PARTICLE THEORY AND EXPERIMENT: FORWARD PHYSICS, FASER, AND THE FPF

Jonathan Feng and Dave Casper

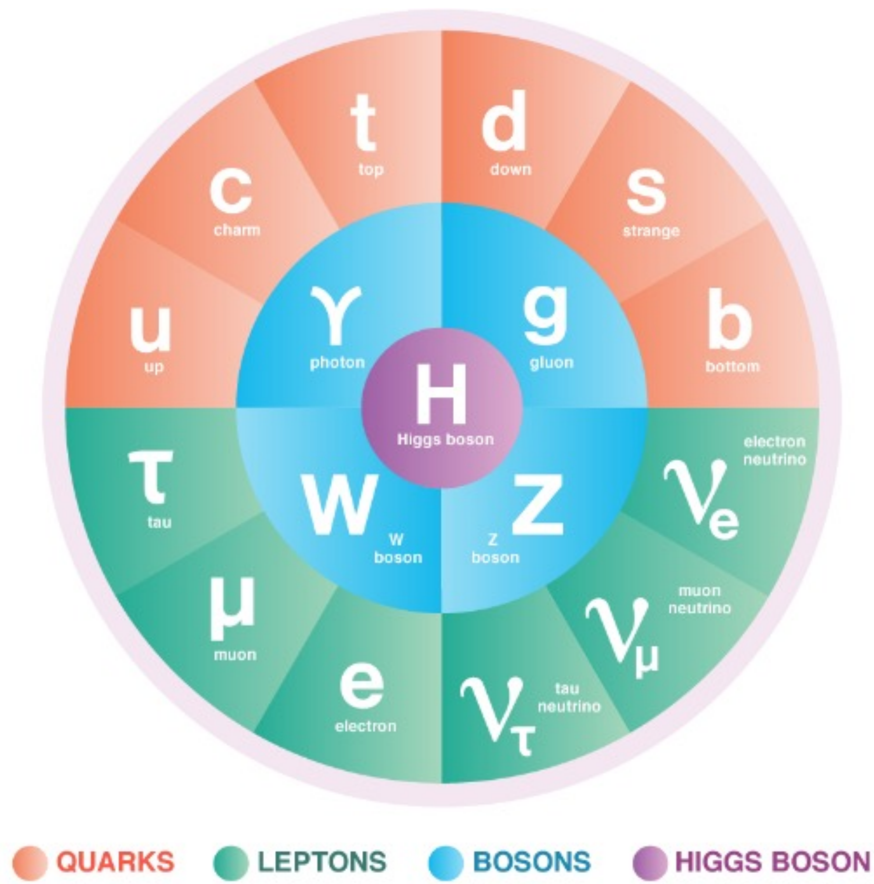
Pizza Seminar, 18 November 2022

THE STANDARD MODEL OF PARTICLE PHYSICS

- The Higgs boson discovery in 2012, completed the Standard Model of particle physics, but many fundamental questions remain.
  - Neutrino Masses
  - Dark Matter
  - Dark Energy
  - Matter–Anti-Matter Asymmetry

  …

Many of the most outstanding questions are at the interface of particle physics and cosmology, are concerned with very weakly-interacting particles, and require new particles.

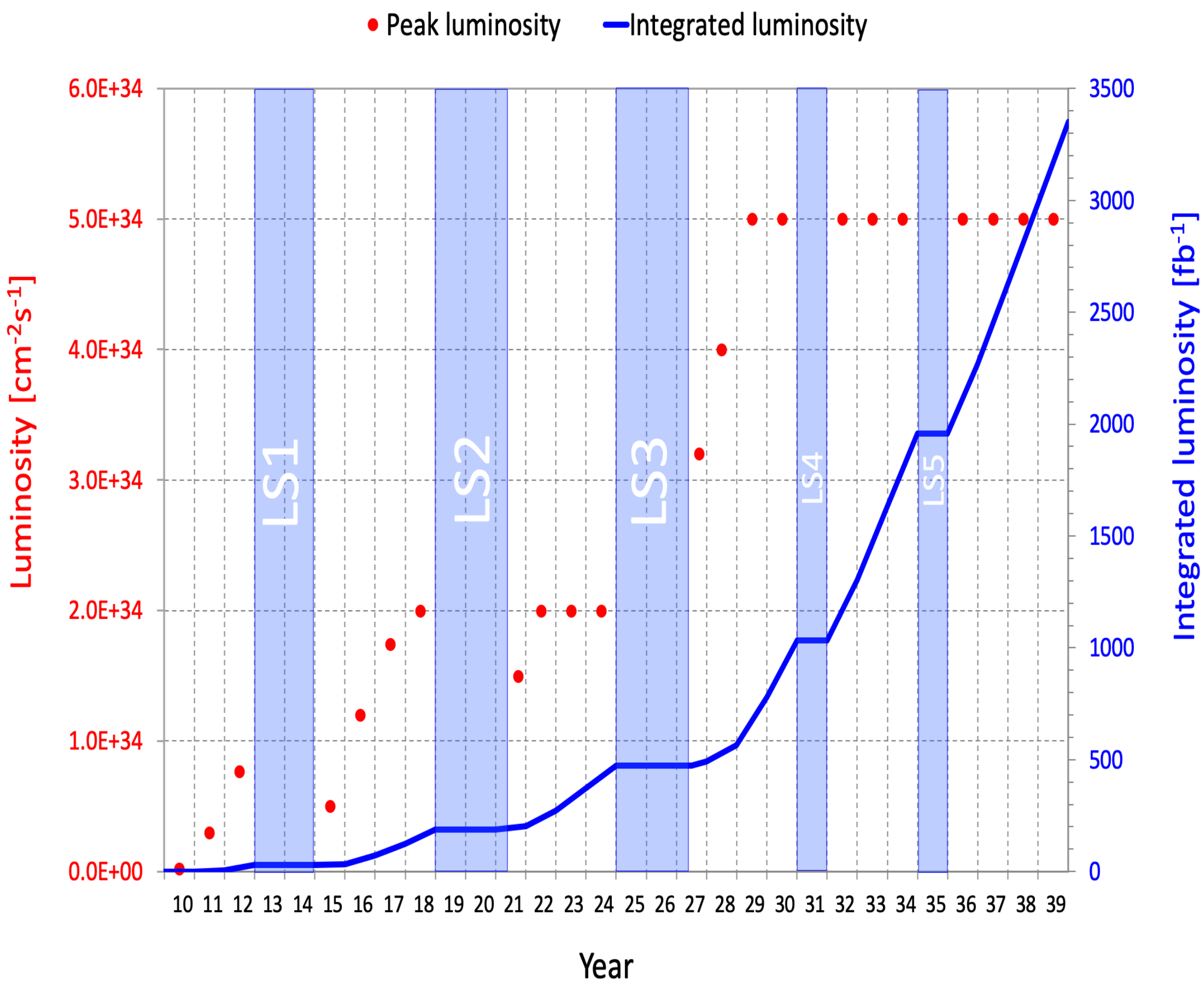


LARGE HADRON COLLIDER

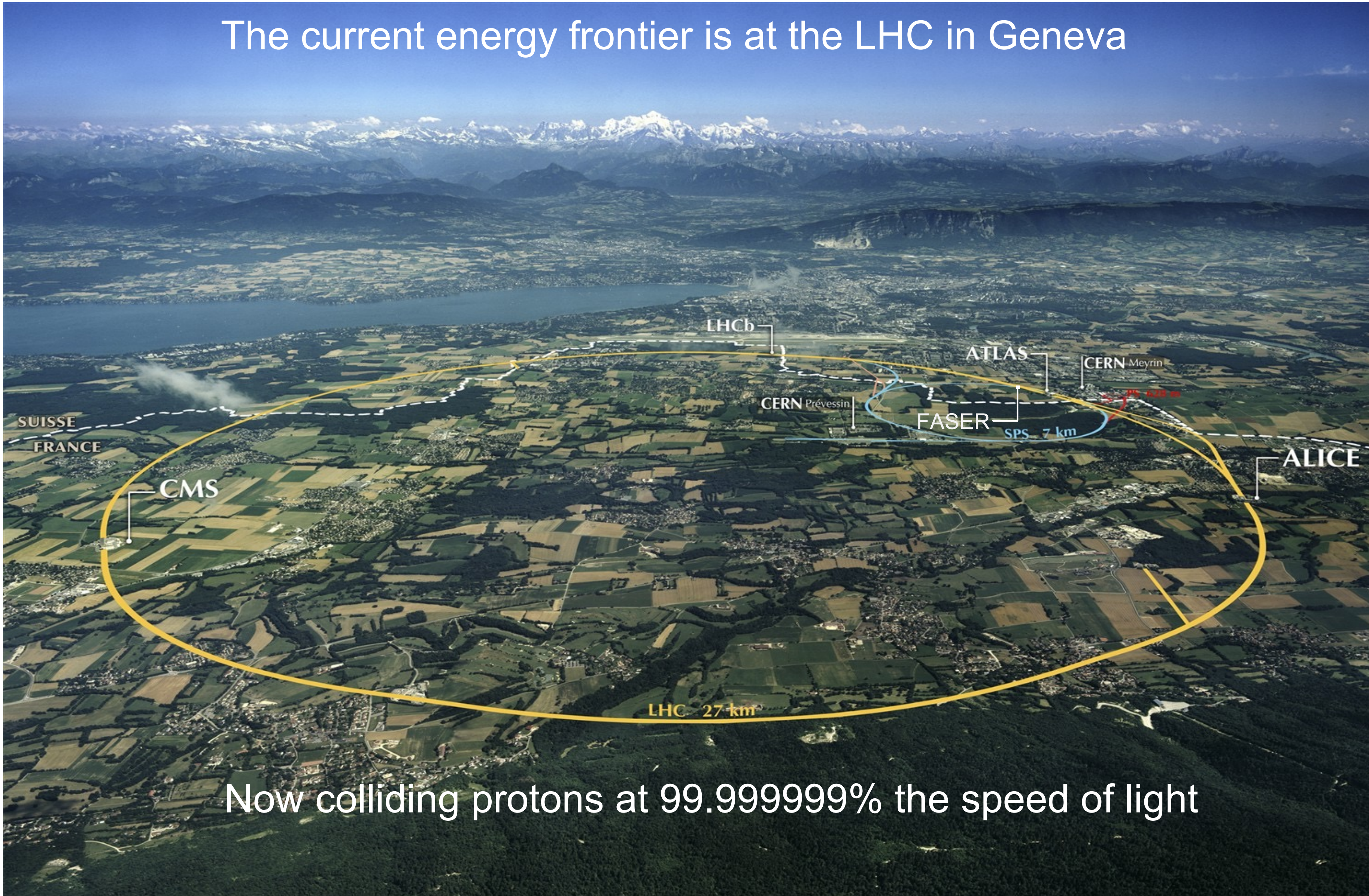
- Particle colliders have been key to progress for many decades. The latest and greatest particle collider is the Large Hadron Collider at CERN in Geneva.

- The LHC started collecting data again in July 2022 and will run until ~2040. Will we find new particles?

- More importantly, what can we do to enhance the prospects for discovering new physics?

