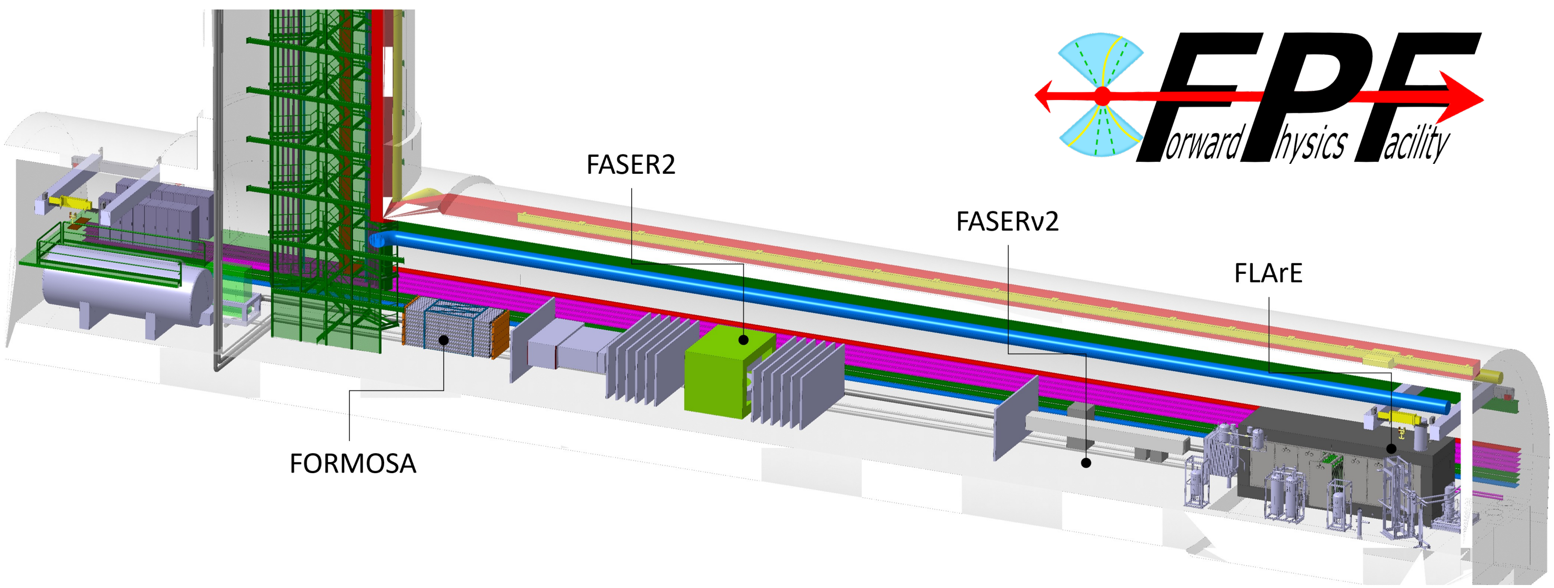
FORWARD PHYSICS FACILITY

NSF Presentation

Jonathan Feng, UC Irvine, 25 November 2024

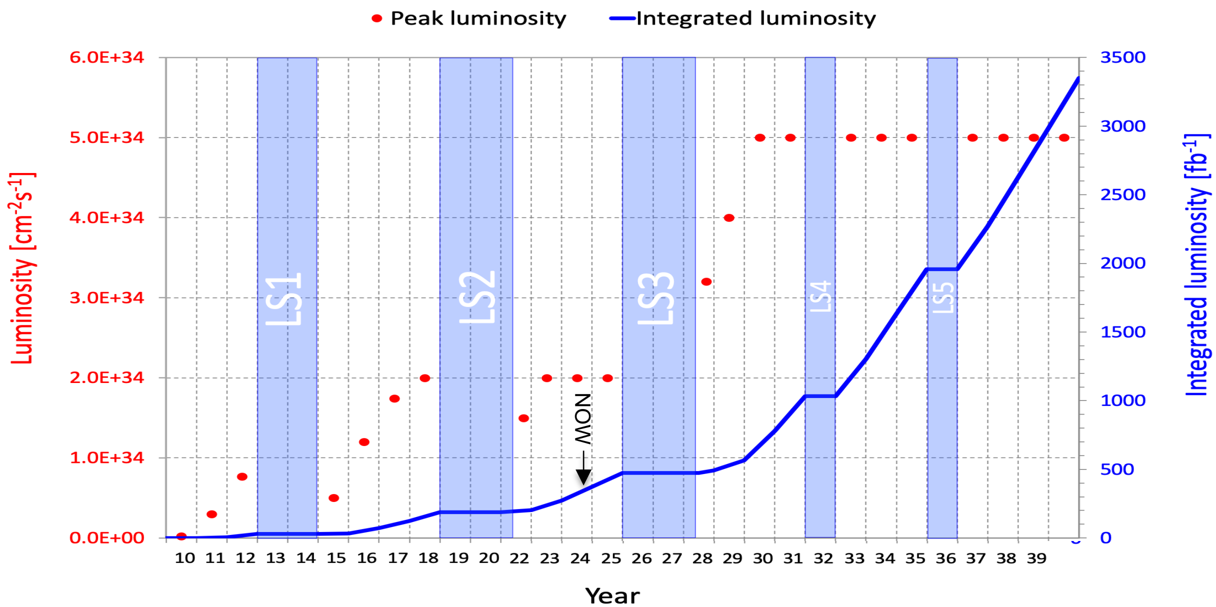
THE PLAN

- Jonathan Feng (UC Irvine): Background, Physics, Organization
- Jamie Boyd (CERN): The Facility, FASER2, FASERν2
- Matthew Citron (UC Davis): FORMOSA
- Milind Diwan (Brookhaven): FLArE

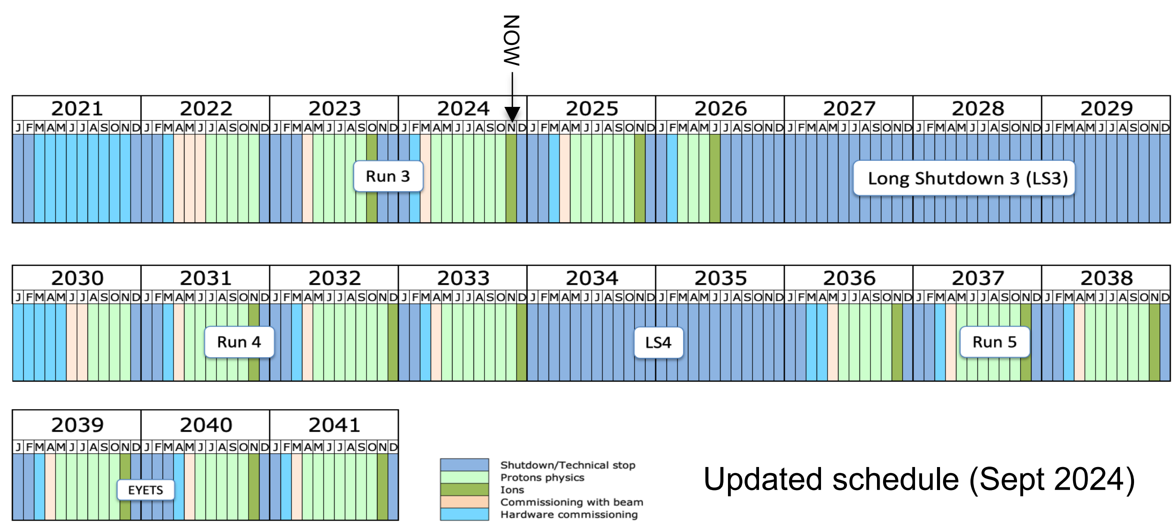


LIFETIME OF THE LHC

- The LHC started running in 2010 and is scheduled to run until the 2040s.
  - Middle-aged in terms of years.
  - But a 4th grader in terms of integrated luminosity.

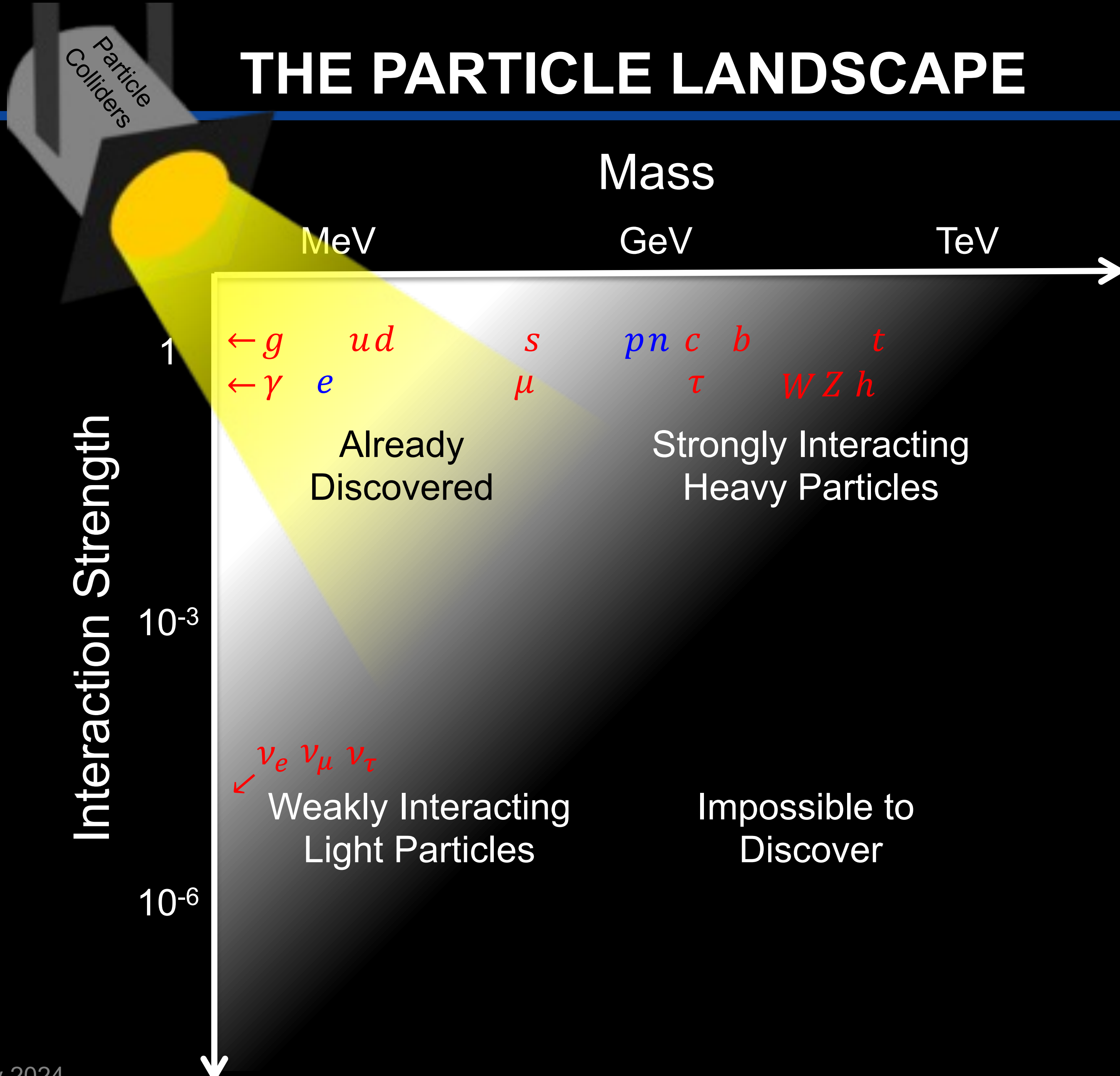


- Are we using the LHC to its full potential? What can we do to enhance its discovery prospects?

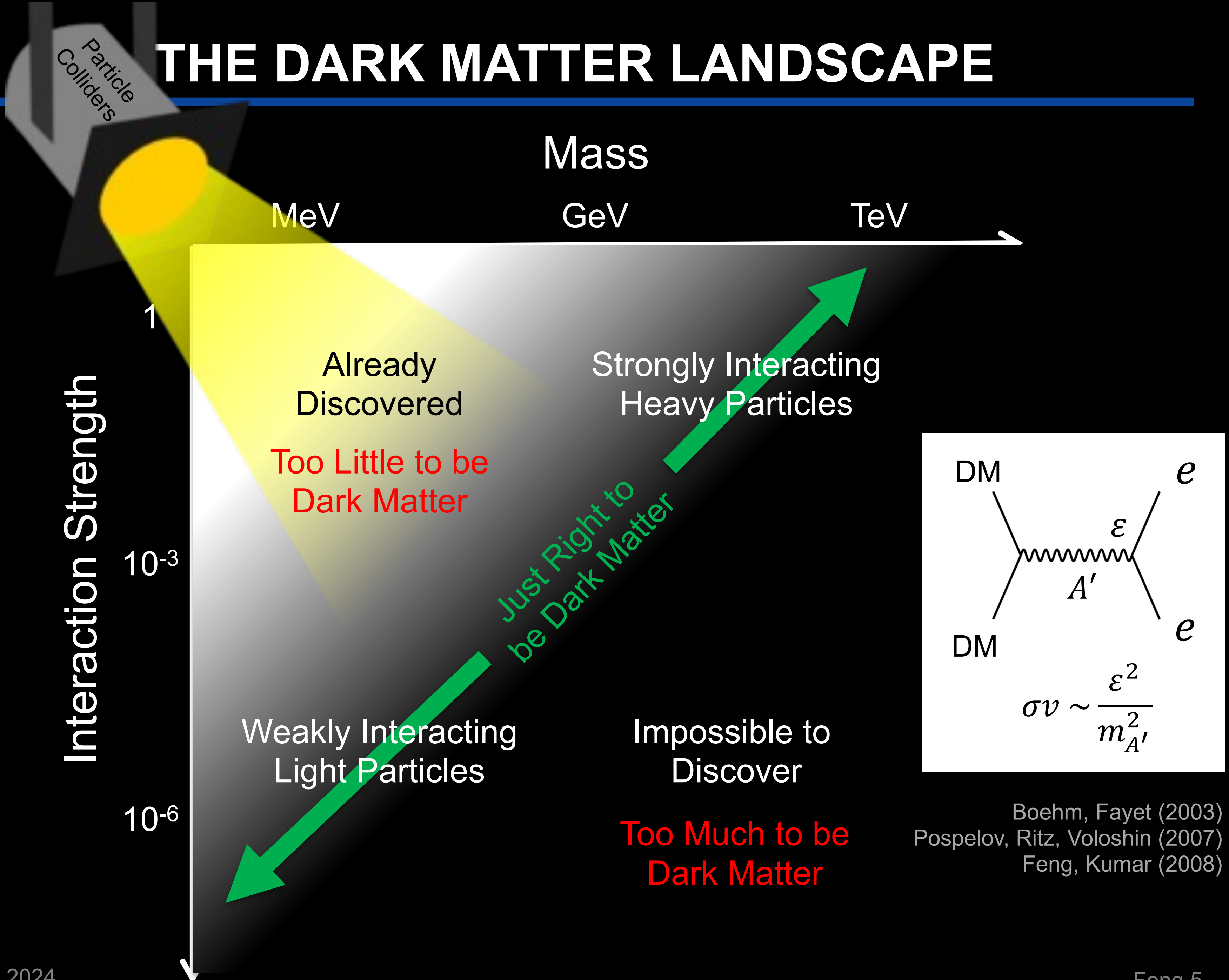


Updated schedule (Sept 2024)

THE PARTICLE LANDSCAPE



THE DARK MATTER LANDSCAPE



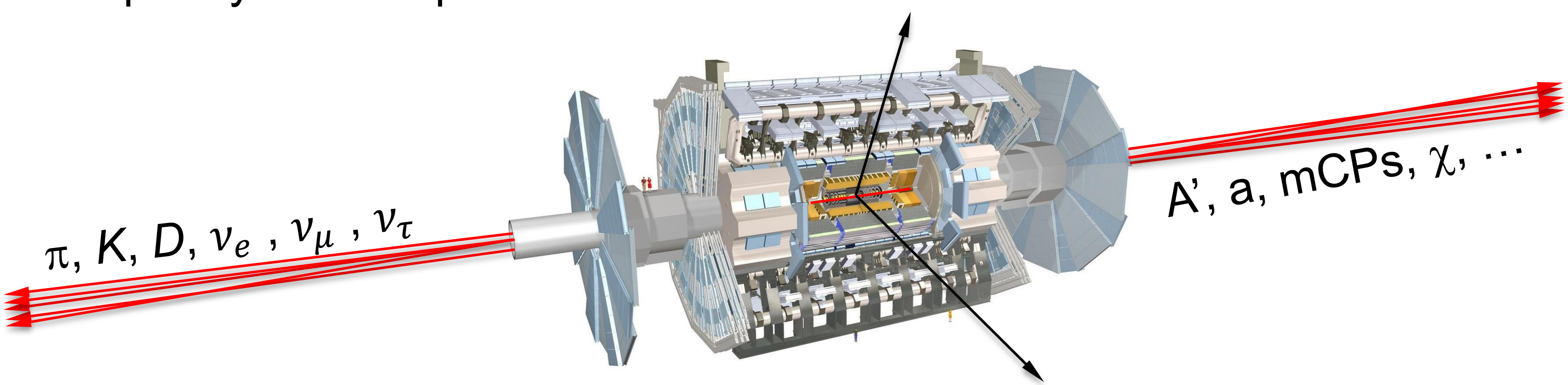
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

- The large LHC detectors, while beautifully optimized to detect strongly-interacting heavy particles, are also almost optimally configured to miss weakly-interacting 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.

