COLLIDER NEUTRINOS

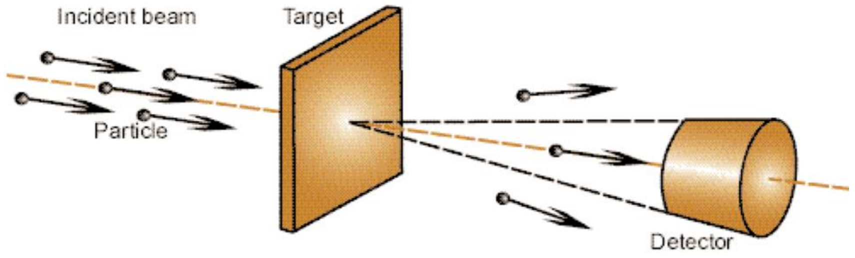
Neutrino University, Neutrino Physics Center, Fermilab

Jonathan Feng, UC Irvine, 1 July 2026

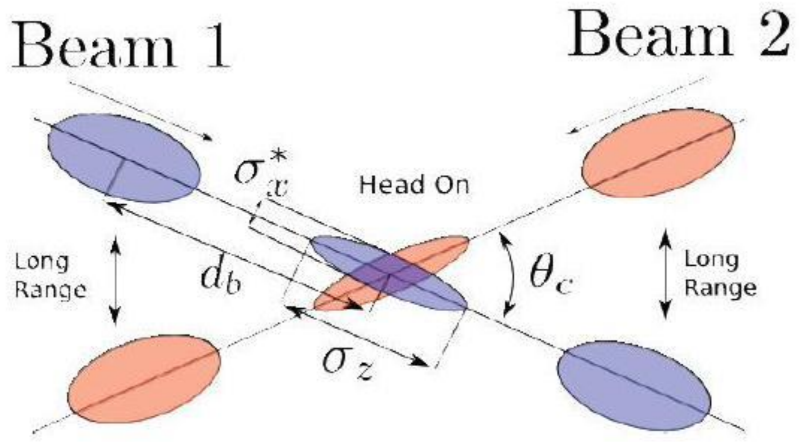
WHAT IS THE DEFINITION OF "COLLIDER"?

- Previous Neutrino University lectures this year have covered Atmospheric, Solar, and Astrophysical Neutrinos, Reactor Neutrinos, and Accelerator Neutrinos. How many of you have attended these?
- This lecture is about Collider Neutrinos. What distinguishes Accelerator Neutrinos from Collider Neutrinos?
  - Accelerator: 1 beam. Collider: 2 beams.
- Shooting a beam of protons into a block of matter is easy – with just a little bit of matter, almost every proton interacts, produces neutrinos. In fact, we characterize the number of interactions by POT: protons on target.
- Getting two beams of protons to interact is hard – have to focus them, most don't interact, don't produce neutrinos. We characterize the number of interactions by the luminosity, which depends on the number of protons in each beam, but also how much we are able to focus the beams.

Accelerator

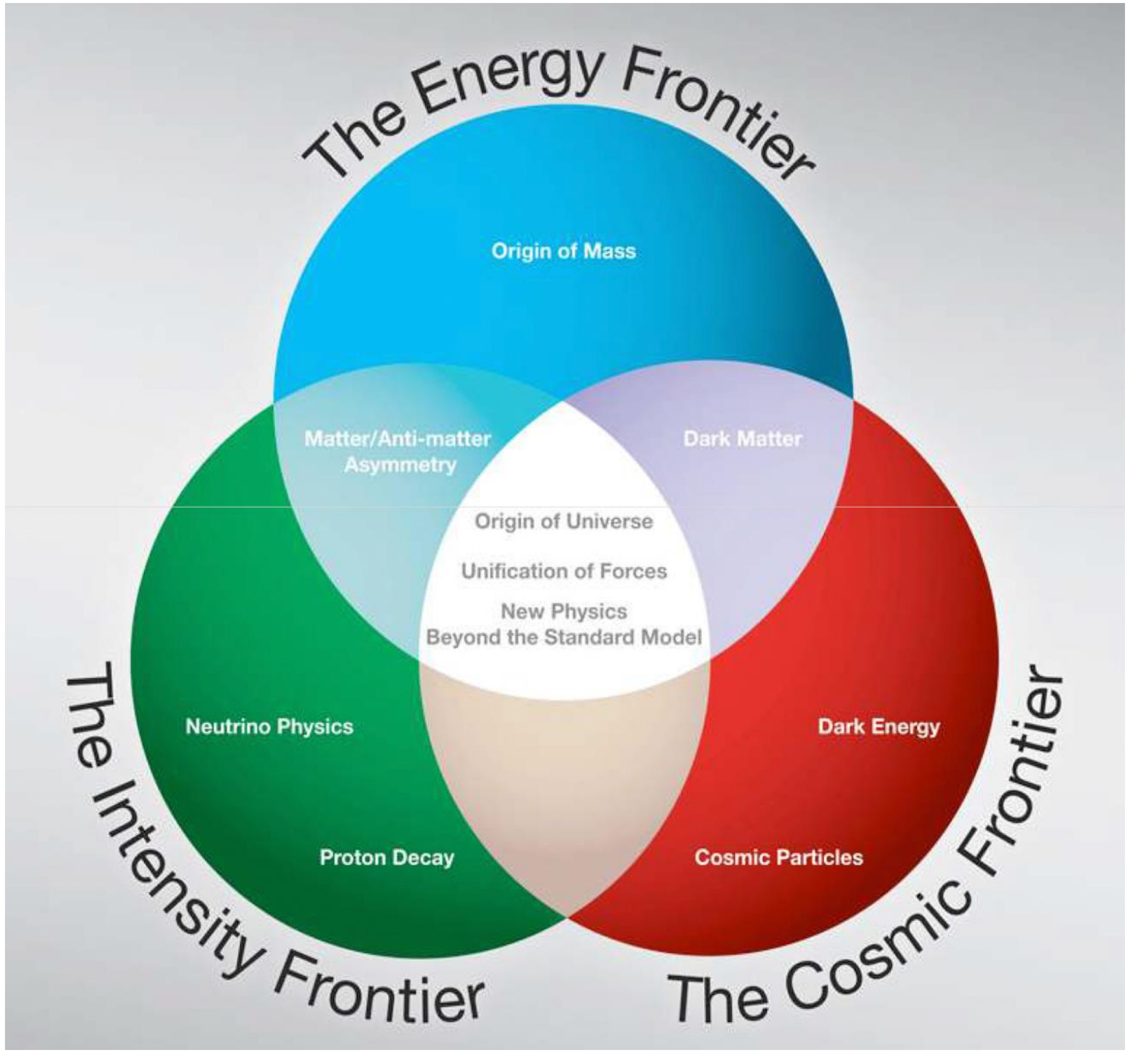


Collider



NEUTRINOS AND THE THREE FRONTIERS

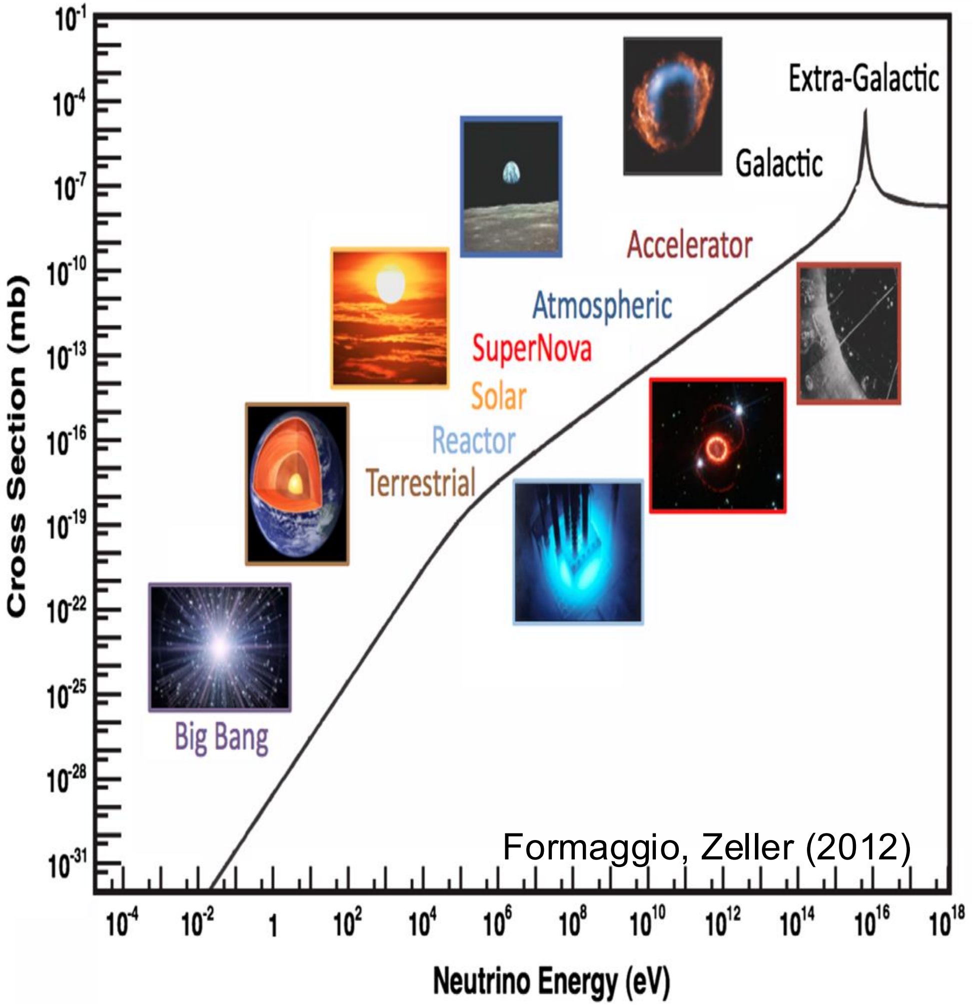
- Why bother with colliders? We can calculate the COM energy of the collisions with special relativity:
  - Accelerators: $E_{\mathrm{COM}} \approx \sqrt{2\, m_p\, E_{\mathrm{beam}}}$.
  - Colliders: $E_{\mathrm{COM}} = 2\, E_{\mathrm{beam}}$.
  - For $E_{\mathrm{beam}} \gg m_p$, E_{COM} is far larger at colliders than at accelerators.
  - Conventional wisdom: colliders are good for finding new heavy particles, not good for light, weakly-interacting particles (like neutrinos).
- In the past, this led to a division of the field of particle physics into the intensity, energy, and cosmic frontiers, with neutrino physics confined to the intensity frontier.



NEUTRINOS AT COLLIDERS

- In the last ~5 years, we have learned a lot, and the truth is far more interesting!

- Neutrinos are not confined to the intensity frontier.
- Neutrinos can be directly detected at particle colliders at the energy frontier.
- Neutrinos can be directly detected at particle colliders with small, fast, and inexpensive detectors.
- Neutrinos at colliders are opening up an entirely new window on the universe.
- Every time neutrinos are discovered from a new source, they tell us something fascinating. Collider neutrinos are the latest new source, and no exception. This is "hot off the press," and a fast-developing subfield; we are learning new things, and also learning what we can learn.