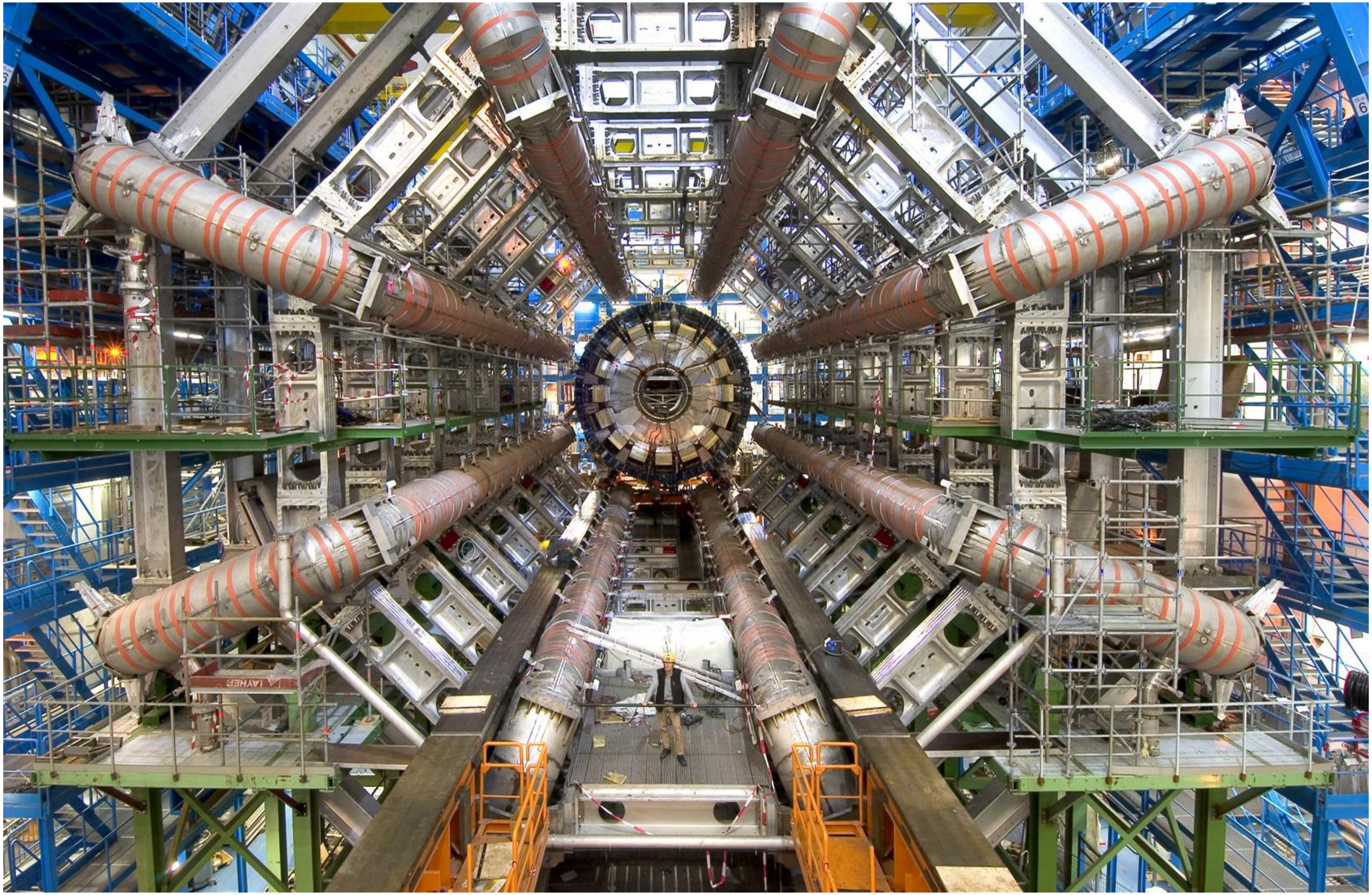


THE LARGE HADRON COLLIDER



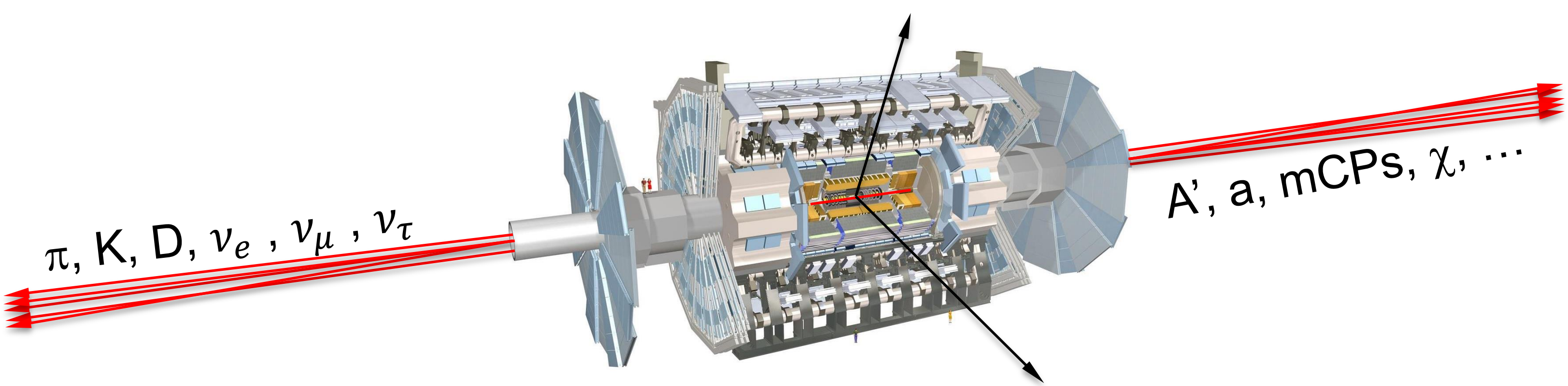
THE ATLAS DETECTOR

One of several giant detectors that observe particle collisions at the LHC



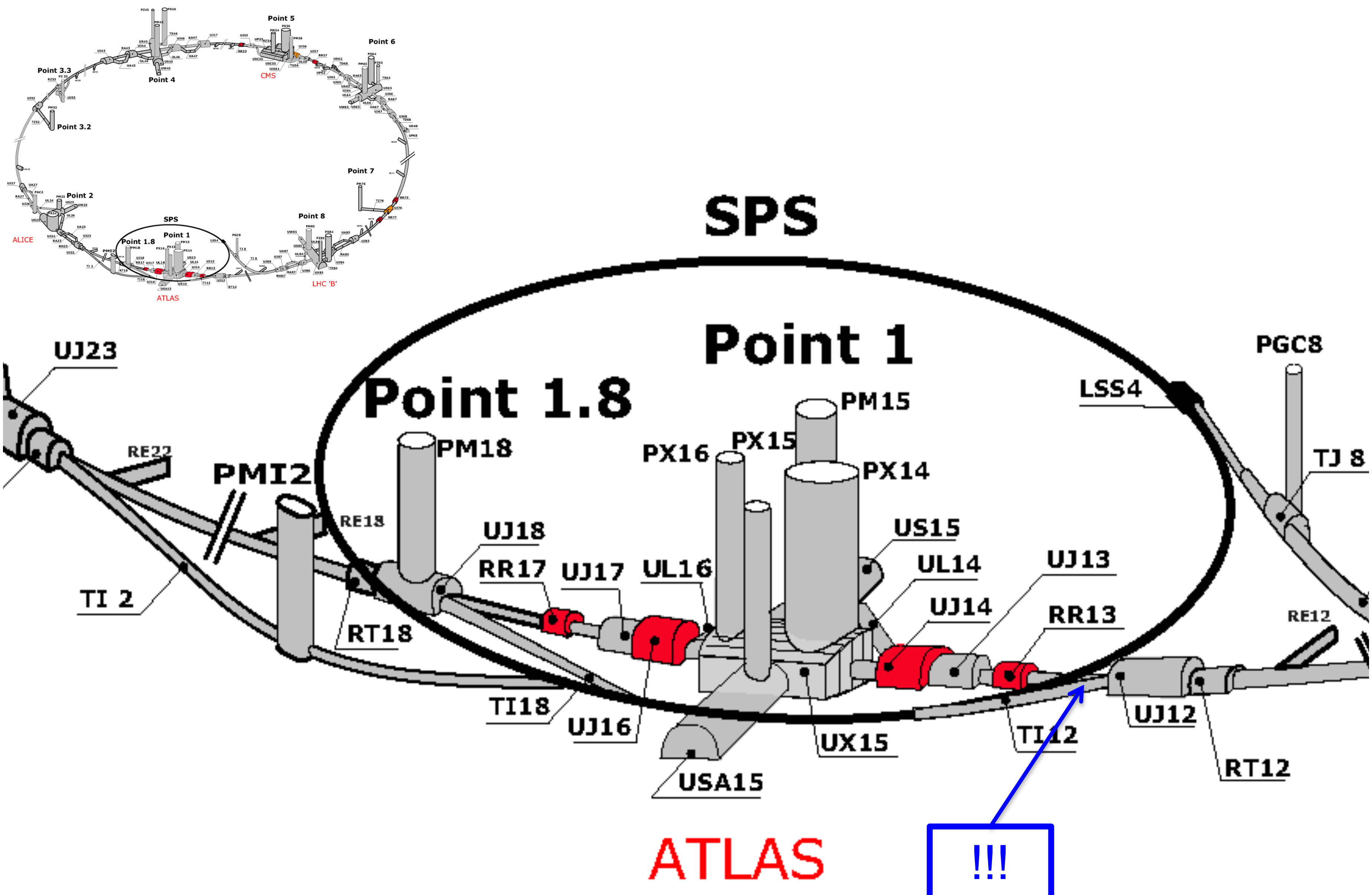
AN OBVIOUS QUESTION

- Are we missing opportunities at the LHC?
- In the last 5 years, we have discovered that the answer is YES: the LHC is far from operating at full potential.
- By far the largest fluxes of high-energy light particles (e.g., pions, kaons, D mesons, neutrinos) are in the far-forward direction.
- This may also be true of many interesting new particle candidates: dark photons, axion-like particles, millicharged particles, dark matter, …
- All of these particles are dominantly produced along the beamline and escape through the blind spots of existing detectors.



