THE FALL AND RISE OF FORWARD PHYSICS

MPS Annual Meeting, Simons Foundation

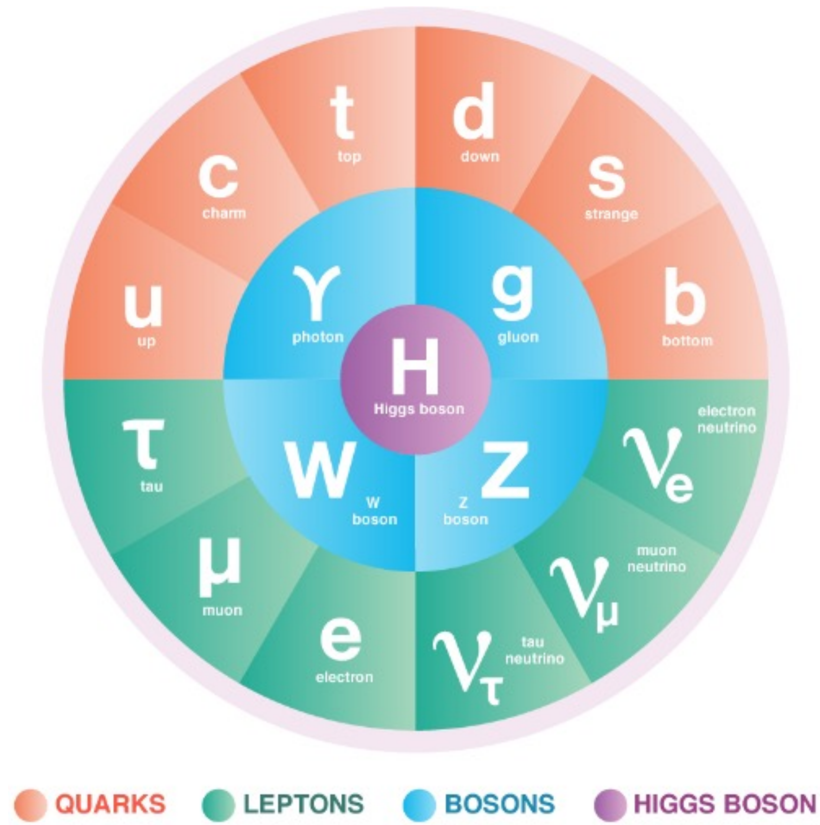
Jonathan Feng, UC Irvine, 17 October 2024

THE STANDARD MODEL OF PARTICLE PHYSICS

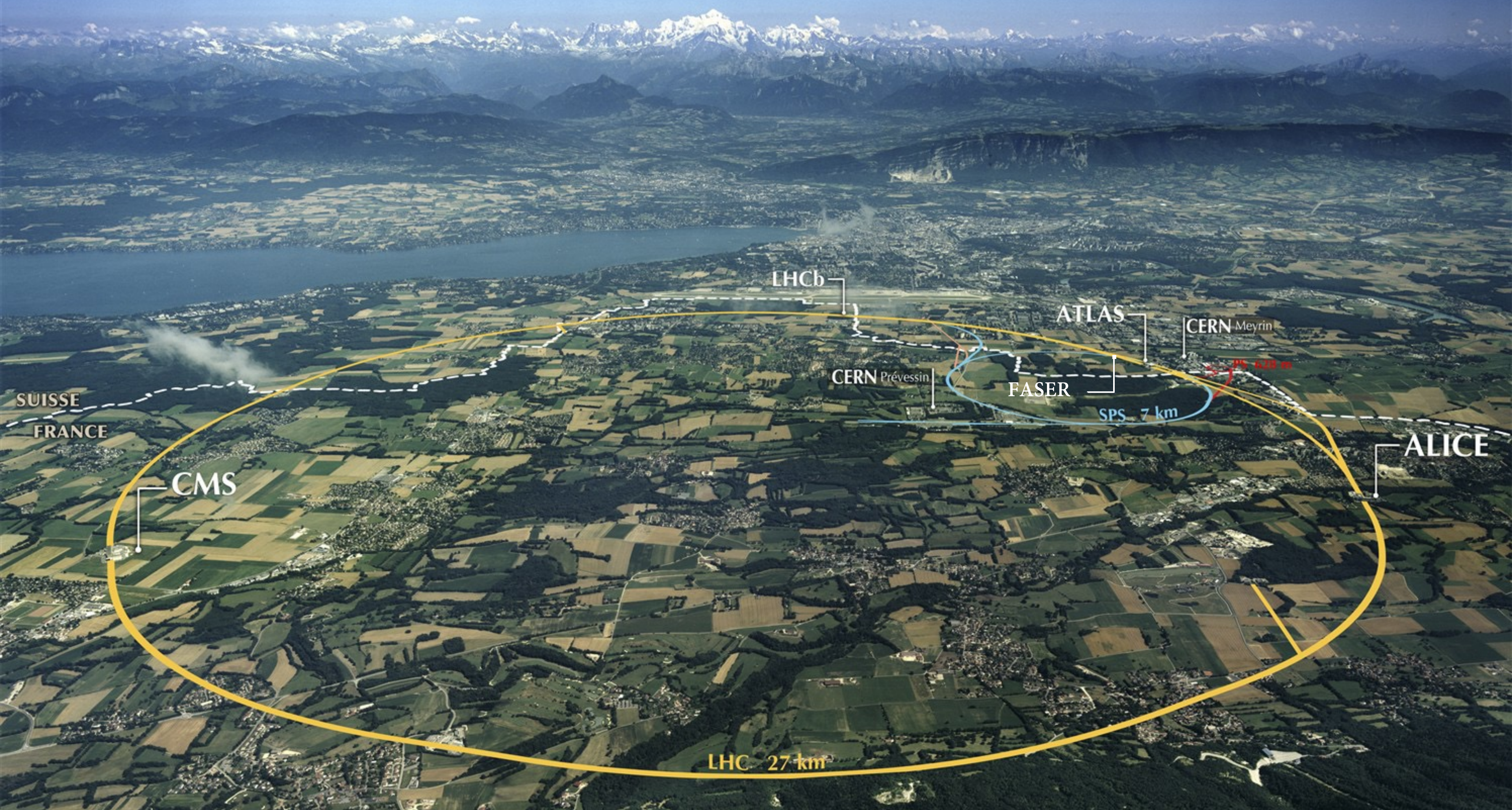
- The Standard Model is the reigning theory of fundamental particles and their interactions. The last particle predicted by the SM, the Higgs boson, was discovered at CERN in 2012.

- But the SM is not the last word, because many fundamental questions remain. For example:
  - Neutrino Masses: the SM predicts that neutrinos are massless, but they aren't.
  - Dark Matter: The particles of the SM make up only ~15% of the matter in the universe.

- These questions imply that there are more particles left to discover, and probably many more.



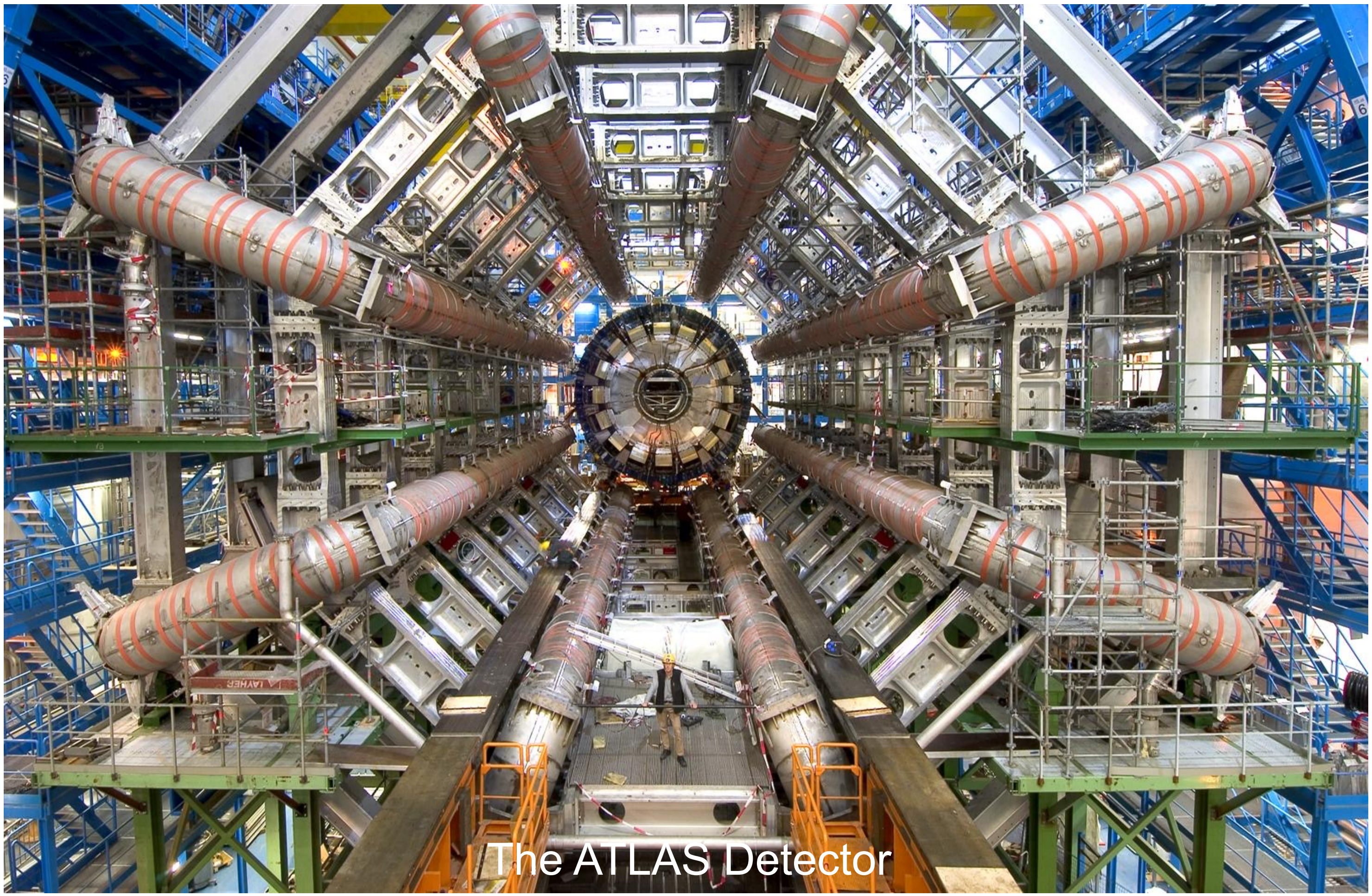
THE LARGE HADRON COLLIDER



Particle colliders have been key to progress for many decades. The state of the art is currently the LHC, which collides protons with protons at a center-of-mass energy of 13.6 TeV ($v \approx 0.9999999905\,c$).

LHC DETECTORS

The protons collide at 4 points, and each point is surrounded by a large detector to view the results of the collisions. These detectors cost billions of dollars and were constructed over decades by thousands of collaborators.