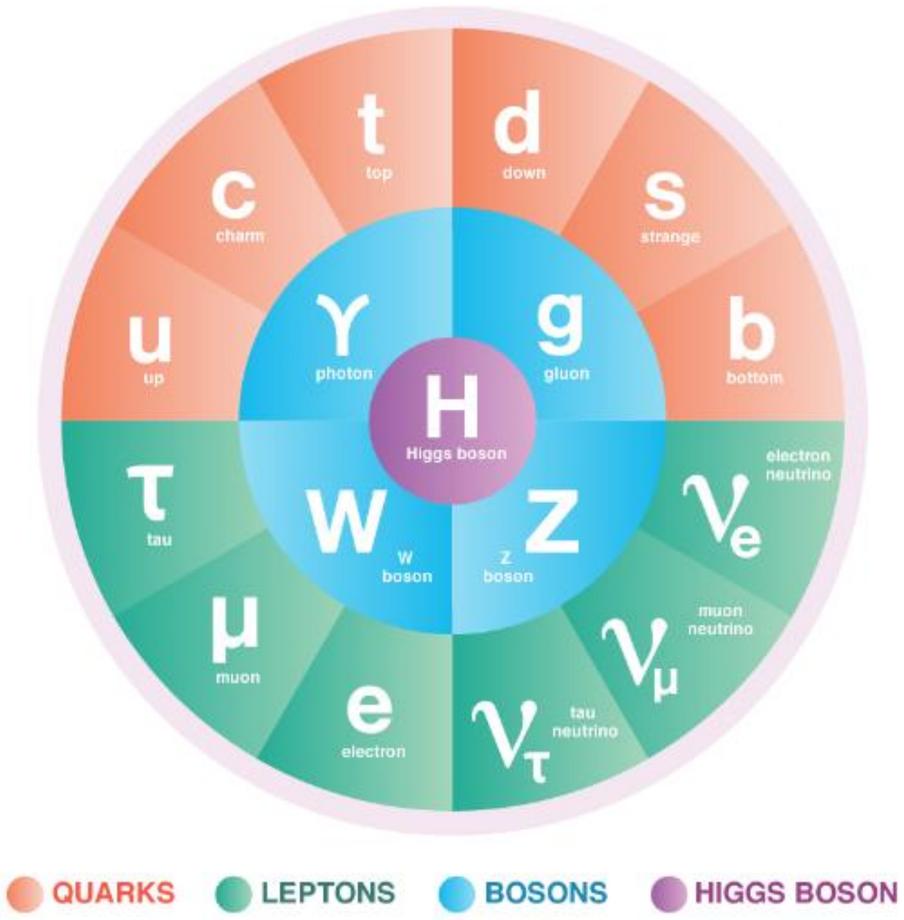


THE STANDARD MODEL OF PARTICLE PHYSICS

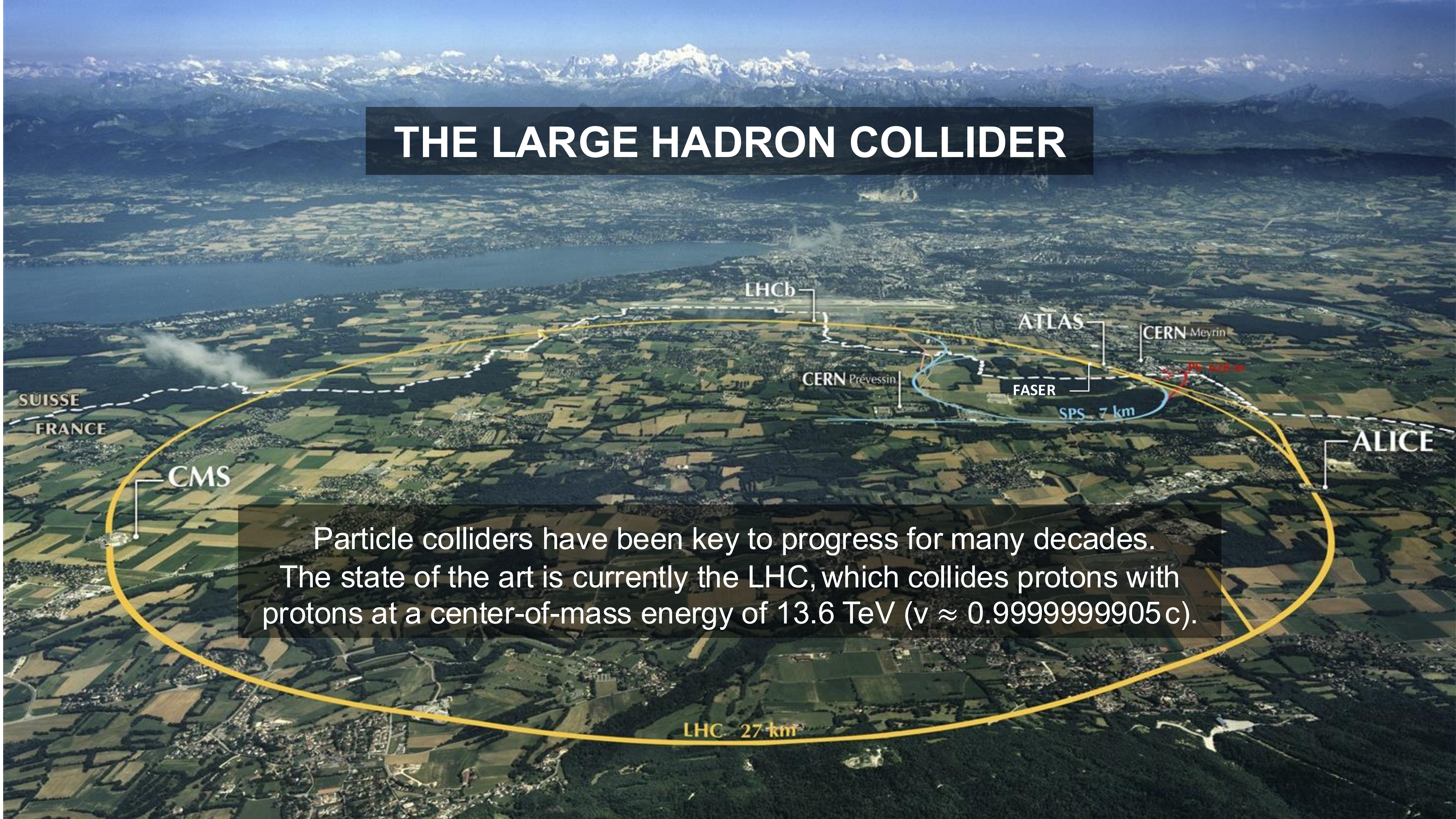
- The Standard Model is the reigning theory of fundamental particles and their interactions. The last particle predicted by the SM, the Higgs boson, was discovered at CERN in 2012.

- 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 is physics beyond the SM to discover, and probably much more.



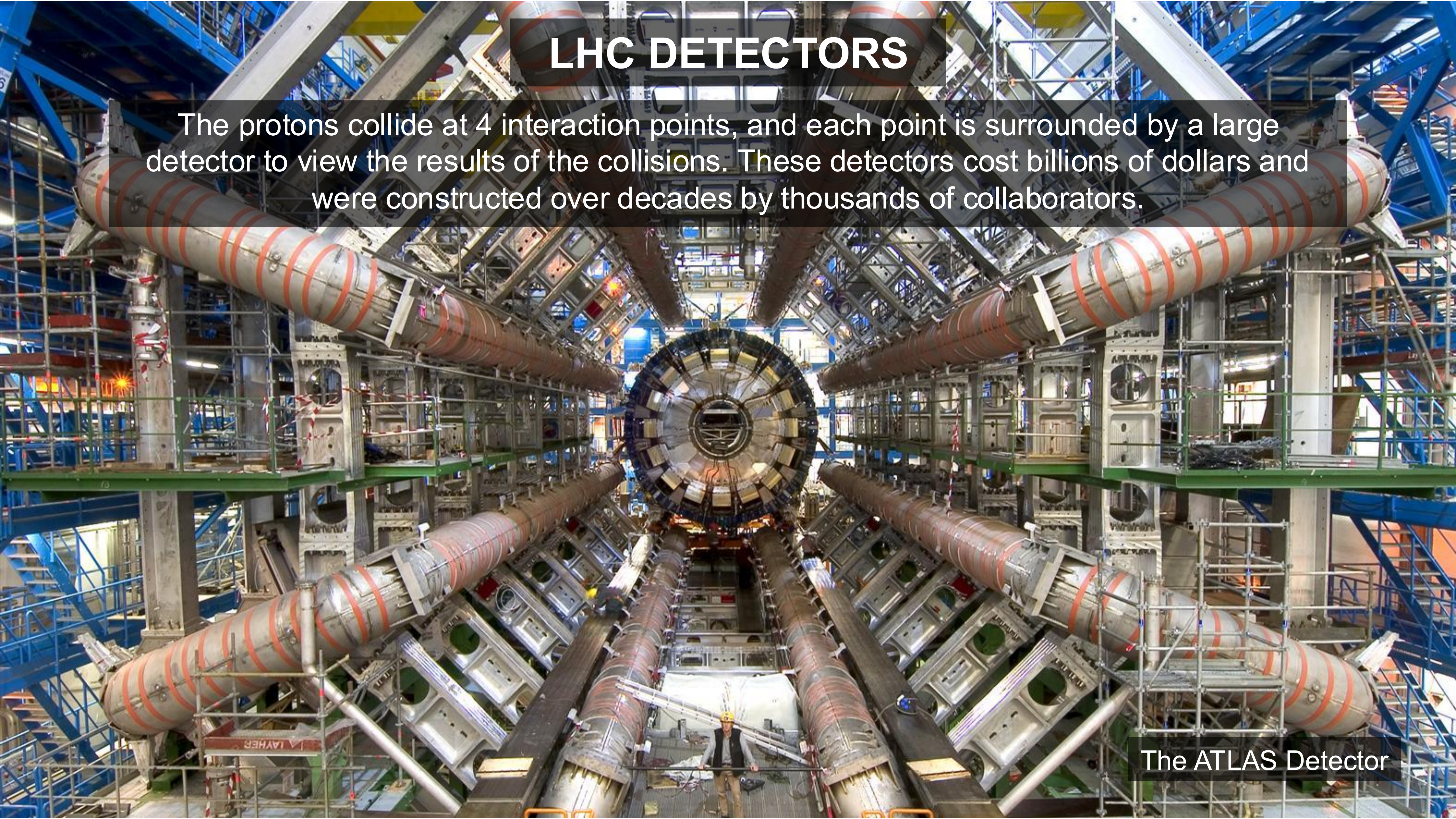
THE LARGE HADRON COLLIDER



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.



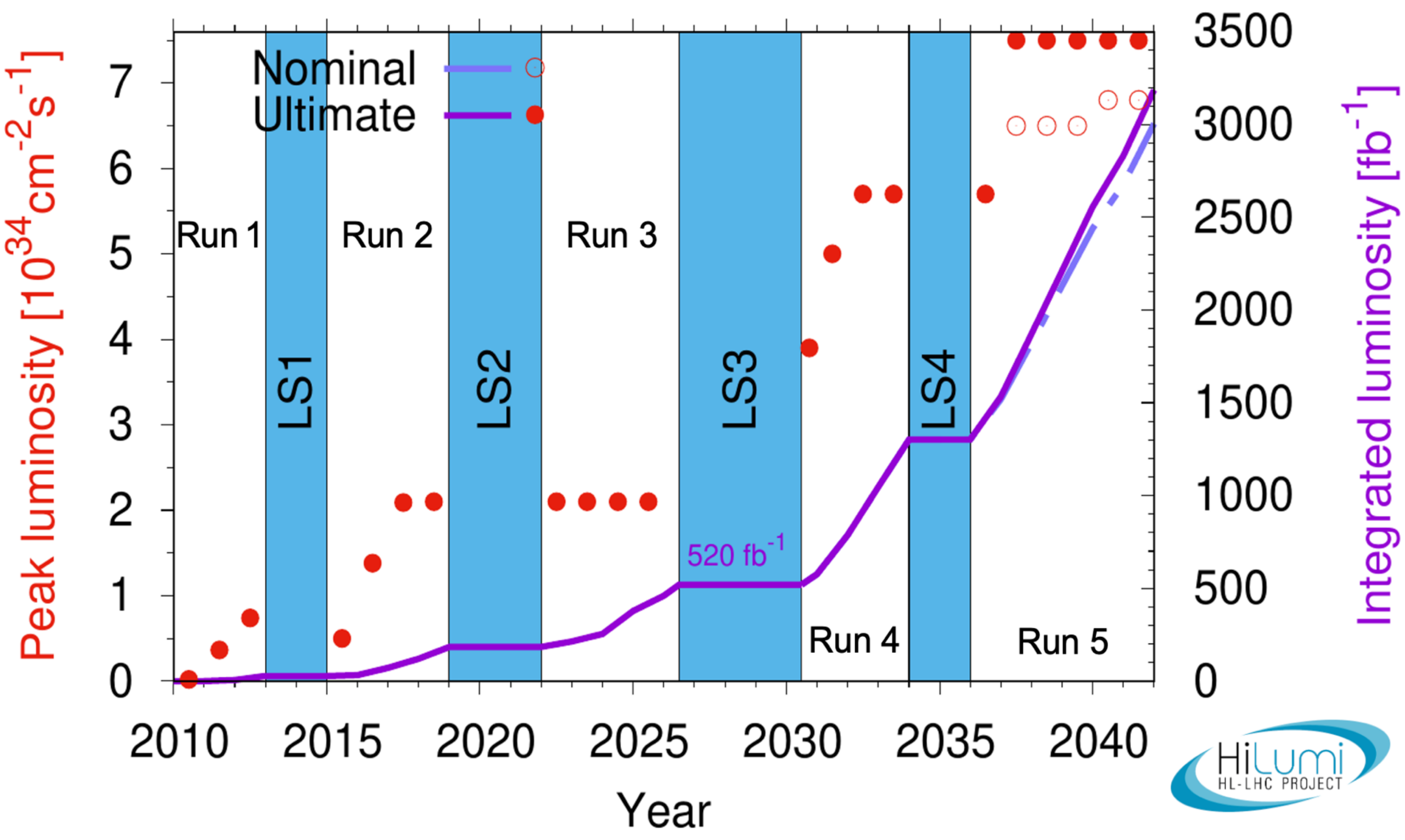
The ATLAS Detector

LIFETIME OF THE LHC

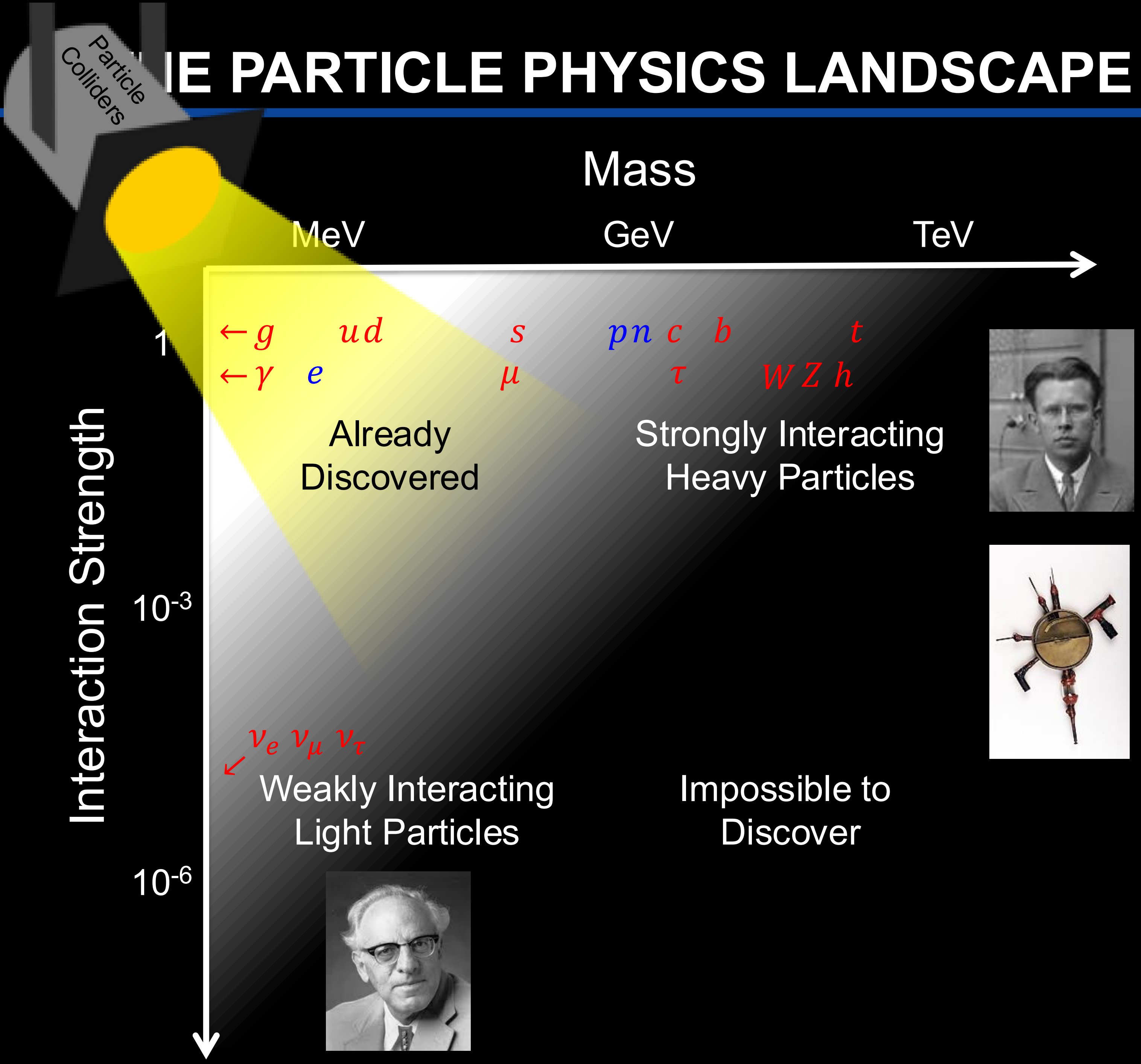
- The LHC became the future of particle colliders in 1993 when the US canceled the SSC.