FASER

MAP OF LHC


SPS
Point 1
Point 1.8
PM15
PX15
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PM18
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UJ23
RE22
RE18
UJ18
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UJ17
UL16
US15
UL14
UJ13
UJ14
RR13
LSS4
PGC8
TJ 8
RE12
TI 2
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UJ16
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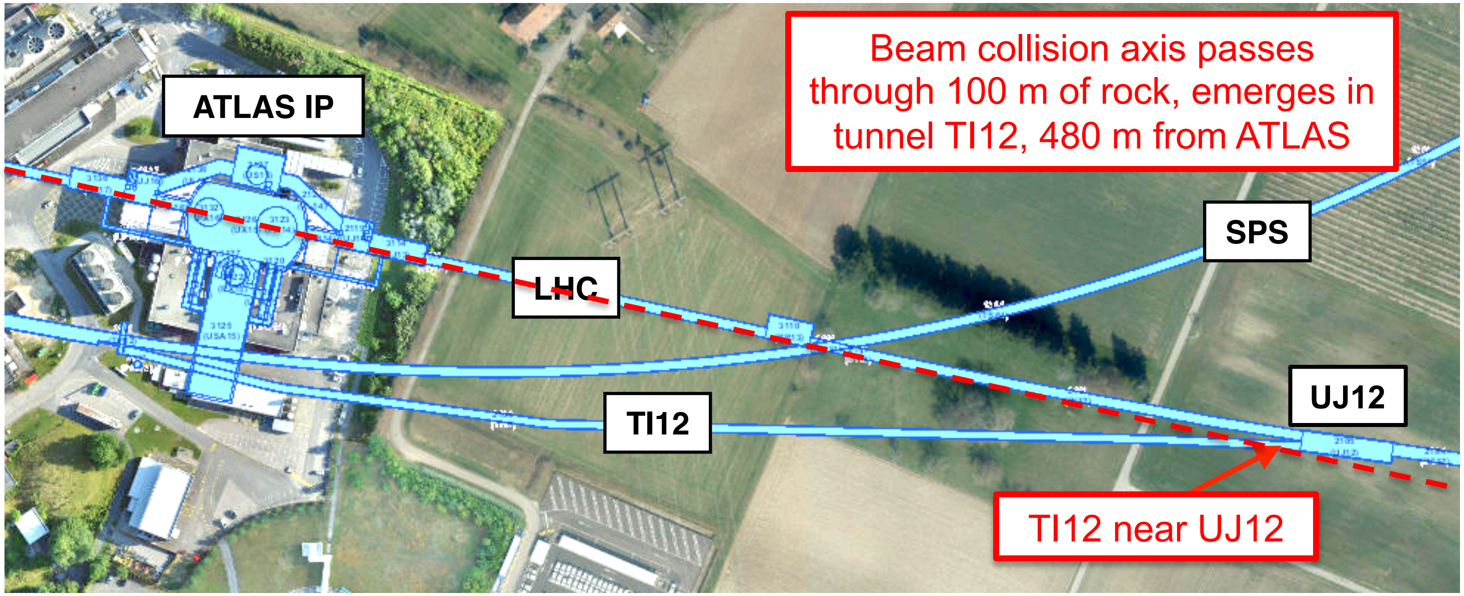
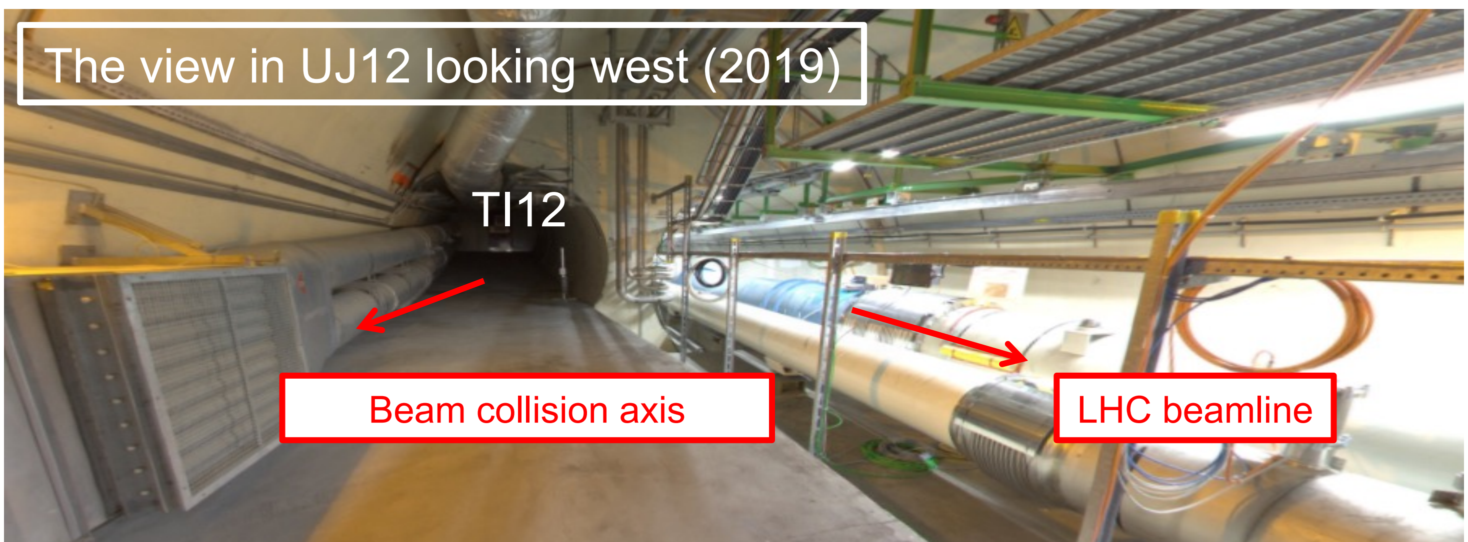
ATLAS
!!!

THE FAR-FORWARD REGION



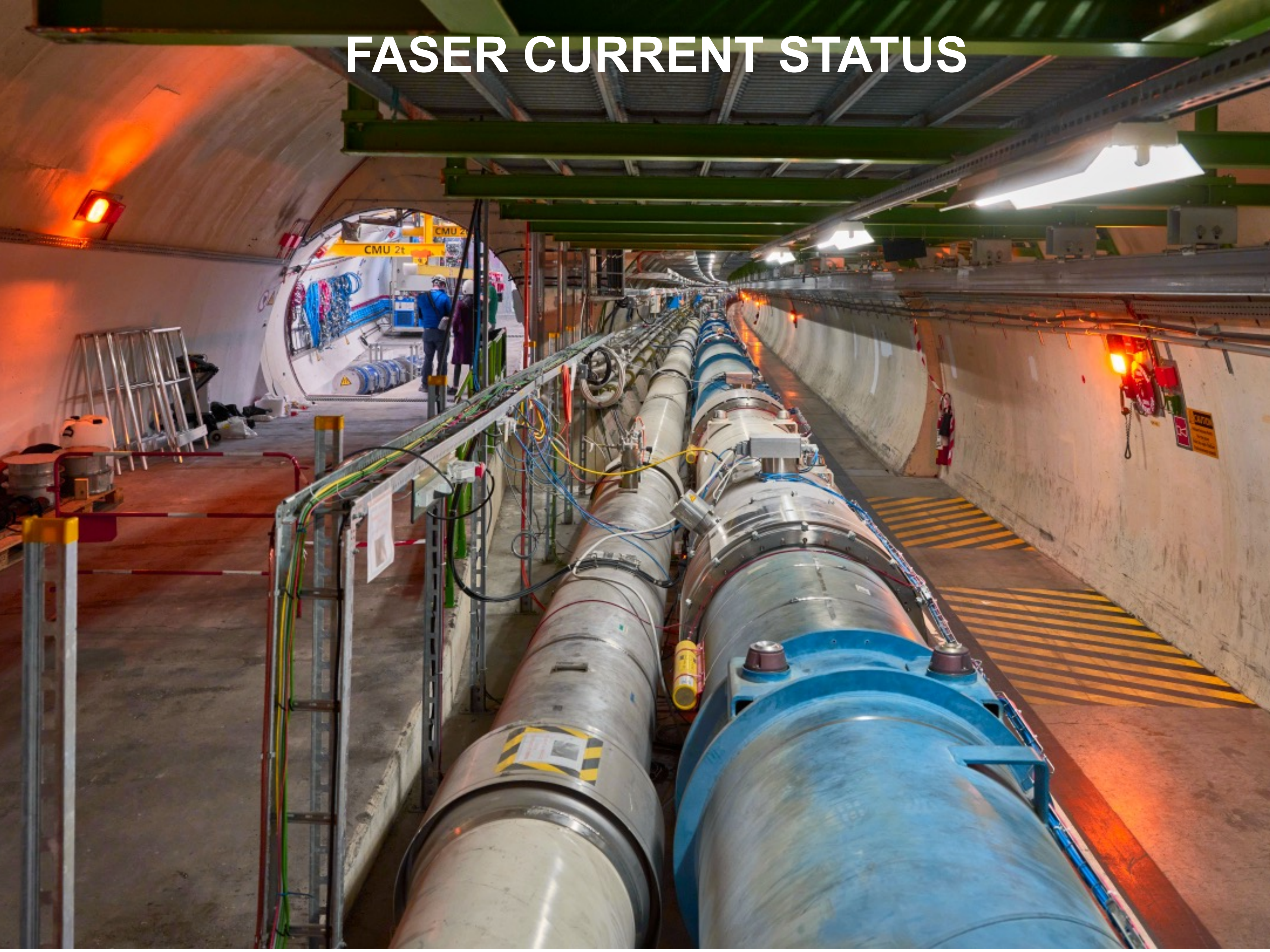


FASER IN TUNNEL TI12

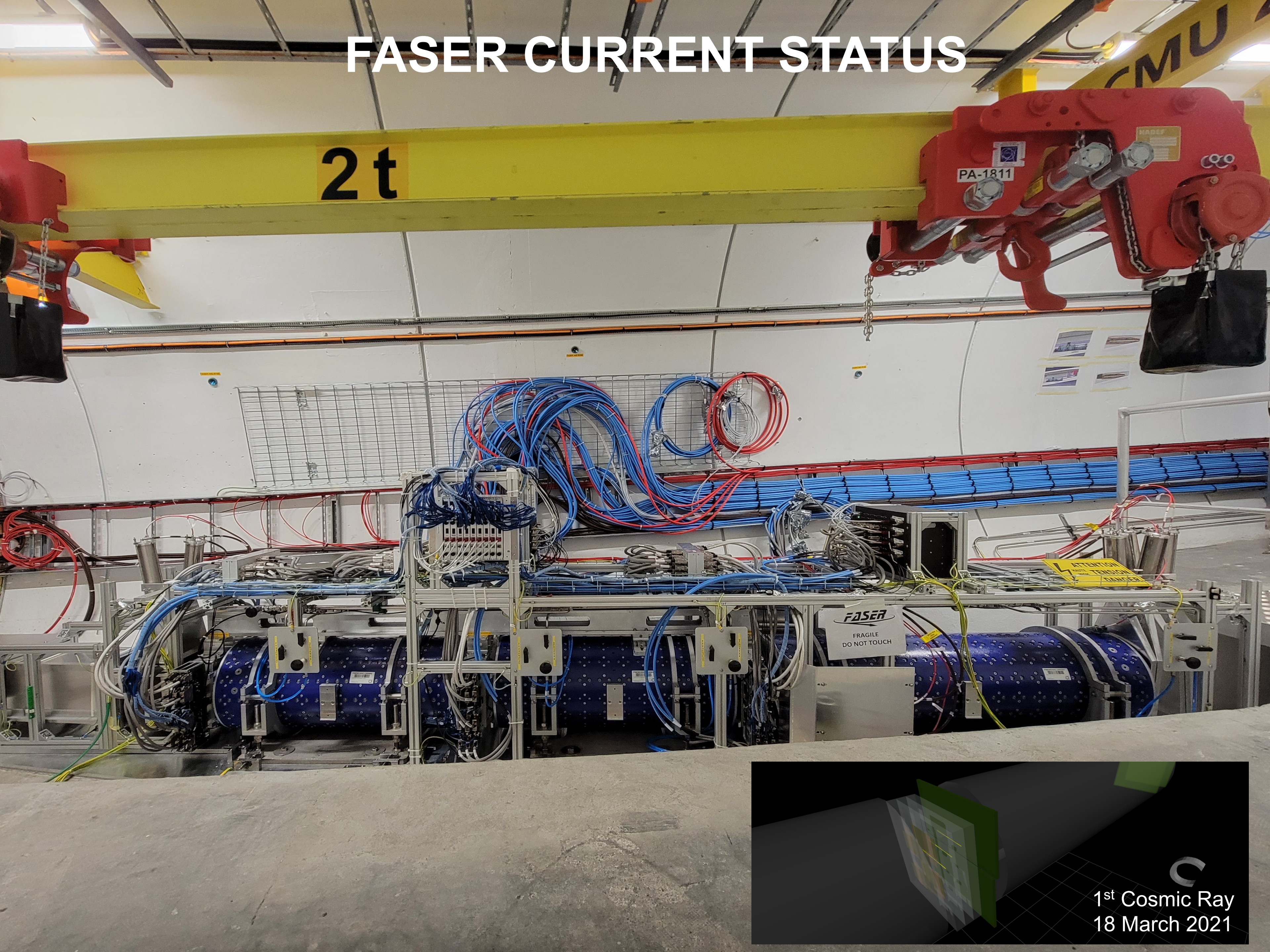
- The beam collision axis was located to mm accuracy by the CERN survey department. To place FASER on this axis, a trench was required to lower the floor by 46 cm.