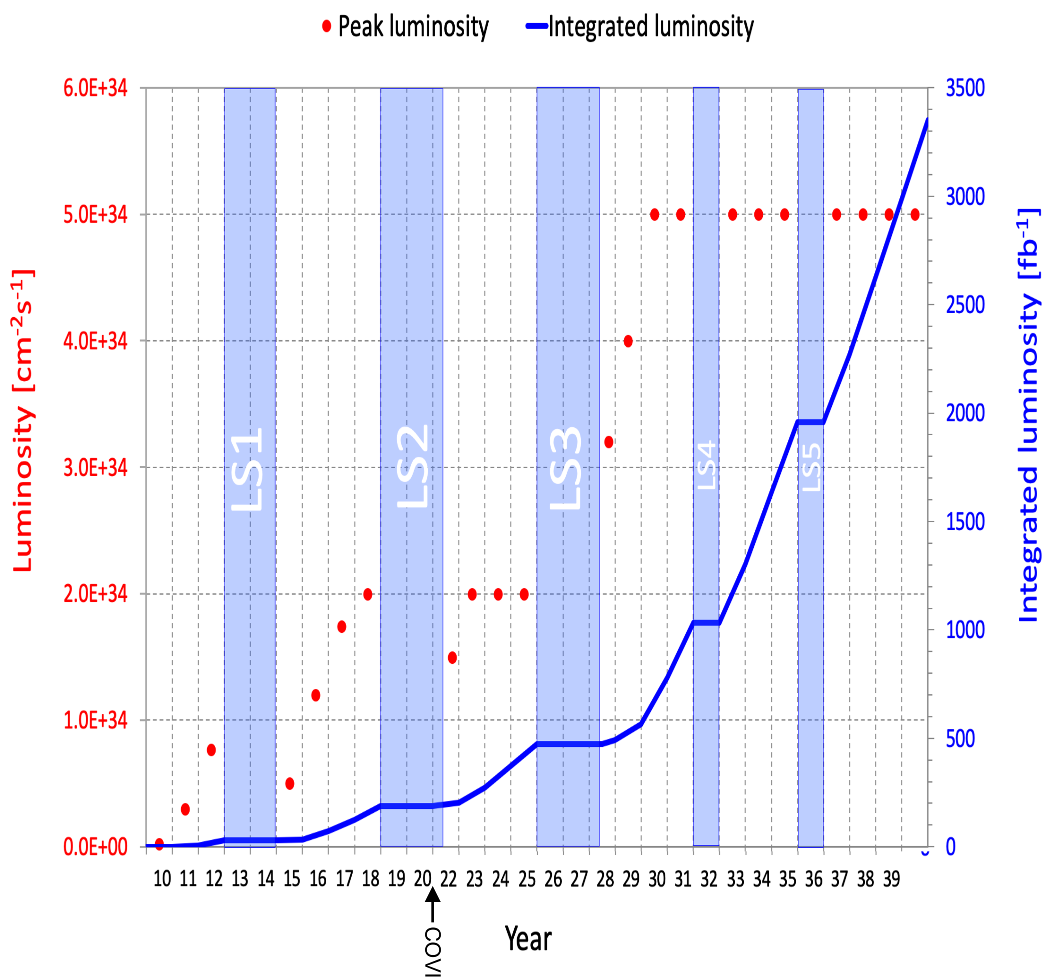


LIFETIME OF THE LHC

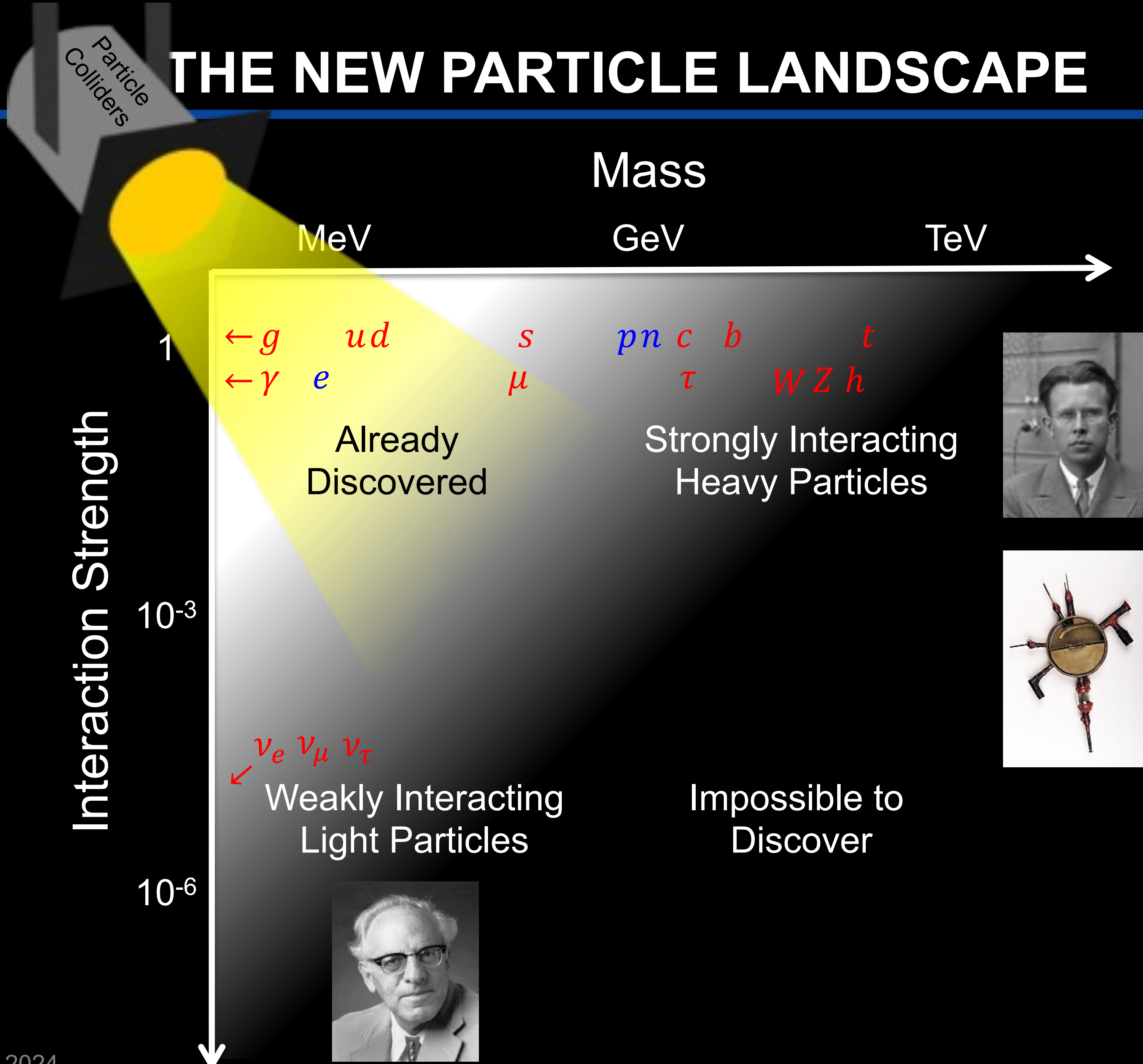
- The LHC became the future of particle colliders in 1993 when the US canceled the SSC, which was being built in Texas.

- 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

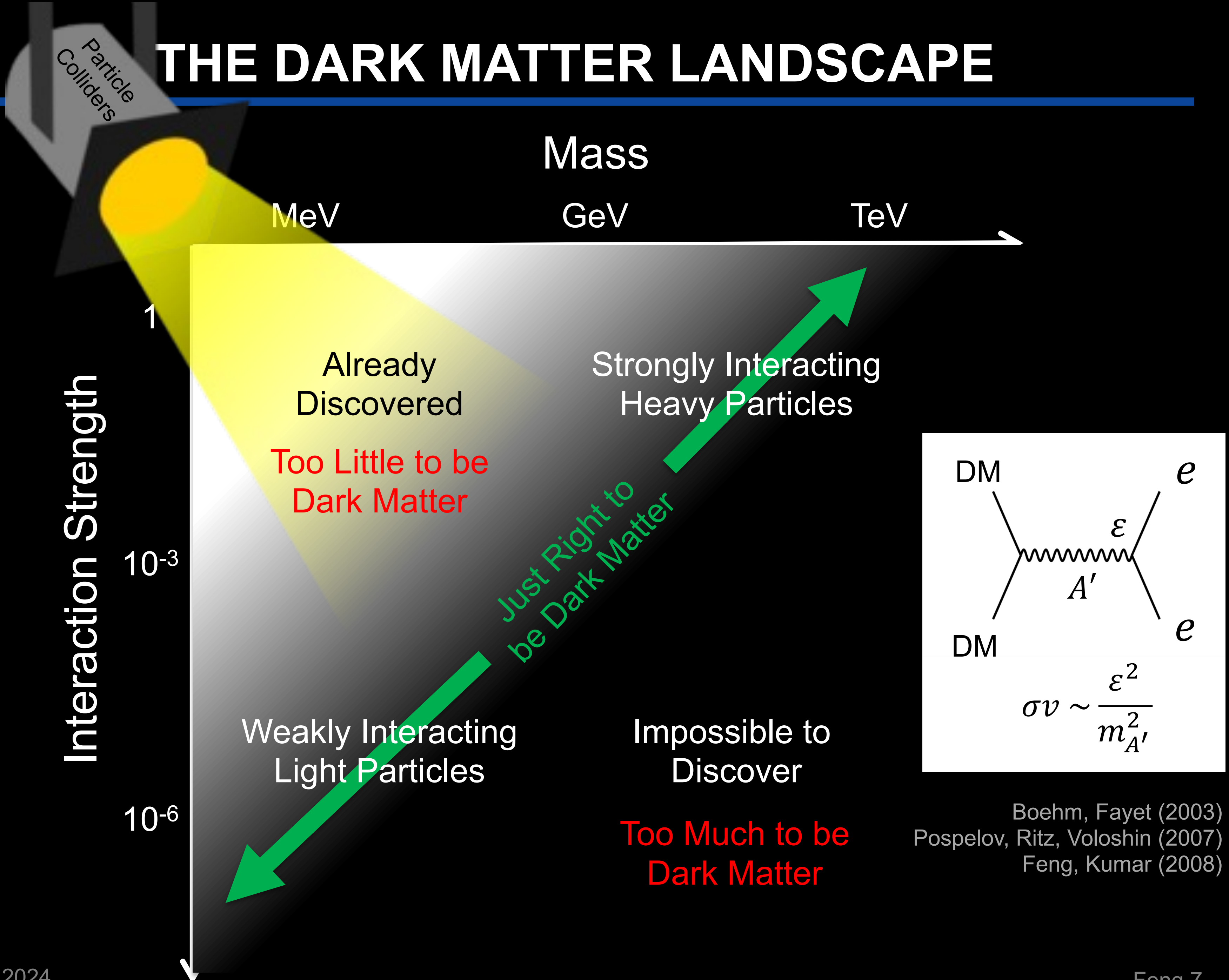
- Are we using the LHC to its full potential? What can we do to enhance its discovery prospects?



THE NEW PARTICLE LANDSCAPE



THE DARK MATTER LANDSCAPE



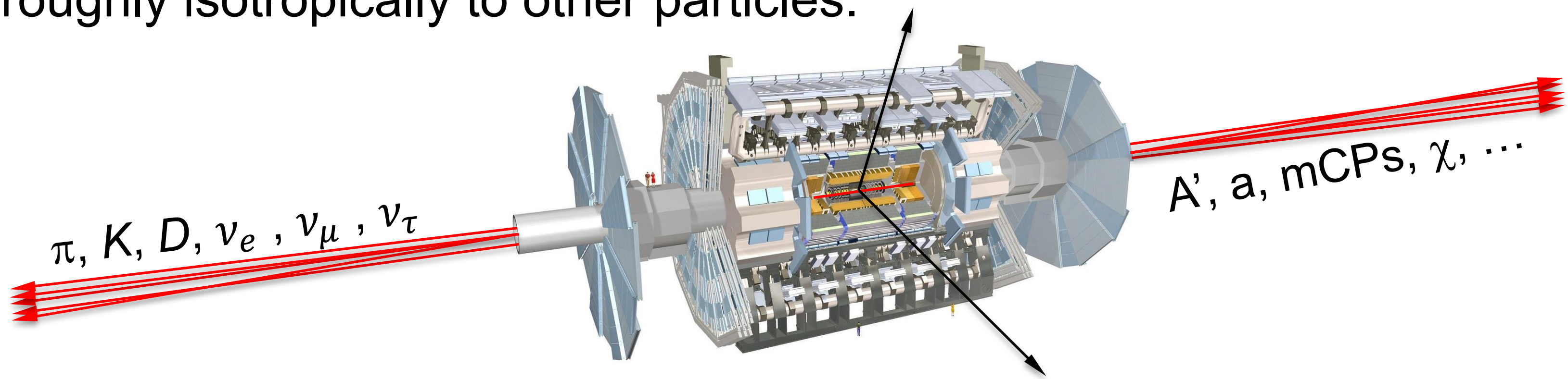
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

- In 2017, we realized that the large LHC detectors, while beautifully optimized to discover new heavy particles, are also almost 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 new particles, especially those motivated by neutrino mass and dark matter.

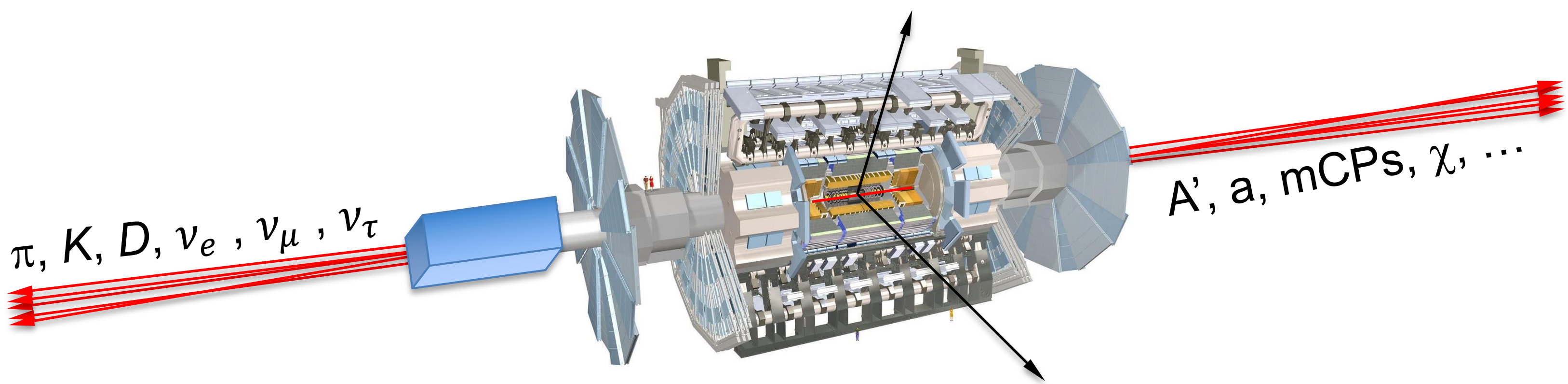
  De Rujula, Ruckl (1984)

