THE FALL AND RISE OF FORWARD PHYSICS

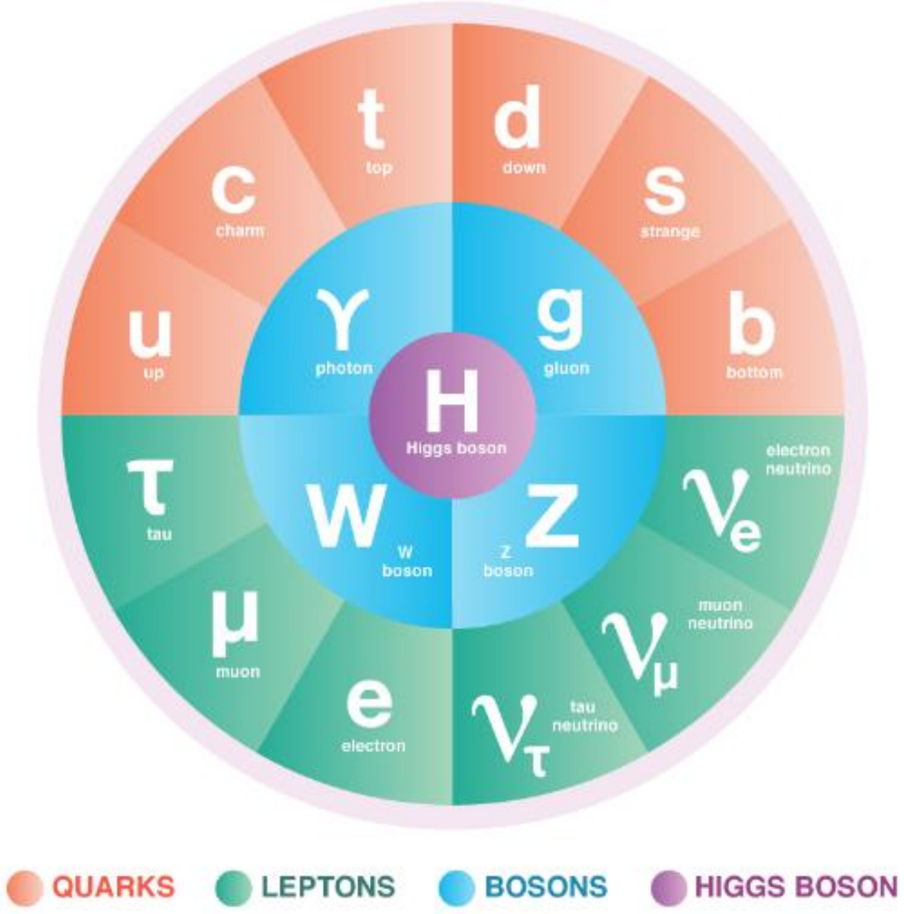
Physics Colloquium, MIT

Jonathan Feng, UC Irvine, 30 April 2026

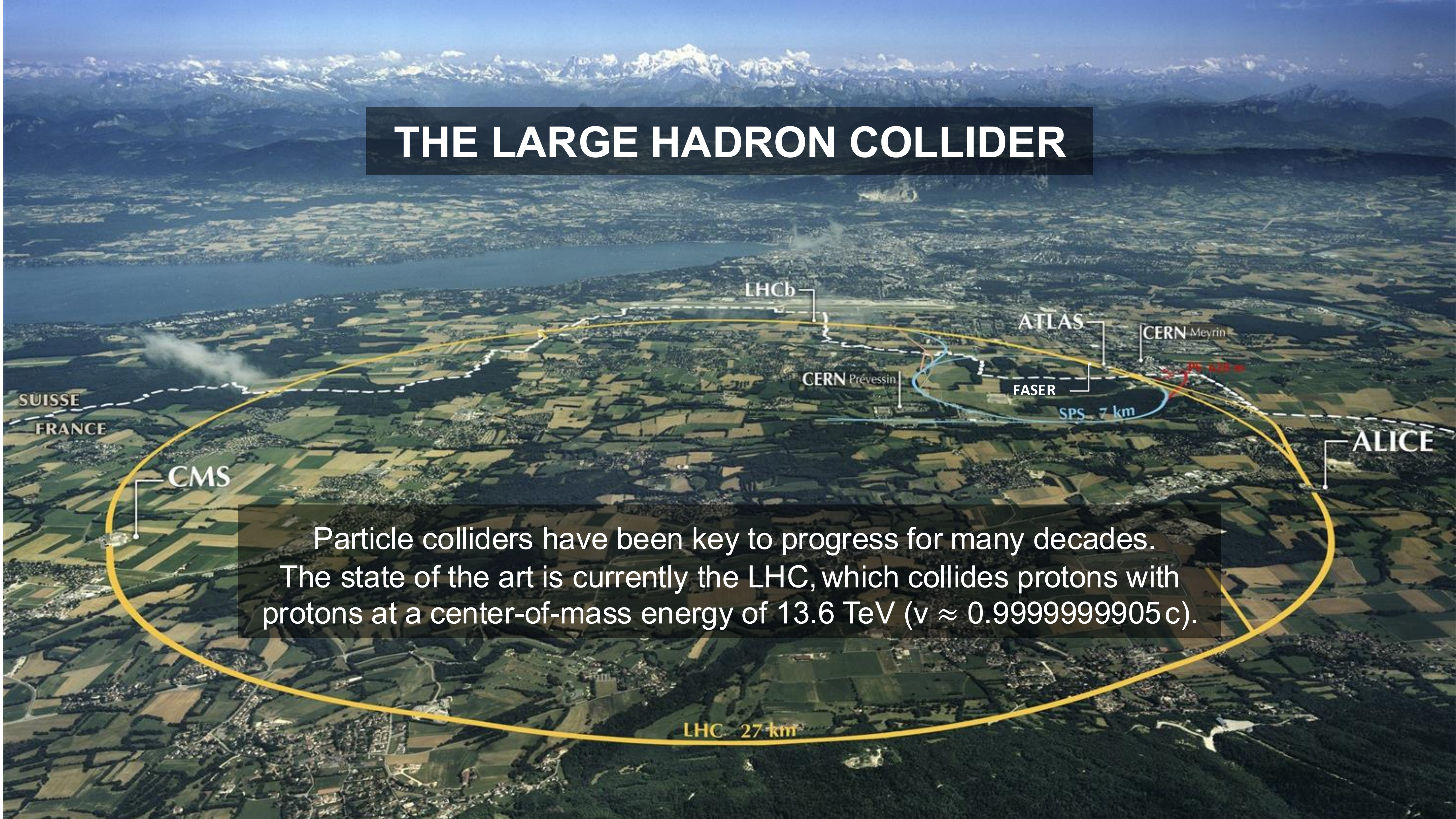
THE STANDARD MODEL OF PARTICLE PHYSICS

- 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.



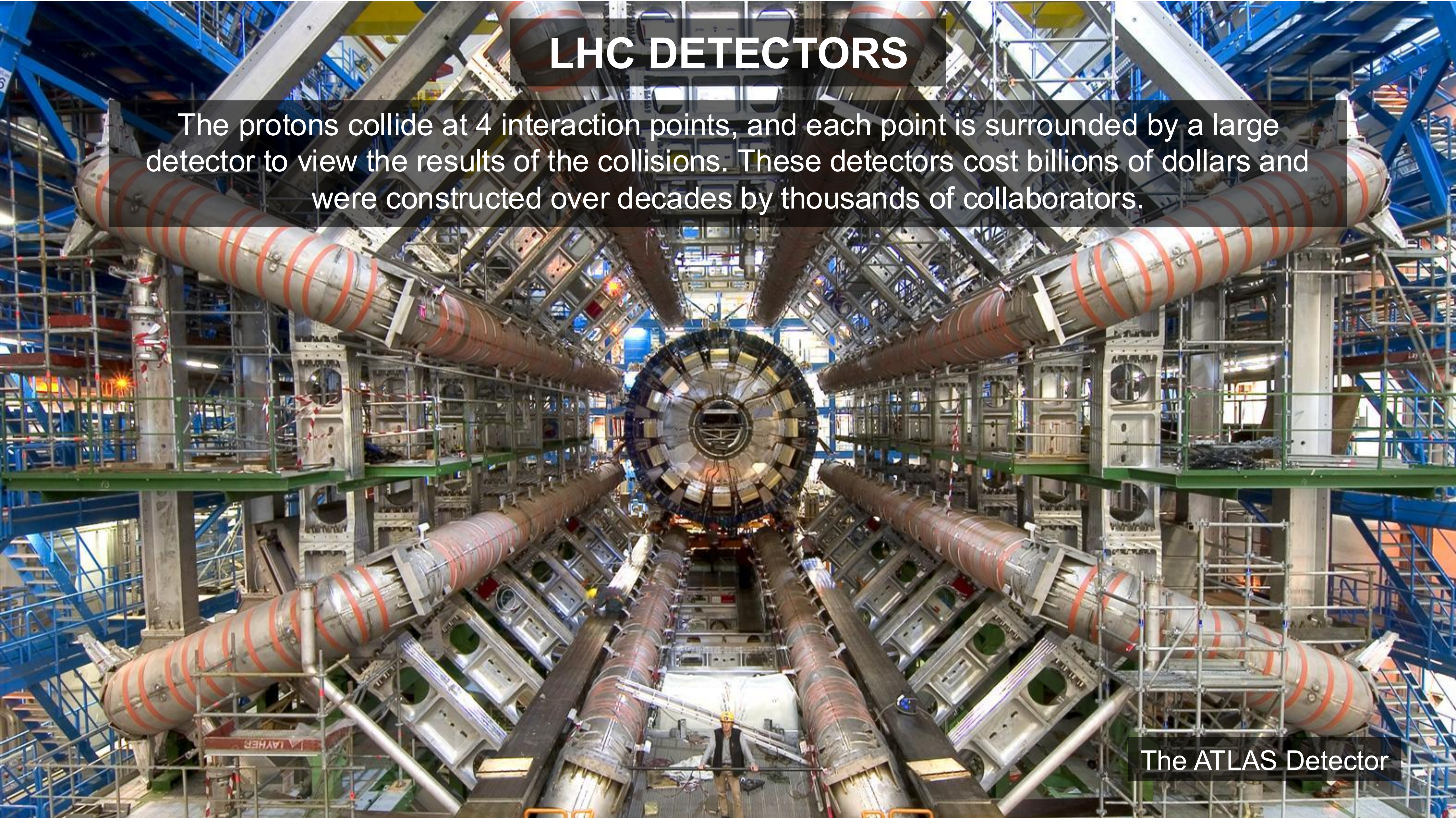
THE LARGE HADRON COLLIDER



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 interaction 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.



