FASTER, SMALLER, CHEAPER

AND THE NEW FRONTIER IN PARTICLE SEARCHES AT THE LHC

Department Colloquium, University of Oregon

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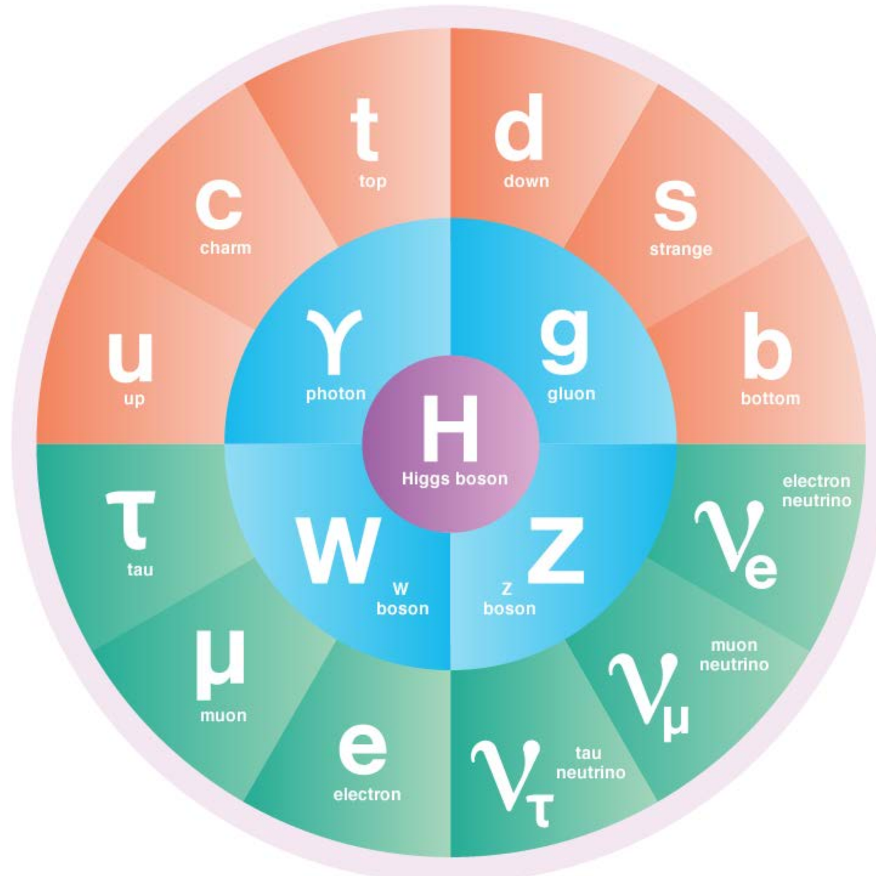
PARTICLE PHYSICS NOW

A BRIEF HISTORY OF PARTICLE PHYSICS

- In the last century, we have been tremendously successful in discovering new particles and deepening our understanding of the laws of nature and the contents of the Universe.



- The workhorse tools leading to much of this progress have been particle accelerators and colliders.

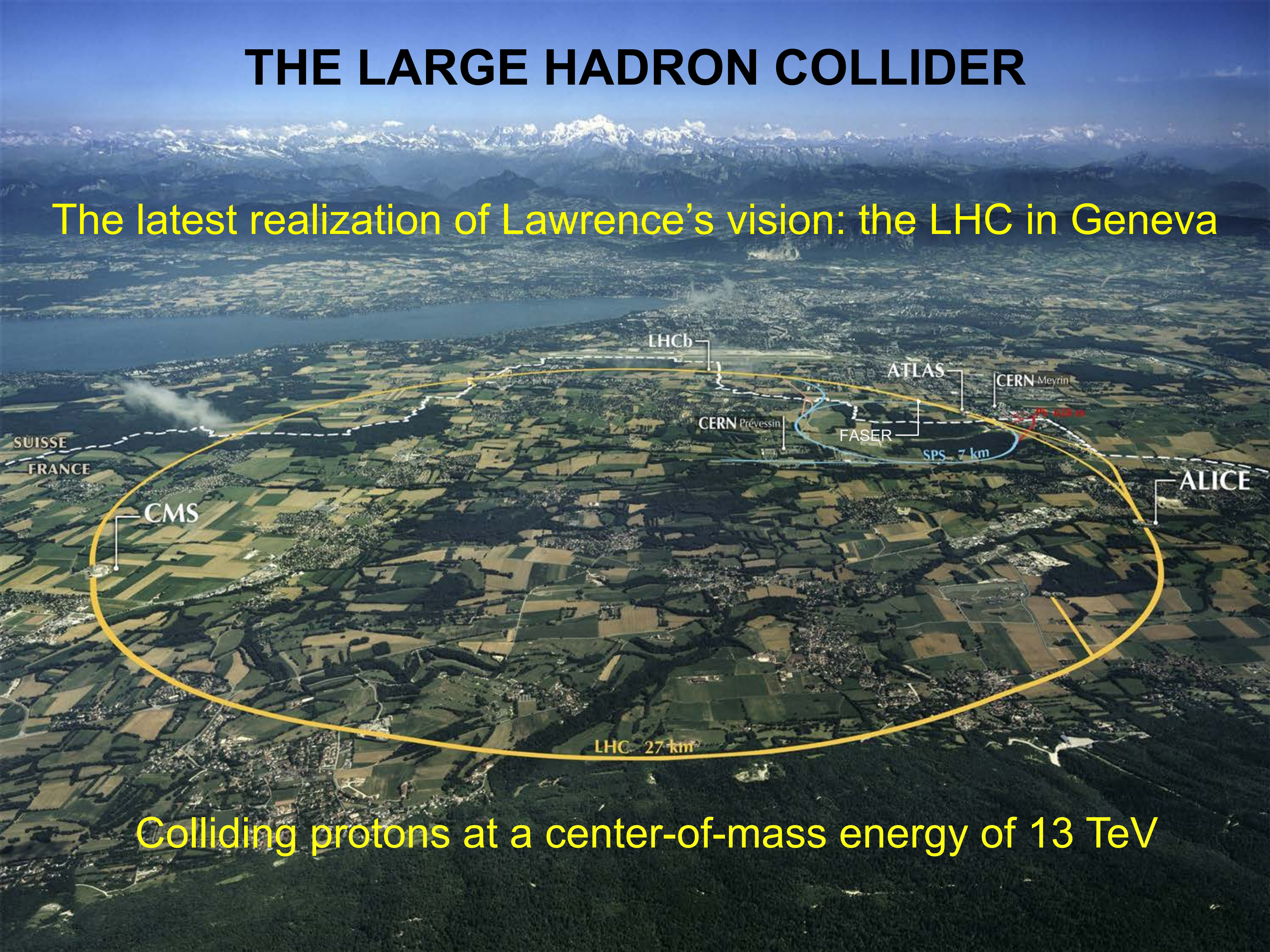
PARTICLE ACCELERATORS AND COLLIDERS

- In the 1930's, E. O. Lawrence made a cyclotron, which accelerated particles to higher velocities and energies.

- The first cyclotron was small, but soon, bigger accelerators led to higher energies, which allowed heavier particles to be produced and discovered.

THE LARGE HADRON COLLIDER

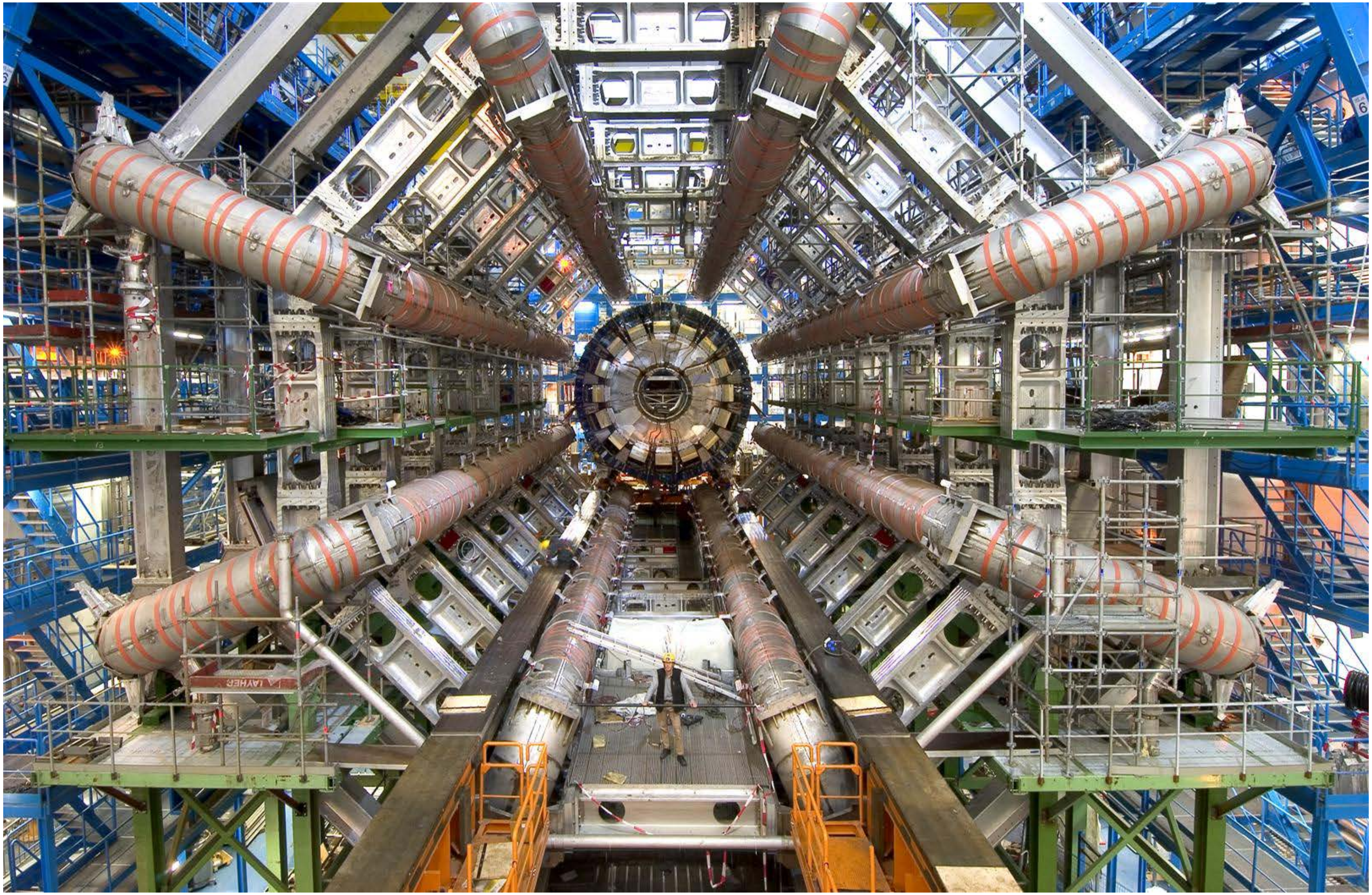
The latest realization of Lawrence’s vision: the LHC in Geneva



Colliding protons at a center-of-mass energy of 13 TeV

THE ATLAS DETECTOR

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



HOW BIG IS BIG SCIENCE?

- Size: Big. Colliders the size of cities, detectors the size of buildings.
- Timescale: Long. The LHC was conceived in the 1980’s. It was constructed from 1998-2008, and has been running since 2008, with periodic shutdowns to upgrade and fix equipment.
- Budget: Expensive. The cost of constructing the LHC and the various experiments was roughly $10 billion. The annual operations budget of CERN, the host laboratory, is about $1 billion/year, or roughly 1 coffee per year per EU citizen.
- People: Many.