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

DETECTING FORWARD PARTICLES

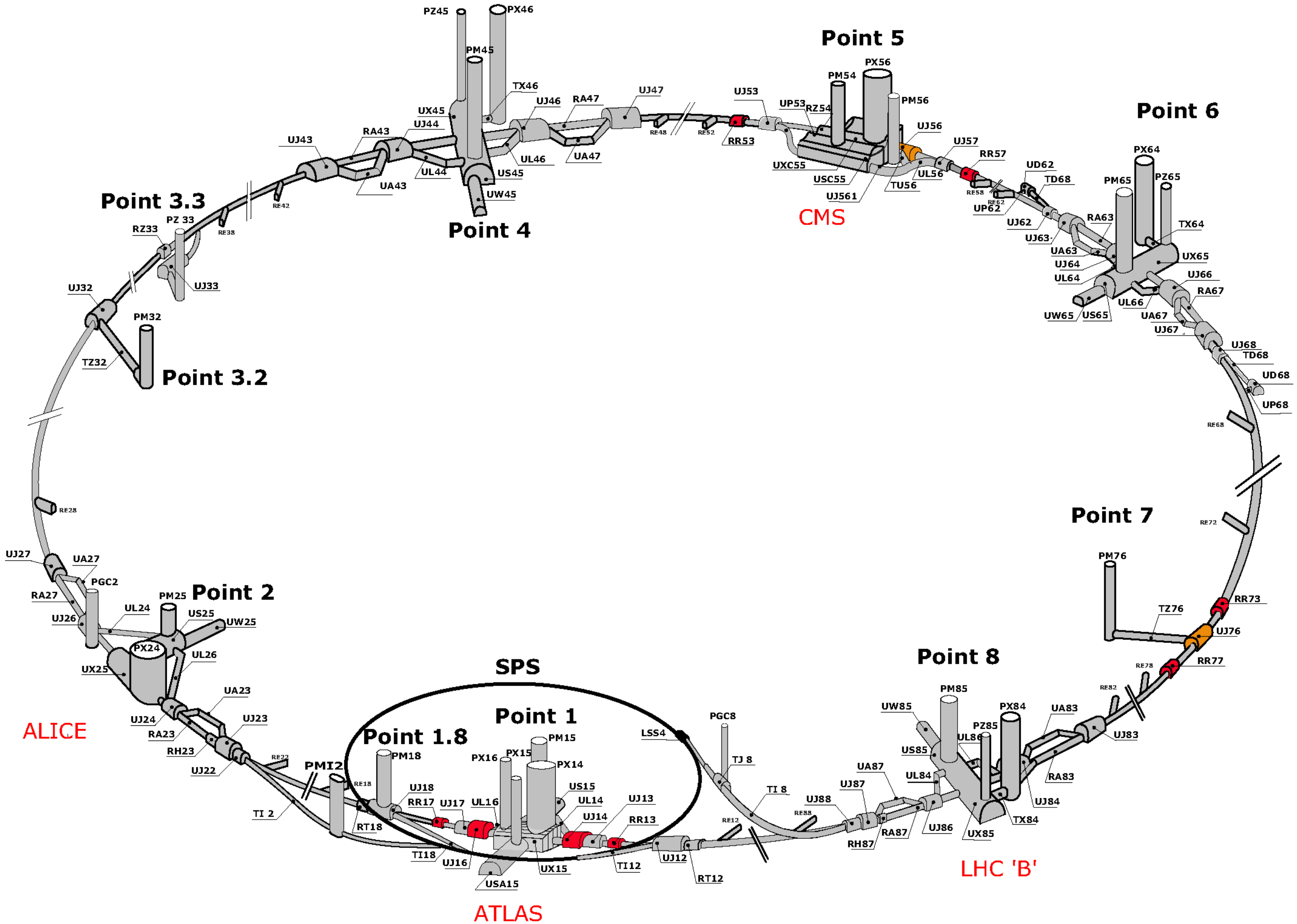
- To capture the enormous forward flux, we need to detect particles that are produced in the forward direction along the beamline.

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



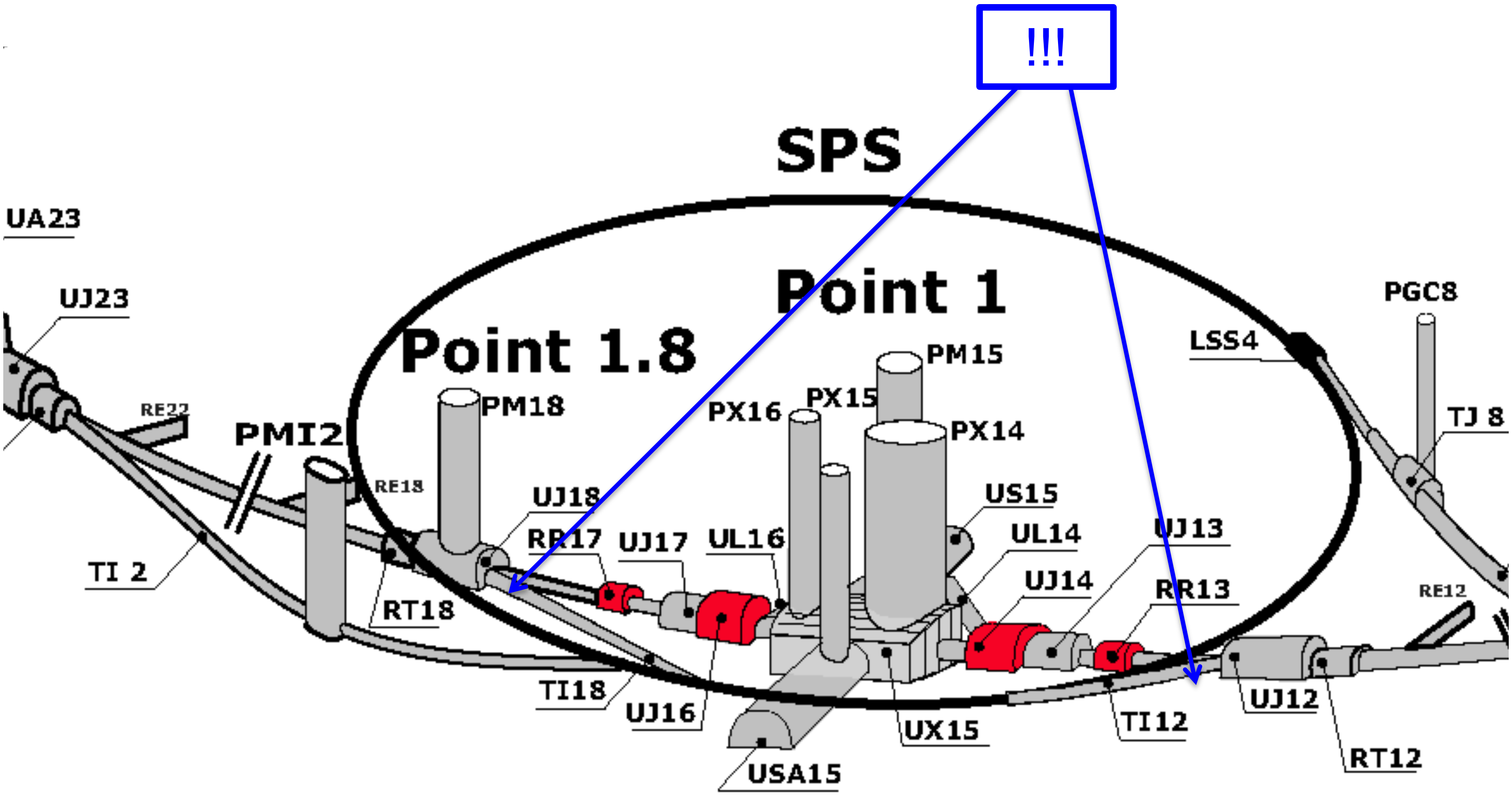
- Solution: the LHC is a circular collider! If we go far enough away, the LHC proton beam will be bent away, while all the light, weakly-interacting particles we are looking for will go straight.

MAP OF LHC



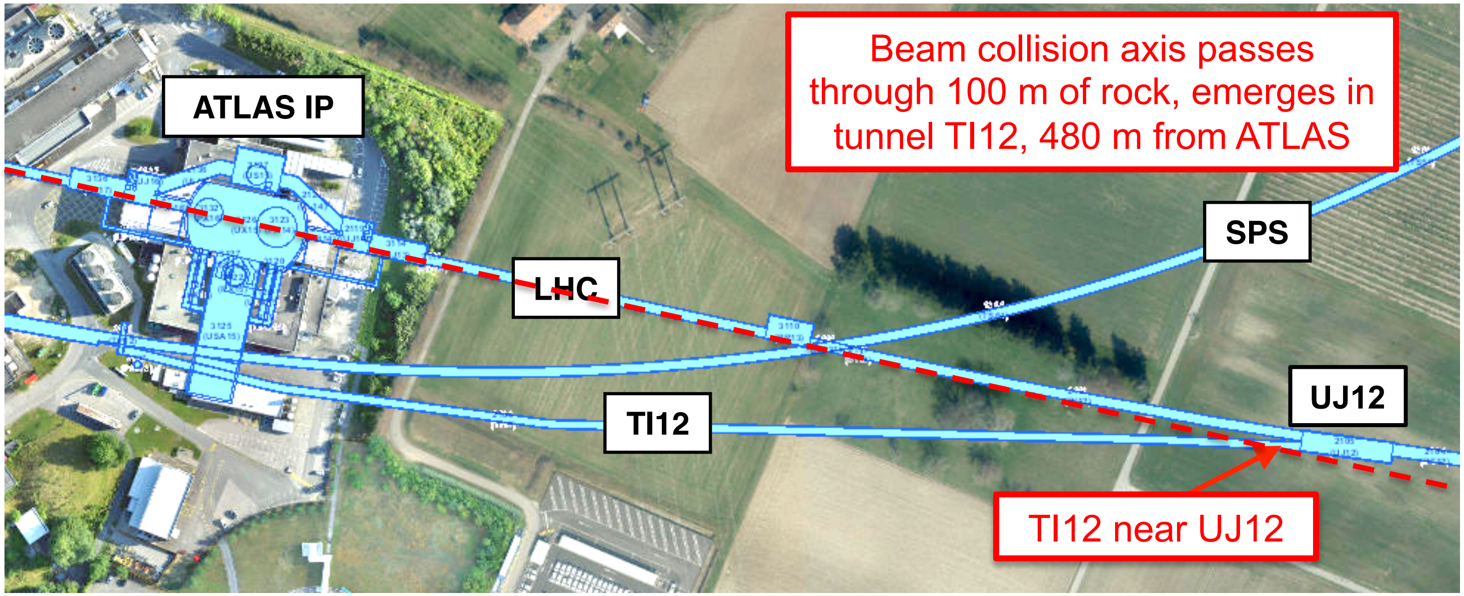
Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ATLAS
ALICE
CMS
LHC 'B'