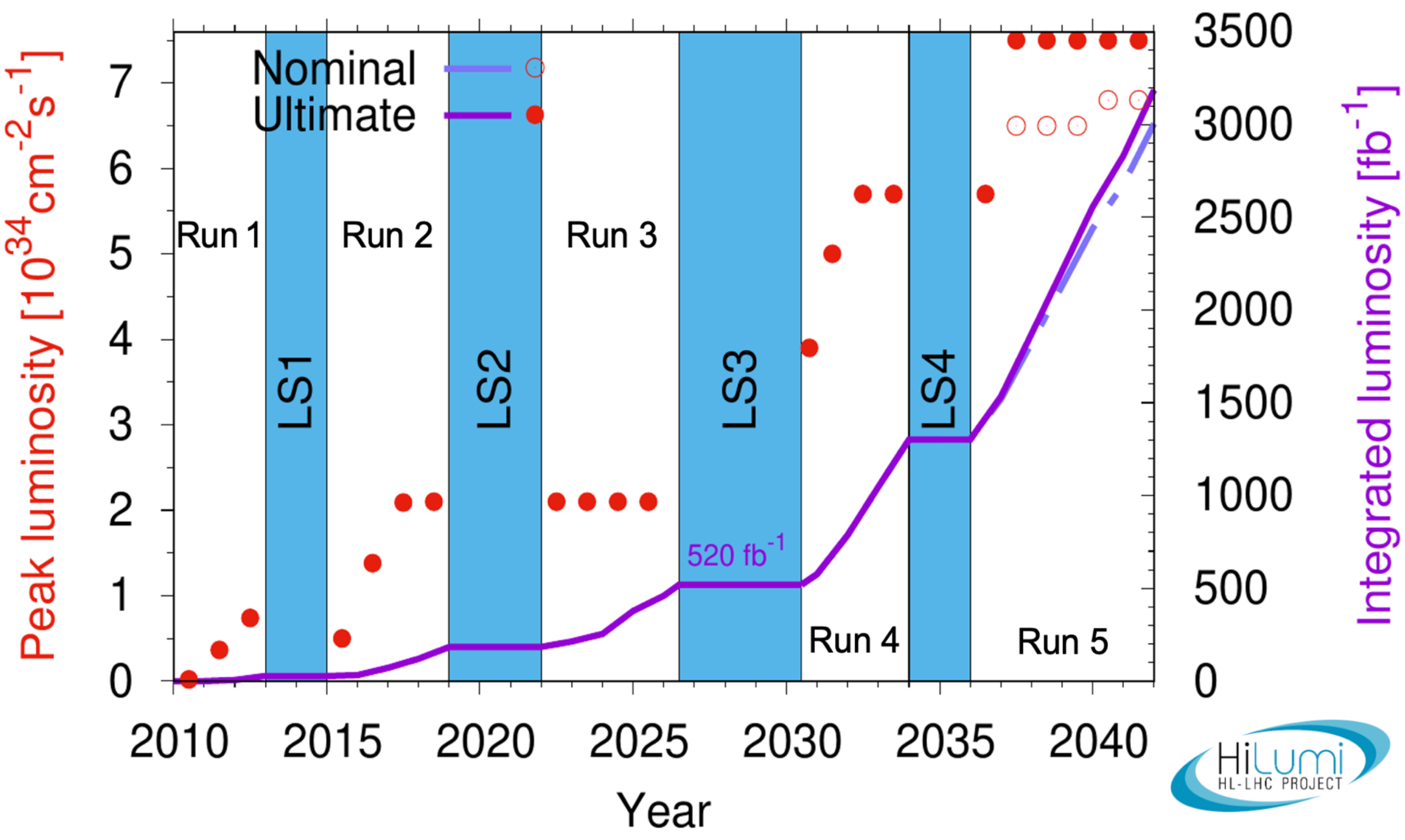
The ATLAS Detector

LIFETIME OF THE LHC

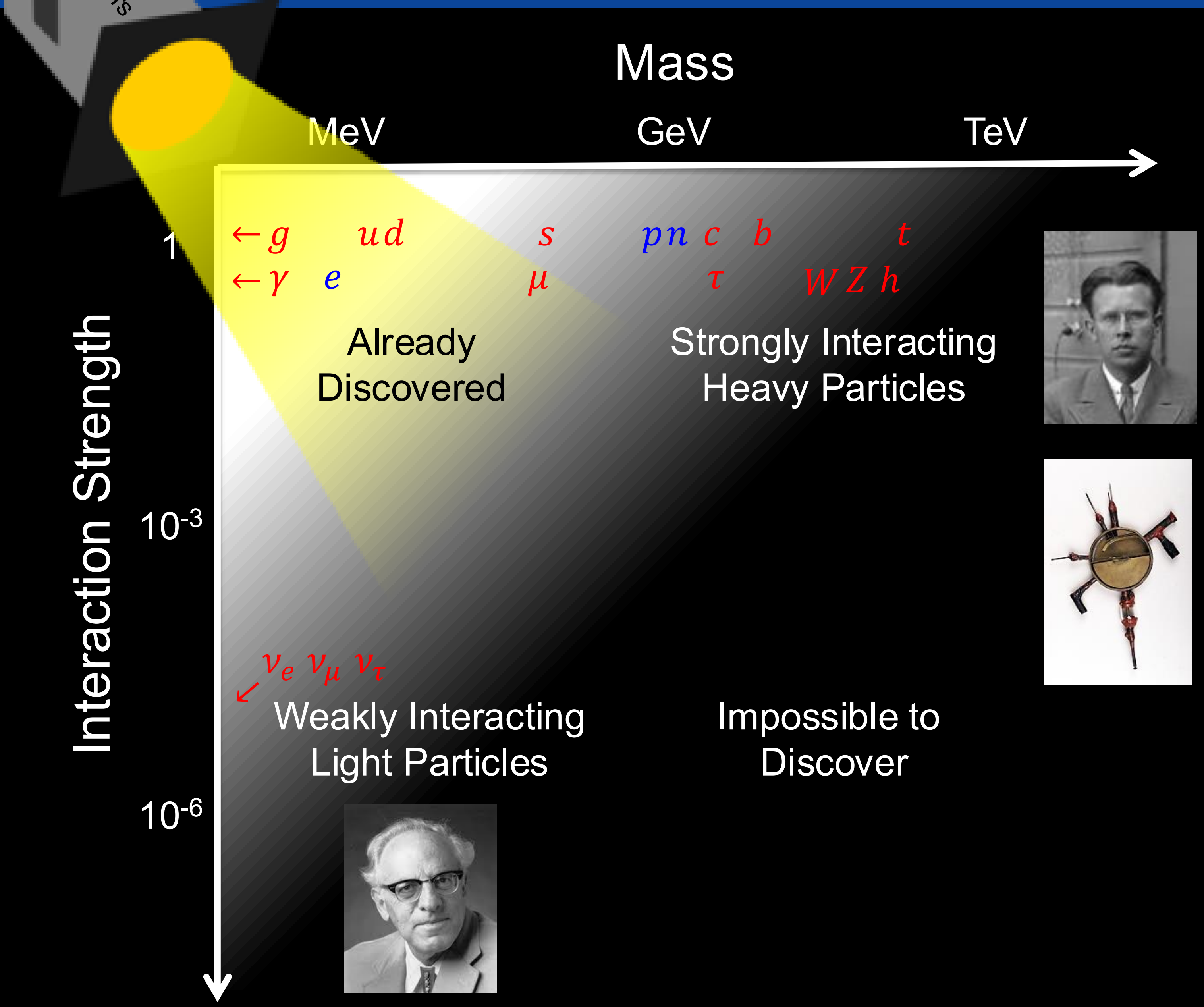
- The LHC became the future of particle colliders in 1993 when the US canceled the SSC.

- The LHC started running in 2010 and is scheduled to run until ~2042.
  - Middle-aged in terms of years
  - But a 12-year-old in terms of integrated luminosity (number of collisions)

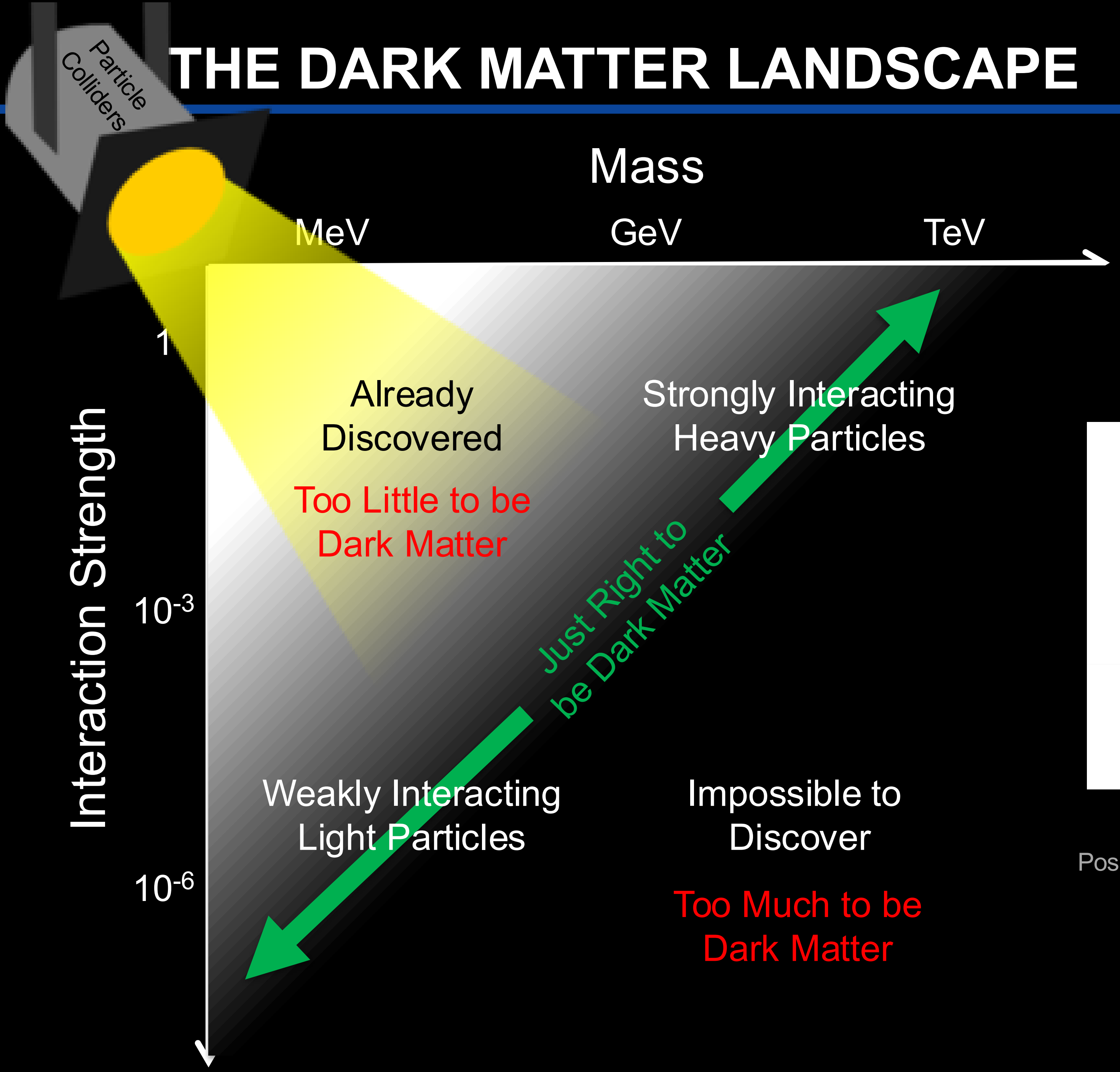
- Are we using the LHC to its full potential? What can we do to enhance its discovery prospects?

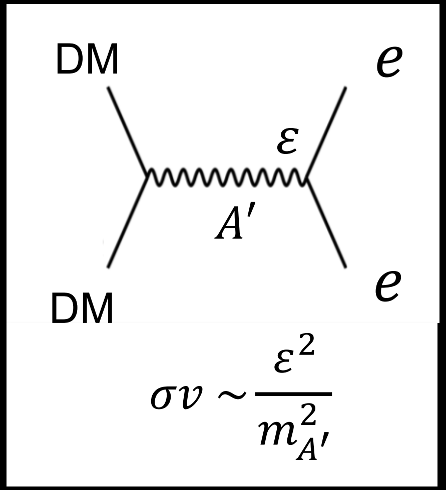


THE NEW PARTICLE LANDSCAPE



THE DARK MATTER LANDSCAPE





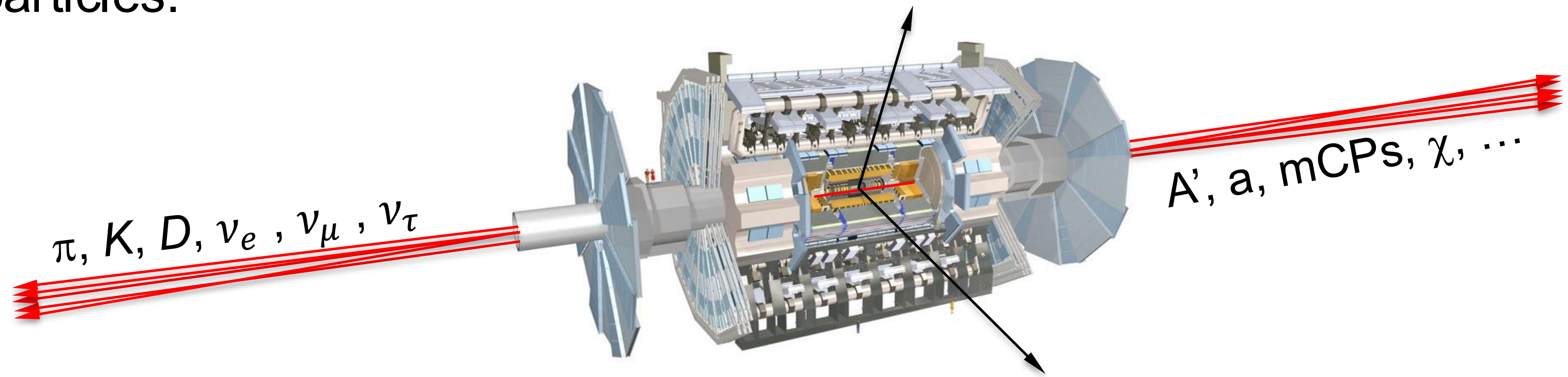
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

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.



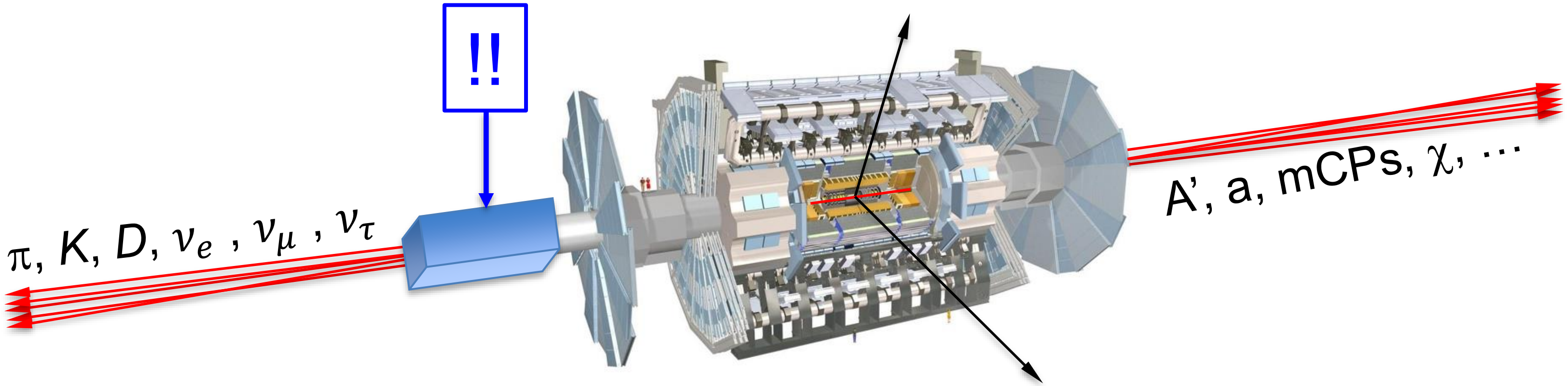
- But high-energy light particles are dominantly produced in the forward (and far-forward) direction (parallel to the beamline) and escape through the blind spots of these detectors.
  - This is true for all known light particles: pions, kaons, *D* mesons, all neutrinos.
  - It is also true for new, weakly-interacting particles motivated by neutrino mass and dark matter.

De Rujula, Ruckl (1984)

- "These blind spots are the Achilles heels of the large LHC detectors." – Dave Casper

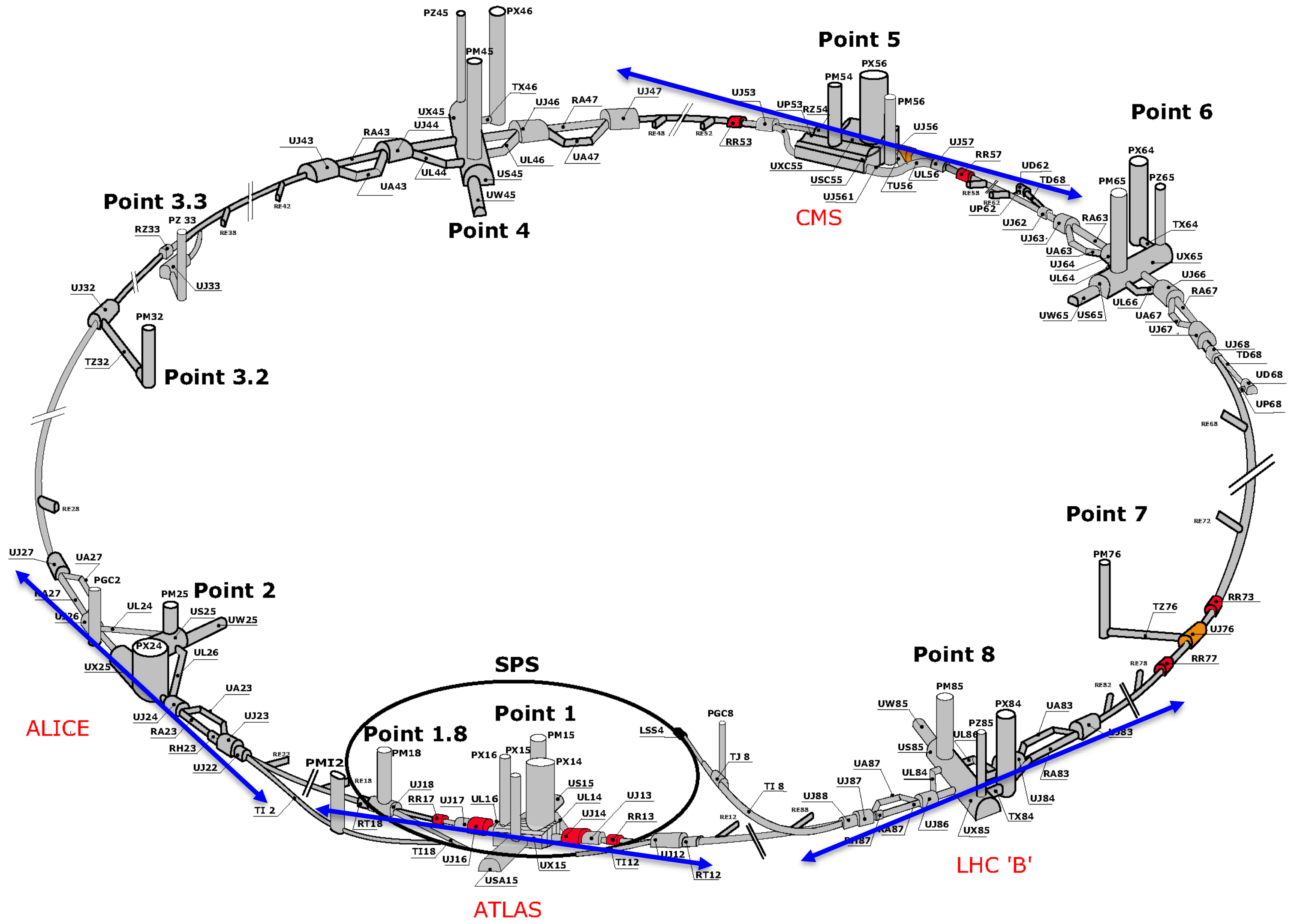
DETECTING FORWARD PARTICLES

- Problem: How can we detect forward particles? We can't just put a detector there, because it will block the protons from coming in and colliding.



