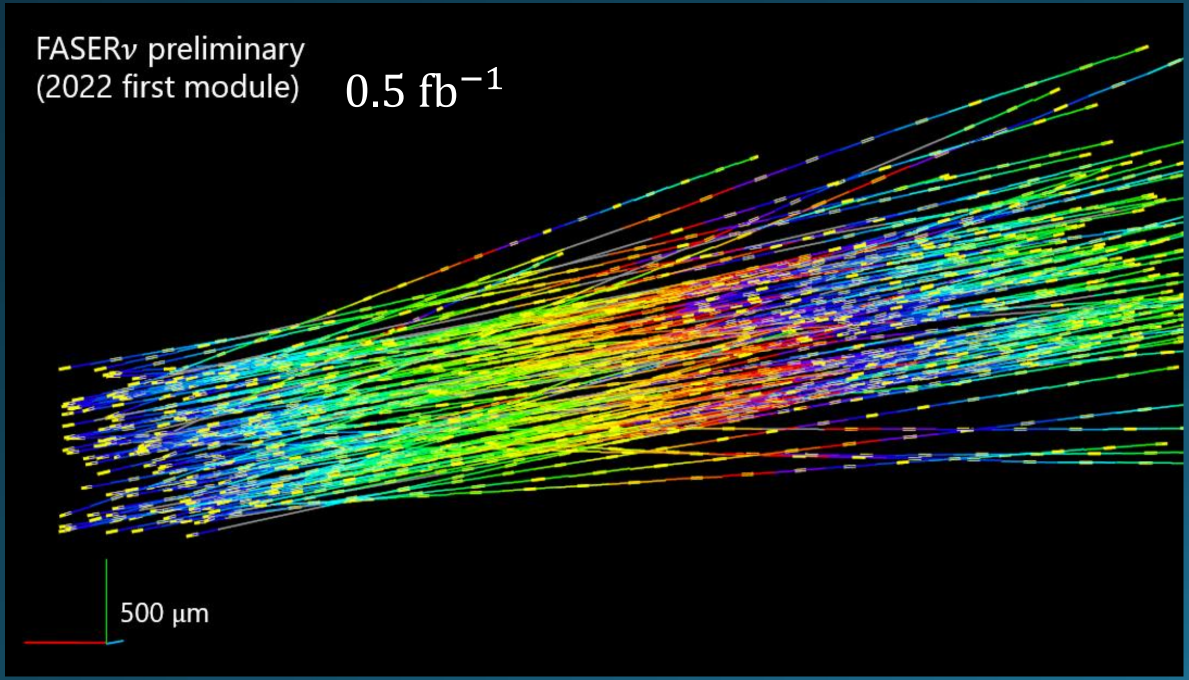
- All detector components performing excellently
- More than 350M single-muon events recorded
  - Example: muon leaving track passing through full detector + scintillator/calorimeter deposits consistent with MIP

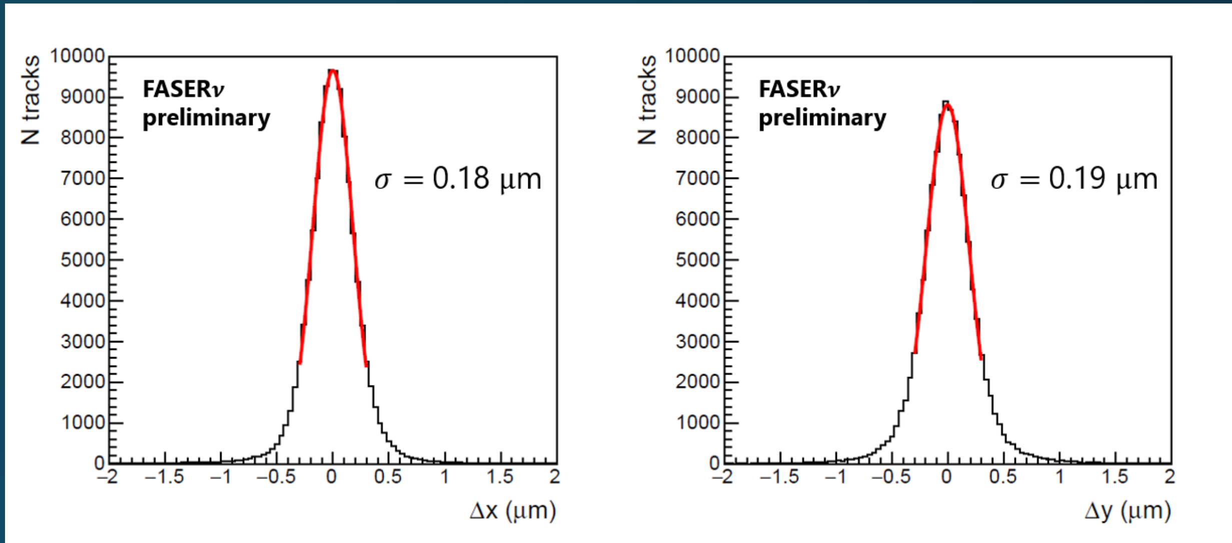


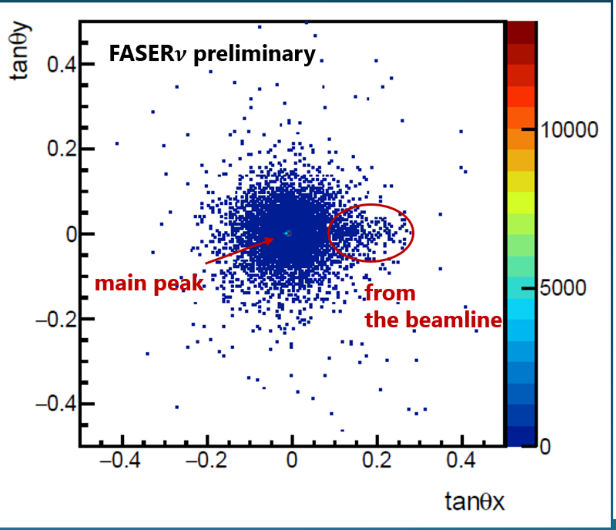


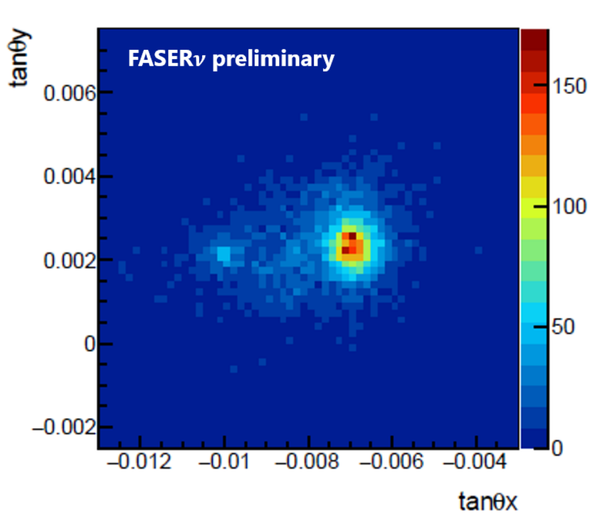
FASERν detector performances

- Track density and angular distributions Consistent with FLUKA simulation
- Excellent hit resolution (0.2 μm) after detailed film alignment





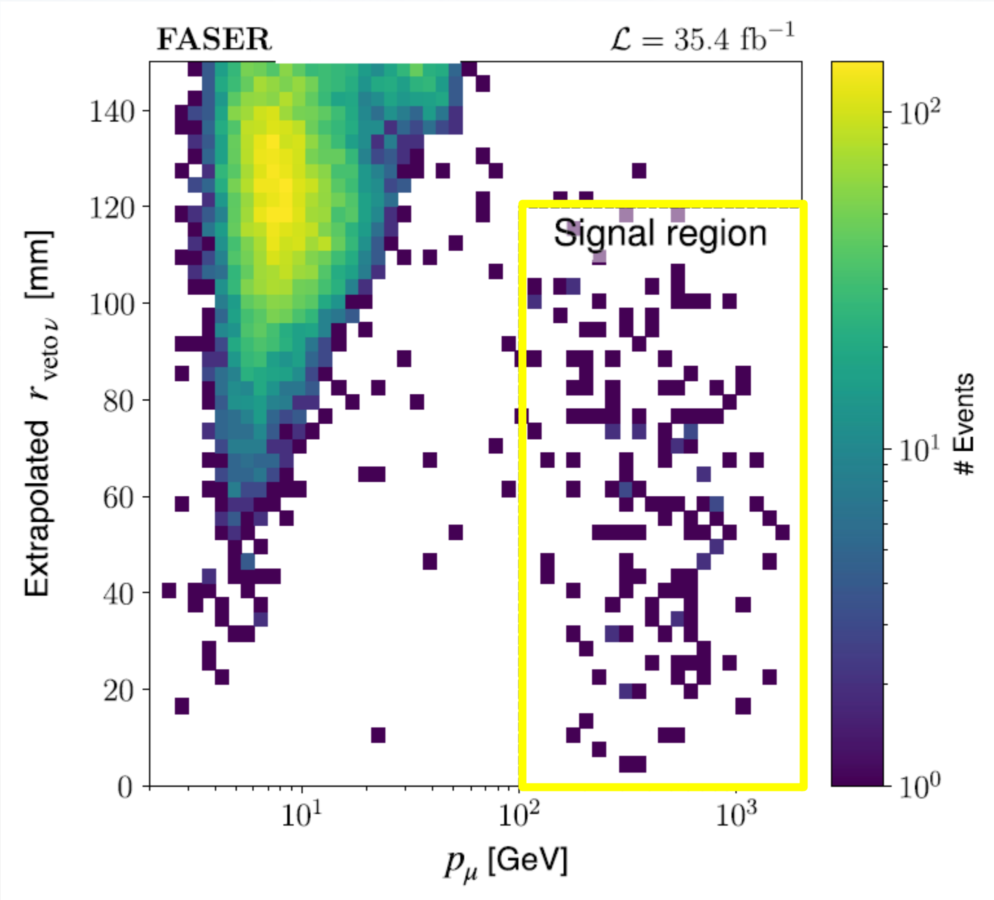




First direct observation of ν_μ interactions at the LHC

by the FASER electronic detectors

Phys. Rev. Lett. 131, 031801 (2023)



Selection: No veto, P>100 GeV, r_{veto}<12cm

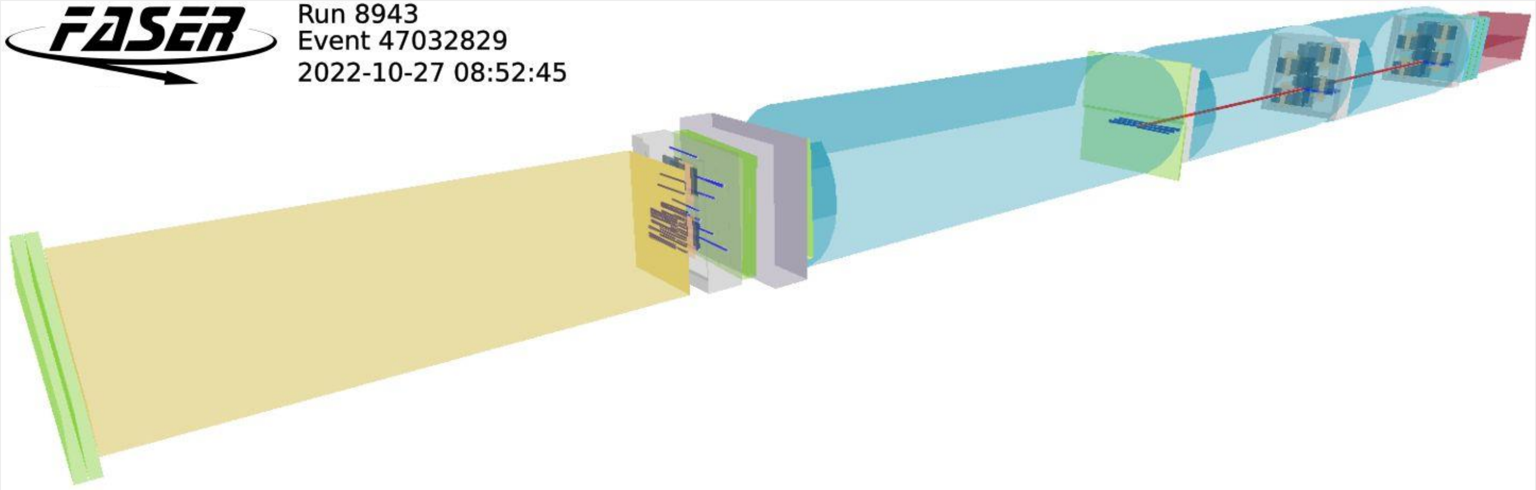
Unblinded results:

153 events in the signal region

(significance of 16σ)

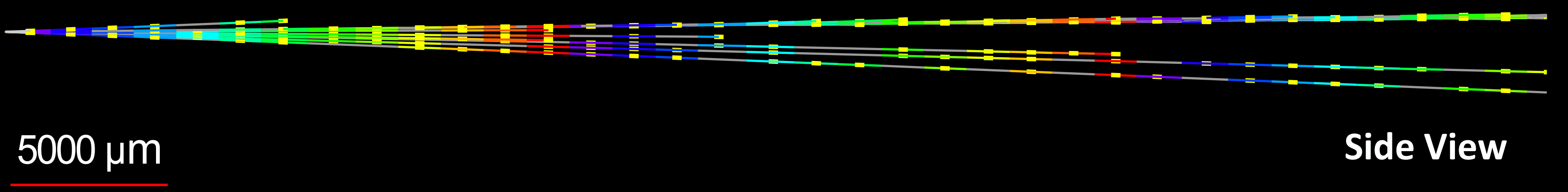
First direct observation of ν_μ interactions at the LHC

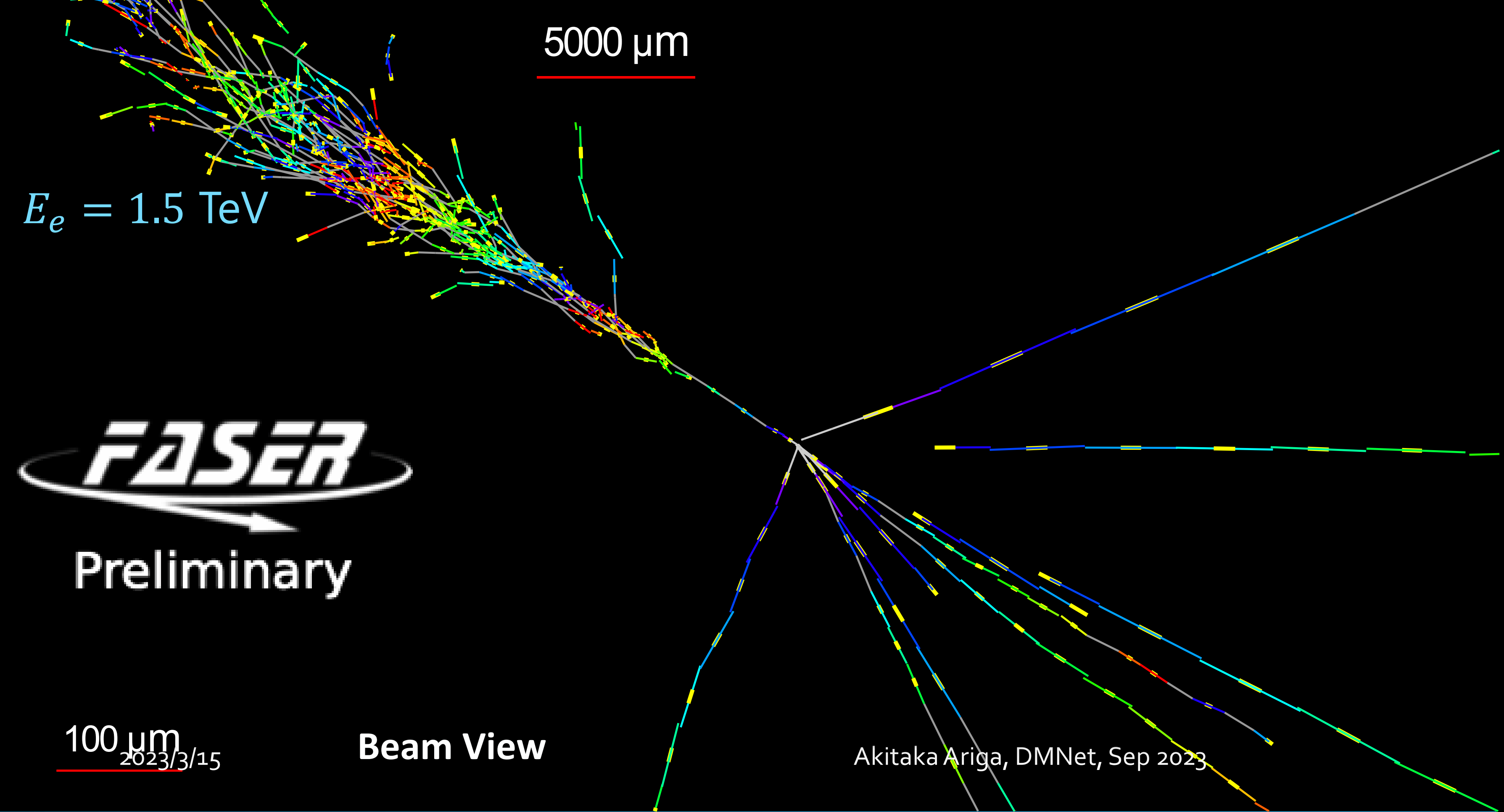
using FASERν as a target



Electron neutrino observation in FASERν

ν_e CC event, "Pika-ν" event





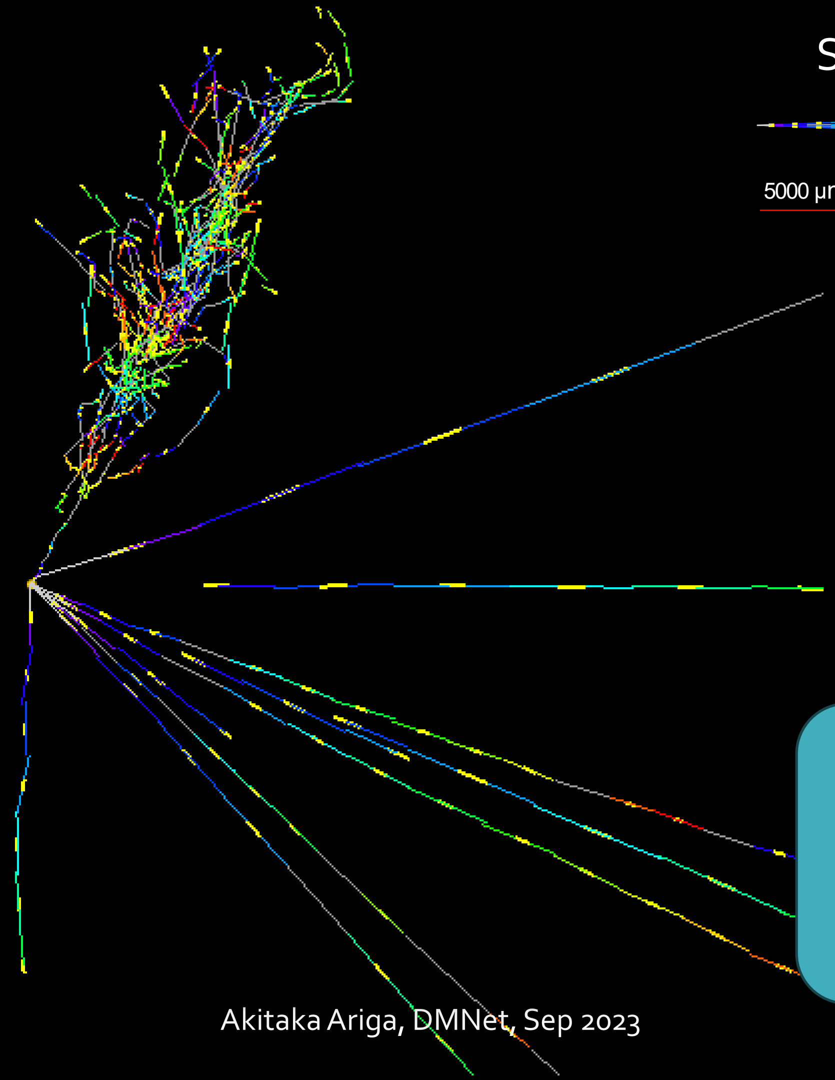
- Vertex with 11 tracks
  - 615 µm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