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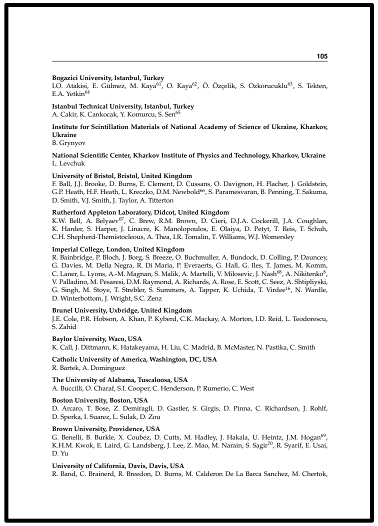
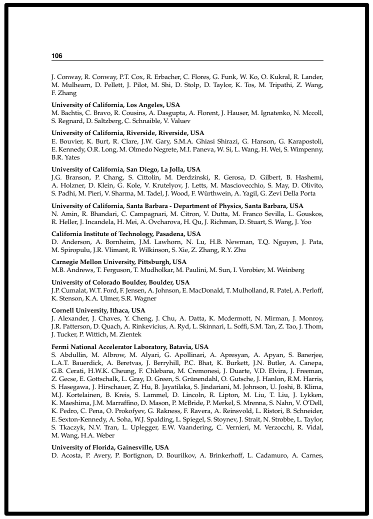
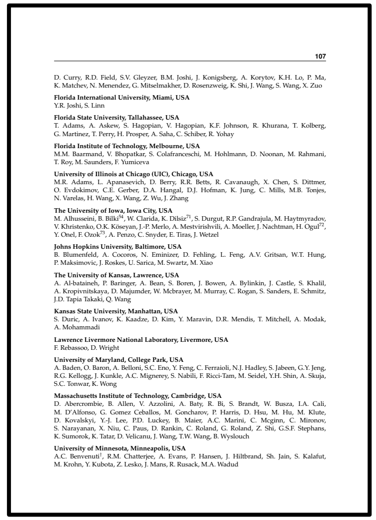
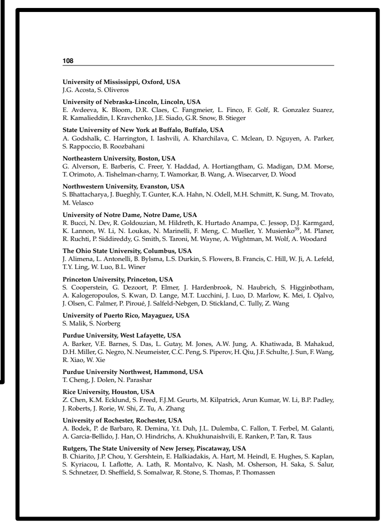
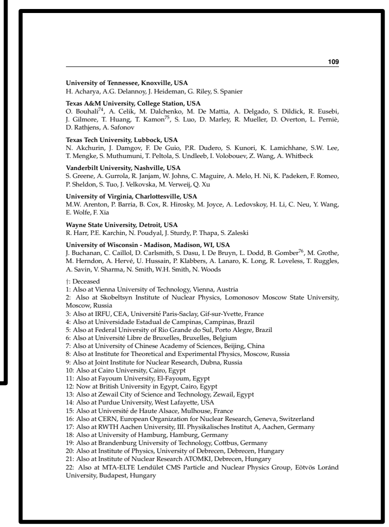
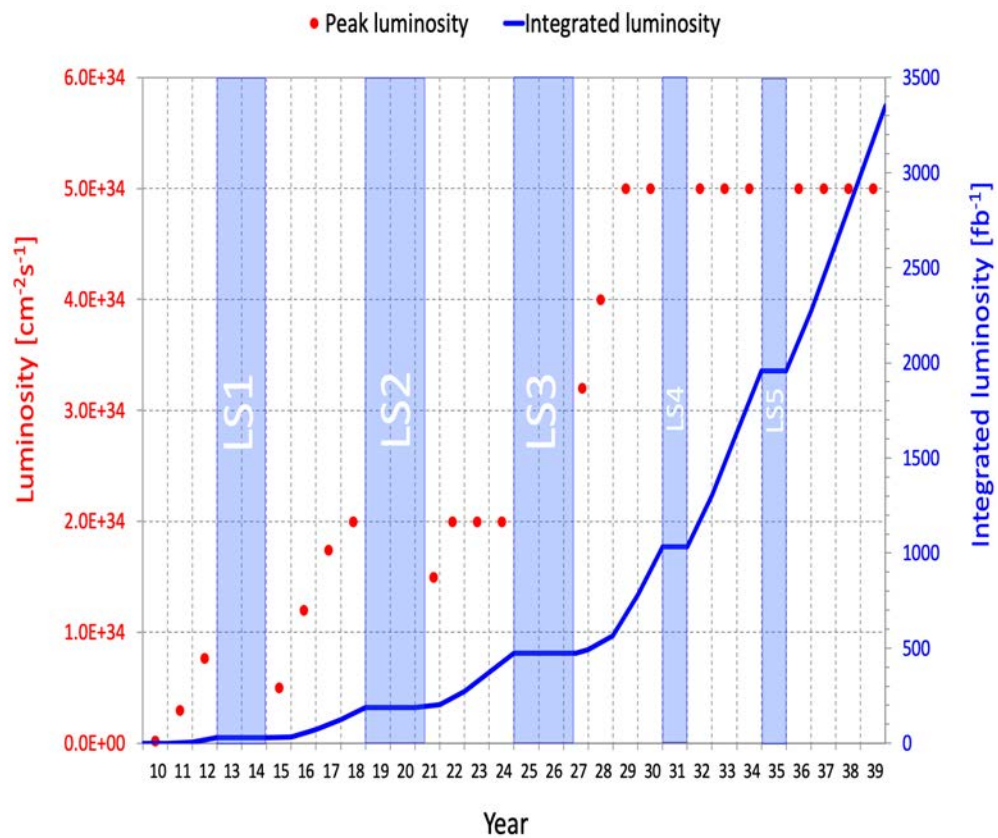






4000 collaborators from 230 institutions in 51 countries

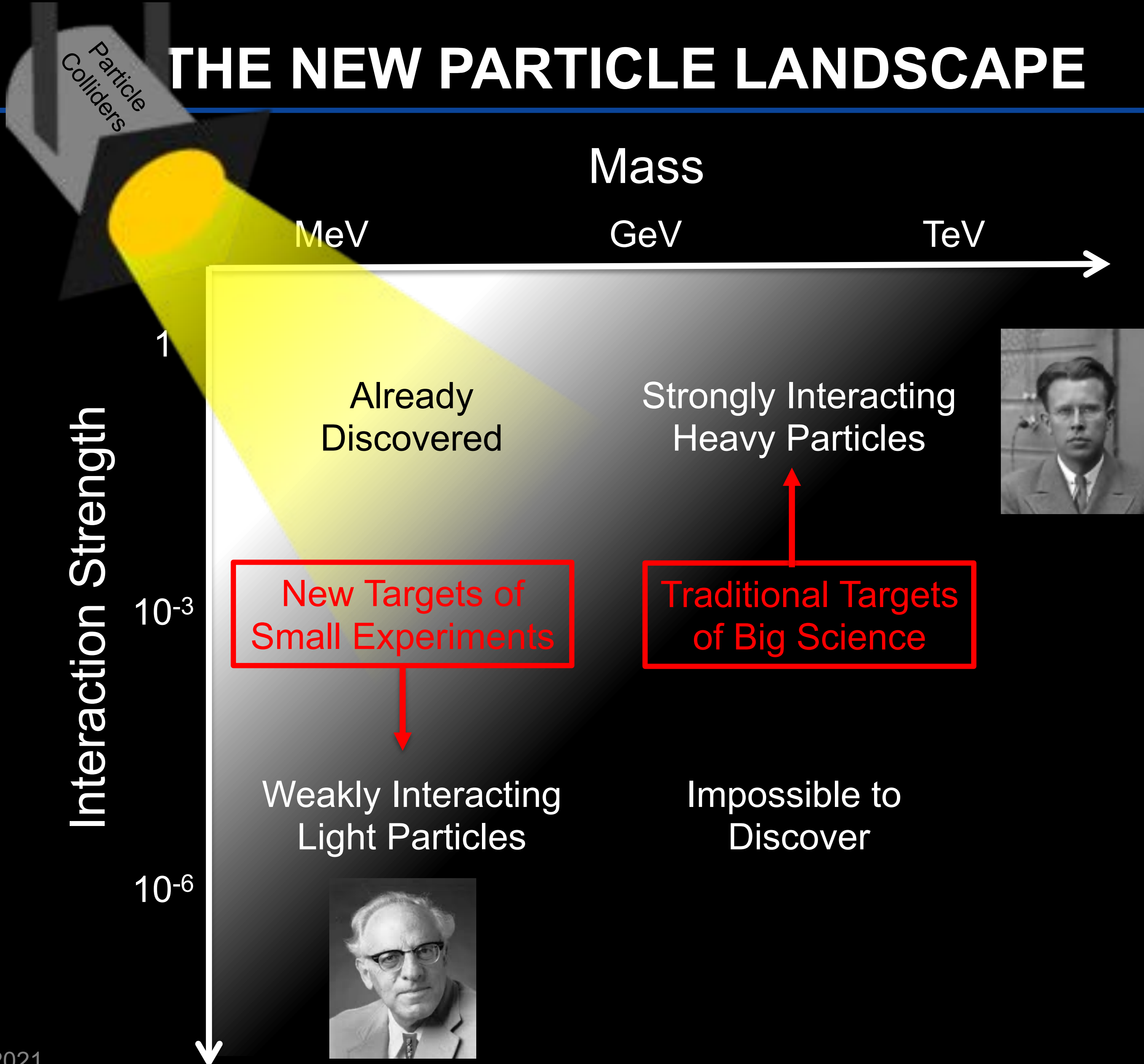
LHC: CURRENT STATUS

- The discovery of the Higgs boson in 2012 completed the standard model of particle physics, a remarkable achievement, but so far there has been no other evidence for new particles.
- The LHC is currently in Long Shutdown 2, but will start up again in 2022 and run till ~2037. Will we find new particles through conventional searches?
- What other approaches can enhance the prospects for discovering new particles?

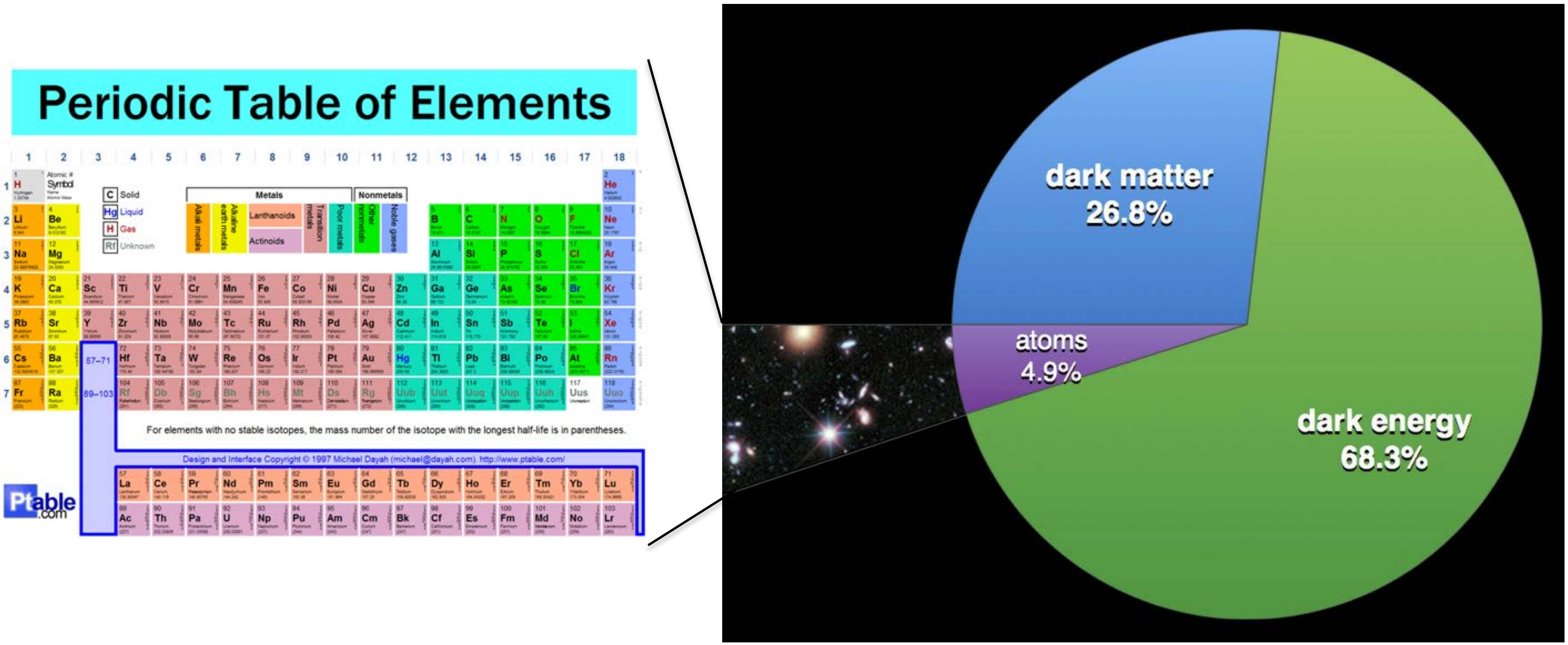


THE LIFETIME FRONTIER

THE NEW PARTICLE LANDSCAPE



THE UNIVERSE TODAY



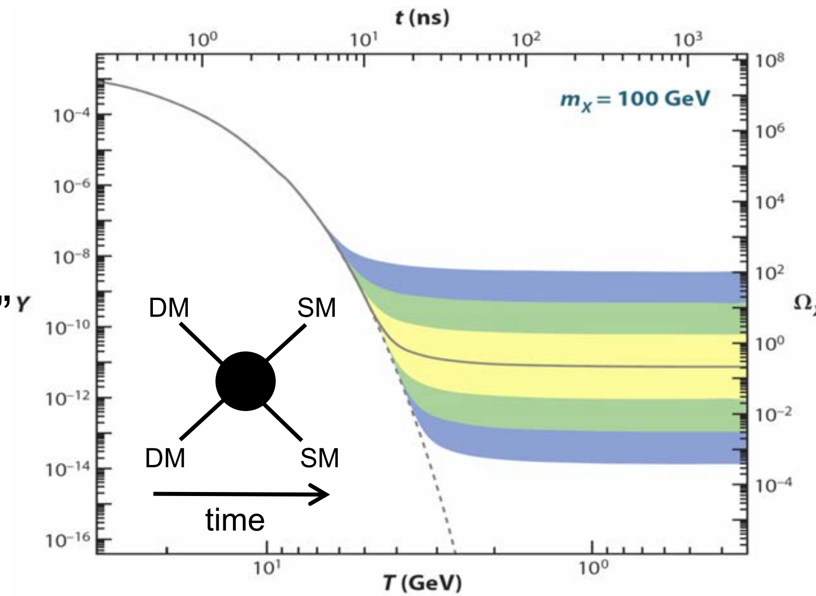
- We now have an overall picture of the Universe.
- We know a lot about a little: the normal matter (5%).
- But we know little about a lot: dark matter / dark energy (95%). Most of the universe is still to be discovered and understood.