- 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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Point 1.8
Point 2
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Point 3.3
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Point 5
Point 6
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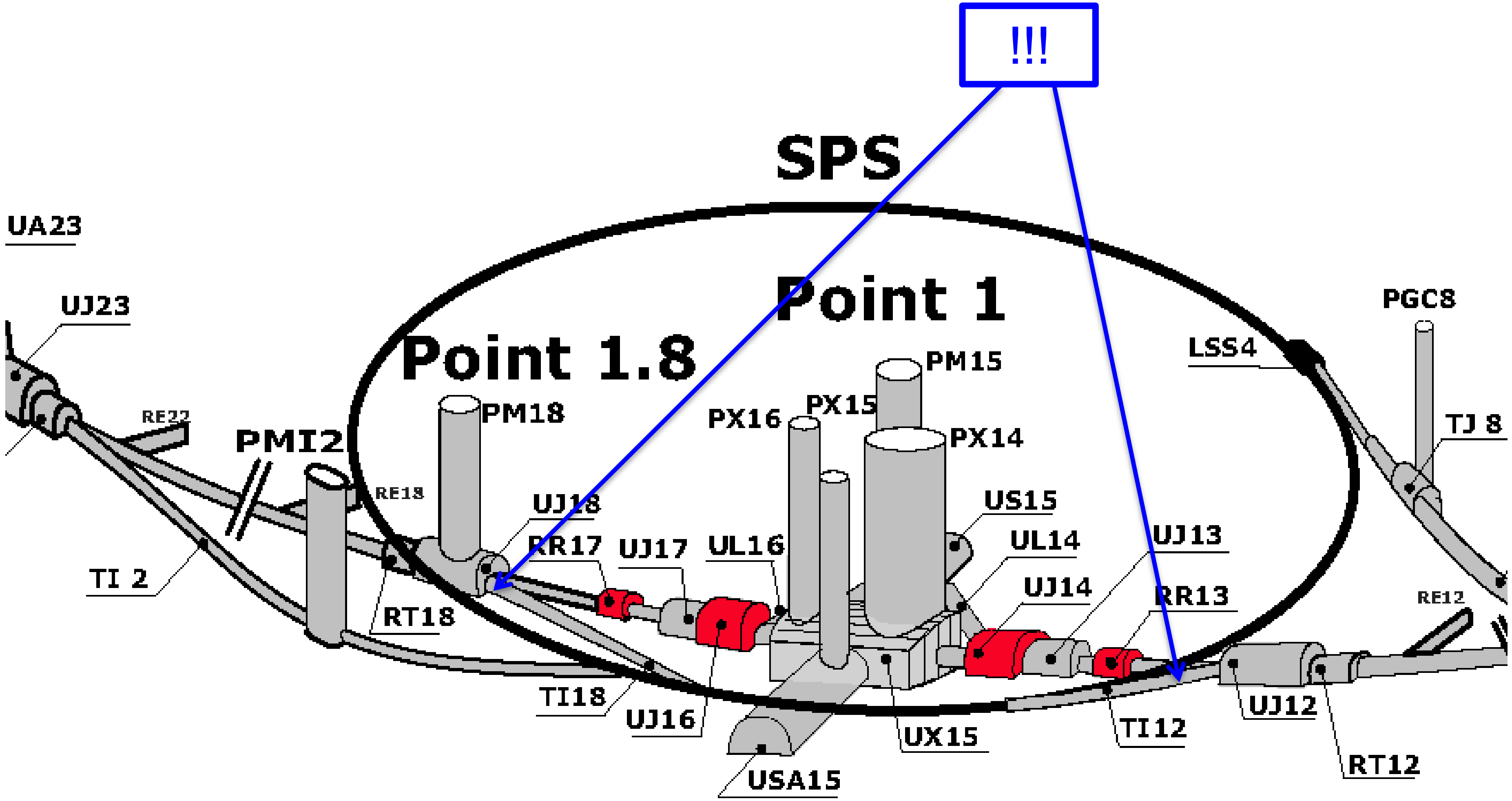
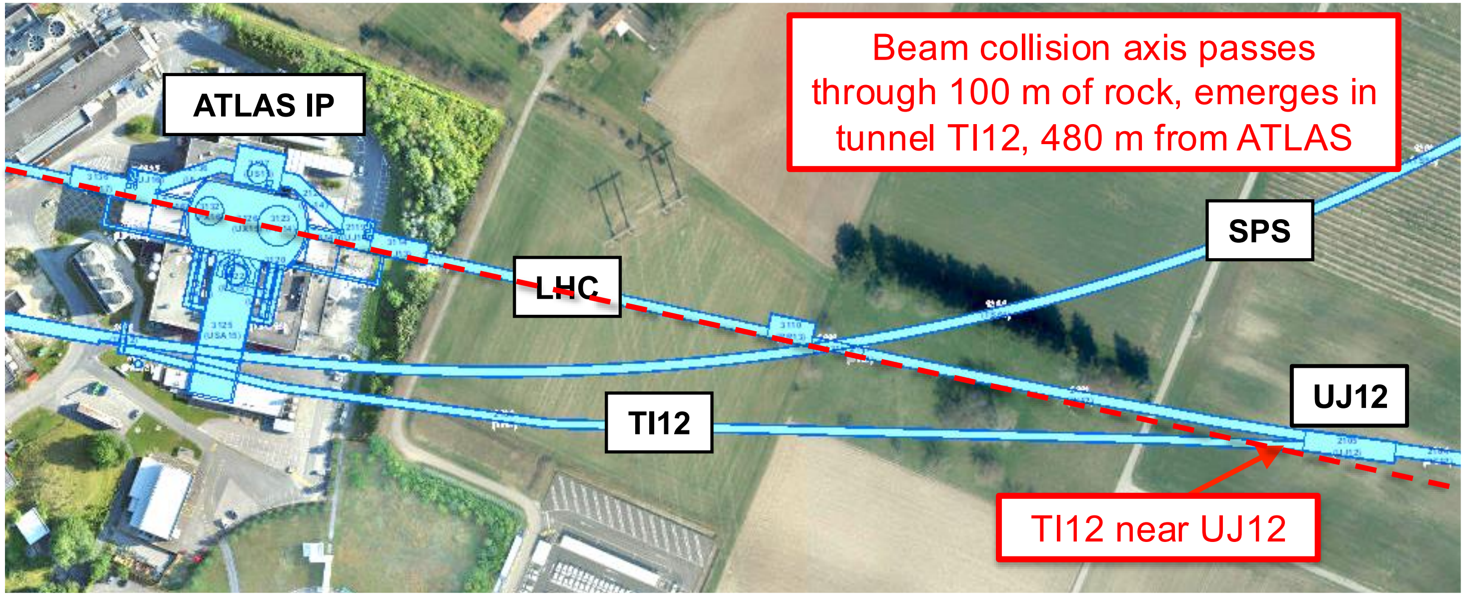
Point 8
SPS
CMS
ALICE
ATLAS
LHC 'B'

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 has 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 and collided protons with protons at center-of-mass energies from 30-60 GeV.

HISTORY: THE FALL OF FORWARD PHYSICS

- During the 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, CERN Courier (2021).
- Bottom line: The collider was creating charm quarks, but experimentalists focused on the forward region and so missed them. (Good for MIT!)
- 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?

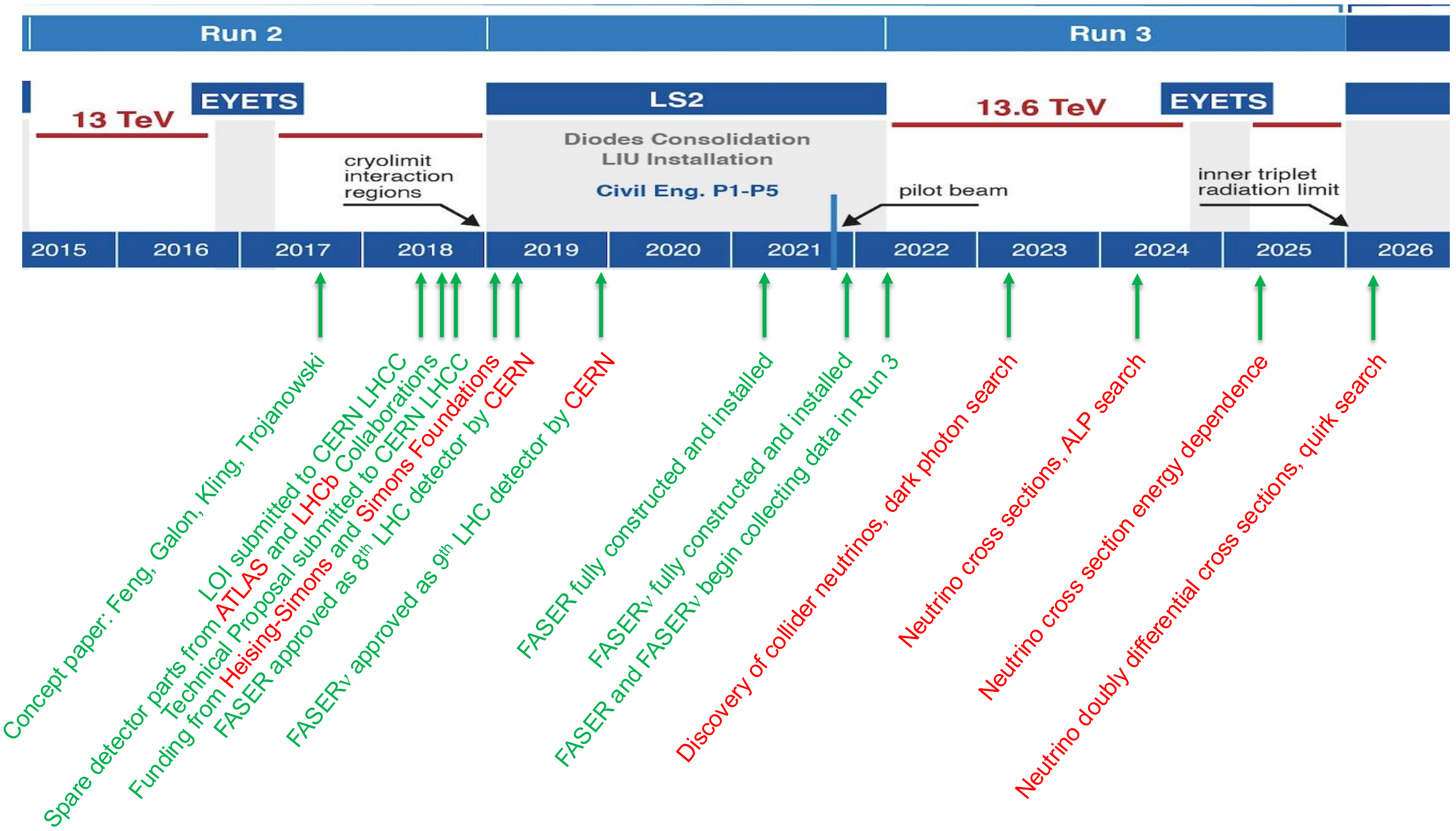
- Momentum: 250 MeV
  1 TeV
- Space: 12 cm
  480 m

- The opening angle is 0.2 mrad (pseudorapidity $\eta \approx 9$). The moon is 7 mrad.

- Even after traveling 480 m, most neutrinos and other proposed new particles pass through an 8.5” x 11” (A4) sheet of paper.

- This motivates a relatively small, fast, and inexpensive experiment at the LHC: the ForwArd Search ExpeRiment (FASER).

FASER TIMELINE



FASER COLLABORATION

124 collaborators, 27 institutions, 11 countries

International laboratory
covered by a cooperation
agreement with CERN

FASER AND THE LHC

THE FASER DETECTOR

THE FASER DETECTOR

2207.11427

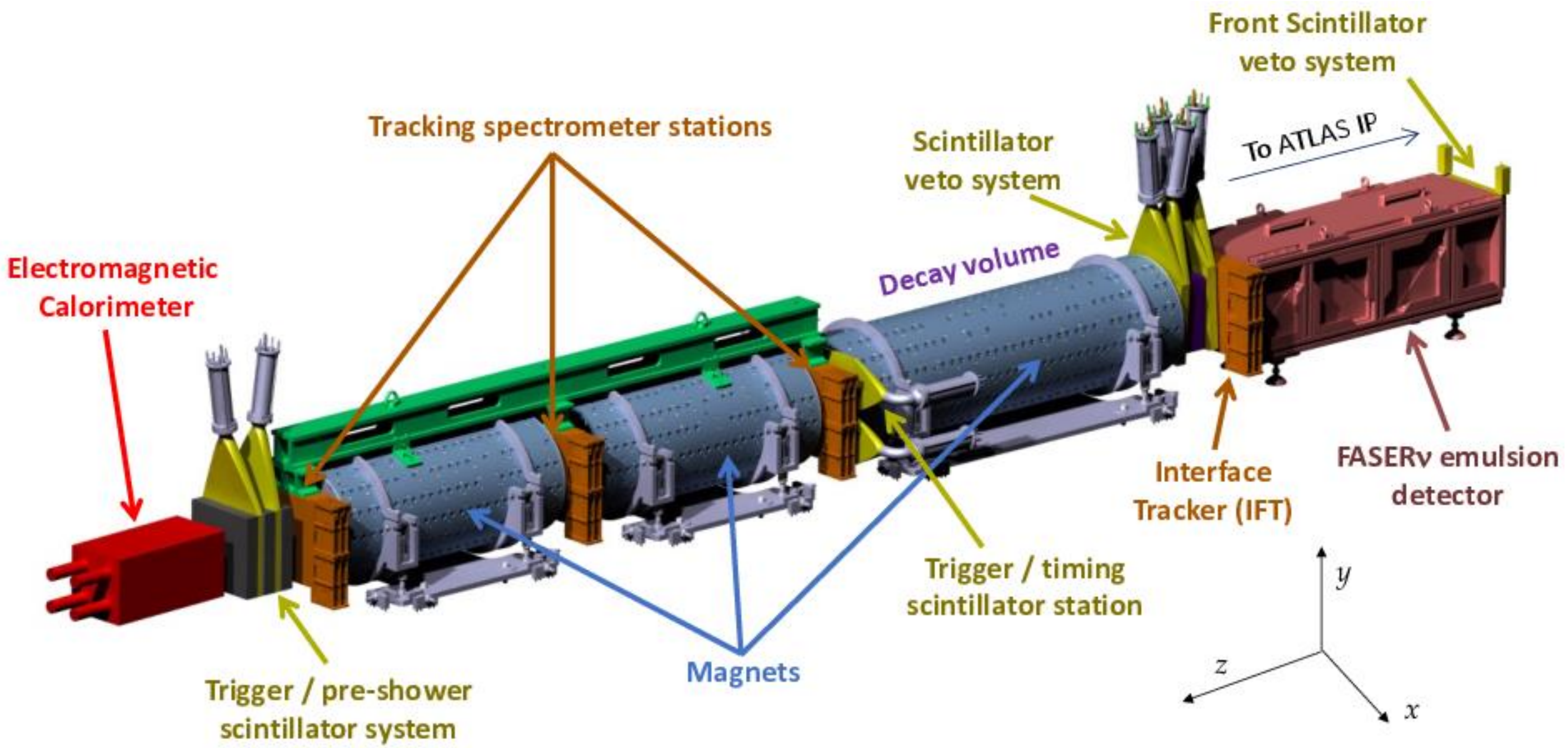
The experimental environment: 88 m underground, shielded from ATLAS by 100 m of rock → extremely quiet. Trigger on everything, ~kHz trigger rate dominated by muons from ATLAS.