Animated event display of Pika-ν event

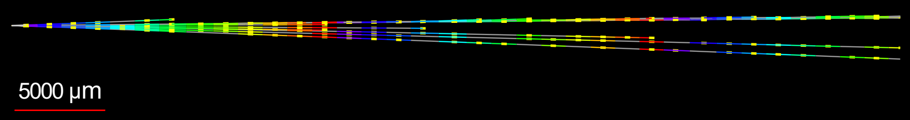
ν_e candidate

Try an interactive display! http://physics.s.chiba-u.ac.jp/lepp/pika-nu.html

Beam view



Side view



FASER Preliminary

- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$

3 observed ν_e events with 0.002 expected BG ($5\ \sigma$)

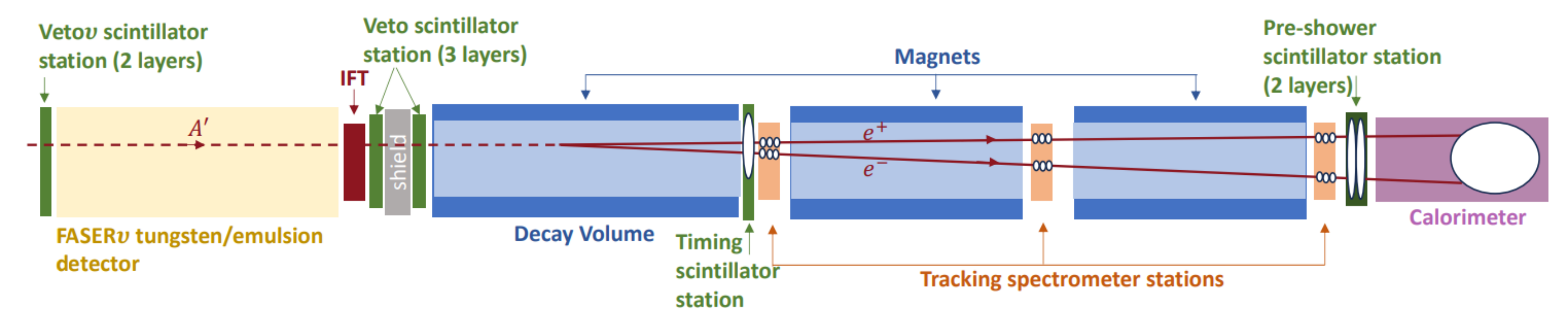
First direct observation of electron-neutrino CC interactions at the LHC

Dark photon search

Simple and robust A′ → e^+e^- selection, optimised for discovery

No veto signal, two tracks and E(calo) > 100 GeV

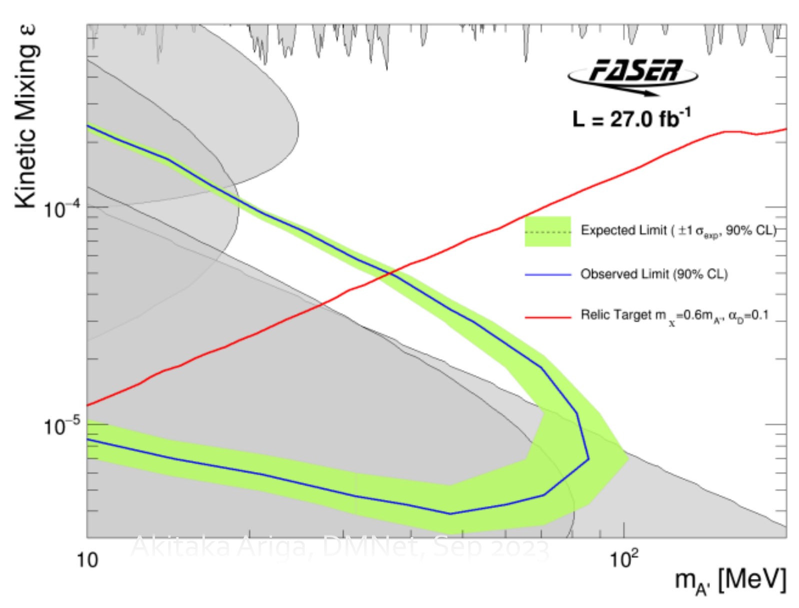
Efficiency of ~50% in region of space where dark photon can act as dark mater mediator

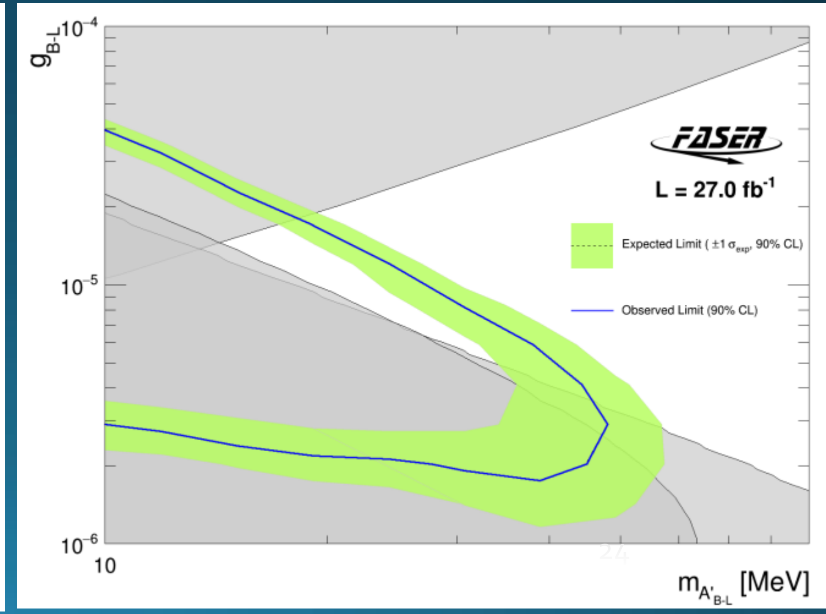


- Total background prediction (dominated by neutrinos)

  $N_{BG} = (2.3 \pm 2.3) \times 10^{-3}$

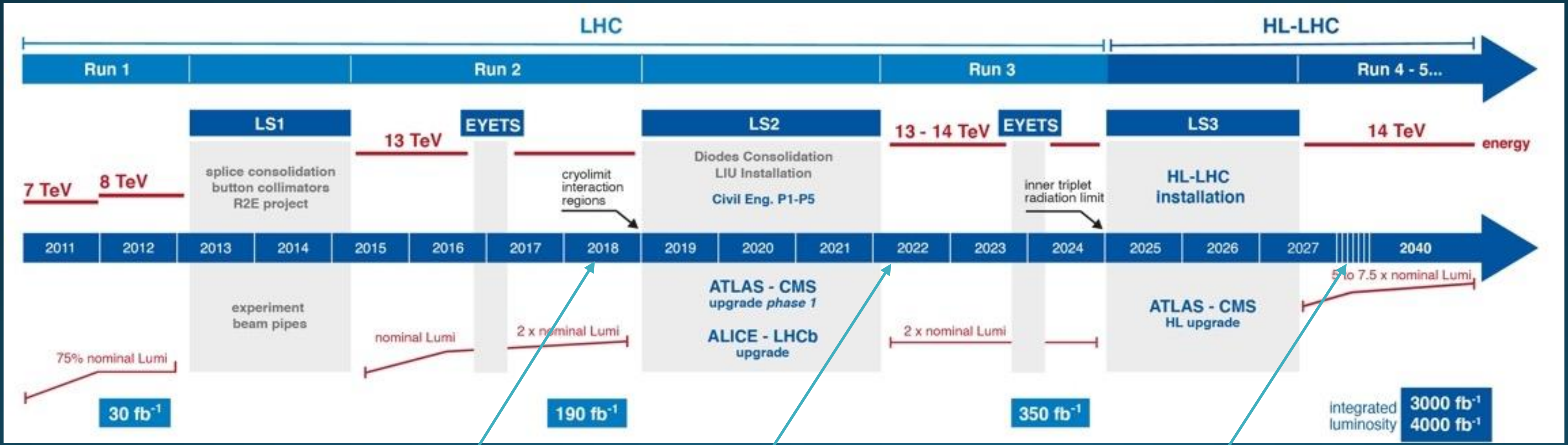
- No events in unblinded signal region





LHC Schedule

- LHC Run-3 will start in 2022, aiming to double the integrated luminosity
- HL-LHC, starting in 2027, will deliver ~20 times integrated luminosity wrt Run3



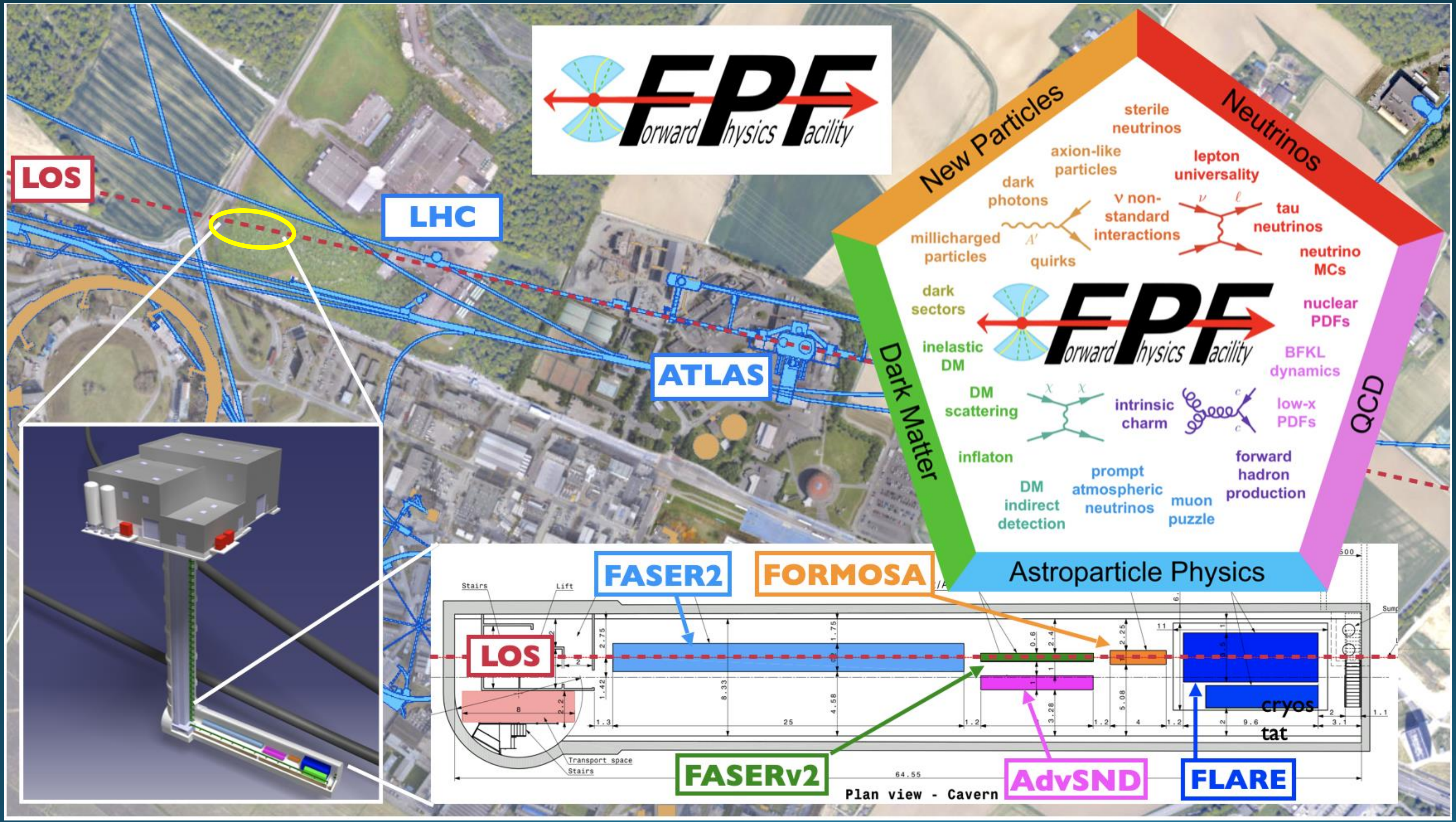
BG measurement, pilot run in 2018

Physics run will start in 2022 (~250 fb^{-1})

Forward experiment in HL-LHC

The Forward Physics Facility

The FPF is a proposed facility that would house a suite of experiments to fully exploit the LHC's physics potential in the forward direction.



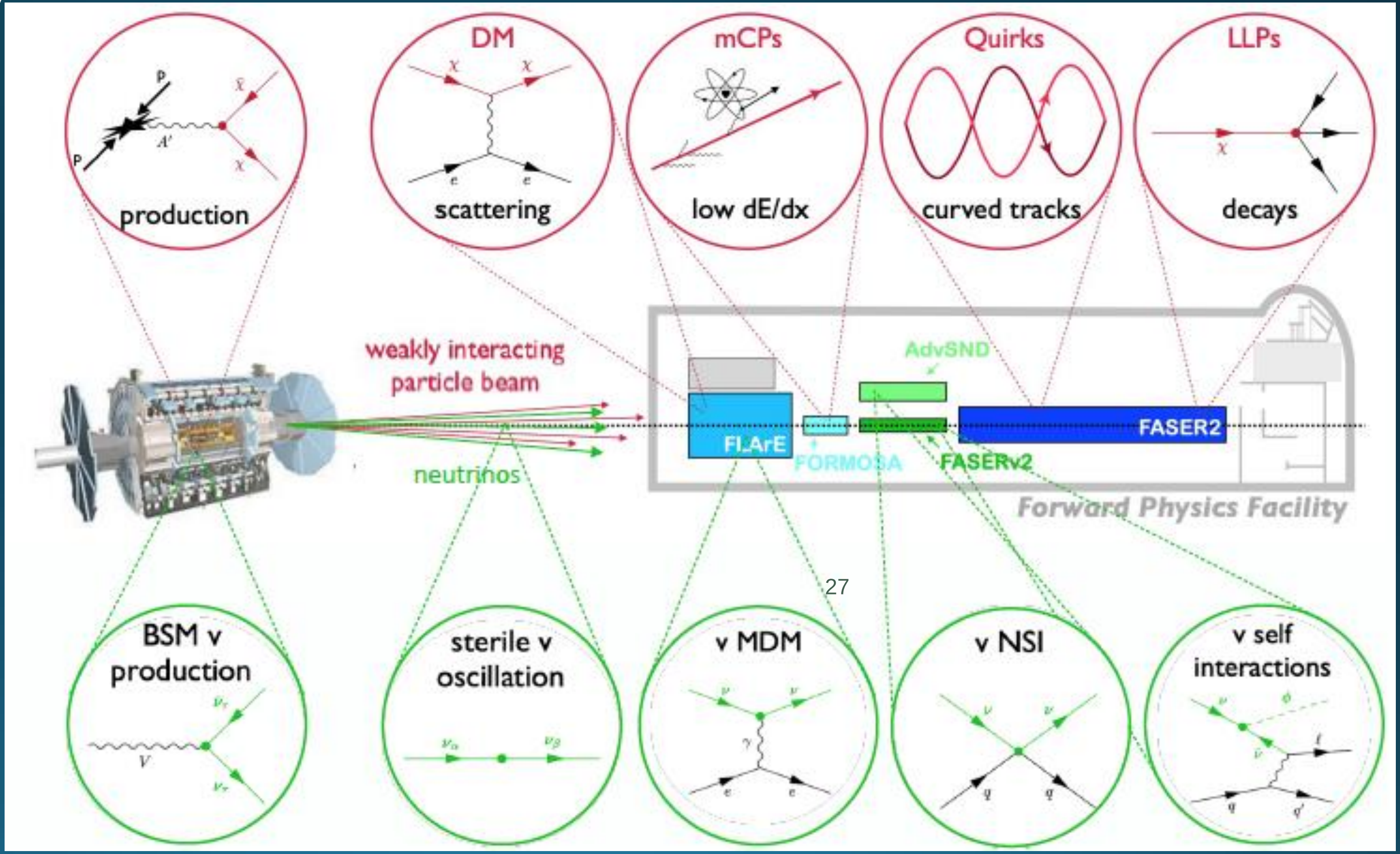
Physics Program of Forward Physics Facility

BSM particles can be detected in various ways

- Giving access to wide range of models

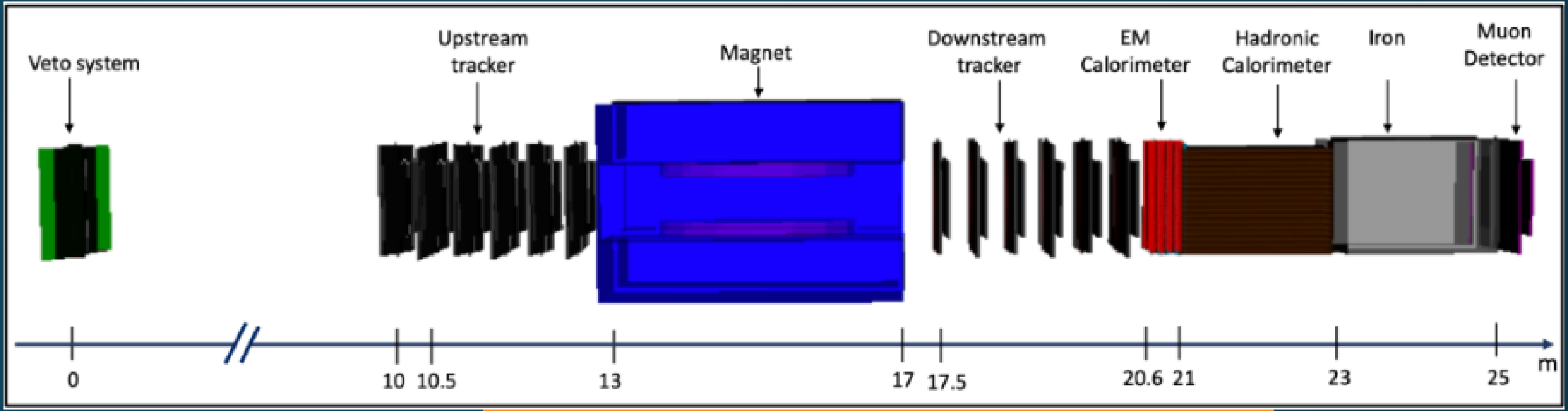
Neutrinos can be used to search for BSM effects