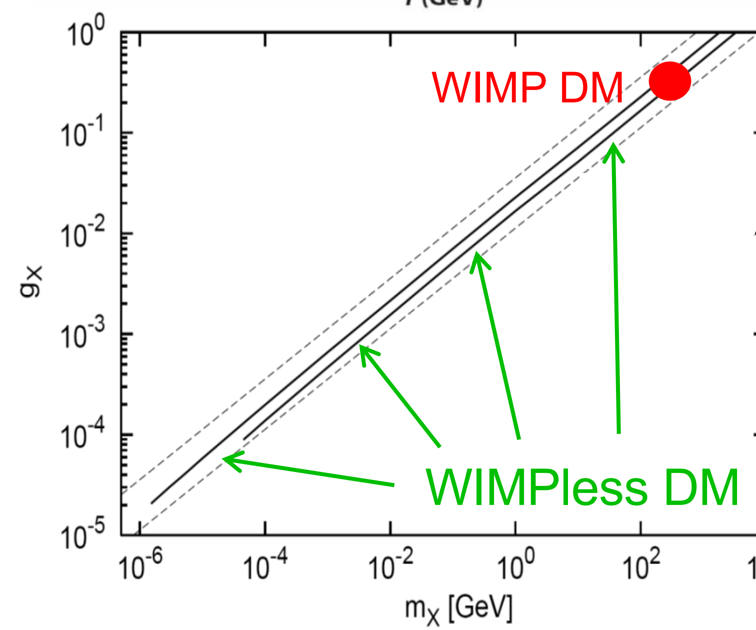
DARK MATTER

- What properties should DM have?
- A simple mechanism for generating DM: DM particles exist in the early universe, then pair annihilate until they “freeze out.”
- The weaker their interactions, the more dark matter survives to the present day:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

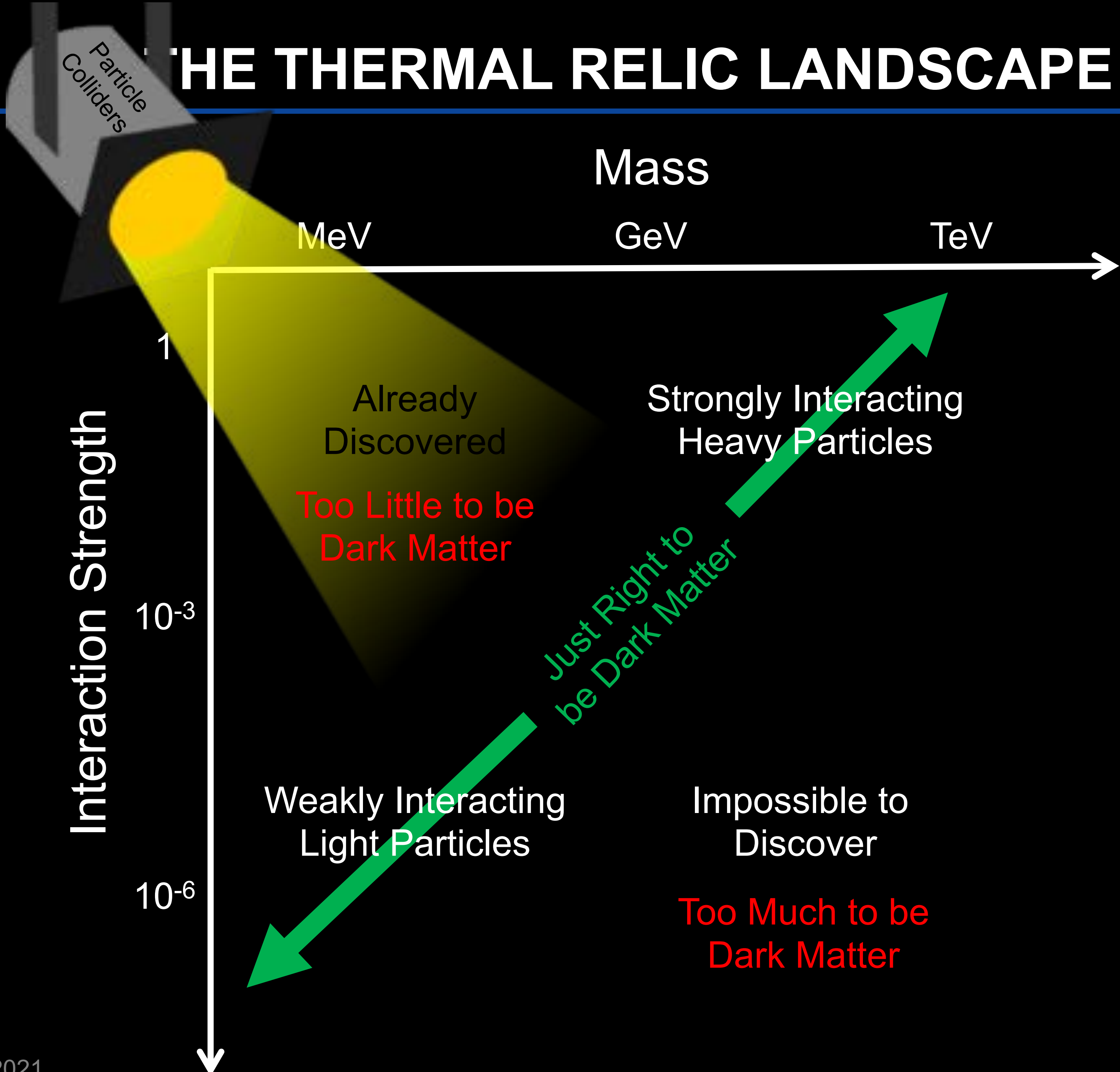
- WIMP Miracle: ~100 GeV to 1 TeV masses, strong couplings → right abundance
- WIMPless Miracle: lighter particles, weaker interactions → right abundance





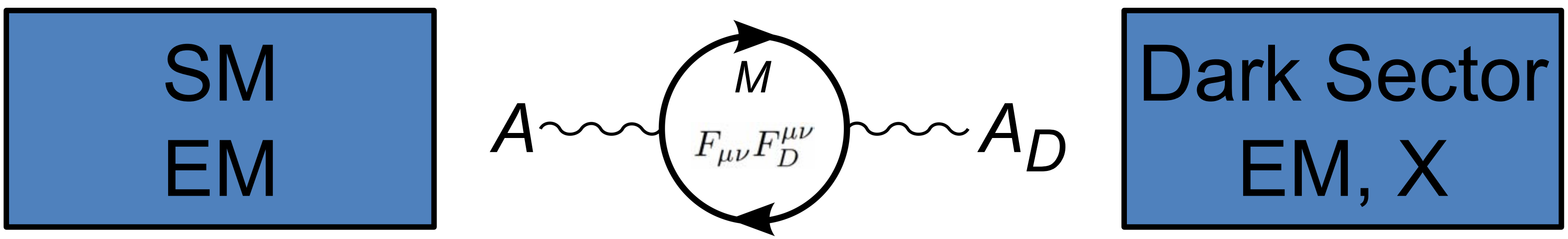
Feng, Kumar (2008); Feng, Tu, Yu (2010)

THE THERMAL RELIC LANDSCAPE



AN EXAMPLE: DARK PHOTONS

- Suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.
- Generically, the force carriers of the SM and dark EM will mix



- The resulting theory contains a new particle, the dark photon. It's like a normal photon, except that it can have a small mass, and its couplings to charged particles are suppressed by a small parameter: it is a weakly-interacting, light particle.

Holdom (1986)

- Finding a dark photon would imply the discovery of a new fundamental force and also our first "portal" through which to view the dark sector.

THE LIFETIME FRONTIER

- What are the basic properties of light and weakly interacting particles?

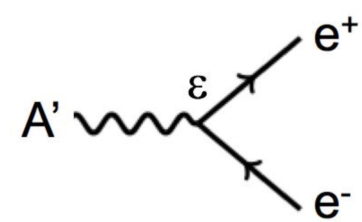
- Consider such a neutral particle with energy E ~ TeV, and
  - mass between electron (0.5 MeV) and proton (1 GeV): take $m \sim 100$ MeV
  - coupling between milli-charged and micro-charged: take $\varepsilon \sim 10^{-5}$

- They pass through matter essentially without interacting: radiation length is (10 cm) $\varepsilon^{-2} \sim 10^9$ m. The distance to the moon!

- They go straight; unaffected by E and B fields.

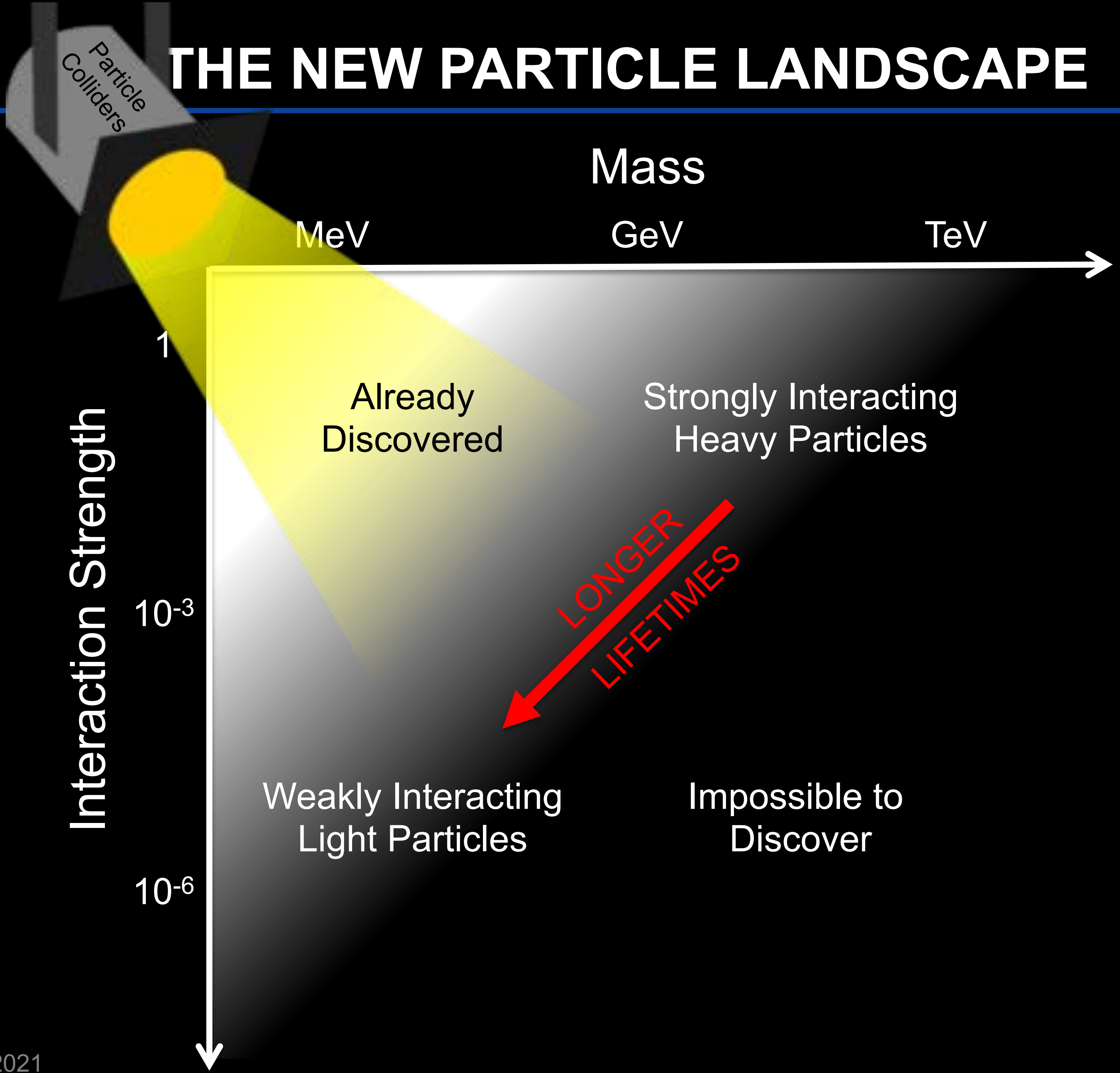
- They may decay to visible particles, but only after a long time:

$$L = v\tau\gamma \sim (100\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{100\ \mathrm{MeV}}{m}\right]^2 \left[\frac{E}{\mathrm{TeV}}\right]$$



- Strong dependence on m and ε, but these are long-lived particles and decay lengths may be meters or kilometers: human length scales!