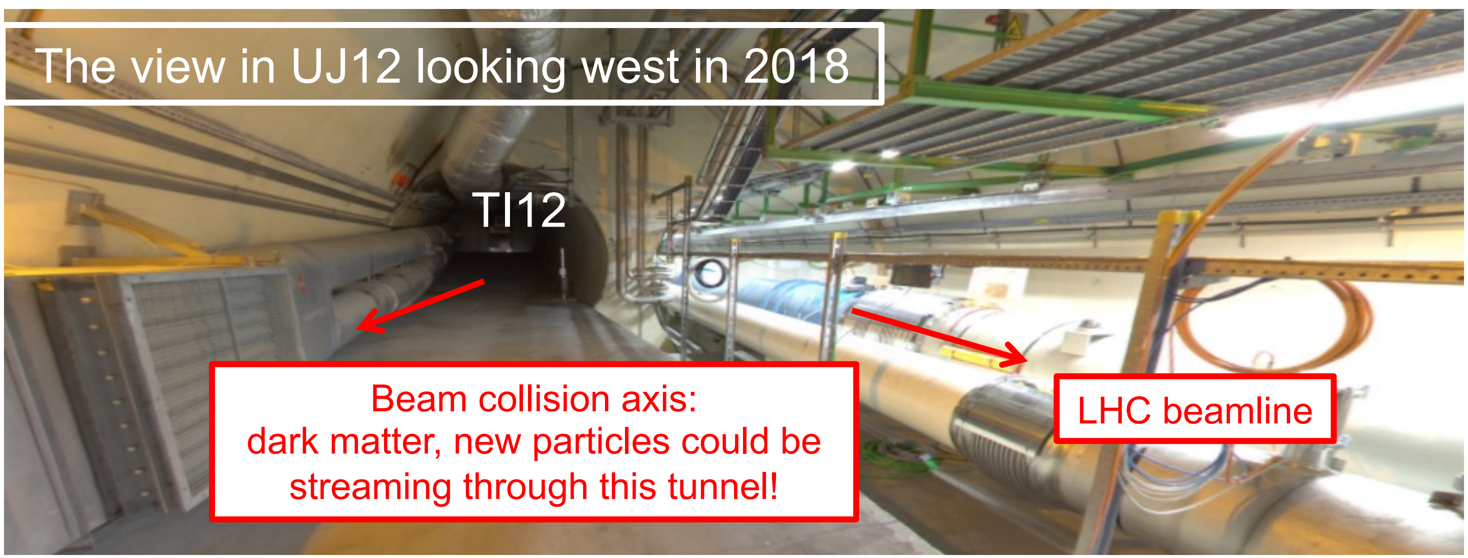
MAP OF LHC



ATLAS

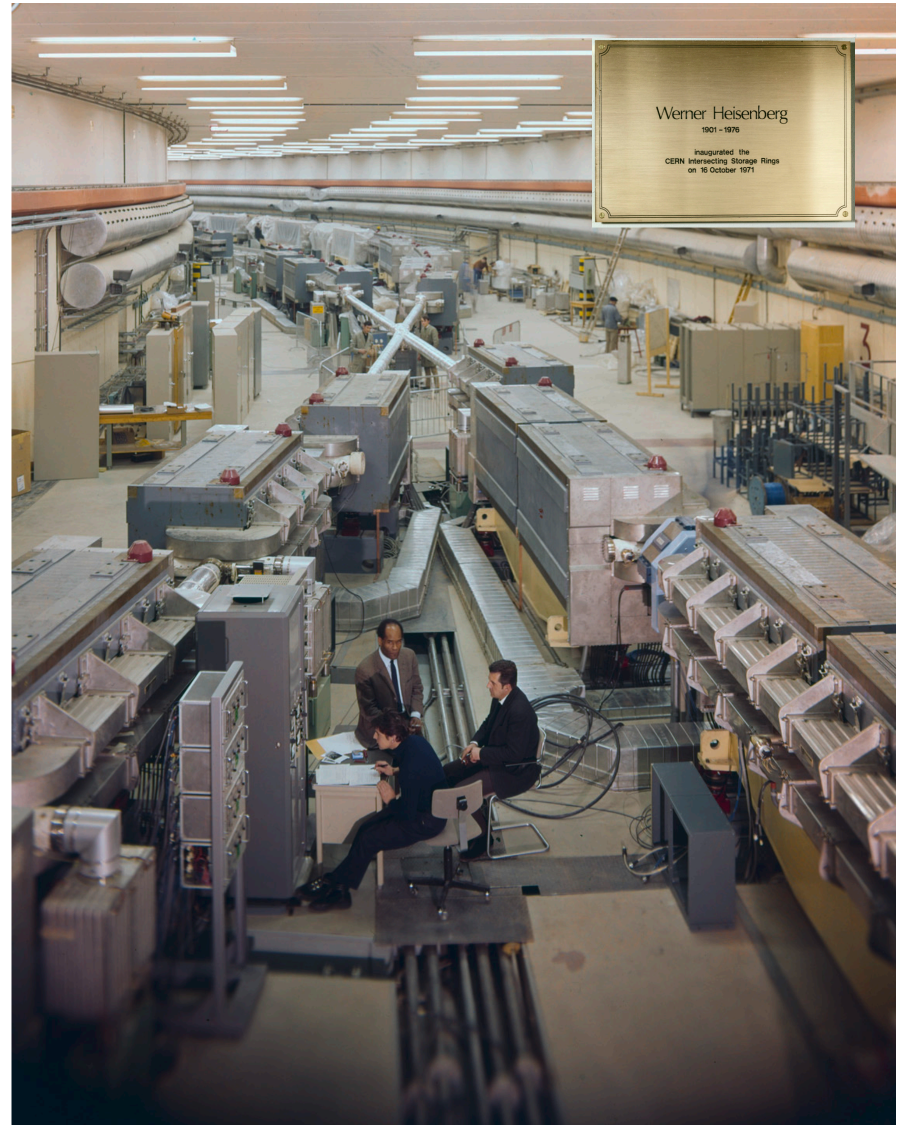
THE FORWARD REGION





HISTORY: THE FALL OF FORWARD PHYSICS

- 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.



HISTORY: THE FALL OF FORWARD PHYSICS

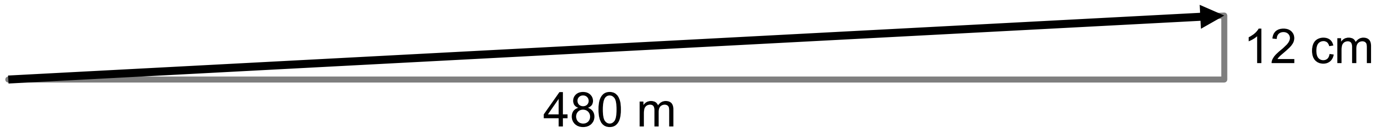
- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.
  - "There was initially 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?

FASER

HOW BIG DOES THE DETECTOR HAVE TO BE?

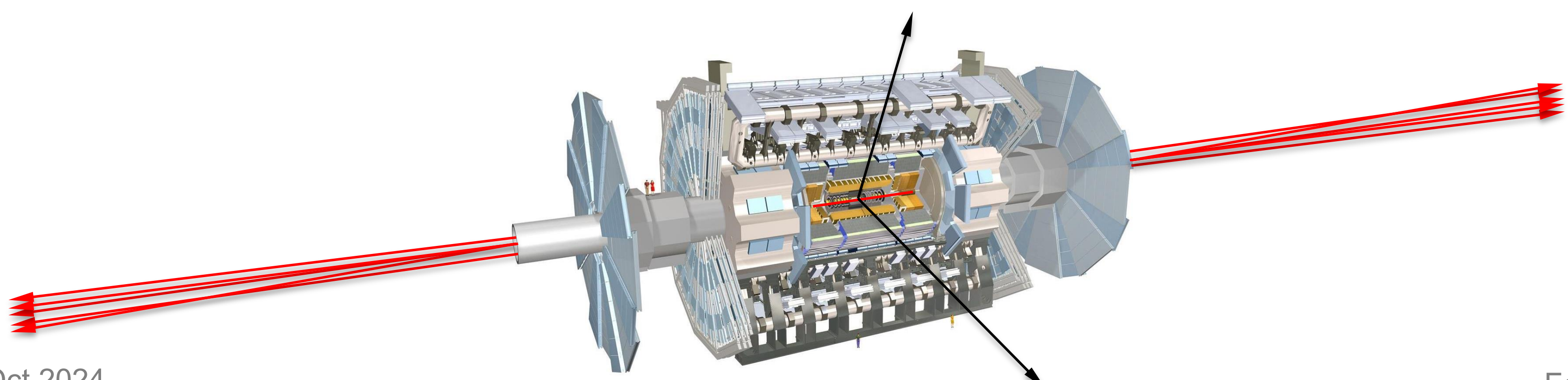
- Momentum:

- Space:

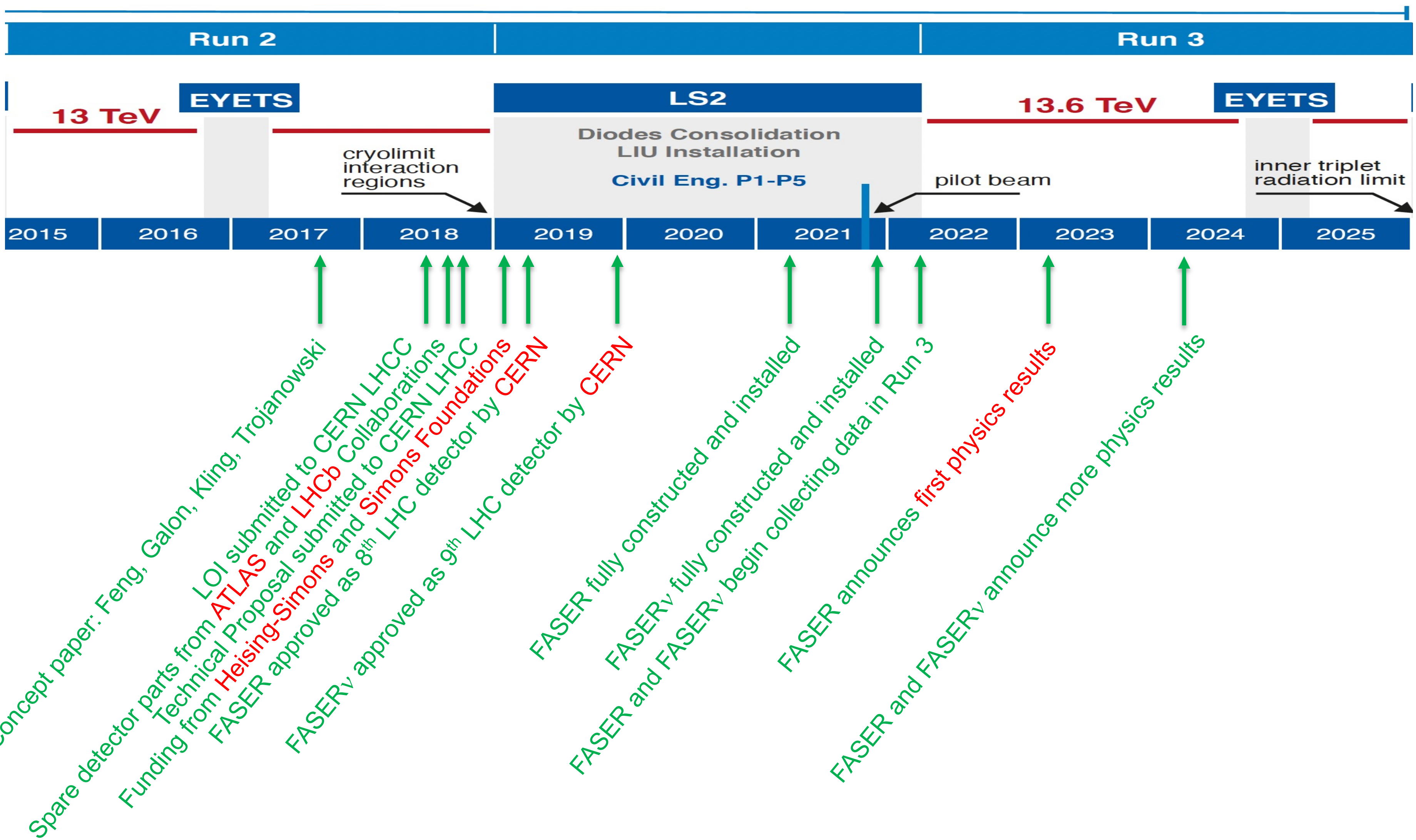


- The opening angle is 0.2 mrad (the moon is 7 mrad). Even 480 m away, most of the signal passes through an 8.5” x 11” (A4) sheet of paper.

- Neutrinos and many new particles are therefore much more collimated than shown below, motivating a relatively small, fast, and inexpensive experiment at the LHC: the ForwArd Search ExpeRiment (FASER).



FASER AND FASERν TIMELINE



FASER COLLABORATION

111 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 JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
CHIBA UNIVERSITY
UNIVERSITY OF OREGON
DESY.
INFN
ISS
International laboratory covered by a cooperation agreement with CERN
清華大学 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
US 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