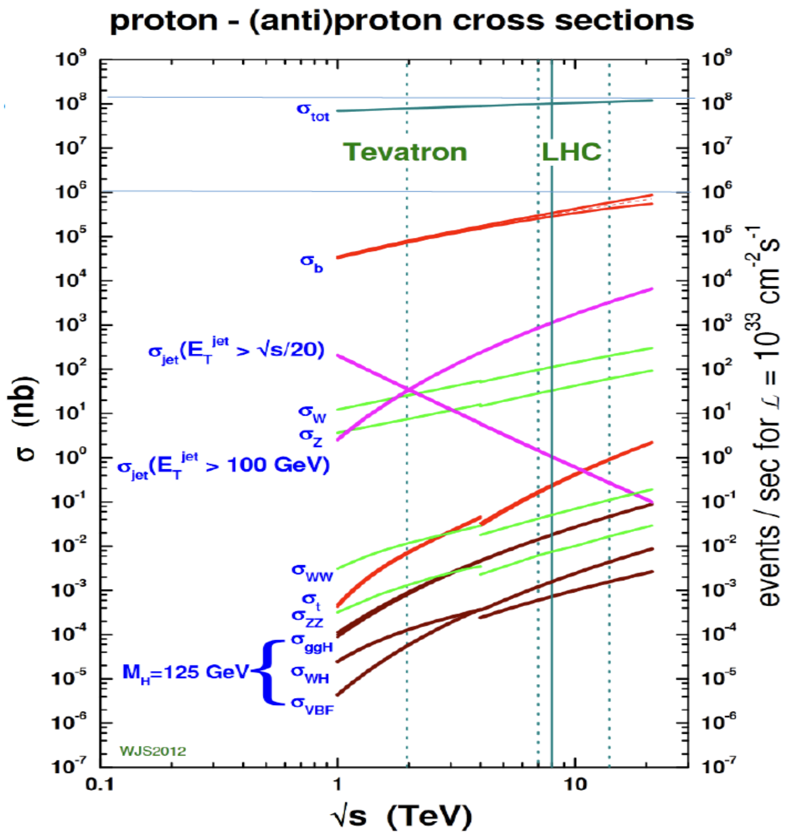


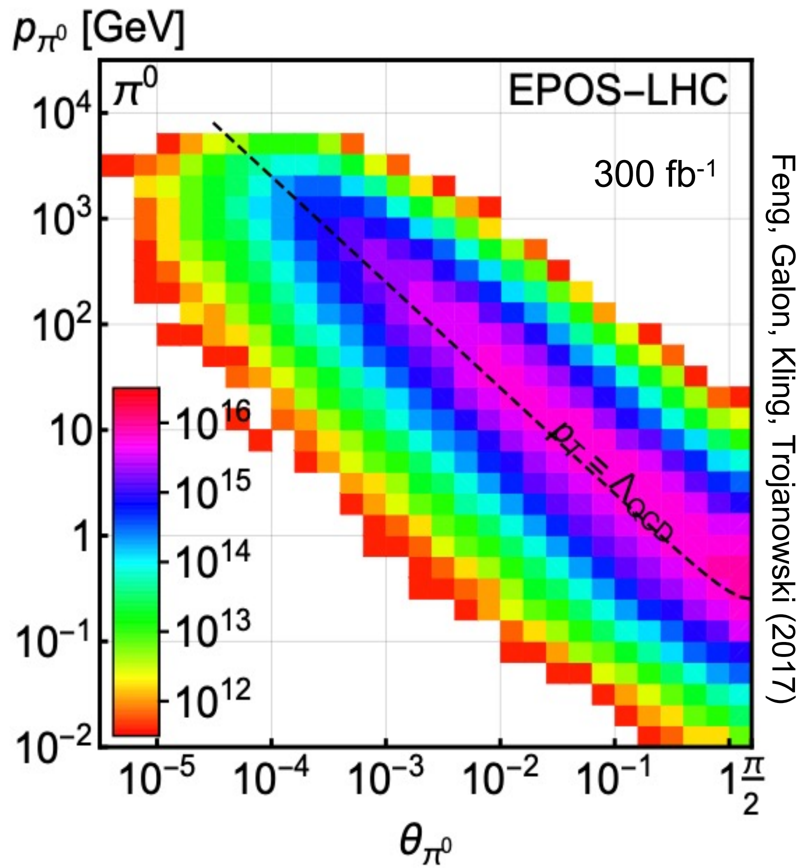
- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles: pions, kaons, *D* mesons, all neutrinos.
  - It is also true for many proposed new particles, especially those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

  De Rujula, Ruckl (1984)

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

LIGHT PARTICLES AT THE LHC



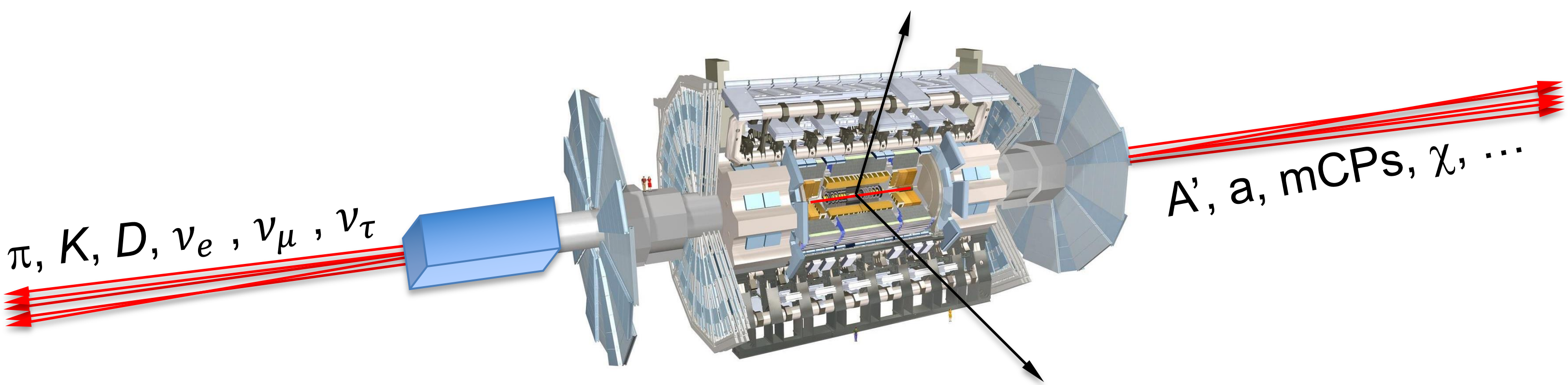


- Most searches have focused on processes with σ ~ fb, pb.
- But the total cross section is σ_{tot} ~ 100 mb and it is typically wasted.
- Consider pions (leading sources of neutrinos and many BSM particles).
- We created an incredibly intense source of TeV neutrinos and, before 2019, didn't even bother to look at it.

DETECTING FORWARD PARTICLES

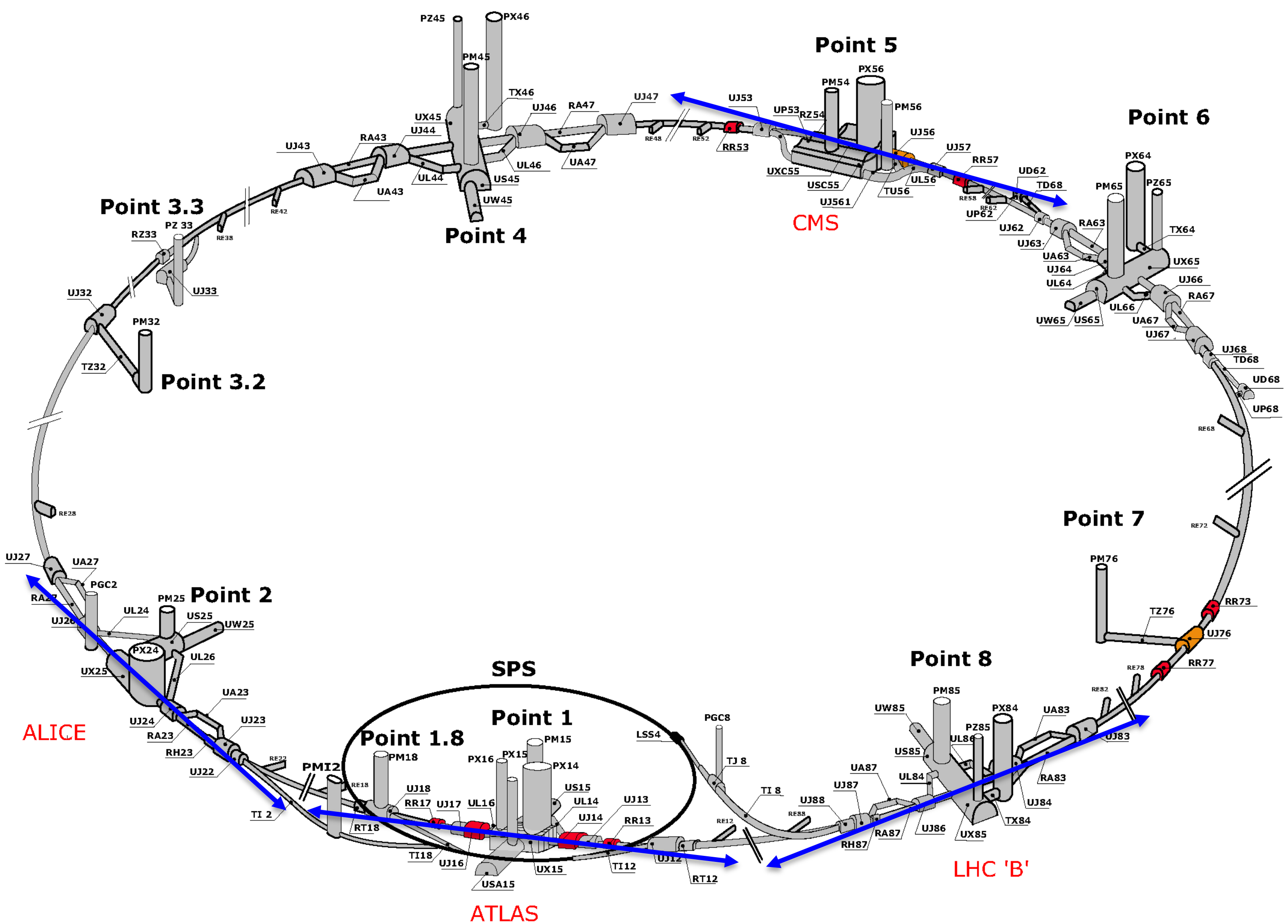
- To capture the enormous flux, we need to detect particles that are produced in the forward direction along the beamline.

- Of course, we can't just put a detector there, because it will block the protons from coming in.



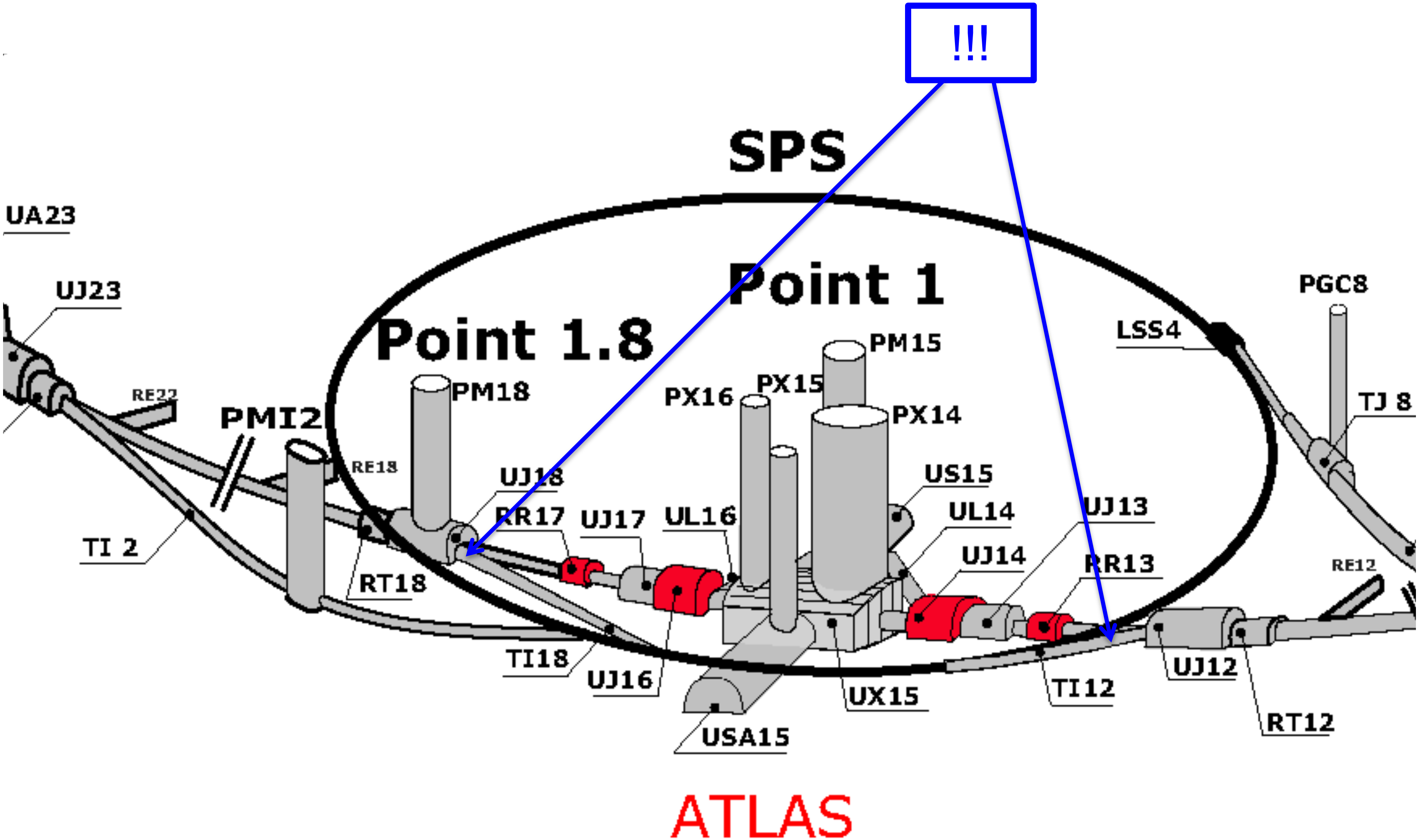
- But the LHC is a circular collider! If we go far enough away, the LHC proton beam will be bent away, while all the weakly-interacting light particles we are looking for will go straight.

