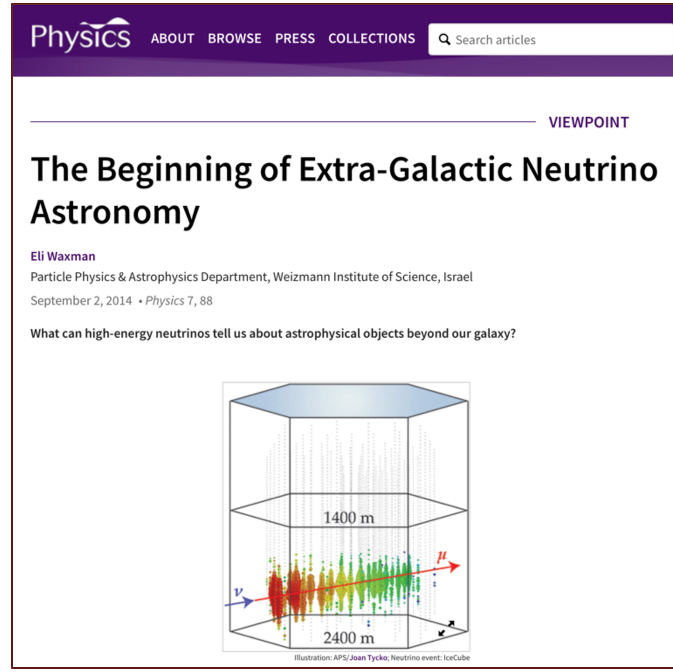
MULTI-MESSENGER COLLIDER PHYSICS

IceCube Fall 2024 Collaboration Meeting, Madison, Wisconsin

Jonathan Feng, UC Irvine, 26 September 2024

THE MULTI-MESSENGER ERA

- Astronomy
  - ~1000 years ago: optical photons
  - ~100 years ago: multi-wavelength photons
  - ~10 years ago: neutrinos (IceCube), gravitational waves (LIGO)
  - Multi-messenger astronomy provides new probes of outer space
- Collider Physics
  - ~70 years ago: photons, charged particles
  - 12 years ago: Higgs bosons (ATLAS/CMS)
  - 1 year ago: neutrinos (FASER)
  - Multi-messenger collider physics provides new probes of inner space
- Many areas of overlap between IceCube and FASER: neutrinos, but also searches for dark matter, other new particles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VIEWPOINT

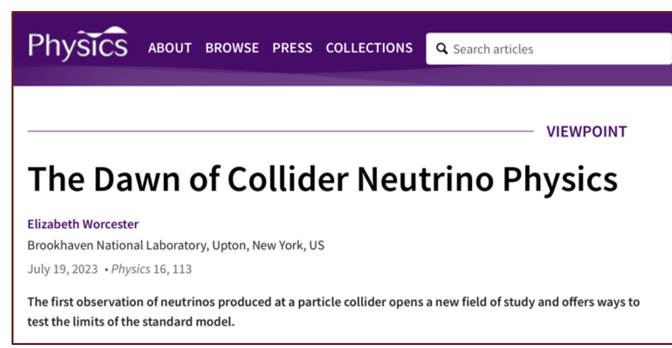
The Beginning of Extra-Galactic Neutrino Astronomy

Eli Waxman

Particle Physics & Astrophysics Department, Weizmann Institute of Science, Israel

September 2, 2014 • Physics 7, 88

What can high-energy neutrinos tell us about astrophysical objects beyond our galaxy?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VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester

Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • Physics 16, 113

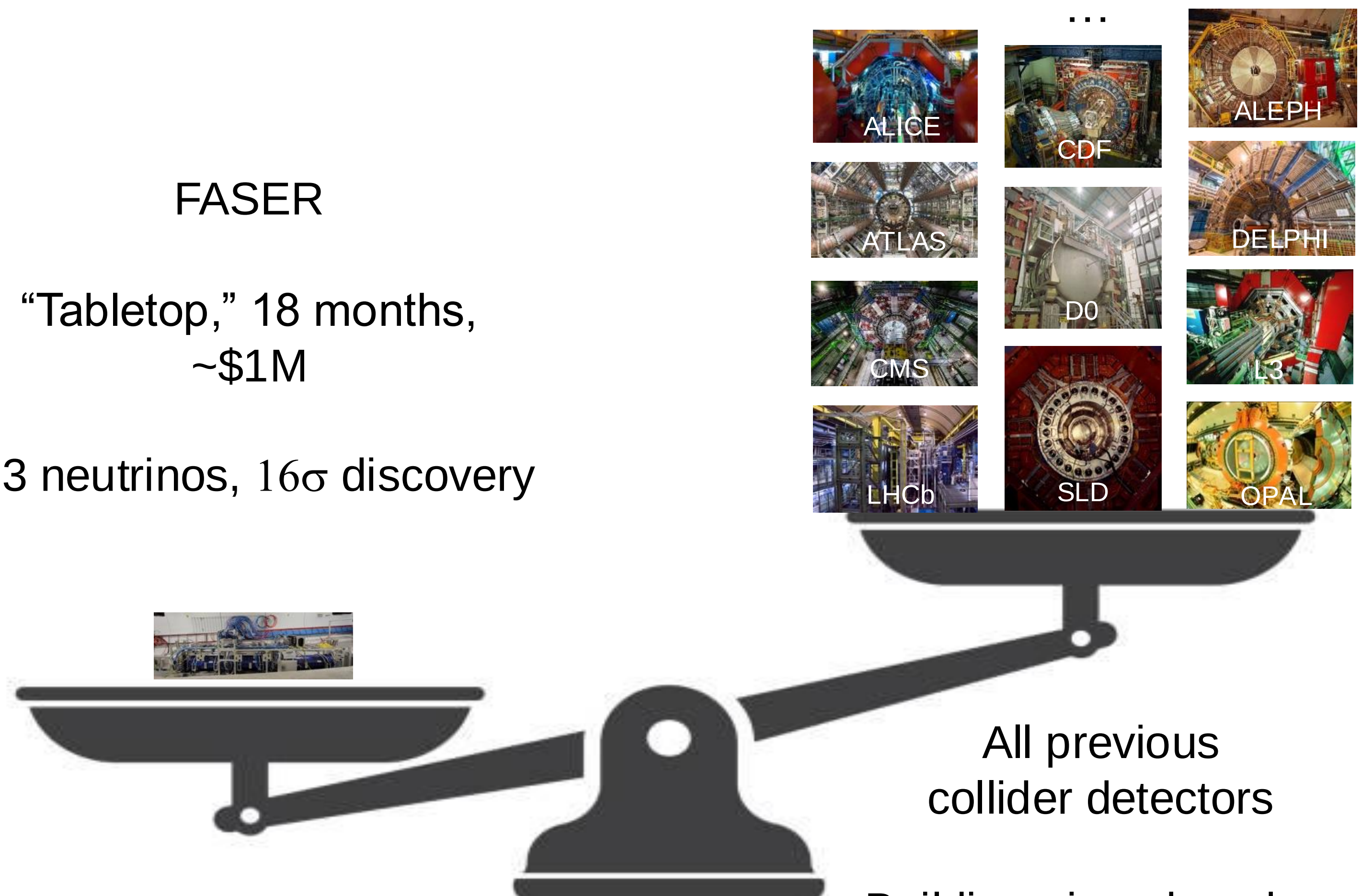
The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.