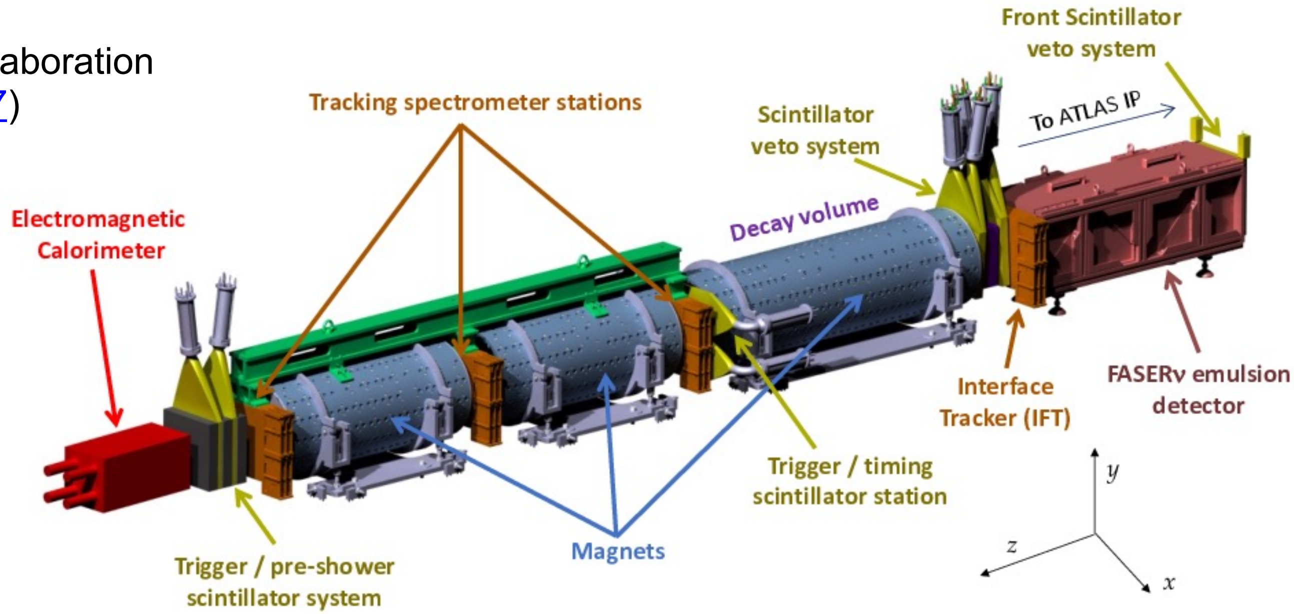
FASER AND THE LHC

THE FASER DETECTOR

THE FASER DETECTOR

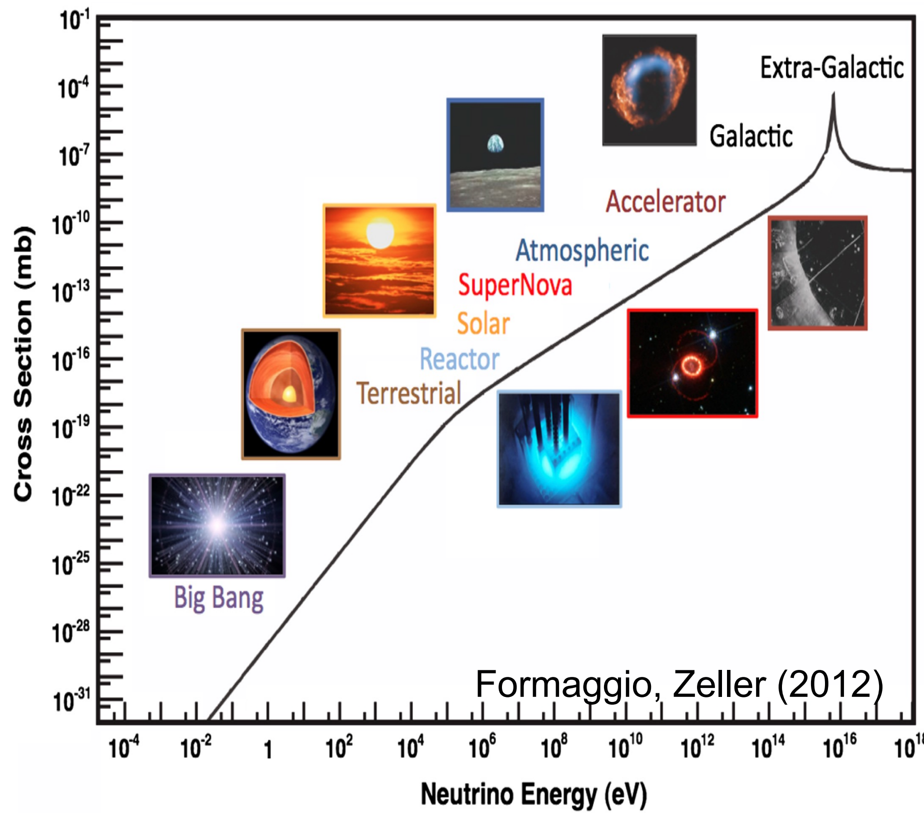
- Design challenges: small (no room), low maintenance (no access), fast (no time).
  - Size: Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.
  - Magnets: 3 permanent dipoles (Halbach design), 0.57 T, deflect charged particles in y.
  - Tracker: composed of 4 stations x 3 layers x 8 mod. = 96 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 NEUTRINOS

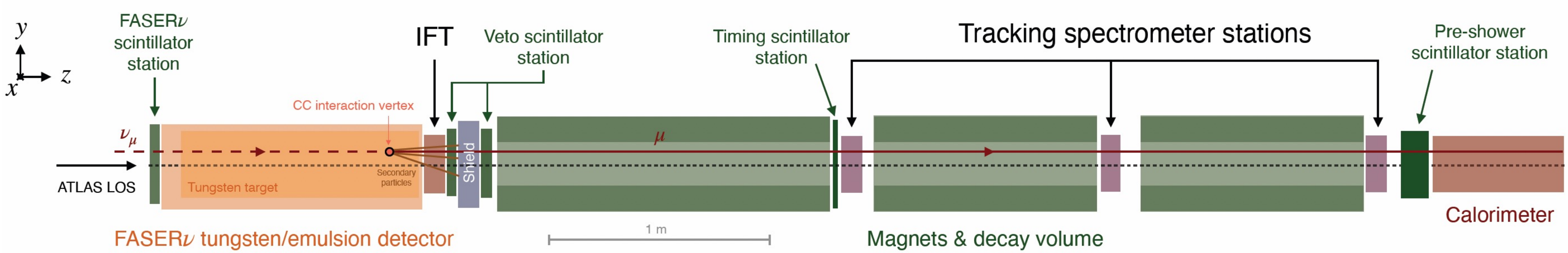
- Neutrinos are the least understood of all known particles, and the only ones with confirmed BSM properties.
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.



- 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.

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)

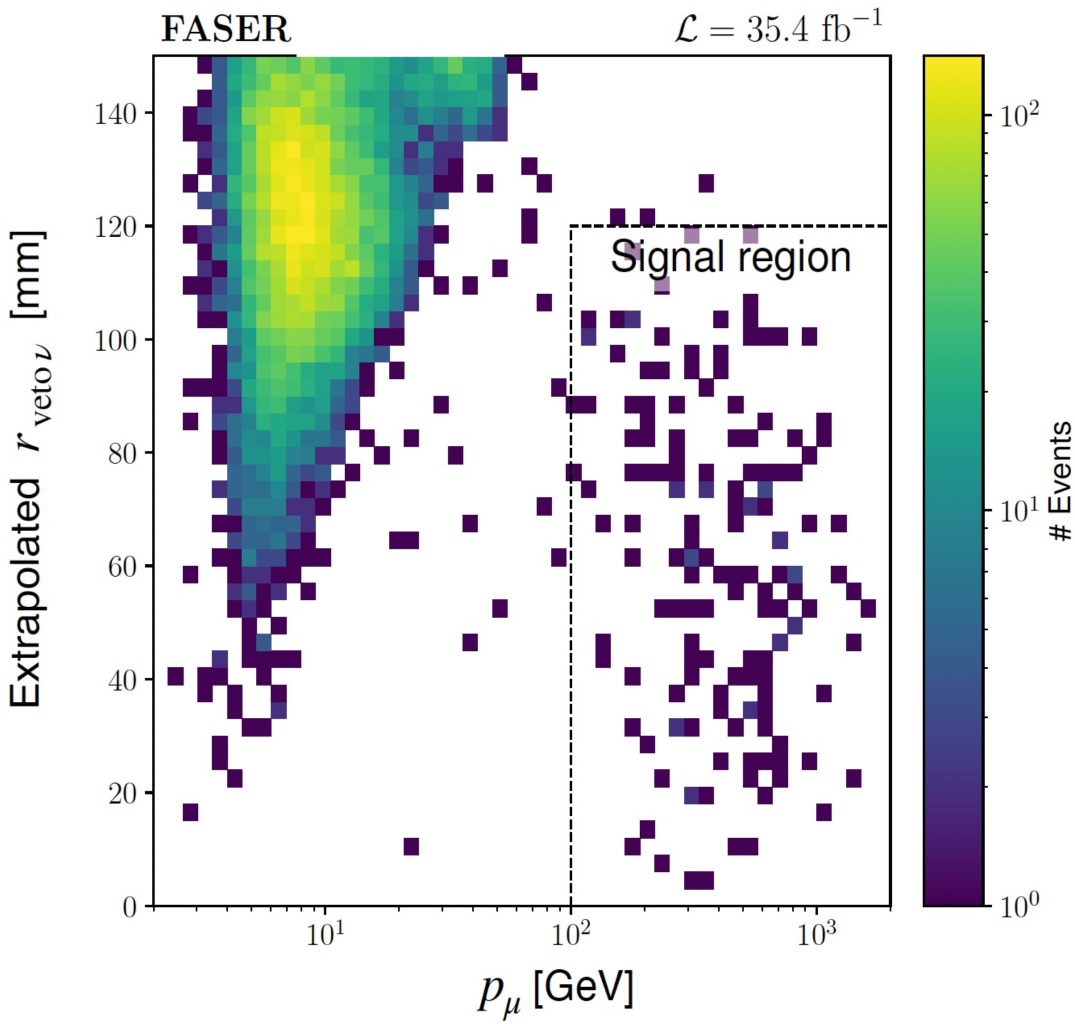
- The signal is no charged particle passing through the upstream veto scintillators, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

- 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.

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.



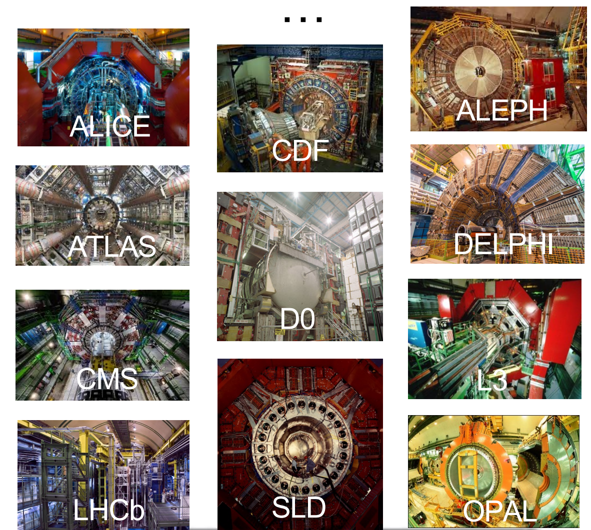
FASER Collaboration (2303.14185, PRL)