MAP OF LHC



Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ATLAS
ALICE
CMS
LHC 'B'
PMI2

MAP OF LHC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SPS
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UA23
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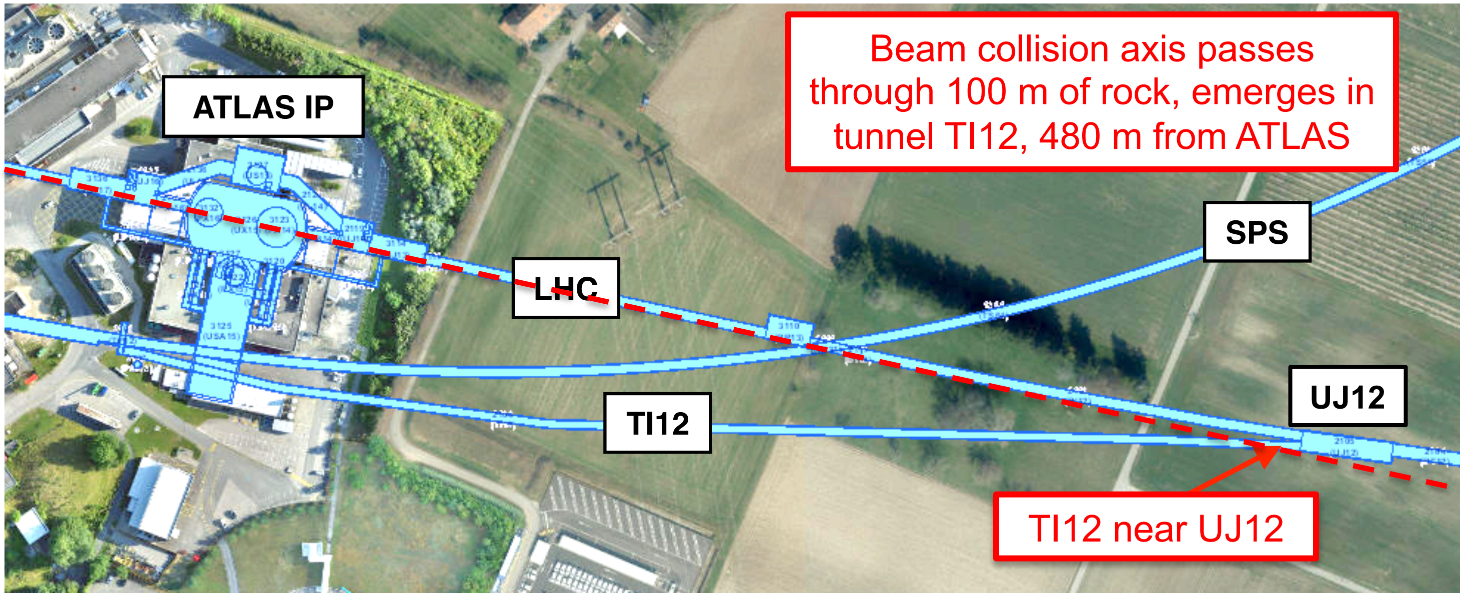
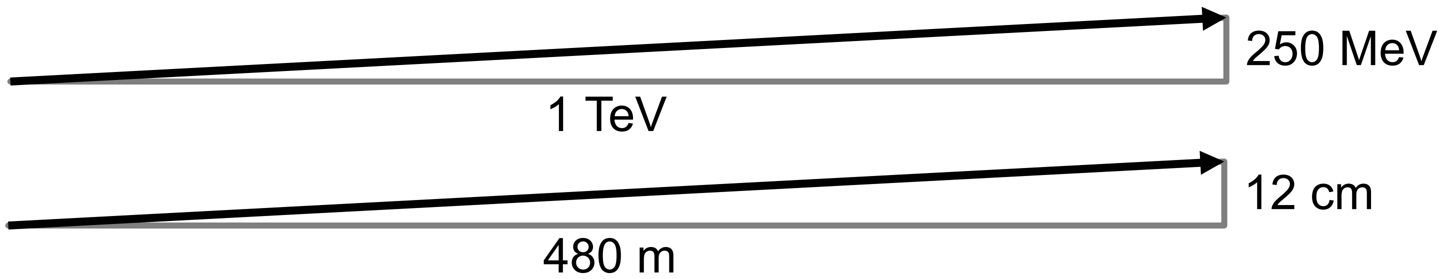
ATLAS

THE FORWARD REGION



HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:
- Space:



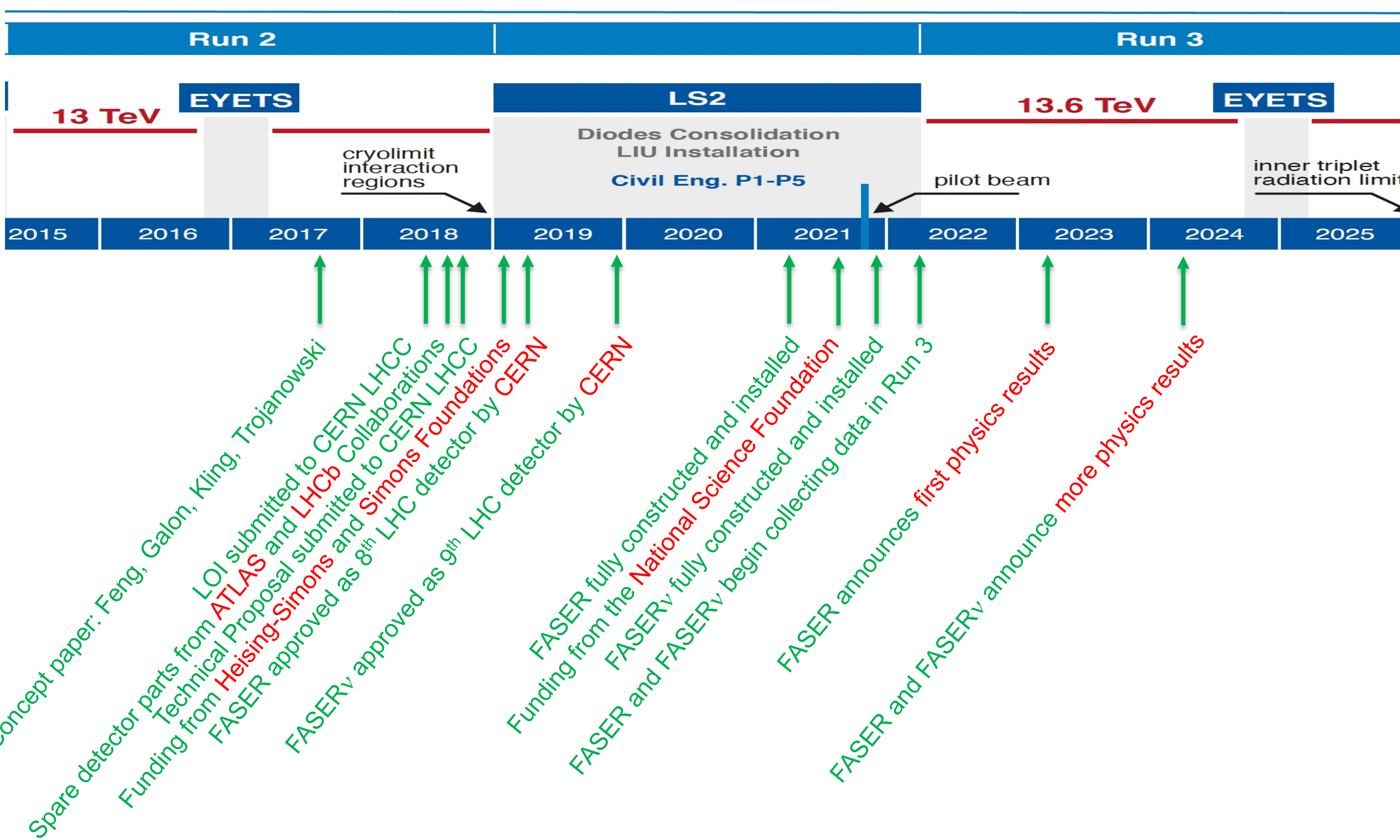
- For particles produced in pion decay
  - The opening angle is 0.2 mrad (the moon is 7 mrad).
  - Even 480 m away, most of the signal passes through an 8.5” x 11” (A4) sheet of paper.
  - A detector with radius 10 cm covers a solid angle of 10^{-8}, but 1% of pions with E > 10 GeV are in this narrow cone.

- The transverse spread of particles from decays of
  - Pions (ν_μ, dark photons, …): ~12 cm
  - Kaons (ν_μ, ν_e, heavy neutral leptons, …): ~24 cm
  - D mesons (ν_μ, ν_e, ν_τ, heavy neutral leptons, …): ~1 m
  - B mesons (ν_μ, ν_e, ν_τ, dark Higgs bosons, …): ~2.4 m

- These beams are extremely collimated. Not only is this physics inaccessible to the large LHC expts, it can be explored with small, fast, and inexpensive detectors.

FASER

FASER AND FASERν TIMELINE



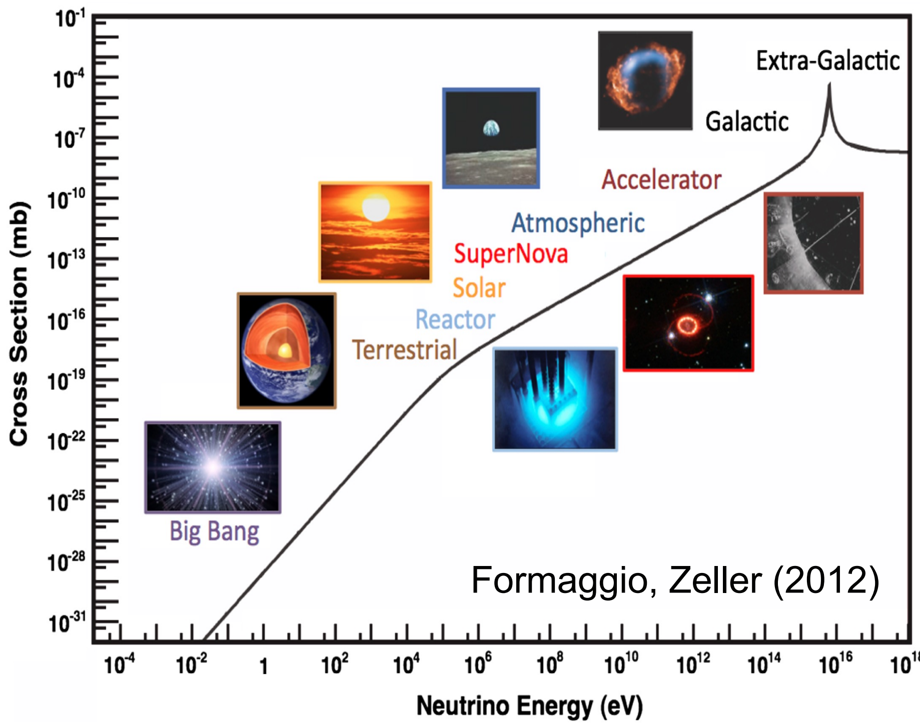
FASER: currently 112 collaborators, 28 institutions, 11 countries

FASER AND THE LHC

THE FASER DETECTOR

COLLIDER NEUTRINOS

- Neutrinos are the least understood of all known particles.
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.

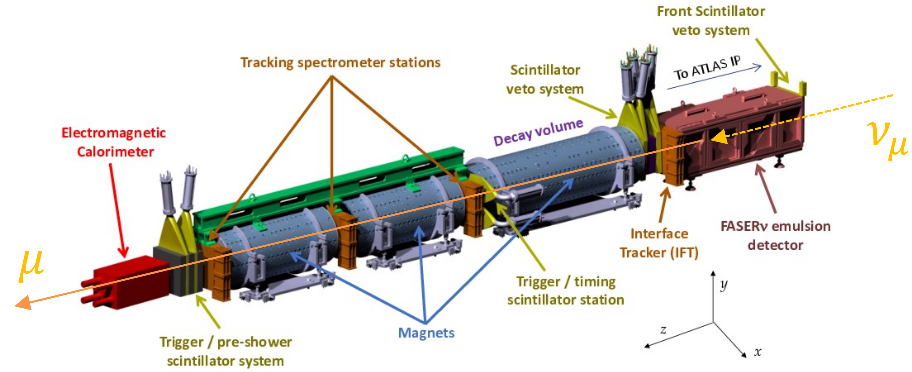


- But before FASER, neutrinos produced at a particle collider had never been directly observed.
  - Conventional wisdom: neutrinos interact very weakly so cannot be detected.
  - The reality: the highest energy ones, which are most likely to interact, pass through the blind spots of existing detectors.

FORWARD NEUTRINO RESULTS

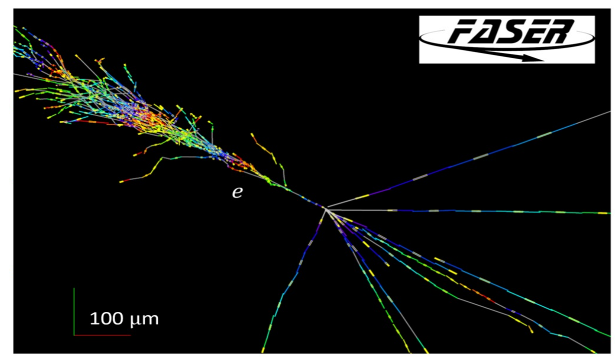
- In 2023, found 153 ν_μ CC events
  - 1st direct detection of collider neutrinos.
  - Signal significance of ~16σ.
  - Highest energy ν and $\bar{\nu}$ interactions ever observed from a human source.

FASER Collaboration (2303.14185, PRL)



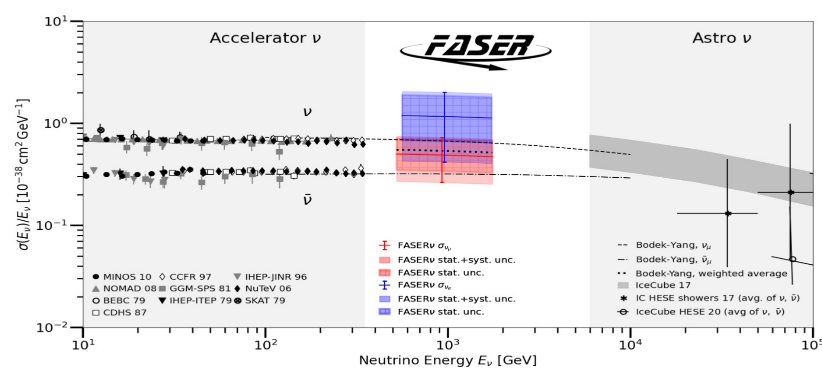
- In 2024, found first ν_e CC events, measured TeV neutrino cross sections.

FASER Collaboration (2403.12520, PRL)



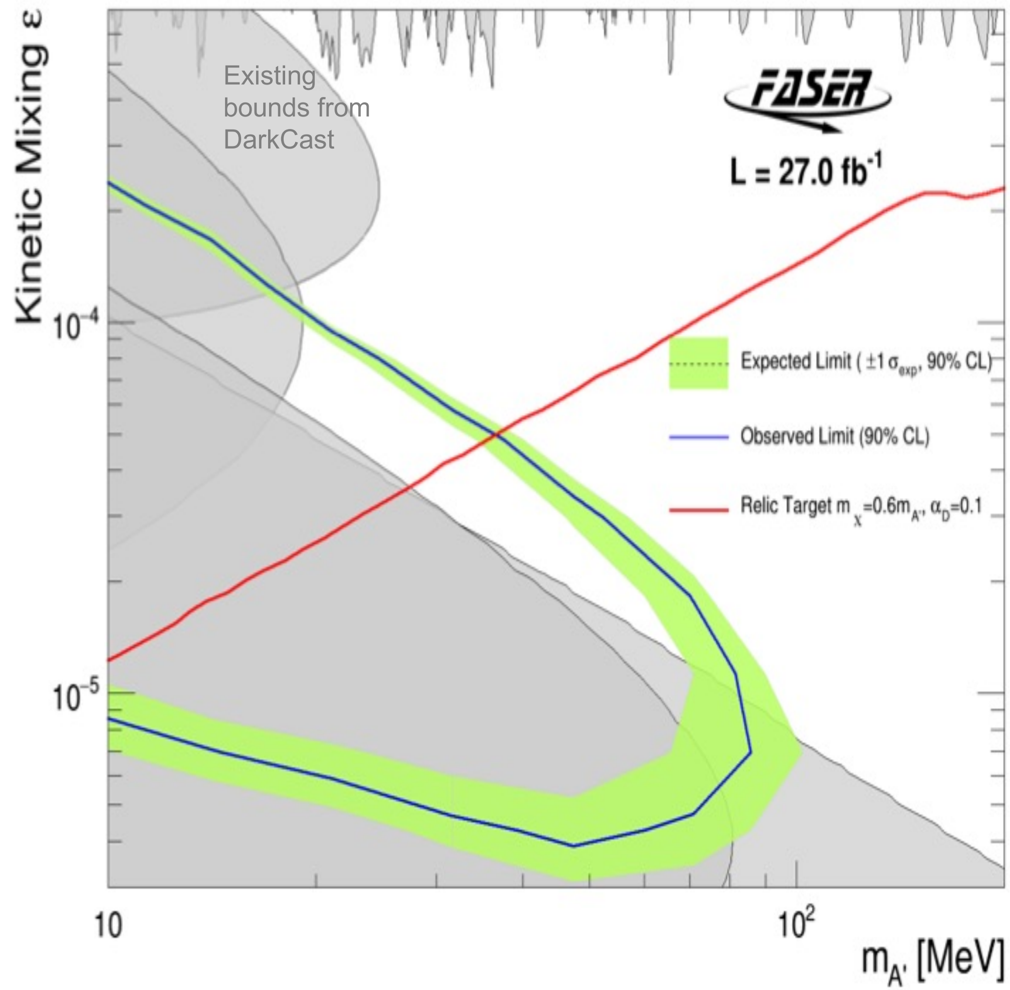
- These measurements used only 1% of the data collected in 2022-24. Much more to come: triple the world's supply of tau neutrinos, identify the first anti-tau neutrino, …. "The dawn of collider neutrino physics."