Design challenges:

no space, no time, no access.

Size: Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.

FASERν: 730 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}.



Calorimeter: 2 x 2 LHCb ECAL modules.

Magnets: 3 permanent dipoles (Halbach design), 0.57 T, deflect charged particles in y.

Scintillators: 4 stations, each 1-2 cm thick, >99.999% efficient. 4-layer veto ~ $(10^{-5})^4 \sim 10^{-20}$.

Trackers: 4 stations x 3 layers x 8 modules = 96 ATLAS SCT modules.

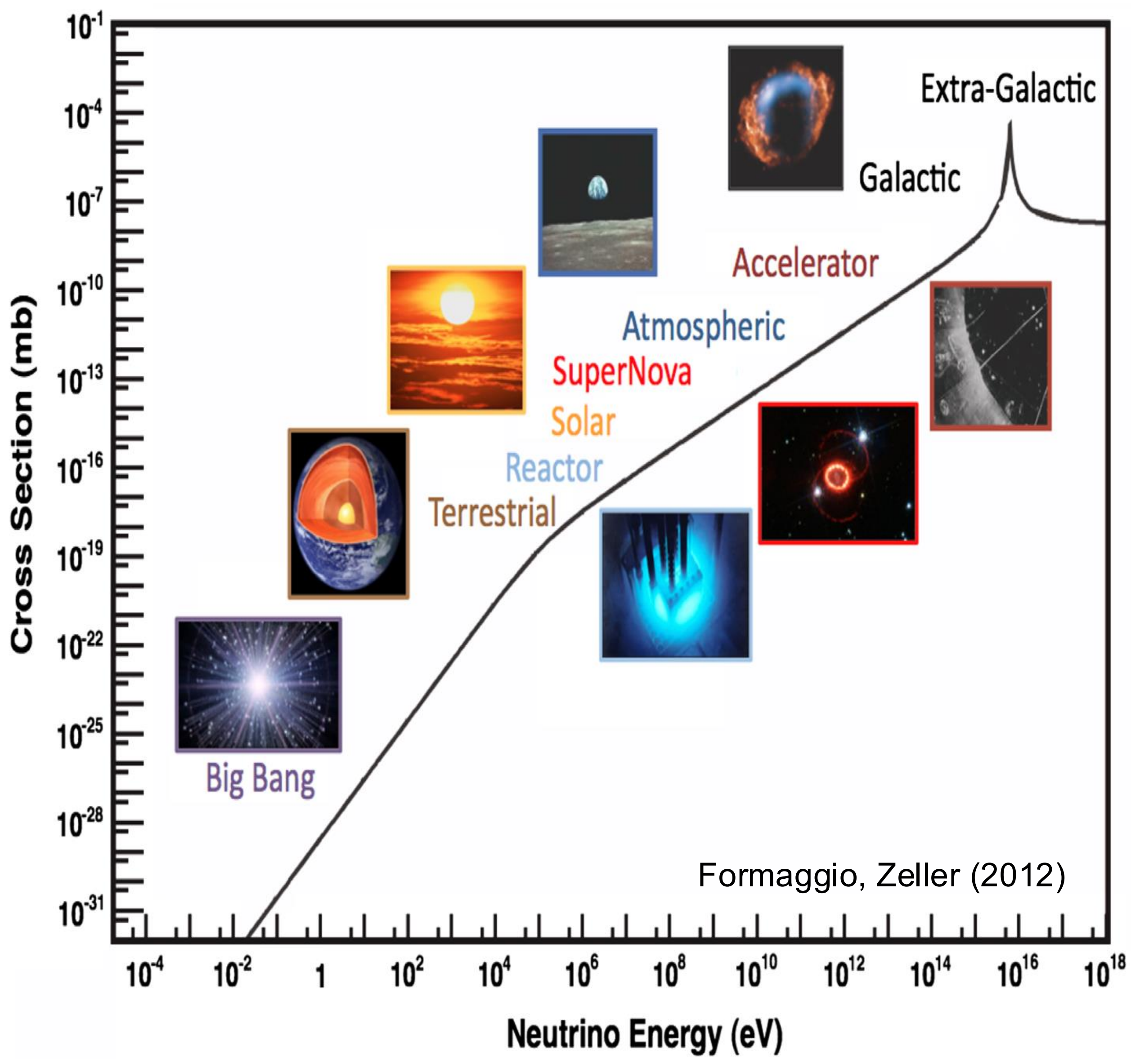
NEUTRINOS

COLLIDER NEUTRINOS

- Neutrinos are the least understood of all particles, and the only ones with confirmed BSM properties (their mass).

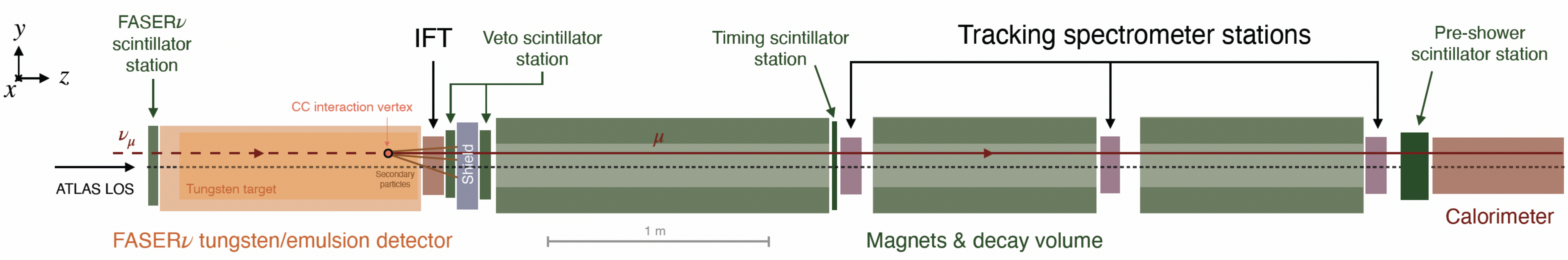
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.

- But before FASER, neutrinos produced at a particle collider had never been directly detected.
  - Conventional wisdom: neutrinos interact too weakly to be seen.
  - But this is not quite true: the real problem is that most of the highest energy (most interacting) neutrinos pass through the blind spots of existing detectors.



COLLIDER NEUTRINO SEARCH

- Neutrinos produced at the ATLAS IP travel 480 m 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)

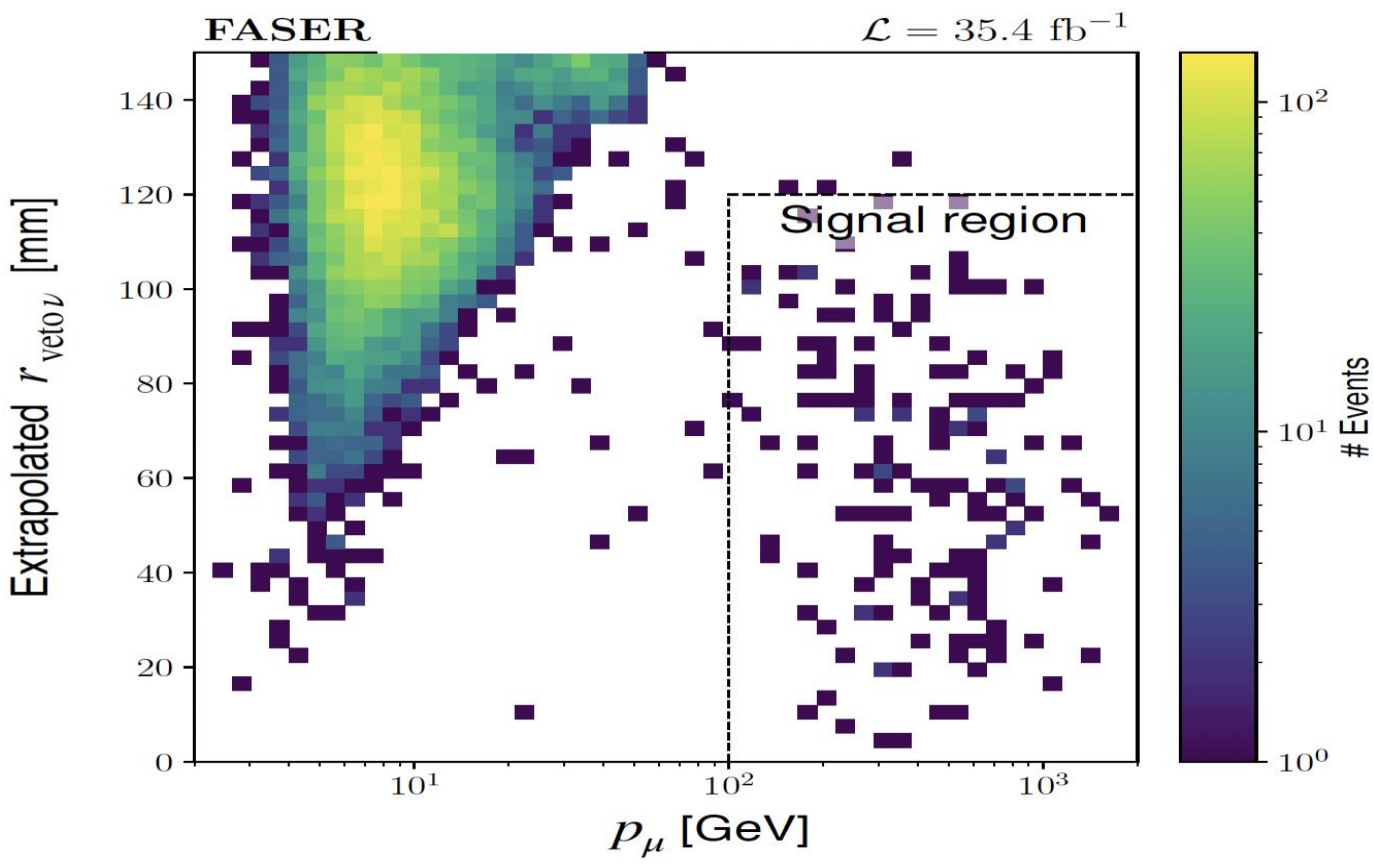
- Backgrounds are extremely suppressed
  - 100 m of rock and concrete between ATLAS and FASER removes almost all particles.
  - The remaining particles are neutrinos and muons, and the muons are removed by requiring no hits in the scintillators.
- In the end, $\lesssim 1$ background event expected, an essentially background-free search.

COLLIDER NEUTRINO RESULTS

- Expect 151 $\pm$ 41 neutrino signal events from simulations, with the large uncertainty arising from poorly understood flux of forward hadrons.

- In 2022, after unblinding, we found 153 signal events
  - 1st direct detection of collider neutrinos
  - ~16σ signal
  - The most energetic neutrinos ever observed from a controlled source
  - Muon charge → ν and $\bar{\nu}$

- Later confirmed by 8 events from SND@LHC, located on the other side of ATLAS.



FASER Collaboration (2303.14185, PRL)

VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester

Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113


FASER observes first collider neutrinos
Physics • CERN

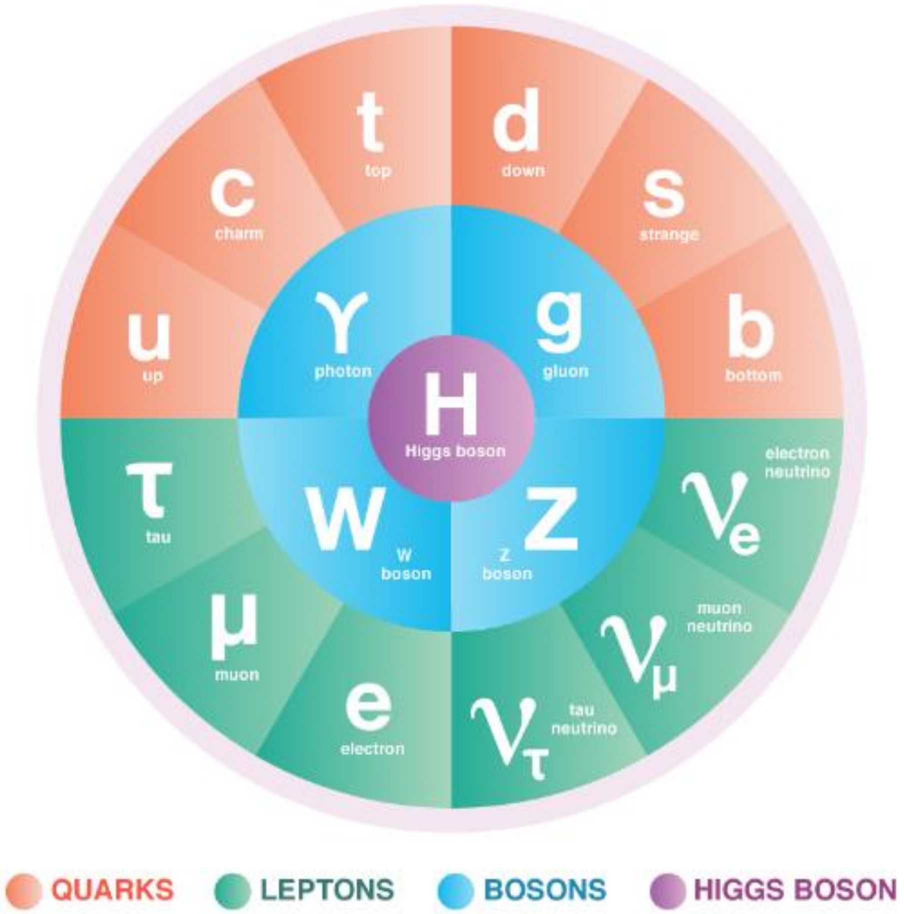
AFTER DISCOVERY: WHAT ARE THESE NEUTRINOS GOOD FOR?

- There are actually 6 kinds of neutrinos with very different characteristics: ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$.
  - Not all are produced in all ways. E.g., nuclear reactors, where neutrinos were first discovered by Fred Reines, only make $\bar{\nu}_e$.
  - Some are even harder to detect than others. E.g., only 19 tau neutrinos have been directly detected, and the $\bar{\nu}_\tau$ has not yet been directly detected.

- Colliders produce all 6: e.g., $\pi^+ \rightarrow \nu_\mu$, $K^+ \rightarrow \nu_e$, $D_s^+ \rightarrow \nu_\tau$, and the charge conjugate processes make anti-neutrinos.