- Production
- Propagation
- Interaction

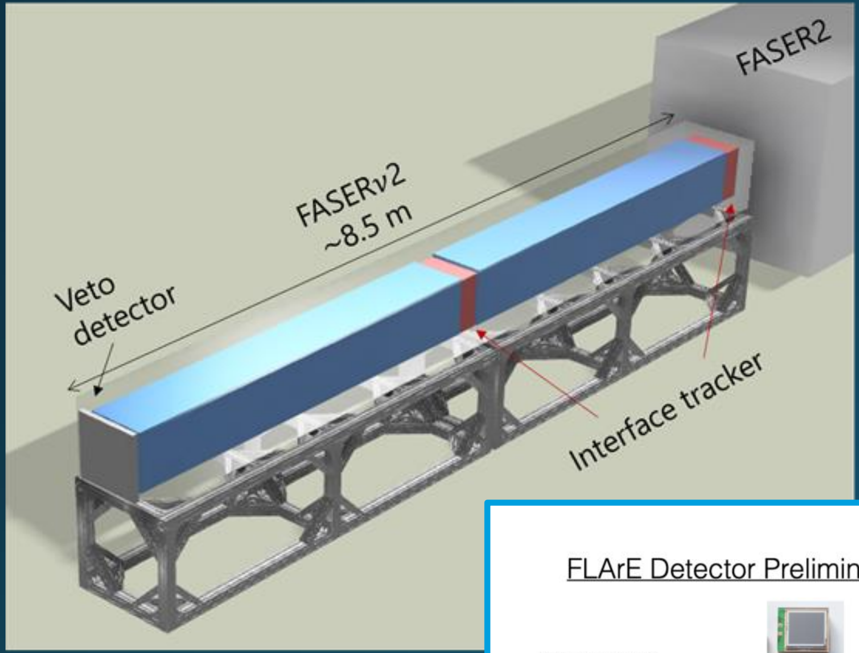


Detectors at the FPF

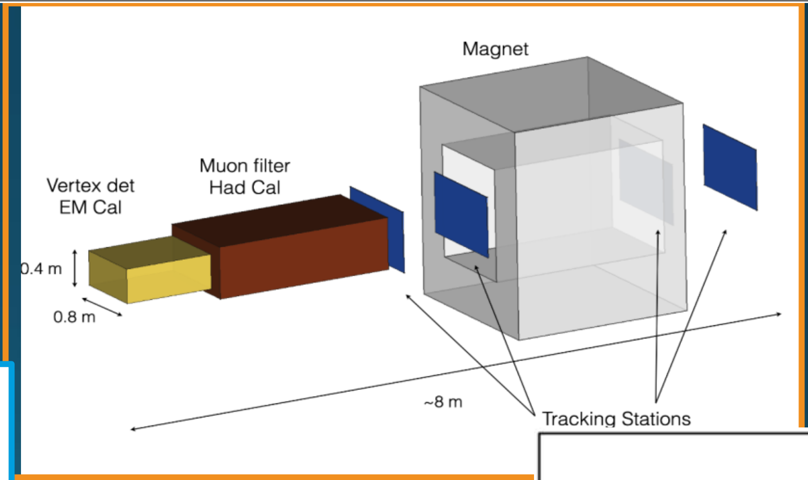
FASER2
LLP searches



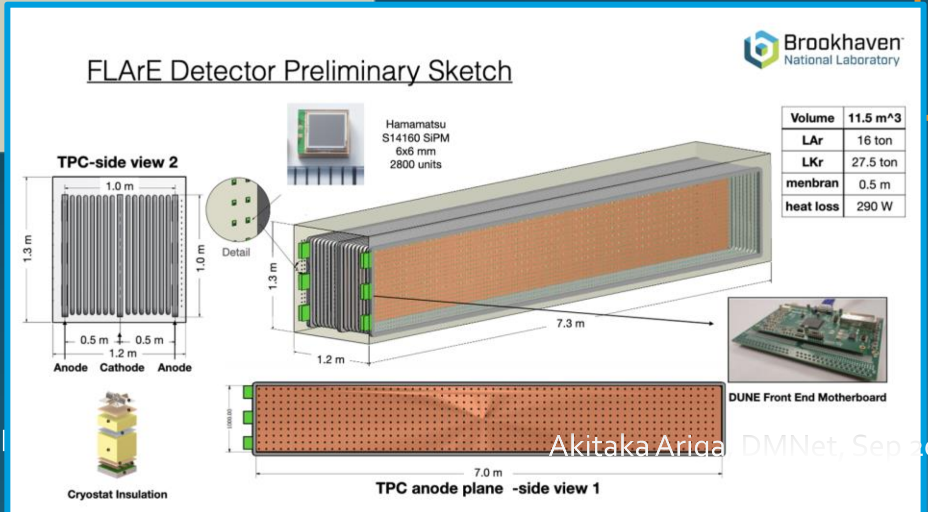
FASERv2
20 tons emulsion neutrino detector followed by FASER spectrometer



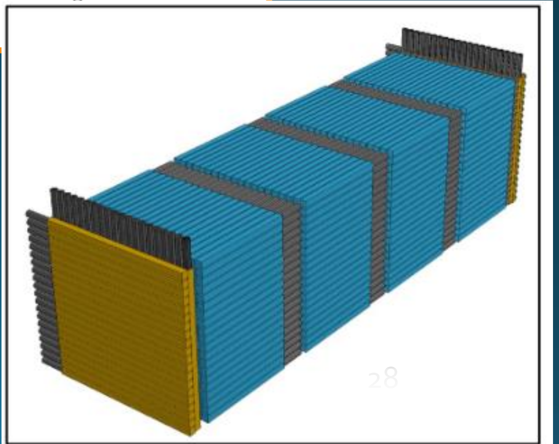
AdvSND
electronic detector
near detector at η~5
far detector at FPF



FLArE
liquid noble gas detector



FORMOSA
Milli charged particle



FASER Collaboration, 1811.12522 (2018)

Meetings and Documentation

FPF workshop series:
FPF1, FPF2, FPF3,
FPF4, FPF5, FPF6

FPF Paper:
2109.10905
~75 pages, ~80 authors

Snowmass Whitepaper:
2203.05090
~450 pages, ~250 authors


4th Forward Physics Facility Meeting

31 January 2022 to 1 February 2022
Europe/Zurich timezone

Overview
Call for Abstracts
Timetable
Contribution List
My Conference
My Contributions
Book of Abstracts
Registration
Participant List

Starts 31 Jan 2022, 16:00
Ends 1 Feb 2022, 21:00
Europe/Zurich

There are no materials yet.

The Forward Physics Facility (FPF) project is moving forward!

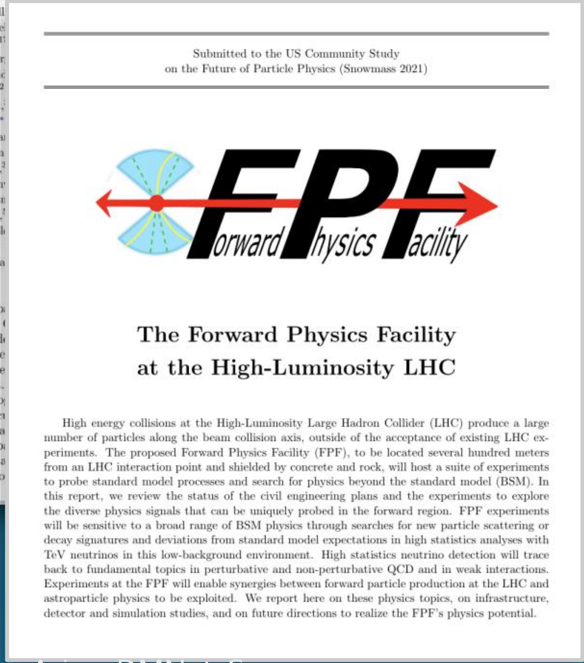
At the 4th Forward Physics Facility Meeting we will discuss the facility, experiments, and physics goals of the proposed FPF at the HL-LHC. The meeting takes place just before the completion of the FPF Snowmass White Paper and will provide an opportunity to summarize the current status of the White Paper and the final steps in its preparation. The whole event will be held online.

The Zoom links are:
Plenary sessions (both Monday and Tuesday): https://uci.zoom.us/j/91591021575
//vu-live.zoom.us
J9RQnRzTjlpdz09
tps://uiowa.zoom.us/j/94645515841
//zoom.us/j/97280888150


The Forward Physics Facility:
Sites, Experiments, and Physics Potential

Luis A. Anchordoqui, Akitaka Ariga, Tomoko Ariga, Weidong Bai, Kincso Balazs, Brian Batell, Jamie Boyd, Joseph Bramante, Adrian Carmona, Mario Campanell… Francesco G. Celiberto, Grigorios Chachamis, Matthew Citron, Giovanni De Le… Albert de Roeck, Hans Dembinski, Peter B. Denton, Antonia Di Crescenzo, … Milind V. Diwan, Liam Dougherty, Herbi K. Dreiner, Yong Du, Rikard Enber… Yasaman Farzan, Jonathan L. Feng, Max Fieg, Patrick Foldenauer, Saeid… Foroughi-Abari, Alexander Friedland, Michael Fucilla, Jonathan Gall, … Maria Vittoria Garzelli, Francesco Giuli, Victor P. Goncalves, Marco Guzzi, … Francis Halzen, Juan Carlos Helo, Christopher S. Hill, Ahmed Ismail, … Ameen Ismail, Sudip Jana, Yu Seon Jeong, Krzysztof Jodłowski, Fnu Kara… Kumar, Kevin J. Kelly, Felix Kling, Rafał Maciuła, Roshan Mammen… Abraham, Julien Manshanden, Josh McFayden, Mohammed M. A. Mohammed, … Pavel M. Nadolsky, Nobuchika Okada, John Osborne, Hidetoshi Otono, Vish… Pandey, Alessandro Papa, Digesh Raut, Mary Hall Reno, Filippo Resn… Adam Ritz, Juan Rojo, Ina Sarcevic, Christiane Scherb, Pedro Schwaller, … Holger Schulz, Dipan Sengupta, Torbjörn Sjöstrand, Tyler B. Smith, Dennis Sol… Anna Stasto, Antoni Szczurek, Zahra Tabrizi, Sebastian Trojanowski, … Yu-Dai Tsai, Douglas Tuckler, Martin W. Winkler, Keping Xie, and Yue Zha…

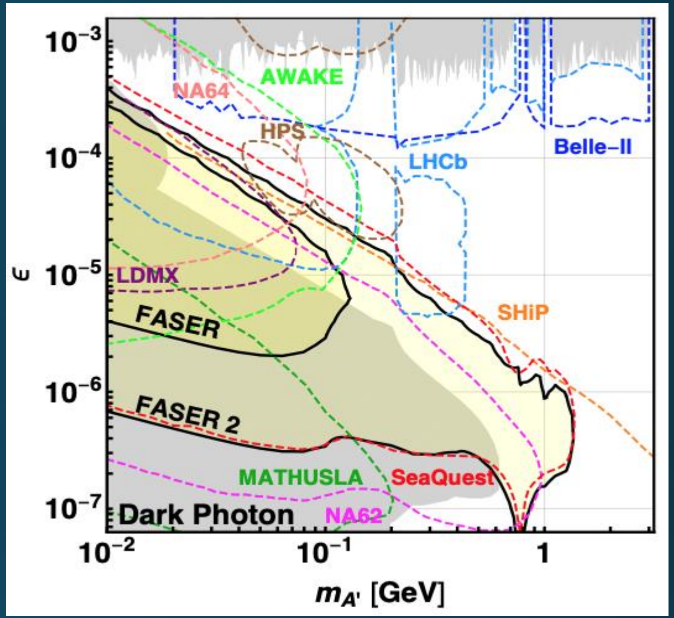
The Forward Physics Facility (FPF) is a proposal to create a cavern with the sp… infrastructure to support a suite of far-forward experiments at the Large Hadron … during the High Luminosity era. Located along the beam collision axis and shield… the interaction point by at least 100 m of concrete and rock, the FPF will house expe… that will detect particles outside the acceptance of the existing large LHC experime… will observe rare and exotic processes in an extremely low-background environment. … work, we summarize the current status of plans for the FPF, including recent pro… civil engineering in identifying promising sites for the FPF; the FPF experiments … envisioned to realize the FPF's physics potential; and the many Standard Model a… physics topics that will be advanced by the FPF, including searches for long-lived p… probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of … flavors, aspects of perturbative and non-perturbative QCD, and high-energy astro… physics.

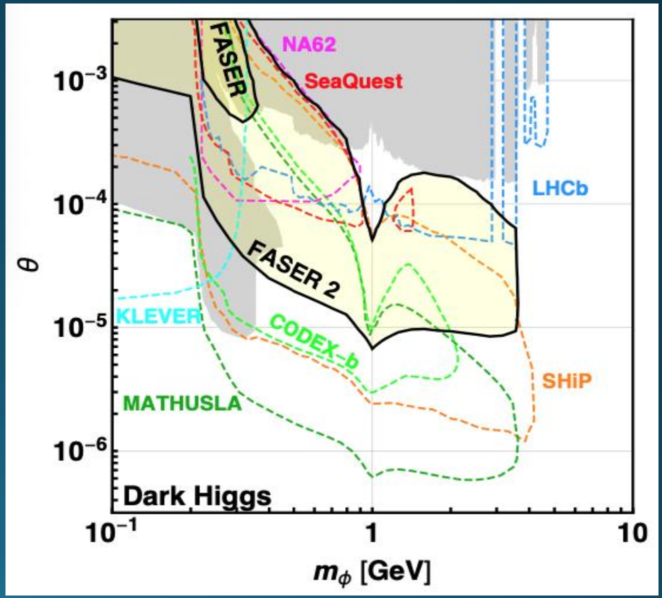

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

FPF
Forward Physics Facility

The Forward Physics Facility
at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from an LHC interaction point and shielded by concrete and rock, will host a suite of experiments to probe standard model processes and search for physics beyond the standard model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from standard model expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will trace back to fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector and simulation studies, and on future directions to realize the FPF's physics potential.





FPF in Snowmass

The FPF was prominently featured in many Snowmass Reports (Thanks to the efforts of many of you!)

Additionally, auxiliary experiments and facilities are proposed to take advantage in far forward kinematic regions. Forward physics facilities allow to further extend the breadth of the HL-LHC physics: they can study regions of parameter phase space for BSM, for example in LLPs and DM searches, that would otherwise remain uncovered, and can perform novel QCD and neutrino measurements in the very forward region

Vision Section of Energy Frontier Report

Auxiliary forward-physics facilities will further extend the physics potential of the HL-LHC both for SM measurements and BSM discoveries. In view of all these considerations, the EF supports continued strong U.S. participation in the success of the LHC, and the HL-LHC construction, operations, and physics programs, including auxiliary experiments.

Energy Frontier Section of Snowmass Summary Report

FPF in Snowmass

Executive Summary (10 pages)

LHC

The Energy Frontier (Science Drivers 1 – 3 & 5): The Energy Frontier currently has a top-notch program with the Large Hadron Collider (LHC) and its planned High Luminosity upgrade (HL-LHC) at CERN, which sets the basis for the Energy Frontier vision. The fundamental lessons learned from the LHC thus far are that a Higgs-like particle exists at 125 GeV and there is no obvious and unambiguous signal of BSM physics. This implies that new physics either occurs at scales higher than we have probed, must be weakly coupled to the SM, or is hidden in backgrounds at the LHC. The immediate goal for the Energy Frontier is to continue to take and analyze the data from LHC Run 3, which will go on for about three more years, and carry out the 2014 P5 recommendations to complete the HL-LHC Upgrade and execute its physics program. The HL-LHC will measure the properties of the Higgs Boson more precisely, probe the boundaries of the SM further, and possibly observe new physics or point us in a particular direction for discovery.

A new aspect of the proposed LHC program is the emergence of a variety of auxiliary experiments that can use the interactions already occurring in the existing collision regions during the normal LHC and HL-LHC running of the ATLAS, CMS, LHCb, and ALICE experiments to explore regions of discovery space that are not currently accessible. These typically involve observing particles in the far forward direction or long-lived particles produced at larger angles but decaying far outside the existing detectors. These are mid-scale detectors in their own right and provide room for additional innovation and leadership opportunities for younger physicists at the LHC. The EF supports continued strong U.S. participation in the success of the LHC, and the HL-LHC construction, operations, and physics programs, including auxiliary experiments.

future collider

New colliders are the ultimate tools to extend the EF program into the next two decades thanks to the broad and complementary set of measurements and searches they enable. With a combined strategy of precision measurements and high-energy exploration, future lepton colliders starting at energies as low as the Z-pole up to a few TeV can shed substantial light on some of these key questions. It will be crucial to find a way to carry out experiments at higher energy scales, directly probing new physics at the 10 TeV energy scale and beyond. The EF supports a fast start for the construction of an e^+e^- Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs Factory will require an immediate, vigorous, and targeted accelerator and detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.

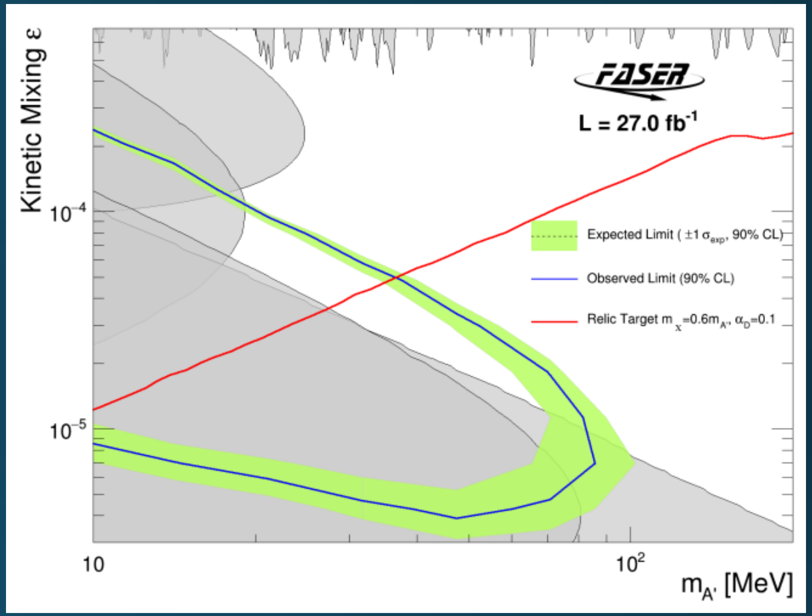
Finally, the U.S. EF community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the U.S., while maintaining its international collaborative partnerships and obligations with, for example, CERN.

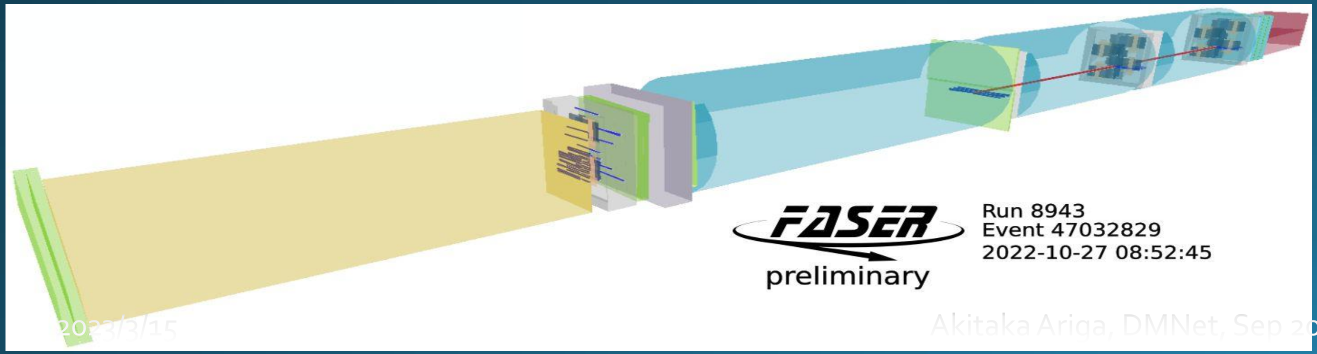
A new aspect of the proposed LHC program is the emergence of a variety of auxiliary experiments that can use the interactions already occurring in the existing collision … to explore regions of discovery space that are not currently accessible. These typically involve observing particles in the far forward direction or long-lived particles … decaying far outside the existing detectors. These are mid-scale detectors in their own right and provide room for additional innovation and leadership opportunities for younger physicists at the LHC. The EF supports continued strong U.S participation … including auxiliary experiments.

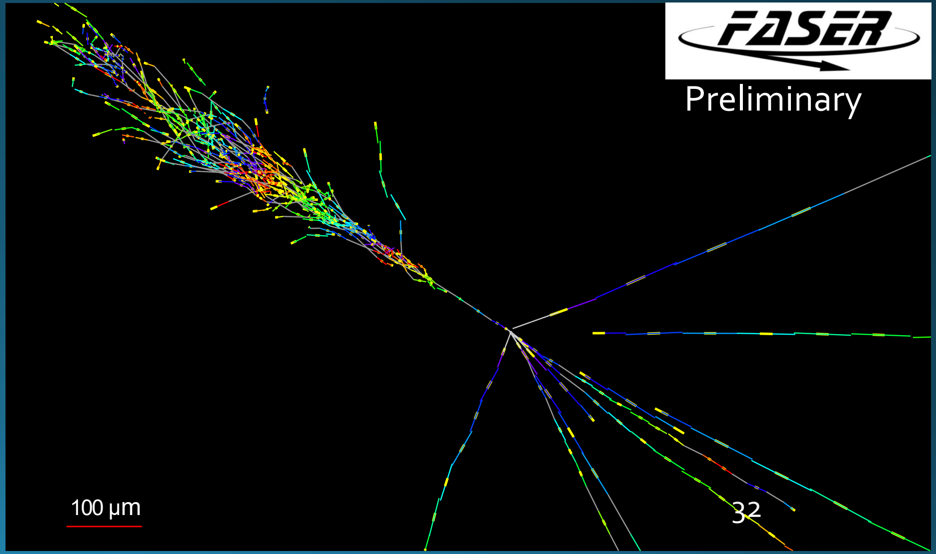
Summary

- FASER successfully took data in first year of Run 3
  - Running with fully functional detector and very good efficiency
- Detected ~150 ν_μ CC interactions in spectrometer
  - First direct detection of collider neutrinos!
  - Opens new window for high-energy ν study
- Detected ν_e CC interactions in FASERν
  - Emulsion analysis is being accelerated
- Excluded A' in region of low mass and kinetic mixing
  - Probes new territory in interesting thermal-relic region
- Forward Physics Facility (FPF) is gaining momentum!
  - With HL-LHC, x 20 luminosity, high sensitive detectors

More results are coming!