THE DAWN OF COLLIDER NEUTRINO PHYSICS

FASER

“Tabletop,” 18 months,
~$1M

153 neutrinos, 16σ discovery



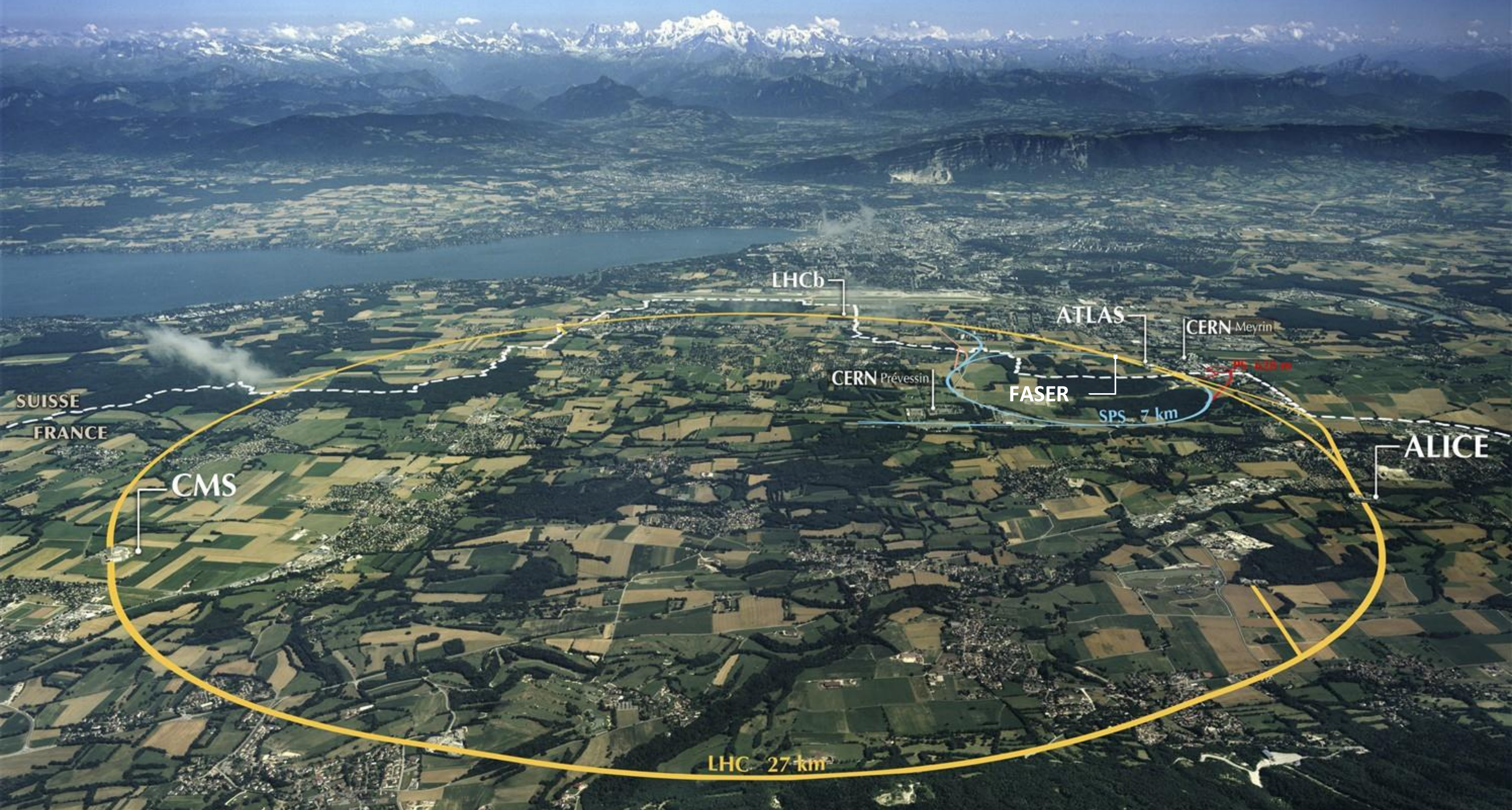
All previous
collider detectors

Building-size, decades,
~$1B

0 neutrinos

In retrospect, collider neutrinos were
discovered “easily.” Lots of room for progress

THE LARGE HADRON COLLIDER



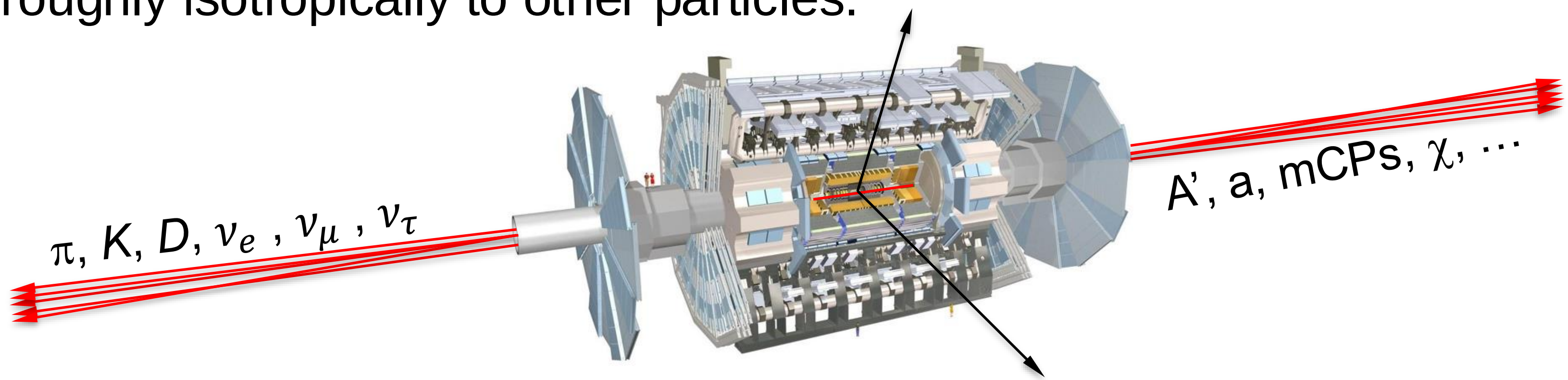
The LHC started running in 2010, and is scheduled to run until the 2040s. It is halfway through its lifetime in years, but only 10% through its lifetime in terms of integrated luminosity.

FORWARD PHYSICS

- In 2017, we realized that the large LHC detectors, while optimally configured to discover new heavy particles, are also optimally configured to miss new light particles.

Feng, Galon, Kling, Trojanowski (2017)

- Heavy particles (W, Z, t, h, …) are produced at low velocity and decay roughly isotropically to other particles.



- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles: pions, kaons, *D* mesons, all neutrinos.
  - It is also true for many proposed particles, especially light, weakly-interacting ones motivated by neutrino mass and dark matter.

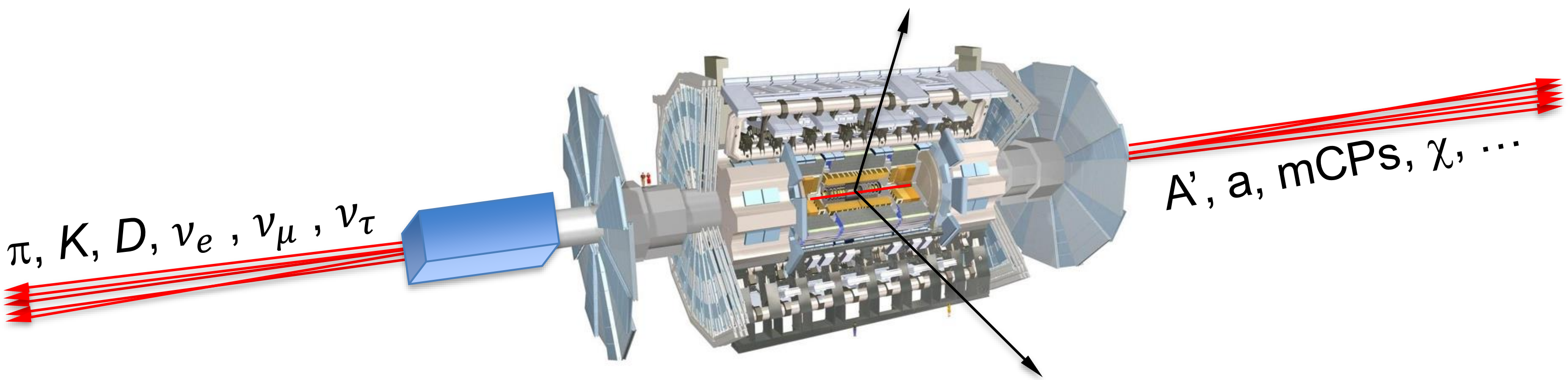
De Rujula, Ruckl (1984)

- These blind spots are the Achilles heels of the large LHC detectors.

DETECTING FORWARD PARTICLES

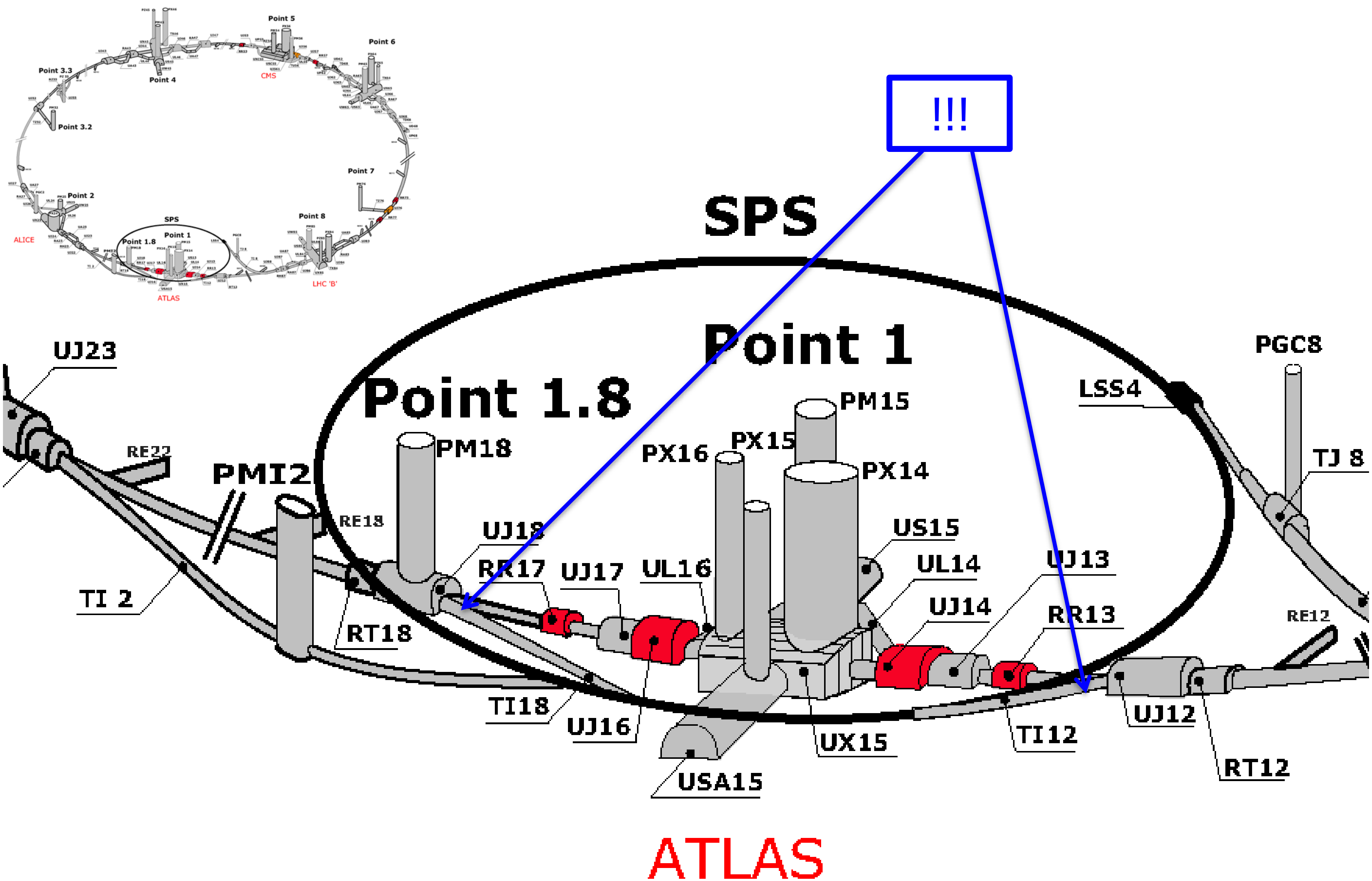
- To capture the enormous forward flux, we need to detect particles that are produced in the forward direction along the beamline.