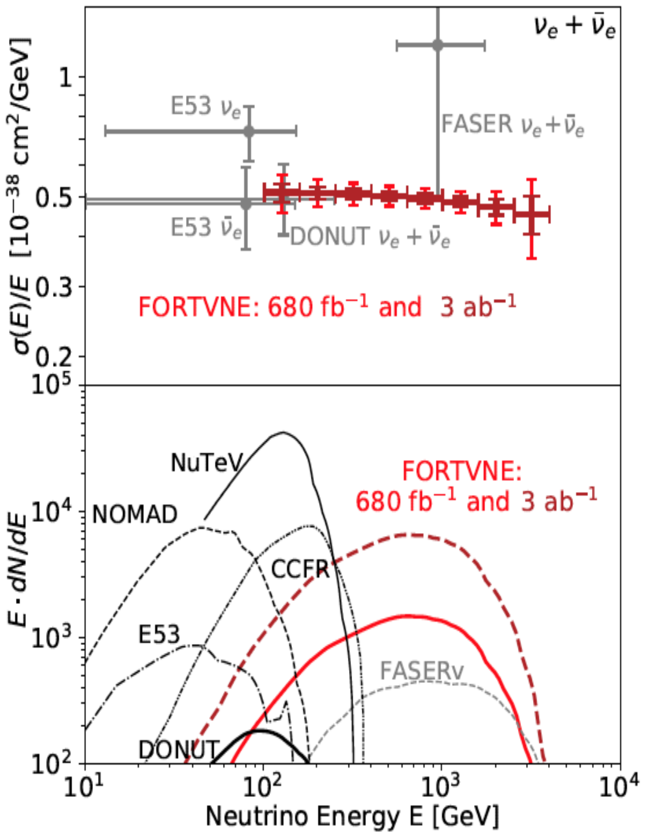
- We would like to detect all 6 neutrinos and study them in detail.

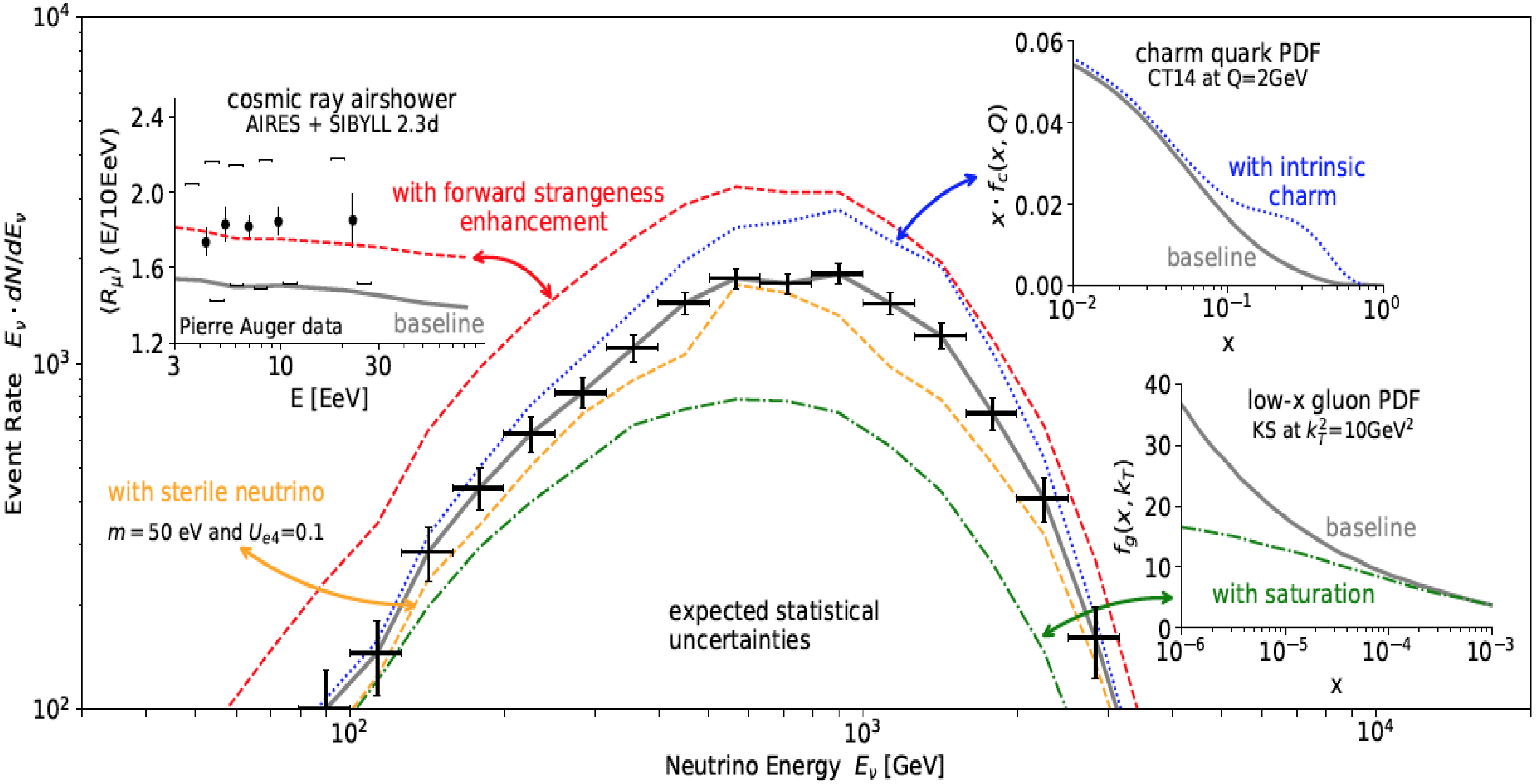
- This will shed light on neutrinos and also allow us to use neutrinos to shed light on other topics.



PHYSICS POTENTIAL OF COLLIDER NEUTRINO STUDIES

- An example: the electron neutrino event rate as a function of energy will tell us about
  - New forms of matter (sterile neutrinos)
  - The structure of protons and nuclei (gluon and quark parton distribution functions)
  - The properties of cosmic ray air showers (the cosmic muon puzzle)

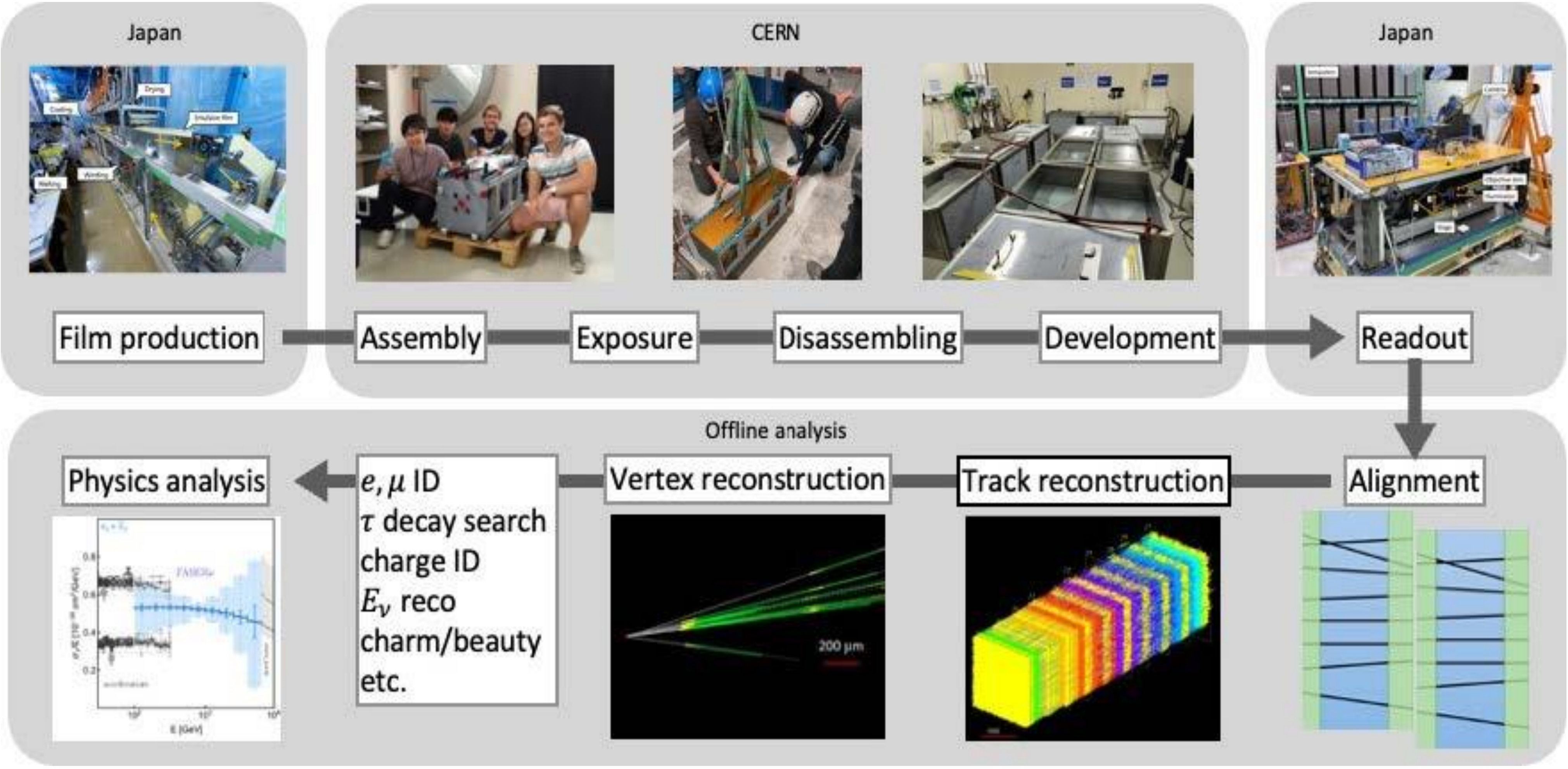




FASERν

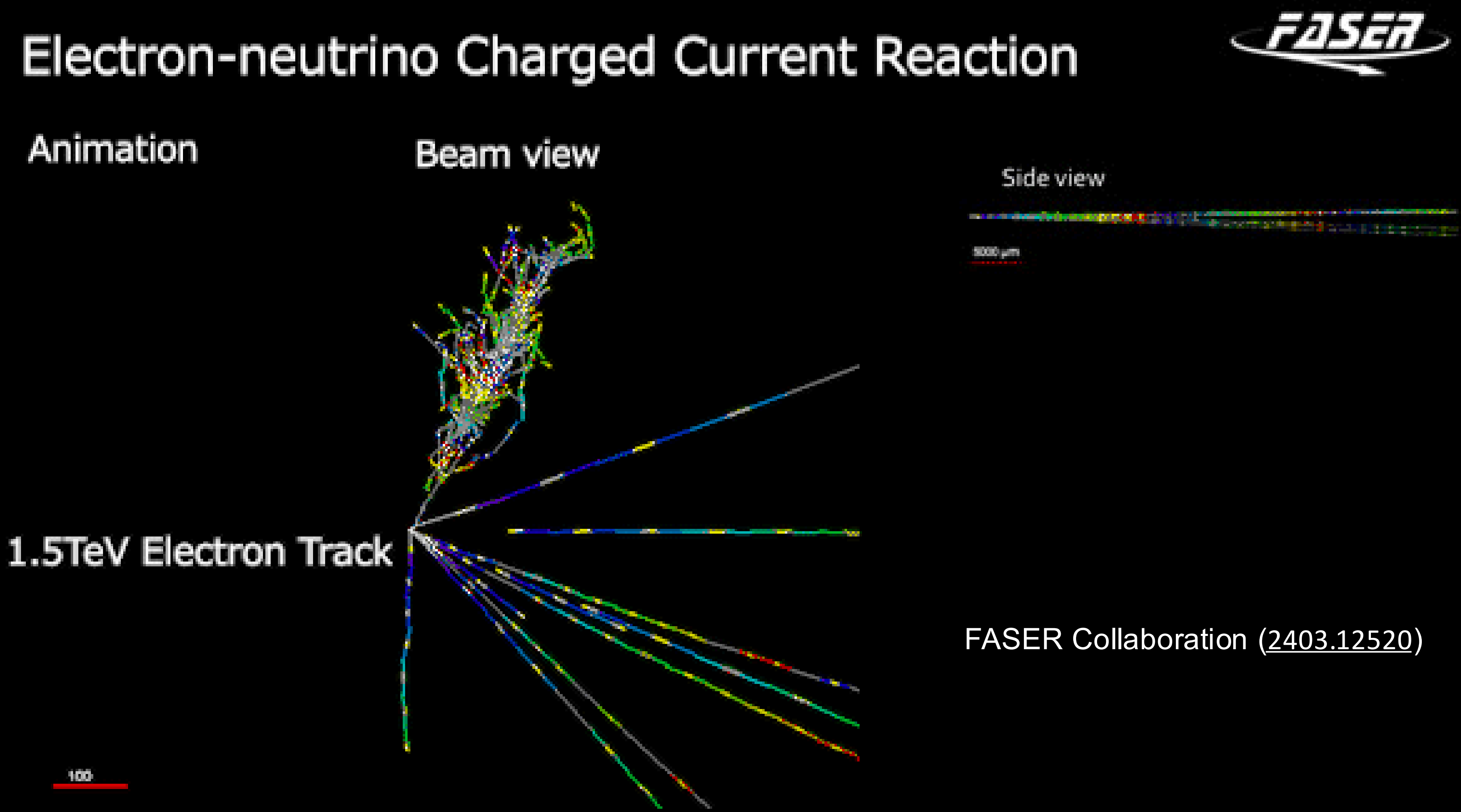
The first neutrinos detected were muon neutrinos in FASER's electronic detector.

But at the front of FASER is FASERν, a 1.1-ton block of 730 interleaved tungsten and emulsion plates. The first neutrino analysis treated this as a big block of matter, but the emulsion provides a photographic image with extraordinary spatial resolution (0.3 microns).



FIRST DETECTION OF COLLIDER ELECTRON NEUTRINOS

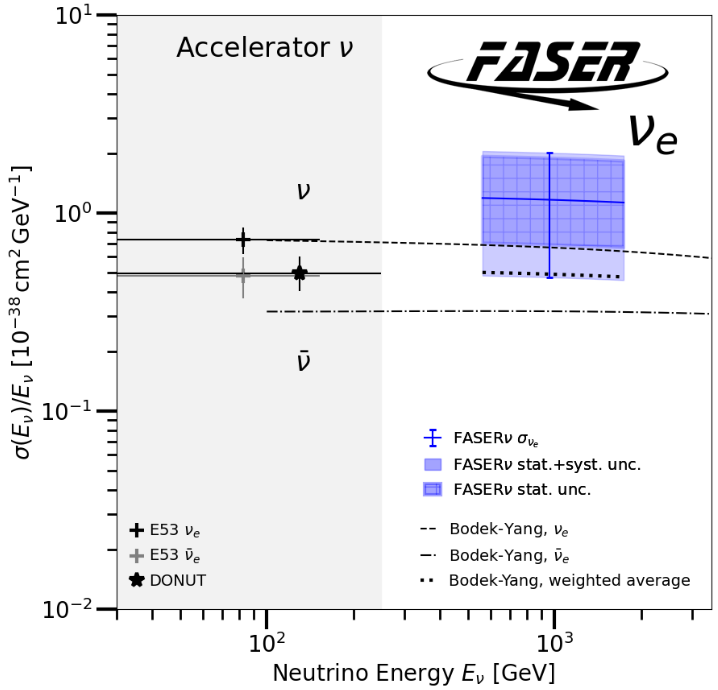
With FASERν, we observed the first collider electron neutrinos, including the "Pika-ν" event, the highest energy (>1.5 TeV) electron neutrino ever seen from a lab source.