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

FASER CURRENT STATUS



FASER CURRENT STATUS



1st Cosmic Ray
18 March 2021

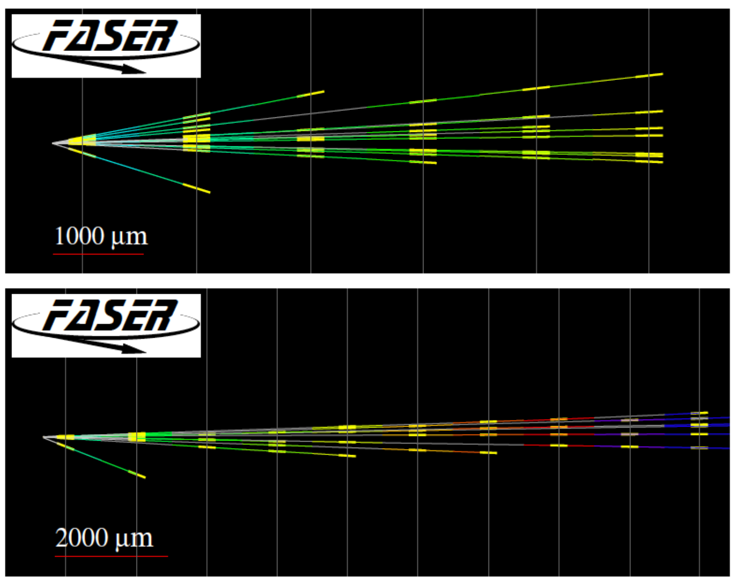
FASERν

FIRST COLLIDER NEUTRINOS

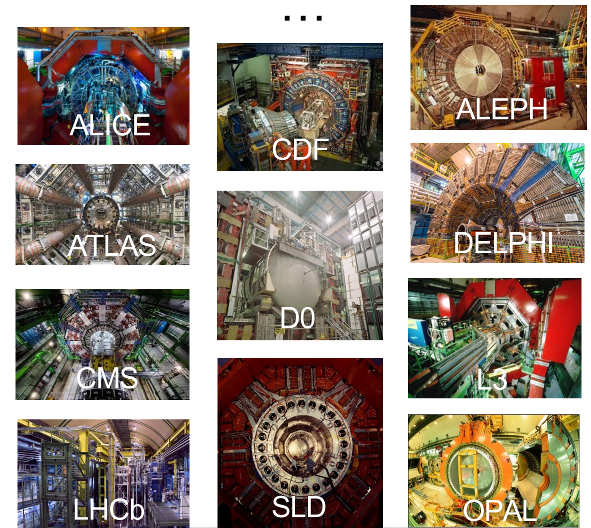
- In 2018 a FASER pilot emulsion detector with 11 kg fiducial mass collected 12.2 fb^{-1} on the beam collision axis (installed and removed during Technical Stops).

- In May 2021, the FASER Collaboration announced the direct detection of 6 candidate neutrinos above 12 expected neutral hadron background events (2.7σ).

- Not the discovery of collider neutrinos, but a sign of things to come.



LOCATION, LOCATION, LOCATION



FASER Pilot Detector

Suitcase-size, 4 weeks
$0 (recycled parts)

6 candidate neutrinos

All previous
collider detectors

Building-size, decades
~$$10^9$

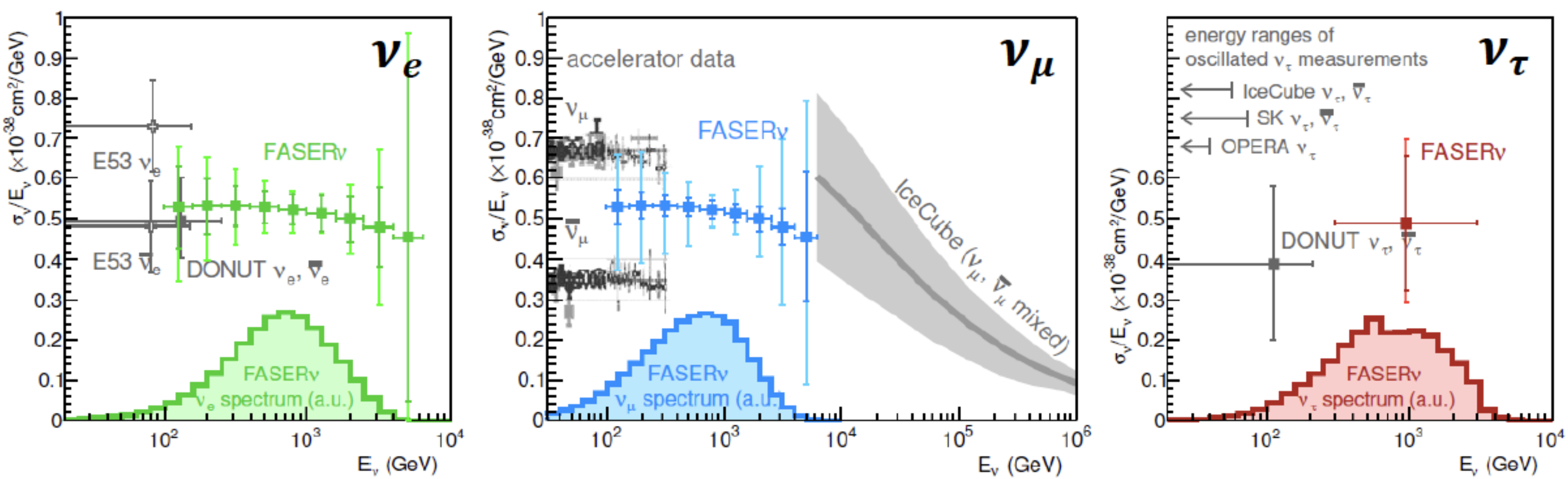
0 candidate neutrinos

SUMMARY

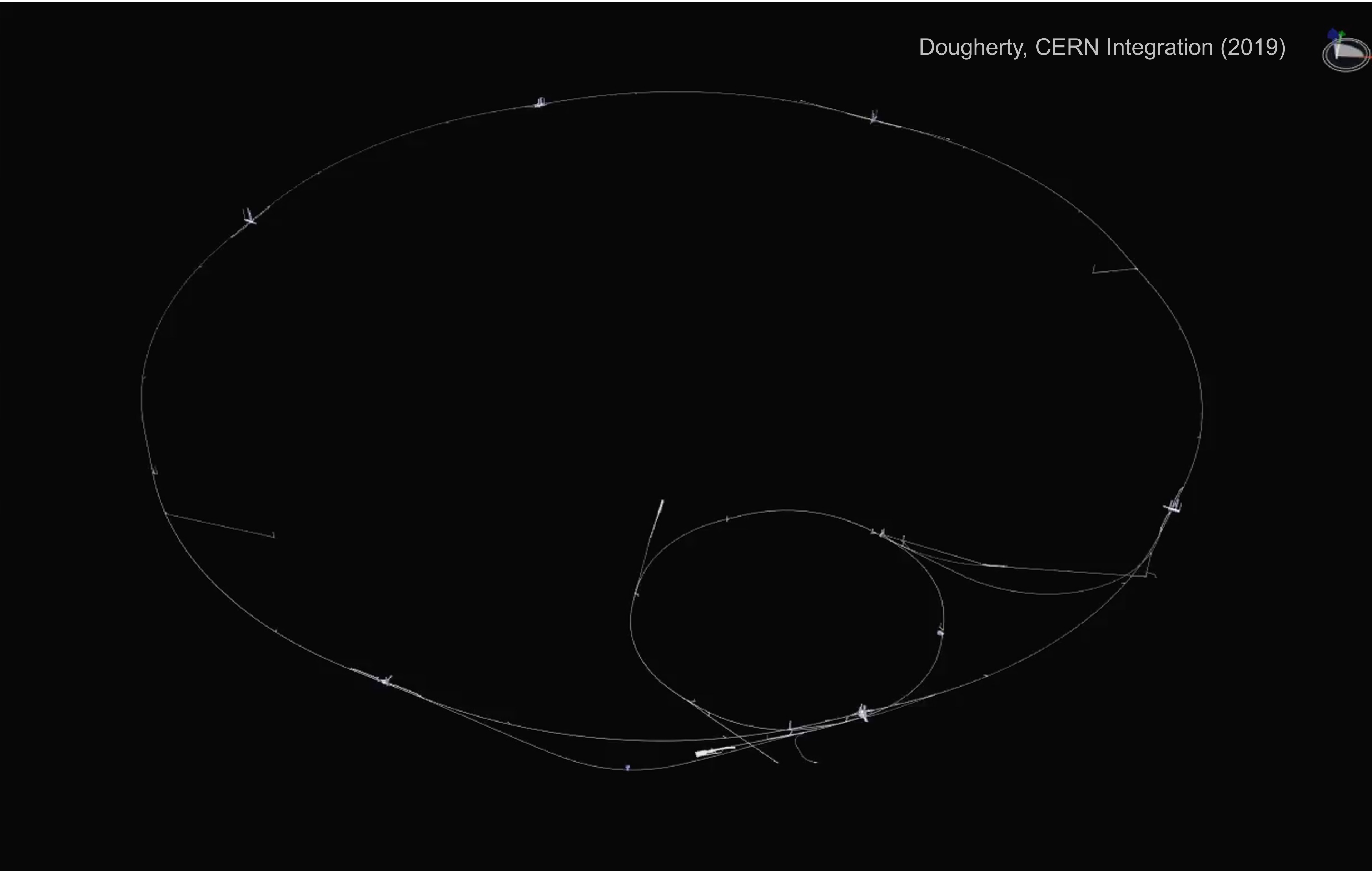
- Forward physics provides a new frontier in high energy particle physics, many new opportunities for fundamental discoveries
  - Standard Model: opens a new field of neutrino physics at colliders, with ~1000 ν_e, ~10,000 ν_μ, ~10 ν_τ at TeV energies in Run 3, ~100 times more in HL-LHC. Implications for neutrino properties, forward hadron production, cosmic rays and cosmic neutrino physics.
  - Beyond the Standard Model: dark photons, sterile neutrinos, dark scalars, axion-like particles, milli-charged particles, dark matter, new forces.
- Many ideas initiated at UC Irvine, research opportunities in both particle theory and experiment with Professors Feng, Casper, and Bian. Current researchers includes graduate students Max Fieg, Savannah Shively, Yiwen Xiao, Alejandro Yankelevich, as well as several postdocs.
- Typically path includes 234AB, 235AB, reading courses. Positions available now; see any of the involved faculty for details.

NEUTRINO PHYSICS

- In Run 3 (2022-25), FASERν will
  - Detect the first collider neutrino.
  - Record ~1000 ν_e, ~10,000 ν_μ, and ~10 ν_τ interactions at TeV energies, the first direct exploration of this energy range for all 3 flavors.
  - Distinguish muon neutrinos from anti-neutrinos by combining FASER and FASERν data, and so measure their cross sections independently.
  - Add significantly to the number of ν_τ and detect the first anti-ν_τ .