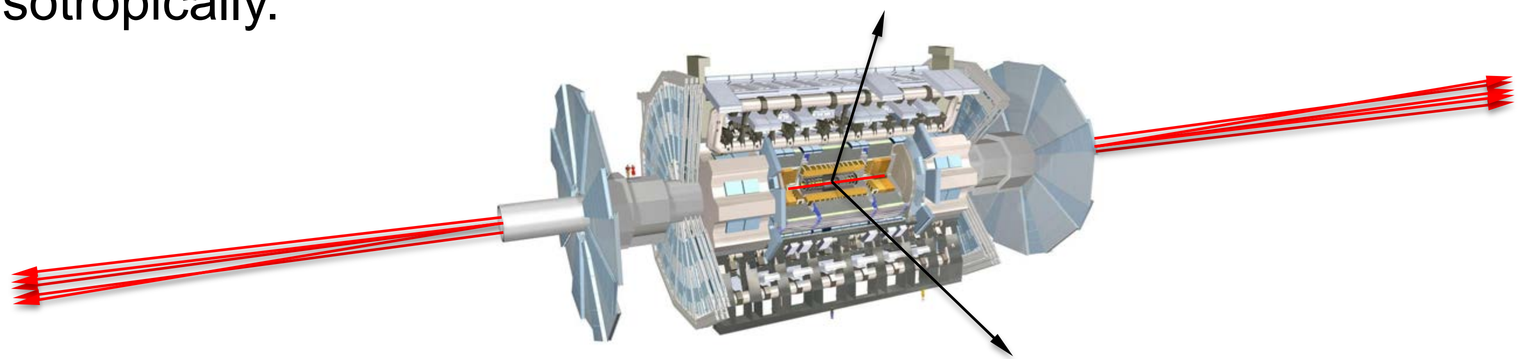
THE NEW PARTICLE LANDSCAPE



FASER

SEARCHES FOR NEW LIGHT PARTICLES

- If new particles are light and weakly interacting, existing detectors are perfectly designed NOT to see them.
- Existing detectors are designed to find new heavy particles. To make such particles, the colliding beam energy is converted mainly to rest mass, and so these particles are produced almost at rest and decay isotropically.

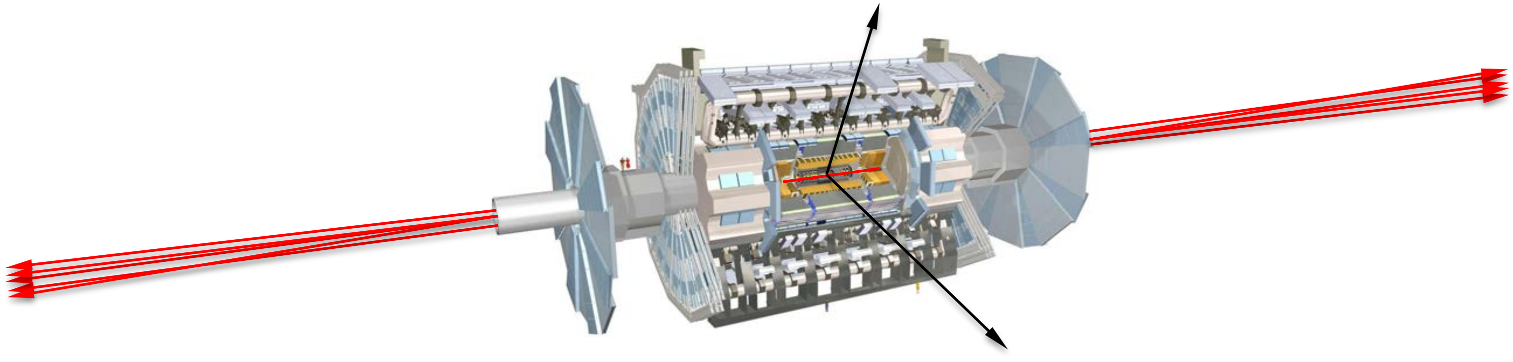


- But new light particles are dominantly produced in glancing collisions and so travel along the beamline, where existing detectors have holes to let the colliding beams in.
- To add insult to injury, light particles are long-lived, and so would anyway pass right through existing detectors and decay far away.

FASER: THE BASIC IDEA

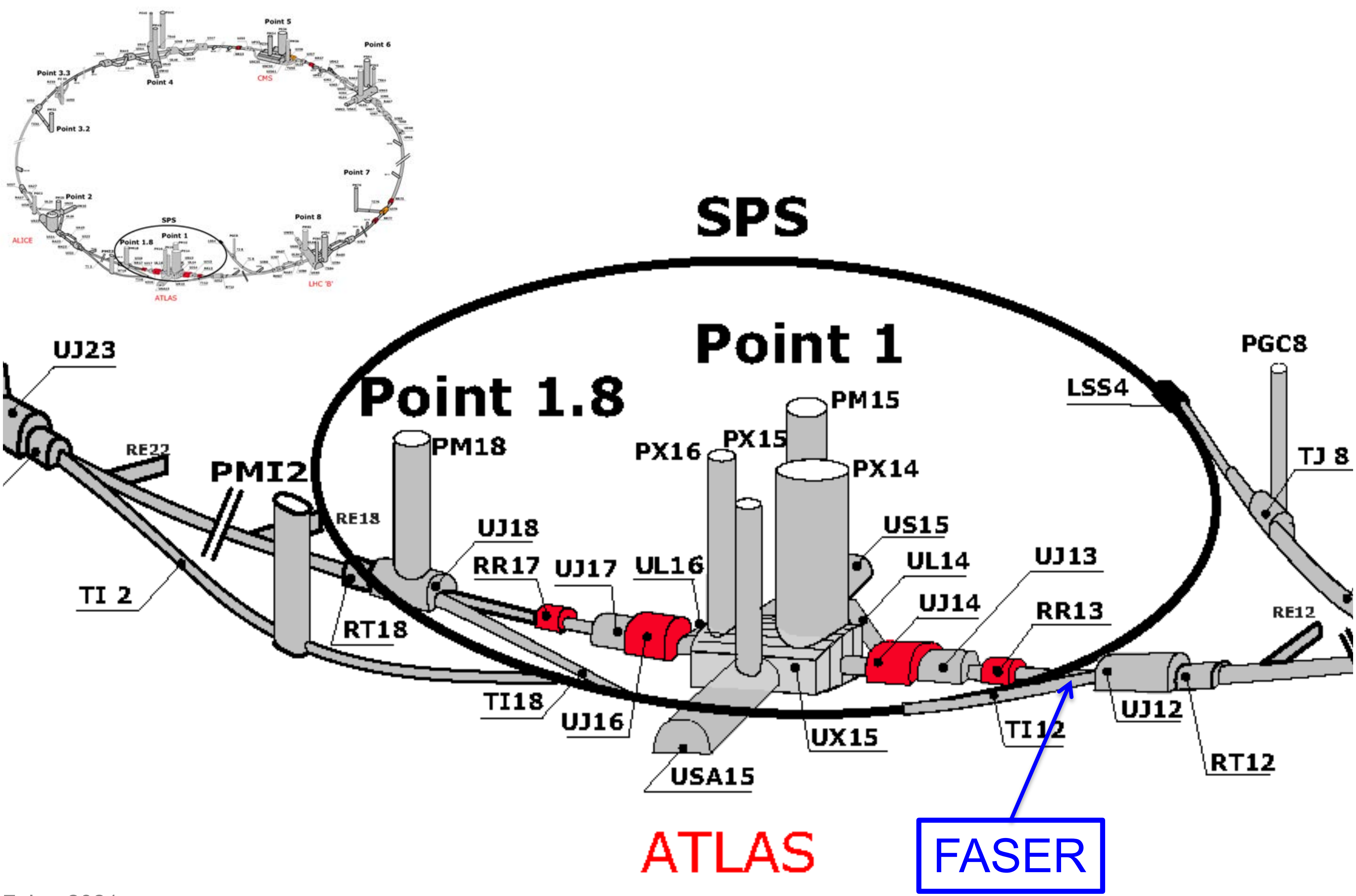
- Clearly what we need is a detector to complement existing detectors and cover their “blind spots.”

- We can’t put such a detector too close to the interaction point, or it would block the beams.



- But if we go far enough away, the protons beams are bent by magnets (it’s a circular collider!), whereas the new light particles will go straight.

MAP OF LHC



Point 5
Point 6
Point 3.3
Point 4
CMS
Point 3.2
Point 7
Point 2
Point 8
SPS
Point 1
Point 1.8
ALICE
ATLAS
LHC 'B'
SPS
Point 1
Point 1.8
UJ23
PGC8
LSS4
PM15
PX15
PX16
PM18
PX14
TJ 8
RE22
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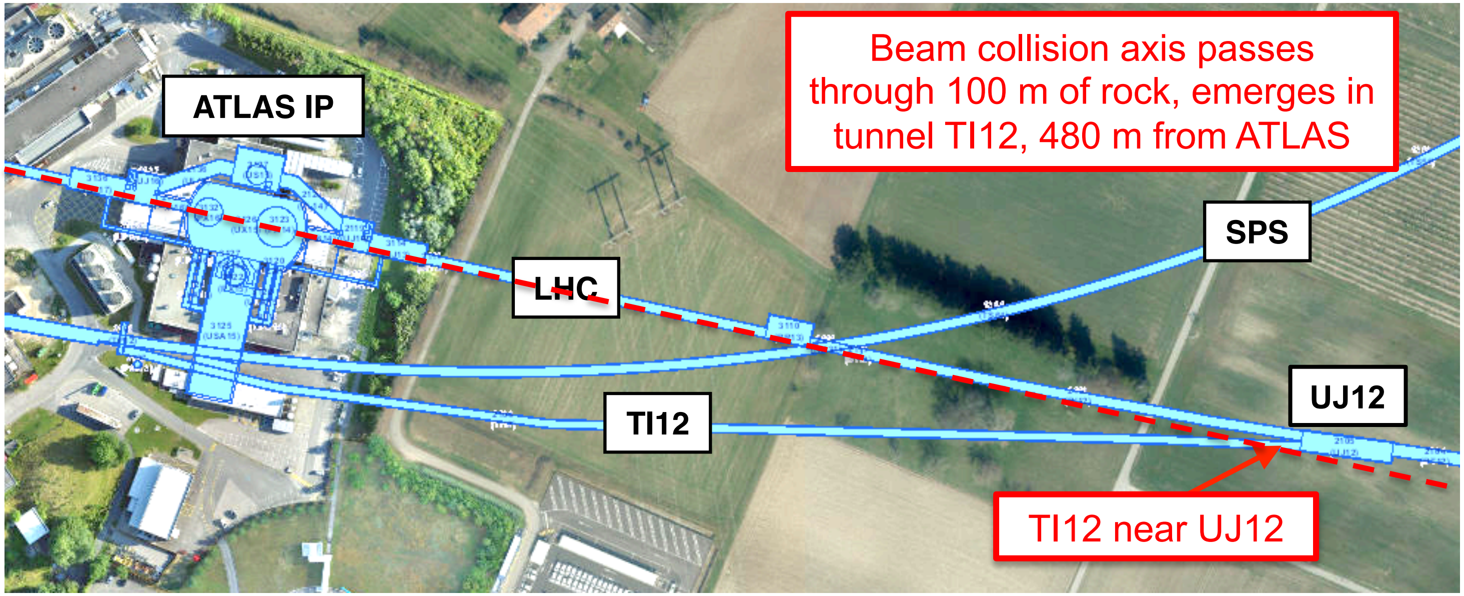
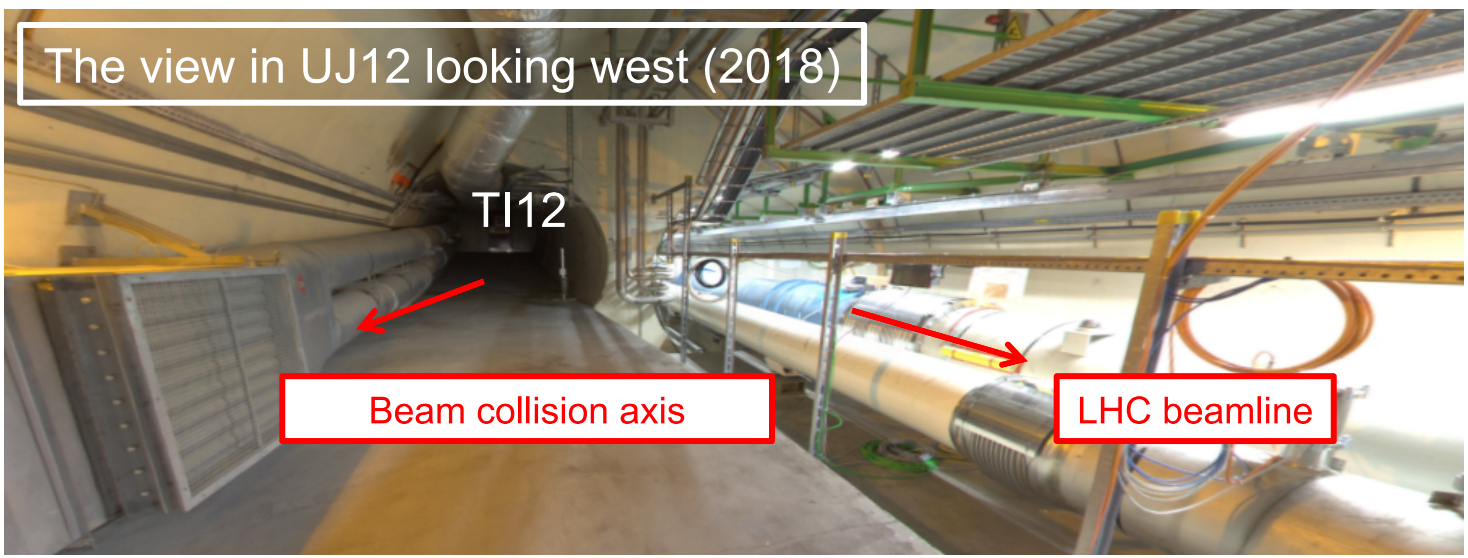
TI12
RT12
USA15
ATLAS
FASER