- Problem: we can't just put the detector there: they will block the protons from coming in.

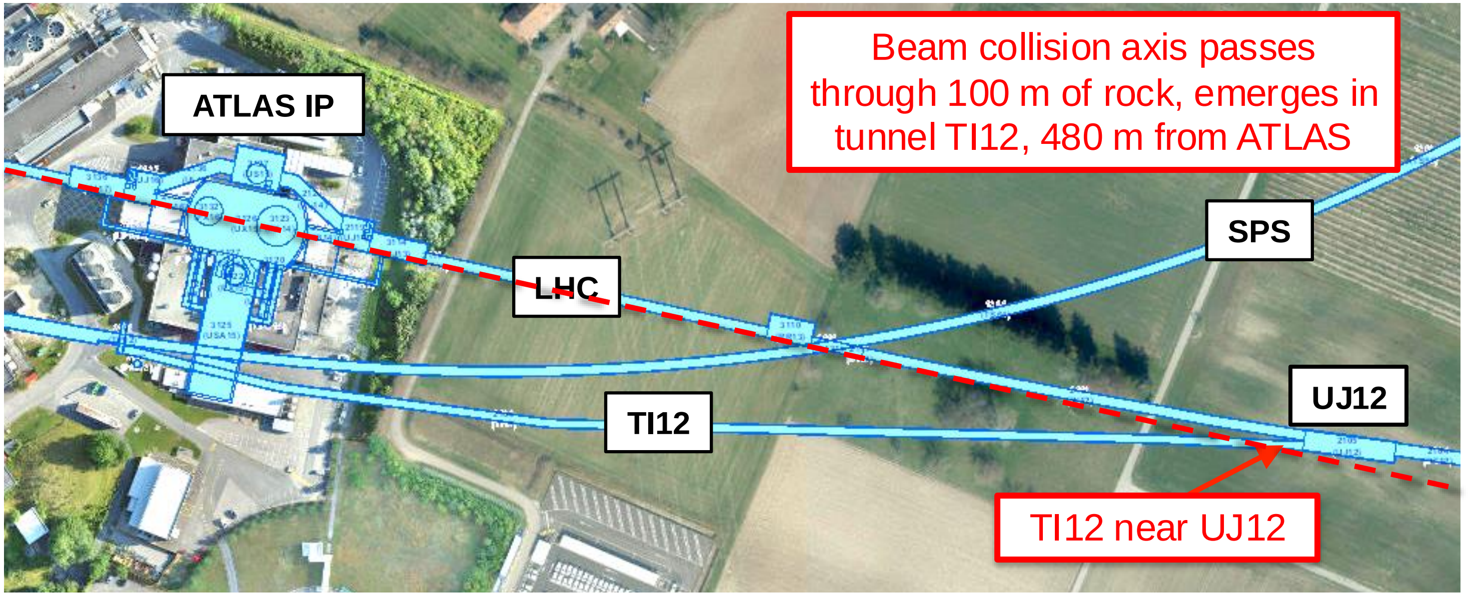


- Solution: the LHC is a circular collider! If we go far enough away, the LHC proton beam will curve away, while all the light, weakly-interacting particles we are looking for will go straight.

MAP OF THE LHC



THE FORWARD REGION



HOW BIG DOES THE DETECTOR HAVE TO BE?

- Consider light, weakly-interacting particles produced in pion decay. E.g.,
  - SM: muon neutrinos produced in $\pi^{\pm} \rightarrow \mu\nu_{\mu}$
  - BSM: dark photons produced in $\pi^{0} \rightarrow \gamma A'$

- Momentum: 250 MeV / 1 TeV

  Space: 12 cm / 480 m

- The opening angle is 0.2 mrad (the moon is 7 mrad). Even 480 m away, most of the signal passes through an 8.5” x 11” sheet of paper.

- Neutrinos and light new particles are therefore extremely collimated, motivating a relatively small, fast, and inexpensive experiment at the LHC: the ForwArd Search ExpeRiment (FASER).

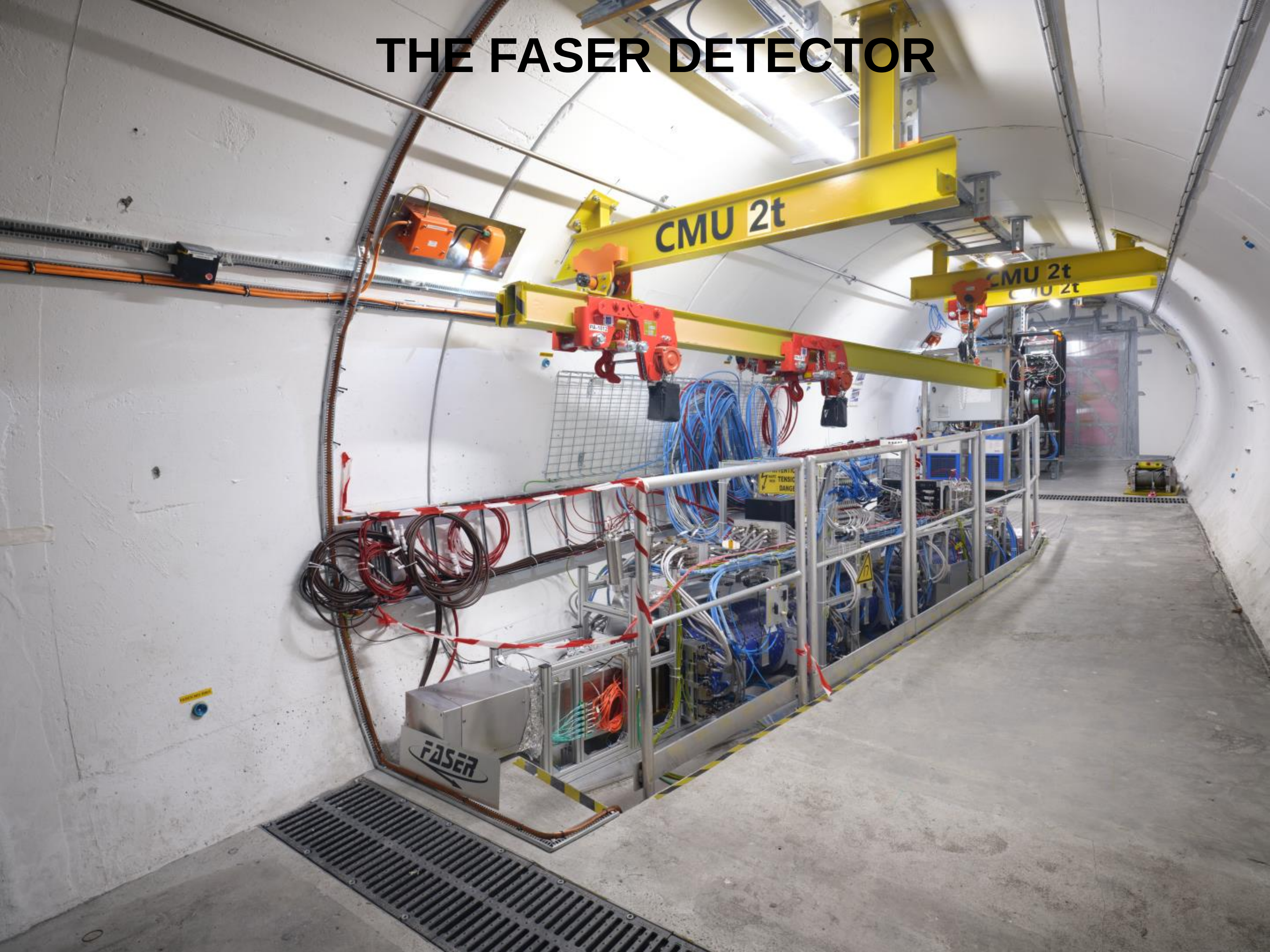
FASER COLLABORATION

108 collaborators, 27 institutions, 11 countries

International laboratory
covered by a cooperation
agreement with CERN

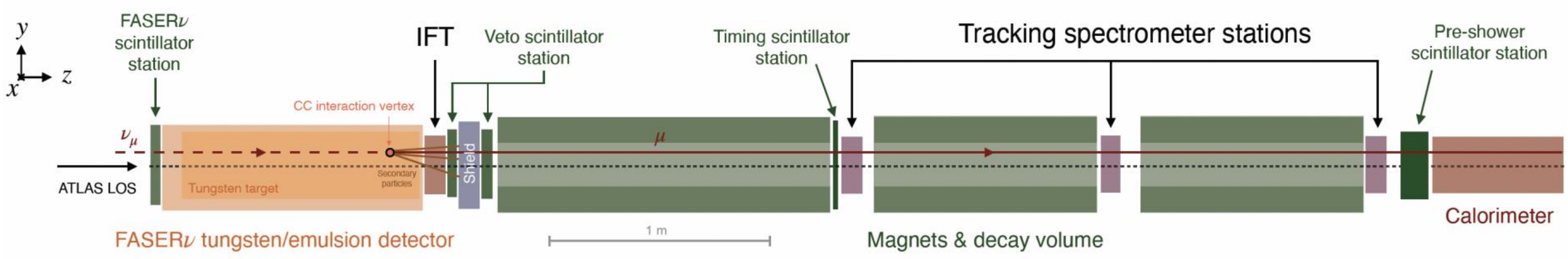
FASER AND THE LHC

THE FASER DETECTOR



COLLIDER NEUTRINO SEARCH

- Neutrinos produced at the ATLAS IP travel 480 m and pass through FASERν. Occasionally, they can interact through $\nu_\mu N \to \mu X$, producing a high-energy muon, which travels through the rest of the detector.