- 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)

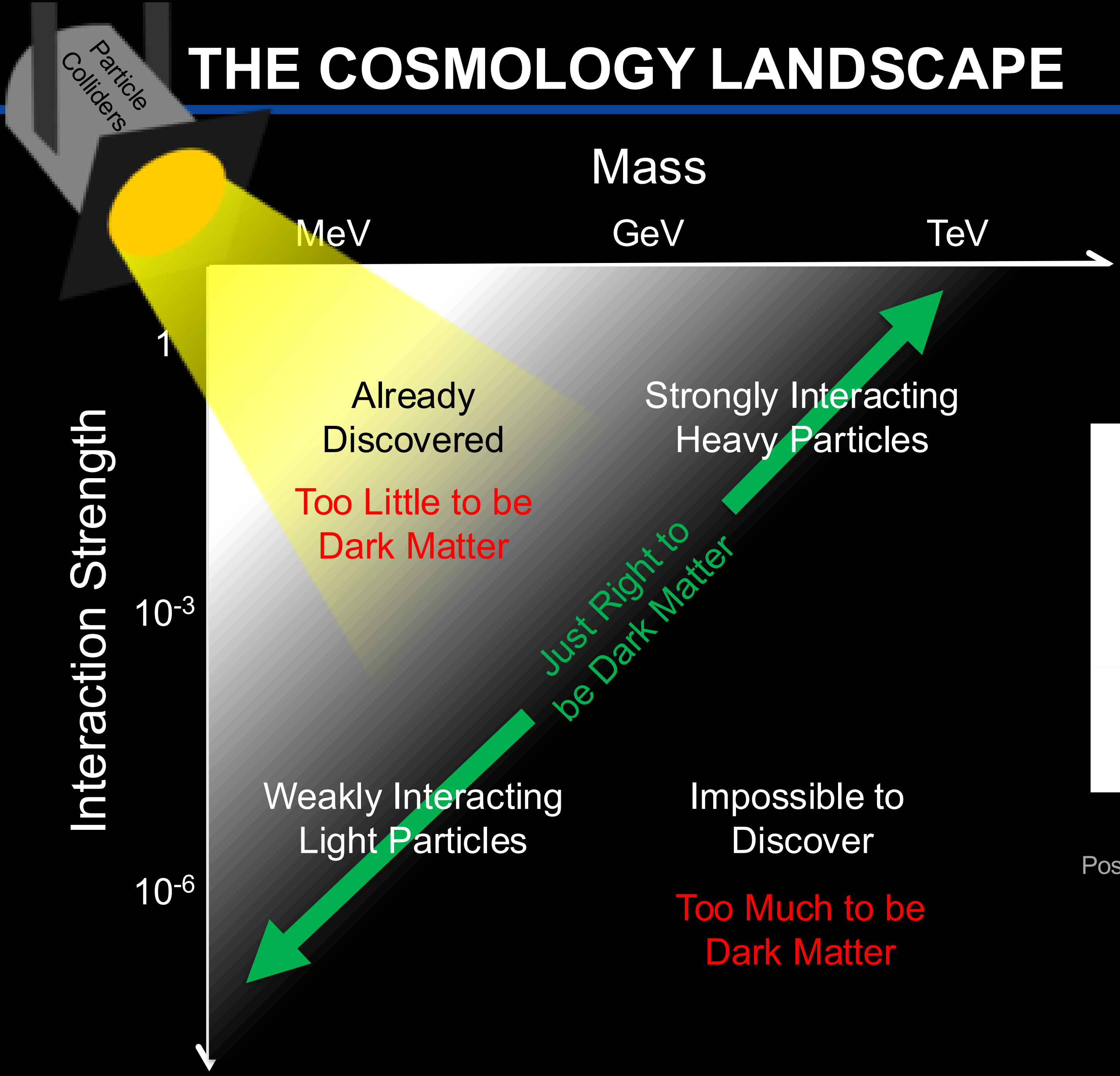
- Are we using the LHC to its full potential? What can we do to enhance its discovery prospects?

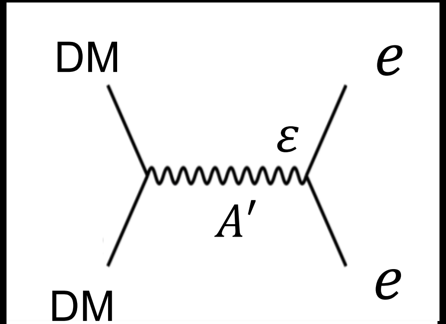


THE PARTICLE PHYSICS LANDSCAPE



THE COSMOLOGY LANDSCAPE





$$\sigma v \sim \frac{\varepsilon^2}{m_{A'}^2}$$

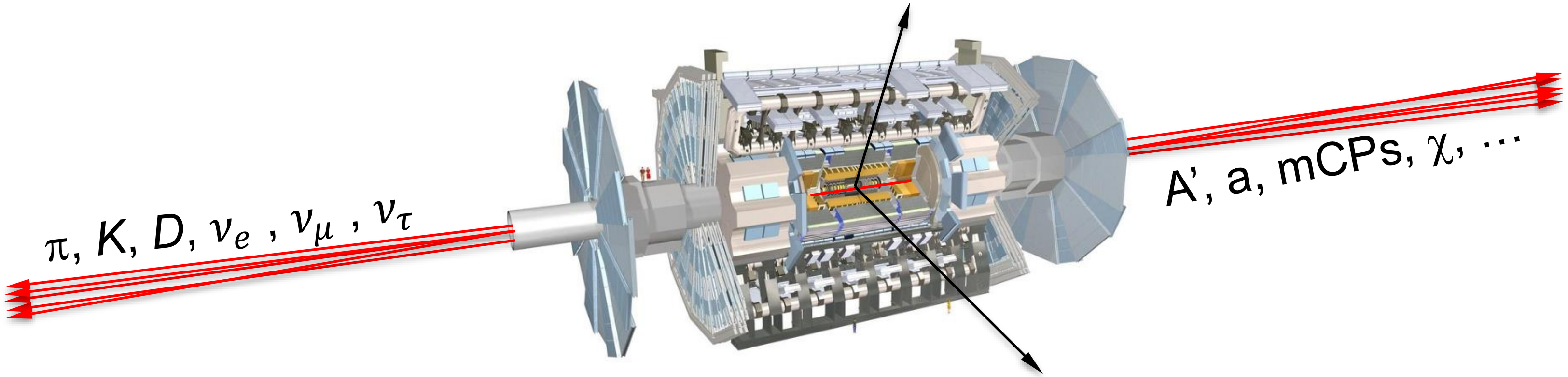
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

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.



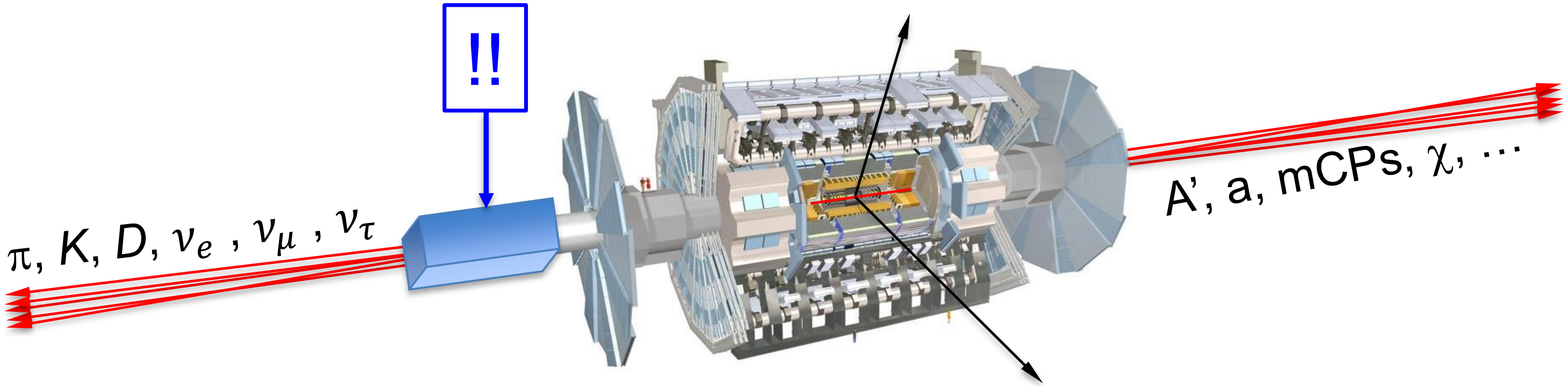
- But high-energy light particles are dominantly produced in the forward (and far-forward) direction (parallel to the beamline) and escape through the blind spots of these detectors.
  - This is true for all known light particles: pions, kaons, D mesons, all neutrinos.
  - It is also true for new, weakly-interacting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