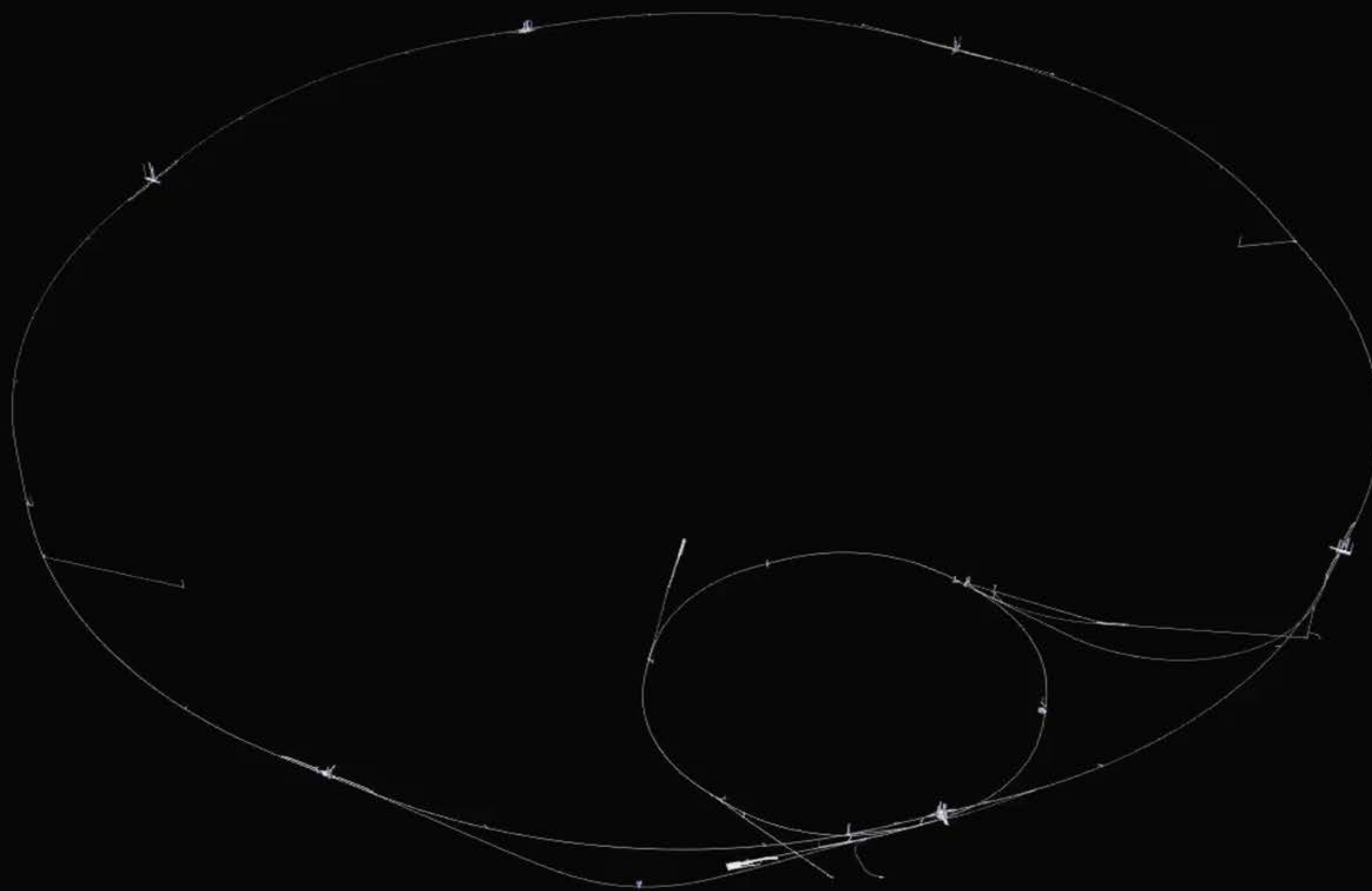
LOCATION OF FASER





PARTICLE PATH FROM ATLAS TO FASER

Dougherty, CERN Integration (2019)



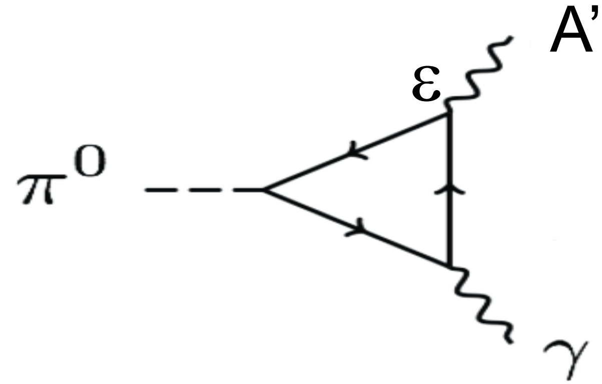
HOW BIG DOES THE DETECTOR HAVE TO BE?

- Consider the dark photon: like normal photons, it can be produced in pion decay.

- The typical transverse momentum is therefore $m_\pi \sim \Lambda_{QCD} \sim 200$ MeV.

- For a TeV dark photon, the typical angle relative to the beampipe is 200 MeV/TeV = 0.2 mrad. Extremely collimated; cf. the moon: 7 mrad.

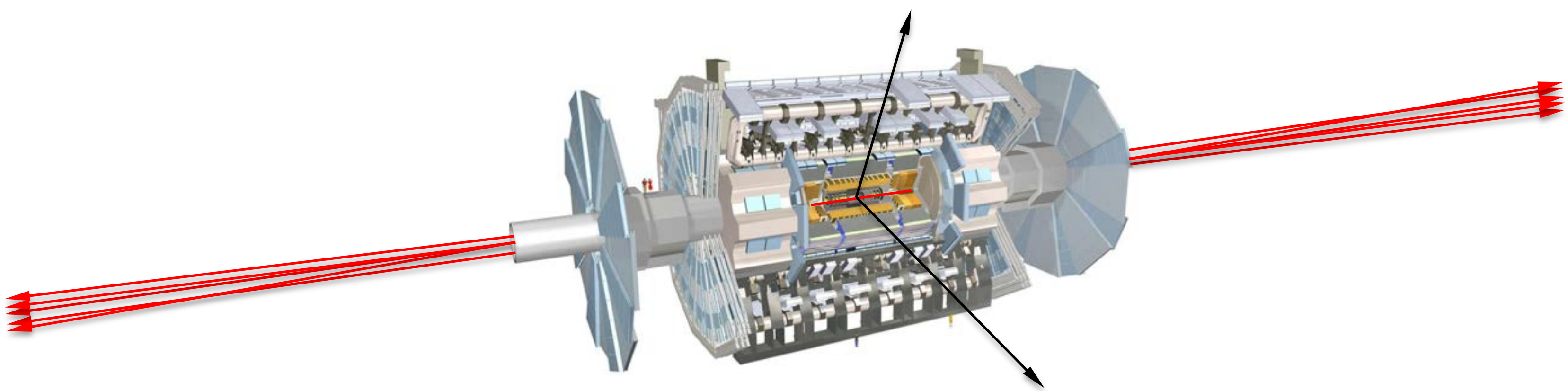
- The spread in the transverse plane after traveling 480 m is therefore ~10 cm, smaller than a sheet of paper.



- These considerations motivate a small, inexpensive experiment placed in the very forward region of ATLAS, 480 m downstream.

FASER: THE BASIC IDEA

- In short, the population of TeV dark photons, or any other new particle produced in pion decay, or even K, D, B, decay, is far more collimated than shown in this diagram.



FORWARD SEARCH EXPERIMENT

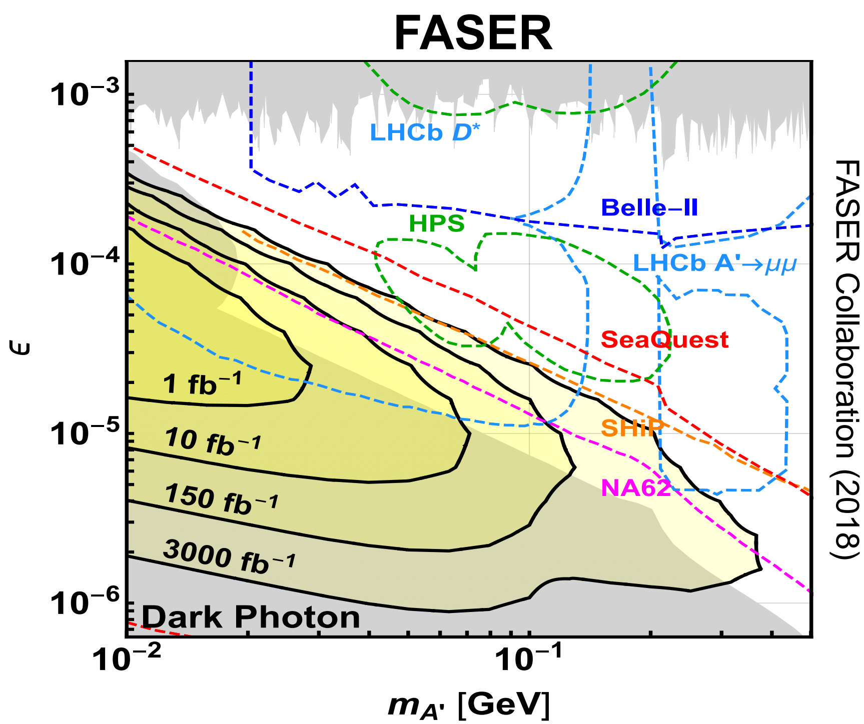
FASER

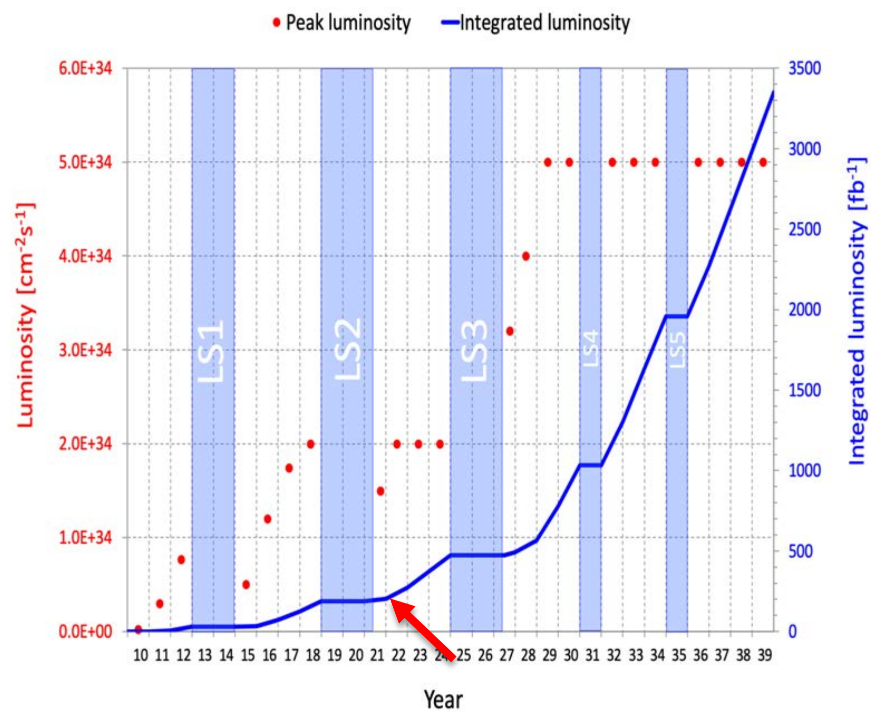
- “The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”

Feng, Galon, Kling, Trojanowski (2017)

DARK PHOTON SENSITIVITY REACH

- Consider cylindrical detectors in two sizes
  - FASER: R = 10 cm, L = 1.5 m, tabletop experiment!
  - FASER 2: R = 1 m, L = 5 m, a possible upgrade





- FASER probes new parameter space with just 1 fb^{-1} starting in 2022.

- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; possible upgrade to FASER 2 extends (L*Volume) by ~10^6.

PHYSICS SUMMARY

- Many other studies: FASER has discover prospects for all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and many other examples; see 1811.12522.

Benchmark Model	FASER	FASER 2	References
V1/BC1: Dark Photon	√	√	Feng, Galon, Kling, Trojanowski, 1708.09389
V2/BC1': $U(1)_{B-L}$ Gauge Boson	√	√	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Invisible Dark Photon	–	–	–
BC3: Milli-Charged Particle	–	–	–
S1/BC4: Dark Higgs Boson	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
S2/BC5: Dark Higgs with hSS	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387
F1/BC6: HNL with e	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
F2/BC7: HNL with μ	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
F3/BC8: HNL with τ	√	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
A1/BC9: ALP with photon	√	√	Feng, Galon, Kling, Trojanowski, 1806.02348
A2/BC10: ALP with fermion	√	√	FASER Collaboration, 1811.12522
A3/BC11: ALP with gluon	√	√	FASER Collaboration, 1811.12522

FASER STATUS

FASER TIMELINE

- September 2017: First theory paper
- November 2017: Support from the two most famous living physicists
- 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 $1M grants from the Heising-Simons and Simons Foundations
- March 2019: FASER fully approved by CERN LHCC and Research Board along with support for infrastructure costs
- April 2019: 1st FASER Collaboration Meeting
- November 2020 – March 2021: Installation of FASER in tunnel during Long Shutdown 2,commissioning of the detector
- Early 2022: Start collecting data in Run 3

FASER ON BIG BANG THEORY

Season 11, Episode 9, “The Bitcoin Entanglement” (November 2017)

FIRST FASER COLLABORATION MEETING

THE FASER COLLABORATION TODAY

66 collaborators, 19 institutions, 8 countries

Henso Abreu (Technion), Yoav Afik (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Tobias Boeckh (Bonn), Jamie Boyd (CERN), Lydia Brenner (CERN), Franck Cadoux (Geneva), Dave Casper (UC Irvine), Charlotte Cavanagh (Liverpool), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Monica D'Onofrio (Liverpool), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Carl Gwilliam (Liverpool), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Umut Kose (CERN), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (Sussex), Sam Meehan (CERN), Dimitar Mladenov (CERN), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Laurie Nevay (Royal Holloway), Hidetoshi Otono (Kyushu), Carlo Pandini (Geneva), Hao Pang (Tsinghua), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Markus Prim (Bonn), Michaela Queitsch-Maitland (CERN), Filippo Resnati (CERN), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), John Spencer (Washington), Yosuke Takubo (KEK), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Serhan Tufanli (CERN), Benedikt Vormvald (CERN), Di Wang (Tsinghua), Gang Zhang (Tsinghua)

HELP FROM MANY OTHERS

The FASER Collaboration has received essential support from the Heising-Simons and Simons Foundations, CERN, the ATLAS SCT and LHCb Collaborations, and also many others at CERN and elsewhere

We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER acknowledges the invaluable assistance from the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; the LHC Machine Committee; the LS2 Committee and the LHCC. FASER gratefully acknowledges the contributions from:

- Jonathan Gall, John Osborne (civil engineering);
- Liam Dougherty, Francisco Galan (integration);
- Pierre Thonet (magnets);
- Francesco Cerutti, Marta Sabate Gilarte (FLUKA simulation and background characterization);
- Salvatore Danzeca, Serge Chalaye (radiation measurements);
- James Storey, Swann Levasseur (beam instrumentation);
- Pierre Valentin, Tobias Dobers (survey);
- Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport);
- Gael Girardot, Olivier Crespo-Lopez, Yann Maurer, Maria Papamichali (LS2 works);
- Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Markus Brugger (LHC access and schedule);
- Marco Andreini, Olga Beltramello, Thomas Otto (safety);
- Dave Robinson (ATLAS SCT), Yuri Guz (LHCb calorimeters);
- Stephen Wotton, Floris Keizer (SCT QA system and SCT readout);
- Burkhard Schmitt, Raphael Dumps, Sune Jacobsen, Giovanna Lehmann (CERN-DT contributions);
- Mike Lamont, Andreas Hoecker, Ludovico Pontecorvo, Christoph Rembser (useful discussions).

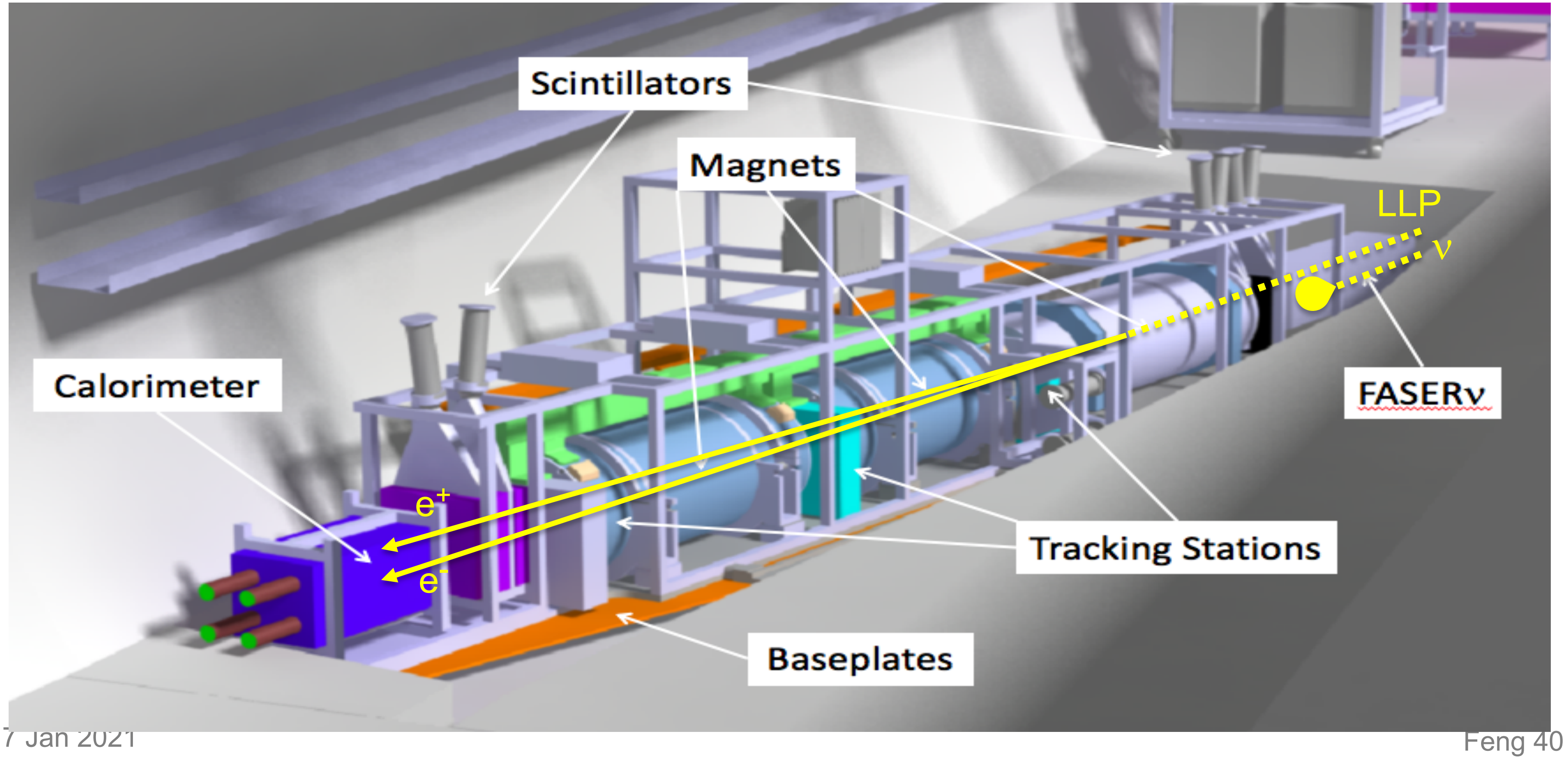
Thanks also to the CERN management for their support!

FASER IN TUNNEL TI12

- The beam collision axis has been located to mm accuracy by the CERN survey department. To place FASER on this axis, a trench is 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.

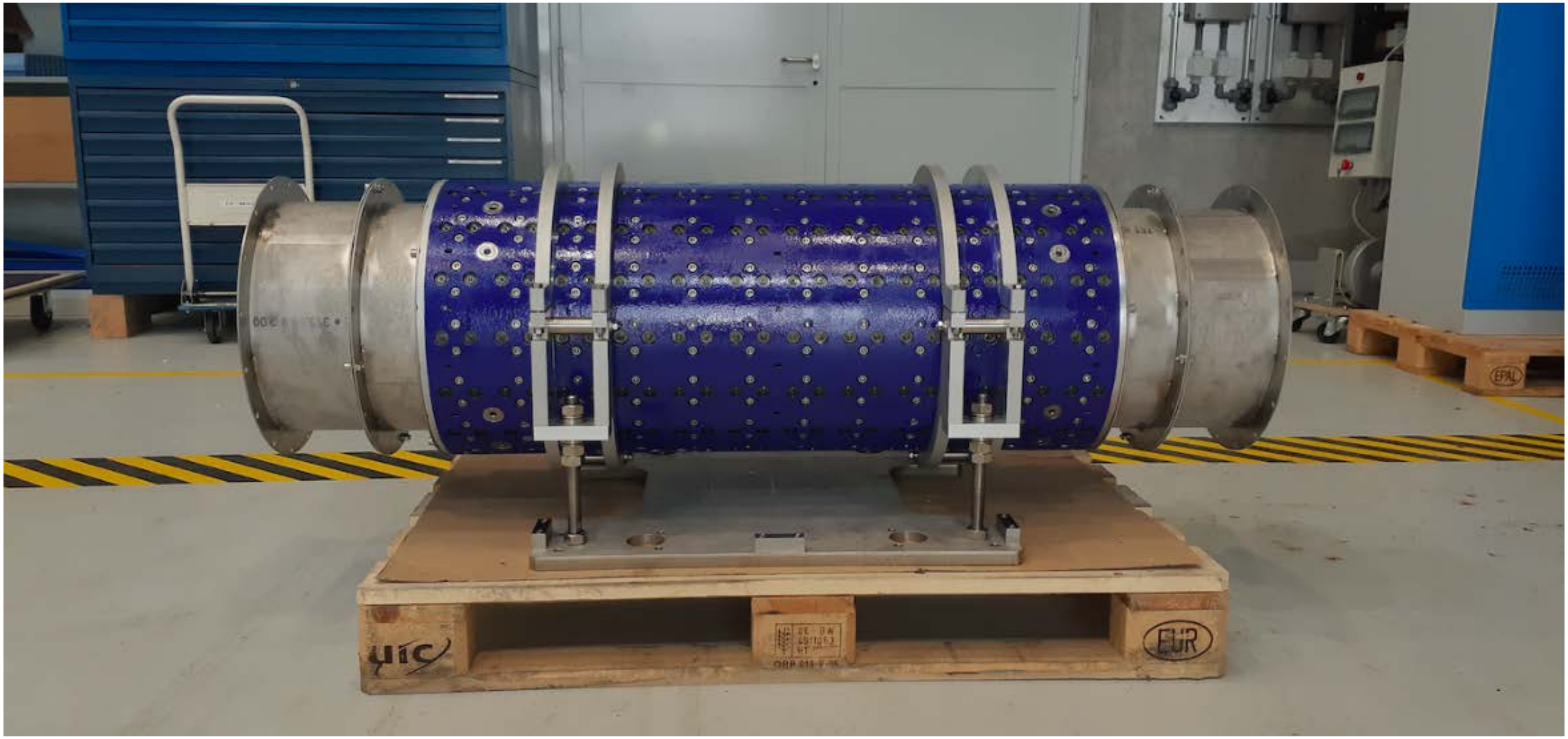
THE FASER DETECTOR

- The signal is spectacular: 2 TeV, opposite-sign charged tracks pointing back to ATLAS IP; a “light shining through (100 m-thick) wall” experiment.
- Permanent dipole magnets split the charged tracks, which are detected by 3 tracking stations and a calorimeter.
- Scintillators veto incoming charged tracks.