FASER Collaboration (2303.14185, PRL)

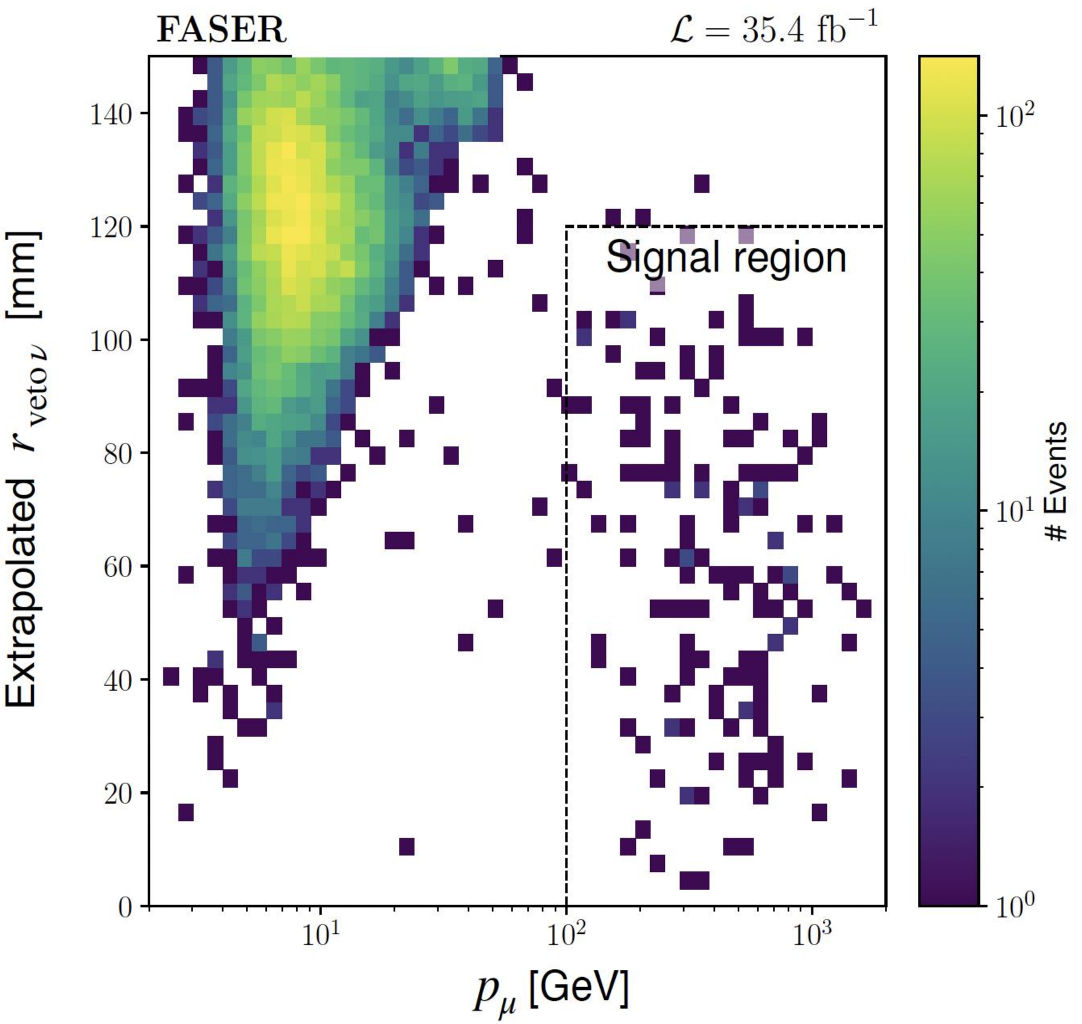
- The signal is no charged particle passing through the upstream veto scintillators, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

- Leading backgrounds from neutral hadrons produced in the rock, muons that enter from the side, or beam 1 background contribute $\lesssim 1$ event.

- Expect 151 ± 41 events from simulations, with the large uncertainty arising from the poorly understood flux of forward hadrons.

COLLIDER NEUTRINO RESULTS

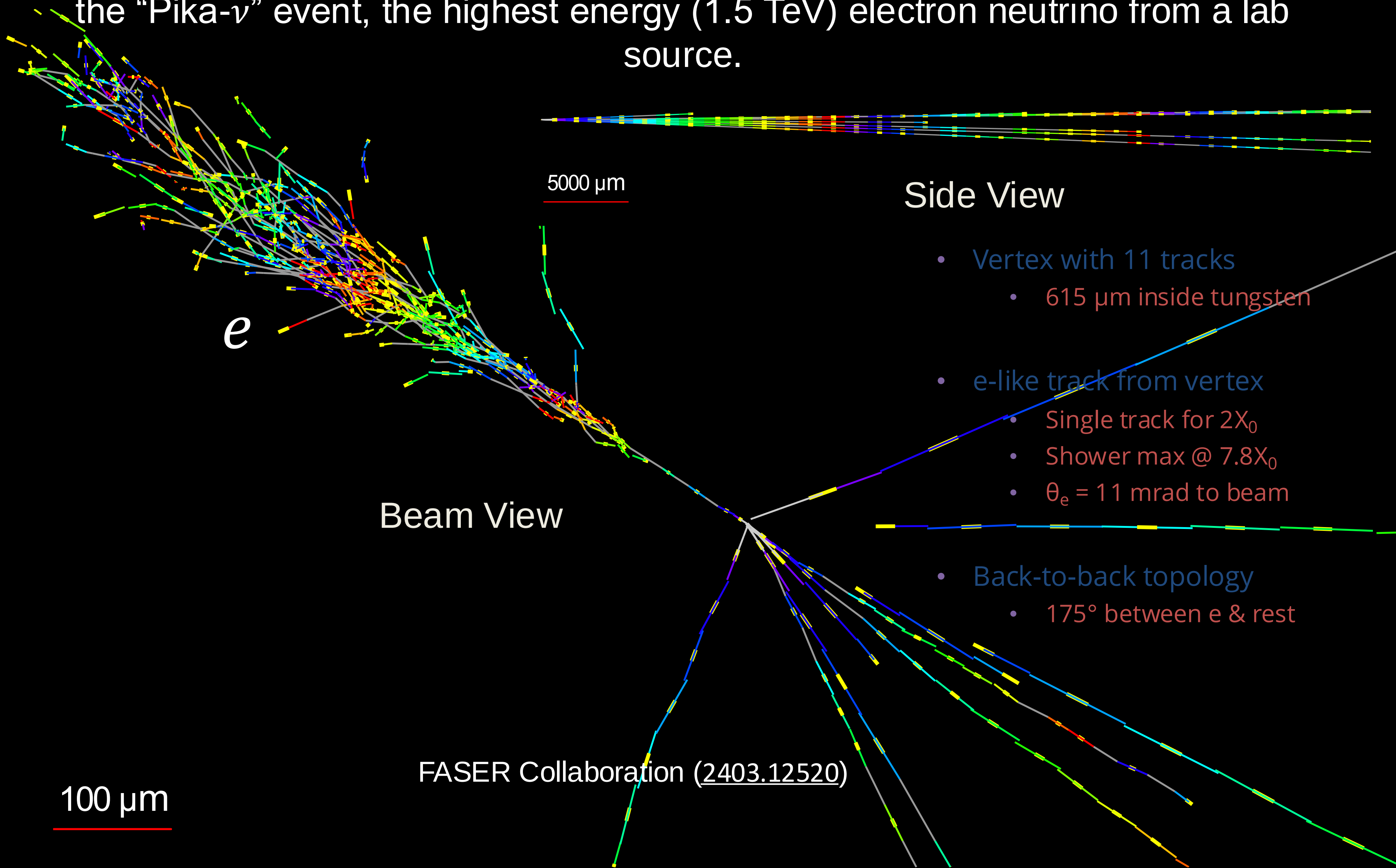
- After unblinding, we found 153 signal events.
- 1st direct detection of collider neutrinos.
  - Signal significance of ~16σ
  - Muon charge → ν and $\bar{\nu}$
  - These include the highest energy ν and $\bar{\nu}$ interactions ever observed from a human source
- Following the FASER observation, SND@LHC, a complementary experiment in the “other” forward direction, discovered an additional 8 neutrinos.



FASER Collaboration (2303.14185, PRL)

NEUTRINOS FROM EMULSION IN FASERν

The discovery analysis did not even use the emulsion detector! With the emulsion, we have now observed the first collider electron neutrinos, including the "Pika-ν" event, the highest energy (1.5 TeV) electron neutrino from a lab source.



- 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

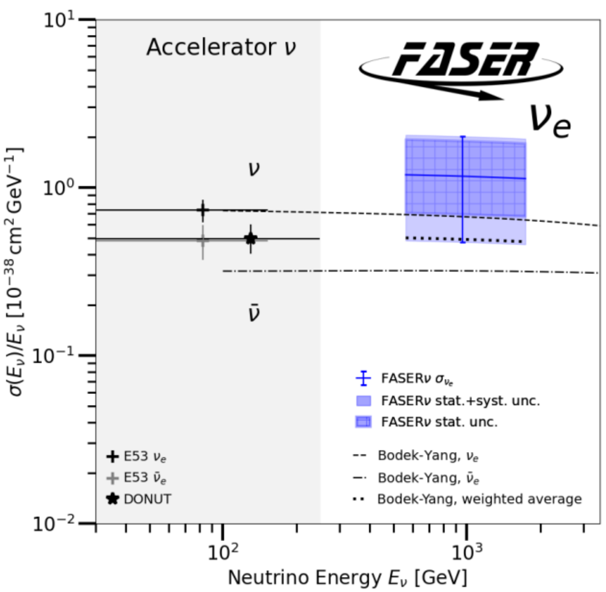
FASER Collaboration (2403.12520)