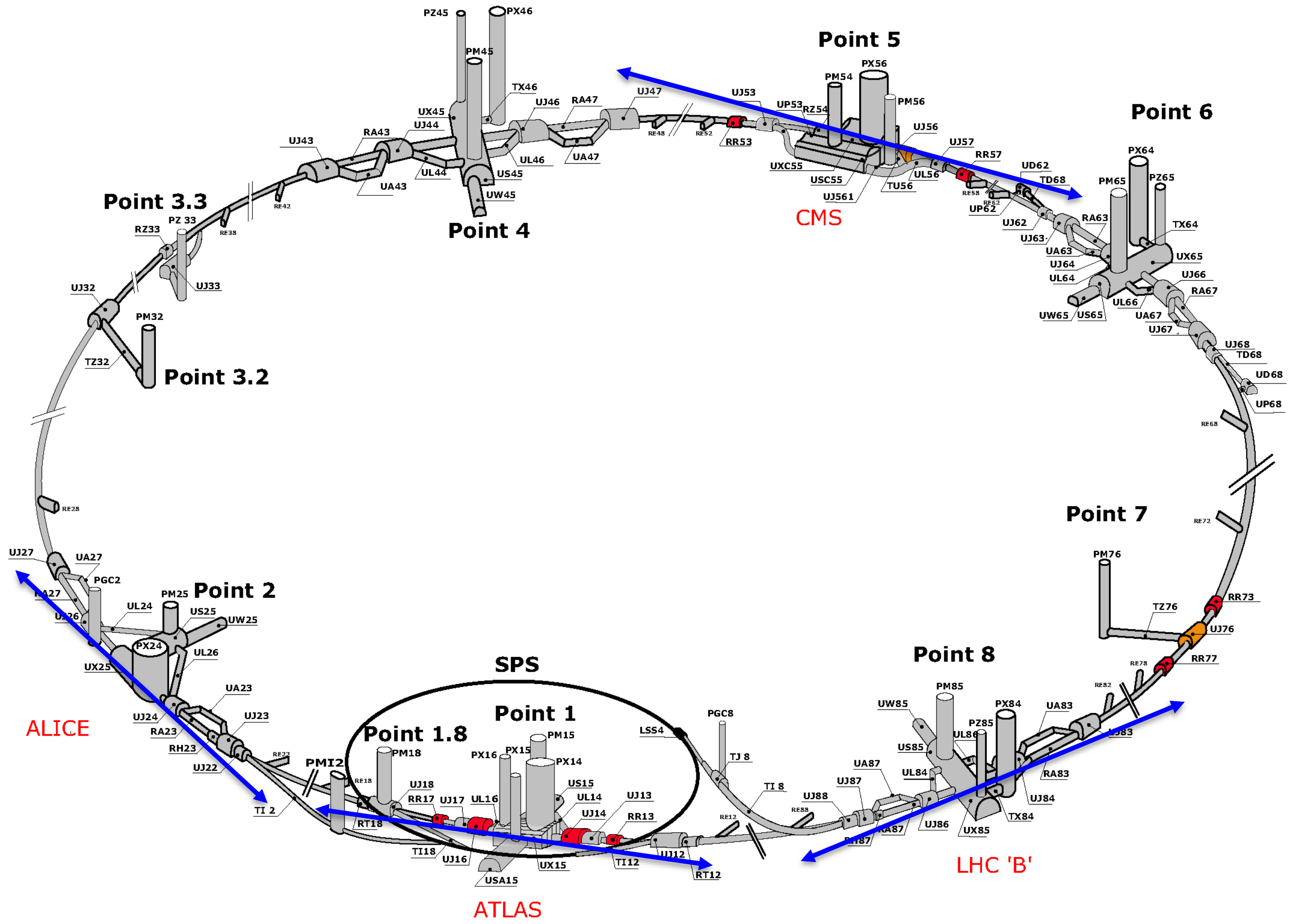
DETECTING FORWARD PARTICLES

- 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


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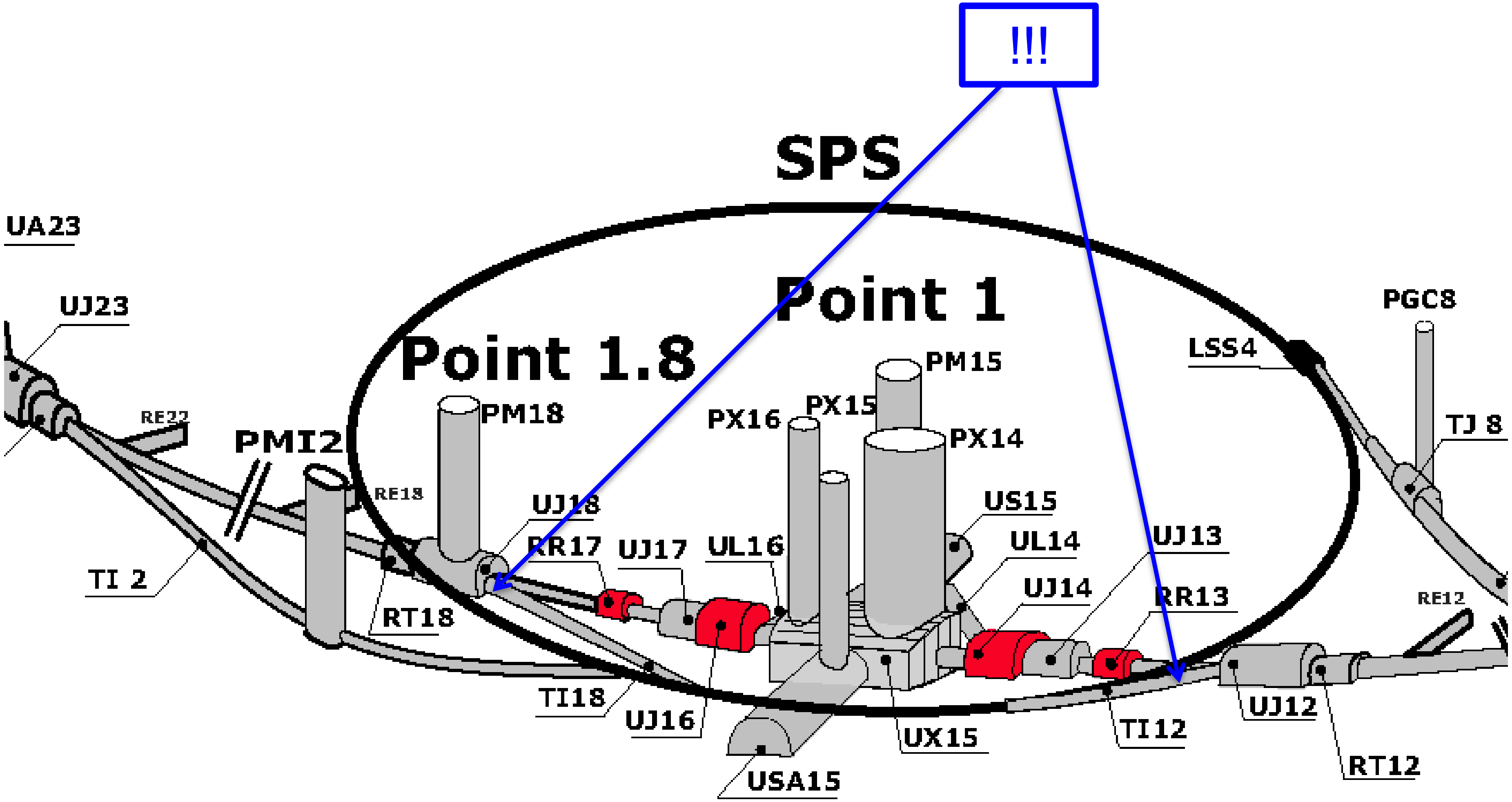
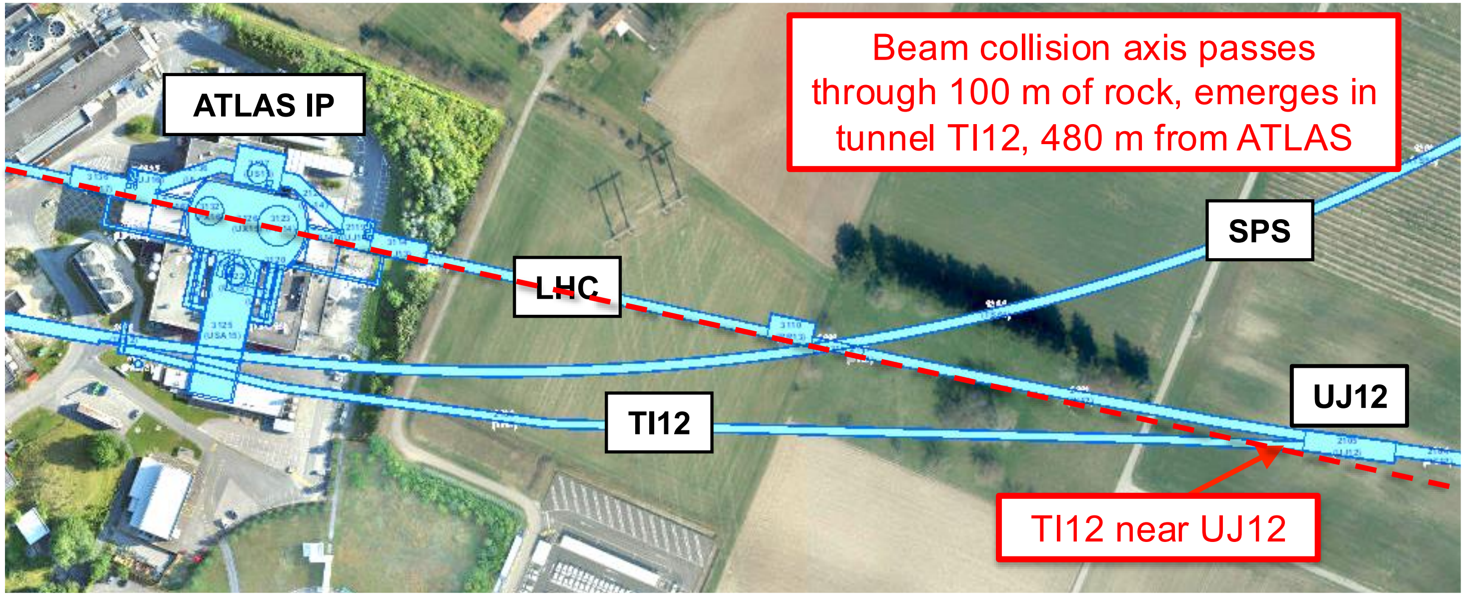
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
CMS
ALICE
ATLAS
LHC 'B'

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 SLAC!)
- 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

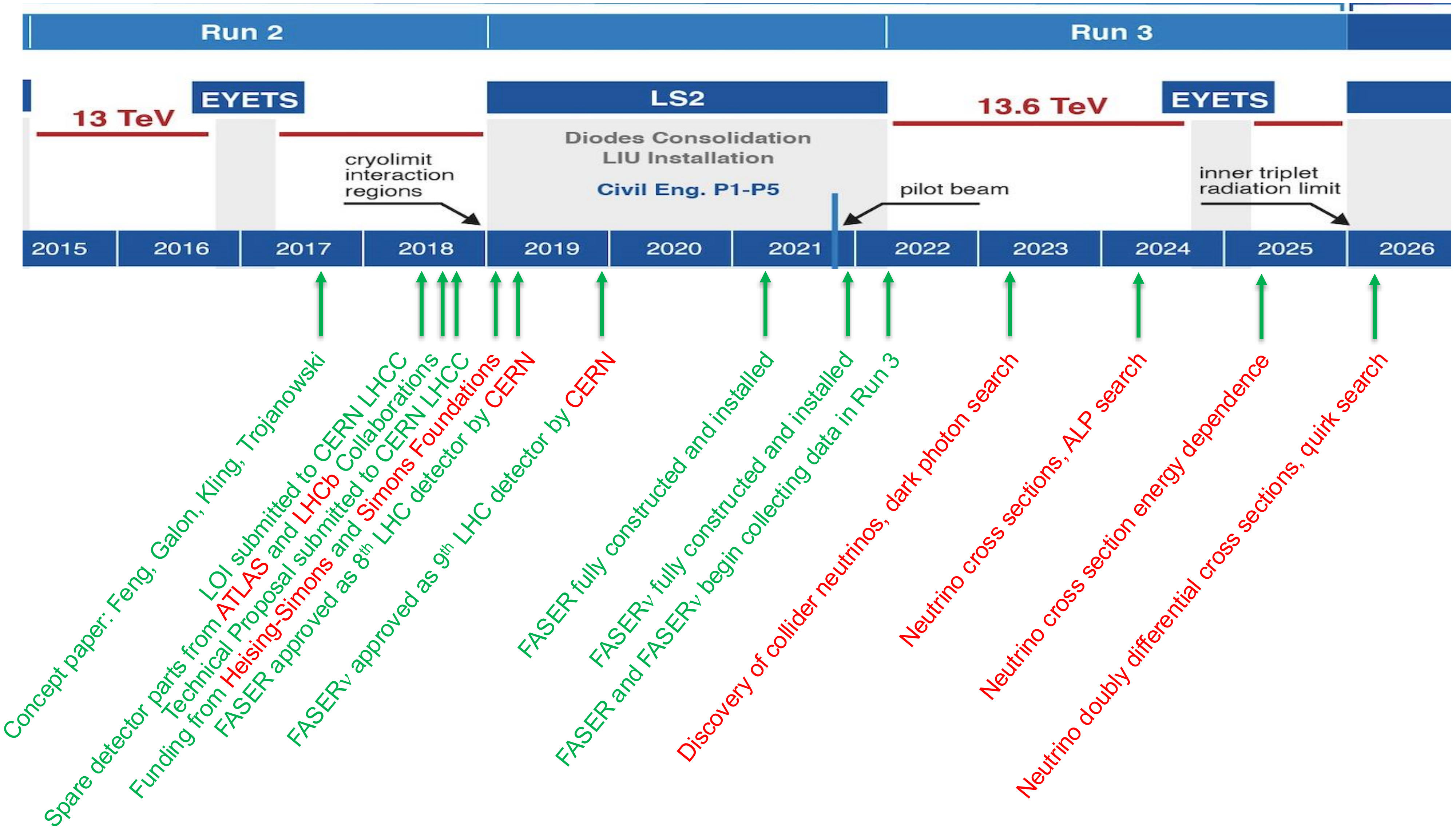
  480 m

- 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

127 collaborators, 27 institutions, 11 countries

FASER AND THE LHC

THE FASER DETECTOR

THE FASER DETECTOR

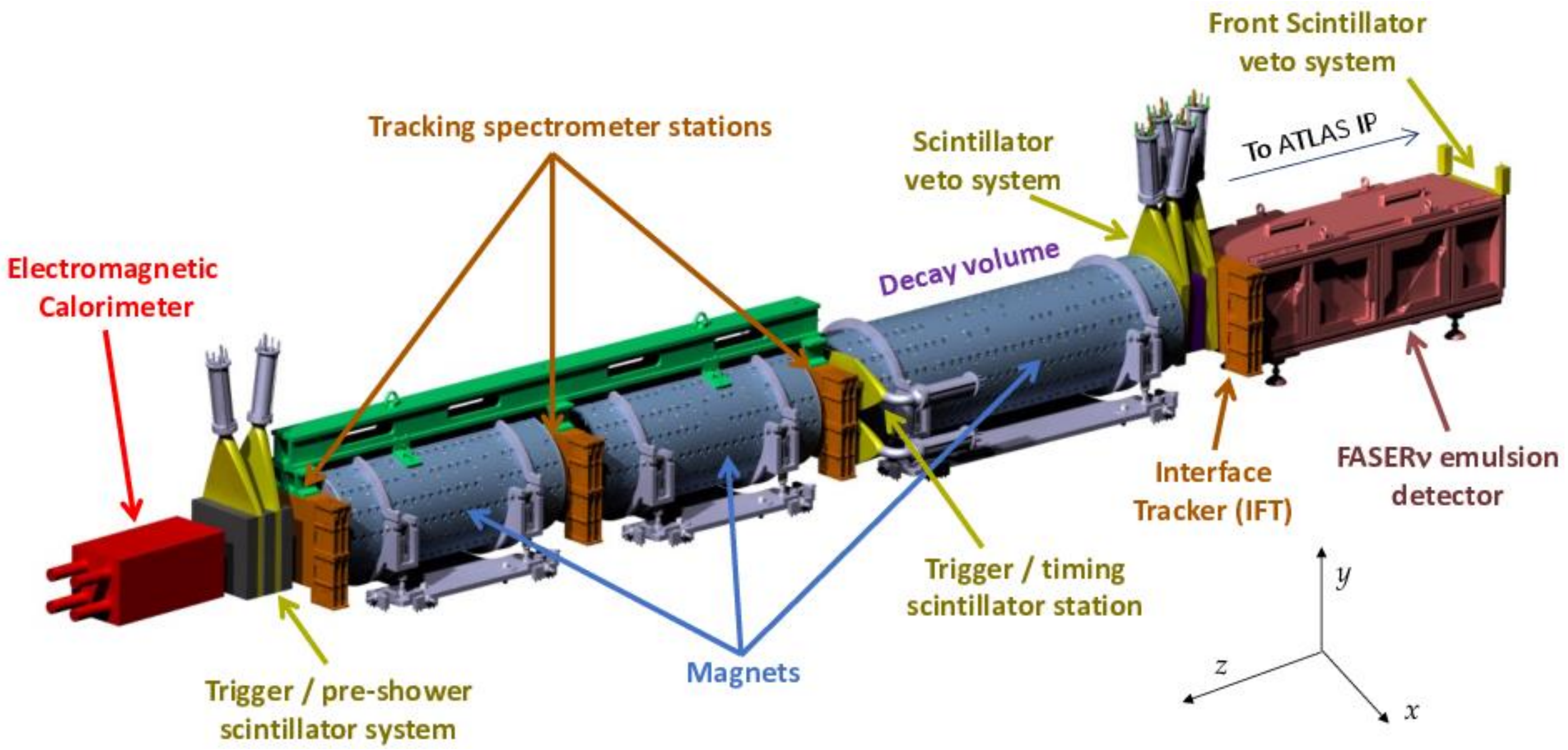
2207.11427

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.