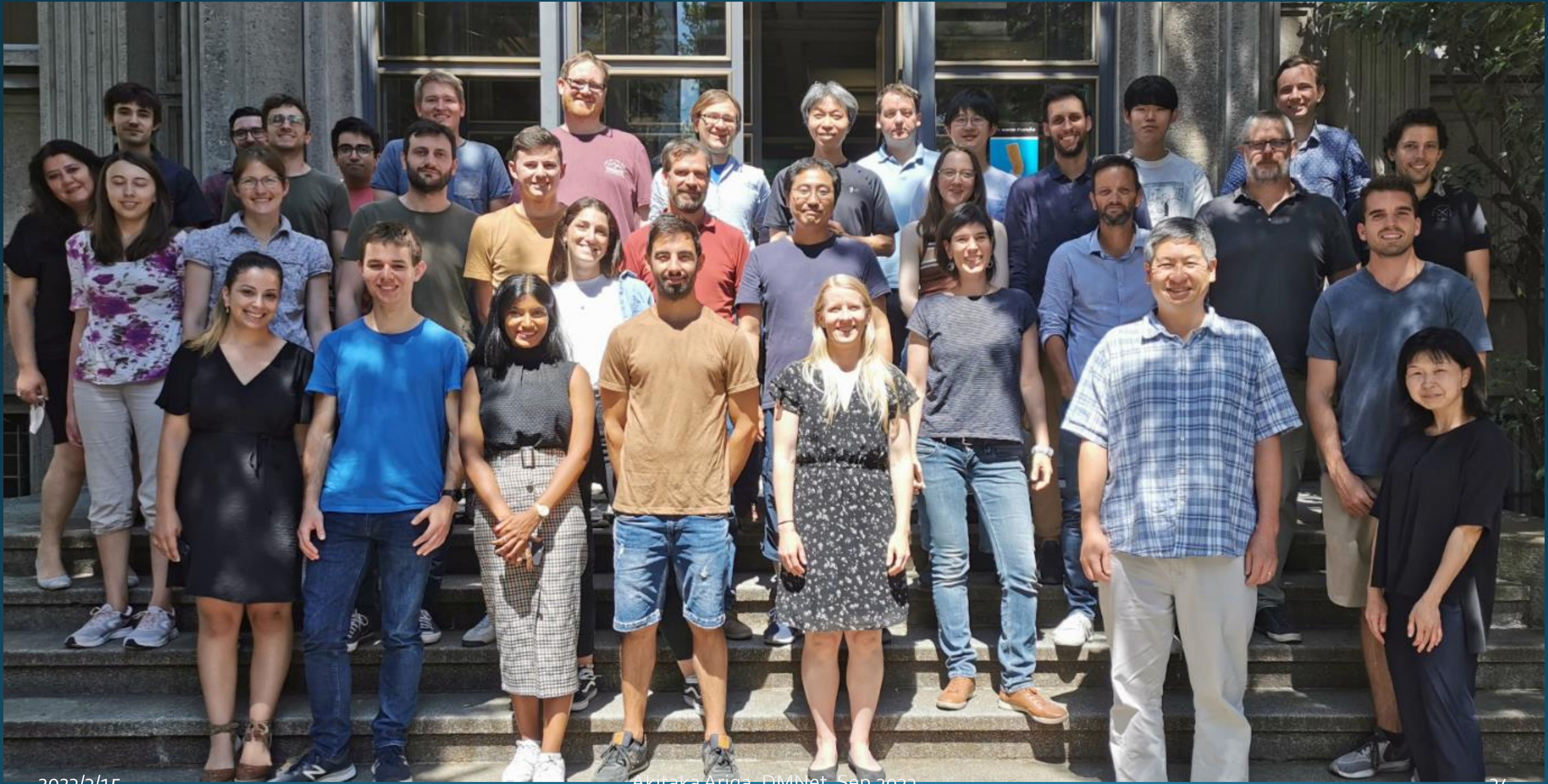


FASER Collaboration

To be updated

- 87 members across 24 institutes from 10 countries

FASER collaboration



To be updated

FASER Publications

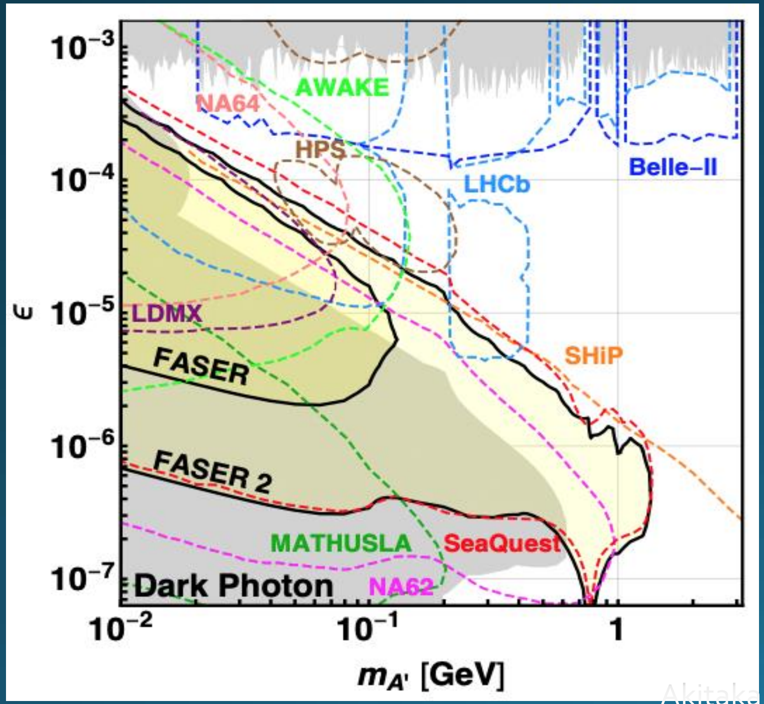
- * Search for Dark Photons with the FASER detector at the LHC: arXiv:2308.05587
- * First Direct Observation of Collider Neutrinos with FASER at the LHC: PhysRevLett.131.031801
- The FASER Detector: arXiv:2207.11427
- The FASER W-Si High Precision Preshower Technical Proposal: CERN Document Server
- The tracking detector of the FASER experiment: NIM 166825 (2022)
- The trigger and data acquisition system of the FASER experiment: JINST 16 P12028 (2021)
- First neutrino interaction candidates at the LHC: PRD 104 L091101 (2021)
- Technical Proposal of FASERν neutrino detector: arXiv:2001.03073
- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC: EPJC 80 61 (2020)
- Input to the European Strategy for Particle Physics Update: arXiv:1901.04468
- FASER's Physics Reach for Long-Lived: PRD 99 090511 (2019)
- Letter of Intent: arXiv:1812.09139
- Technical Proposal: arXiv:1811.10243

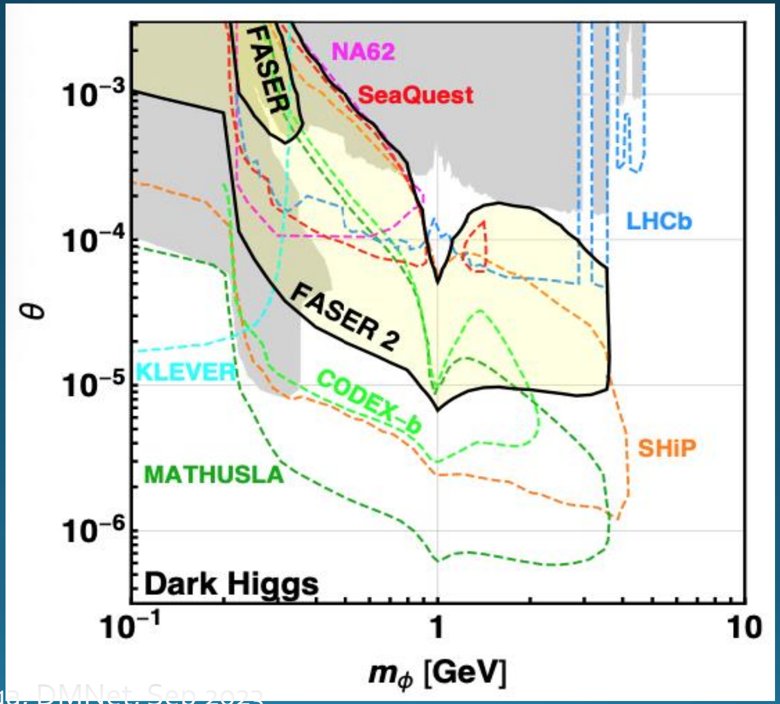
FASER2: New particle searches (Long Lived Particles)

- FASER2, New larger detector at Forward Physics Facility
  - FASER (R=10cm, L=1.5m, Run 3) → FASER 2 (R=1m, L=5m, HL-LHC)
  - Largely explore unexplored parameter space

x 300 decay volume
x 20 beam

Dark photon





Dark higgs

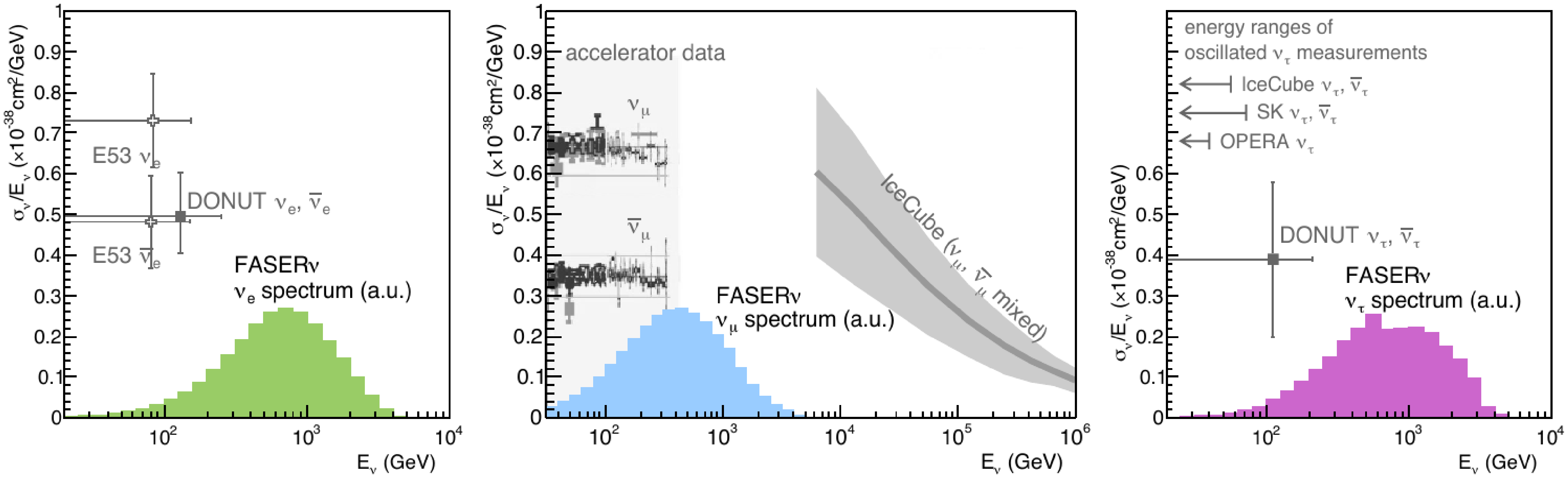
FASER Collaboration, 1811.12522 (2018)

Collider Neutrinos

- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → high interaction cross section
- Extends FASER physics program into SM measurements
  - Targets measurement of highest energy man-made neutrinos
  - Energy range complementary to existing neutrino experiments

For 35 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaons	Pions	Charm
# traversing FASERν	~10^{10}	~10^{11}	~10^{8}
# interacting in FASERν	≈200	≈1200	≈4

PRD 104, 113008



Study at colliders originally proposed by Rújula and Rückl in 1984!

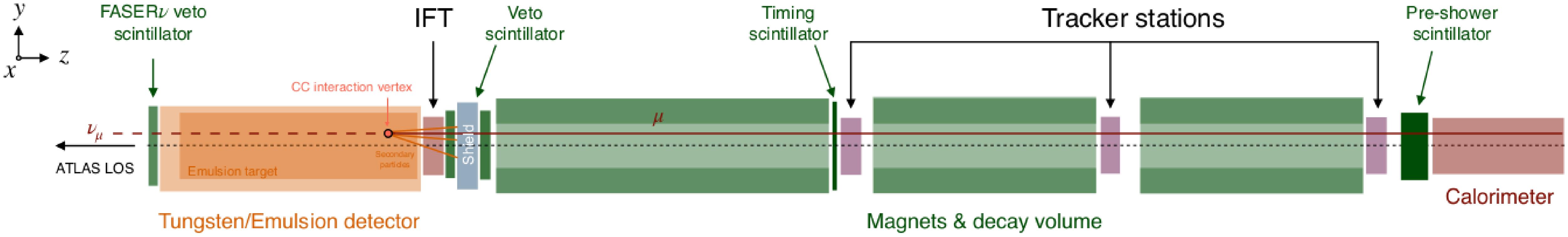
Click t

First direct observation of ν_μ interactions at the LHC
by the FASER electronic detectors

Phys. Rev. Lett. 131, 031801 (2023)

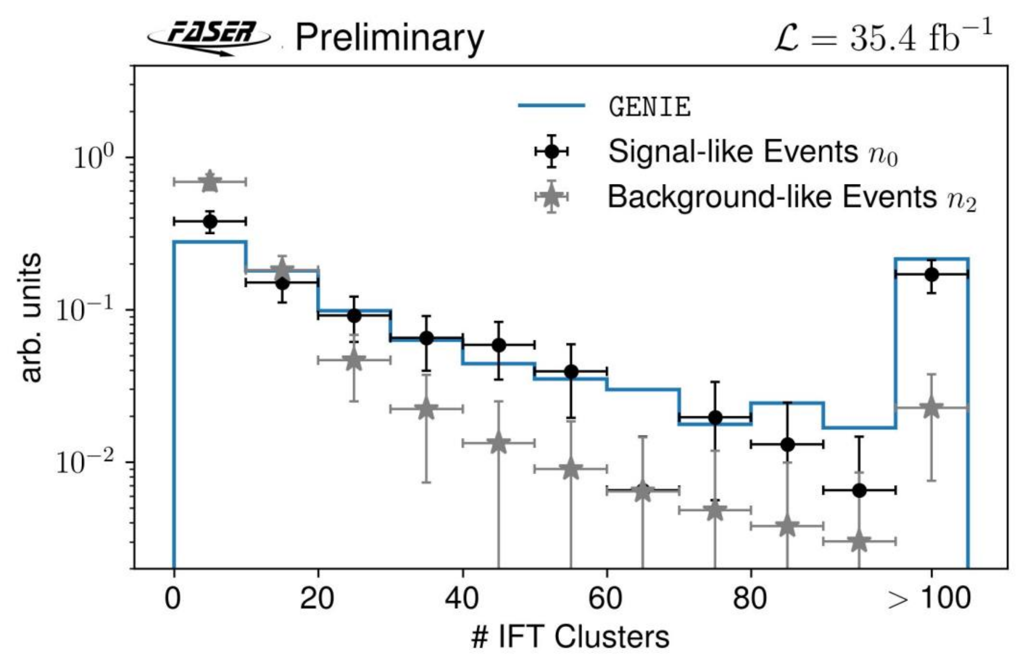
- **Event selection**
  - Collision event with good data quality (35.4 fb^{-1})
  - **No signal in two front veto scintillators** (<40 pC~0.5 MIP)
  - Signal in last two veto layers
  - Signal and pre-shower scintillators consistent with ≥1 MIPs
  - Exactly **one good quality spectrometer track with p>100 GeV**
  - Track in fiducial tracking volume, r<95 mm
  - Track extrapolate to r<120 mm in front veto scintillator
  - Track polar angle less than 25 mrad

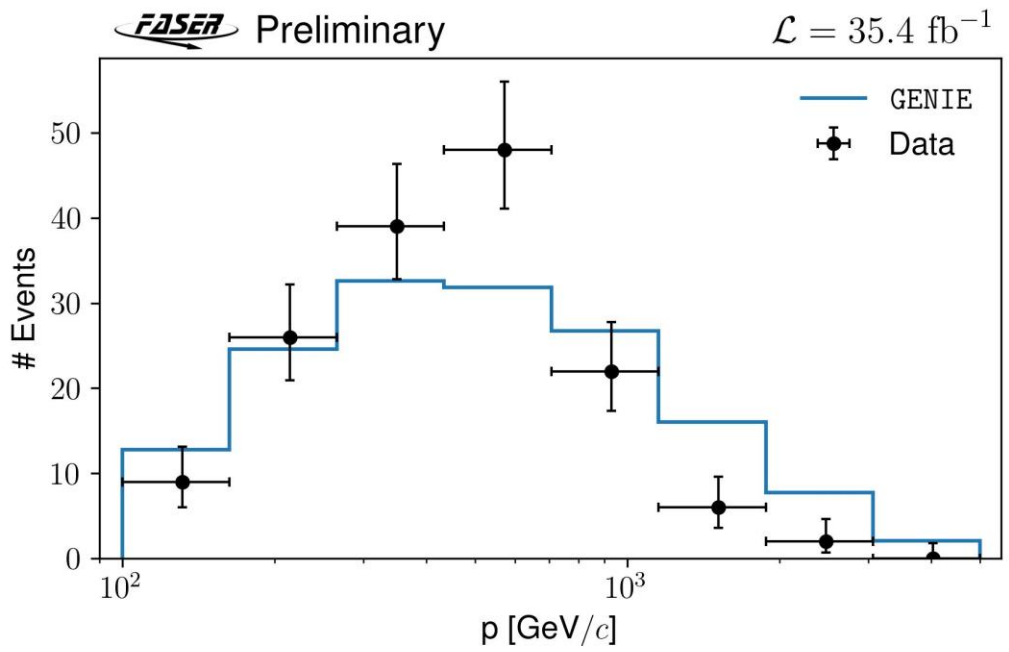
- **Signal expectation**
  - 151 ± 41 events
  - Uncertainty from DPMJET vs SIBYLL
- **Background estimate**
  - Neutral hadrons: 0.11 ± 0.06 events
  - Scattered muons: 0.08 ± 1.83 events
  - Front veto inefficiency: negligible

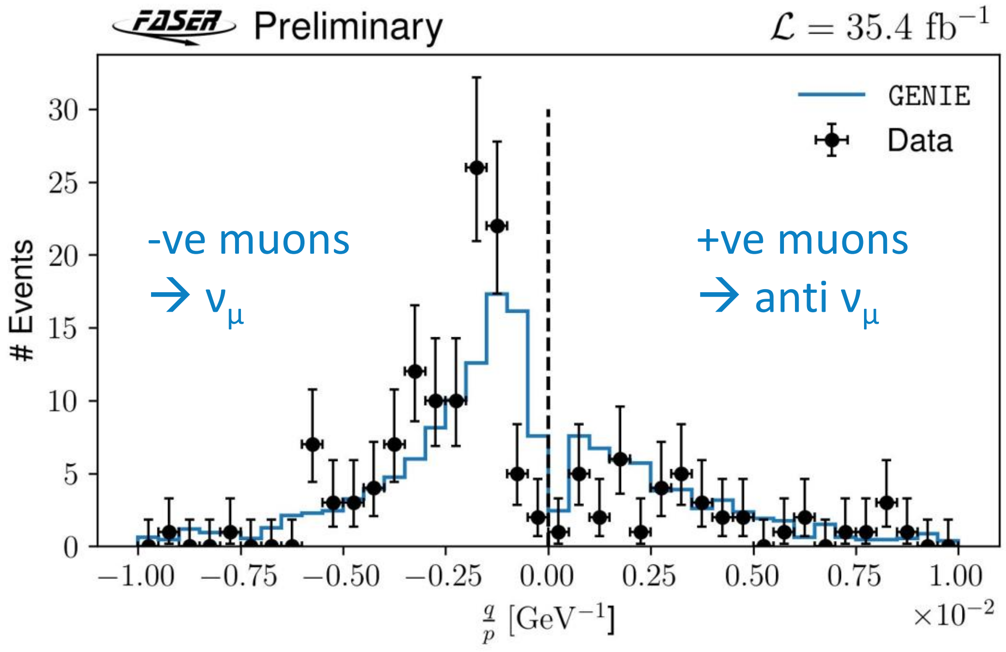


Neutrino Characteristics

- Candidate neutrino events match expectation from signal
  - High occupancy in front tracker station
  - Most events have high μ momentum
  - More ν_μ than anti- ν_μ
- Note: no acceptance corrections nor any systematic uncertainties in these plots







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Neutrino results from FASERν

FASERν Preliminary

	Expected background		Expected signal	**Observed**
	Hadron int.	ν NC int.		
ν_e CC	0.002 $\pm$0.002(stat)$\pm$0.002(syst)	-	$1.2^{+4.0}_{-0.6}$	3
ν_μ CC	0.32 $\pm$0.15(stat)$\pm$0.16(syst)	0.19$\pm$0.15	$4.4^{+4.2}_{-1.4}$	4

$p = 1.6 \times 10^{-7}$ (5.1σ)

$p = 5.2 \times 10^{-3}$ (2.5σ)

3 ν_e CC candidate events are observed.
→ Probability to be explained by background is 1.6×10^{-7}, corresponding to 5σ exclusion of the background-only hypothesis.