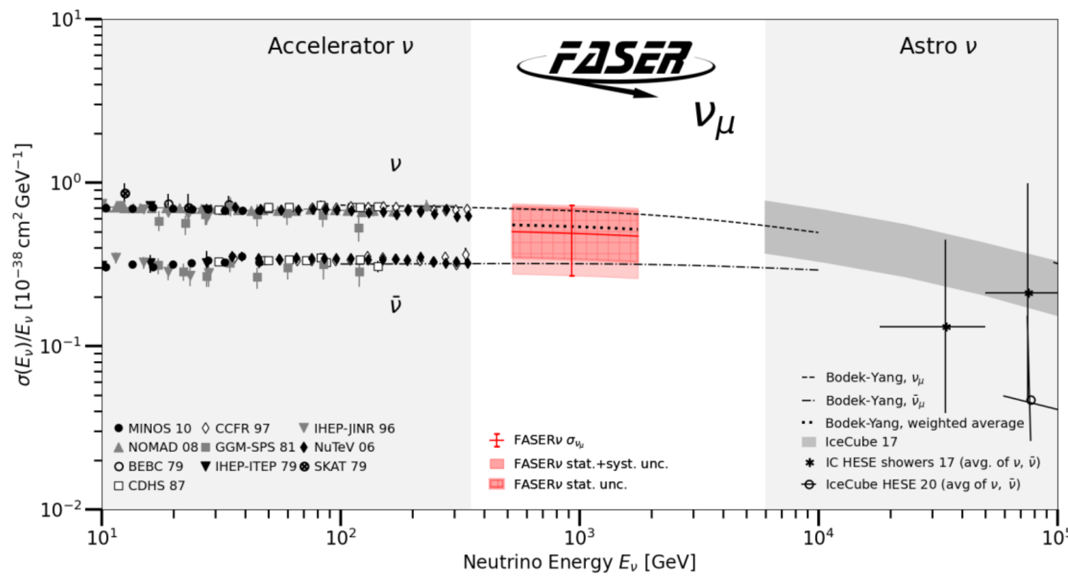
TEV NEUTRINO CROSS SECTIONS

- Following these discoveries, we can then move on to studies, including the first measurement of neutrino cross sections at TeV energies.

- Results are consistent with SM DIS predictions.

Xie, Gao, Hobbs, Stump, Yuan (2024)



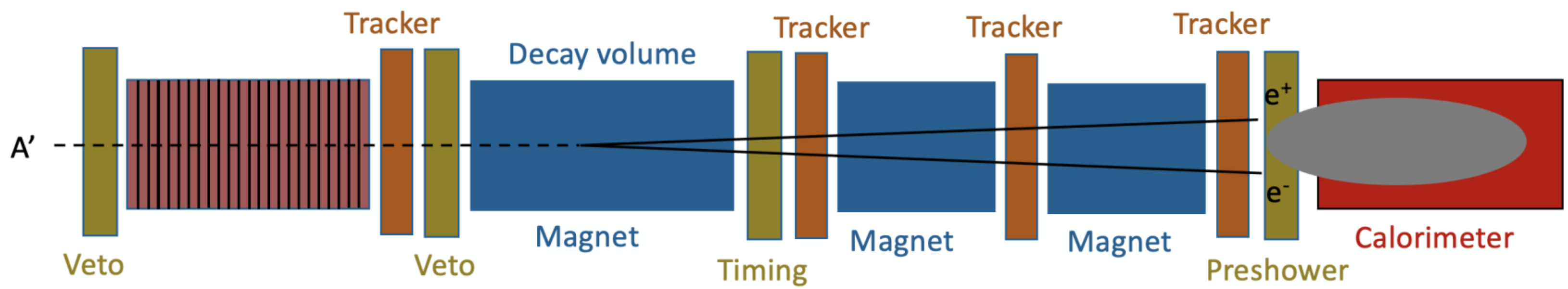


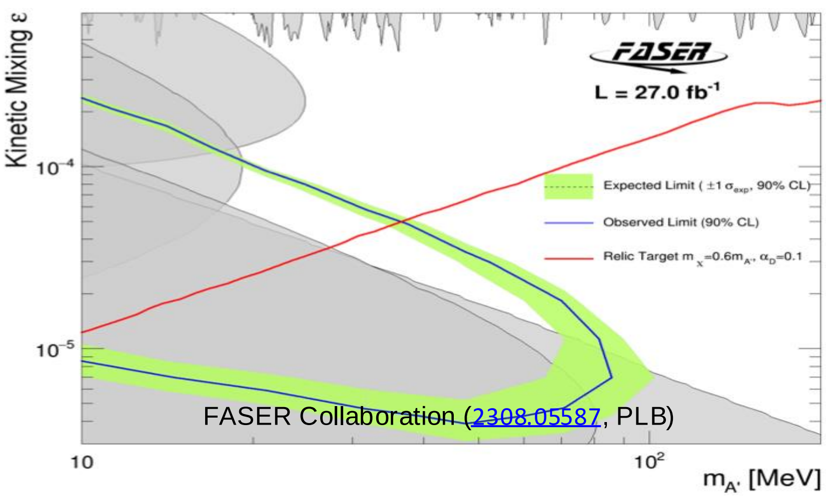
FASER Collaboration (2403.12520)

- These measurements use only 1.7% of the data collected in 2022 and 2023.

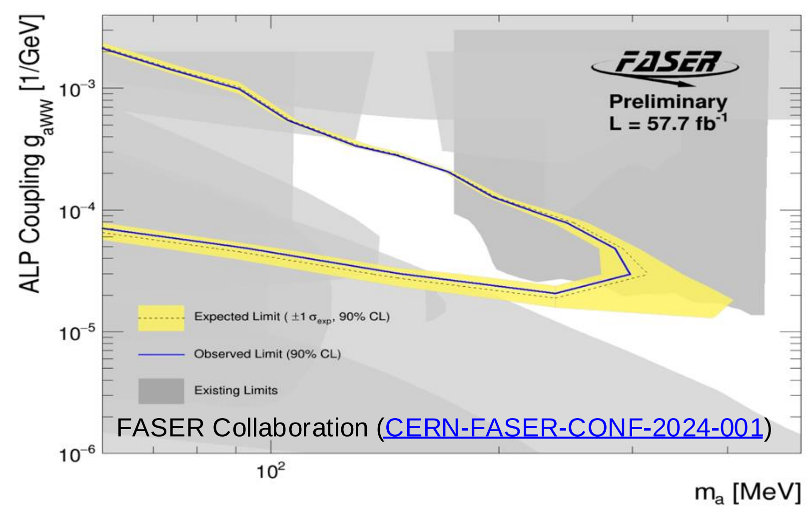
NEW PARTICLE SEARCHES

- FASER is also sensitive to an entire zoo of light, weakly-interacting new particles. For example:
  - Dark photons produced through $\pi/\eta \to A'\gamma$ or $pp \to ppA'$, then decay $A' \to e^+e^-$.
  - ALPs coupled to *W*s, produced through $B \to K\, a$, then decay $a \to \gamma\gamma$.





FASER Collaboration (2308.05587, PLB)

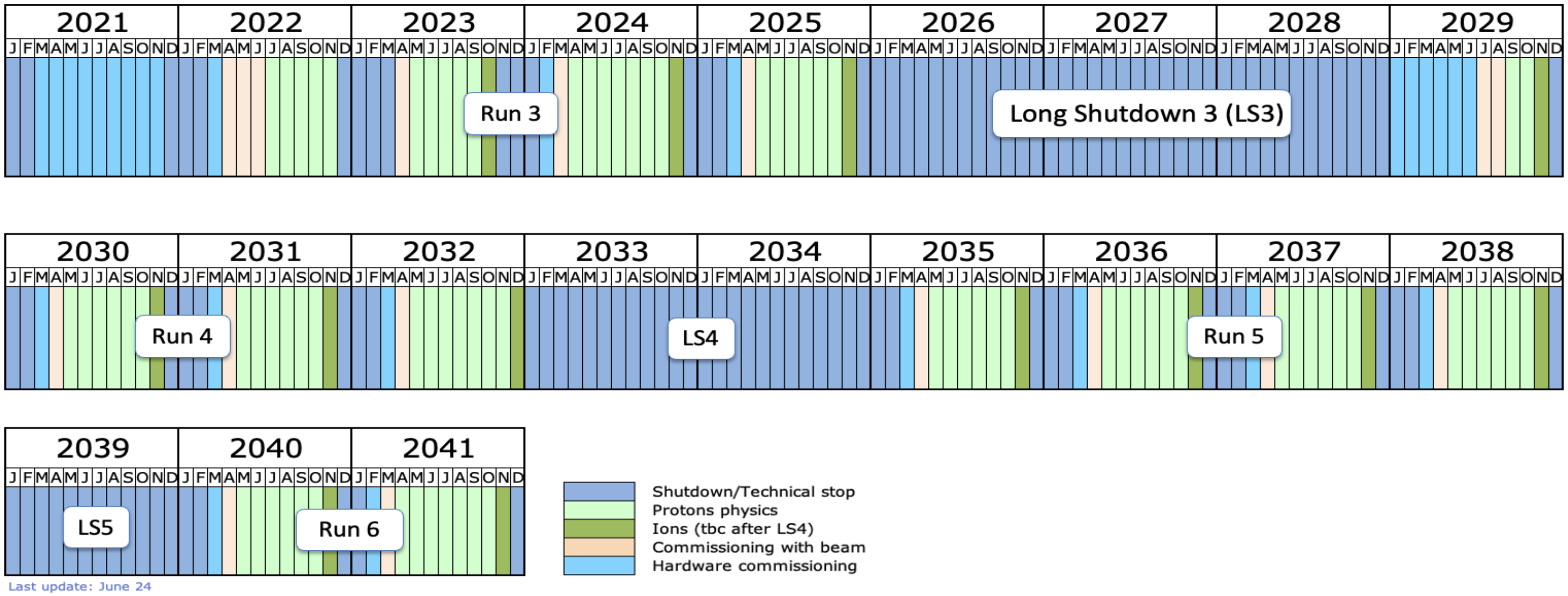


FASER Collaboration (CERN-FASER-CONF-2024-001)

- FASER started probing new parameter space after 1 day of LHC running.