PRL Editor's Selection (2024)



FORWARD PARTICLE SEARCHES

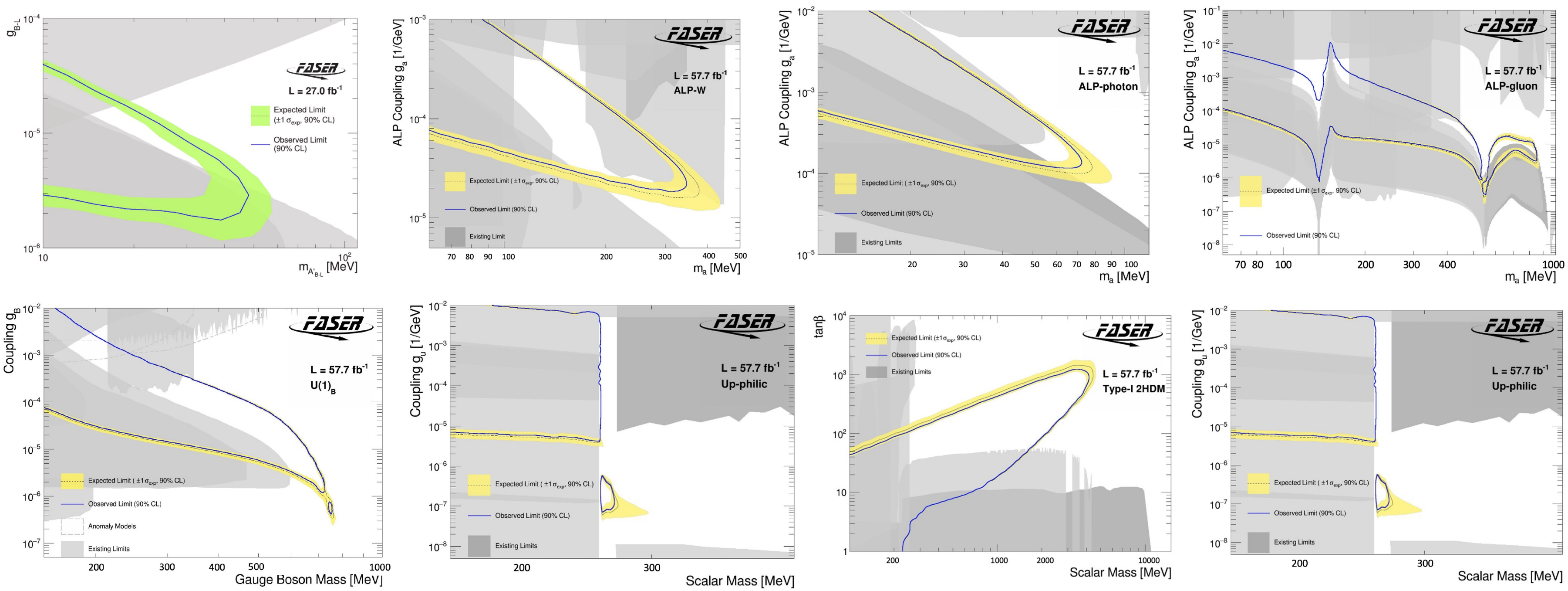
- The forward region is also a region of enhanced BSM particle fluxes.
- For example: dark photons from $\pi^0 \rightarrow \gamma A'$, followed by $A' \rightarrow e^+ e^-$.
- Started probing new parameter space in the first day (< fb^{-1}), ended up background-free, ~100 times more sensitive than previous experiments.
- First new probe of the parameter space favored by dark matter from low coupling since the 1990's.



FASER Collaboration (2308.05587, PLB)

MORE SEARCH RESULTS

- FASER has now probed many other models with world-leading sensitivity: other new force carriers ($U(1)_{B-L}$, $U(1)_B$), axion-like particles with photon, *W*, gluon couplings, up-philic scalars, two Higgs doublet models. Probes particles produced by pions or by B mesons, decays include charged tracks or only photons, ….
- CERN has approved FASER for LHC Run 4 2030-2034, providing a golden opportunity to upgrade the detector within the tight space constraints of TI12.



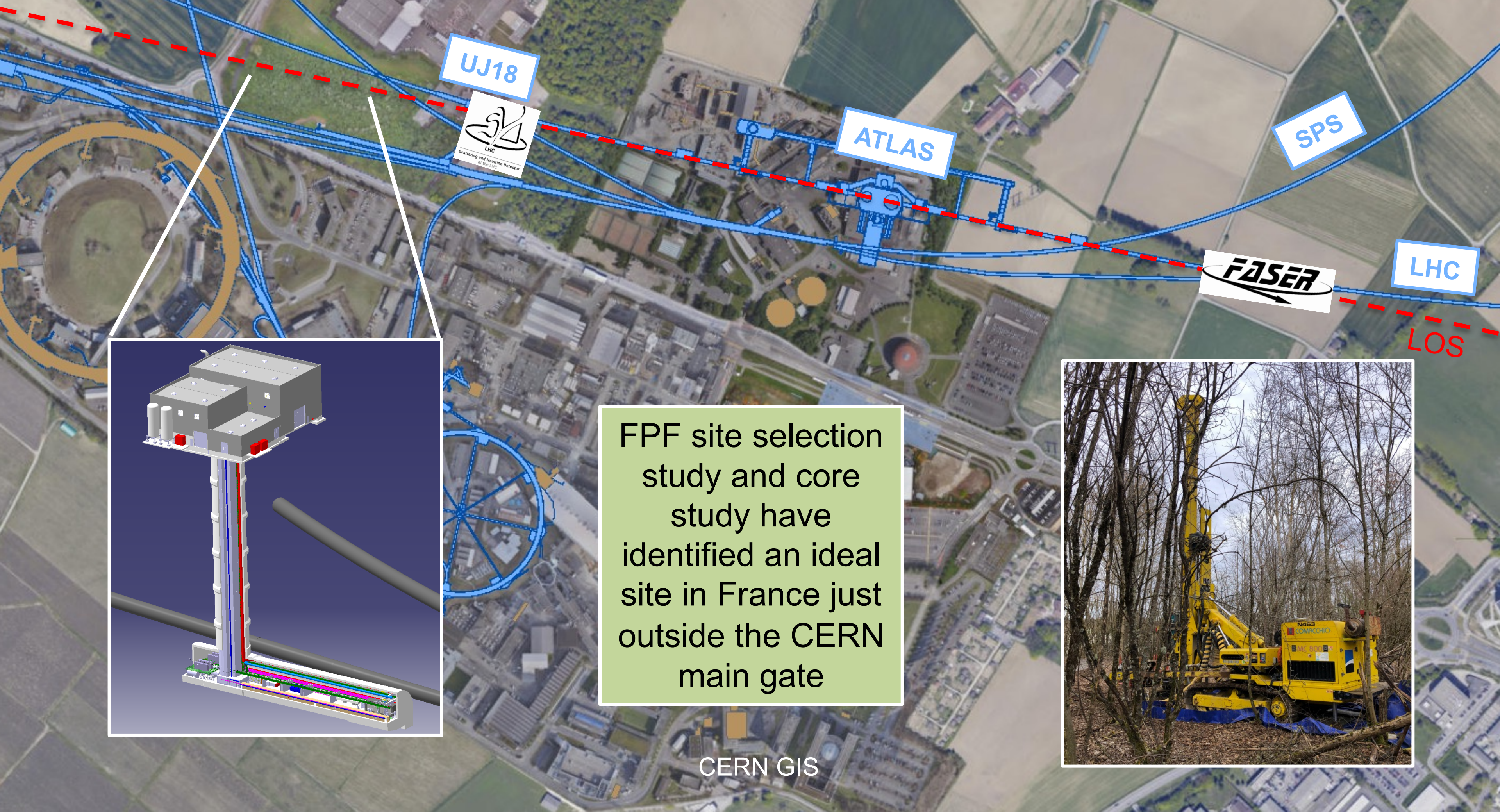
FASER Collaboration (2308.05587, PLB; 2410.10363)

FPF

Forward Physics Facility

FORWARD PHYSICS FACILITY

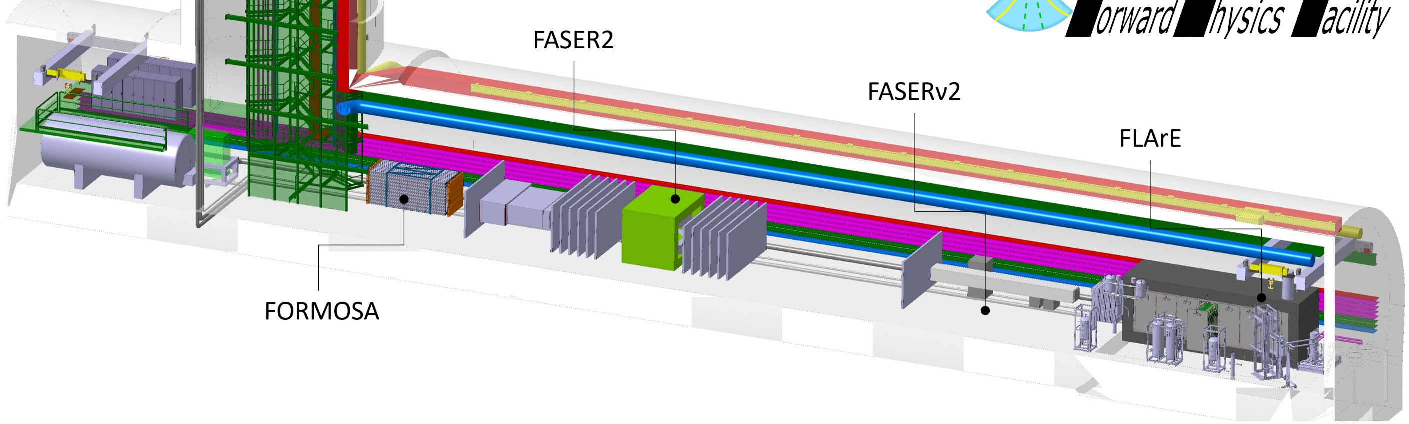
- Following the results of FASER and SND@LHC, CERN is considering the possibility of creating a dedicated Forward Physics Facility to house far-forward experiments for the rest of the LHC era until the 2040s.



THE FPF AND ITS 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)

- With strong support from CERN’s Physics Beyond Colliders group, the Facility has been designed in detail. Estimated (Class 4) cost is 35 MCHF for Facility, core costs of the experiments vary from 2 to 15 MCHF.



FPF ORGANIZATION

- The FPF activities are organized into 9 WGs consisting of experimentalists, theorists, and multiple CERN technical teams, with active exp/th interactions and optimization between experiments. For more, see fpf.web.cern.ch.

THE FACILITY · EXPERIMENTS · PHYSICS · PAPERS · TALKS · EVENTS · ORGANIZATION · PRESS · WEB UPDATES

Organization

FPF Working Group Conveners

- **Steering Committee:** Jamie Boyd (CERN), Albert De Roeck (CERN), Milind Diwan (Brookhaven), Jonathan Feng (UC Irvine), Juan Rojo (Nikhef)
- **Coordination Panel:** Aki Ariga (Chiba), Alan Barr (Oxford), Brian Batell (Pittsburgh), Jianming Bian (UC Irvine), Jamie Boyd (CERN), Albert De Roeck (CERN), Milind Diwan (Brookhaven), Jonathan Feng (UC Irvine), Chris Hill (Ohio State), Felix Kling (DESY), Juan Rojo (Nikhef), Dennis Soldin (Utah), Anna Stasto (Penn State)
- **WG0 Facility:** Jamie Boyd (CERN)
- **WG1 Neutrino Interactions**: Juan Rojo (Nikhef)
- **WG2 Charm Production:** Anna Stasto (Penn State)
- **WG3 Light Hadron Production and Astroparticle Connections:** Luis Anchordoqui (Lehman), Dennis Soldin (Utah)
- **WG4 New Physics:** Brian Batell (Pittsburgh), Sebastian Trojanowski (Warsaw)
- **WG5 FASER2:** Alan Barr (Oxford), Josh McFayden (Sussex), Hide Otono (Kyushu)
- **WG6 FASERv2** :Aki Ariga (Chiba), Tomoko Ariga (Kyushu)
- **WG7 FLArE:** Jianming Bian (UC Irvine), Milind Diwan (Brookhaven)
- **WG8 FORMOSA:** Matthew Citron (UC Davis), Chris Hill (Ohio State)

Exp/Th Working Group Liaisons

- **WG5 FASER2:** Josh McFayden (Sussex)
- **WG6 FASERnu2:** Aki Ariga (Chiba), Tomoko Ariga (Kyushu)
- **WG7 FLArE:** Steve Linden (Brookhaven), Wenjie Wu (UC Irvine)
- **WG8 FORMOSA:** Matthew Citron (UC Davis)

PBC FPF Subgroup

- **Convener:** Jamie Boyd (CERN)
- **Core Members**: Marco Andreini (CERN), Kincso Balazs (CERN), Jean-Pierre Corso (CERN), Jonathan Feng (UC Irvine), John Osborne (CERN)

FORWARD PHYSICS FACILITY

- The physics program has been defined in numerous meetings and papers.
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020
  - FPF2 Meeting, 27-28 May 2021
  - FPF3 Meeting, 25-26 Oct 2021
  - FPF4 Meeting, 31 Jan - 1 Feb 2022
  - FPF5 Meeting, 15-16 Nov 2022
  - FPF6 Meeting, 8-9 Jun 2023
  - FPF Theory Workshop, 19-20 Sep 2023
  - FPF7 Meeting, 29 Feb – 1 Mar 2024
  - FPF8 Meeting, 21-22 Jan 2025
- FPF Papers
  - FPF "Short" Paper: 75 pages, 80 authors, Phys. Rept. 968, 1 (2022), 2109.10905.
  - FPF White Paper: 429 pages, 392 authors+endorsers representing over 200 institutions, J. Phys. G (2023), 2203.05090.
  - FPF Source Document for ESPPU, 2411.04175.

Physics Reports 968 (2022) 1–50

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

The Forward Physics Facility: Sites, experiments, and physics potential

OPEN ACCESS

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **50** (2023) 030501 (410pp) https://doi.org/10.1088/1361-6471/ac865e

Major Report

The Forward Physics Facility at the High-Luminosity LHC

SCIENCE AND PROJECT PLANNING FOR THE FORWARD PHYSICS FACILITY IN PREPARATION FOR THE 2024–2026 EUROPEAN PARTICLE PHYSICS STRATEGY UPDATE

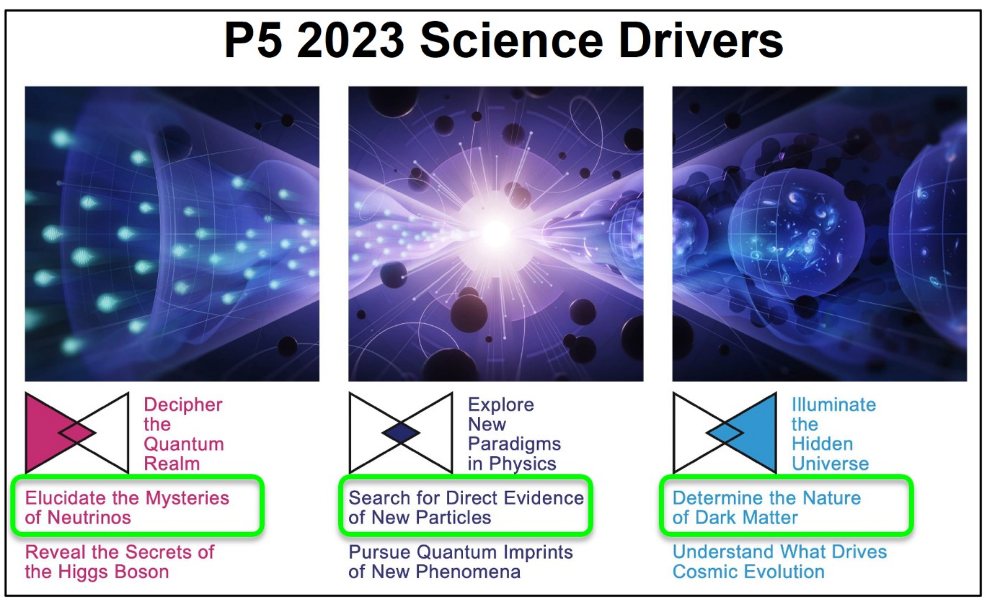
Jyotismita Adhikary,[1] Luis A. Anchordoqui,[2] Akitaka Ariga,[3,4] Tomoko Ariga,[5] Alan J. Barr,[6] Brian Batell,[7] Jianming Bian,[8] Jamie Boyd,[9] Matthew Citron,[10] Albert De Roeck,[9] Milind V. Diwan,[11] Jonathan L. Feng,[8] Christopher S. Hill,[12] Yu Seon Jeong,[13] Felix Kling,[14] Steven Linden,[11] Toni Mäkelä,[8] Kostas Mavrokoridis,[15] Josh McFayden,[16] Hidetoshi Otono,[5] Juan Rojo,[17,18] Dennis Soldin,[19] Anna Stasto,[20] Sebastian Trojanowski,[1] Matteo Vicenzi,[11] and Wenjie Wu[8]

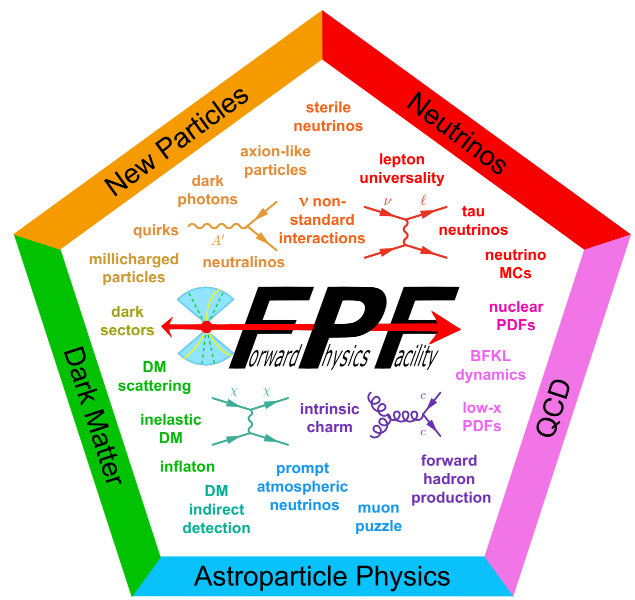
on behalf of the FPF Working Groups

The recent direct detection of neutrinos at the LHC has opened a new window on high-energy particle physics and highlighted the potential of forward physics for groundbreaking discoveries. In the last year, the physics case for forward physics has continued to grow, and there has been extensive work on defining the Forward Physics Facility and its experiments to realize this physics potential in a timely and cost-effective manner. Following a 2-page Executive Summary, we present the status of the FPF, beginning with the FPF's unique potential to shed light on dark matter, new particles, neutrino physics, QCD, and astroparticle physics. We summarize the current designs for the Facility and its experiments, FASER2, FASERν2, FORMOSA, and FLArE, and conclude by discussing international partnerships and organization, and the FPF's schedule, budget, and technical coordination.