LOCATION, LOCATION, LOCATION

FASER

“Tabletop,” 18 months,
~$1M

153 neutrinos



All previous
collider detectors

Building-size, decades,
~$1B

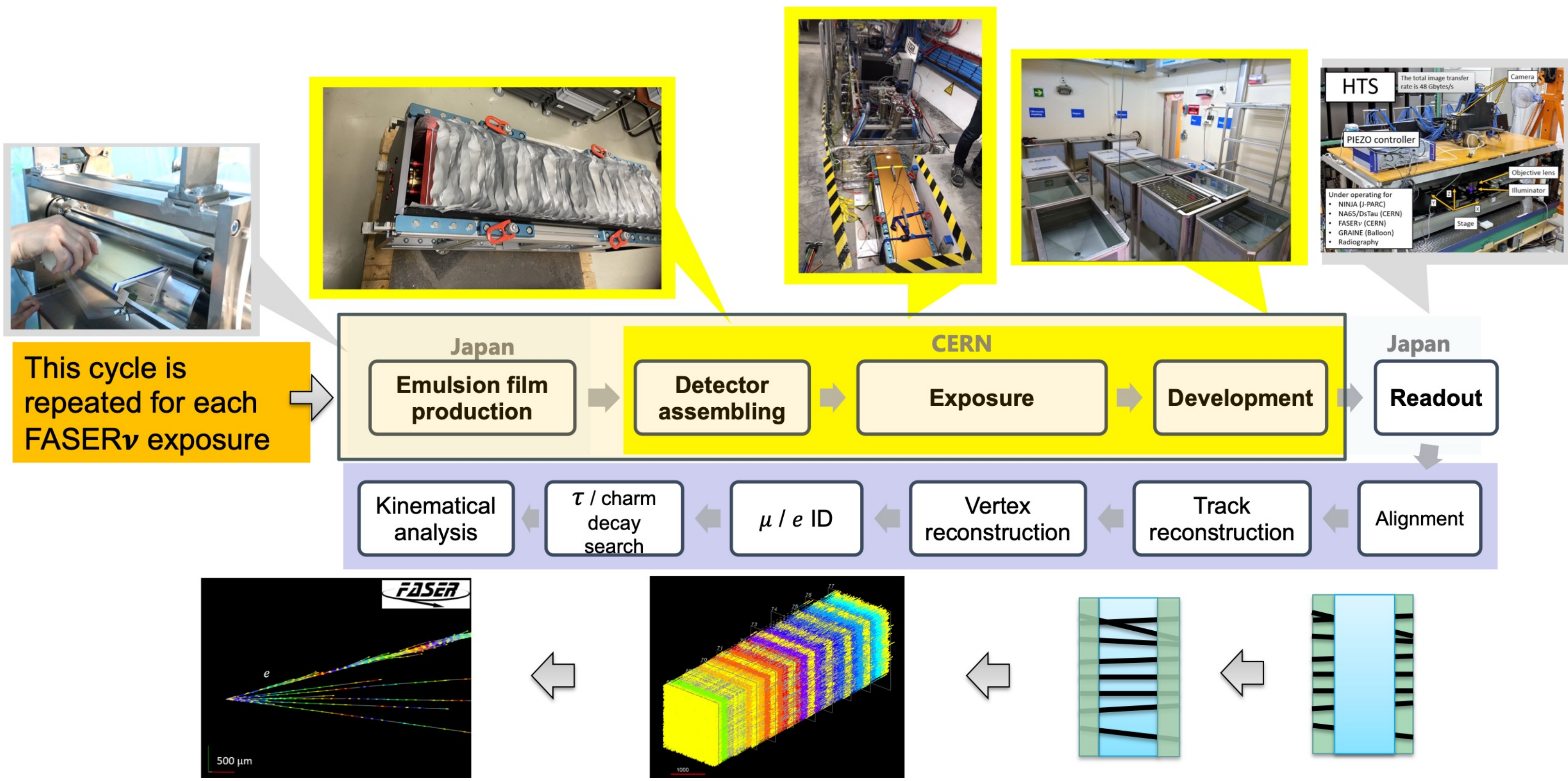
0 neutrinos

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

DISCOVERY OF COLLIDER NEUTRINOS

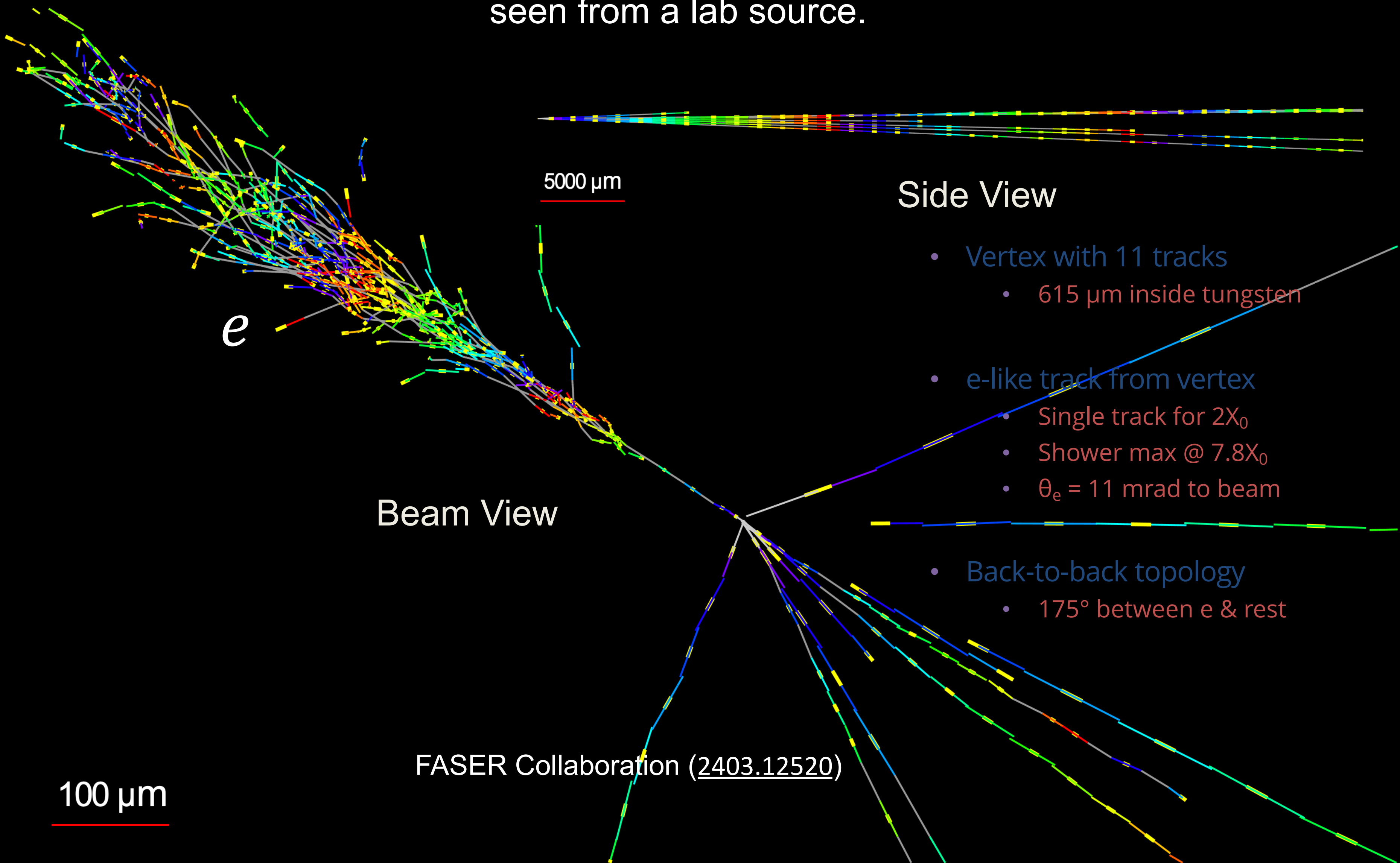
NEUTRINOS IN FASERν

- 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

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.



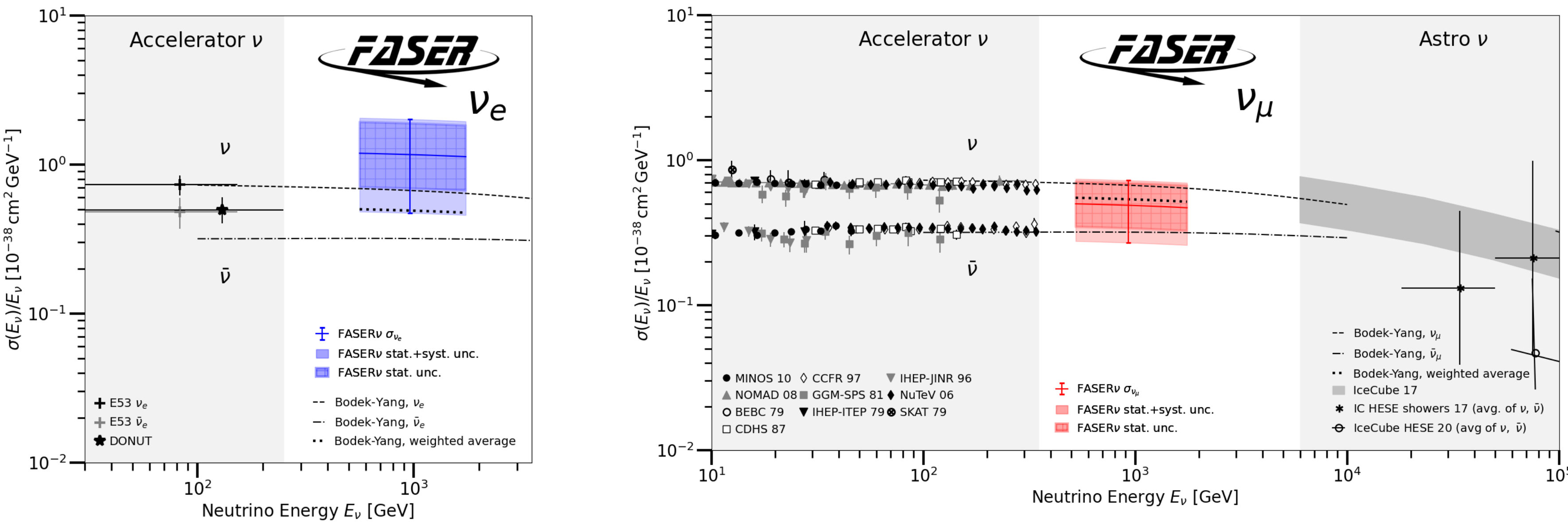
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

FASER Collaboration (2403.12520)

TEV NEUTRINO CROSS SECTIONS

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

- Results are consistent with SM DIS predictions.

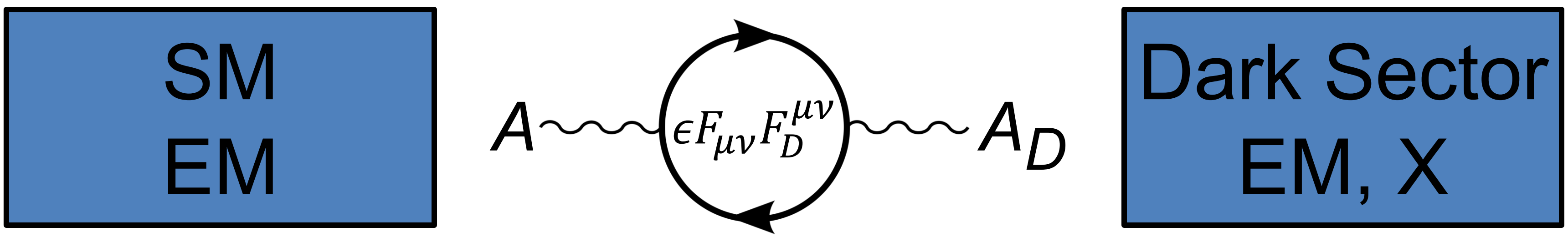


FASER Collaboration (2403.12520, PRL)

- These measurements use only 1.7% of the data collected in 2022 and 2023. Much more to come; triple the world's supply of tau neutrinos, identify the first anti-tau neutrino, look for BSM physics.

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.



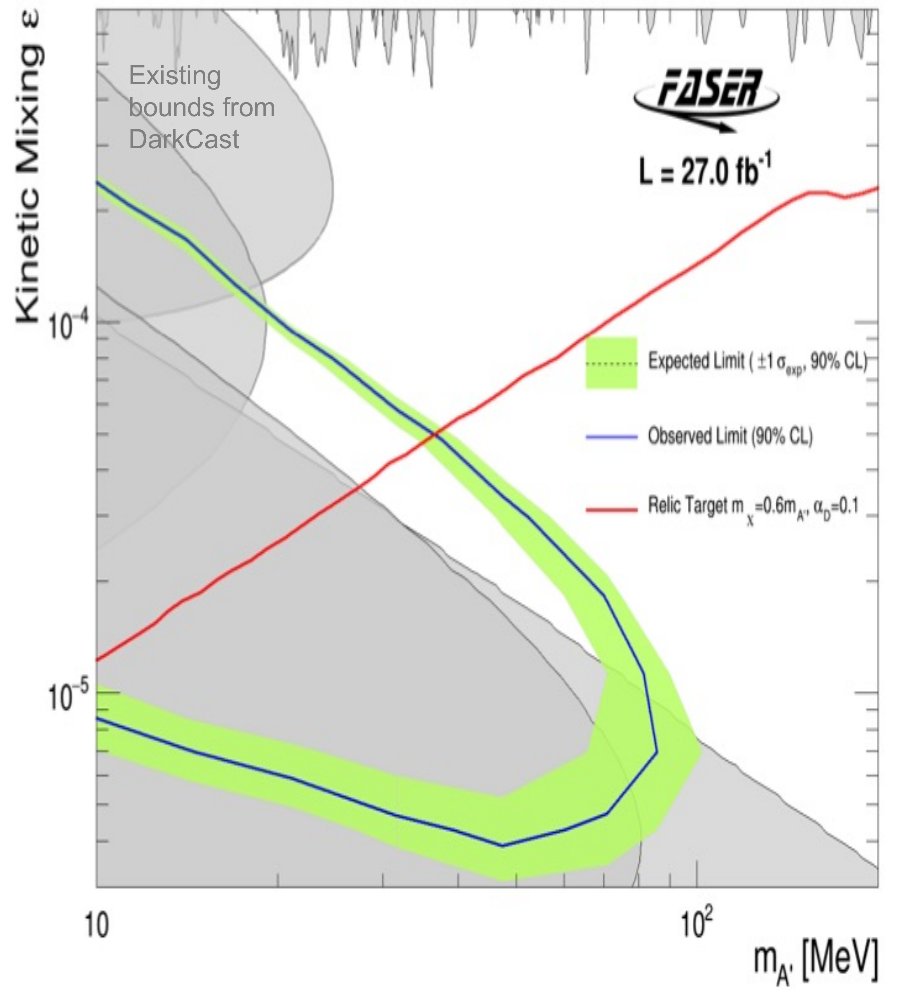
- The result? Dark photons A' , like photons, but with mass $m_{A'}$, couplings suppressed by ϵ.

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.

DARK PHOTON RESULTS

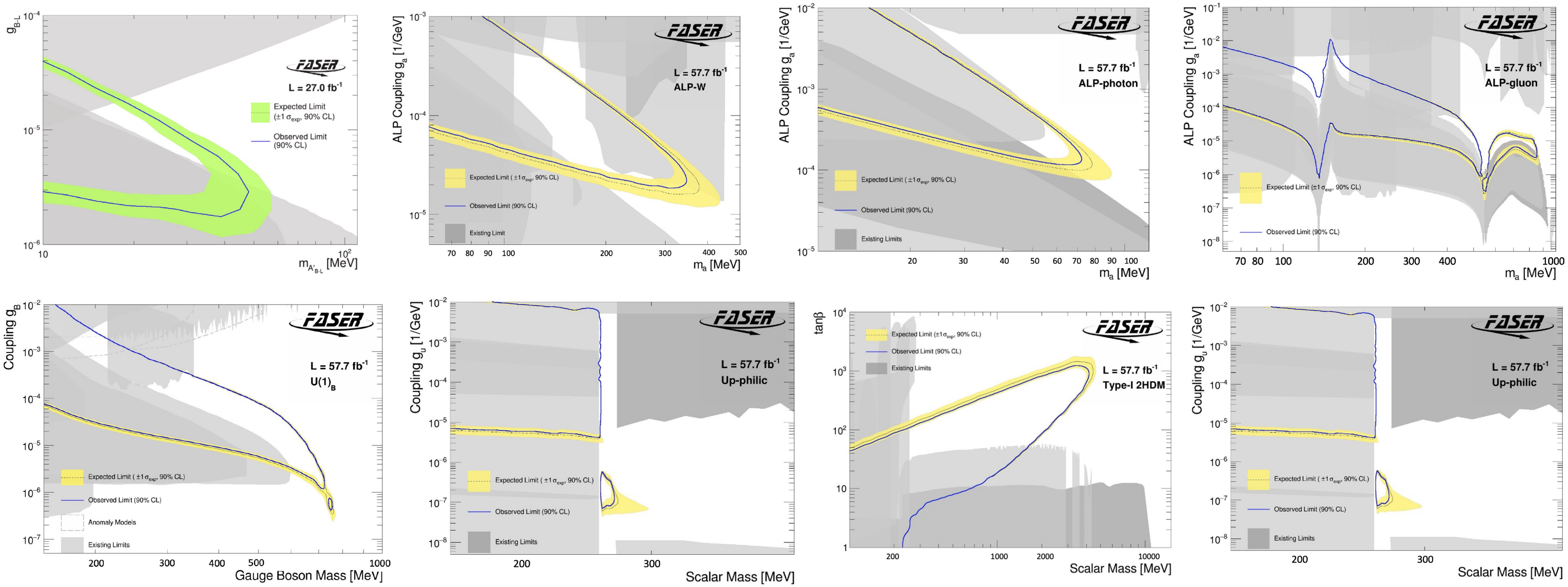
- After unblinding, no events seen, FASER sets limits on previously unexplored parameter space.
- First new probe of the parameter space favored by dark matter from low coupling since the 1990's.
- Prospects for the future
  - Background-free analysis
  - Started probing new parameter space in the first day of running
  - Ended up ~100 times more sensitive than previous experiments
  - Improvements in analysis and 40 times more data to come



FASER Collaboration (2308.05587, PLB)

MORE SEARCH RESULTS

- We are now looking for many other new particles: other new force carriers ($U(1)_{B-L}$, $U(1)_B$, protophobic), axion-like particles with photon, W, gluon couplings, up-philic scalars, two Higgs doublet models, sterile neutrinos, dark matter, light neutralinos, quirks, etc., all with world-leading sensitivities.
- FASER is approved to run through 2033, with High-Luminosity LHC, hardware upgrades, improvements in analysis.