First direct observation of electron-neutrino CC interactions at the LHC

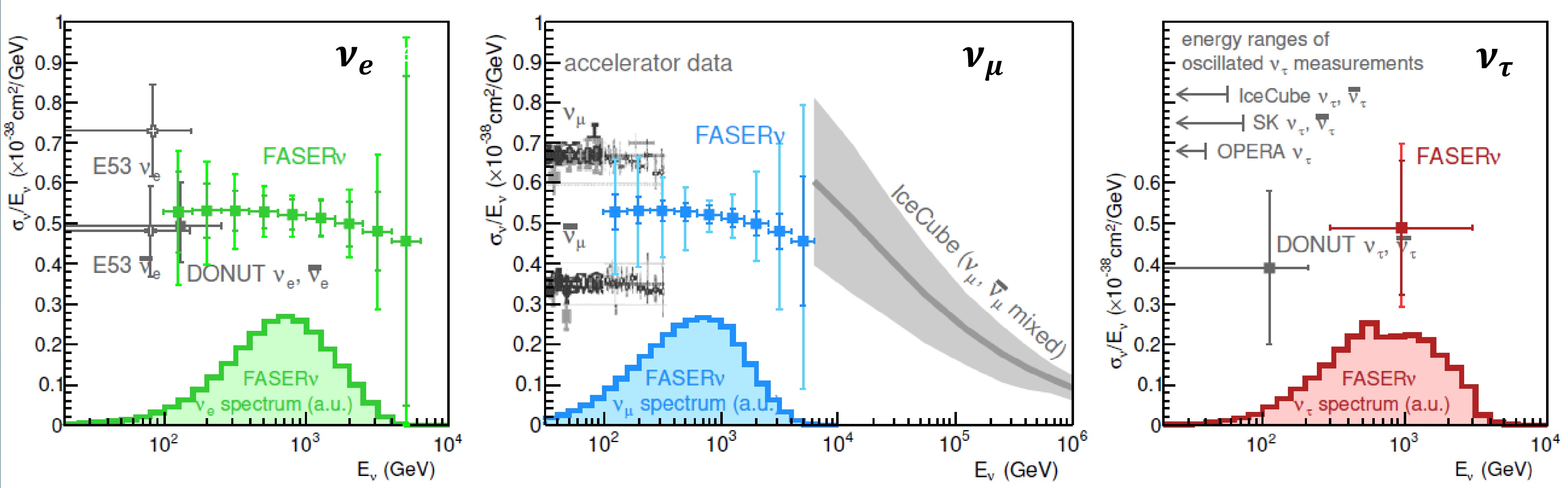
The performance of ν_μ detection will be improved in future analysis using a longer range for μ ID.

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})

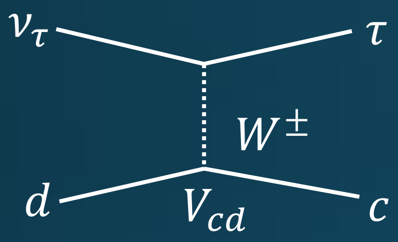


inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.

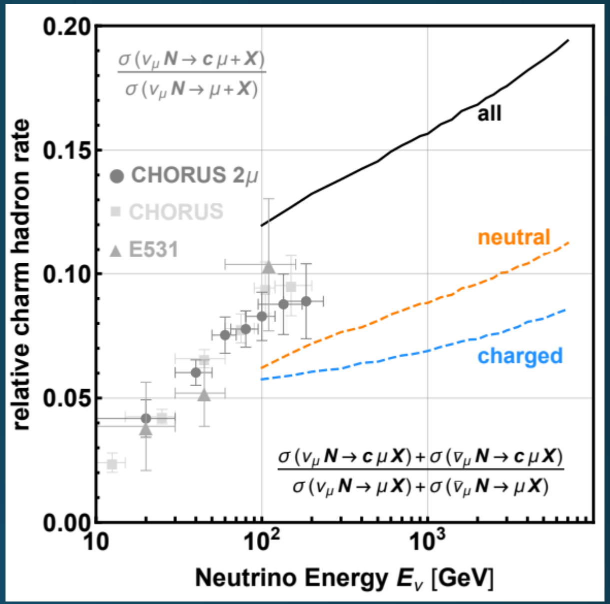
Physics studies in the LHC Run 3 (2):

Heavy-flavor-associated channels

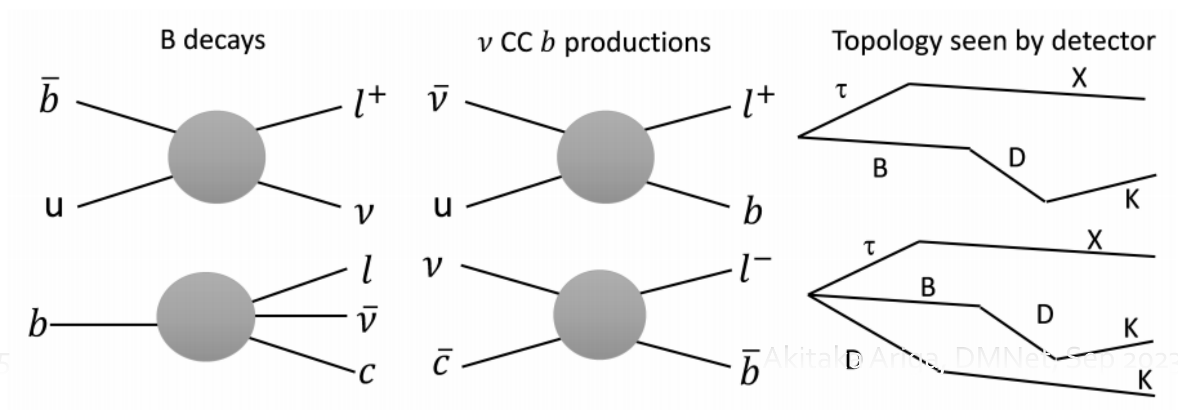
- Measure charm production channels
  - Large rate ~ 10% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.



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



- 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, $V_{ub}^2 \simeq 10^{-5}$

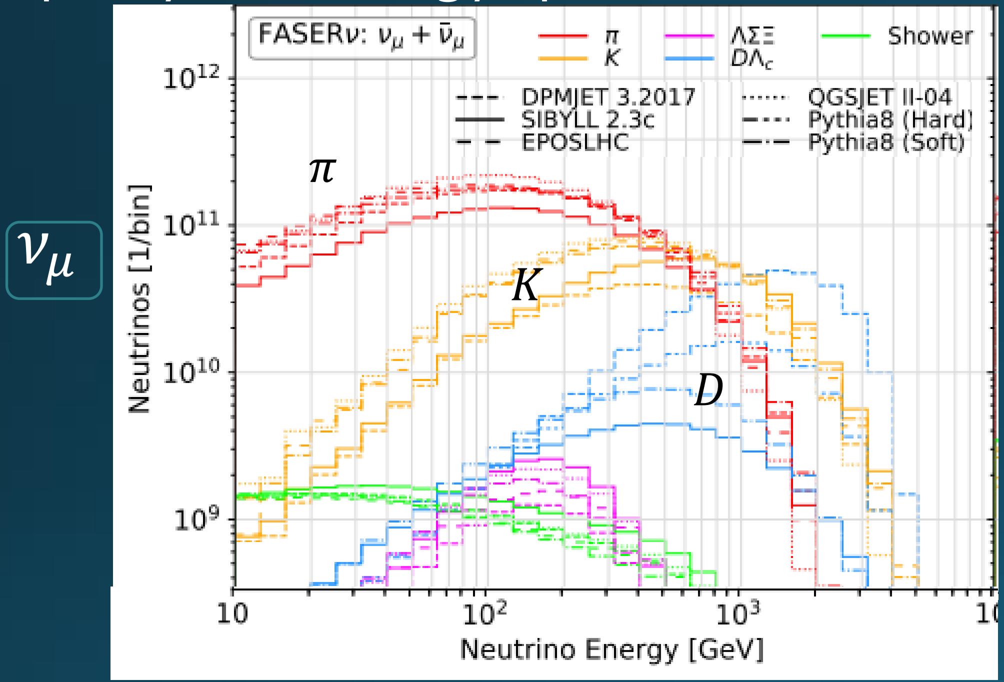


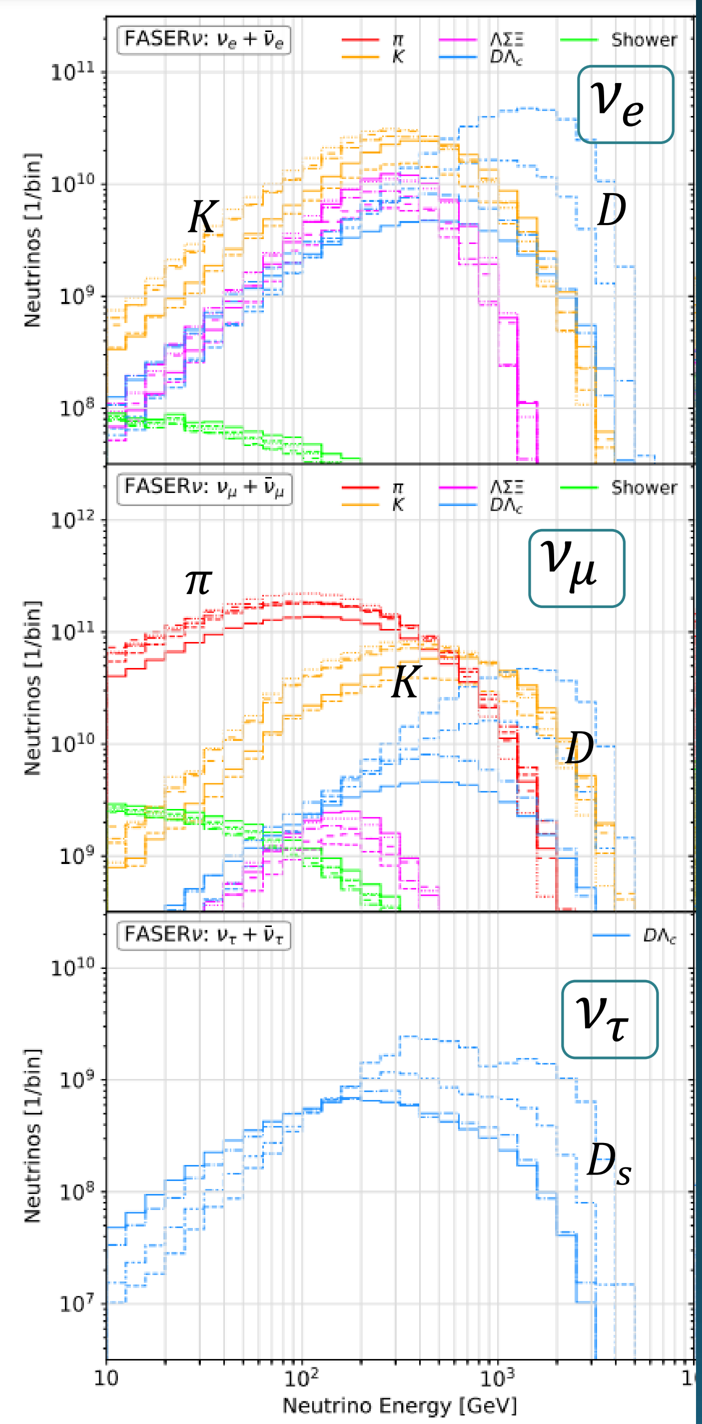
$\bar{\nu} N \to \ell \bar{B} X$

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

Neutrinos = proxy of forward hadron production

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

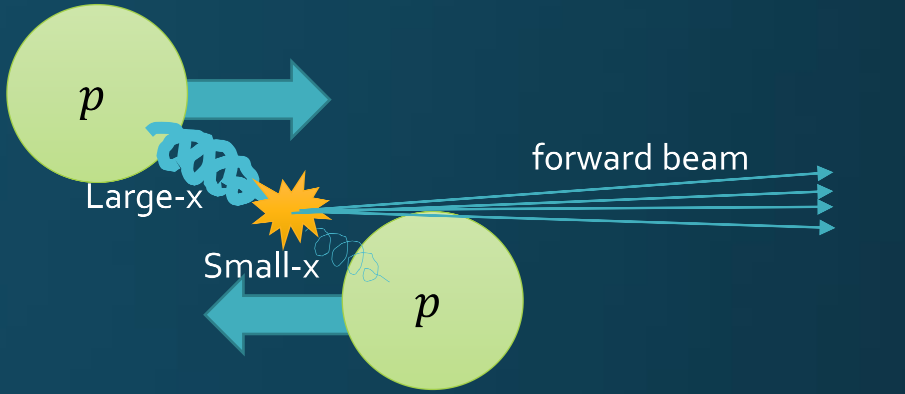


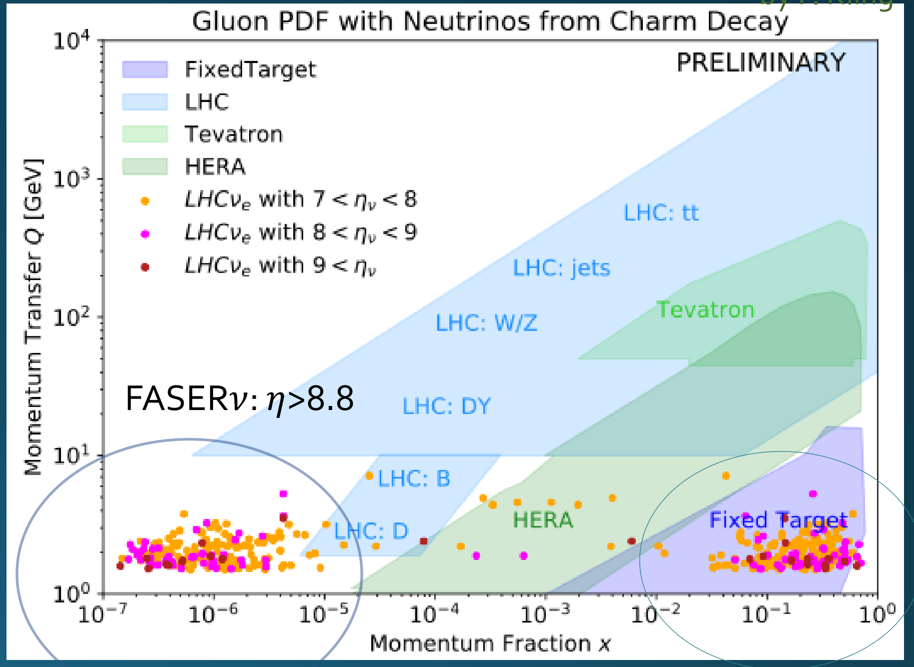


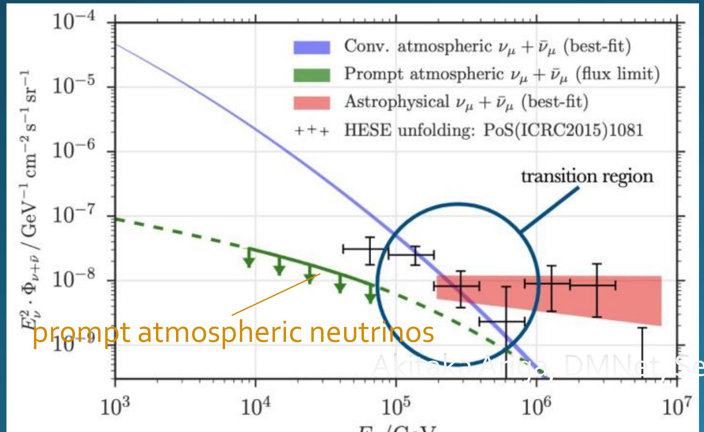
- FASERν provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

Physics studies in the LHC Run 3 (2): 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. Contributing to QCD
- Deep understanding of atmospheric prompt neutrinos is essential for astrophysical neutrino observations

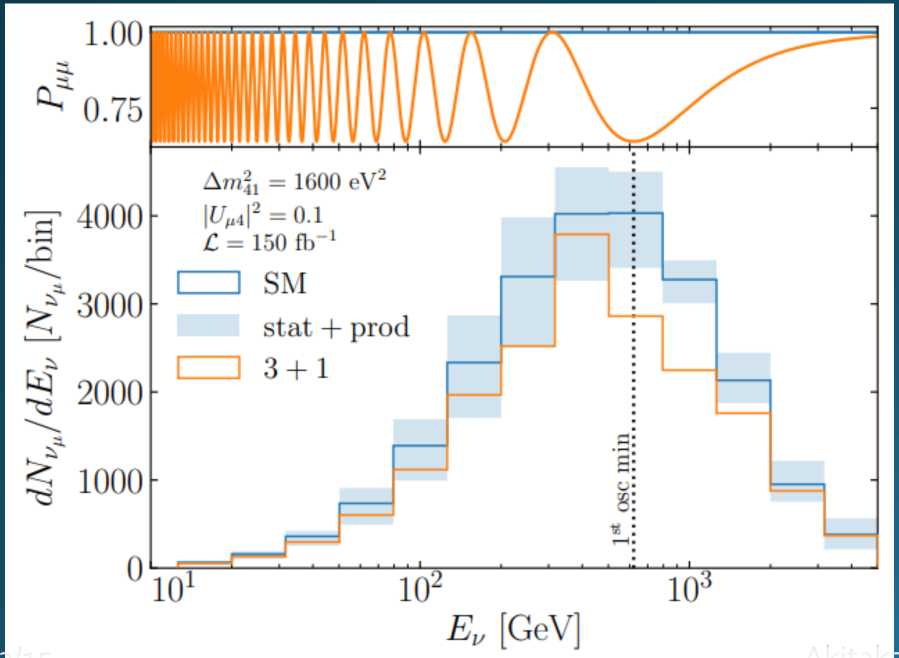




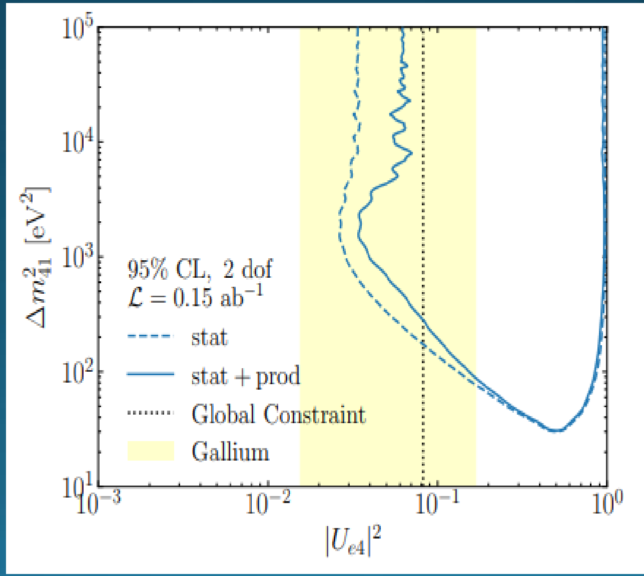


Sterile neutrino oscillation

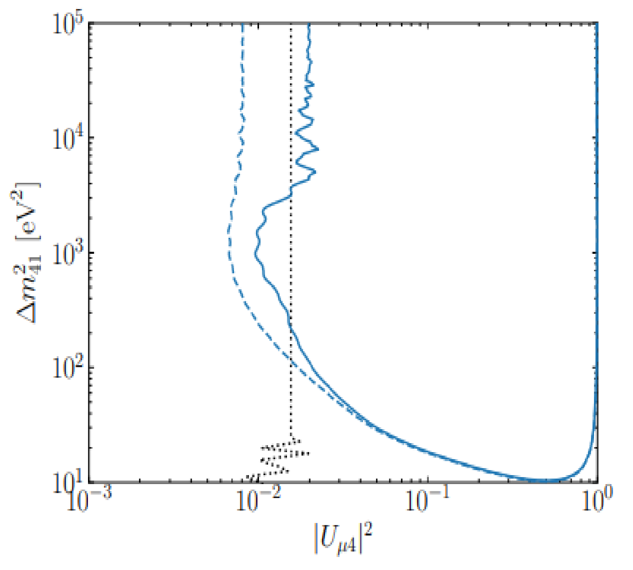
- Due to unique energy and baseline ($L/E \sim 10^{-3}$ m/MeV), FASERν is sensitive to large $\Delta m^2 \sim 10^3$ eV².
- Neutrino spectrum deformation
- Competitive in disappearance channels.