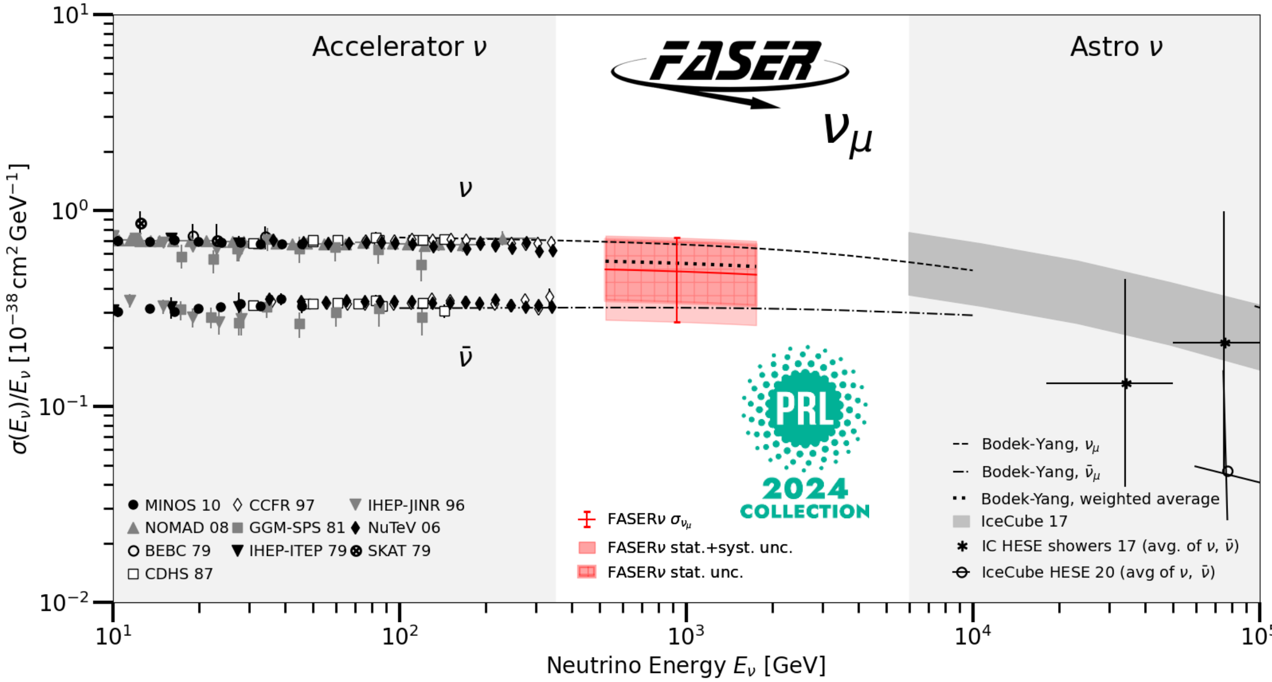


FASER Collaboration (2403.12520)

TEV NEUTRINO INTERACTION STRENGTHS

- After these discoveries, we have moved on to studies, including the first measurement of neutrino cross sections at TeV energies. Results so far are consistent with SM DIS predictions.





FASER Collaboration (2403.12520)

- Highlighted as 1 of 6 particle physics papers selected for the PRL Collection of 2024.

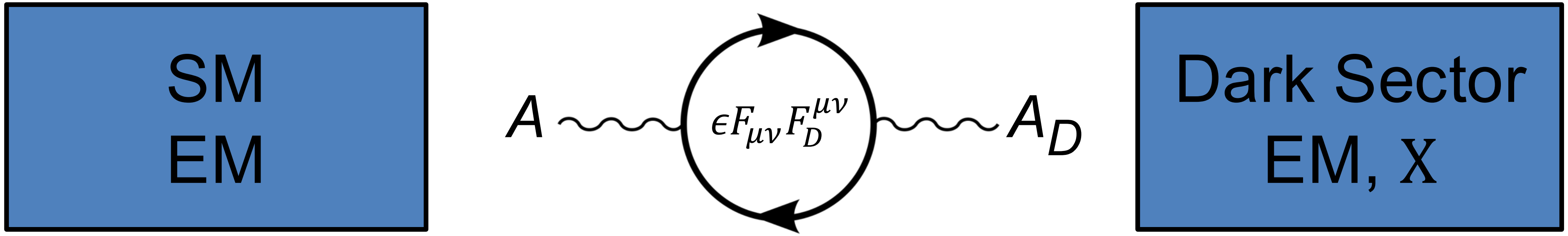
- These measurements used only 1.7% of the data collected in 2022 and 2023. FASER has now seen hundreds of neutrinos, measured the cross section as a function of energy, published doubly differential cross sections.

CERN-FASER-CONF-2026-005

DARK SECTORS
NEW PARTICLES

NEW PARTICLE SEARCHES

- FASER is also looking for new dark particles, new fundamental forces, and new forms of matter.
- 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 a mass $m_{A'}$, couplings suppressed by ϵ.

Holdom (1986)

- For low ϵ, dark photons are very weakly-interacting, long-lived particles. A huge field of activity in both cosmology and particle physics. At CERN, these include ongoing and proposed searches at ATLAS, CMS, LHCb, MilliQan, NA62, NA64, SHiP, Codex-b, ANUBIS, FORMOSA, …
- For FASER, dark photons can be produced in ATLAS in meson decays, pass through rock and magnetic fields unhindered, and then decay through $A' \to e^+e^-$ in FASER, producing a striking signature of 2 ~TeV-energy charged particles emerging from 100 m of rock.

DARK PHOTON SEARCH

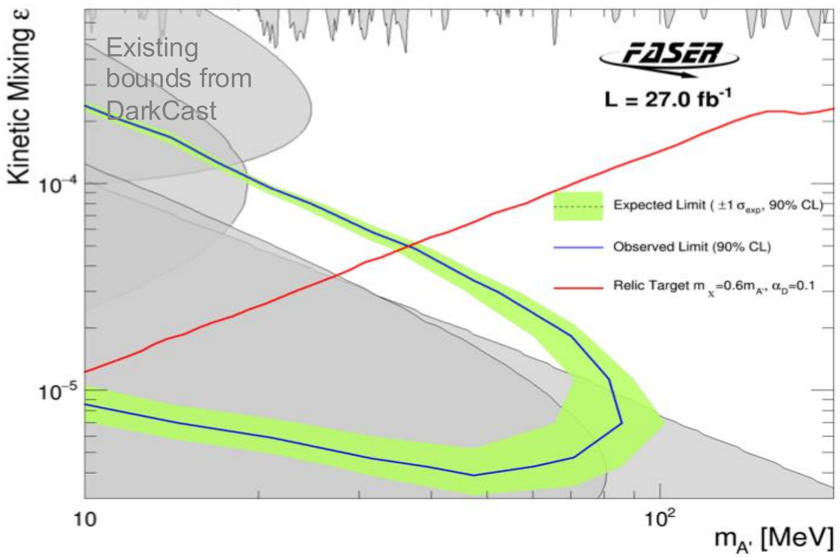
- In 2023, in a blind analysis of 2022 data, no events were seen, and FASER set limits on previously unexplored parameter space.
  - First new probe of the parameter space favored by dark matter relic density arguments from low coupling since the 1990's.
  - Started probing new parameter space on Day 1 (0.3 fb^{-1})
  - In this region of parameter space, ended up ~100 times more sensitive than previous experiments

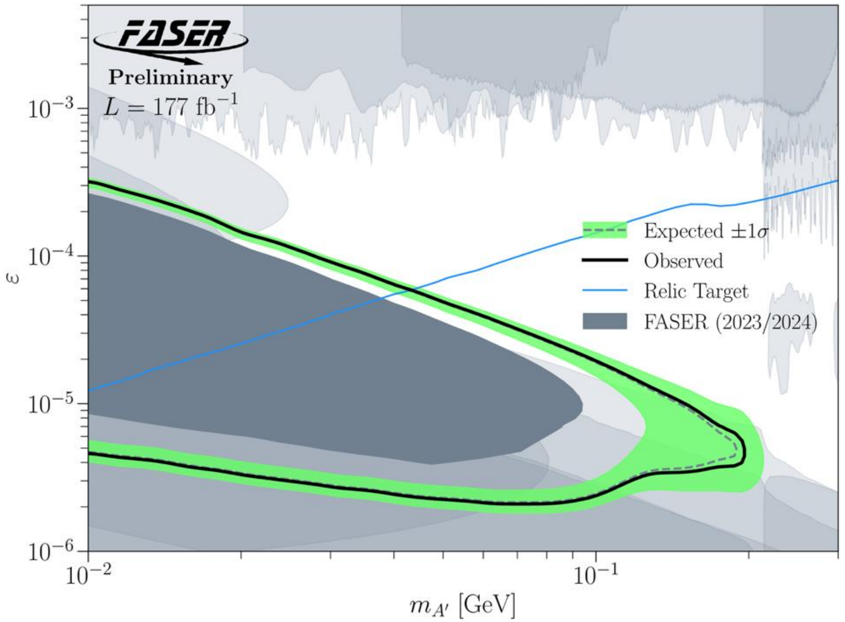
FASER Collaboration (2308.05587, PLB)

- In 2026, in another blind analysis, based on 2022-24 data, again no events were seen.
  - ~6x the amount of data.
  - ~3x more powerful analysis (more general signatures).

FASER Collaboration (CERN-FASER-CONF-2026-001)

- Prospects for the future
  - The analyses have been essentially background-free.
  - ~20x more data expected at the LHC.



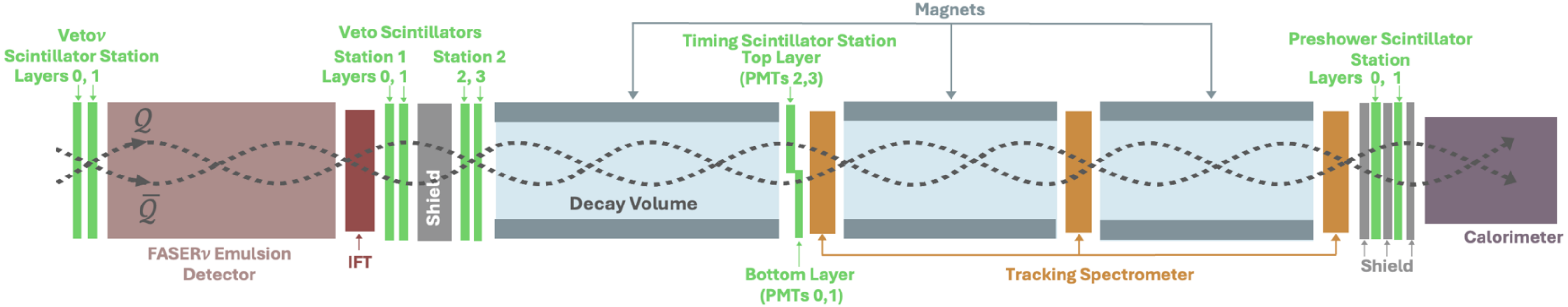


QUIRK SEARCH

- What if the dark sector does not have electromagnetism, but instead has particles bound together by a strong force, similar to QCD? Can get bizarre new particles: quirks.

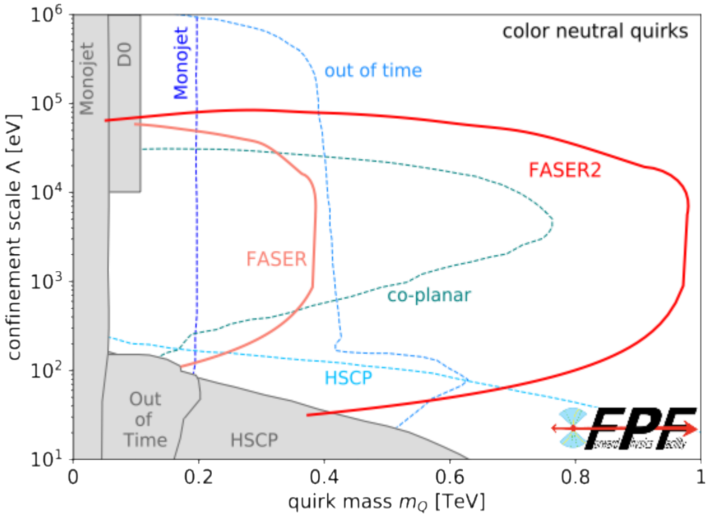
Kang, Luty (2008)

- Quirks are particles with dark QCD interactions and
  – Mass $m \sim$ O(100) GeV.
  – Confining scale $\Lambda_{\mathrm{QCD}}^{\mathrm{dark}} \ll m$.



- These particles cannot neutralize their color charge by popping pairs of quirks out of the vacuum. Instead, they oscillate around their center of mass and propagate slowly in the forward direction.

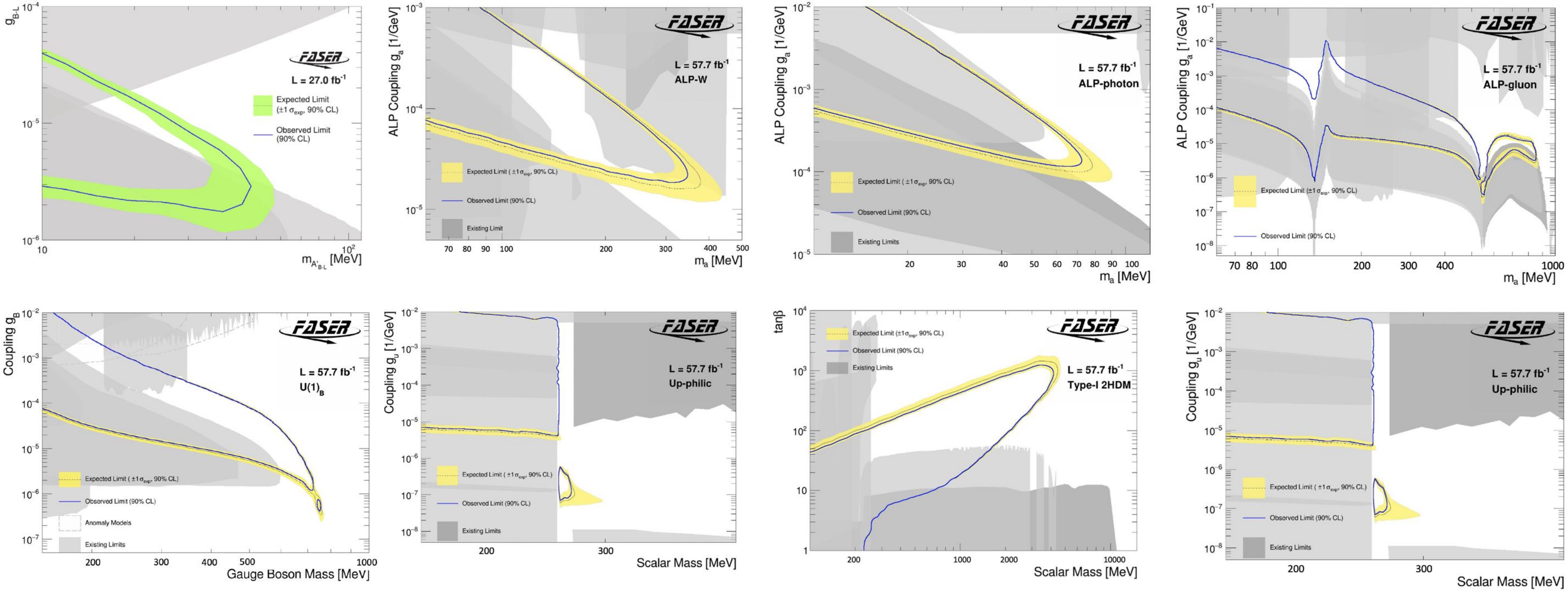
- By looking for 2 coincident tracks that are slow and delayed (out of time with bunch crossings), can discover quirks with masses well beyond current bounds. Turns FASER's liability (distance from ATLAS) into a virtue! Results coming soon (Eli Welch, UC Irvine student).