FASER Collaboration 1908.02310 (2019)

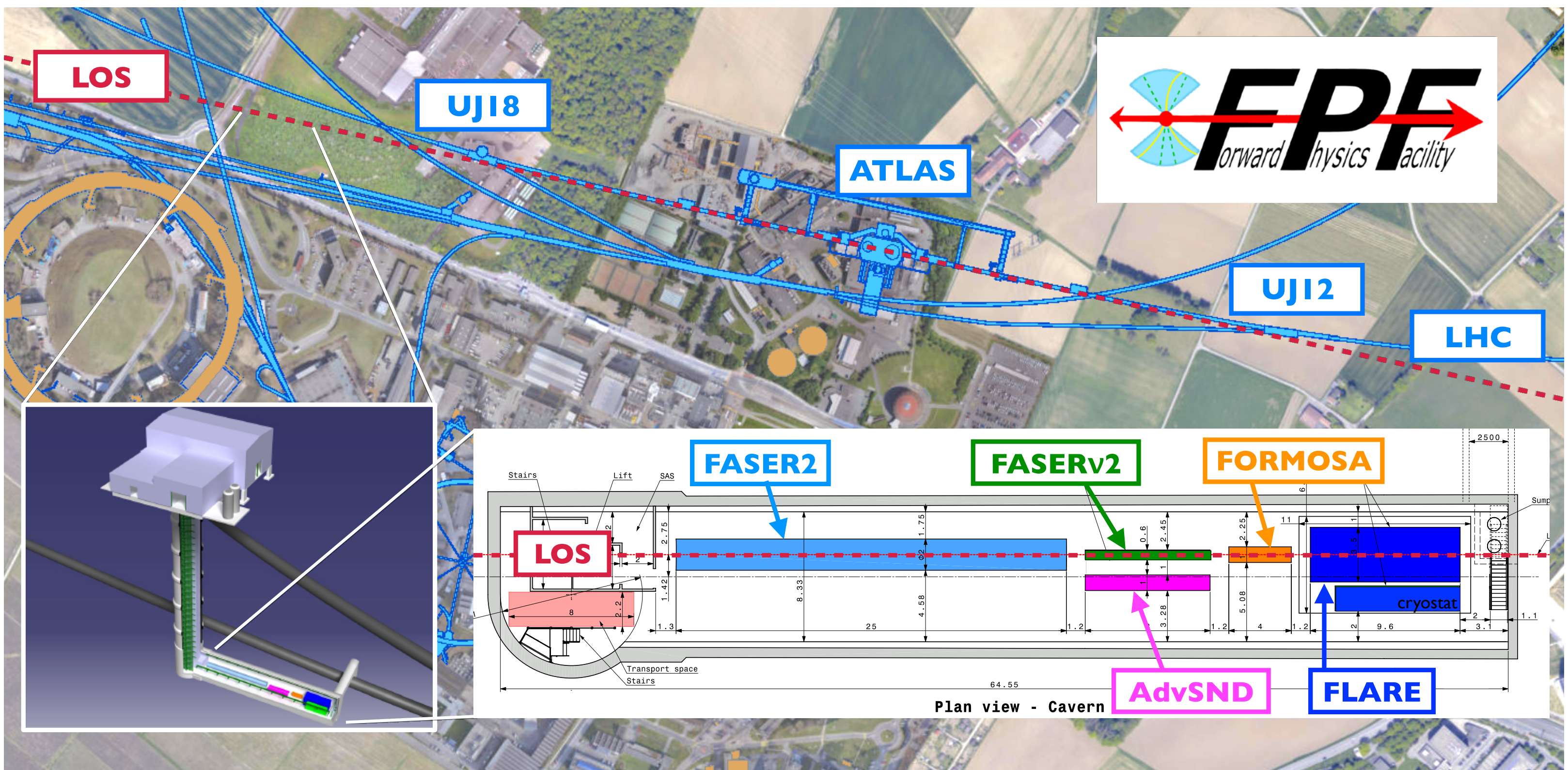


Dougherty, CERN Integration (2019)

FPF
Forward Physics Facility

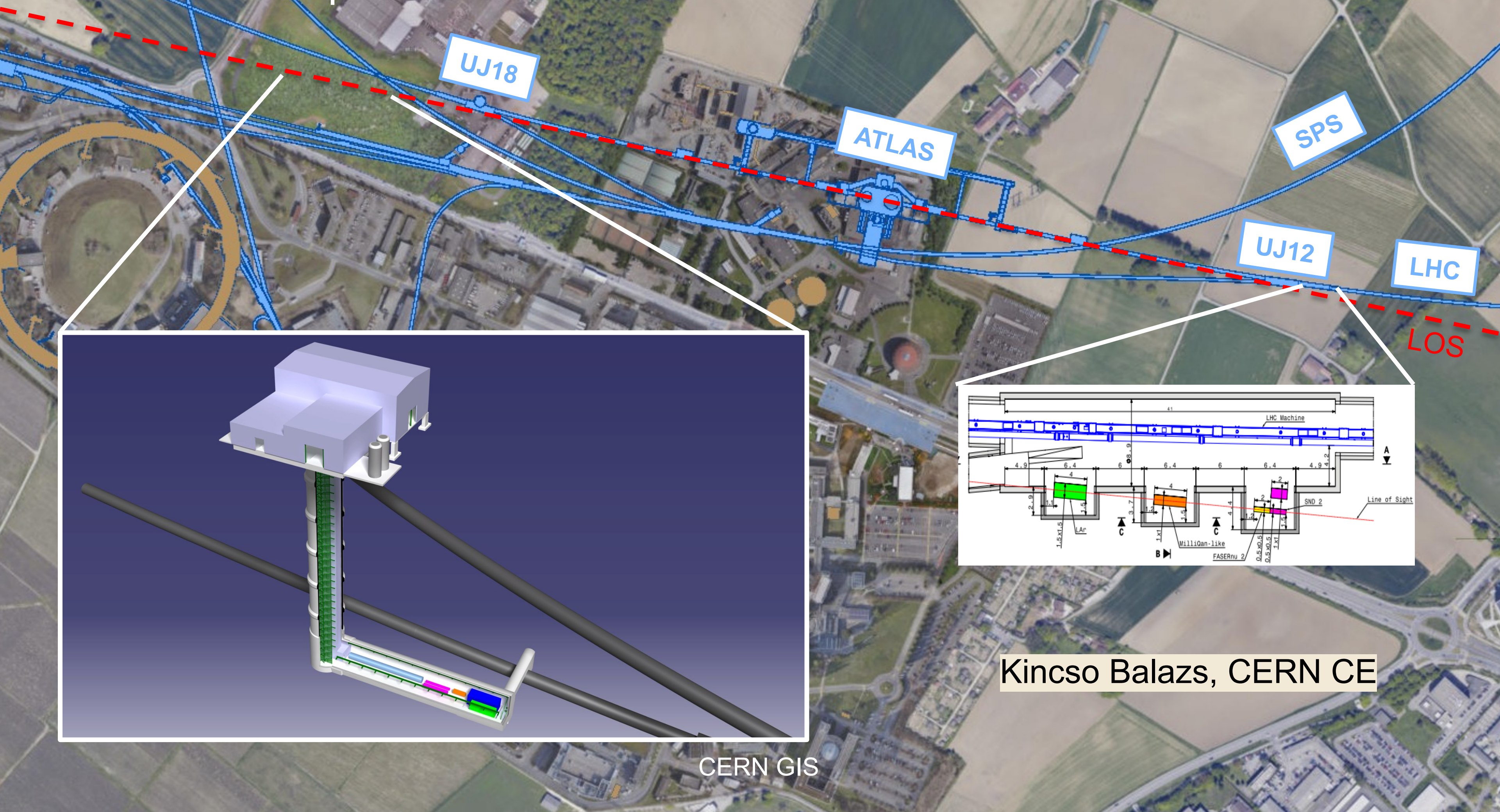
FORWARD PHYSICS FACILITY

- The FPF is proposed to run at the HL-LHC with implications for
  - Neutrinos: neutrino blind → neutrino factory (10^6 neutrinos at the highest human-made energies ever).
  - New particles: dark matter, dark sectors, milli-charged particles, new force particles, new Higgs-like particles, sterile neutrinos, quirks, …

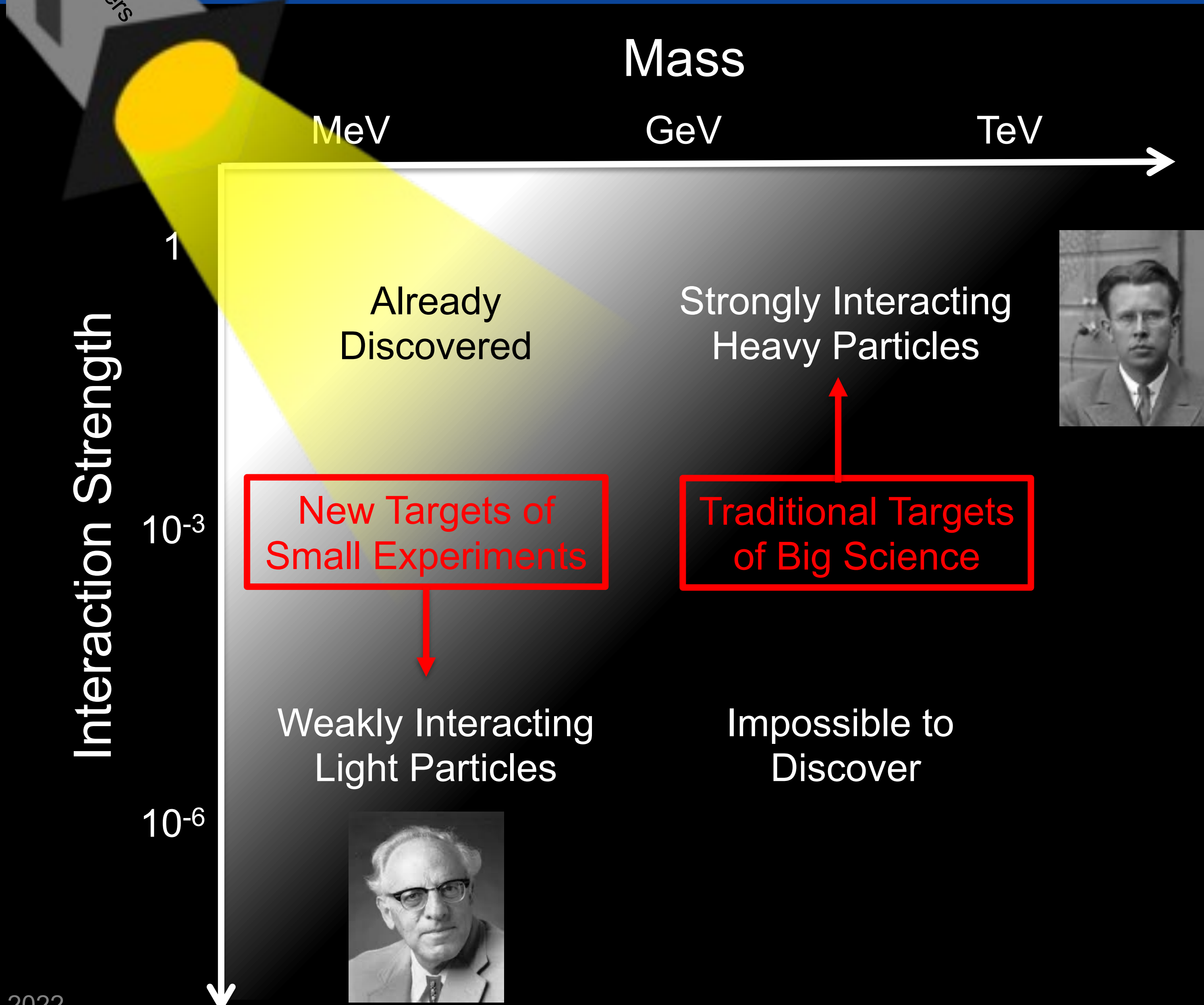


FORWARD PHYSICS FACILITY

- The rich physics program in the far-forward region therefore strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2027-37.