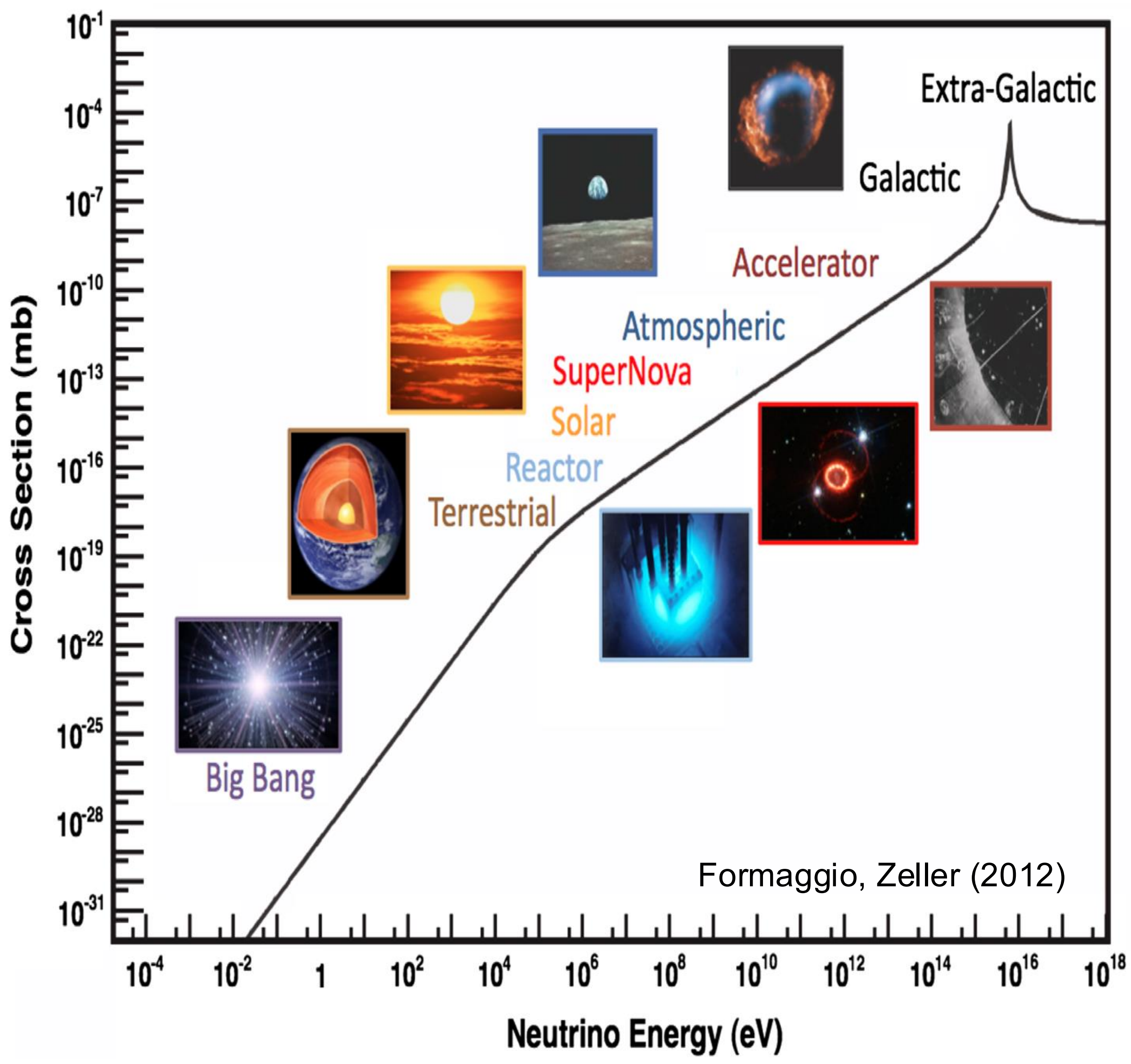
NEUTRINOS

COLLIDER NEUTRINOS

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

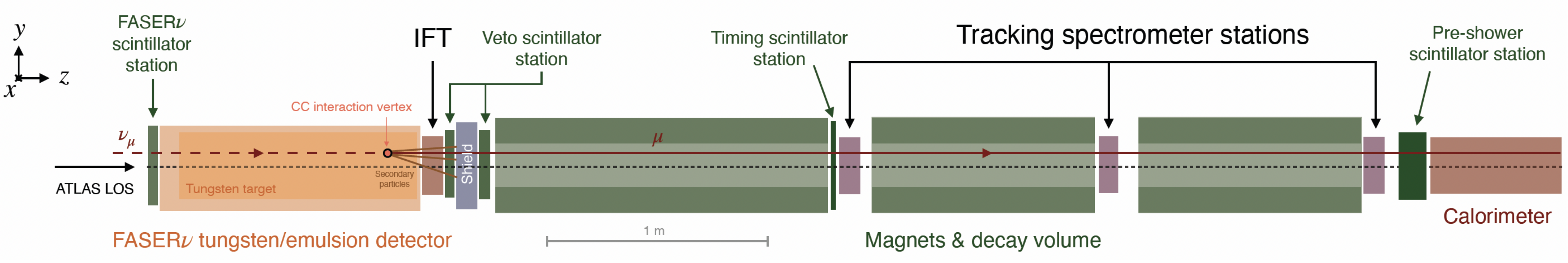
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.

- But before FASER, neutrinos produced at a particle collider had never been directly detected.
  - Conventional wisdom: neutrinos interact too weakly to be seen.
  - The truth: 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](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 upstream (veto) scintillators.

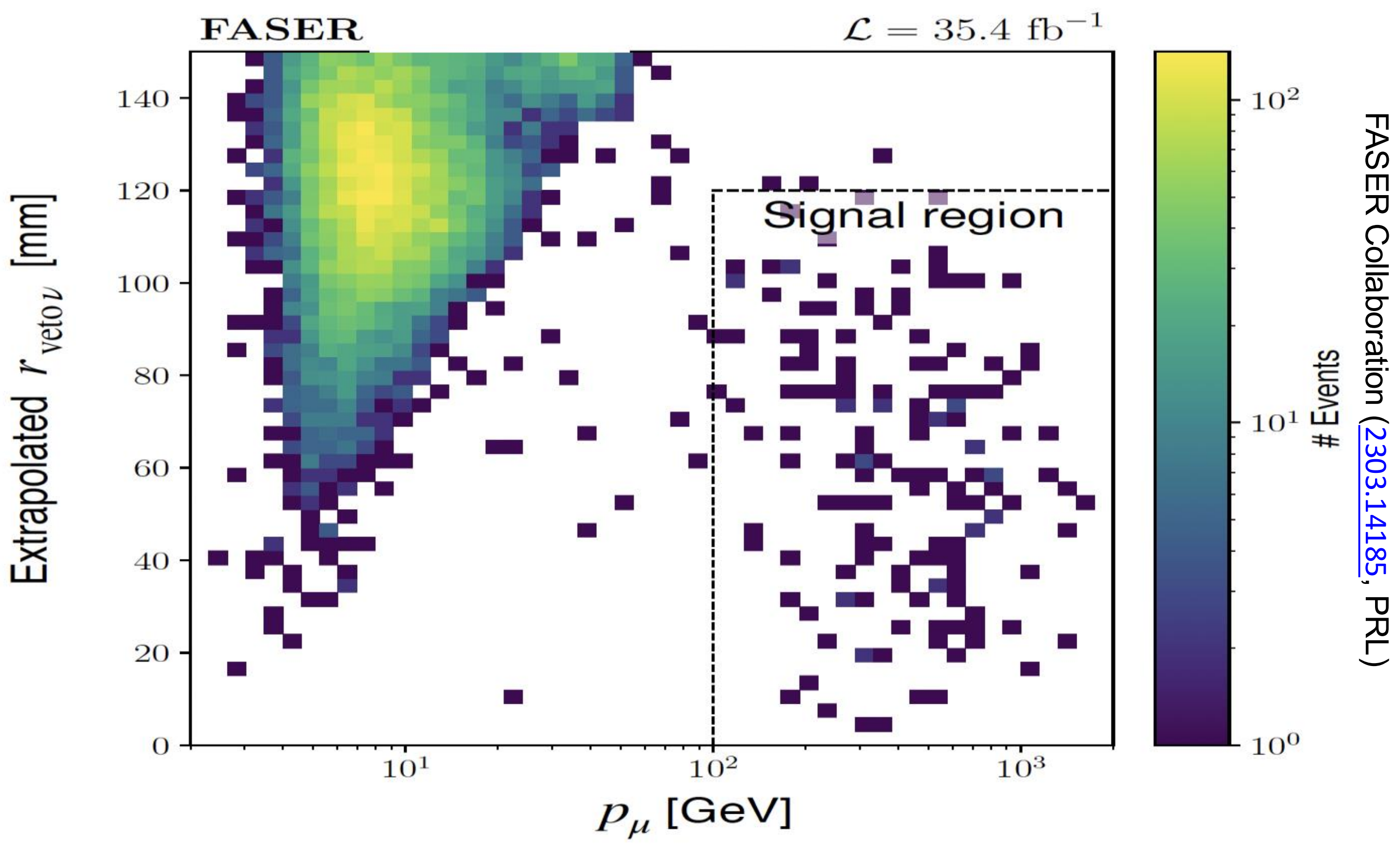
- In the end, $\lesssim 1$ background event expected, an essentially background-free search.

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 2023, 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.



VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester

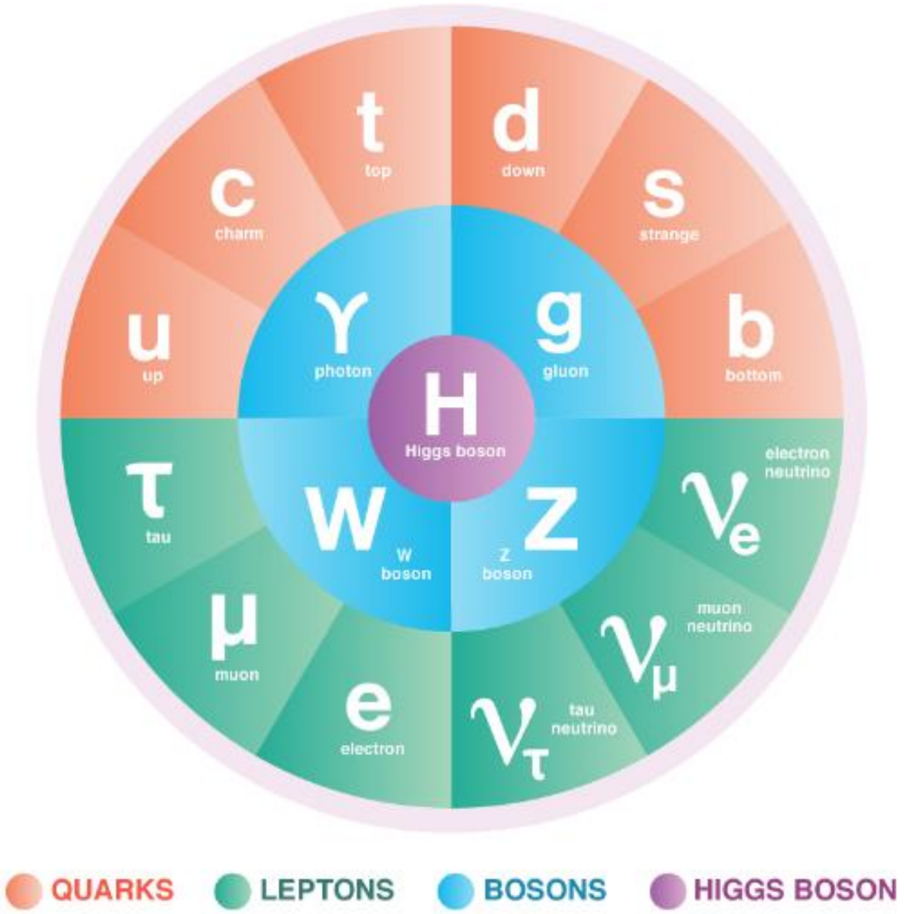
Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113


FASER observes first collider neutrinos
Physics • CERN

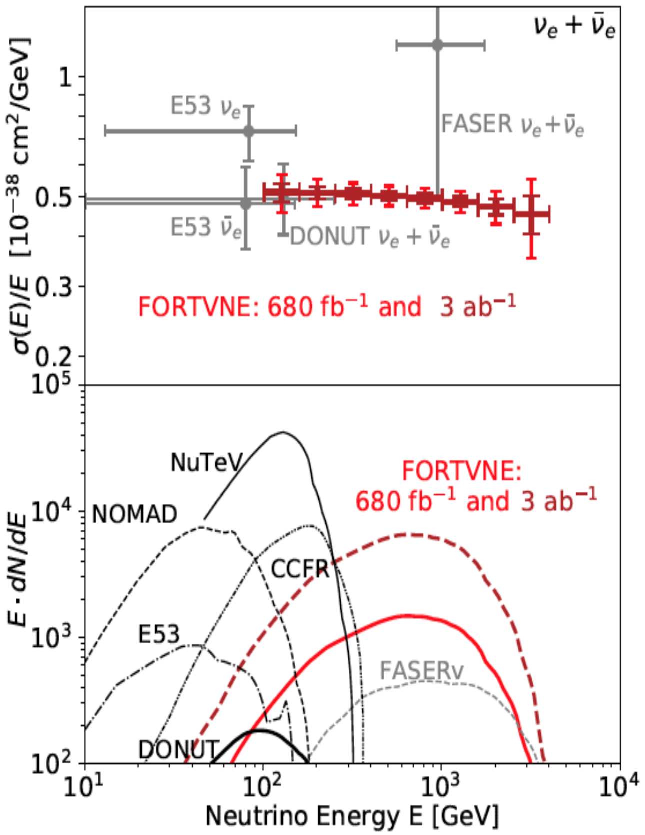
AFTER DISCOVERY: WHAT ARE THESE NEUTRINOS GOOD FOR?