ν_e disappearance

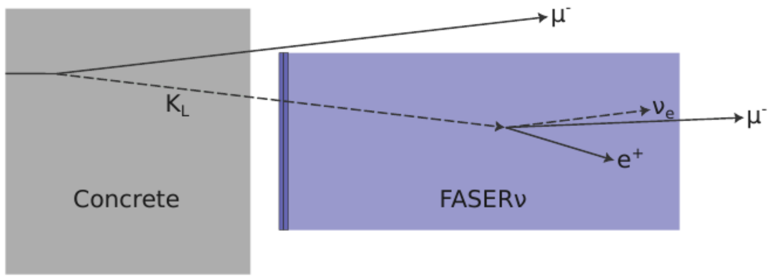


ν_μ disappearance

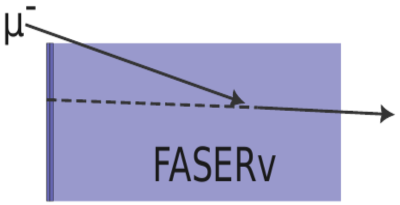


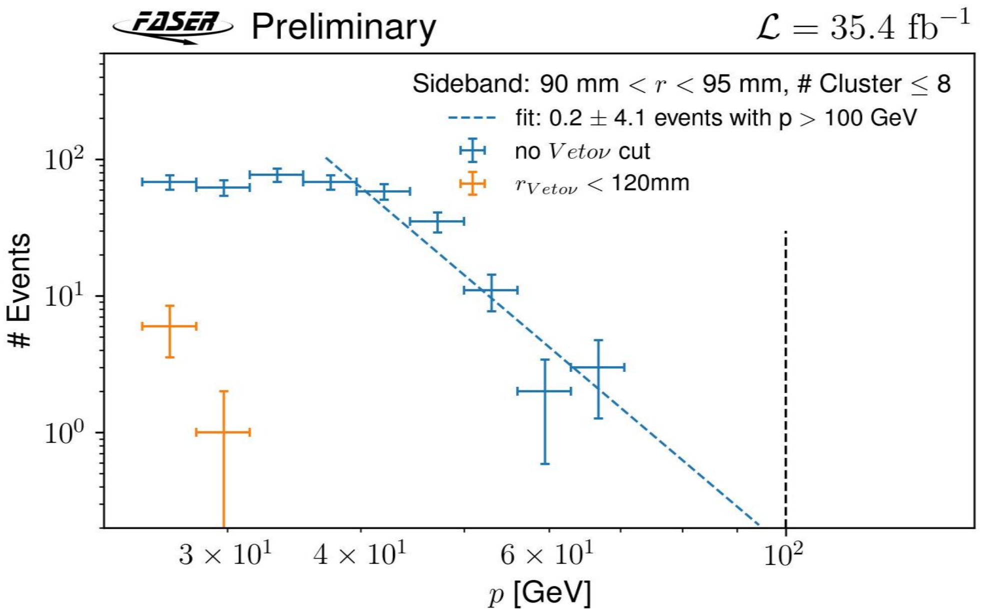
Neutrino Backgrounds

- Neutral hadrons estimated from 2-step simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
    - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
    - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events



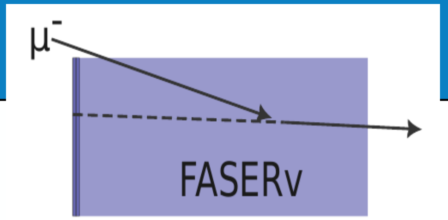
- Scattered muons estimated from data SB
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
    - Uncertainty from varying selection



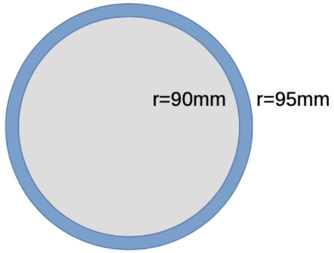


- Veto inefficiency estimated from final fit
  - Fit events with 0 (SR) and also 1 (1st or 2nd) or 2 front veto layers firing
  - Final negligible background due to very high veto efficiency

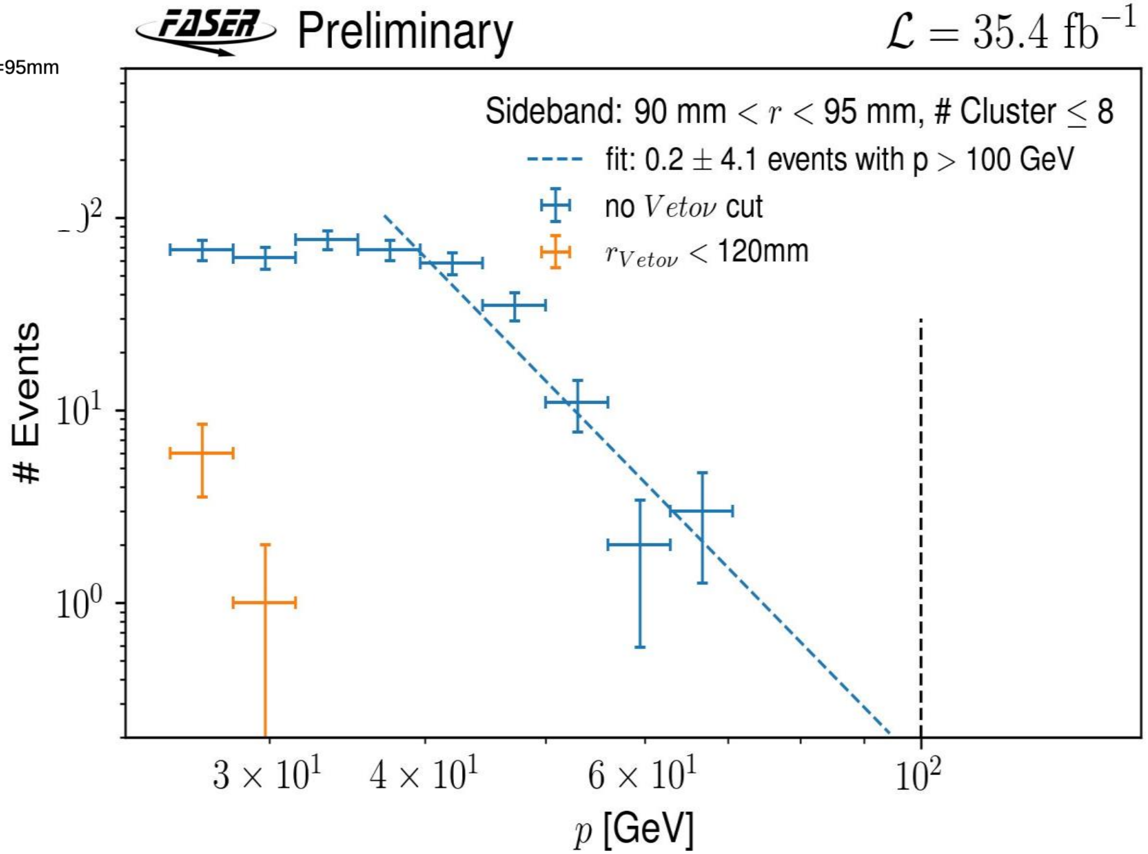
Neutrinos: Geometric Background



- Measure geometric background by counting # events in SB and scale to SR
- SB defined to enhance muons missing FASERν veto that still give a track in the spectrometer
  - Single IFT segment in 90 < r < 95 mm anulus
  - Loosened momentum requirement
  - No FASERν veto radius requirement
  - Negligible neutrino background

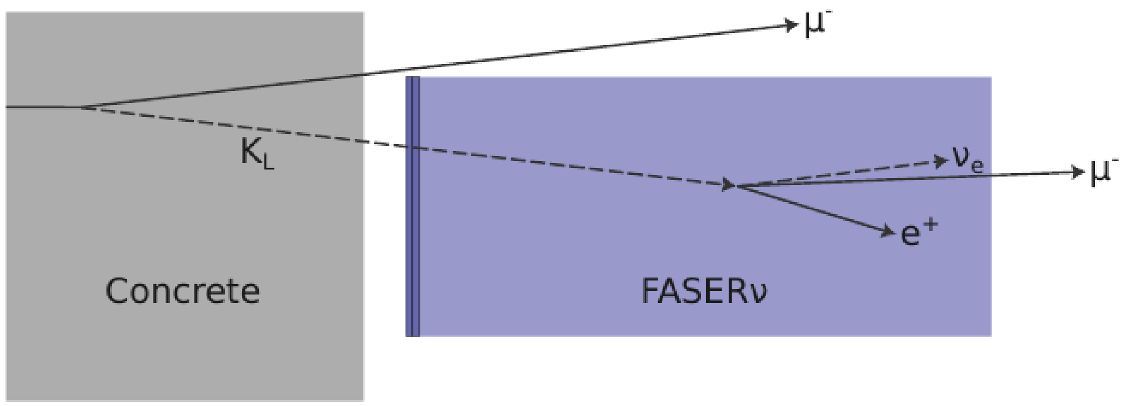


- Fit mom. to extrapolate to p > 100 GeV
- Scale to rate of events with r_{VetoNu} < 120 mm
  - 0 events so use 5.9 events as 3σ upper limit
- Scale from anulus to full acceptance
  - Using large angle muon simulation
- Expect 0.08 ± 1.83 events



Neutrinos: Neutral Hadron Background

- Simulated 10^9 μ^+ and μ^- events
  - Start from FLUKA Spectra
  - G4 propagation through last 8 m of rock
  - Number of hadrons with p > 100 GeV reaching FASER ≈ 300.
- Estimate fraction of these passing event selection
  - Simulate kaons (Ks/Kl) and neutrons with p > 100 GeV following expected spectra
  - Most are absorbed in tungsten with no high-momentum track → only small fraction pass



- Scale neutral hadrons produce by muons reaching FASER by fraction passing selection
  - Predicts N = 0.11 ± 0.06 events

Neutrinos: fit

- Fit to events with 0, 1 or 2 front veto hits
  - Splitting those were 1 hit is in 1st/2nd layer
- Construct likelihood as product of Poissions
  - With additional 3 Gaussian constraints for Neutral hadron background, Geometric background and the extrapolation factor

$$\mathcal{L} = \prod_i^4 \mathcal{P}(n_i|\nu_i) \cdot \prod_j^3 \mathcal{G}_j$$

obs exp

- Determine number of in each category
  - Along with inefficiencies of 2 forward vetos, which are found to be close to expected vals.

Inefficiencies: 6 / 9 x 10^{-8}

1 - p1 = 99.999994(3)%

1 - p2 = 99.999991(4)%

n_0: A neutrino enriched category from events that pass all event selection steps.

n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.

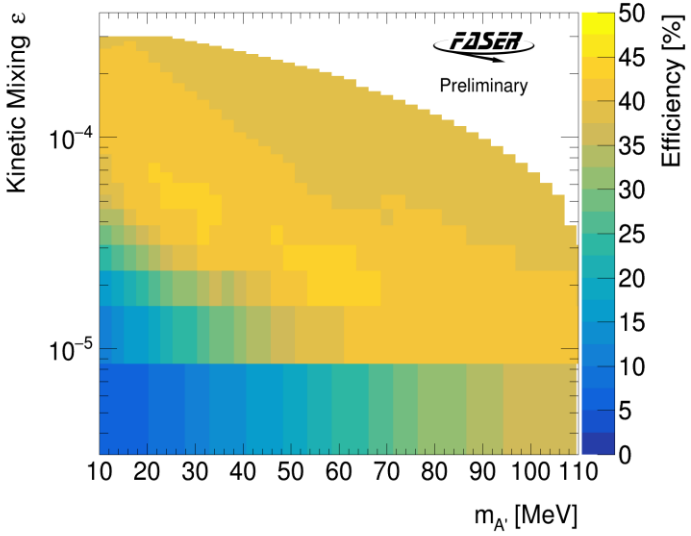
n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

n_2: Events for which both layers observe more than 40 pC of charge.

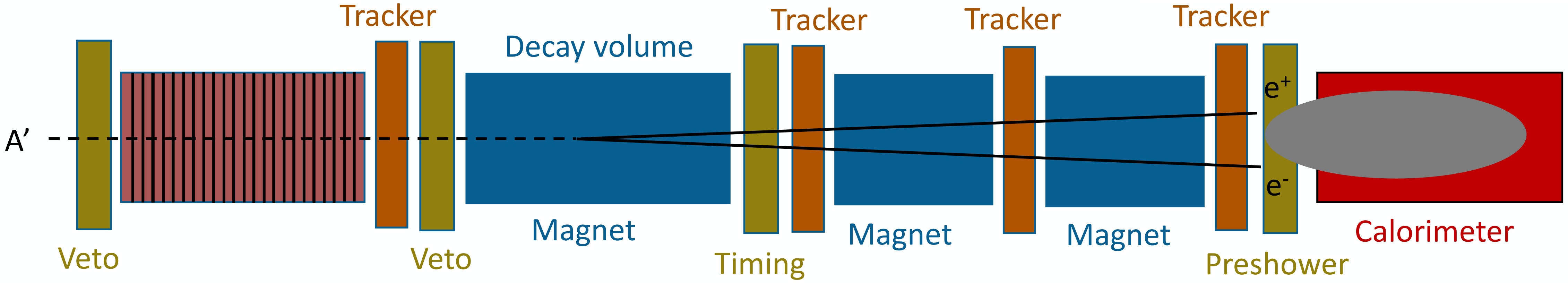
Category	Events	Expectation
n_0	153	$\nu_\nu + \nu_b \cdot p_1 \cdot p_2 + \nu_{\text{had}} + \nu_{\text{geo}} \cdot \eta_{\text{geo}}$
n_{10}	4	$\nu_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$\nu_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$\nu_b \cdot (1 - p_1) \cdot (1 - p_2)$

Dark Photon Selection

- Simple and robust A’ → e^+e^- selection, optimised for discovery
  - Blind events with no veto signal and E(calo) > 100 GeV
  - Efficiency of ~40% across region sensitive to



1. Collision event with good data quality
3. Timing and preshower consistent with ≥2 MIPs



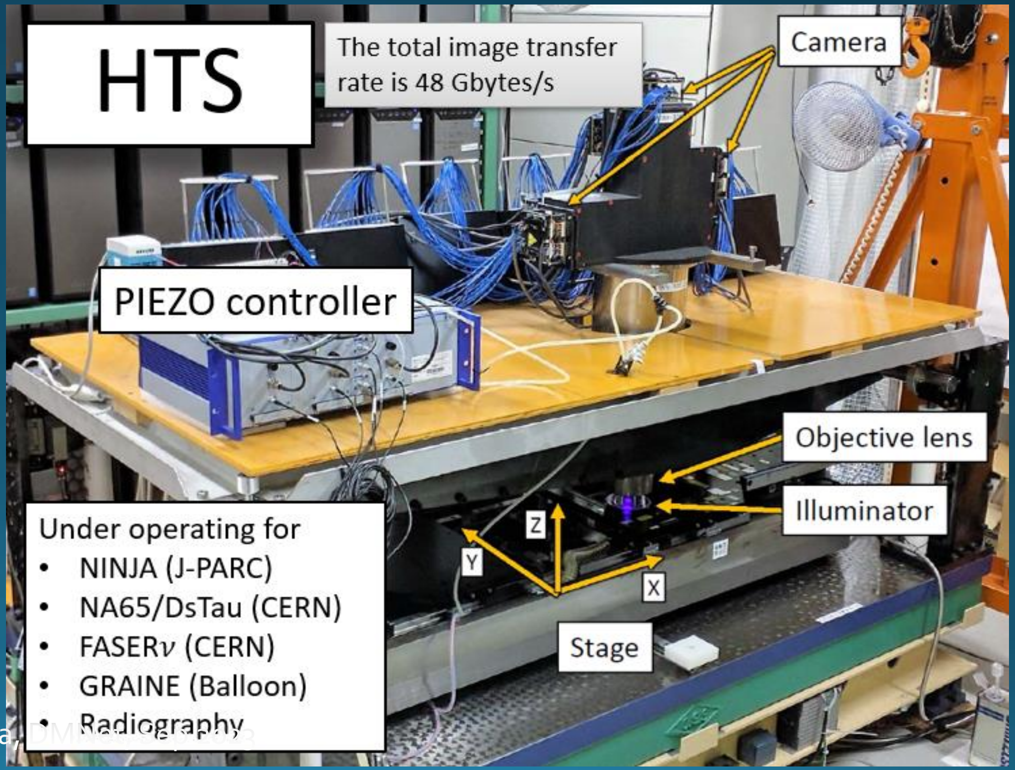
2. No signal (< 40 pc) in any veto scintillator
4. Exactly 2 good fiducial tracks
   - p > 20 GeV and r < 95 mm
   - Extrapolating to r < 95 mm at vetos
5. Calo E > 500 GeV

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

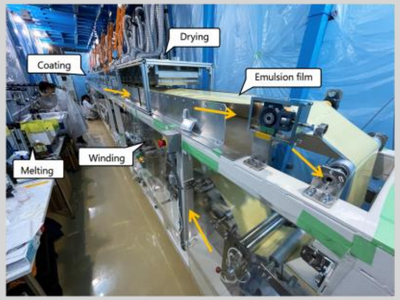
	Start year	Field of view (mm^2)	Readout speed (cm^2/h/layer)
S-UTS	2006	0.05	72
HTS-1	2015	25	4700
HTS-2	2021	50	25000