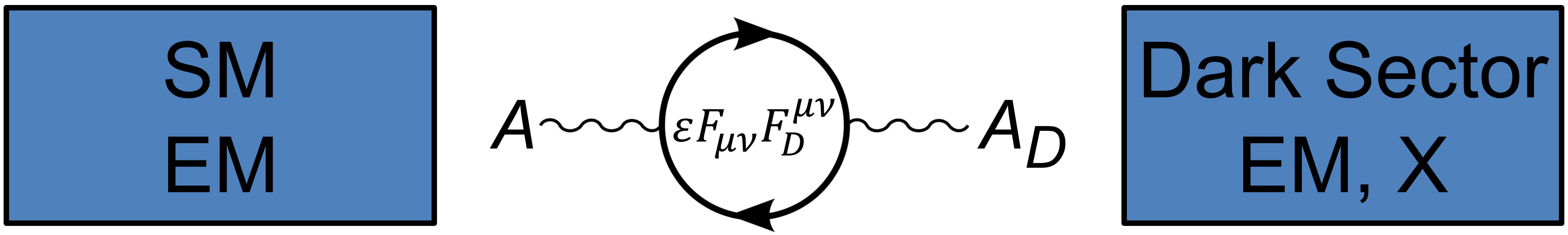


THE NEW PARTICLE LANDSCAPE



AN EXAMPLE: DARK SECTORS

- Suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.
- The force carriers of the SM and dark EM will mix
  - perhaps suppressed, but completely generic, since a renormalizable operator

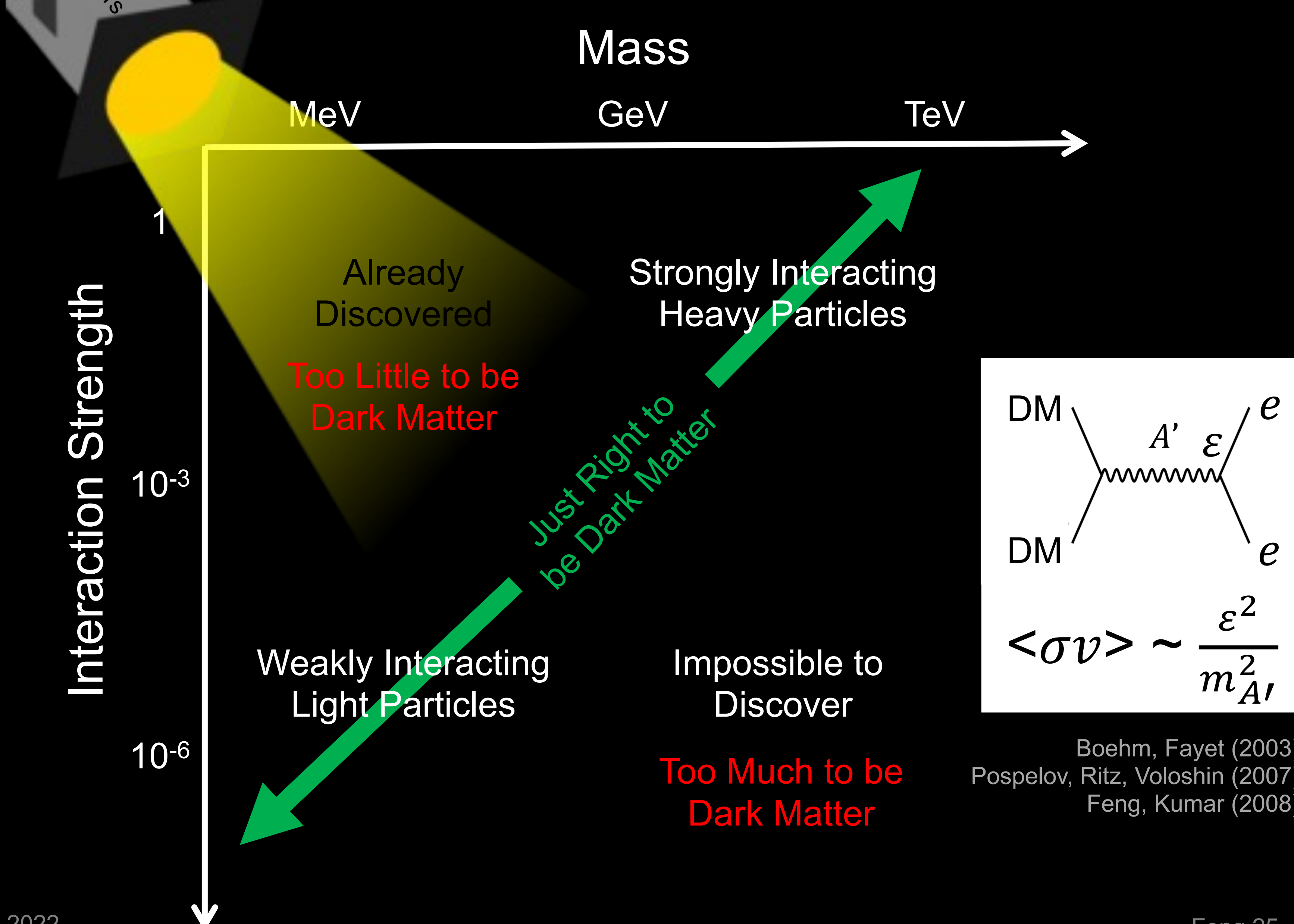


- The result? Two possibilities:
  - Dark photons A', like photons, but with mass $m_{A'}$, couplings suppressed by ε.
  - Milli-charged particles (mCPs), with charges suppressed by ε.

Holdom (1986)

- Finding either of these would imply new fundamental forces or new matter particles, possibly a "portal" to the dark sector.

THE THERMAL RELIC LANDSCAPE



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

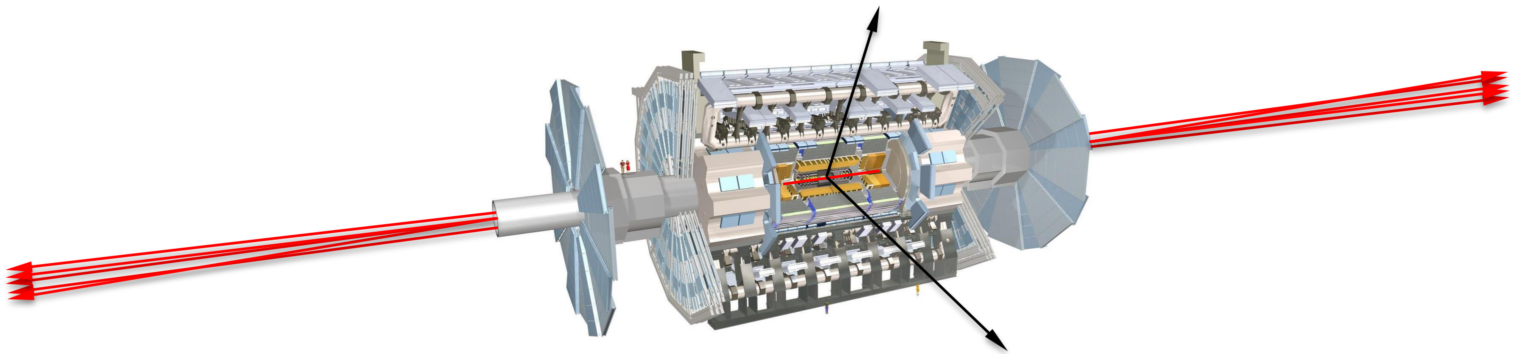
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

SEARCHES FOR NEW LIGHT PARTICLES

- If new particles are light and weakly interacting, the existing big LHC detectors are perfectly designed NOT to see them.

- Existing detectors are designed to find new heavy particles. These particles are produced almost at rest and decay isotropically.

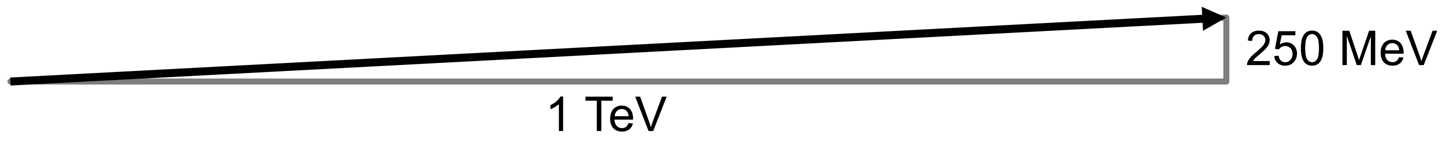


- But new light particles are mainly produced in the decays of light particles: π, η, K, D and B mesons. These are mainly produced along the beamline, and so the new particles disappear through the holes that let the beams in.

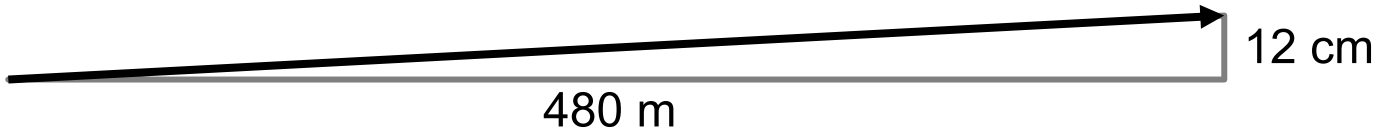
- Clearly we need a detector to exploit the "wasted" $\sigma_{inel} \sim 100$ mb and cover these "blind spots" in the forward region. If we go far enough away, the proton beams are bent by magnets (it's a circular collider!), whereas the new light particles will go straight.

HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:

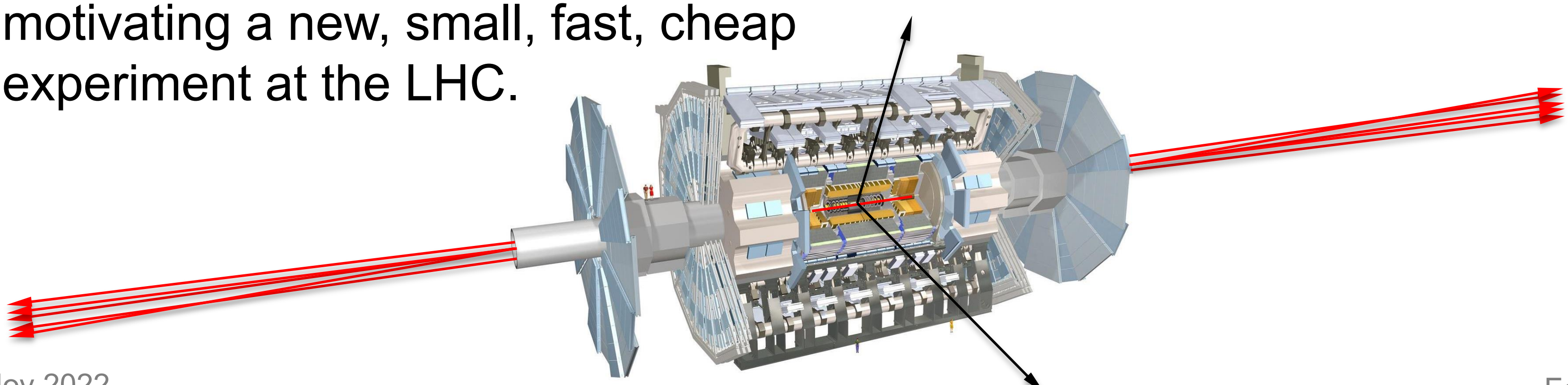


- Space:



- The opening angle is 0.2 mrad (η ~ 9); cf. the moon (7 mrad). Most of the signal passes through 1 sheet of paper at 480 m.