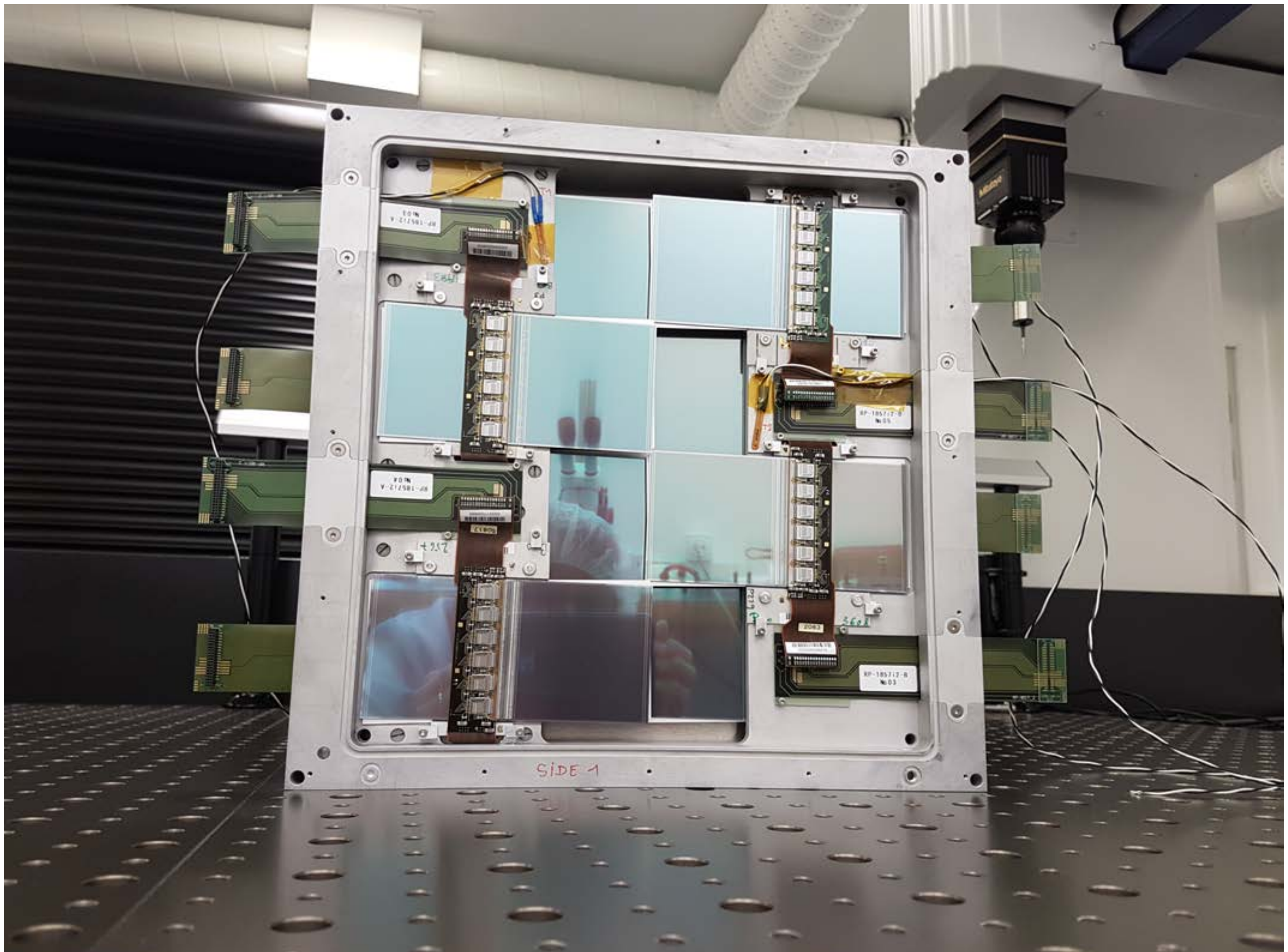
MAGNETS

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

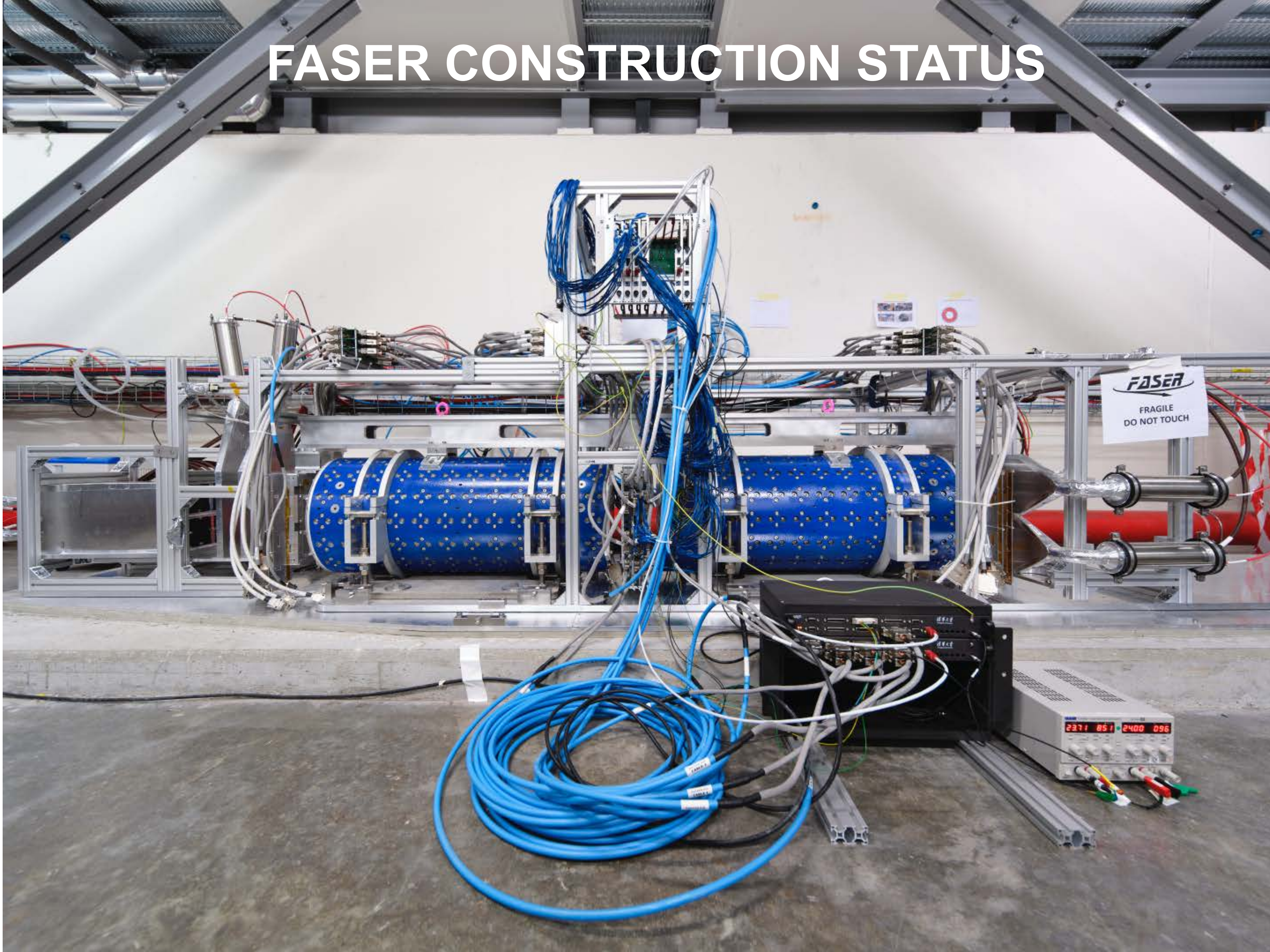


TRACKERS

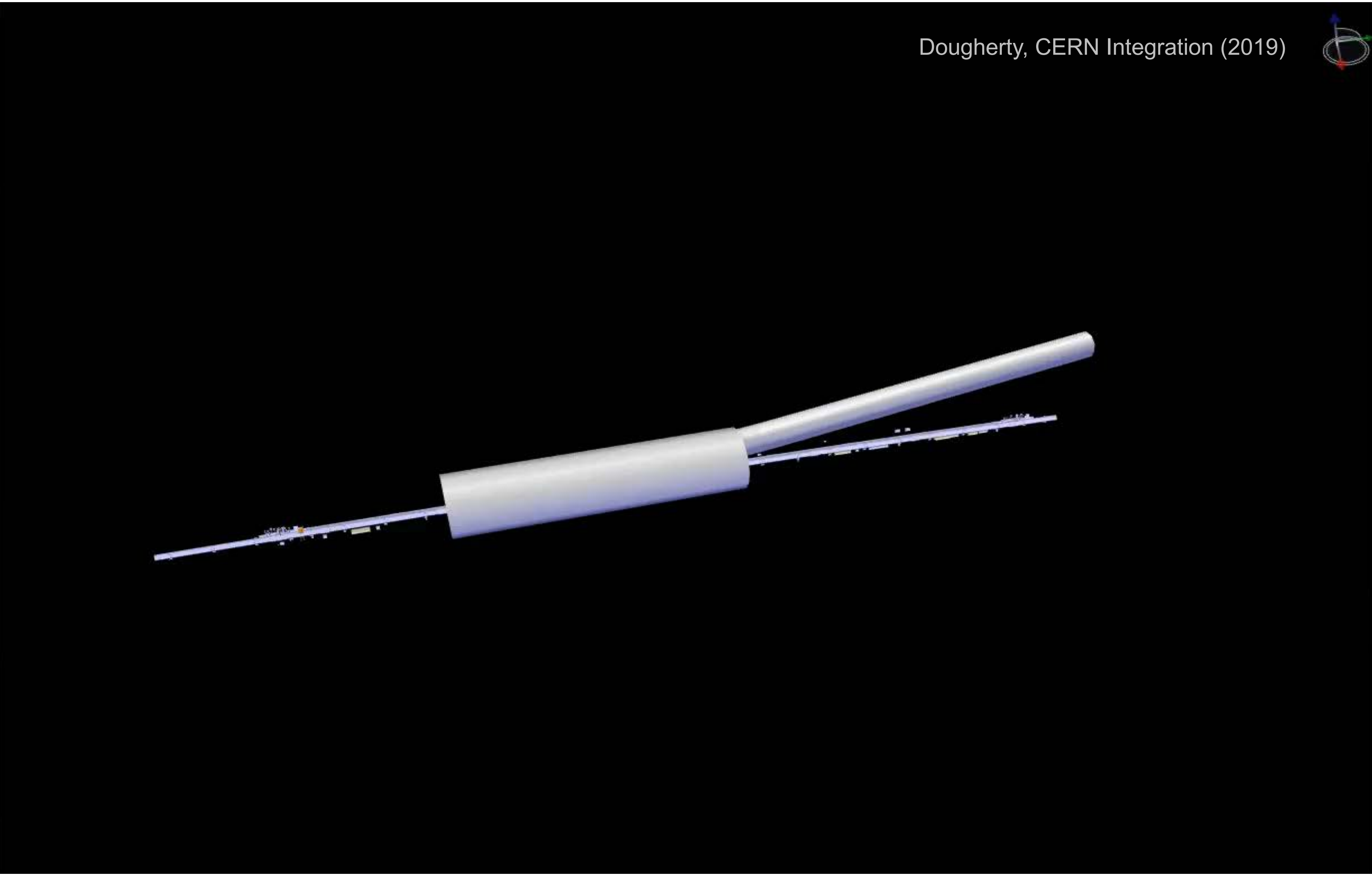
- 8 ATLAS SCT modules per tracking plane, 3 tracking planes per tracking station, 3 tracking stations at FASER.