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

MORE NEW PARTICLE SEARCHES

We are also 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, etc., all with world-leading sensitivities in interesting regions of parameter space.



FASER Collaboration (2308.05587, PLB; 2410.10363)

FUTURE DETECTORS

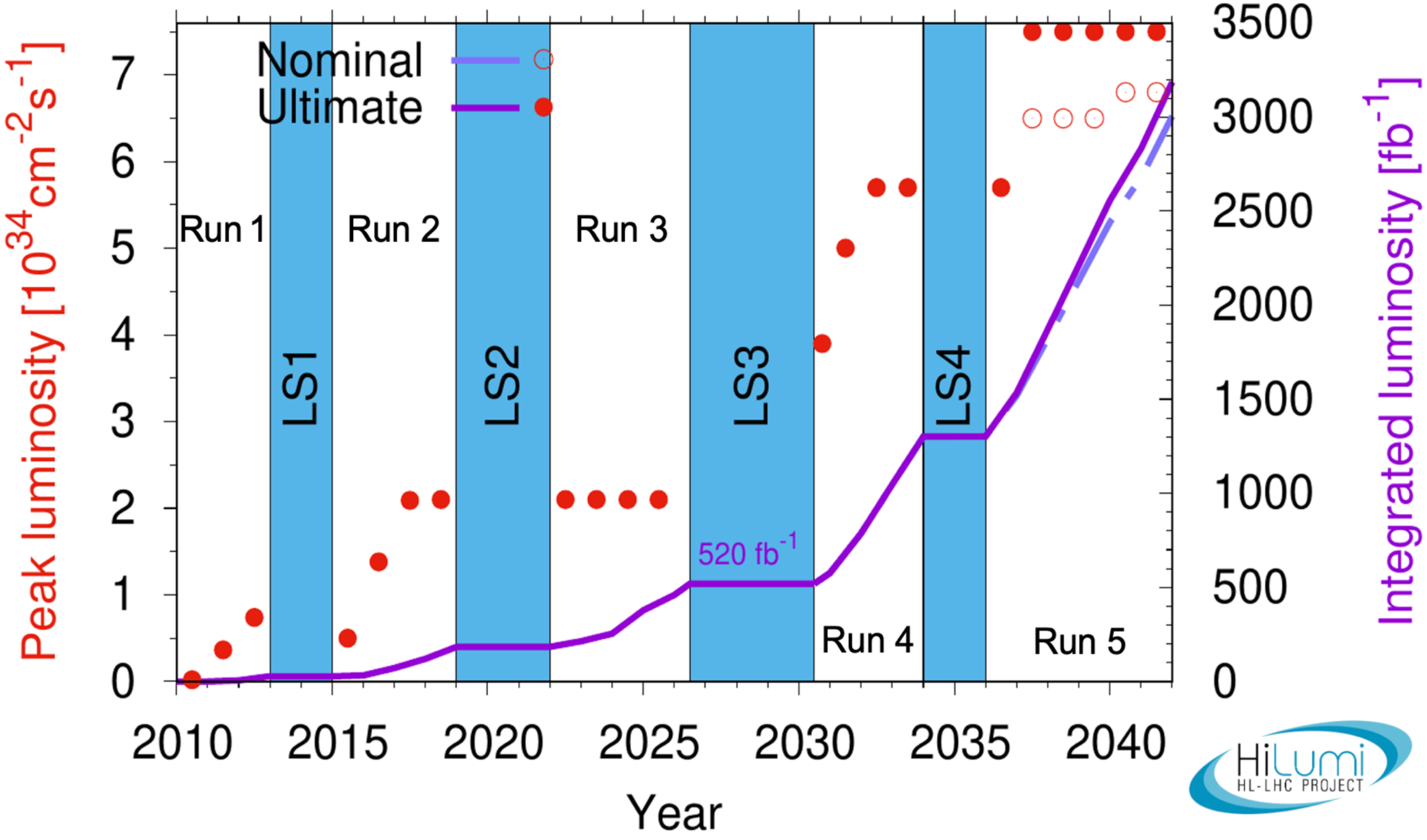
DETECTOR UPGRADES

- LHC Run 3 from 2022-2026 will continue for another few weeks until ~ May-June 2026.

- The LHC then enters Long Shutdown 3 from 2026-2029, and starts up again as the High-Luminosity LHC with Run 4 from 2030-2033, and Run 5 from 2036-2042.

- FASER is approved for Run 4, and there are many proposals to upgrade the detector.

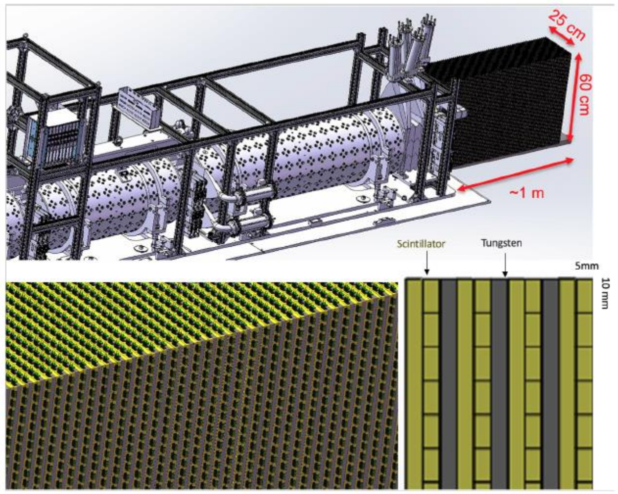
- In addition, there are plans to build the Forward Physics Facility, an entirely new detector hall.

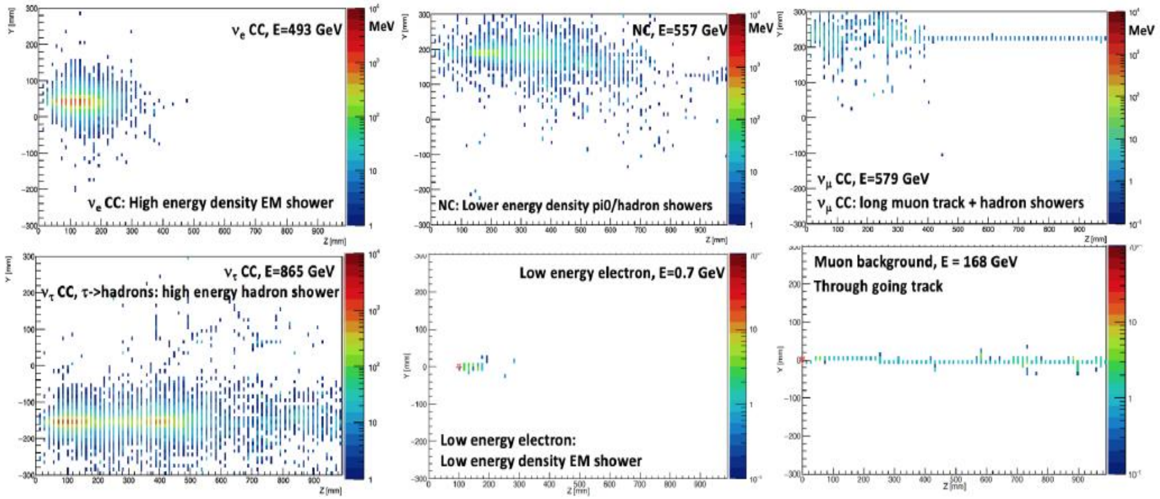


FORTVNE

- For Run 4, a group of us at UC Irvine has proposed the Forward TeV Neutrino Experiment (FORTVNE), a scintillator / tungsten detector, which will detect ~10,000 neutrinos.

- Different types of neutrinos produce different patterns of light in the detector; machine learning can help distinguish these neutrinos, measure their properties.

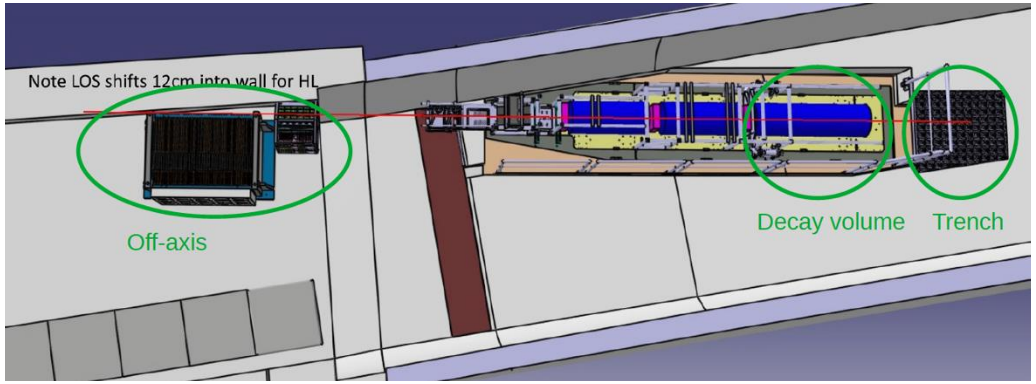


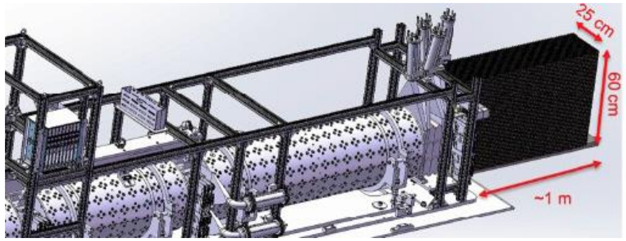


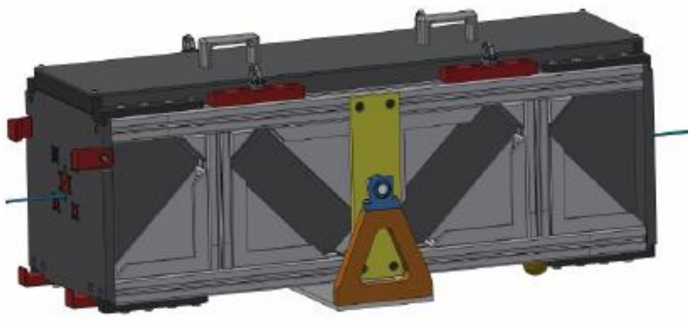
- Such detectors provide a remarkable opportunity for students to build an LHC detector from scratch, commission and install it, and collect and analyze data, all in the typical time it takes to get a PhD.

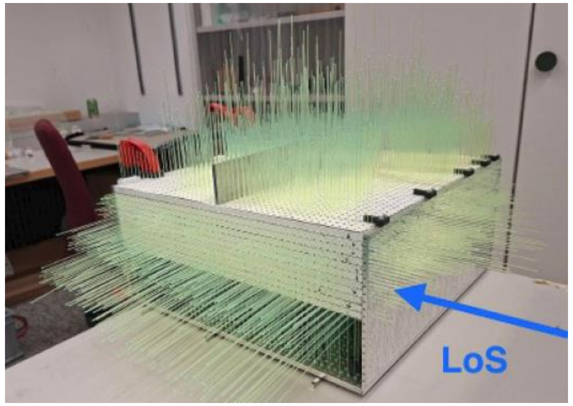
OTHER RUN 4 UPGRADE PROPOSALS

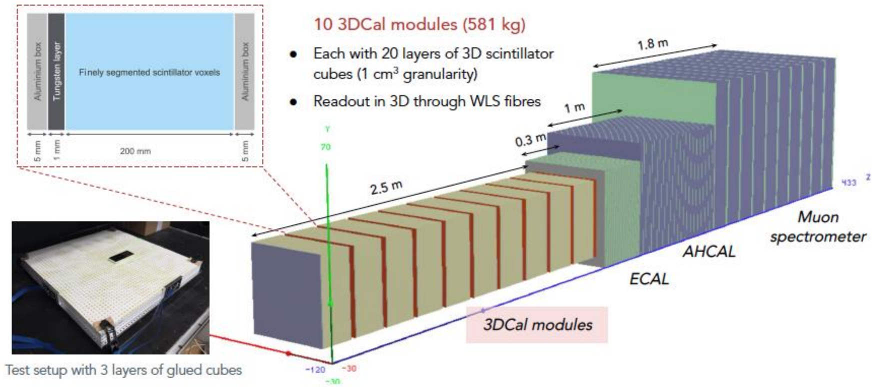
There are also many other Run 4 upgrade ideas from leading groups around the world, all vying to be placed on or near the LOS, with prototype detectors already built and installed, proposals being sent to funding agencies around the world. It has become a crowded field (literally).

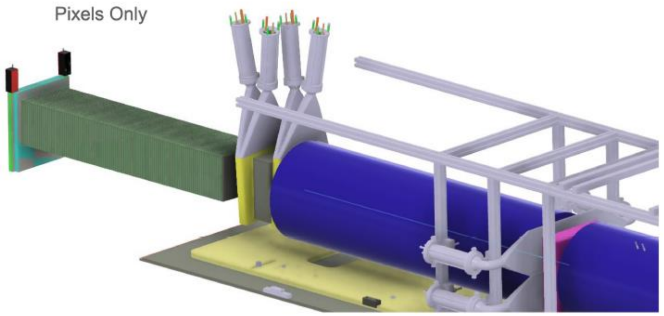










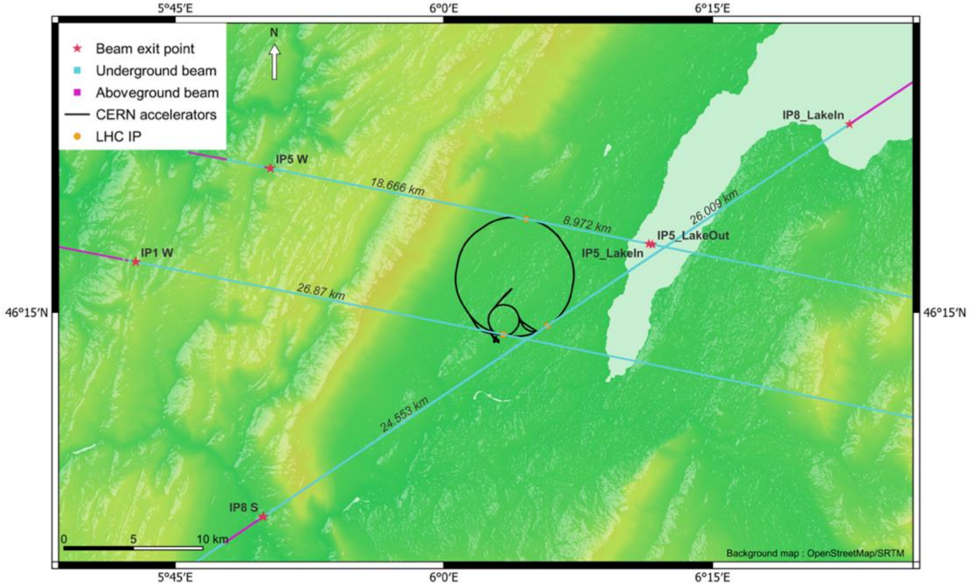


FLOUNDER

- Another interesting idea is to place a detector where the neutrino / new particle beams emerge from the ground. One proposal is FLOUNDER (Forward LHC Observatory Underwater for Neutrinos and the Dark sEctoR), led at UC Irvine by Steve Barwick (expt) and Toni Makela (theory postdoc). Another is by Nicholas Kamp and collaborators.