PHYSICS AT THE FPF

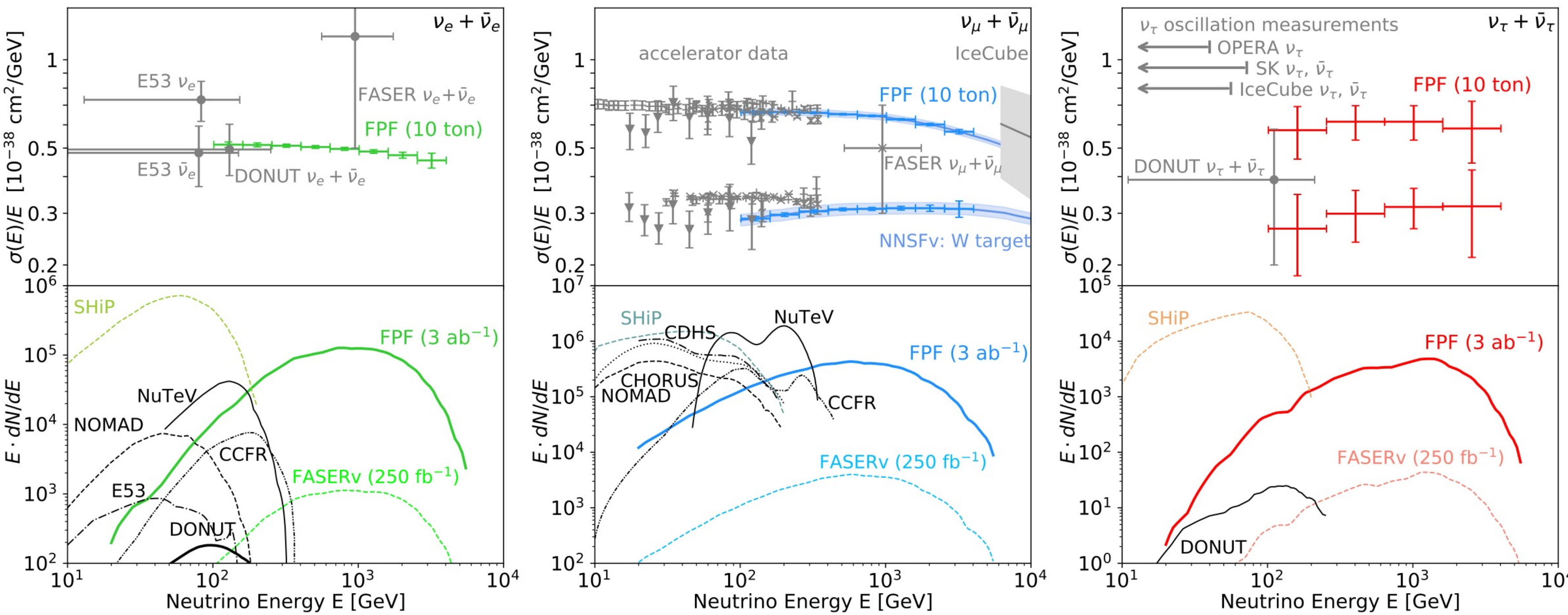
- The FPF will allow the LHC to fulfill its physics potential and encompasses many of the major science drivers of our field.
  - Neutrinos: neutrino blind → neutrino factory: 10^6 neutrinos (1000 per day!) at the highest human-made energies ever.
  - New particles: up to 10,000 more sensitive than current experiments, searches for particles that cannot be found anywhere else, enhances the core physics programs of CMS, ATLAS, IceCube, Auger, other experiments.





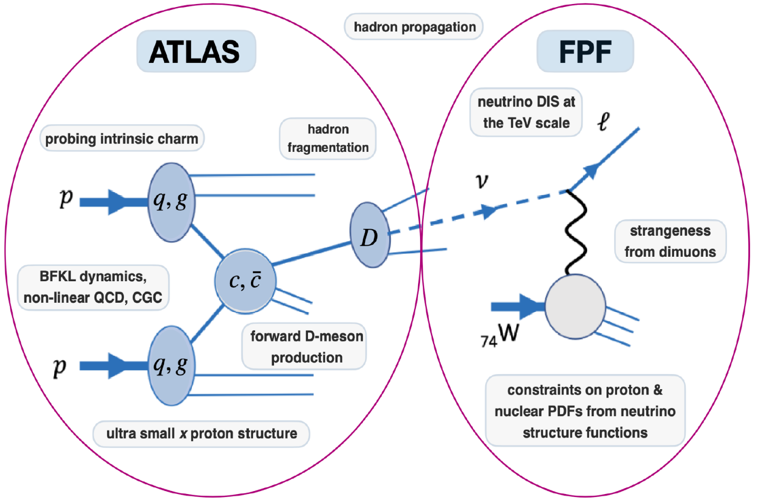
NEUTRINOS

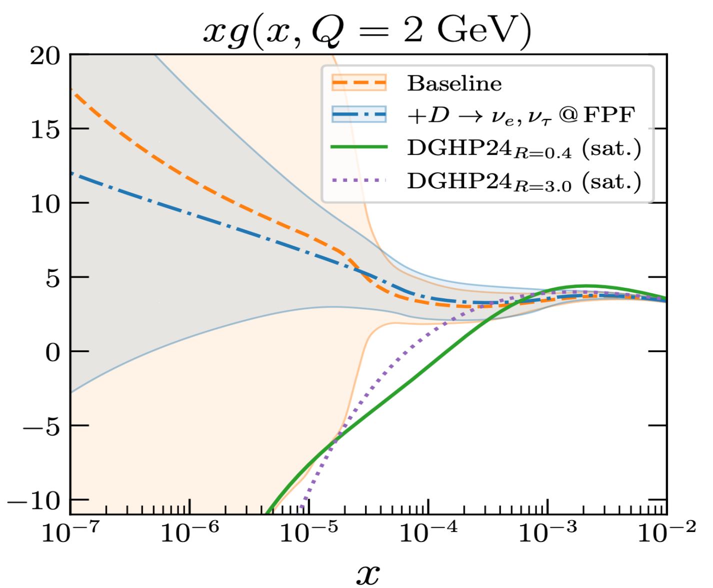
- FPF experiments will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^4\ \nu_\tau$ interactions at TeV energies, where there is currently little data. Brings even the tau neutrino into the realm of precision studies.

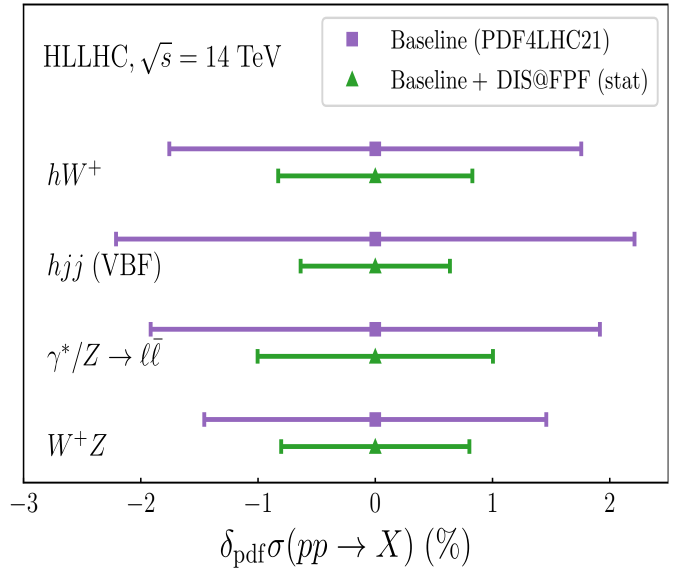


QCD

- The FPF will enable a rich program of QCD and hadron structure studies.
- Forward neutrino production is a probe of forward hadron production, constrains pdfs at ultra small x ~ 10^{-7} to 10^{-6}.
- Sharpens SM predictions at ATLAS and CMS, removes degeneracies between pdfs and new physics ("fitting away new physics").

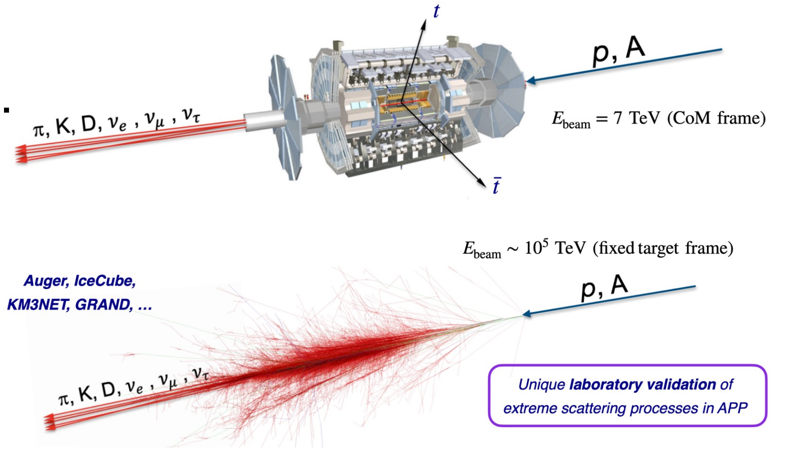


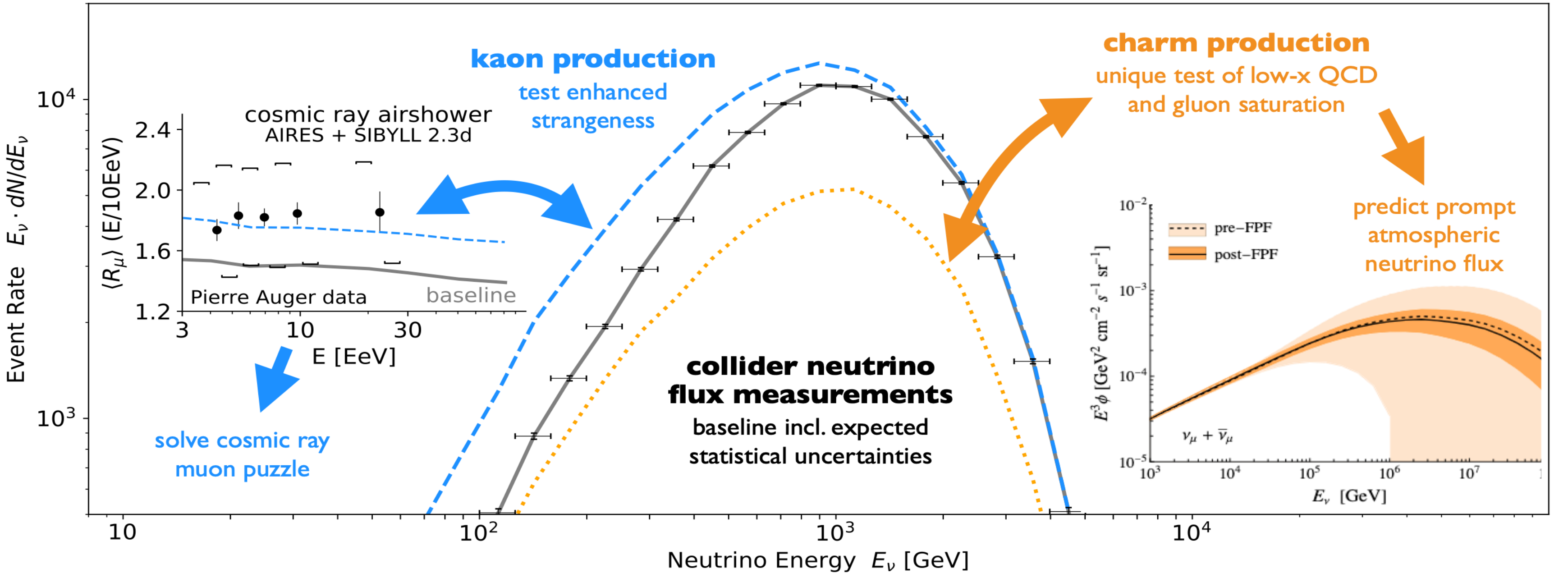




ASTROPARTICLE PHYSICS

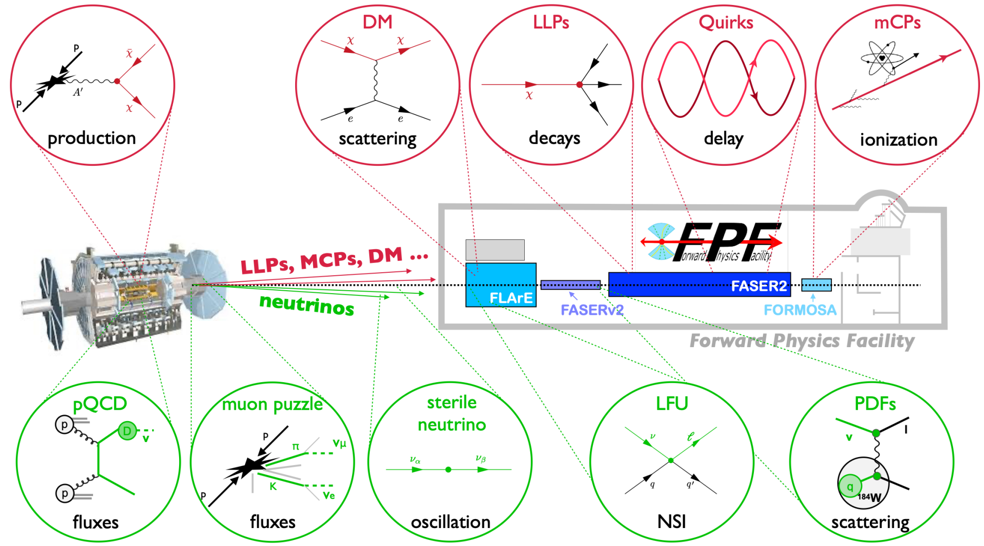
- FPF experiments are essentially controlled high-energy cosmic ray experiments in the lab.
- Will shed light on topics of critical interest to astroparticle experiments, including the cosmic-ray muon puzzle at Auger and Telescope Array, and the prompt atmospheric neutrino background at IceCube.