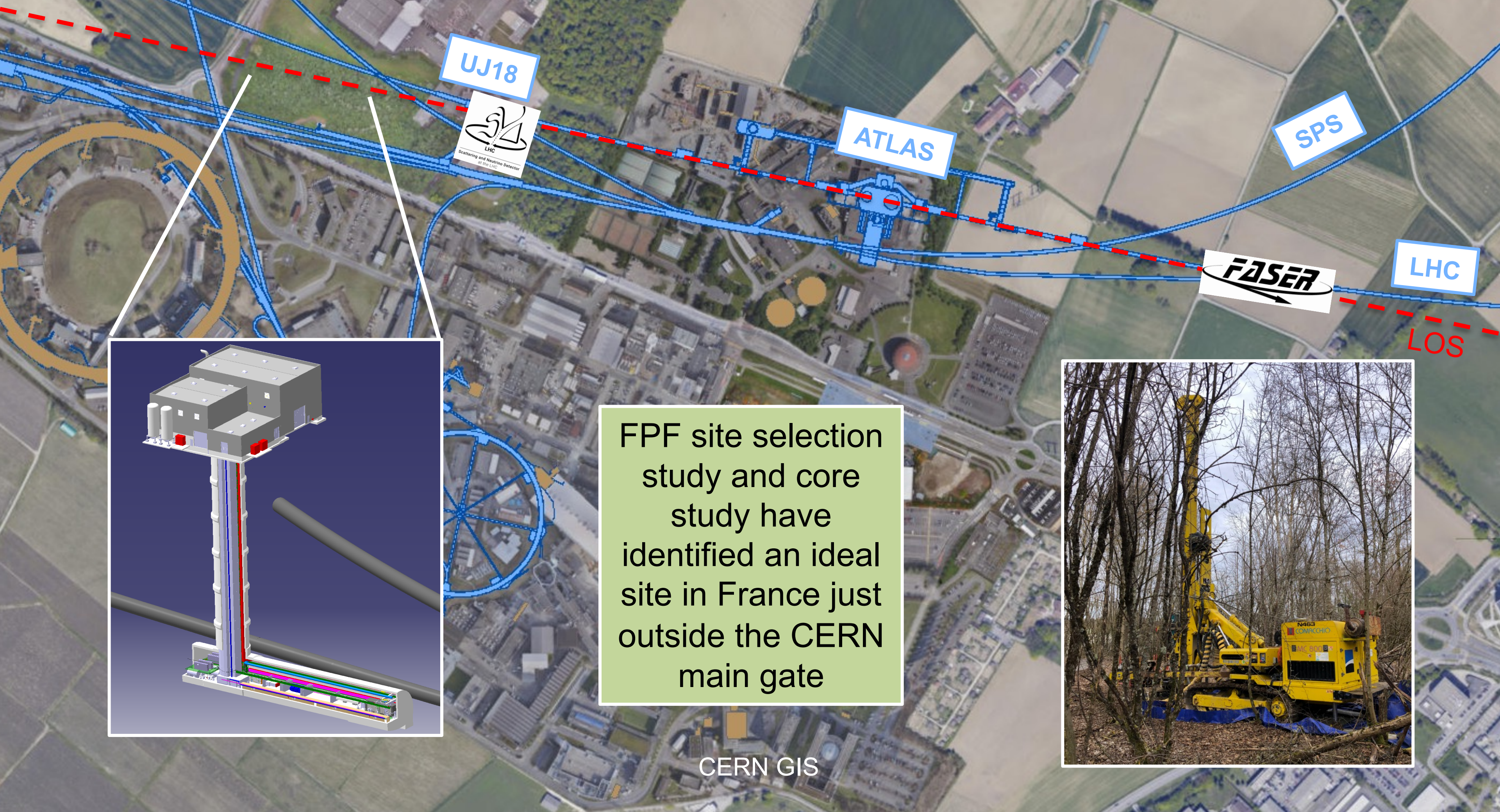
FASER Collaboration (2308.05587, PLB; 2410.10363)

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.

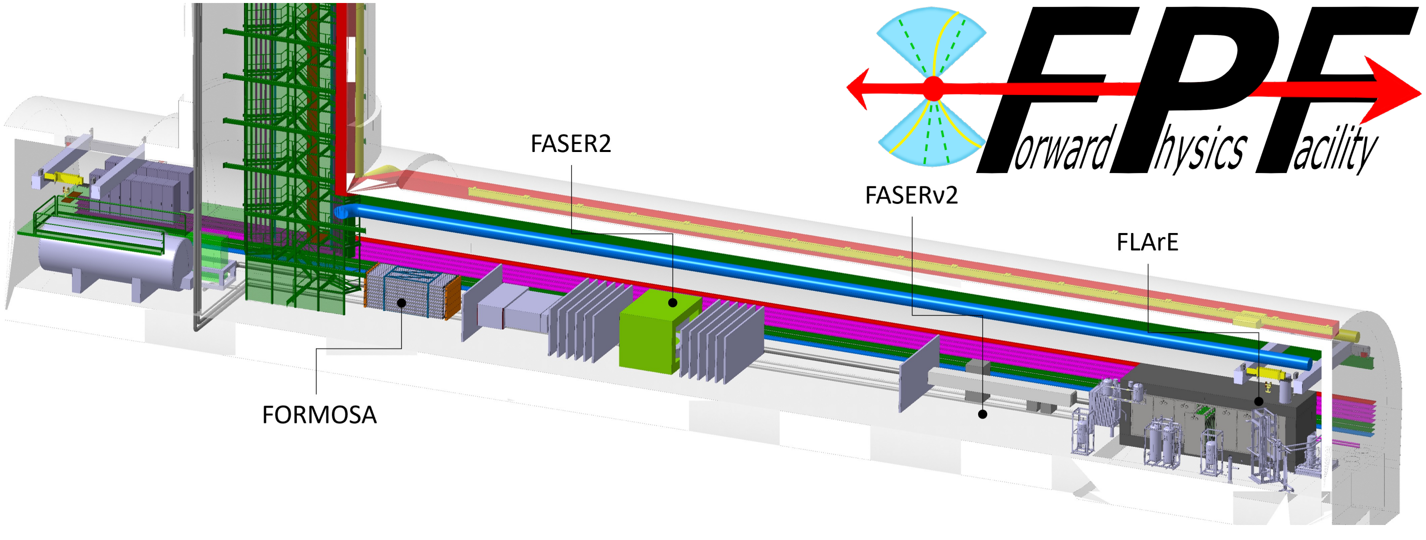


FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

THE FPF AND ITS EXPERIMENTS

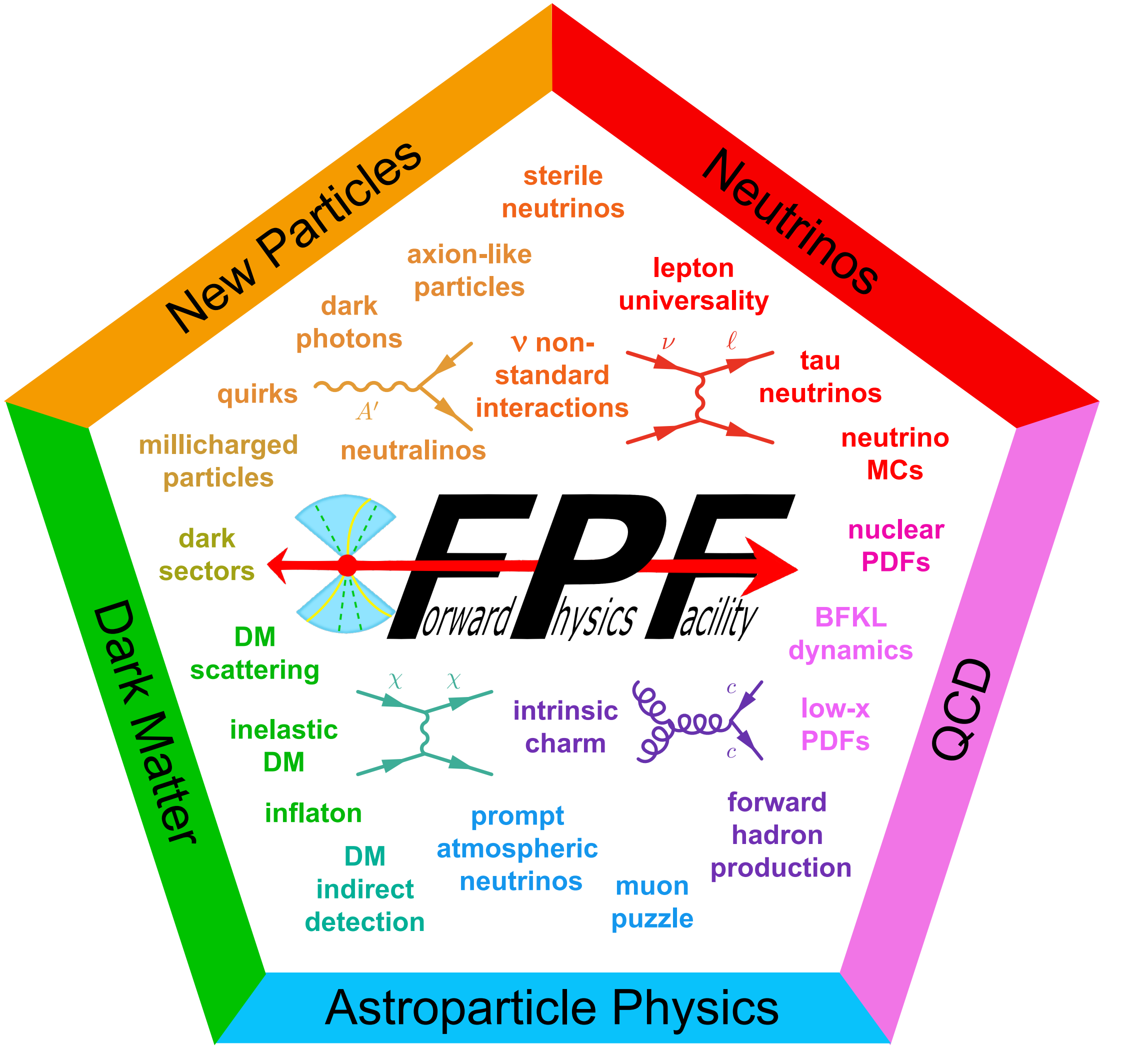
- At present there are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASERν2: emulsion-based neutrino detector
  - FLArE: LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)

- With great support from CERN, 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.



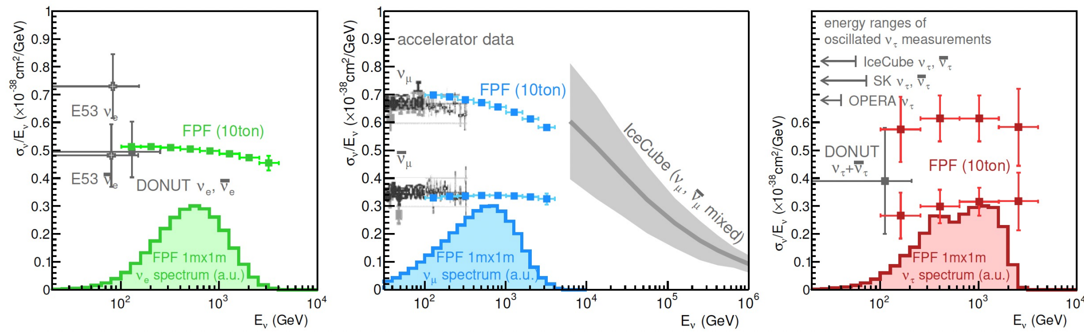
PHYSICS AT THE FPF

- The FPF at the HL-LHC will have many unique capabilities:
  - New physics in neutrino properties: neutrino blind → neutrino factory: 10^6 neutrinos (1000 per day!) at the highest human-made energies ever.
  - New particles:10,000 more powerful than current experiments, enhancement of conventional LHC searches, and many searches for particles that cannot be found anywhere else.