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



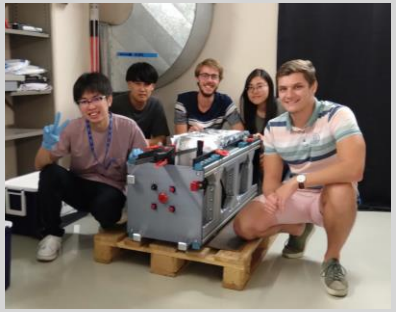
FASERν steps, 3 detectors per year

Nagoya



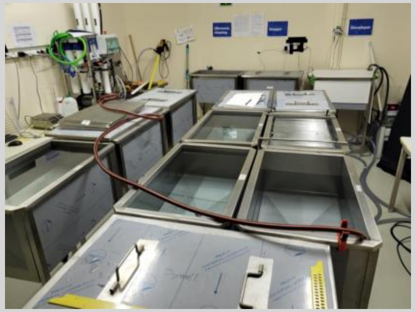
Film production

CERN



Assembly

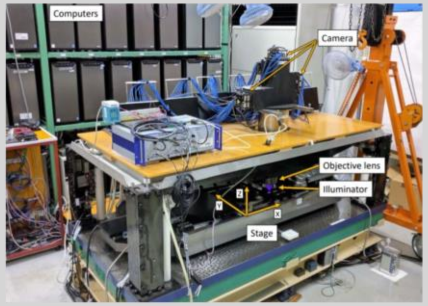
Exposure



Disassembling

Development

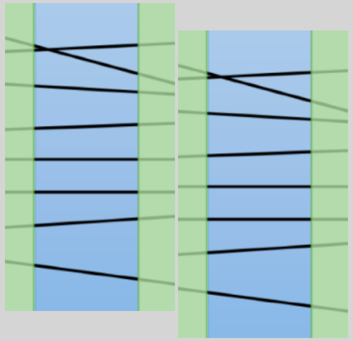
Nagoya



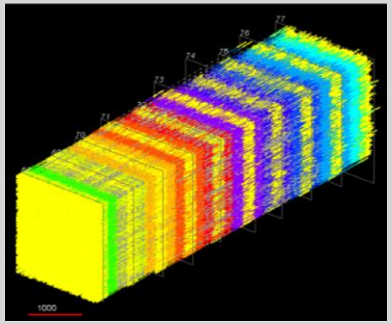
Readout

Offline analysis

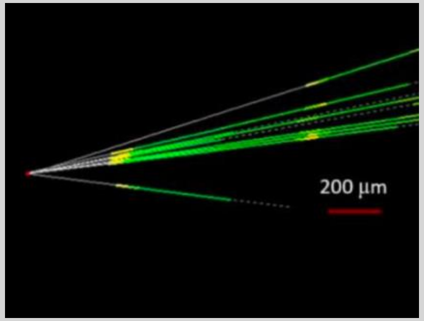
Alignment



Track reconstruction

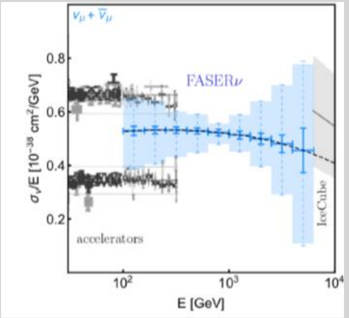


Vertex reconstruction

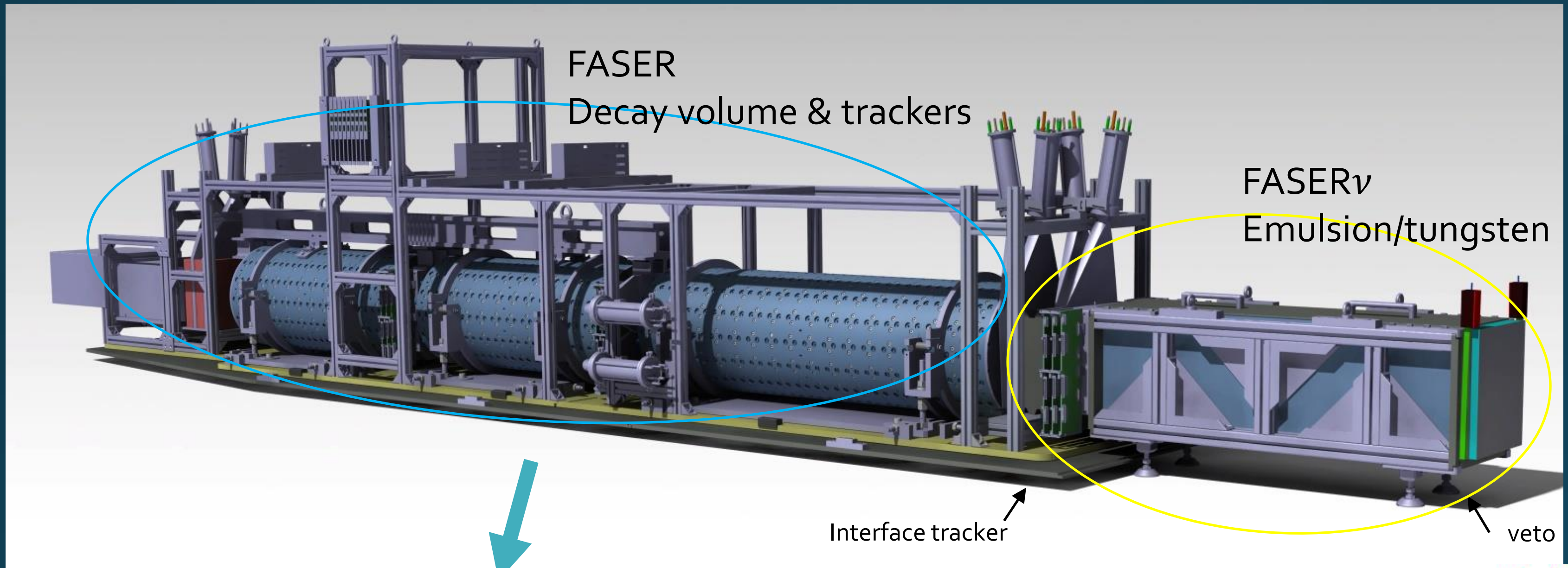


e, μ ID
τ decay search
charge ID
Eν reco
charm/beauty
etc.

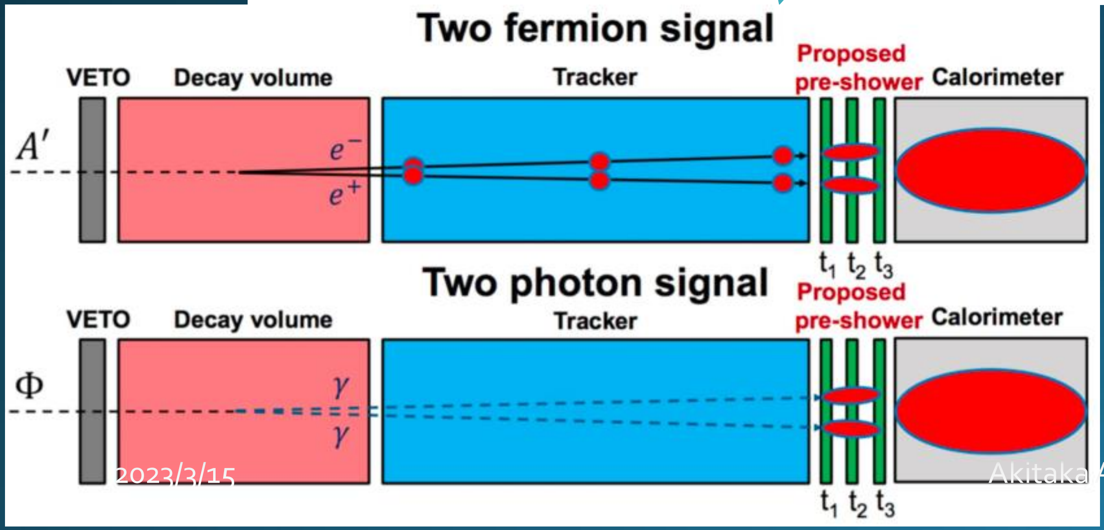
Physics analysis

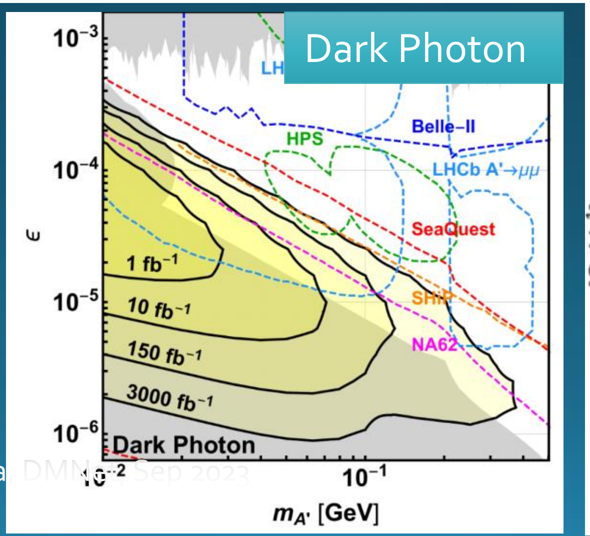


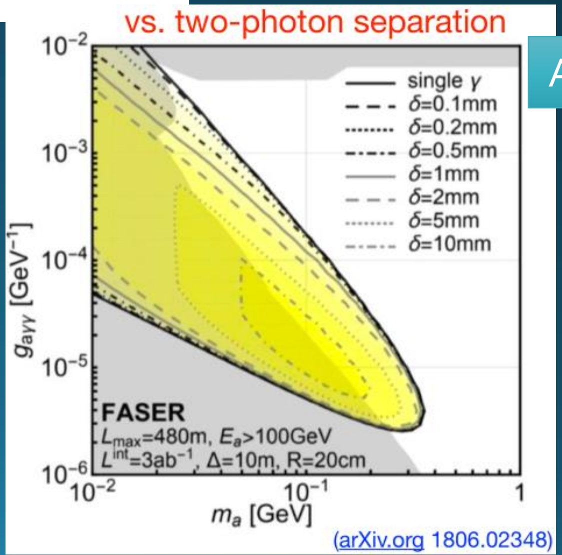
FASER/FASERν detector



Forward beam (A′, ν, etc)



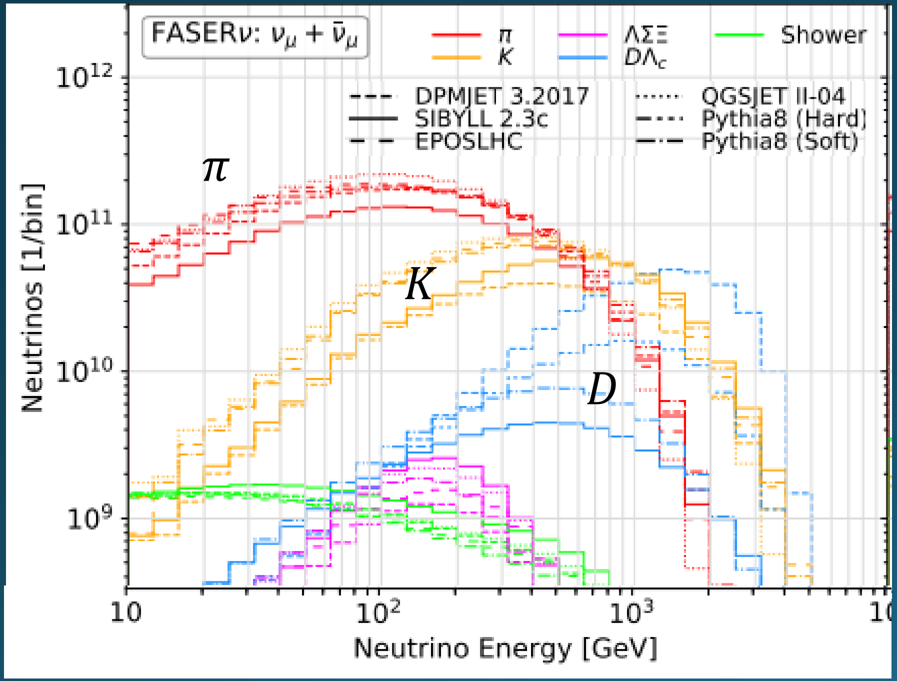




Neutrinos = proxy of forward hadron production

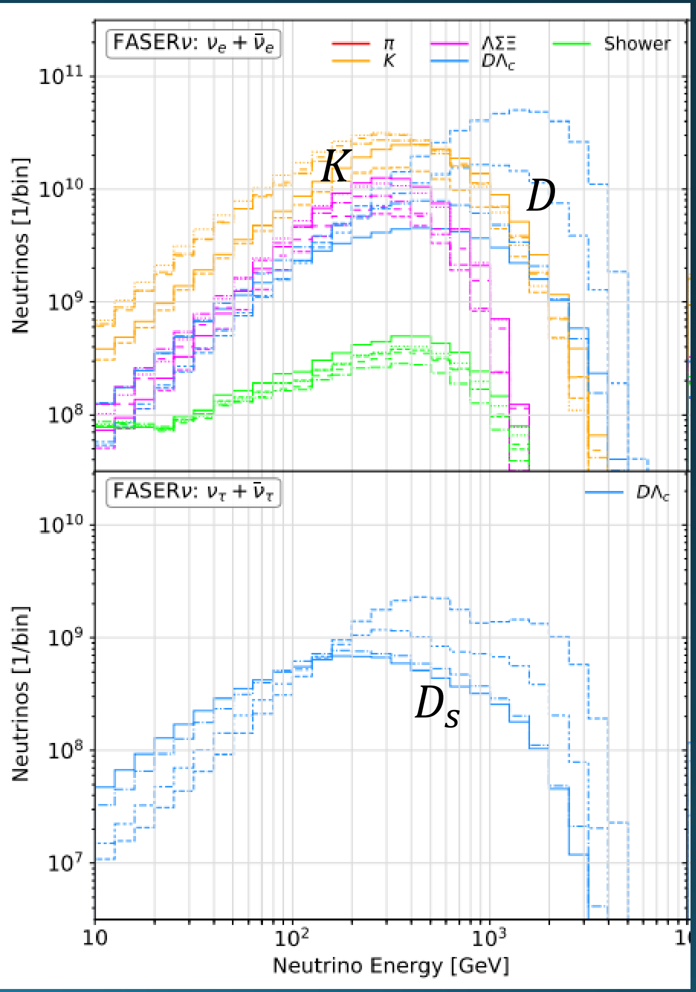
- Pion, Kaon, charm contribute to different part of energy spectra and flavor

ν_μ



ν_e

ν_τ

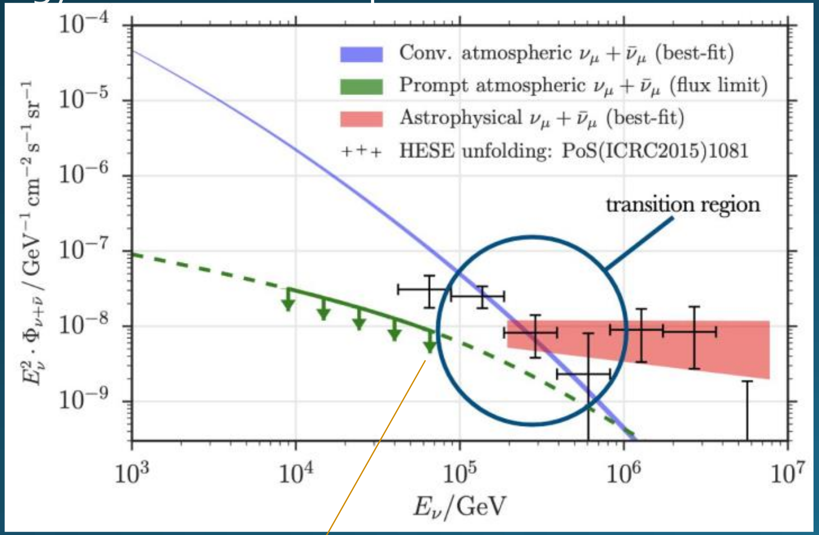


- FASERν provides important inputs to validate/improve generators → Muon excess, prompt neutrinos

Physics studies in the LHC Run 3 (4):

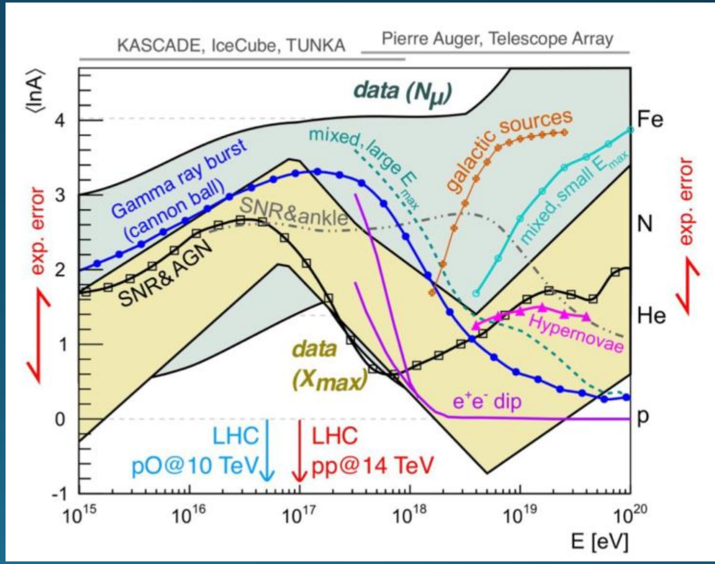
Cosmic rays and neutrino

- 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.
- Muon problem in CR physics: cosmic ray experiments have reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level. New input from LHC is crucial to reproduce CR data consistently.



prompt atmospheric neutrinos

IceCube Collaboration, Astrophys. J. 833 (2016)



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

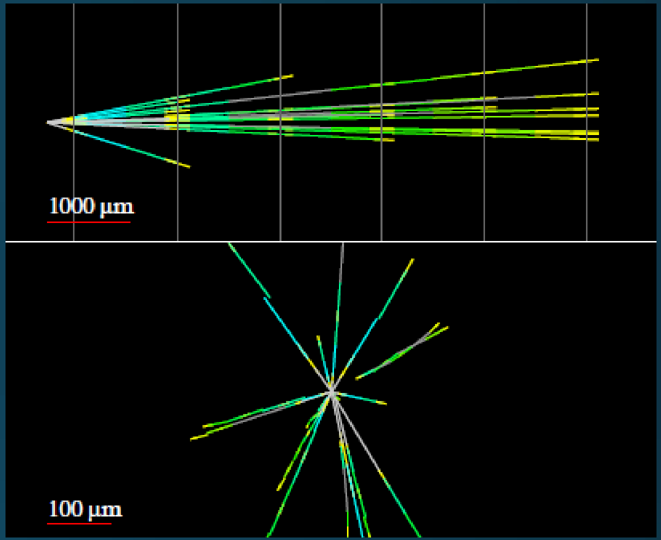
FASER2 Physics Sensitivity

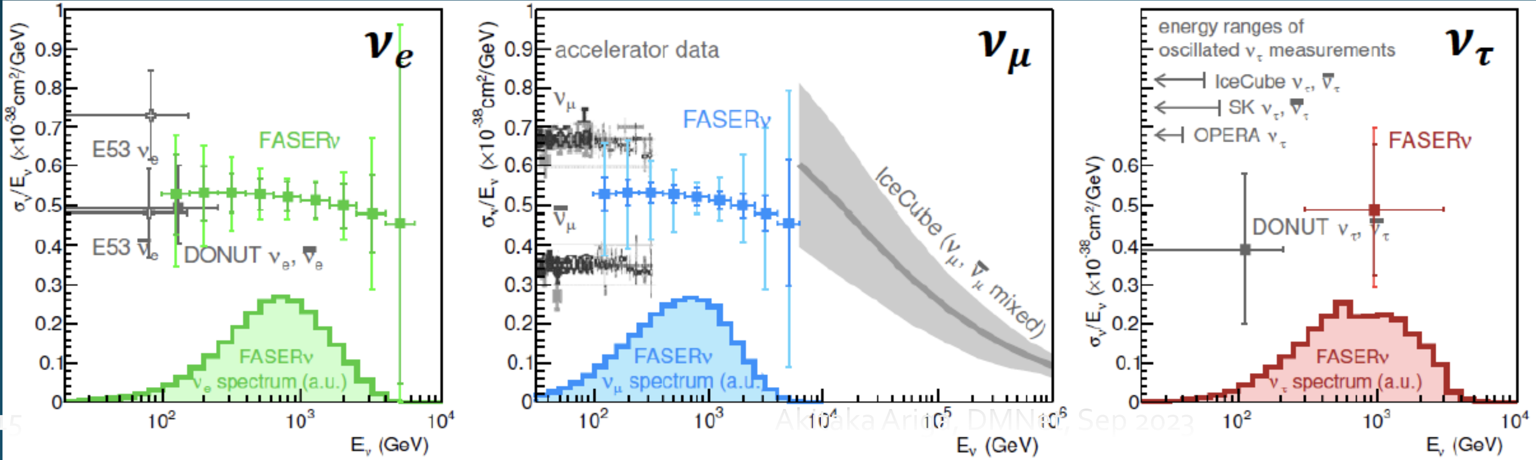
- Physics Beyond Colliders benchmark cases

Benchmark Model	FASER	FASER 2	References
V1/BC1: Dark Photon	√	√	Feng, Galon, Kling, Trojanowski, 1708.09389
V2/BC1': $U(1)_{B-L}$ Gauge Boson	√	√	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Invisible Dark Photon	–	–	–
BC3: Milli-Charged Particle	–	–	–
S1/BC4: Dark Higgs Boson	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
S2/BC5: Dark Higgs with hSS	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387
F1/BC6: HNL with e	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
F2/BC7: HNL with μ	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
F3/BC8: HNL with τ	√	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
A1/BC9: ALP with photon	√	√	Feng, Galon, Kling, Trojanowski, 1806.02348
A2/BC10: ALP with fermion	√	√	FASER Collaboration, 1811.12522
A3/BC11: ALP with gluon	√	√	FASER Collaboration, 1811.12522