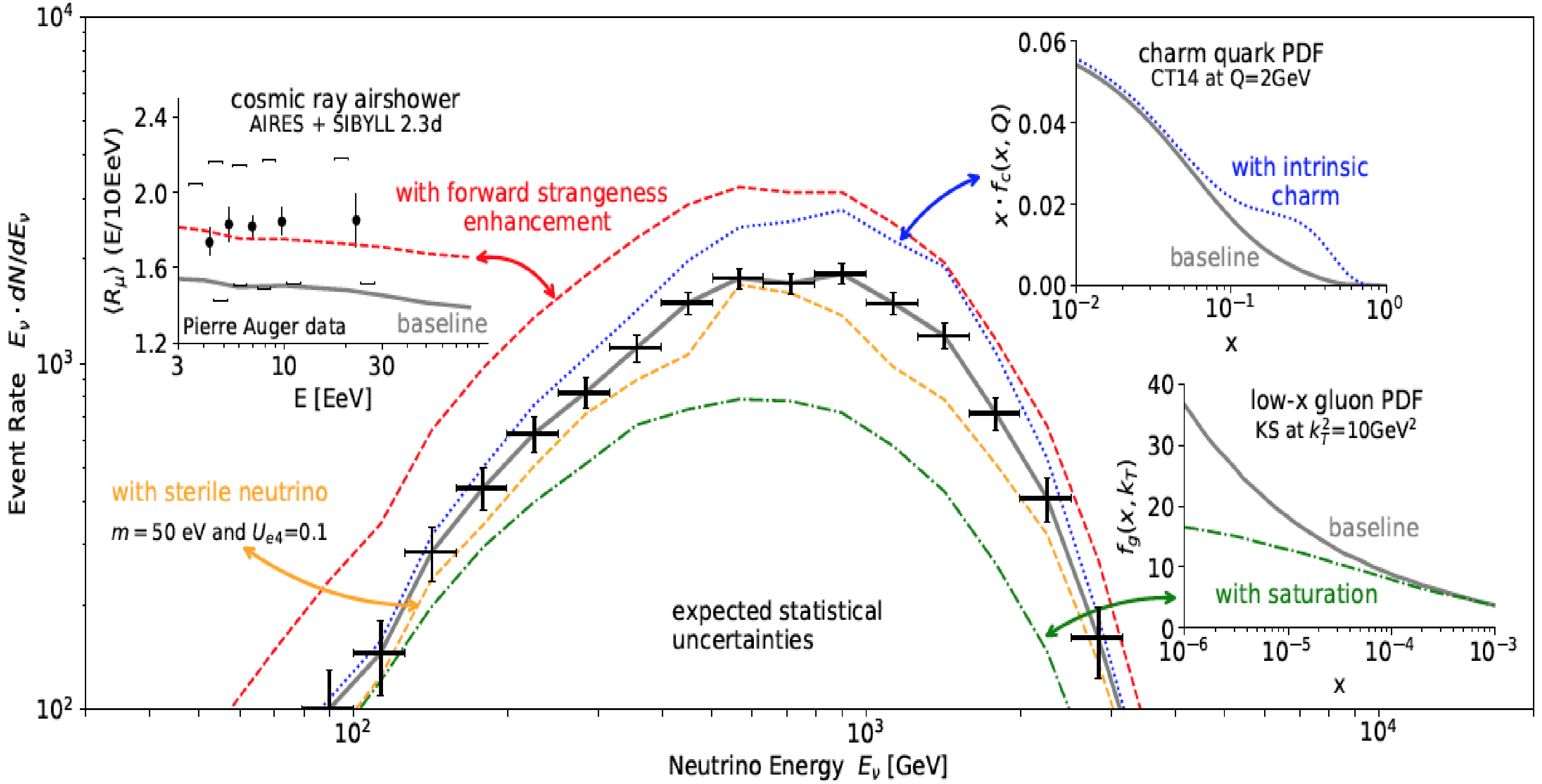
- There are actually 6 kinds of neutrinos with very different characteristics: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$.
  - Not all are produced in all ways. E.g., nuclear reactors, where neutrinos were first discovered by Fred Reines, only make $\bar{\nu}_e$.
  - They are all hard to detect, but 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)

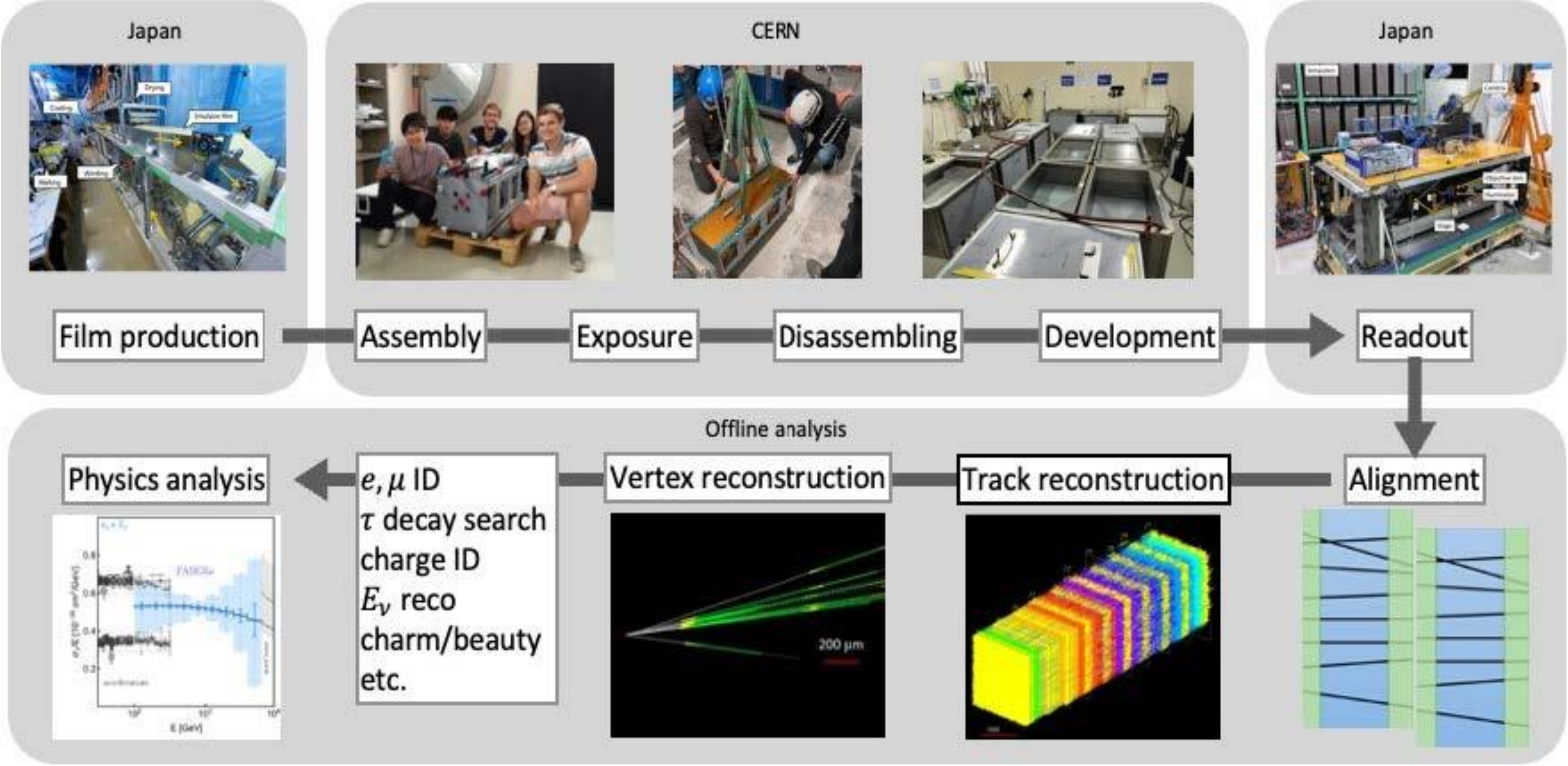




FASERν

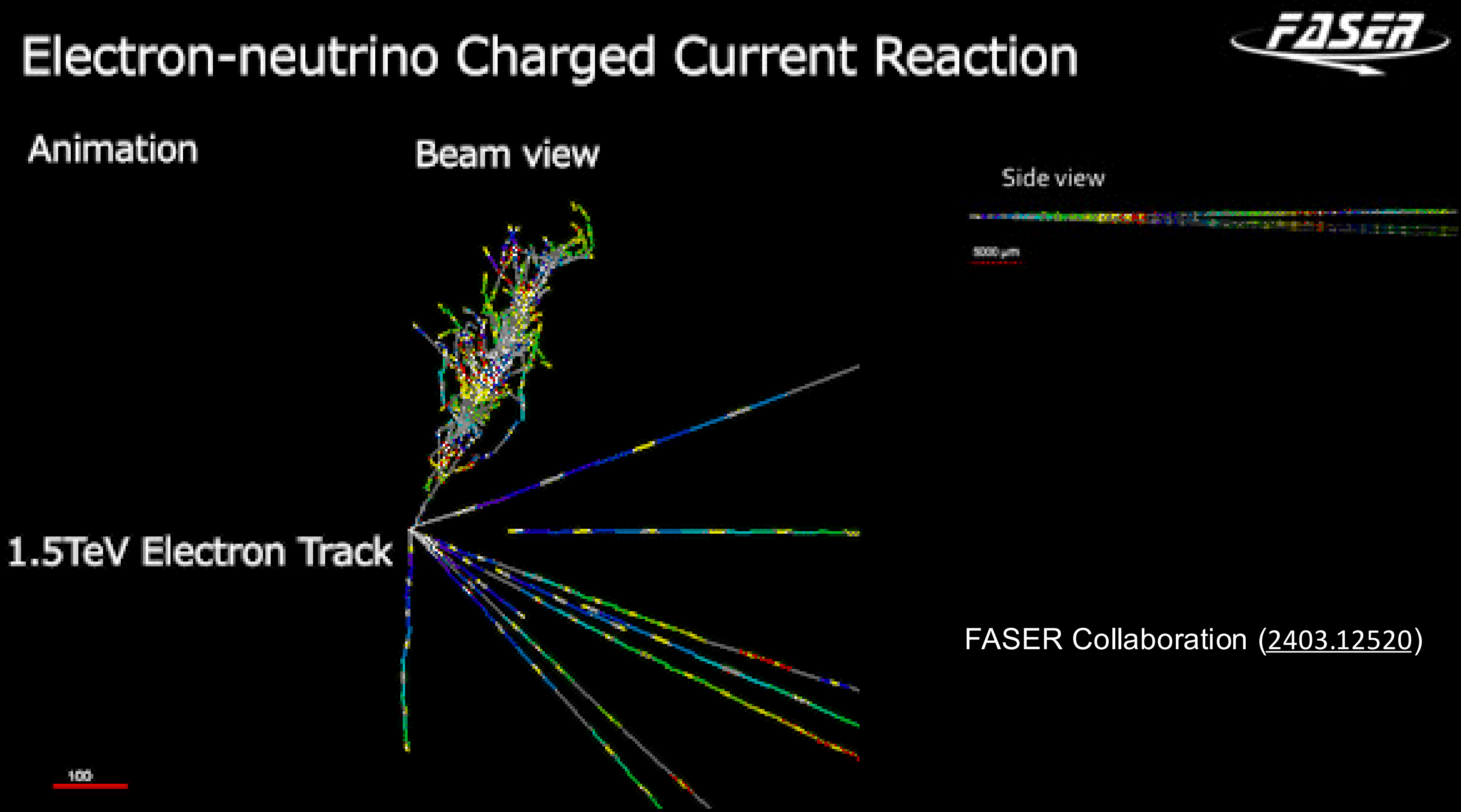
The first neutrinos detected were muon neutrinos in FASER's electronic detector.

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

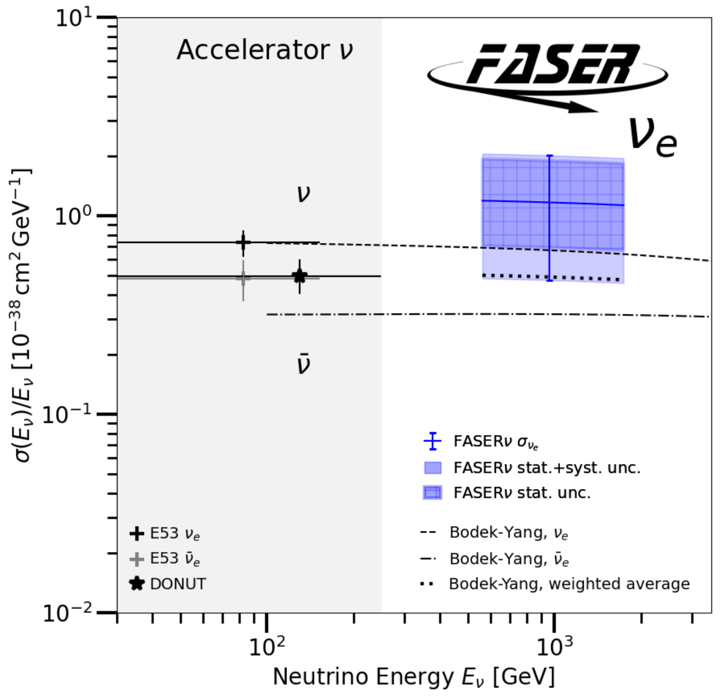
With FASERν, we observed the first collider electron neutrinos, including the "Pika-ν" event, the highest energy (>1.5 TeV) electron neutrino ever seen from a lab source.

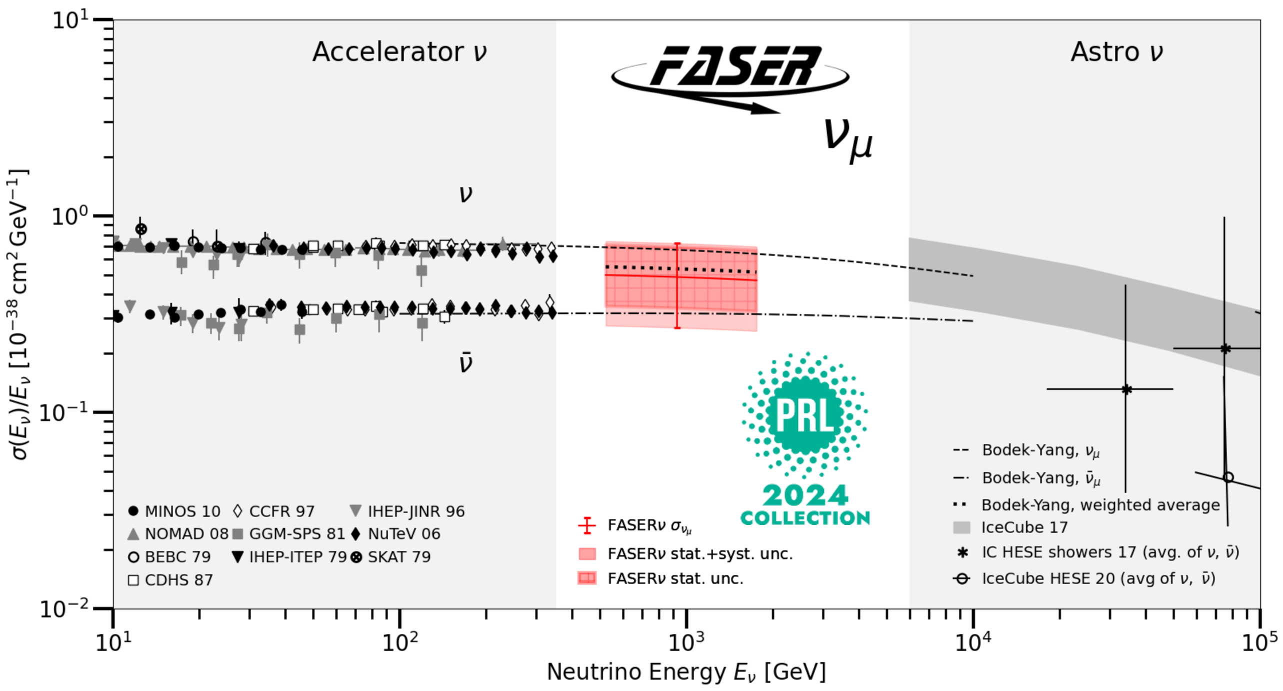


FASER Collaboration (2403.12520)

TEV NEUTRINO INTERACTION STRENGTHS

- After these discoveries, we have moved on to studies, including the first measurement of neutrino cross sections at TeV energies and doubly differential cross sections. So far, all consistent with SM DIS predictions.