- TeV dark photons (or any other new particles produced in π, η, K, D, B decay) are far more collimated than shown below, motivating a new, small, fast, cheap experiment at the LHC.



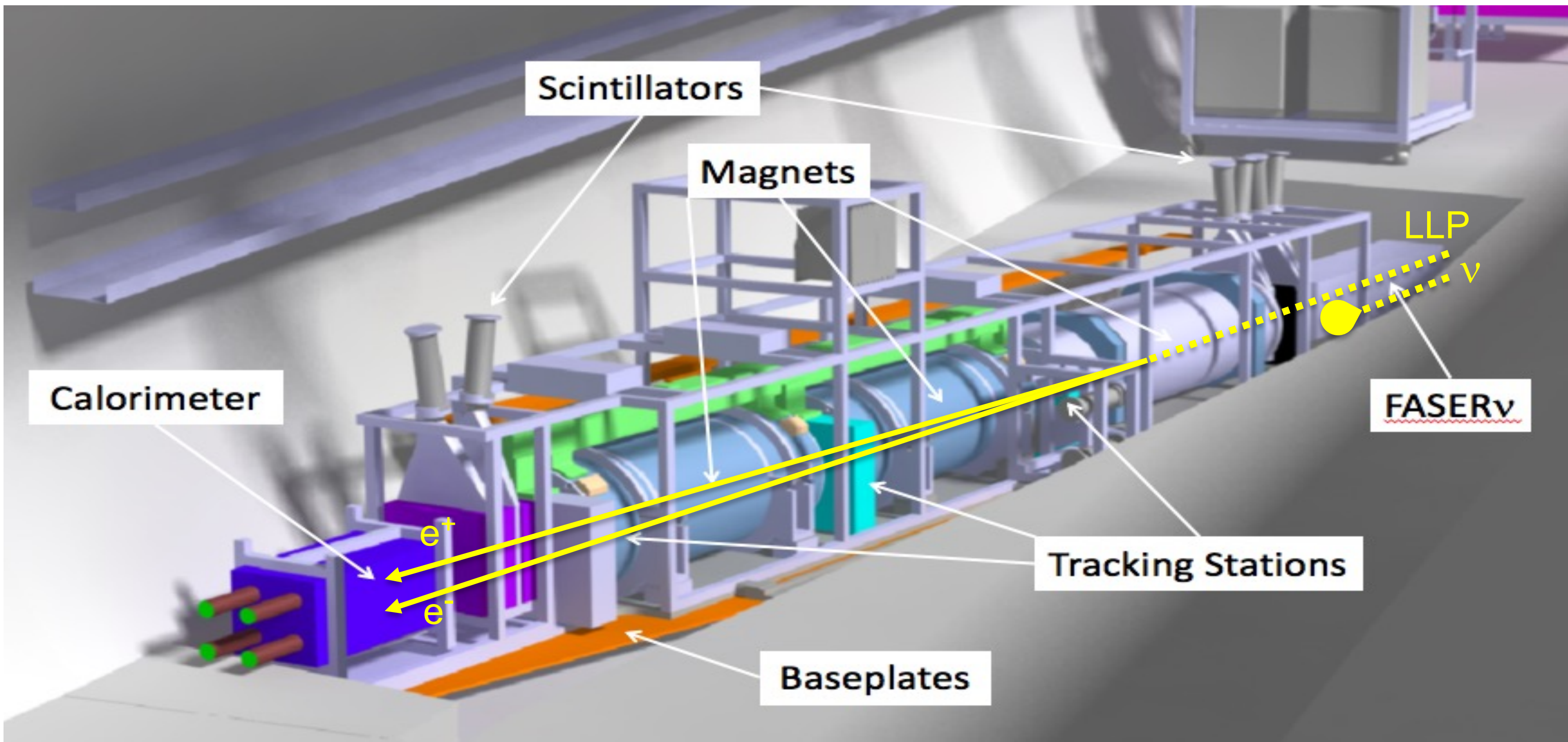
FASER TIMELINE

- September 2017: Initial proposal (Feng, Galon, Kling, Trojanowski)
- July 2018: Submitted LOI to CERN LHCC
- October 2018: Approval from ATLAS SCT and LHCb Collaborations for use of spare detector modules
- November 2018: Submitted Technical Proposal to LHCC
- November 2018 – January 2019: Experiment funded by the Heising-Simons and Simons Foundations
- March 2019: FASER approved as 8th LHC detector by CERN
- December 2019: FASERν approved as 9th LHC detector by CERN
- March 2021: FASER fully installed, commissioning of the detector begins
- May 2021: FASERν announces first candidate collider neutrinos
- Mid-2022: FASER and FASERν begin collecting data in Run 3

FIRST FASER COLLABORATION MEETING

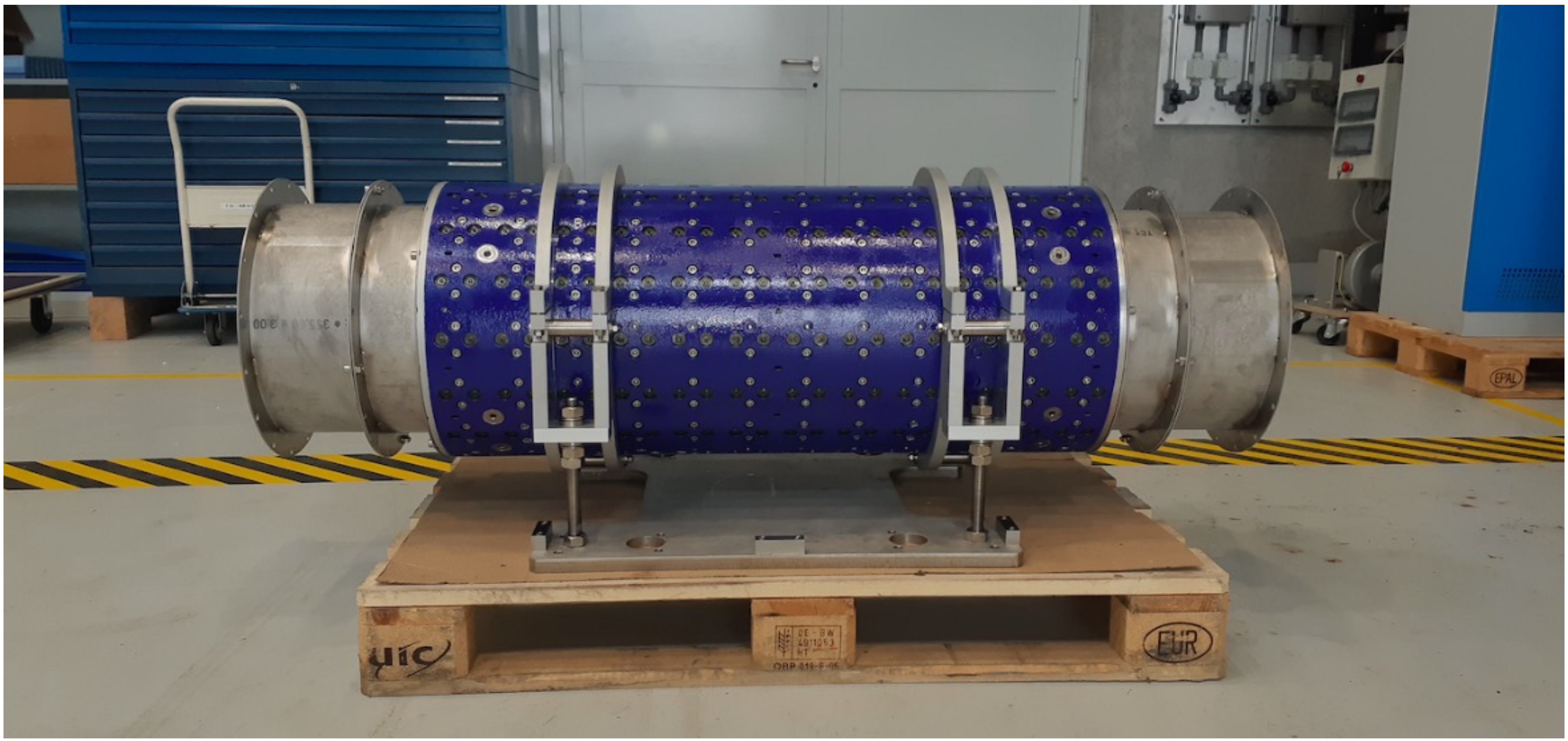
THE FASER DETECTOR

- Nothing incoming and 2 ~TeV, opposite-sign charged tracks pointing back to the ATLAS IP: a “light shining through (100 m-thick) wall” experiment.
- Scintillators veto incoming charged tracks (muons), magnets split the charged tracks, which are detected by tracking stations and a calorimeter.



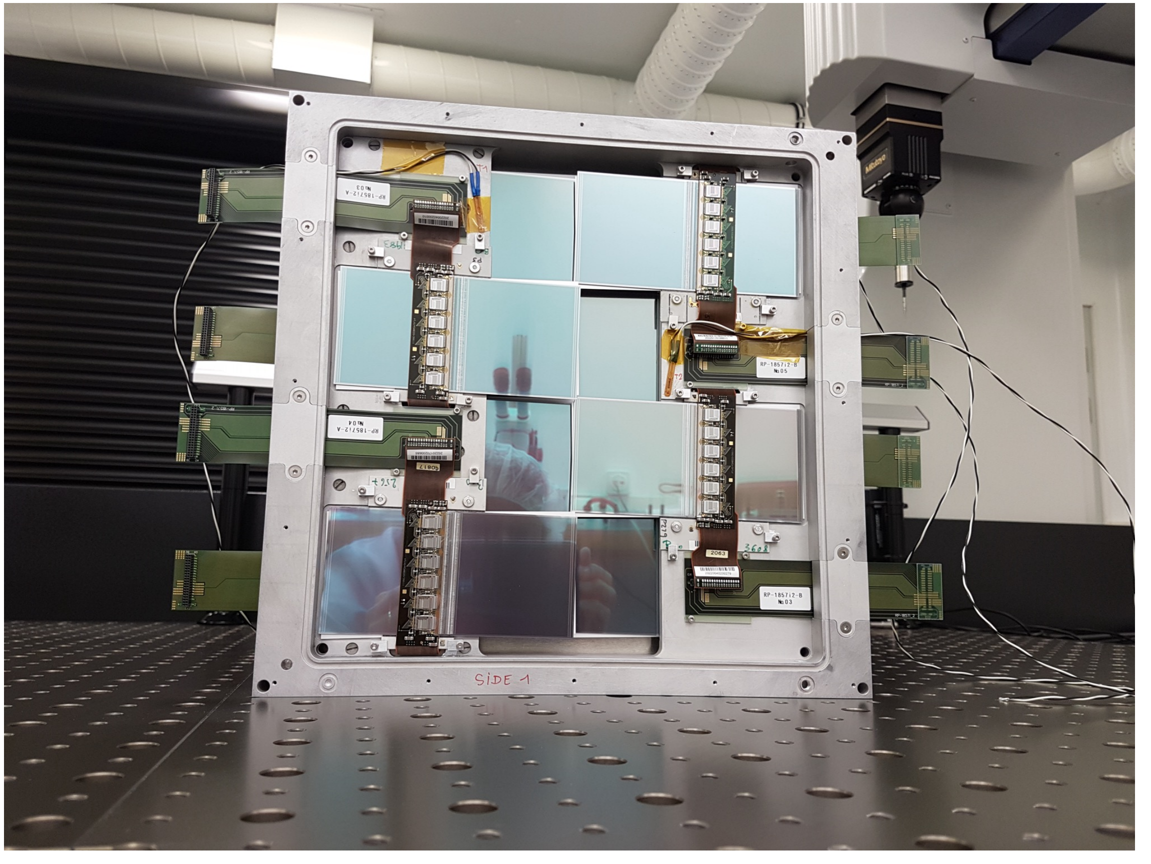
MAGNETS

- FASER includes 3 magnets: 1.5 m, 1 m, and 1m long.
- 0.57 T permanent dipoles with an inner diameter of 20 cm, require little maintenance.
- Constructed by the CERN magnet group.