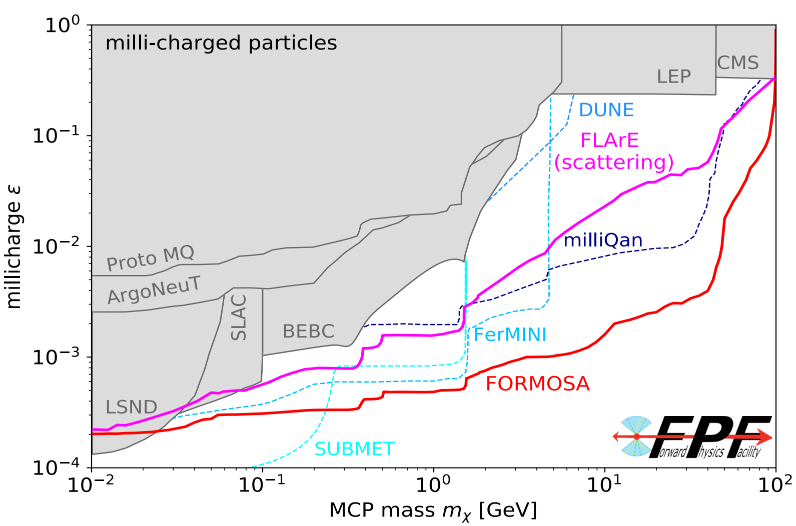


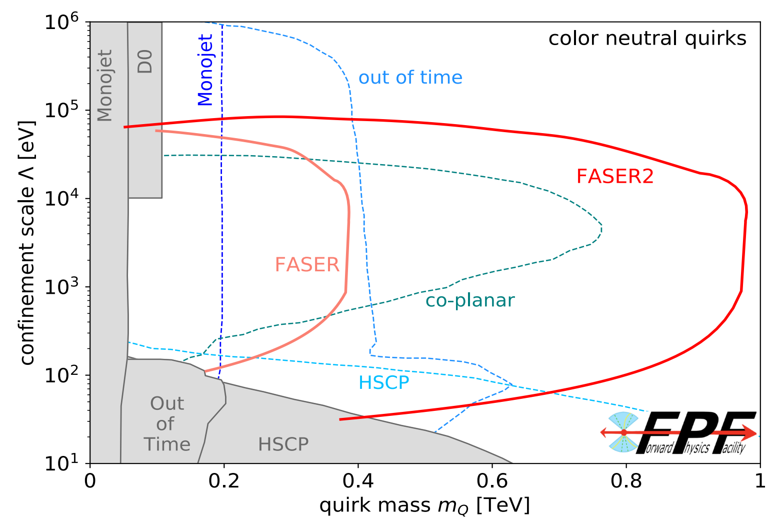


NEW PARTICLES

- FPF experiments have the potential to discover BSM physics with unparalleled sensitivity.
- Many examples: all dark sector portal particles (LLPs), axion-like particles, new gauge bosons, millicharged particles, quirks, …

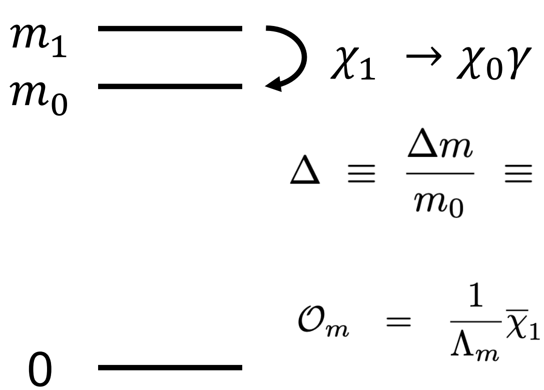






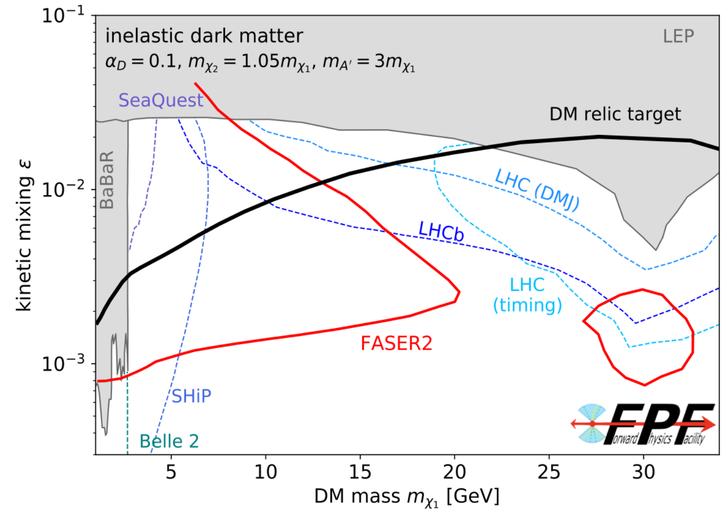
DARK MATTER

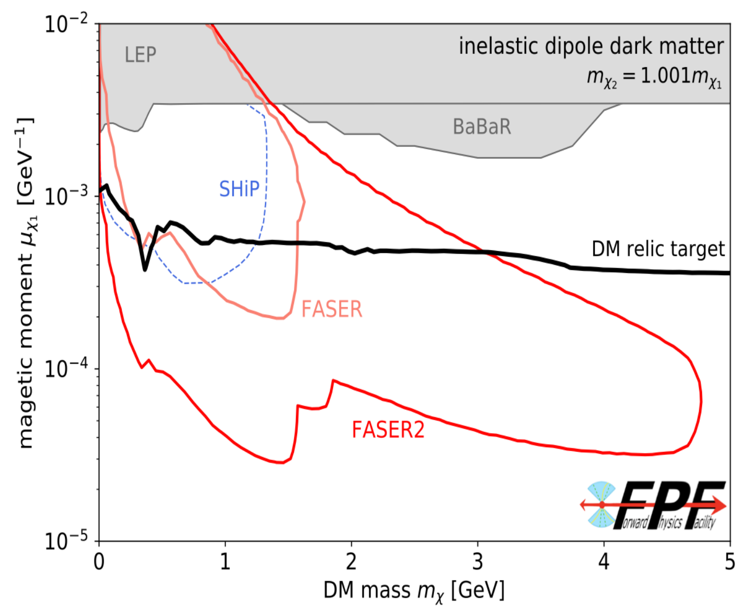
- Light (~0.1 – 10 GeV) dark sector states can scatter or decay in FPF detectors.
- For example: inelastic dark matter, where there are two nearly-degenerate dark states with off-diagonal couplings to the SM.
- Difficult or impossible to probe with direct, indirect detection, fixed target or other LHC experiments.
- FPF can discover ~10 GeV DM or very soft decay products, which can be seen only if highly boosted.



$$\Delta \equiv \frac{\Delta m}{m_0} \equiv \frac{m_1 - m_0}{m_0}$$

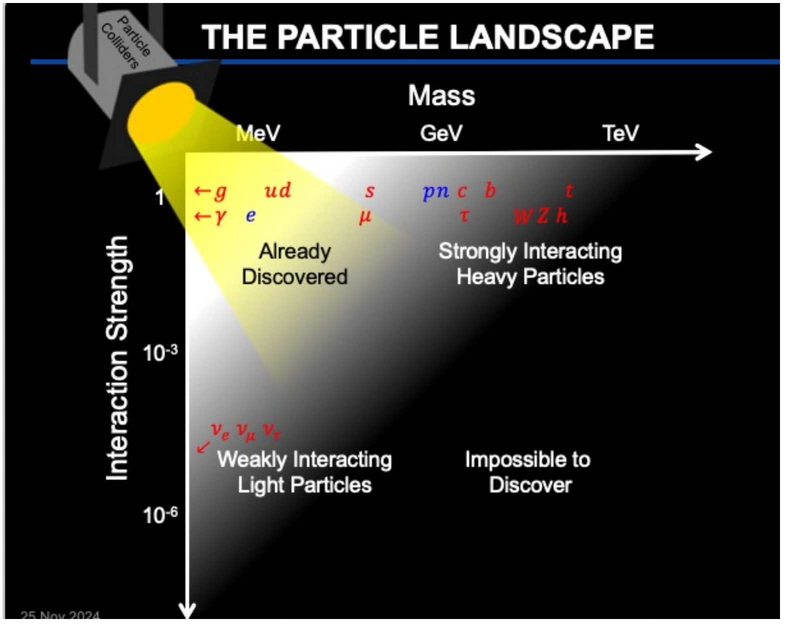
$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$

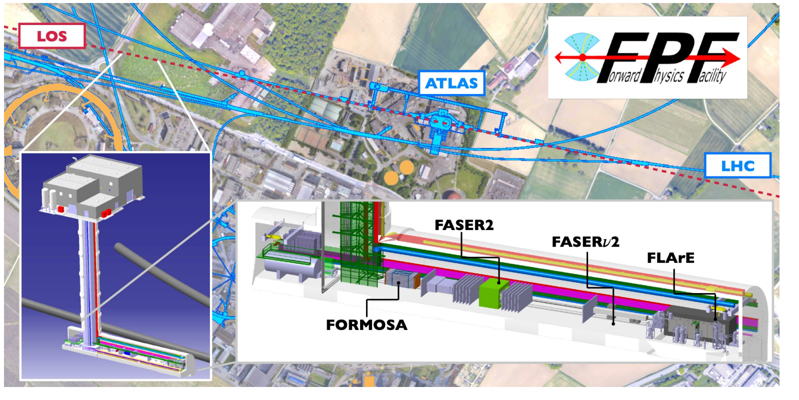




SUMMARY

- LHC detectors are currently optimized for strongly-interacting heavy particles. The FPF is required to cover weakly-interacting light particles.
- The detection of collider neutrinos has opened up an entirely new space for discovery: the dawn of multi-messenger collider physics!
- Pathfinder experiments have shown that this space can be explored by fast, small, inexpensive detectors.
- Forward detectors, like calorimeters and trackers, are required so we can detect all the particles produced at the energy frontier.





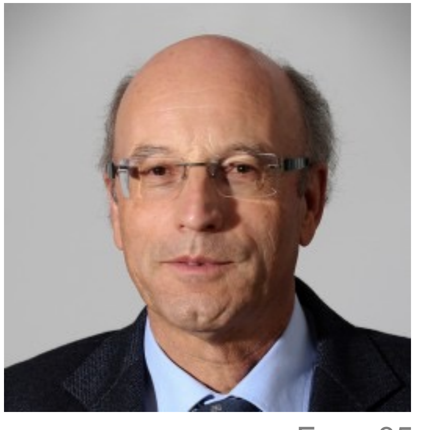
BACKUP

A LESSON FROM CHARM

- Is it really possible that a collider is making new particles, and we are missing them simply because we are looking in the wrong place?
- Yes. In fact, it happened before at CERN.
- In 1971, the first hadron collider, CERN's Intersecting Storage Rings (ISR), began operation.
- It had a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.

A LESSON FROM CHARM

- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.
  - "There was initially a broad belief that physics action would be in the forward directions at a hadron collider…. It is easy to say after the fact, still with regrets, that with an earlier availability of more complete… experiments at the ISR, CERN would not have been left as a spectator during the famous November revolution of 1974 with the J/ψ discoveries at Brookhaven and SLAC ." – Lyn Evans and Peter Jenni, "Discovery Machines," CERN Courier (2021).
- Bottom line: The collider was creating charm quarks, but, based on theoretical prejudice, experimentalists focused on the forward region and so missed them.
- Since that time, forward physics at colliders has been almost completely ignored for new particle searches.
- But are we making the same mistake now (in reverse)? And could there be another November revolution waiting for us in the forward direction?



FPF BUDGETS

From FPF Source Document for ESPPU, 2411.04175.

Component	Approximate Cost	Comments
Facility Costs		
FPF civil construction	35.3 MCHF	Construction of shaft and cavern
FPF outfitting costs	10.0 MCHF	Electrical, safety, and integration
Cryogenic infrastructure	3.8 MCHF	Cryogen storage and cooling systems
Total	**49.1 MCHF**	Includes integration for infrastructure
Experiment Costs		Core costs only
FASER2	11.6 MCHF	3+3 tracker layers, SAMURAI-style magnet, dual-readout calorimeter
FASERν2	15.9 MCHF	Tungsten target, scanning system, emulsion films (10 replacements), interface detector
FLArE	10.8 MCHF	Cryostat, proximity cryogenics, detectors
FORMOSA	2.3 MCHF	Plastic scintillator, PMTs, readout
Total	**40.6 MCHF**	Core cost experimental program

TABLE I. Cost for components of the FPF and the experimental program. Costs of the infrastructure at CERN are Class 4 estimates according to international standards; they have a range from −30% to +50%. The costs for experimental components are estimated as core costs, which consist of direct costs of materials and contracts only. Each core cost was computed with conservative technical choices; as new ideas and designs are considered, the costs are expected to change.

Civil Engineering Cost Estimate FPF // September 2024

Ref.	Work Package	Cost [CHF]	Percentage of the CE Works
1.	Underground Works	12,392,344.00	35%
1.1	Preliminary activities	1,845,000.00	5.2%
1.2	Access shaft	4,424,143.00	12.5%
1.3	Experimental Cavern	6,123,201.00	17.3%
2.	Surface Works	6,727,231.00	19%
2.1	General items	720,776.00	2.0%
2.2	Topsoil and earthworks	702,227.00	2.0%
2.3	Roads and network	796,122.00	2.3%
2.4	Buildings	4,508,106.00	12.8%
2.4.1	Access building	2,224,786.00	6.3%
2.4.2	Cooling and ventilation building	1,497,350.00	4.2%
2.4.3	Electrical Building	563,689.00	1.6%
2.4.5	External platforms	222,281.00	0.6%
3.	General items	11,815,899.00	33.4%
4.	Miscellaneous	4,397,504.00	12.4%
	TOTAL CE WORKS	35,332,978.00	100.0%

Assumptions

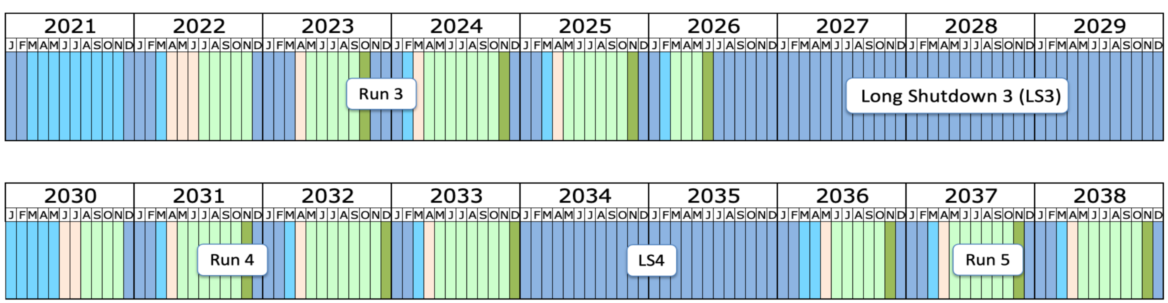
1. Services not included
2. Technical galleries not included
3. Cranes not included
4. Access building as a conventional steel portal frame structure with cladding, only one floor
5. CV Building as a reinforced concrete building, only one floor
6. Finished floor level at 450m ASL
7. Sectional doors not included
8. Unit costs are based on a combination of Hi-Lumi (2018), Faser (2018), SPS Tunnel eye enlargement
9. Inflation figures have been taken dating from 2017-T4, with 2021 as the benchmark year

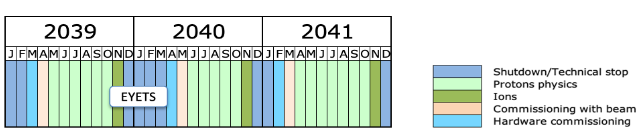
FPF BUDGET PROFILE

From FPF Source Document for ESPPU, 2411.04175.

Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
(HL-)LHC Nominal Schedule	Run 3	Run 3	Run 3 / LS 3	LS 3	LS 3	LS 3	LS 3 / Run 4	Run 4	Run 4	Run 4
FPF Milestones	Pre-CDR and physics proposal	R&D and prototype detectors	CDR, long lead items, magnet	Start of civil construction, TDR for detectors	Detector construction start	Major equipment acq.	End of civil construction, Install services	Detector install	Detector commissioning, physics start	Physics running all detectors
Experiment Core Costs (kCHF)		154	1275	3473	7257	11220	9503	6978	741	

TABLE II. Proposed funding profile for the FPF experimental program using the core cost numbers from Table I. The infrastructure cost profile is being developed. The approval and cost rules will be different for the different sponsors who are proposed to contribute to this overall profile. Nevertheless, for the purpose of this illustration, the profile is shown in as-spent funds in a single currency.





Updated schedule (Sept 2024)

FASER COLLABORATION

112 collaborators, 28 institutions, 11 countries

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
CHIBA UNIVERSITY
UNIVERSITY OF OREGON

DESY.
INFN
ISS
International laboratory covered by a cooperation agreement with CERN
清華大學 Tsinghua University
ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
UNIVERSITY OF LIVERPOOL
ZHENGZHOU UNIVERSITY
NATIONAL INSTITUTE OF TECHNOLOGY (KOSEN), NIIHAMA COLLEGE
UNIVERSITY OF SUSSEX

Nikhef
UNIVERSITÄT BONN
ETH zürich
UKRI Science and Technology Facilities Council Rutherford Appleton Laboratory
MANCHESTER 1824 The University of Manchester

PREPARATION OF THE FASER LOCATION

- The nominal beam collision axis was located to mm accuracy by the CERN survey department. (In fact, it moves around by several cm, depending on the beam crossing angle and orientation.) To place FASER on this axis, a trench was required to lower the floor by 46 cm.

- The trench was completed by an Italian firm just hours before COVID shut down CERN in March 2020.


2019


Spring 2020

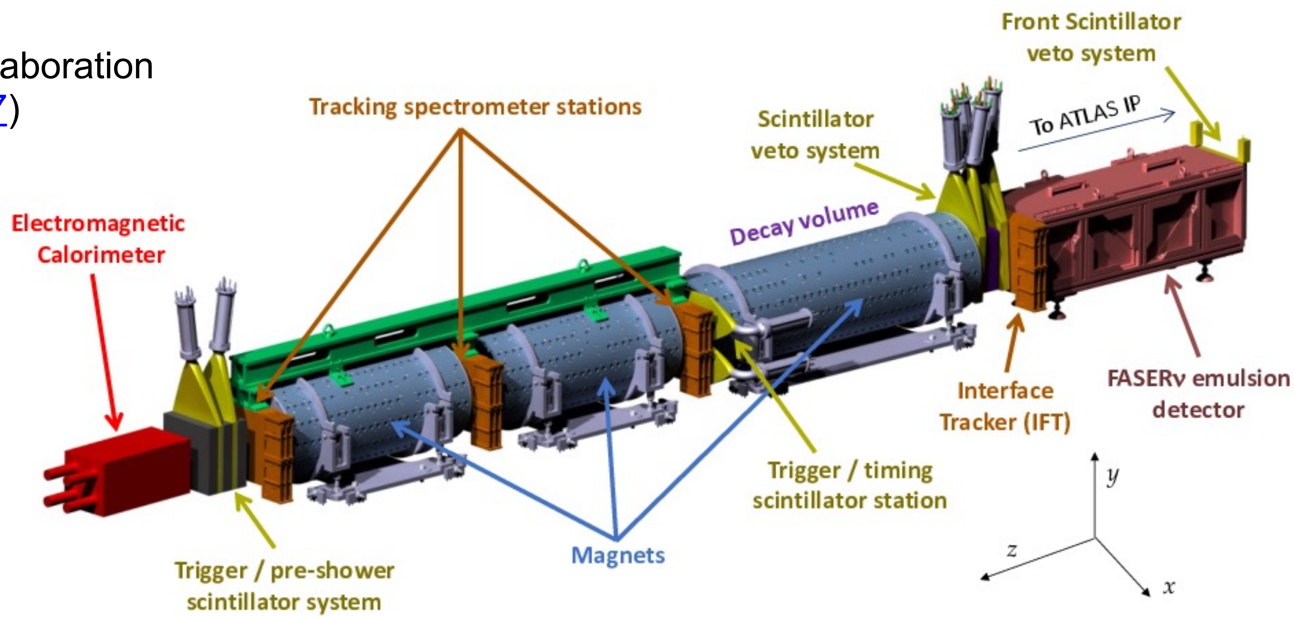

Summer 2020

THE FASER DETECTOR

- Design challenges: small (no room), low maintenance (no access), fast (no time).
  - Size: Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.
  - Magnets: 3 permanent dipoles (Halbach design), 0.57 T, deflect charged particles in y.
  - Tracker: composed of 4 stations x 3 layers x 8 mod. = 96 ATLAS SCT modules.
  - Calorimeter: composed of 2 x 2 LHCb ECAL modules.
  - Scintillators: 4 stations, each 1-2 cm thick, >99.999% efficient. 4-layer veto ~ $(10^{-5})^4 \sim 10^{-20}$.
  - FASERν: 770 interleaved sheets of tungsten + emulsion. 1 m long, 1.1 ton total mass. Micron-level spatial resolution, but no timing. Becomes over-exposed from muons, must be replaced after ~30 fb^{-1}.