FASER Collaboration (2403.12520)

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

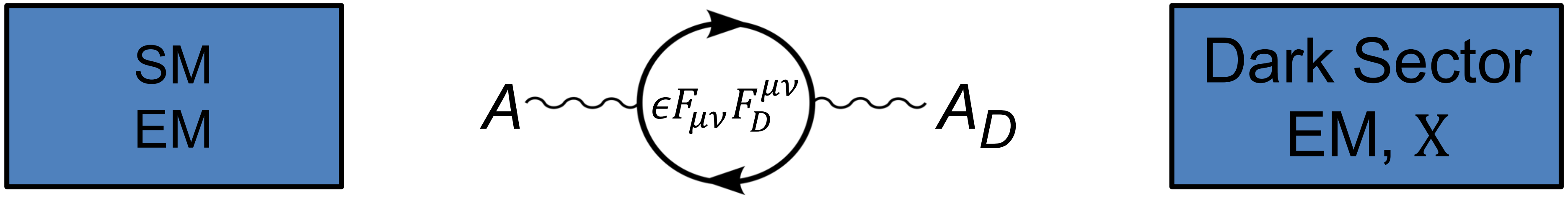
- These measurements used only 1.7% of the data collected in 2022 and 2023. Much more to come.

CERN-FASER-CONF-2026-005

DARK SECTORS
NEW PARTICLES

NEW PARTICLE SEARCHES

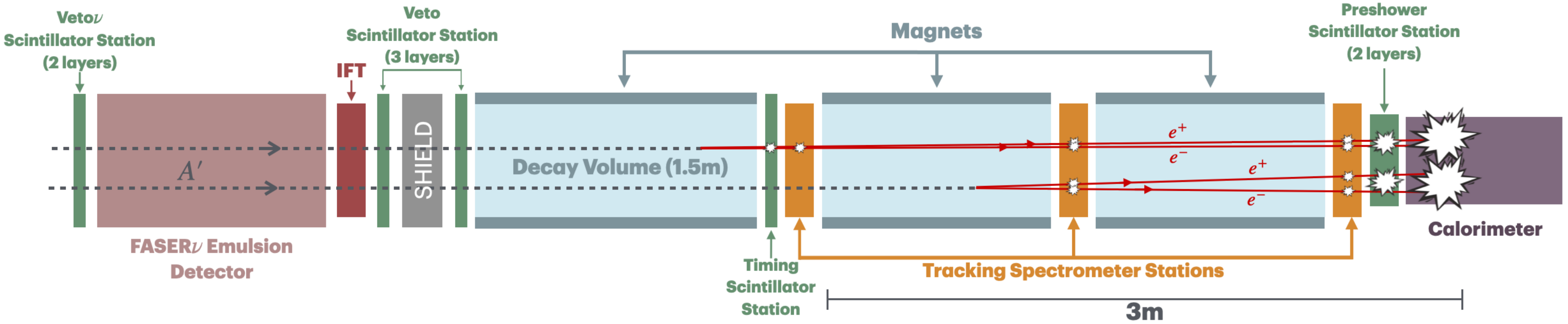
- FASER is also looking for new dark particles, new fundamental forces, and new forms of matter.
- For example: suppose there is a dark sector that contains a dark force: dark electromagnetism.



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

Holdom (1986)

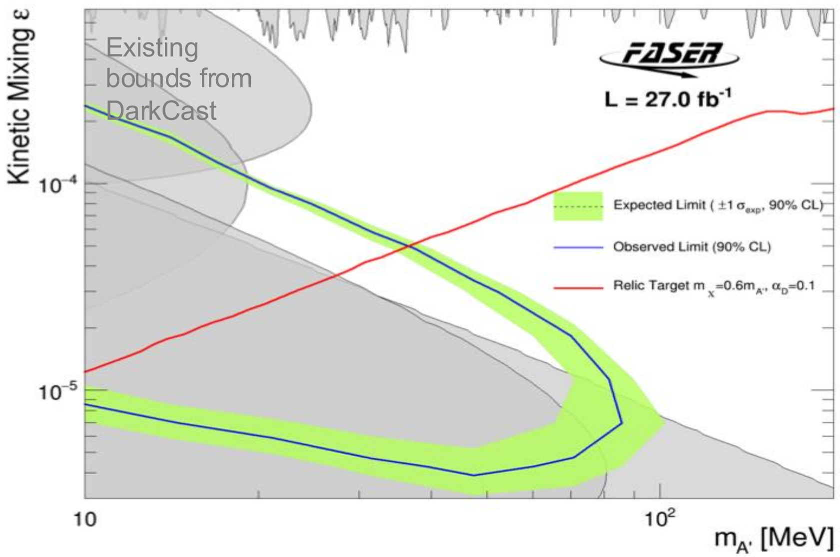
- For low ϵ, dark photons are very weakly-interacting, long-lived particles. Like neutrinos, but decay through $A' \to e^+e^-$, producing a 2 ~TeV-energy charged particles emerging from 100 m of rock.



DARK PHOTON SEARCH

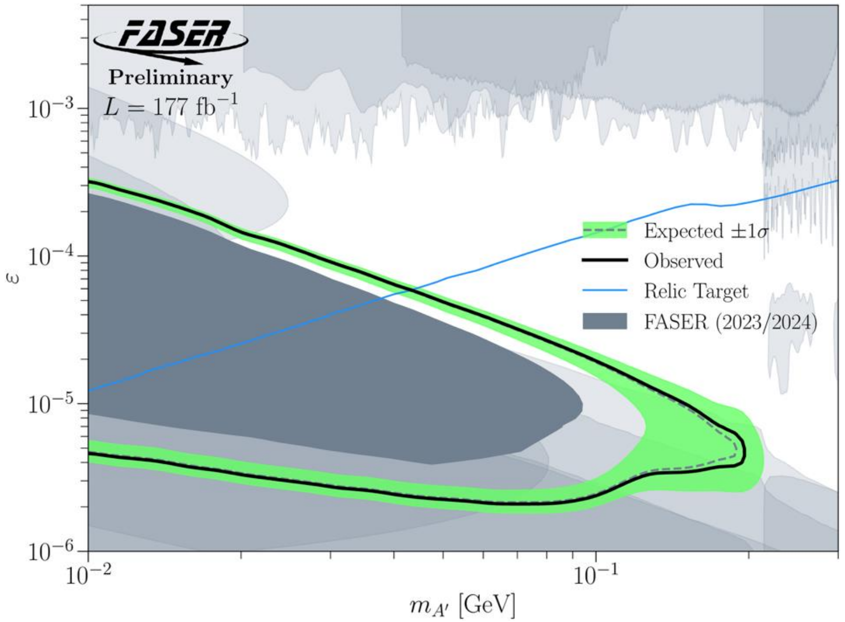
- In 2023, in a blind analysis of 2022 data, no events were seen, and FASER set limits on previously unexplored parameter space.
  - First new probe of the parameter space favored by dark matter relic density arguments from low coupling since the 1990’s.
  - Started probing new parameter space on Day 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).

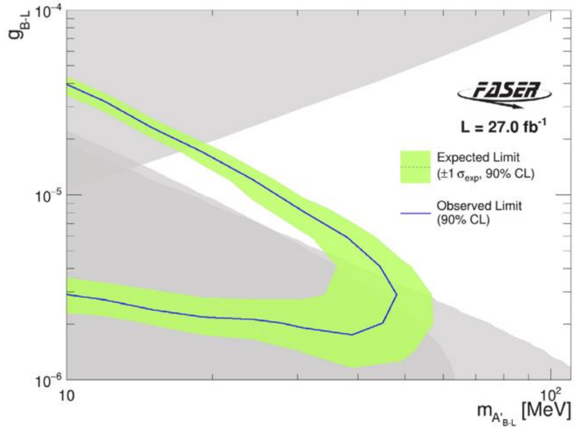
FASER Collaboration (CERN-FASER-CONF-2026-001)

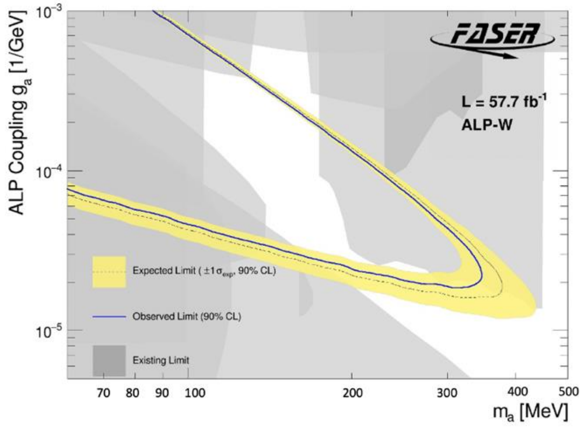


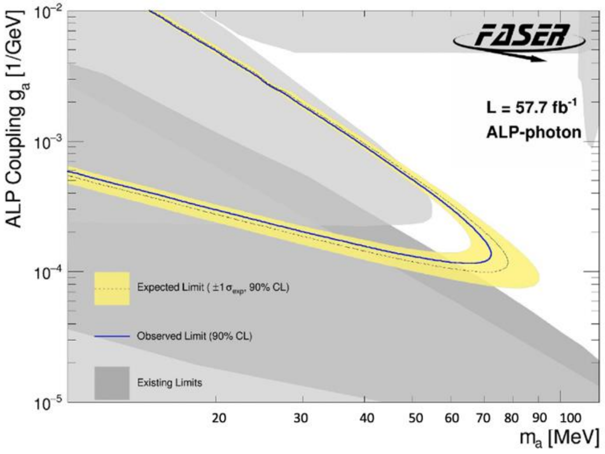
- Prospects for the future
  - The analyses have been essentially background-free.
  - ~20x more data expected at the LHC.

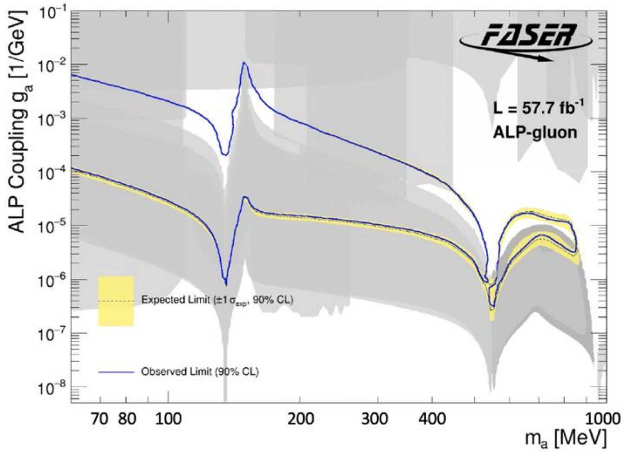
MORE NEW PARTICLE SEARCHES

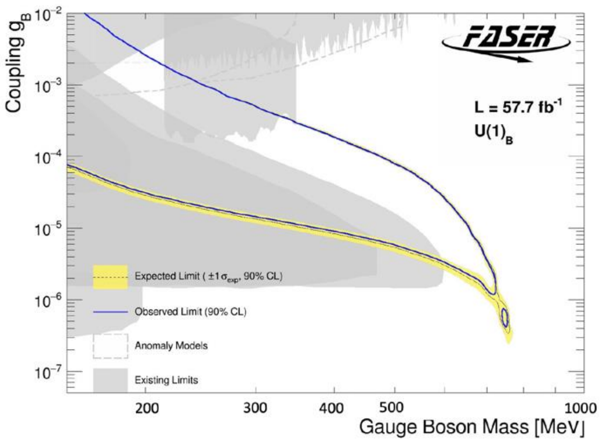
We are also looking for many other new particles: other new force carriers ($U(1)_{B-L}$, $U(1)_B$, protophobic), axion-like particles with photon, W, gluon couplings, up-philic scalars, two Higgs doublet models, etc., all with world-leading sensitivities in interesting regions of parameter space.