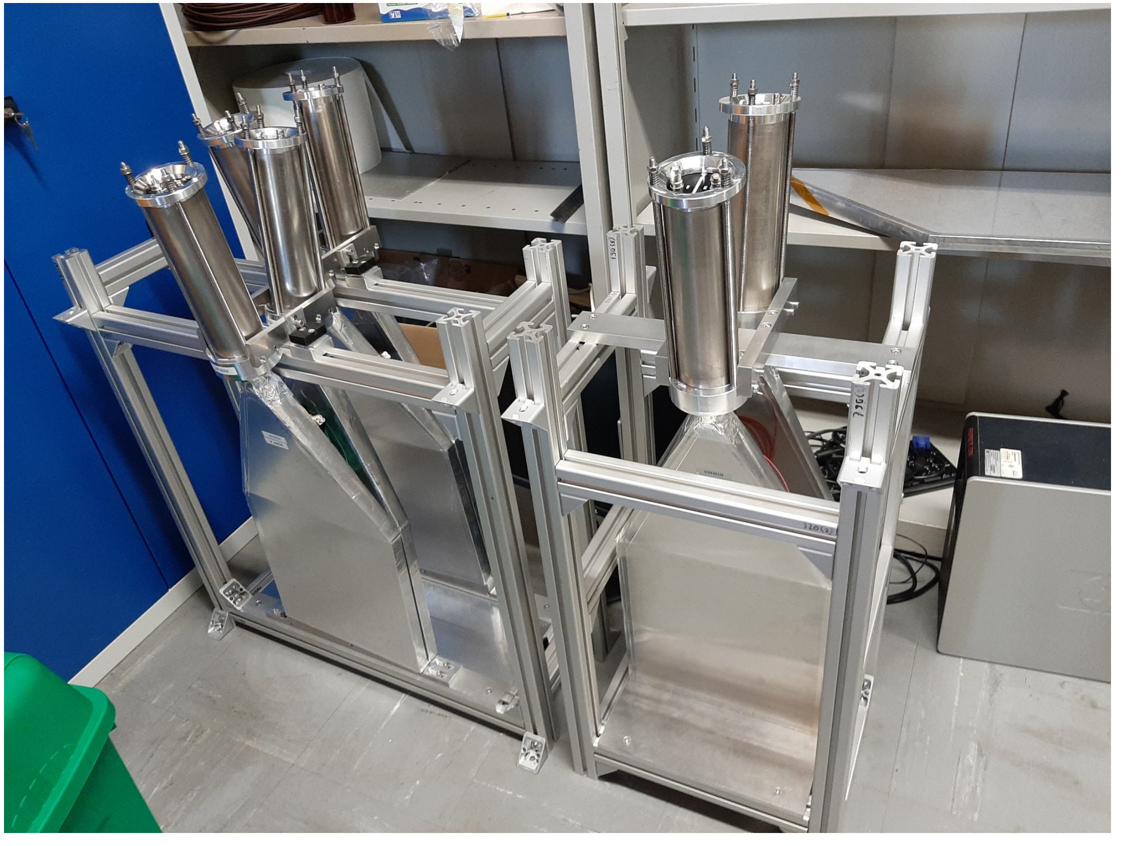
TRACKERS

- ATLAS tracker consists of ~3000 SCT modules.
- ~300 spares were never used. ~100 of these were generously donated to FASER: 8 modules x 3 tracking planes x 4 tracking stations at FASER.

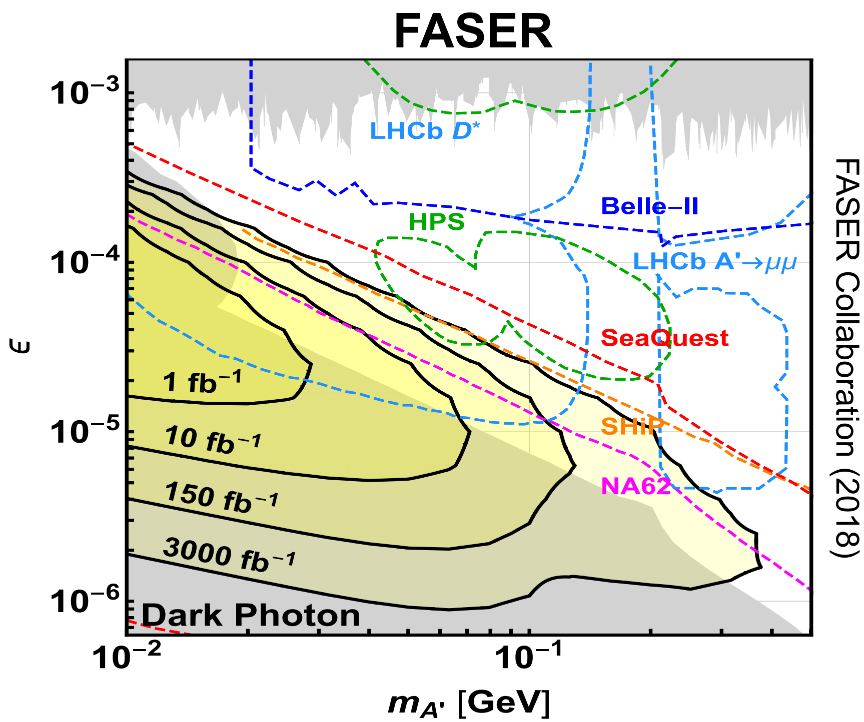


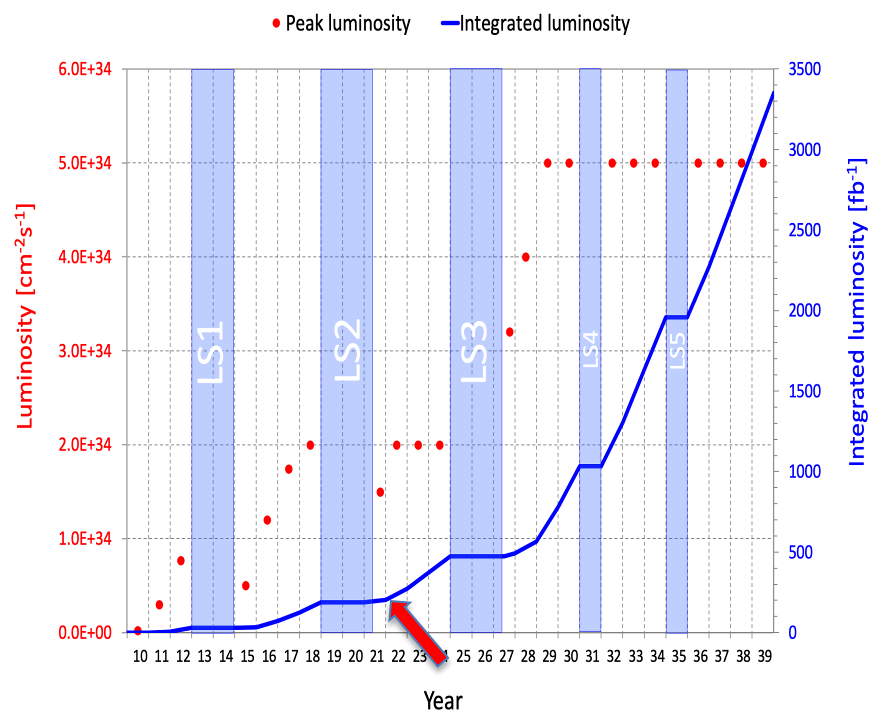
SCINTILLATORS

- 4 veto scintillators, each 2cm x 30cm x 30cm, upstream of the detector. Efficiency of each one is > 99.99%, makes muon background negligible.
- Additional beam backgrounds, simulated with FLUKA and validated with pilot detectors in 2018, are also expected to be negligible.



DARK PHOTON SENSITIVITY REACH

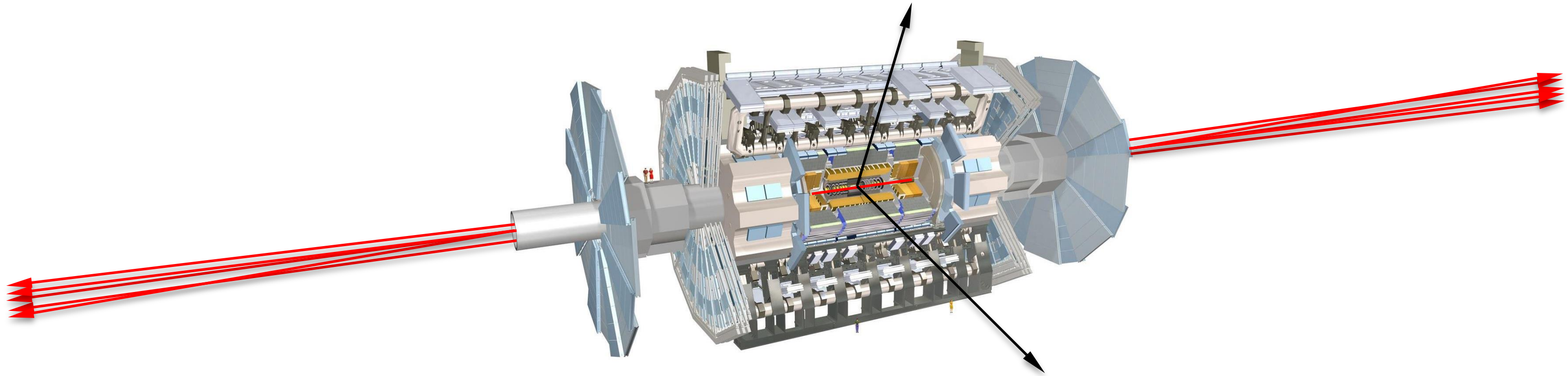




- FASER probes new parameter space with just 1 fb^{-1} starting in 2022.
- Without upgrade, HL-LHC extends (Luminosity*Vol) by factor of 3000 – could detect as many as 10,000 dark photons.
- Possible upgrade to FASER 2 (R=1m, L=20m) extends (Luminosity*Vol) by factor of ~10^6 – could detect as many as 3 x 10^6 dark photons.

COLLIDER NEUTRINOS

- In addition to the possibility of hypothetical new light, weakly-interacting particles, there are also known light, weakly-interacting particles: neutrinos.
- The high-energy ones, which interact most strongly, are overwhelmingly produced in the far forward direction. Before May 2021, no candidate collider neutrino had ever been detected.



- If they can be detected, there is a fascinating new world of LHC neutrinos that can be explored.
  - The neutrino energies are ~TeV, highest human-made energies ever.
  - All flavors are produced ($\pi \rightarrow \nu_\mu$, $K \rightarrow \nu_e$, $D \rightarrow \nu_\tau$) and both neutrinos and anti-neutrinos.

De Rujula, Ruckl (1984); Winter (1990); Vannucci (1993)