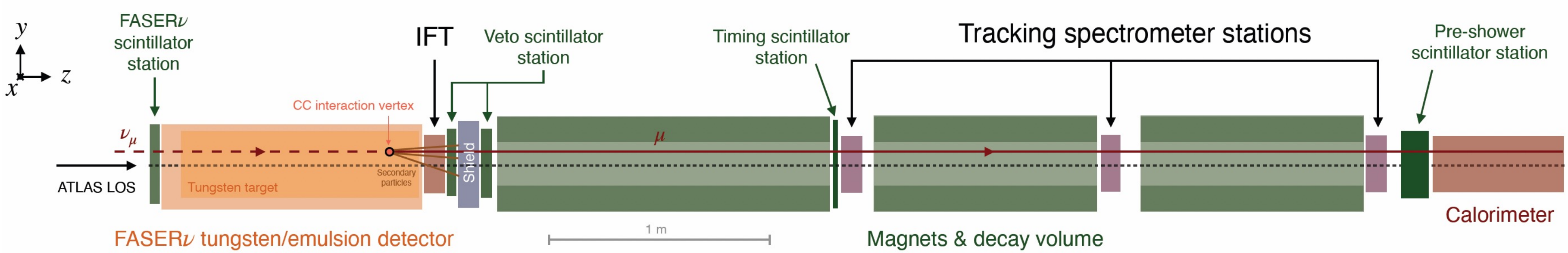
- The experimental environment: 88 m underground, shielded from ATLAS by 100 m of rock → extremely quiet. Trigger on everything, ~kHz trigger rate dominated by muons from ATLAS.

FASER Collaboration
(2207.11427)



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)

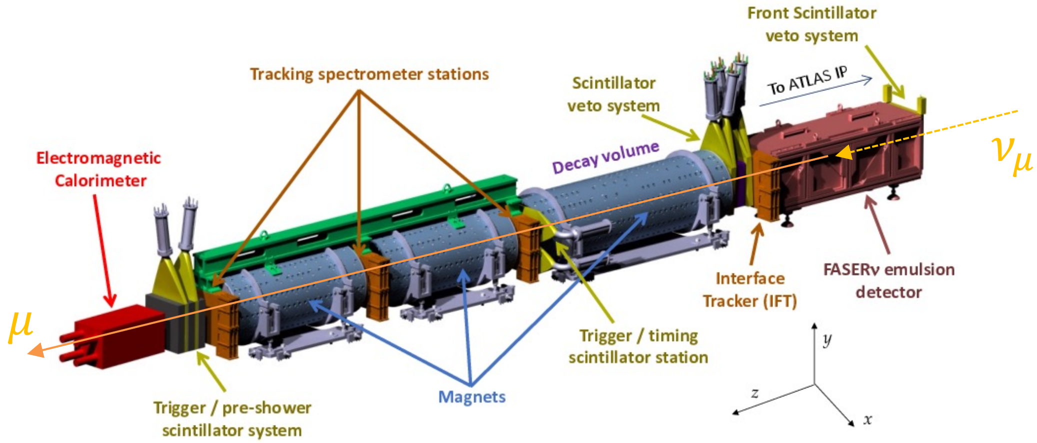
- The signal is no charged particle passing through the upstream veto scintillators, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

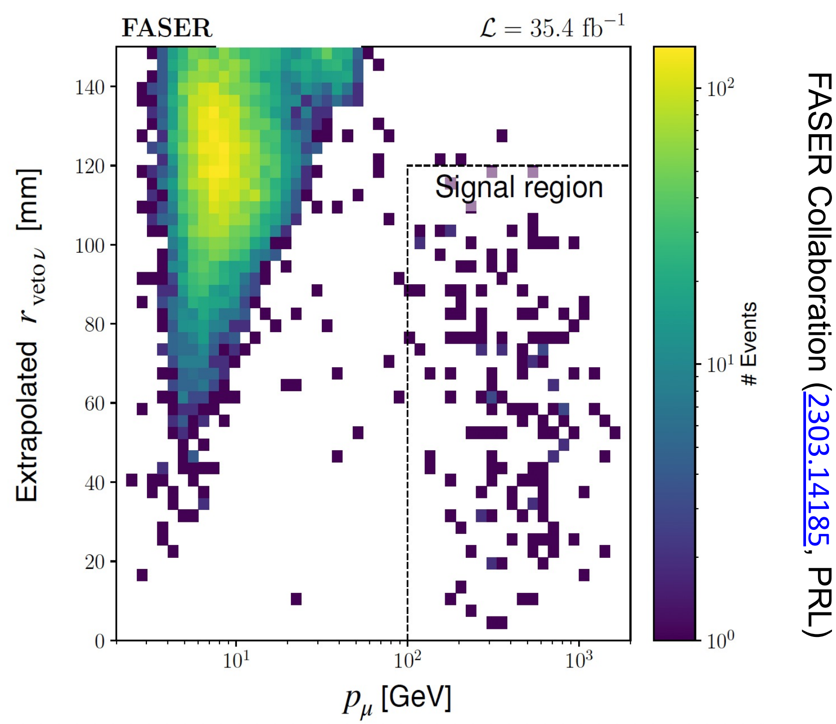
- Backgrounds are extremely suppressed by the fact that we are shielded from ATLAS by 100 m of rock and concrete, $\lesssim 1$ background event.

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

1ST DETECTION OF COLLIDER NEUTRINOS

- After unblinding, we found 153 ν_μ CC 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
  - Confirmed by 8 neutrinos detected by SND@LHC
- The dawn of neutrino collider physics: the beginning of multi-messenger collider physics.

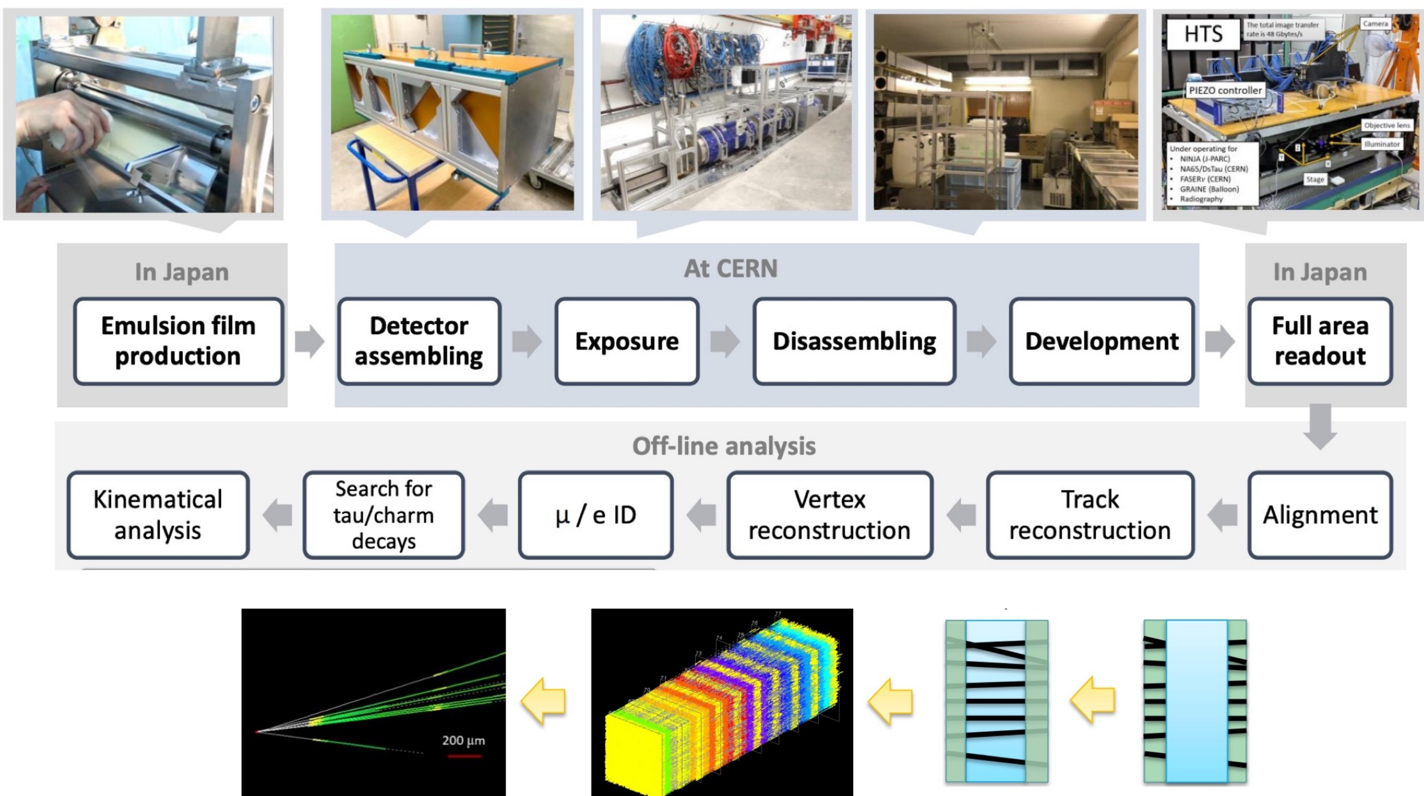




DISCOVERY OF COLLIDER NEUTRINOS

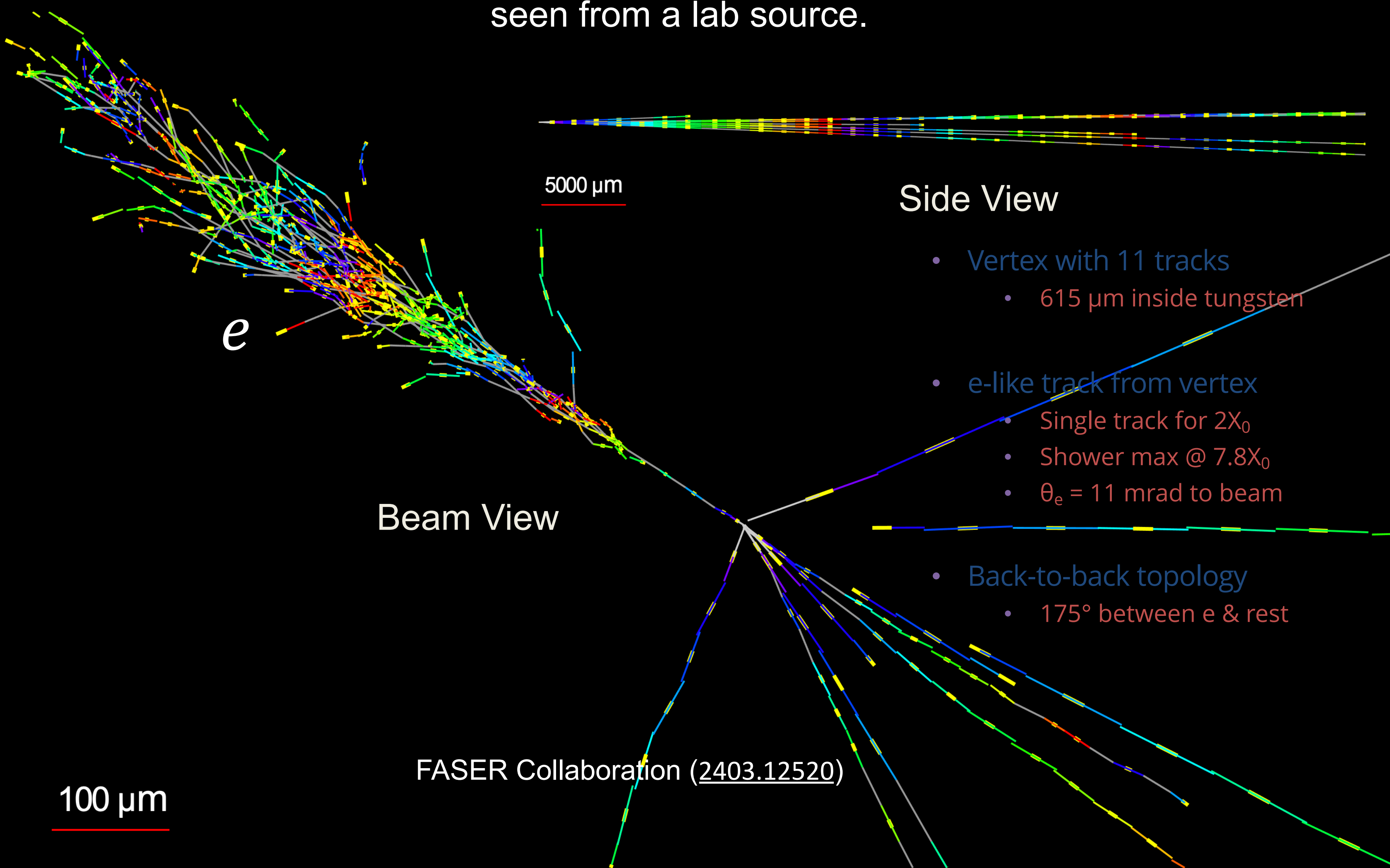
NEUTRINOS IN FASERν

- At the front of FASER is FASERν, a 1.1-ton block of interleaved tungsten and emulsion plates. The first neutrino analysis treated this as a big block of matter, but the emulsion provides far more detailed information.
- Emulsion is essentially old-fashioned photographic film, has unmatched spatial resolution (~0.5 microns).



NEUTRINOS IN FASERν EMULSION

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 ever seen from a lab source.



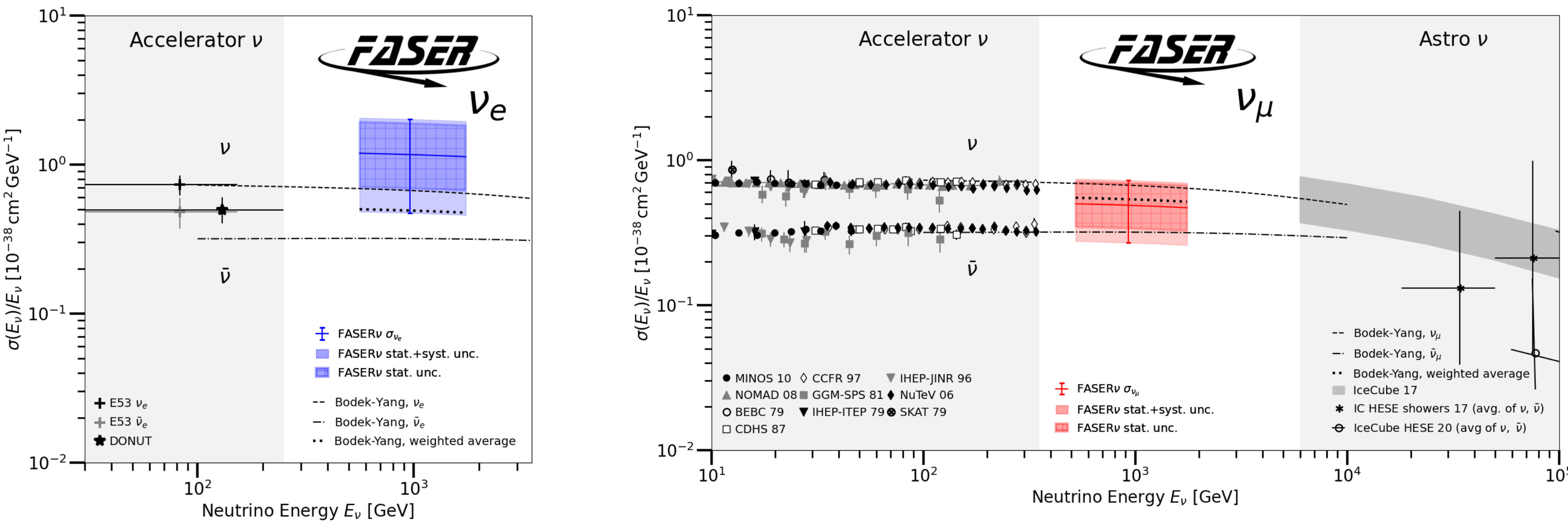
- Vertex with 11 tracks
  - 615 µm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

FASER Collaboration (2403.12520)

TEV NEUTRINO CROSS SECTIONS

- Following these discoveries, we have now moved on to studies, including the first measurement of neutrino cross sections at TeV energies.