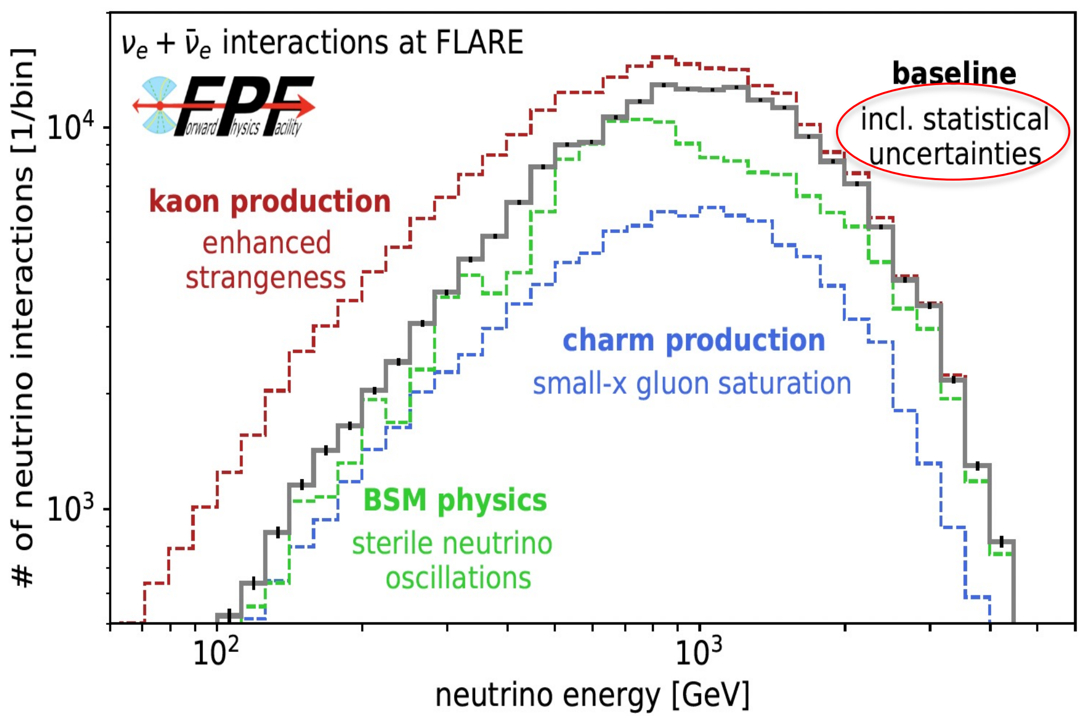


NEUTRINOS AT THE FPF

- The FPF experiments will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^4\ \nu_\tau$ interactions at TeV energies. The last chance to probe this in a controlled environment for at least 50 years.

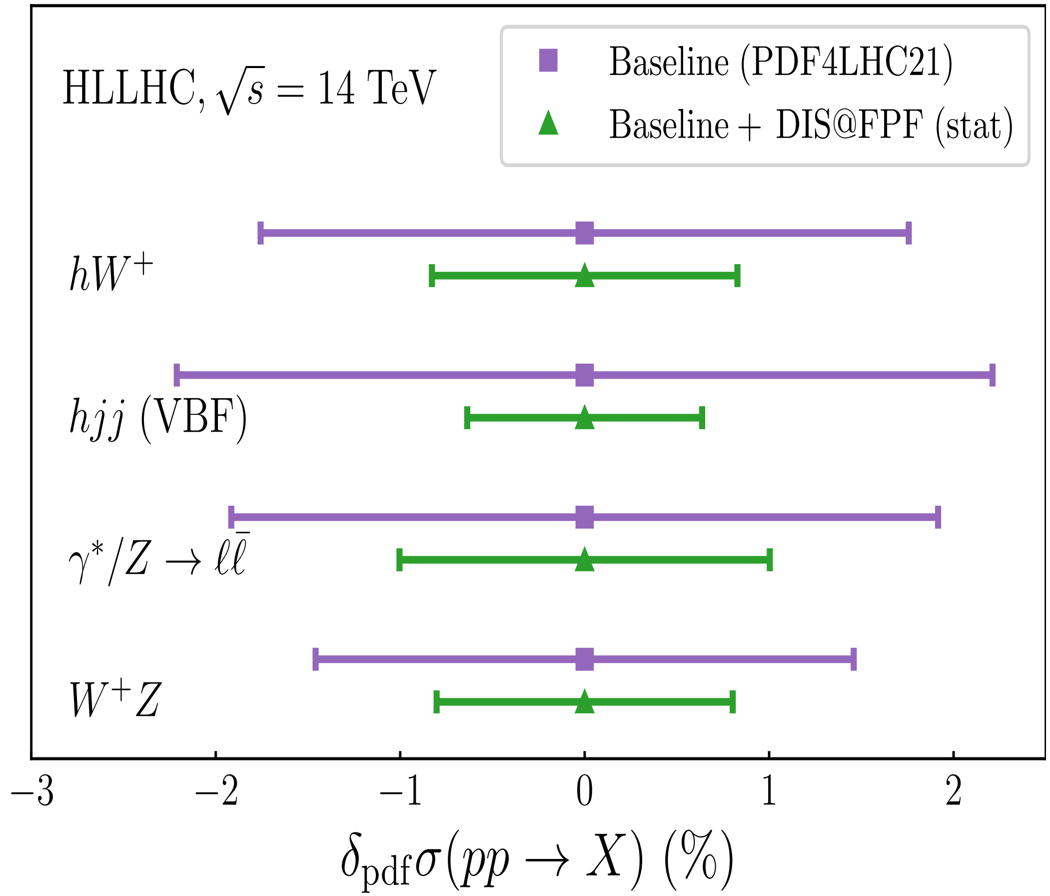


- Neutrinos are produced by forward hadron production: π, K, D, ... Dependence on E, η will inform
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x $\sim 10^{-1}$, x $\sim 10^{-7}$, intrinsic charm, small-x gluon saturation, …
  - Neutrino oscillations: ν_s with $\Delta m^2 \sim 10^3\ \text{eV}^2$



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)

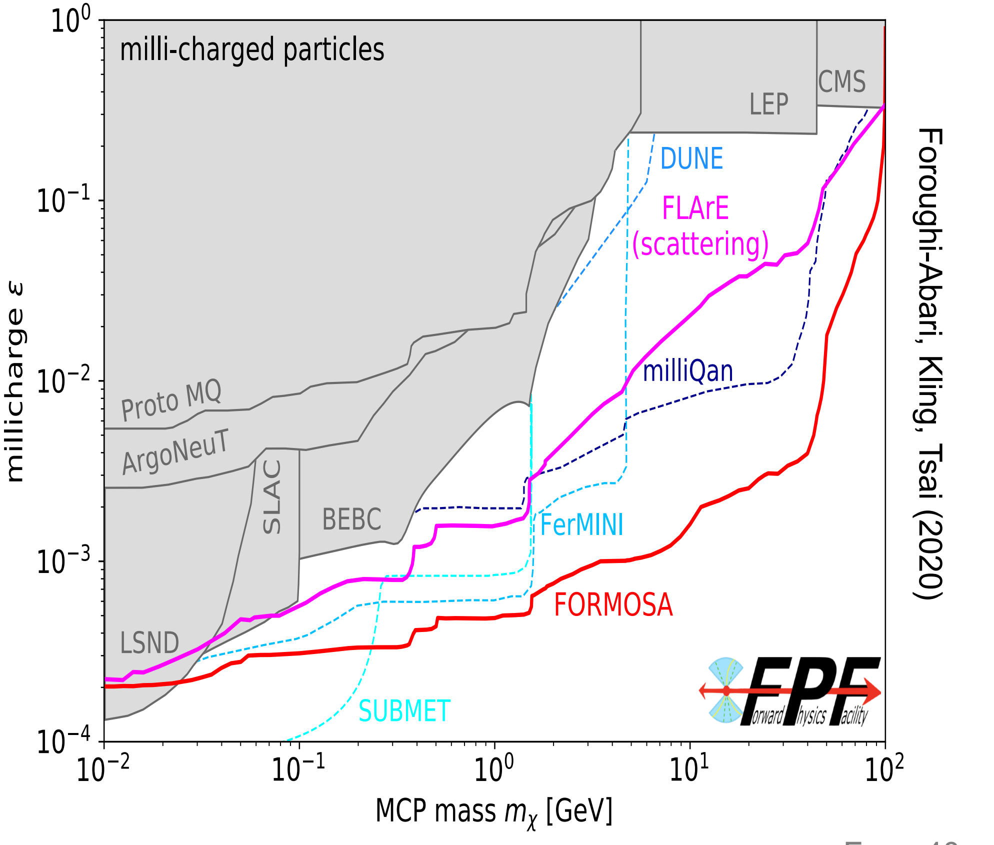
UNIQUE DISCOVERY OPPORTUNTIES

- FPF experiments have the potential to discovery BSM physics that cannot be seen anywhere else. Many examples:

- Millicharged particles: a completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a “non-forward” tunnel.

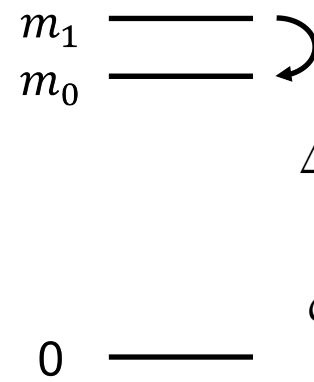
- Can be explored at the FPF with both FLArE and FORMOSA, a dedicated experiment in the forward region with much greater sensitivity for a wide range of masses from 10 MeV to 100 GeV.

- Currently being investigated with the FORMOSA Demonstrator behind FASER.



DARK MATTER

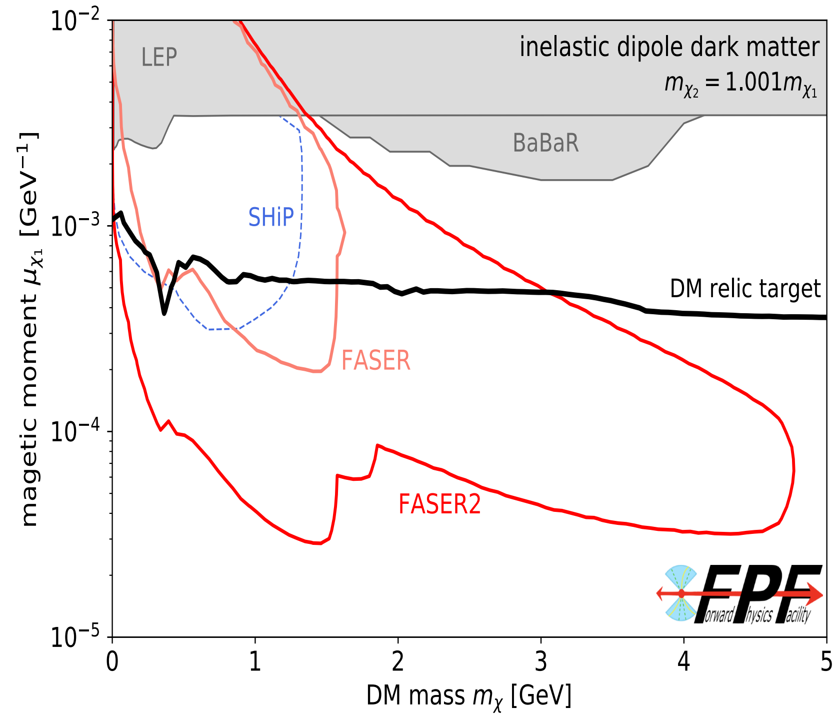
- In the last few decades, there has been an intense effort to detect dark matter through non-gravitational couplings, all yielding null results.
- One generic possibility that is infamously hard to detect: inelastic dark matter, where there are two nearly-degenerate dark states with off-diagonal couplings 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, …)



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

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

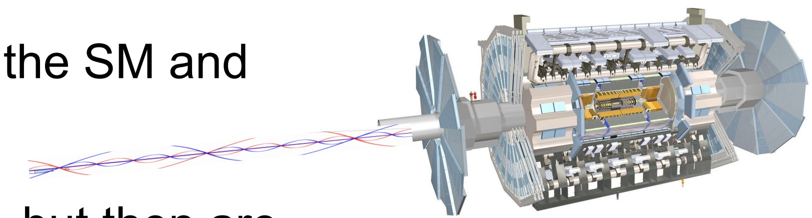
$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$



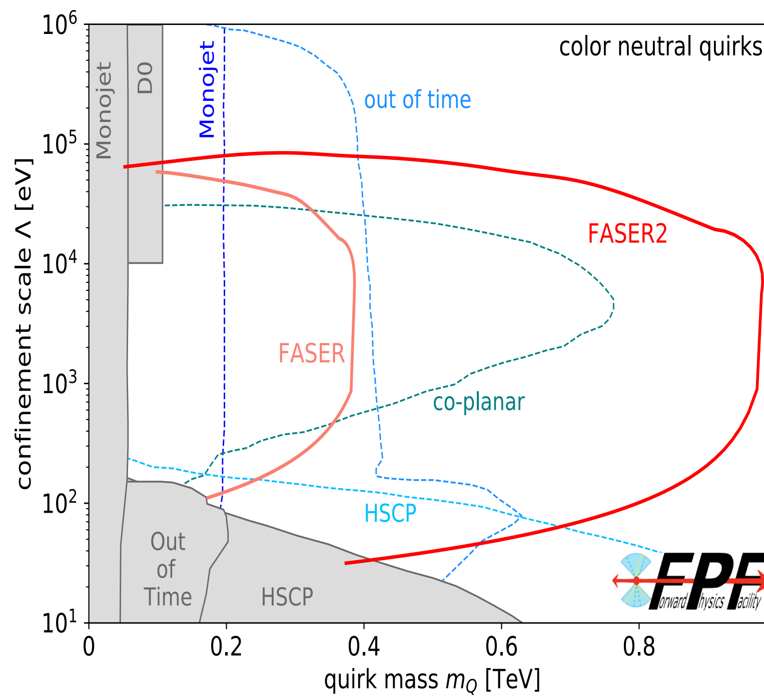
Dienes, Fieg, et al. (2023)

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)

SUMMARY AND ACKNOWLEDGEMENTS

- Neglected for decades, the forward region at particle colliders turns out to be a treasure trove of interesting physics that can be mined with small, fast, inexpensive experiments. Much more to come!

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