WHAT'S NEXT

- FASER is running now, will collect data through the rest of 2024 and 2025 (and 2026, if LS3 is delayed), for a total of ~300 fb^{-1}.

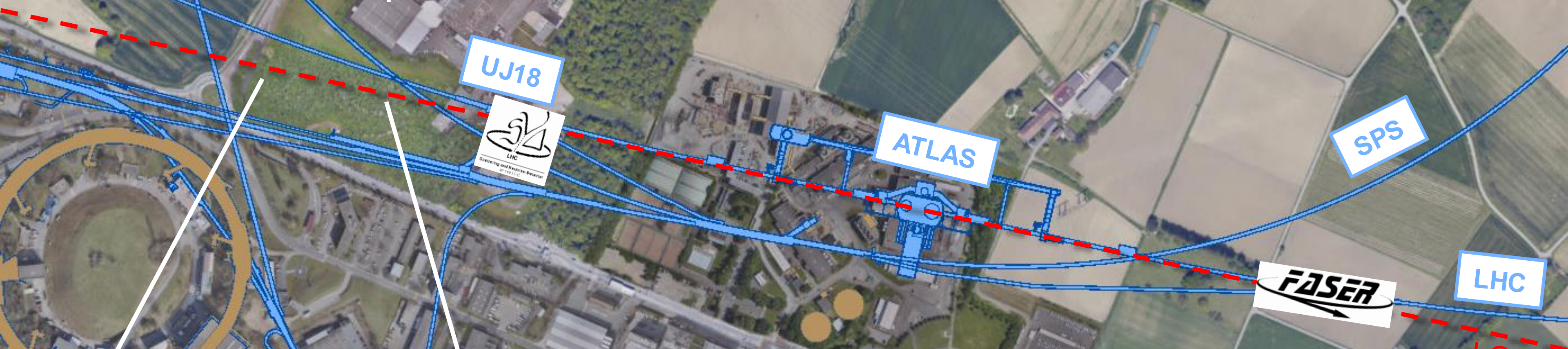


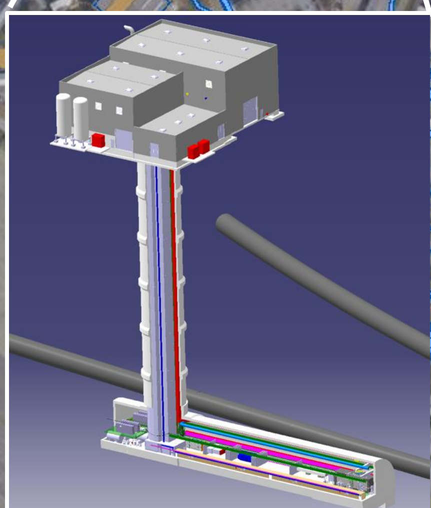
- FASER is approved for LHC Run 4, when High-Luminosity LHC running will add ~700 fb^{-1}, with various detector upgrades in the works.

- For the rest of the HL-LHC era, the proposed Forward Physics Facility, will enable the LHC to fully realize the potential of forward physics.

FORWARD PHYSICS FACILITY

- Following the results of FASER and SND@LHC, CERN is considering the possibility of creating a dedicated Forward Physics Facility to house far-forward experiments for the rest of the LHC era from 2028-2040s.

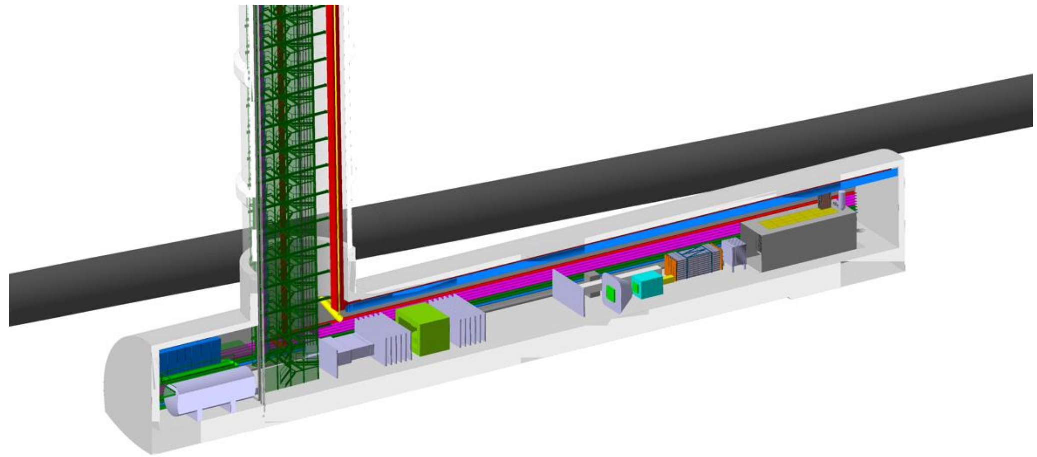




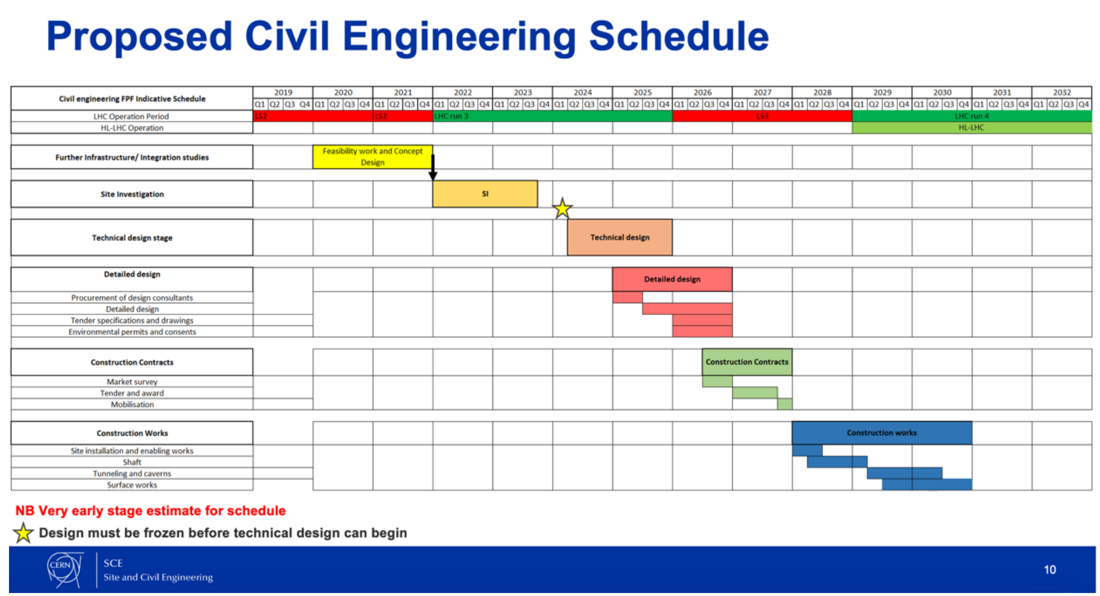
FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

THE FACILITY

- A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.
- 75 m long, 12 m in diameter, covers $\eta > 5.1$.
- Preliminary (Class 4) cost estimate: 35 MCHF.
- Can be constructed independently of the LHC, does not disrupt LHC running.
- Timeline: construct in LS3/early Run 4, physics starts in late Run 4/Run5.

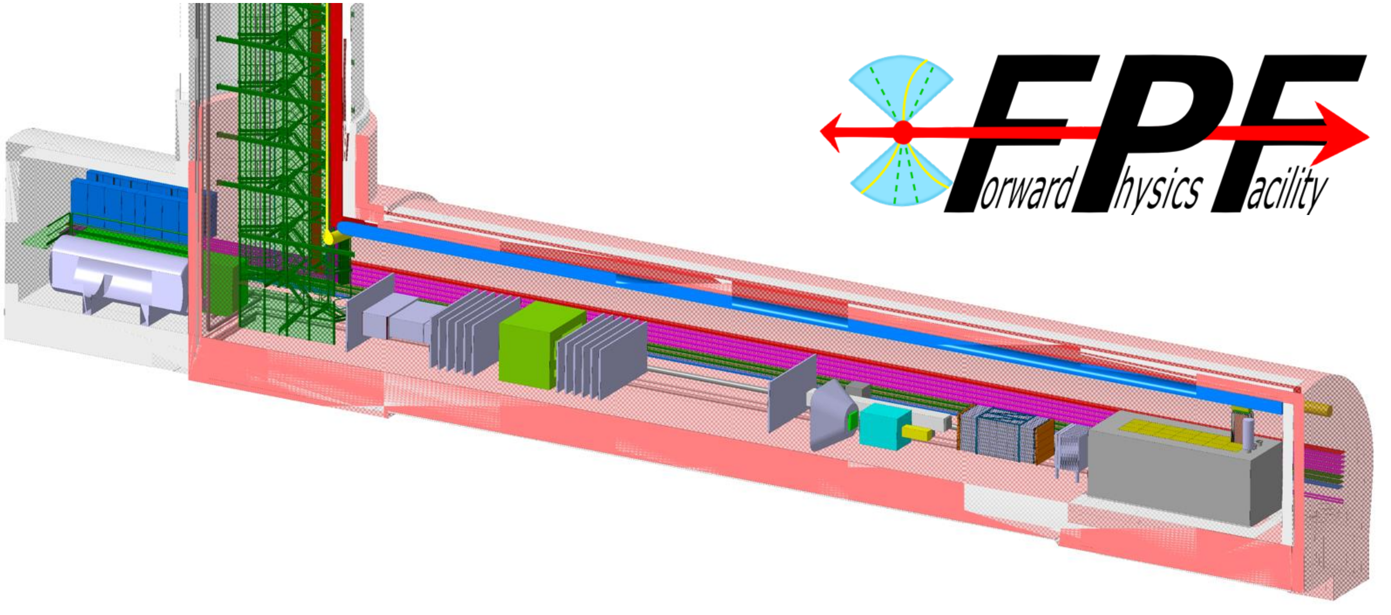


Bud, Magazinik, Pál, Osborne, et al. CERN CE (2024)



FPF EXPERIMENTS

- At present there are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASERν2: emulsion-based neutrino detector
  - FLArE: LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)



- These represent a huge jump relative to the existing experiments:
  - 10,000 times greater (decay volume * luminosity) for BSM searches, unique discovery potential in many models of dark matter and new particles.