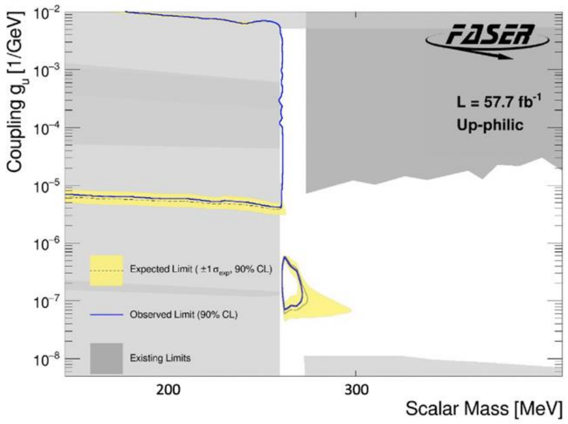


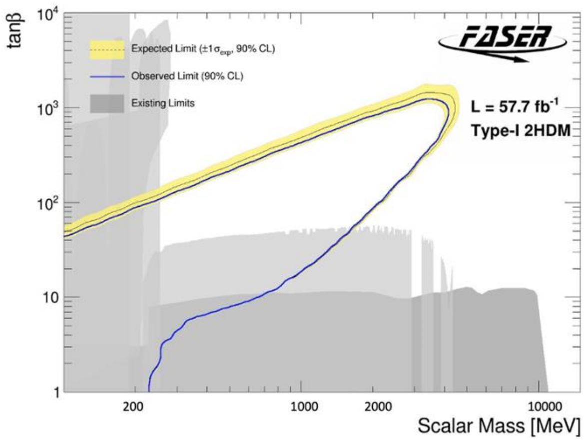


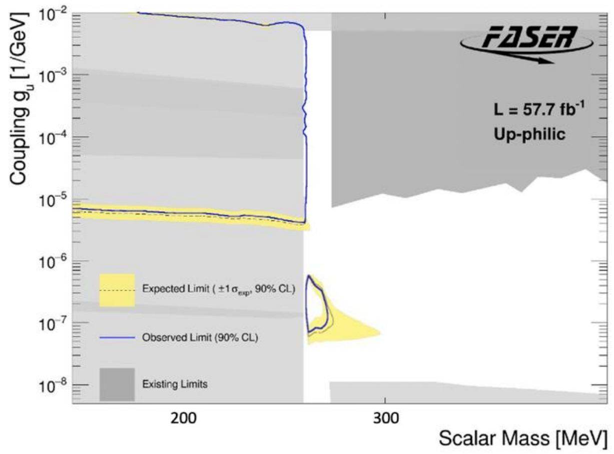












FASER Collaboration (2308.05587, PLB; 2410.10363)

FUTURE DETECTORS

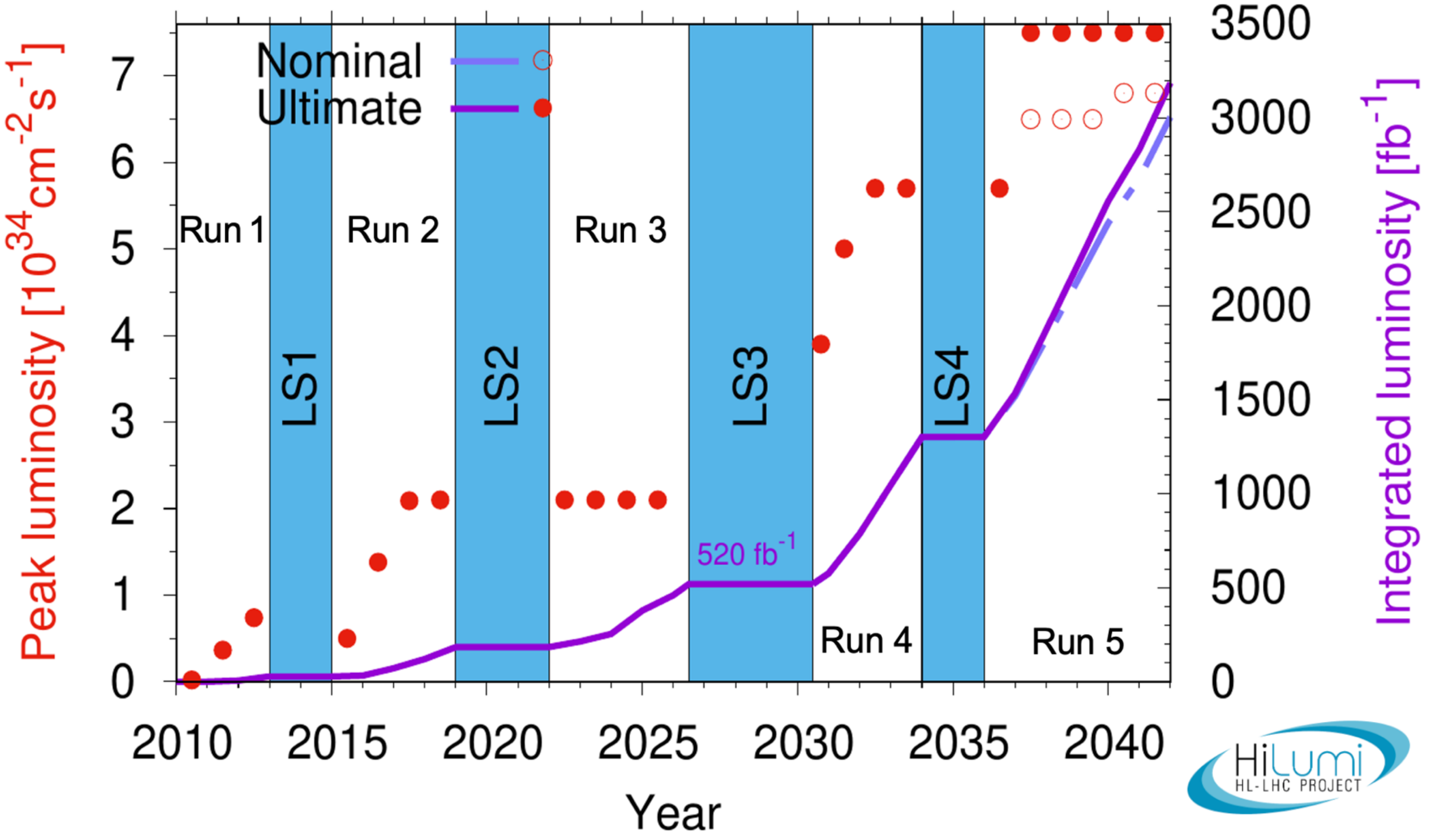
DETECTOR UPGRADES

- LHC Run 3 from 2022-2026 has just concluded.

- LHC now enters Long Shutdown 3 from 2026-2029, will start 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.

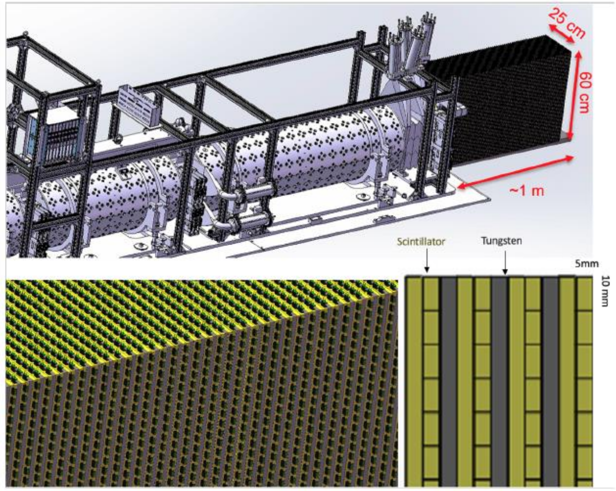
- In addition, there are plans to build the Forward Physics Facility, an entirely new detector hall.

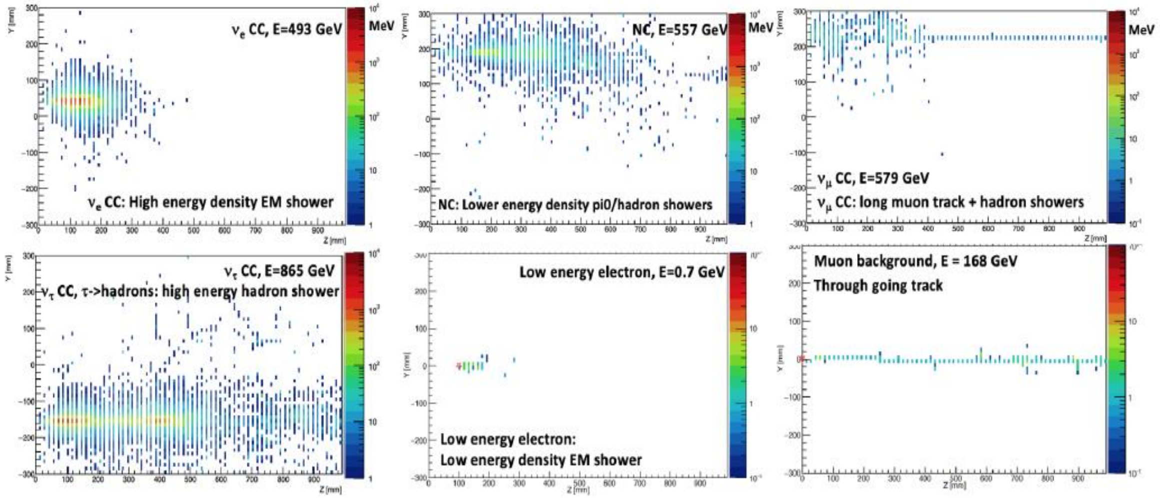


FORTVNE

- 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.

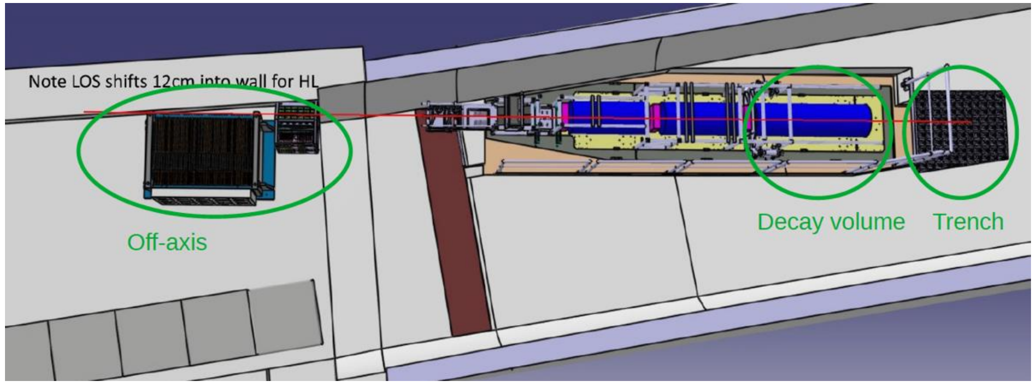


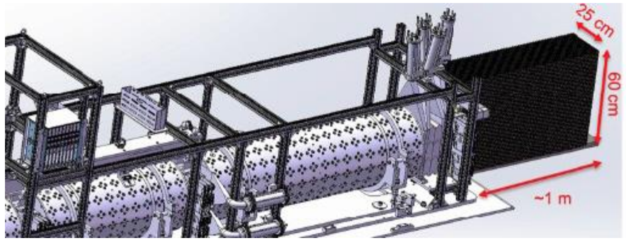


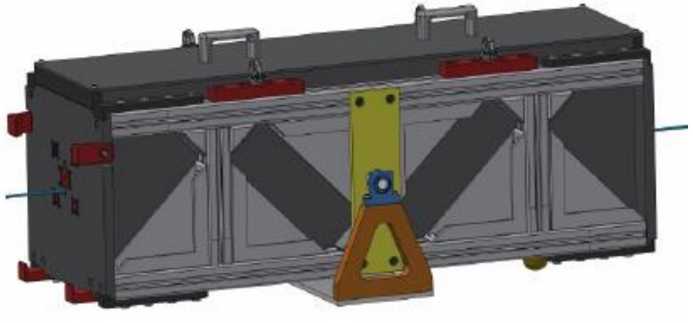
- Such detectors provide a remarkable opportunity for students to build an LHC detector from scratch, commission and install it, and collect and analyze data, all in the typical time it takes to get a PhD.

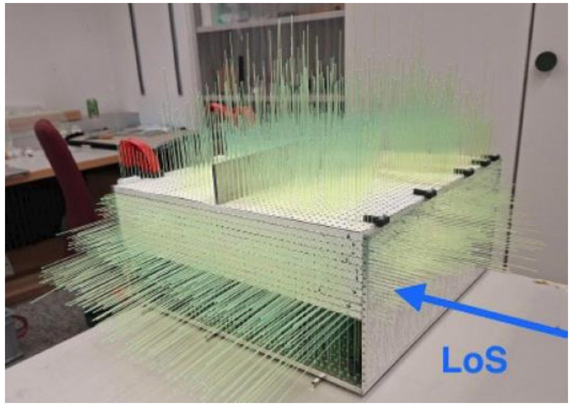
OTHER RUN 4 UPGRADE PROPOSALS

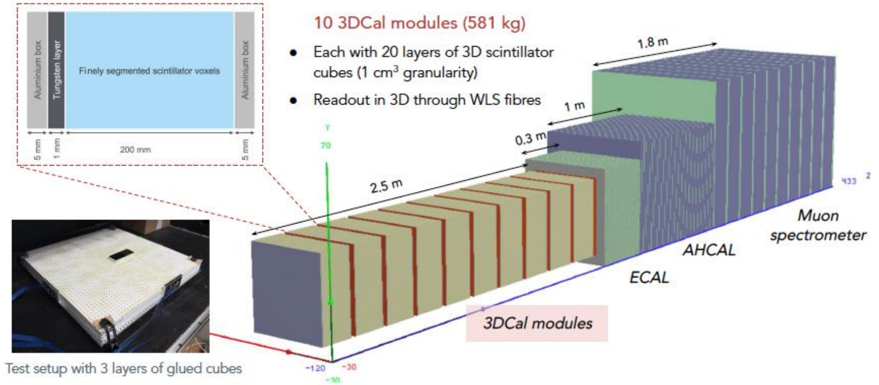
There are also many other Run 4 upgrade ideas from leading groups around the world, all vying to be placed on or near the LOS, with prototype detectors already built and installed, proposals being sent to funding agencies around the world. It has become a crowded field (literally).

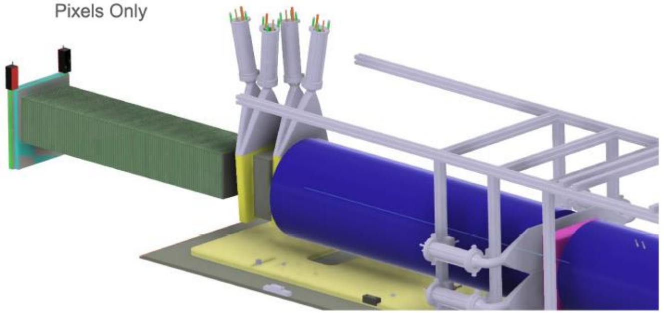












FORWARD PHYSICS FACILITY

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.

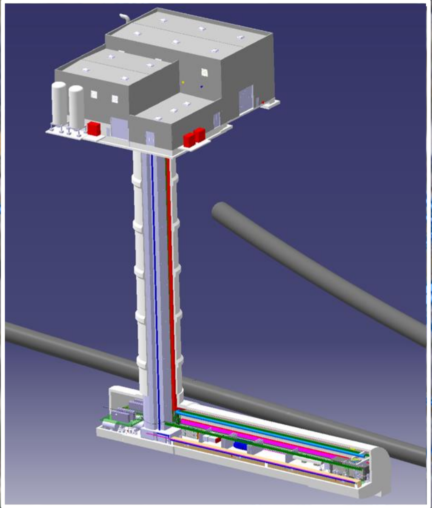
ATLAS

SPS

LHC

FASER

LOS



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

CONCLUSIONS

SUMMARY AND ACKNOWLEDGEMENTS

- After 60+ years, we have now detected neutrinos produced at a particle collider. This is "hot off the press," and we are still learning many things.

- But it is clear that this opens up many ways for small, fast, and 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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