FASERν2: Neutrino physics

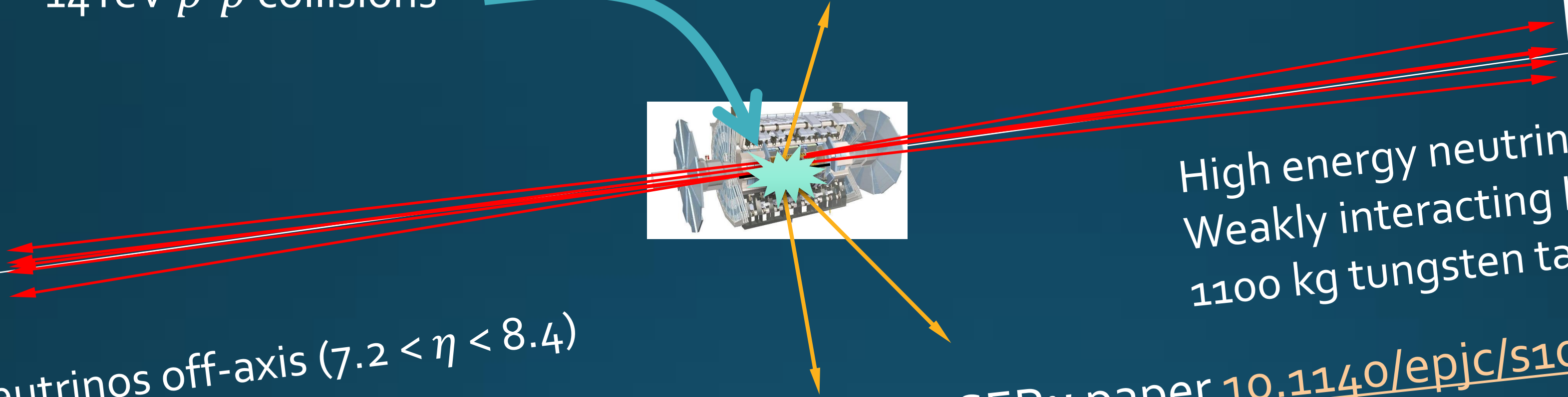
- FASERν @ LHC-Run 3 (1.2 ton)
  - Unexplored TeV energy ~1000 ν_e, ~10,000 ν_μ, ~10 ν_τ CC events
  - Also SND@LHC (off-axis)
- FASERν2 @HL-LHC (~10 ton)
  - FASERν2: Beam x 20, ~10 tons mass →200 times FASERν~10^5 ν_e, 10^6 ν_μ, 10^3 ν_τ CC events
- Tau neutrino physics, precise measurement of cross sections, rare process





Neutrino experiments at the LHC

14TeV p-p collisions

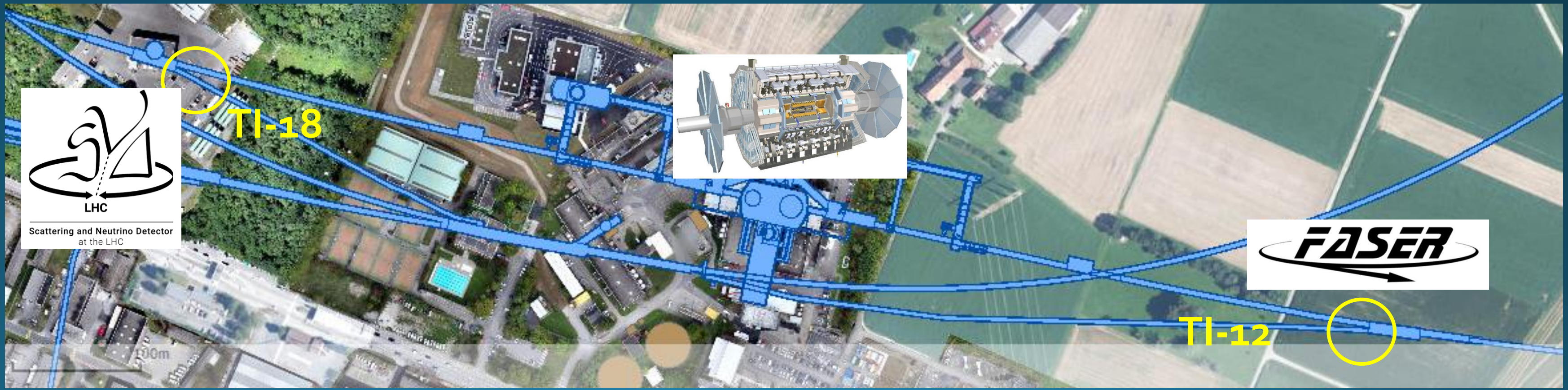


High energy neutrinos at on-axis ($\eta > 8.8$)
Weakly interacting light particles (A′, ALP)
1100 kg tungsten target

Mid-high energy neutrinos off-axis ($7.2 < \eta < 8.4$)
800 kg tungsten target

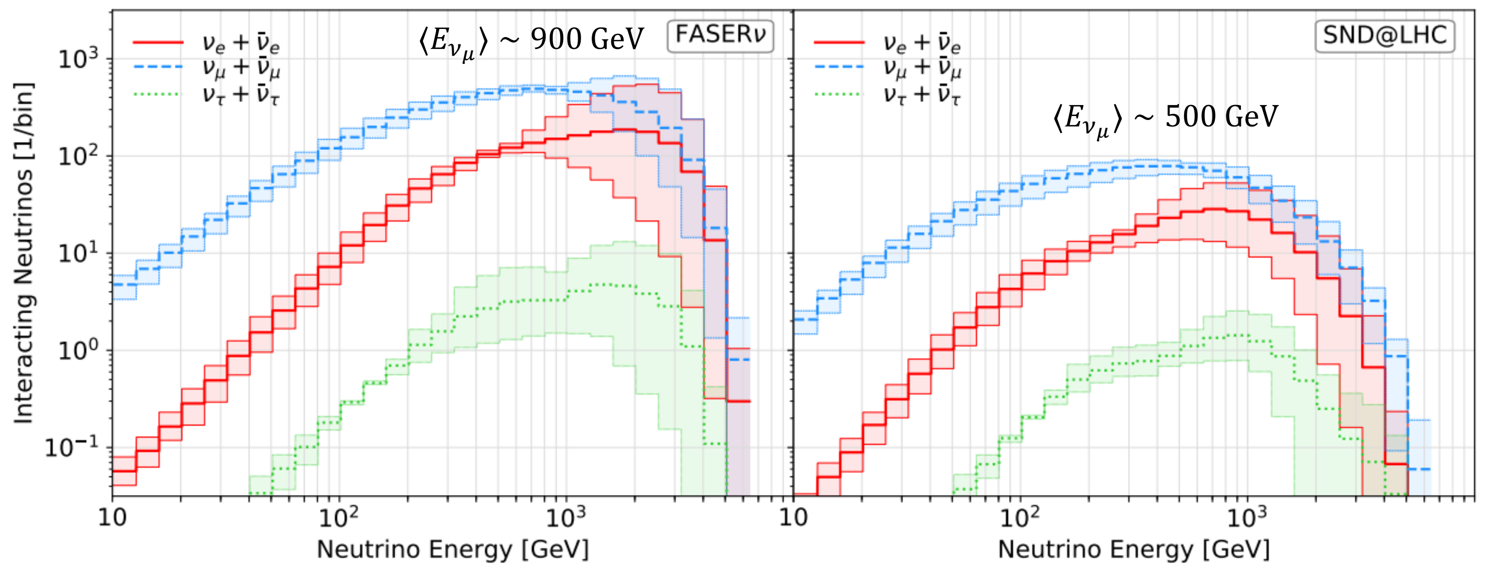
SND@LHC was approved in Mar 2021,
TP arXiv:2002.08722

FASERν paper 10.1140/epjc/s10052-020-7631-5
FASERν was approved in Dec 2019, TP arXiv:2001.03073



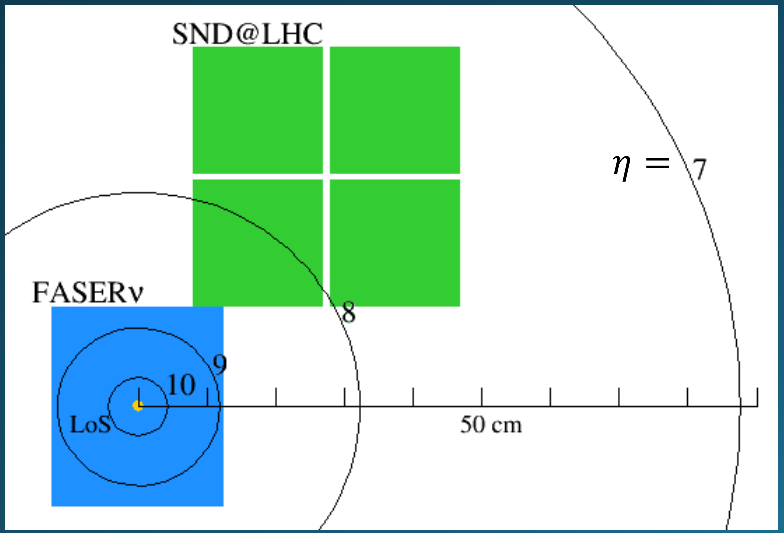
Expected neutrino spectra

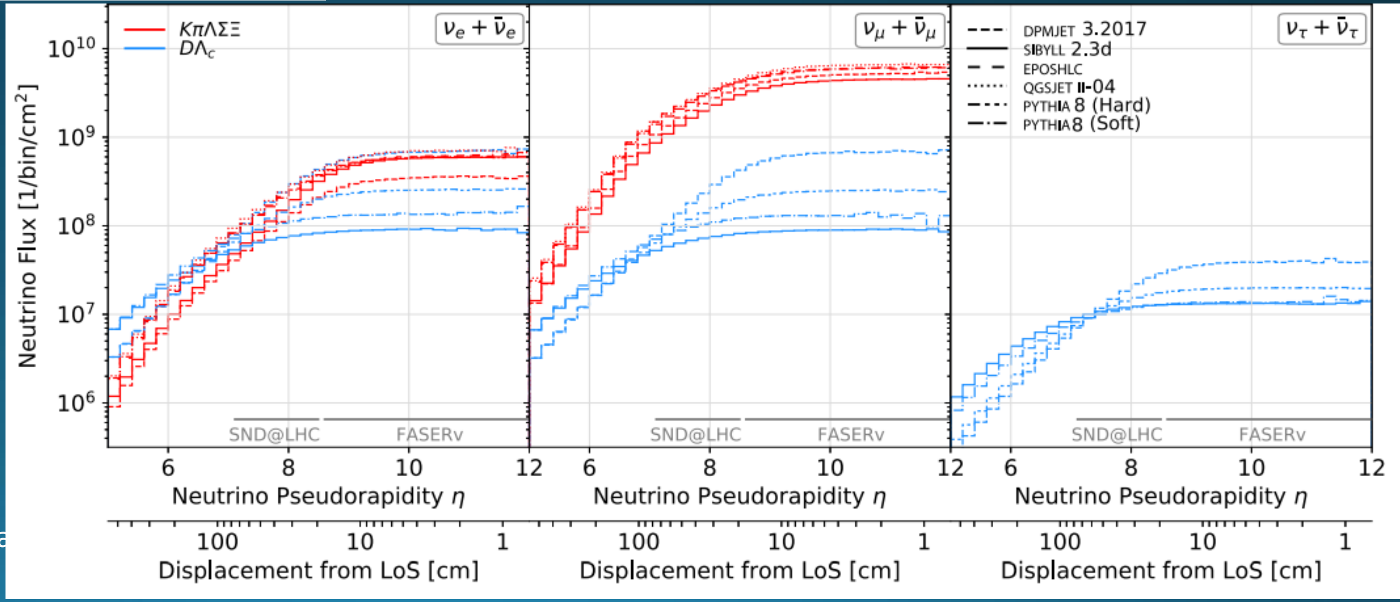
Expected CC interactions with 150 fb^{-1}



	FASERν	SND@LHC
Target mass	1100 kg	800 kg
Location	On axis	Off axis
Features	High energy & high statistics	More neutrinos from charm decay

10.1103/PhysRevD.104.113008





Expected number of CC interactions

10.1103/PhysRevD.104.113008

Three flavors neutrino cross section measurements at unexplored energies

O(10,000) ν interactions expected in LHC Run 3

Test Lepton Universality in CC-int

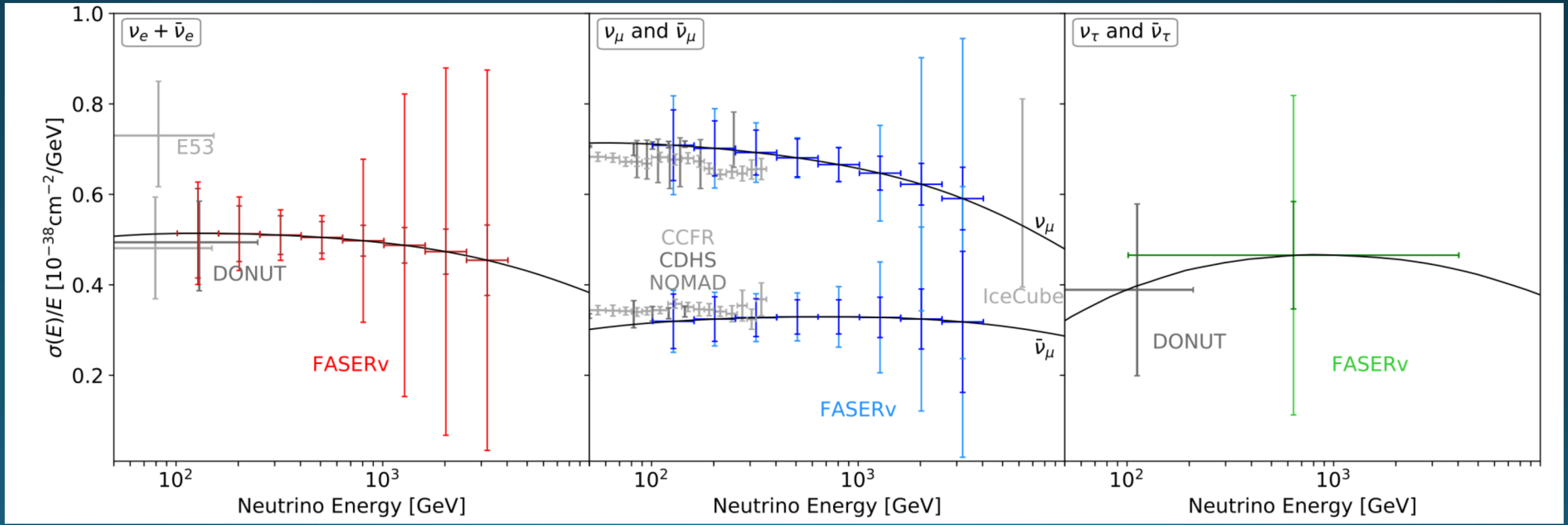
Also NC interaction studies

250 fb^{-1}

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	1501	7971	24.5	223	1316	12.6
DPMJET	DPMJET	5761	11813	161	658	1723	31
EPOSLHC	Pythia8 (Hard)	2521	9841	57	445	1871	19.2
QGSJET	Pythia8 (Soft)	1616	8918	26.8	308	1691	12
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}	408^{+248}_{-185}	1651^{+220}_{-333}	$18.8^{+12}_{-6.6}$
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$	325^{+118}_{-101}	1626^{+243}_{-308}	$14.6^{+4.5}_{-2.5}$

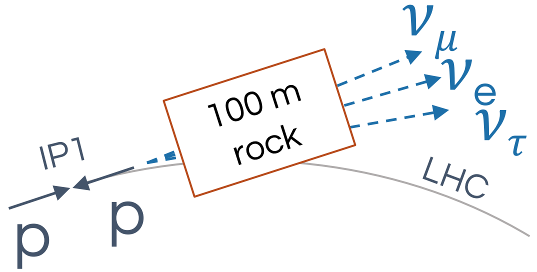
TABLE II. Expected number of charged current neutrino interaction events occurring in FASERν and SND@LHC during LHC Run 3 with 250 fb^{-1} integrated luminosity. Here we assume a target mass of 1.2 tons for FASERν and 800 kg for SND@LHC;

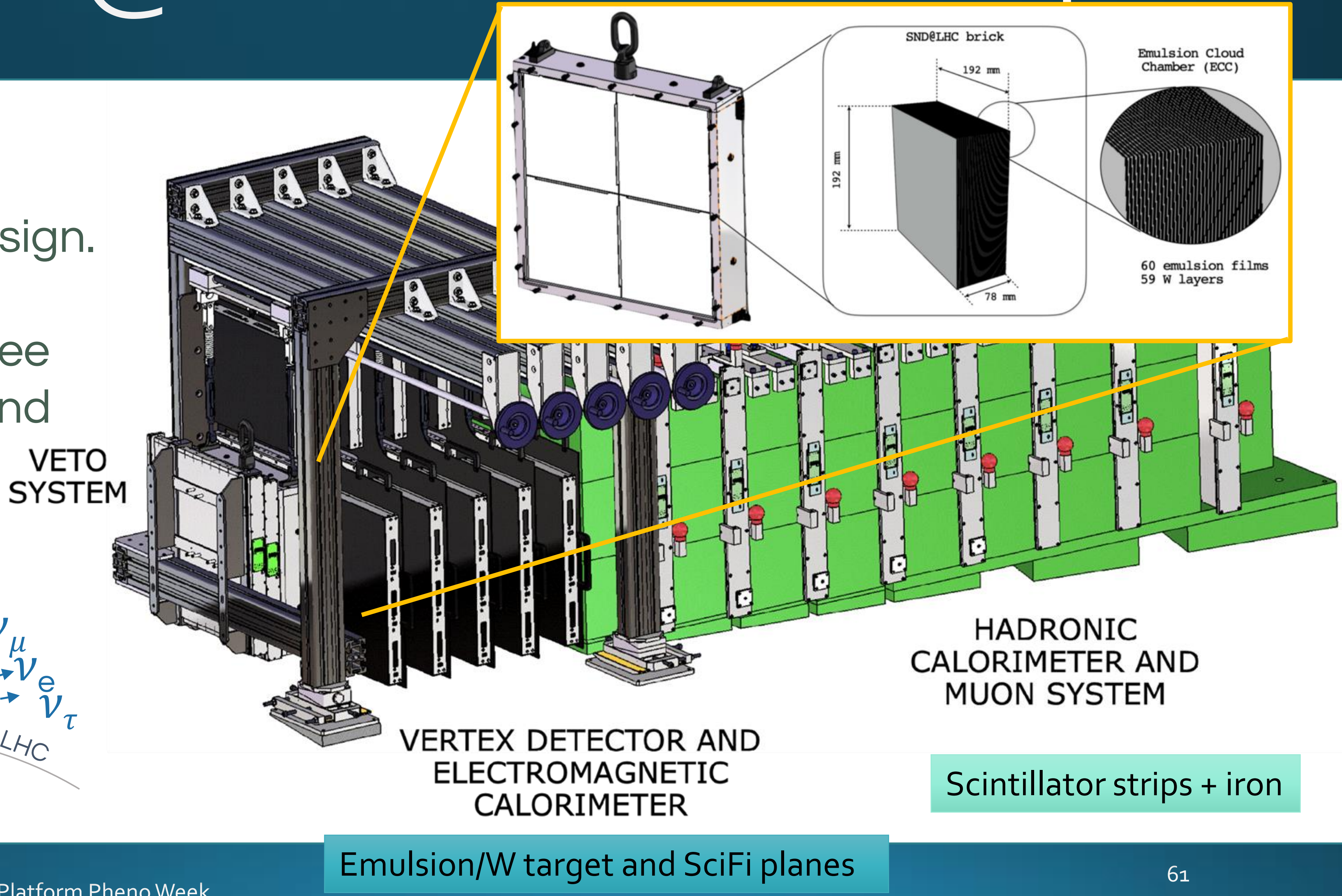
Projected cross section sensitivities (FASERν, plot for 150 fb^{-1})



The SND@LHC detector concept

- Hybrid detector design.
- Optimized for the identification of three neutrino flavours and feebly interacting particles.





Construction

- Despite the difficult period, both neutrino experiments were constructed in time for Run3!
- Amazingly quick works!