IMPLICATIONS FOR ASTROPARTICLE PHYSICS

- Current and future LHC neutrino detectors will detect many neutrinos, determine their flavor, and distinguish nu from anti-nu (at least for mu and tau)

- Current LHC neutrino detectors: ~10,000 TeV neutrinos

  Future LHC neutrino detectors: ~1,000,000 TeV neutrinos (~1,000 per day!)

Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k

Kling, Nevay (2021); FASER Collaboration (2024)

- What can we do with these?

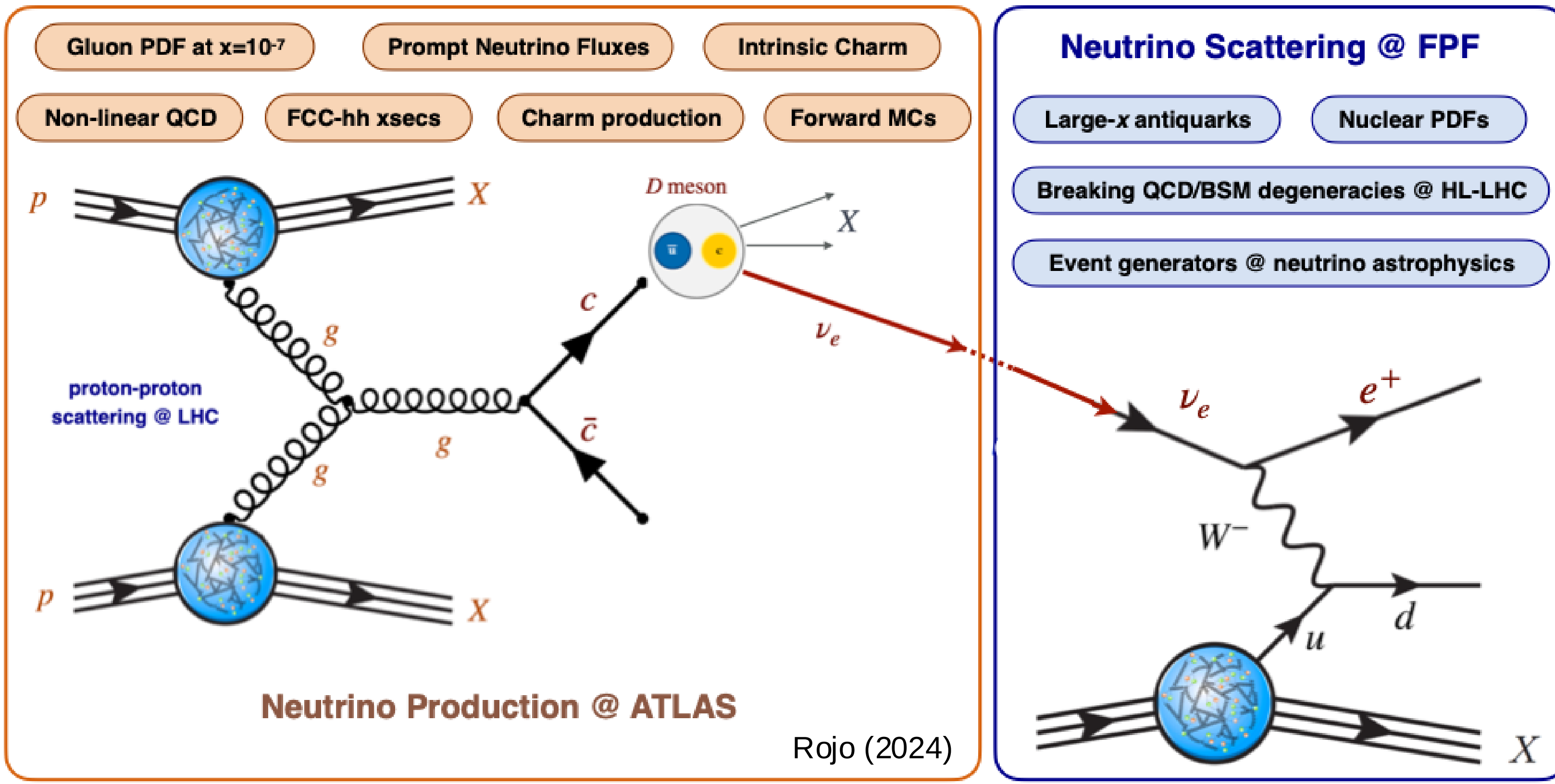
- Many interesting probes of neutrino properties, QCD, and complementarities with IceCube and other astroparticle experiments.

FPF WG4 conveners: Luis Anchordoqui, Dennis Soldin

Other FPF workshop participants: Halzen, Engel, Pierog, Fedynitch, Sarkar, Lu, …

PRODUCTION, PROPAGATION, INTERACTION

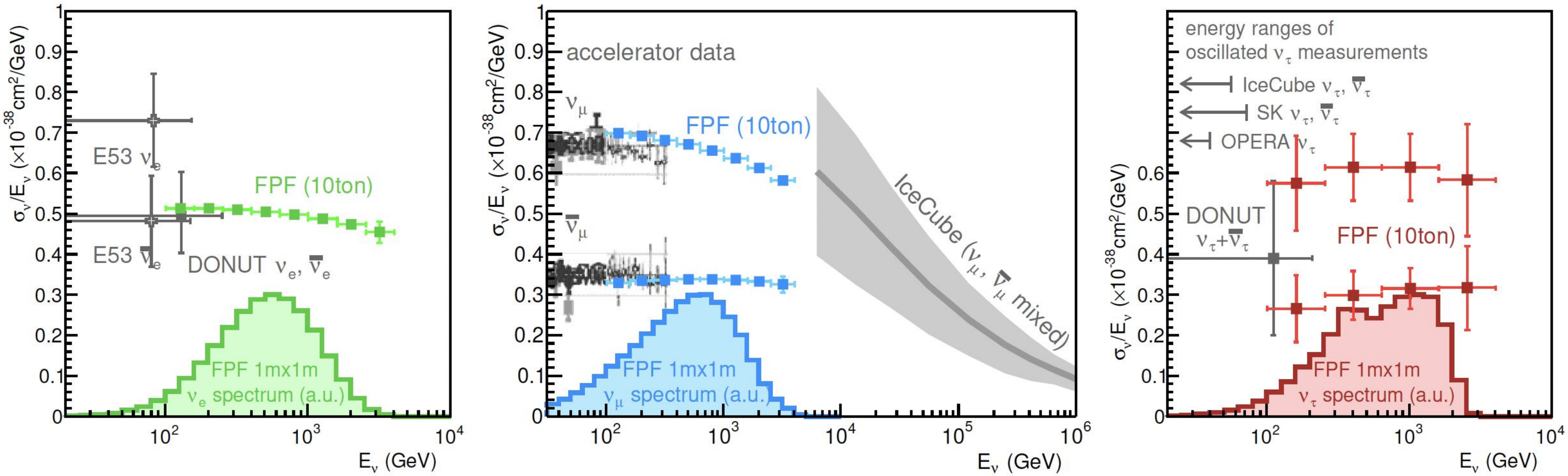
- The large statistics will allow for double differential event rates as a function of energy and pseudorapidity for each neutrino flavor.
- These differential distributions probe a vast number of interconnected topics.



NEUTRINO PROPERTIES

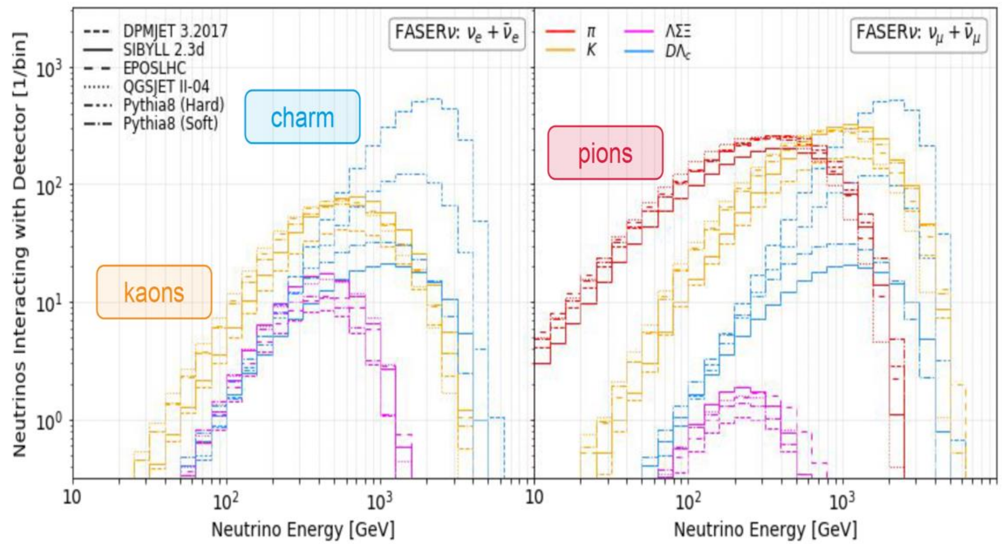
- Assuming known forward hadron production, the large event rates will enable precise measurements of neutrino interaction cross section at TeV energies between fixed target experiments and IceCube.