2501.06142, JHEP

- Beam emerges ~30 m under the surface of Lake Geneva. Building on experience with neutrino detectors in the Antarctic (IceCube), could place a row of shipping containers filled with water and PMTs in Lake Geneva.

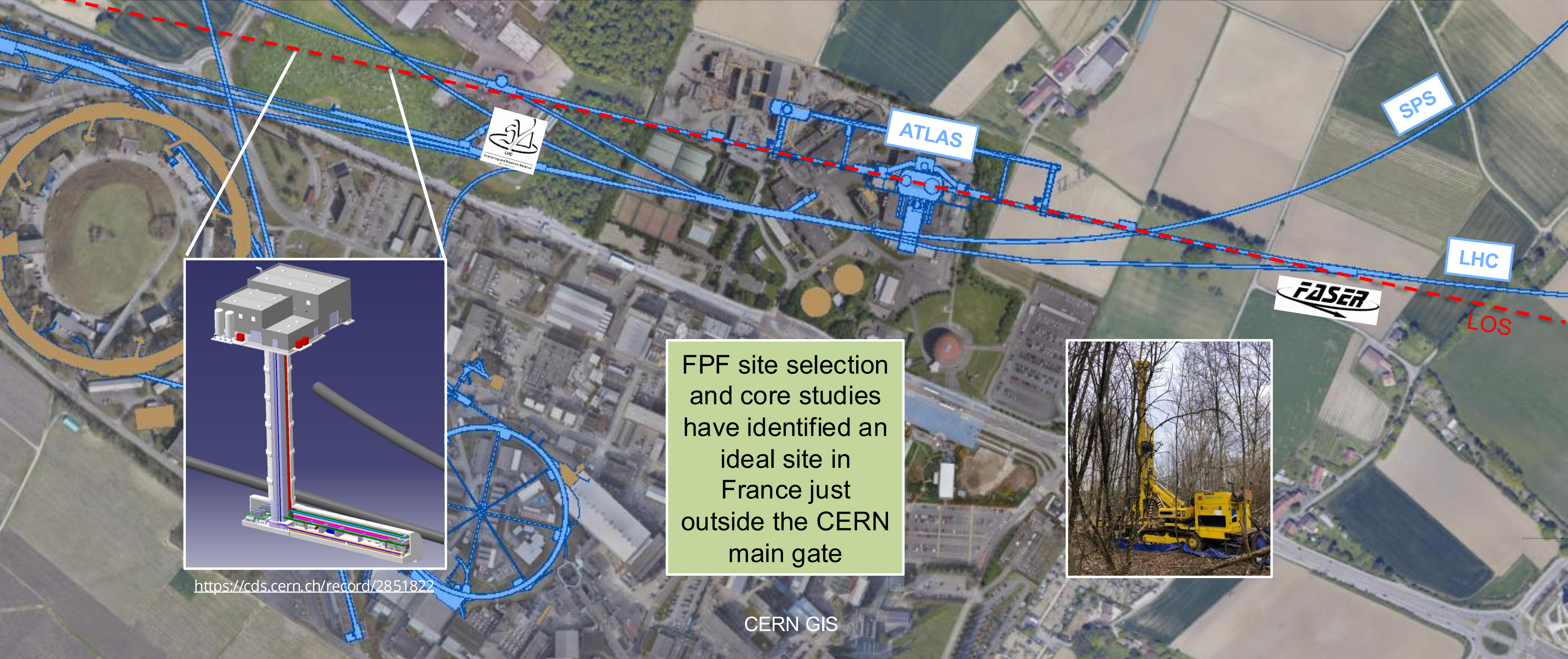


FPF

Forward Physics Facility

FORWARD PHYSICS FACILITY

CERN is also considering the possibility of excavating a new underground detector hall to house diverse forward experiments for the rest of the LHC's lifetime into the 2040s.



https://cds.cern.ch/record/2851822

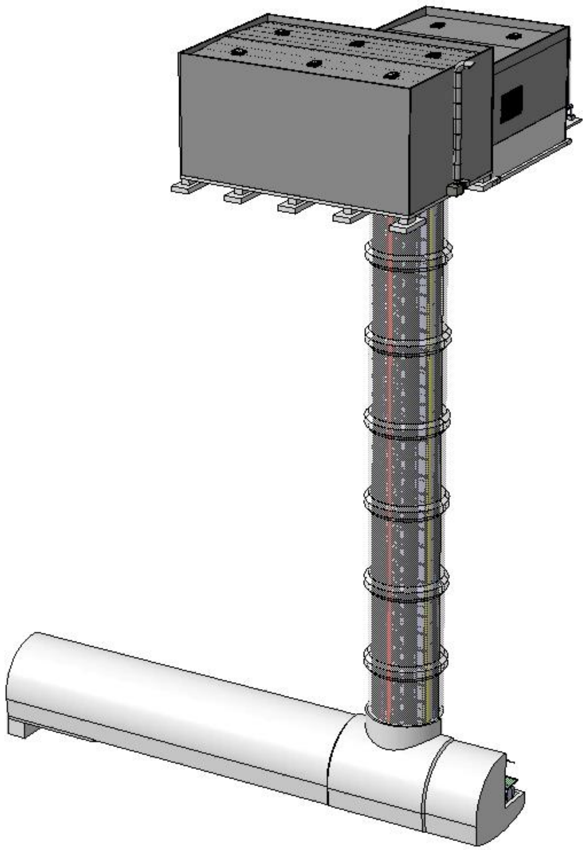
FPF site selection and core studies have identified an ideal site in France just outside the CERN main gate

CERN GIS

FORWARD PHYSICS FACILITY

ENGINEERING
DEPARTMENT

ACTEMIUM



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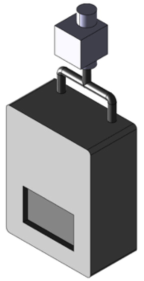
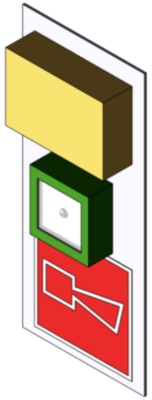
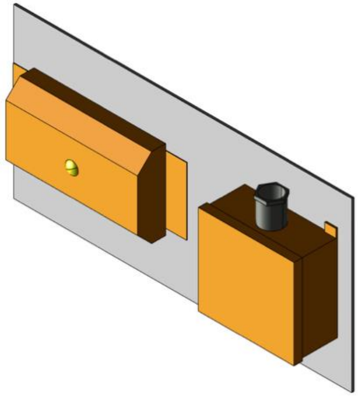
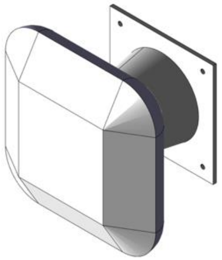
FORWARD PHYSICS FACILITY: SAFETY DESIGN

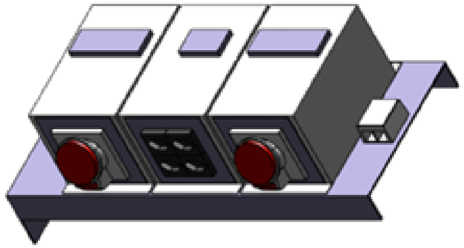

Fire detector

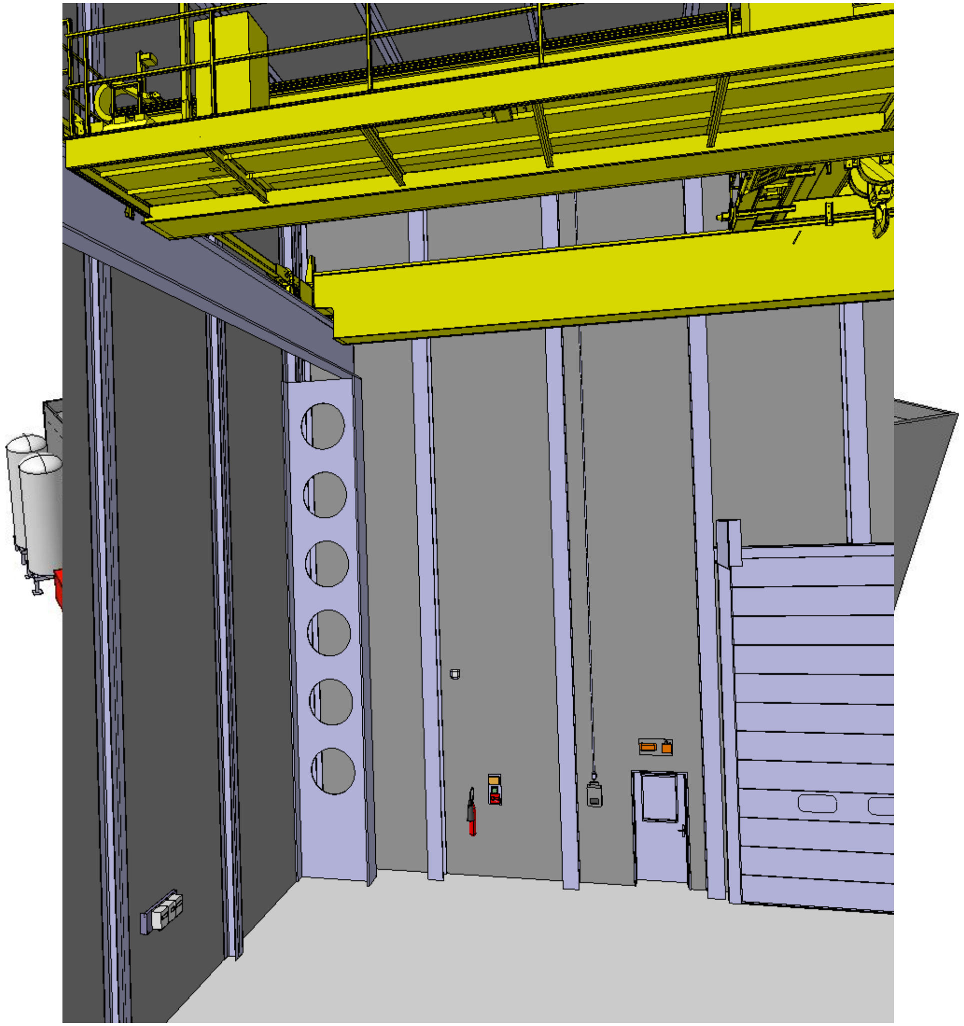

Evacuation panel


Anti Panic light


WIFI


Fire extinguisher


Electrical boxes



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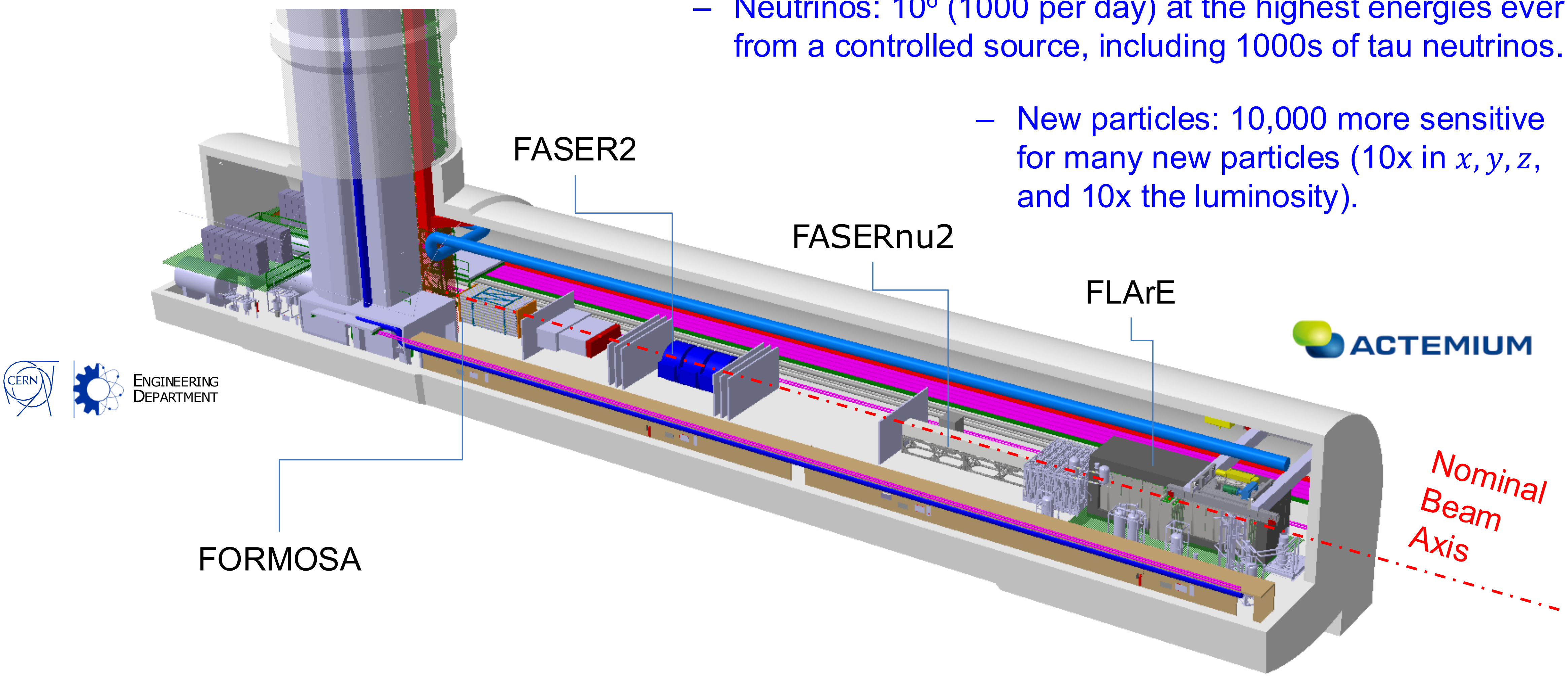
FORWARD PHYSICS FACILITY

4 experiments, all on the LOS to maximize the discovery potential of the LHC.

- Neutrinos: 10^6 (1000 per day) at the highest energies ever from a controlled source, including 1000s of tau neutrinos.
- New particles: 10,000 more sensitive for many new particles (10x in x, y, z, and 10x the luminosity).



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CONCLUSIONS

SUMMARY AND ACKNOWLEDGEMENTS

The forward region at particle colliders, neglected for decades, turns out to be a treasure trove of interesting physics. This can be mined with small, fast, inexpensive experiments to study neutrinos and look for new particles.

Is there another November revolution waiting for us in the forward region?

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