- Results are consistent with SM DIS predictions.



FASER Collaboration (2403.12520, PRL)

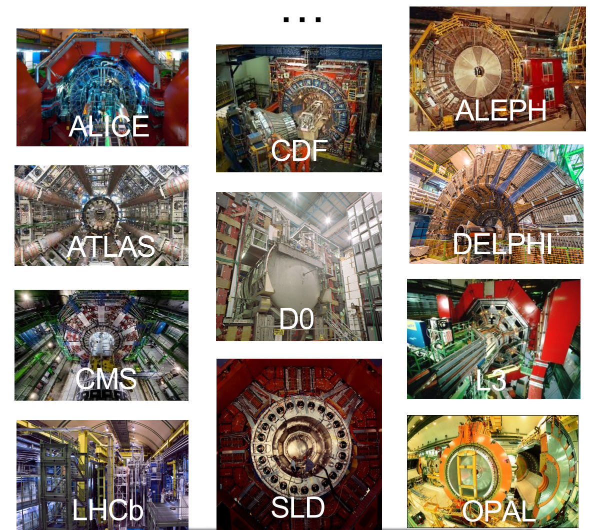
- These measurements use only 1% of the data collected in 2022-24. Much more to come; we expect triple the world's supply of tau neutrinos, possibly identify the first anti-tau neutrino, …

LOCATION, LOCATION, LOCATION

FASER

“Tabletop,” 18 months, ~$1M

153 neutrinos



All previous collider detectors

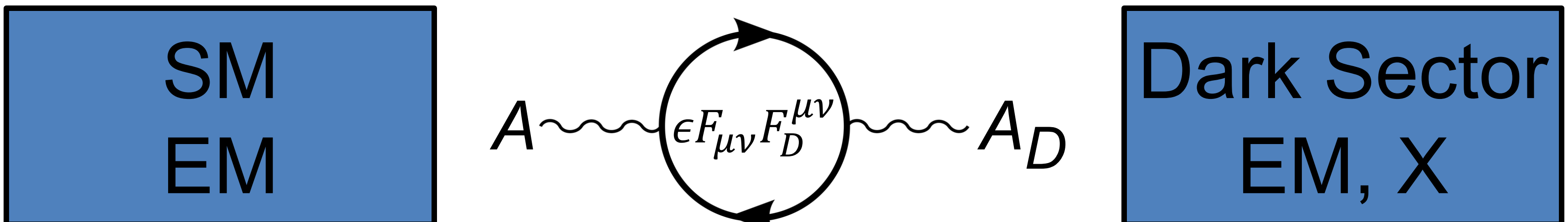
Building-size, decades, ~$1B

0 neutrinos

16σ discovery, opening a new window at the high energy frontier

NEW PARTICLE SEARCHES

- FASER can also look for new light and weakly-interacting particles.
- For example: suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.



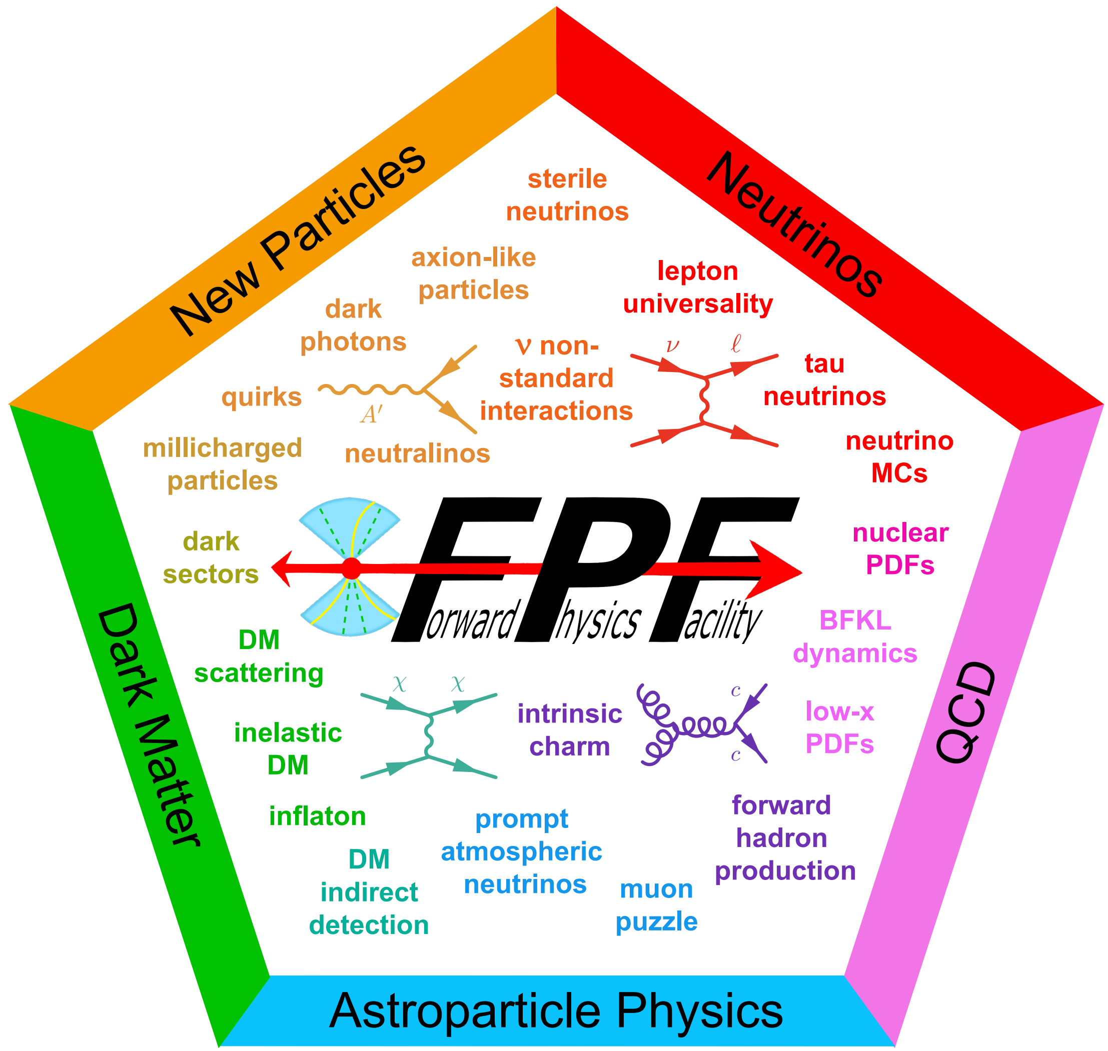
- The result? Dark photons A' , like photons, but with mass $m_{A'}$, couplings suppressed by ϵ.

Holdom (1986)

- For low ϵ, dark photons are long-lived particles (LLPs), can be produced in ATLAS, pass through rock and magnetic fields unhindered, and then decay through $A' \to e^+e^-$ in FASER.

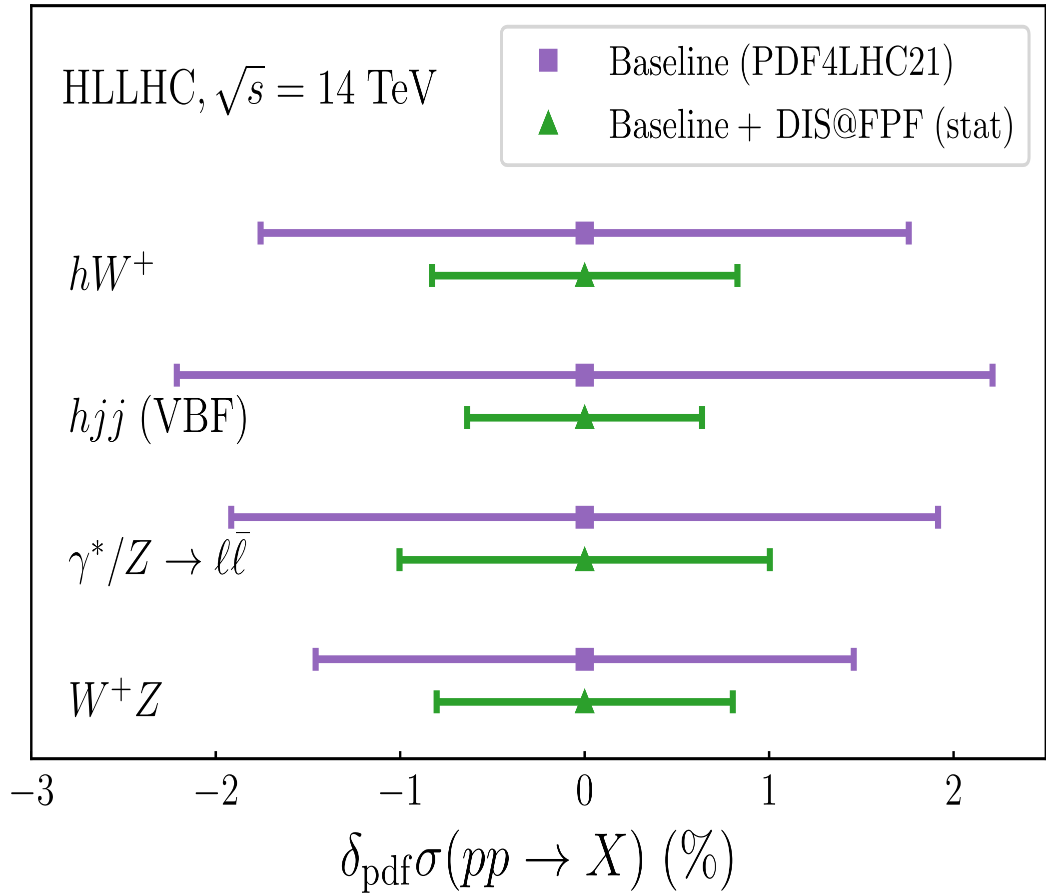
PHYSICS AT THE FPF

- The FPF at the HL-LHC will have many unique capabilities:
  - Neutrinos: neutrino blind → neutrino factory: 10^6 neutrinos (1000 per day!) at the highest human-made energies ever.
  - New particles: up to 10,000 more powerful than current experiments, searches for particles that cannot be found anywhere else, and enhances the core physics programs at CMS, ATLAS, IceCube, Auger, …



ENHANCEMENT OF HIGH P_T SEARCHES

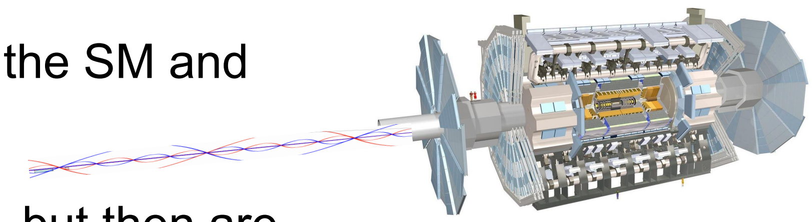
- The FPF will provide new constraints on pdfs that will sharpen studies at ATLAS and CMS.
- For example, W, Z, and Higgs boson studies.
- Will also remove degeneracies between pdfs and new physics ("fitting away new physics"), extending the reach for new particle searches (e.g., ~10 TeV W', Z').



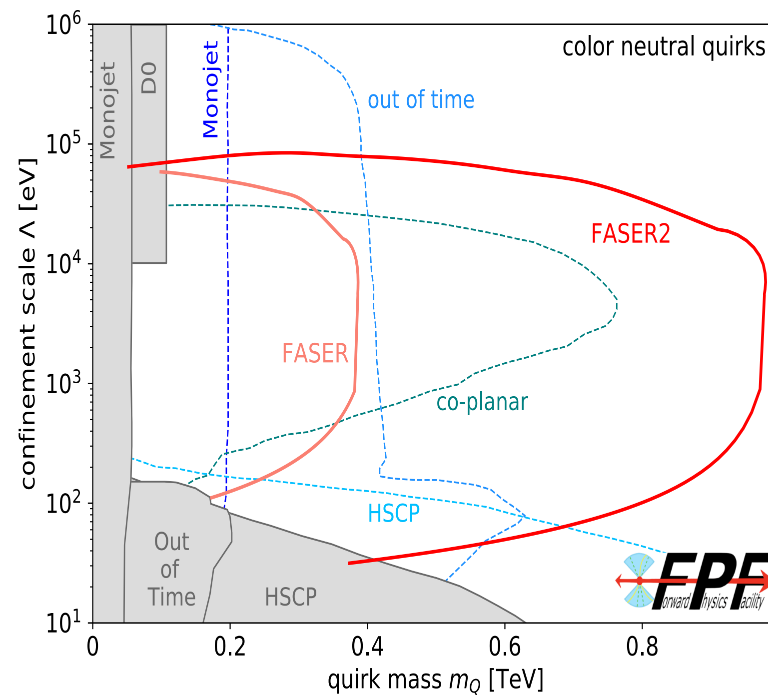
Cruz-Martinez, Fieg, Giani, Krack, Makela, Rabemananjara, Rojo (2023)

QUIRKS

- There may be another strong (non-Abelian) force.
- Quirks are particles charged under both the SM and another strong force, with $m \gg \Lambda$.



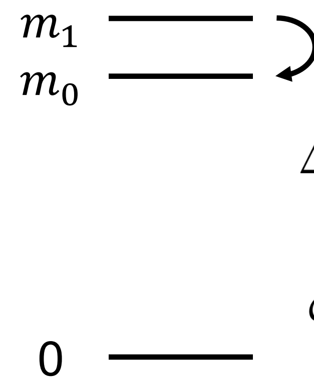
- Quirks can be pair-produced at the LHC, but then are bound by a color string, oscillate about their center-of-mass and travel down the beamline.
- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FPF experiments can discover quirks with masses up to ~TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.
- Unique discovery potential at the FPF: very challenging at ATLAS/CMS, impossible at fixed target experiments.



Feng, Li, Liao, Ni, Pei (2024)

DARK MATTER

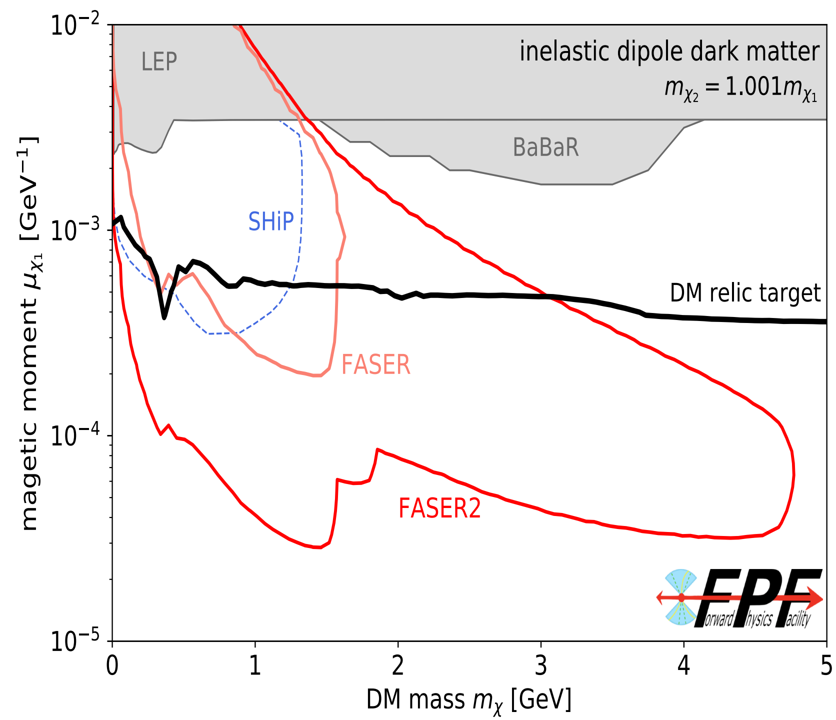
- In the last few decades, there has been an intense effort to detect dark matter through non-gravitational couplings, all yielding null results.
- One generic possibility that is infamously hard to detect: inelastic dark matter, where there are two nearly-degenerate dark states with off-diagonal couplings to the SM.
- These generically lead to long-lived particles, but with soft decay products, but these are highly boosted to observable levels at the FPF.
- Bottom line: the FPF can discover DM (or any compressed spectrum), which cannot be seen anywhere else (ATLAS/CMS, SHiP and other fixed target expts, direct and indirect DM searches, …)



$$\chi_1 \to \chi_0 \gamma$$

$$\Delta \equiv \frac{\Delta m}{m_0} \equiv \frac{m_1 - m_0}{m_0}$$

$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$



Dienes, Fieg, et al. (2023)