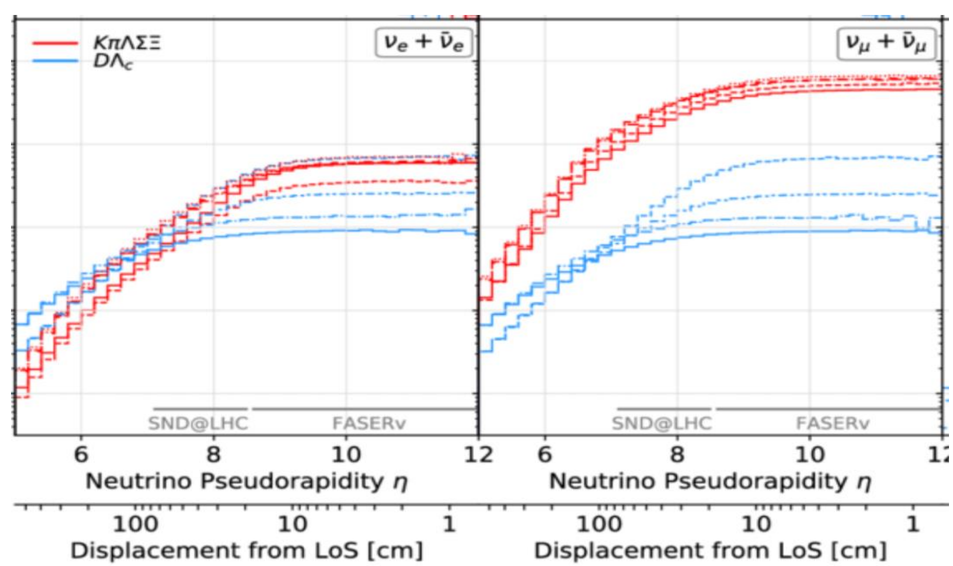
- Can confirm neutrino deep-inelastic scattering or test non-standard neutrino interactions, enable precision tau neutrino studies.



NEUTRINOS AS TRACERS OF HADRON PRODUCTION

- Alternatively, assuming neutrino DIS, event rates probe neutrino fluxes, that is, forward hadron production.
- Pions produce ν_μ, kaons produce ν_μ and ν_e, charm mesons produce ν_μ, ν_e, and ν_τ with distinct energy and pseudorapidity distributions.
- There are currently significant differences in forward hadron production models, which can be greatly constrained by data from forward experiments.





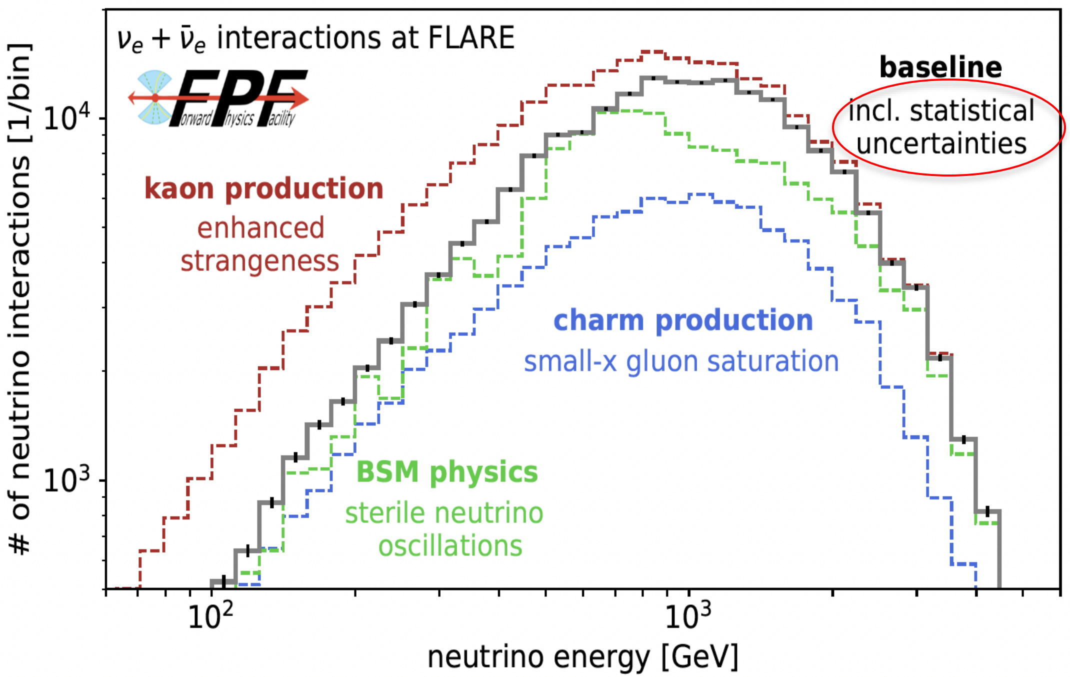
Kling, Nevay (2021)

LIGHT FLAVORS AND COSMIC MUON PUZZLE

Soldin (2108.08341), Albrecht et al. (2022)

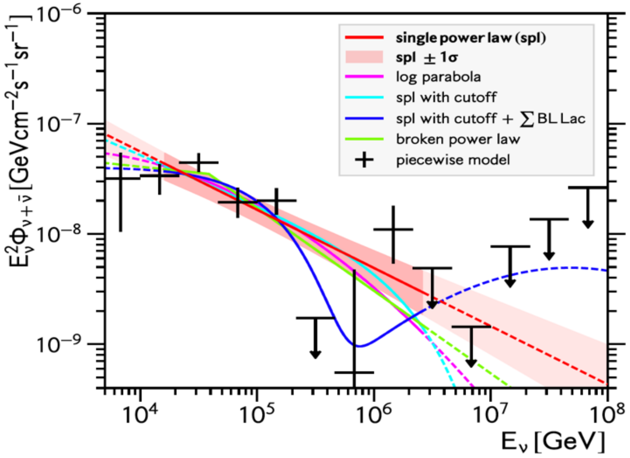
- Observations of extensive air showers see a significant excess of muons compared to hadronic interaction models.
- A proposed resolution is enhanced strangeness: pions replaced by kaons.
- A kaon/pion enhancement would be reflected as an enhanced ν_e/ν_μ ratio, which would be very obvious in the ν_e spectrum.

Anchordoqui, Garcia Canal, Kling, Sciutto, Soriano (2022)



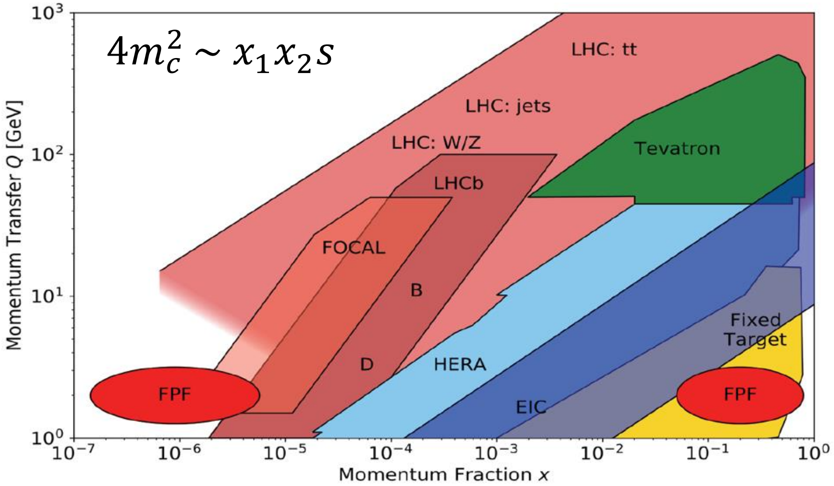
CHARM AND PROMPT ATMOSPHERIC NEUTRINOS

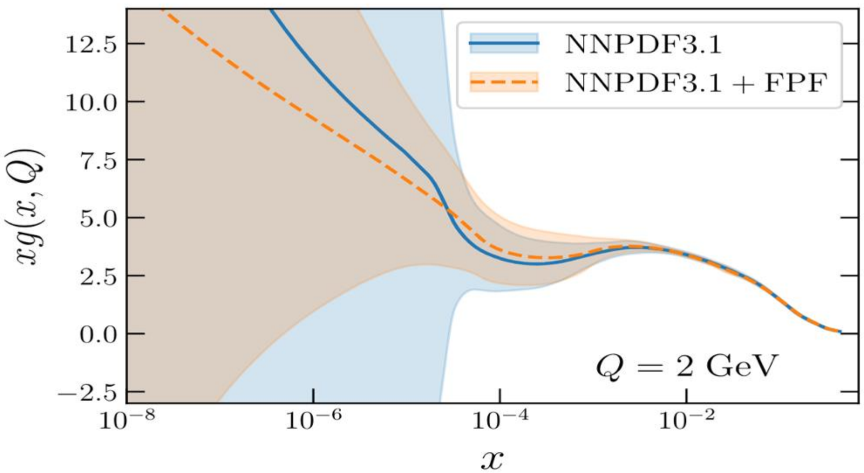
- Prompt atmospheric neutrino production is a difficult background to extragalactic astrophysical neutrinos at IceCube, with similar zenith angle distribution (isotropic).



IceCube (2001.09520)

- $gg \to cc$ is perturbative, but a leading uncertainty is the gluon pdf at small x. This can be measured in the controlled environment of a collider if
  - $\sqrt{s} \sim \sqrt{2E_\nu m_p} \sim 10$ TeV for $E_\nu \sim 10^7$ GeV: Requires the energy of the LHC
  - $x_{1,2} \sim \frac{m_c}{\sqrt{s}} e^{\pm\eta} \Rightarrow \eta \sim 7$ to 9: Requires the far forward angular coverage of the FPF





FASER White Paper (2022); Rojo et al. (2024)

SUMMARY

- The forward region, previously thought of as uninteresting, is in fact a treasure trove of interesting physics.
  - Collider neutrinos at TeV energies, with implications for neutrino properties, QCD, and astroparticle physics.
  - Unique searches for new light, weakly-interacting particles and other BSM particles, including many motivated by dark matter.
- Particularly interesting interplay with astroparticle physics, will shed light on forward hadron interaction models, the cosmic muon puzzle, prompt atmospheric neutrinos, …
- FASER and SND@LHC are currently operating, with many more results to come. The proposed Forward Physics Facility will be able to fully realize the LHC's forward physics potential in the HL-LHC era from 2028-2042.