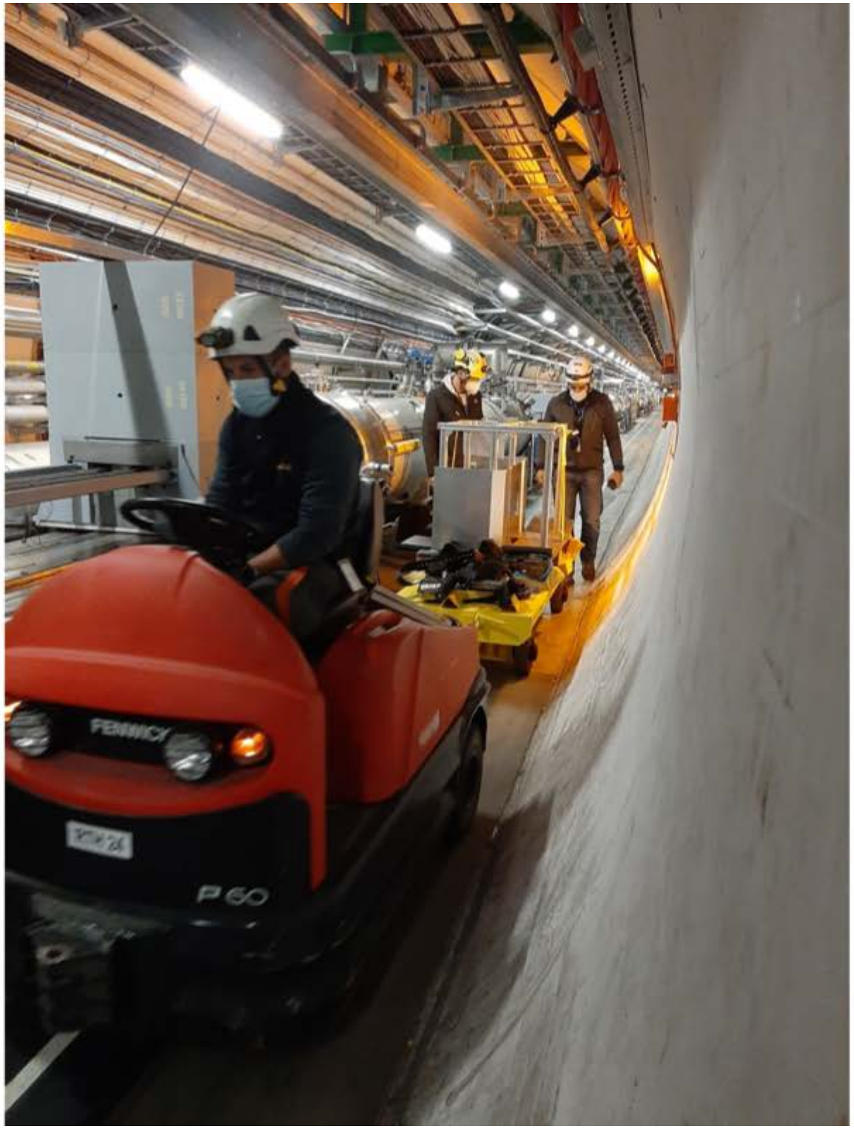
FASER CONSTRUCTION STATUS



FASER INSTALLATION



FASER INSTALLATION



FASER INSTALLATION

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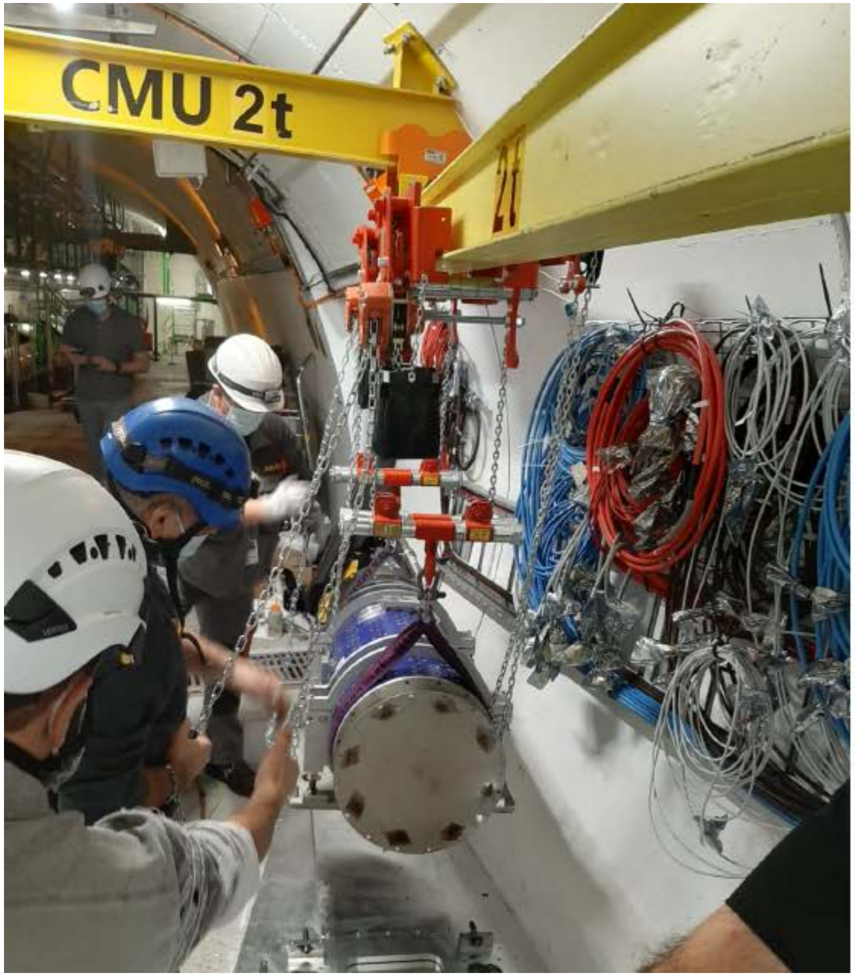


FASER CURRENT STATUS

FASER CURRENT STATUS

FASERν

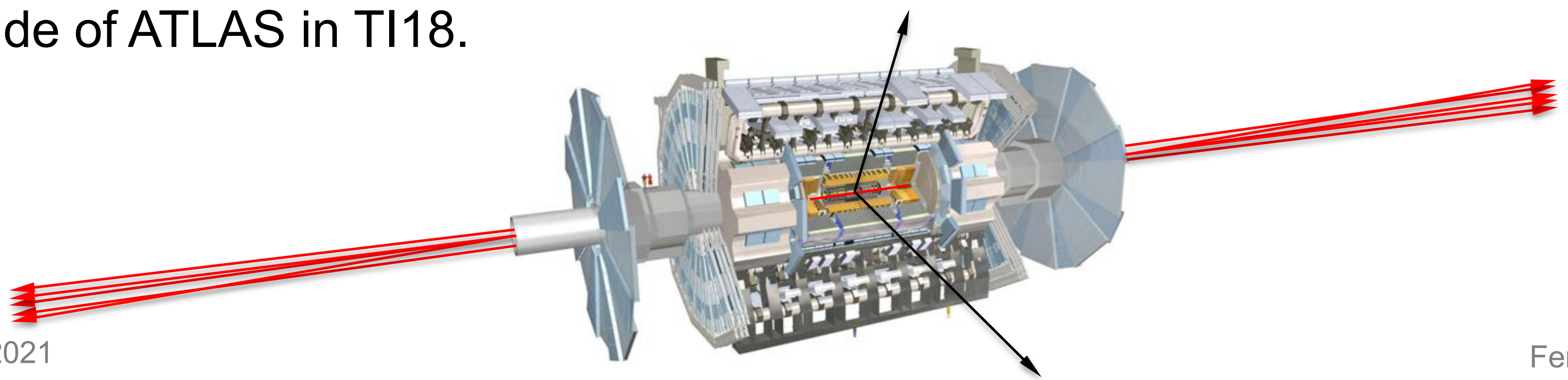
COLLIDER NEUTRINOS

- In addition to the possibility of hypothetical new light, weakly-interacting particles, there are also known light, weakly-interacting particles: neutrinos.

- But the high-energy ones, which interact most strongly, are overwhelmingly produced in the far forward direction, travel down the beampipe, and escape all existing detectors. **No collider neutrino has ever been detected.**
  - If they can be detected, there is a rich SM physics program: all flavors are produced($\pi \to \nu_\mu$, $K \to \nu_e$, $D \to \nu_\tau$) and both neutrinos and anti-neutrinos.

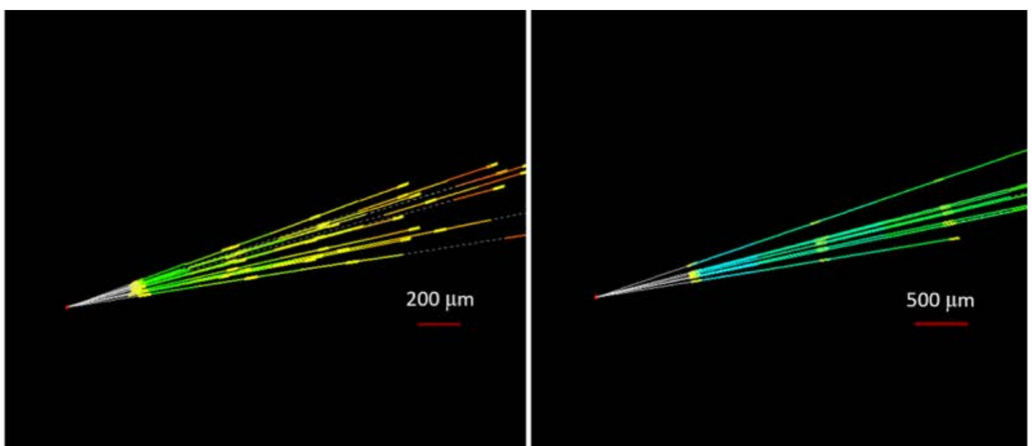
De Rujula, Ruckl (1984); Winter (1990)

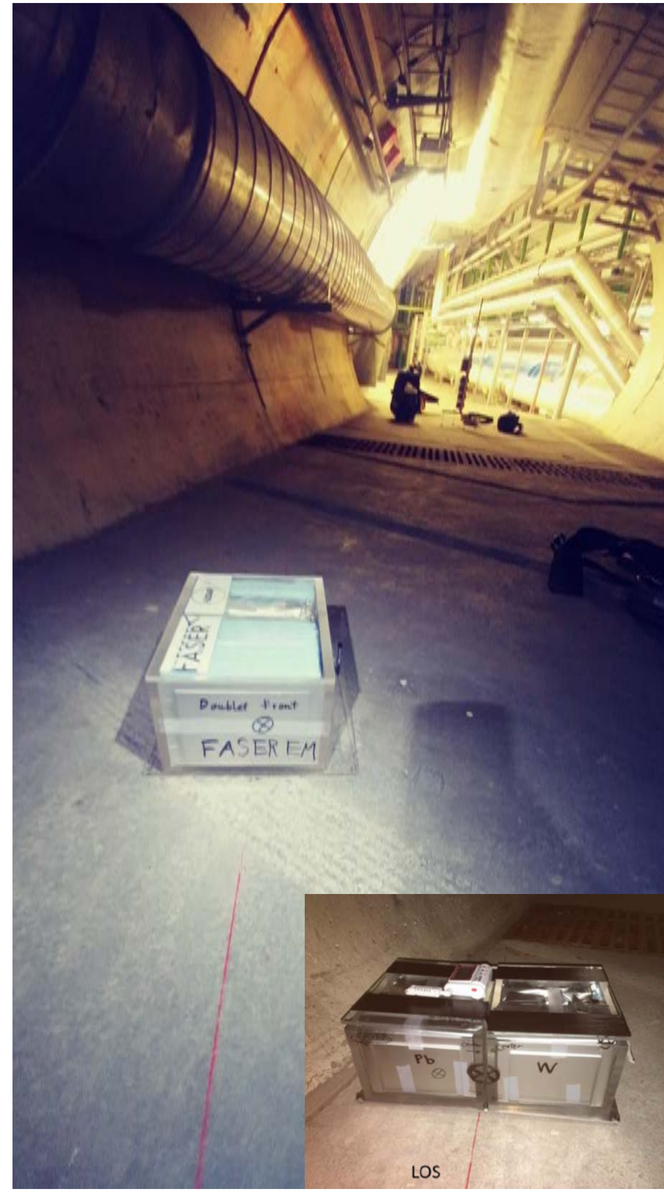
- Currently two experiments targeting this opportunity: FASERν, to be located just in front of FASER in TI12, and SND, proposed for the opposite side of ATLAS in TI18.



NEUTRINO FLUXES

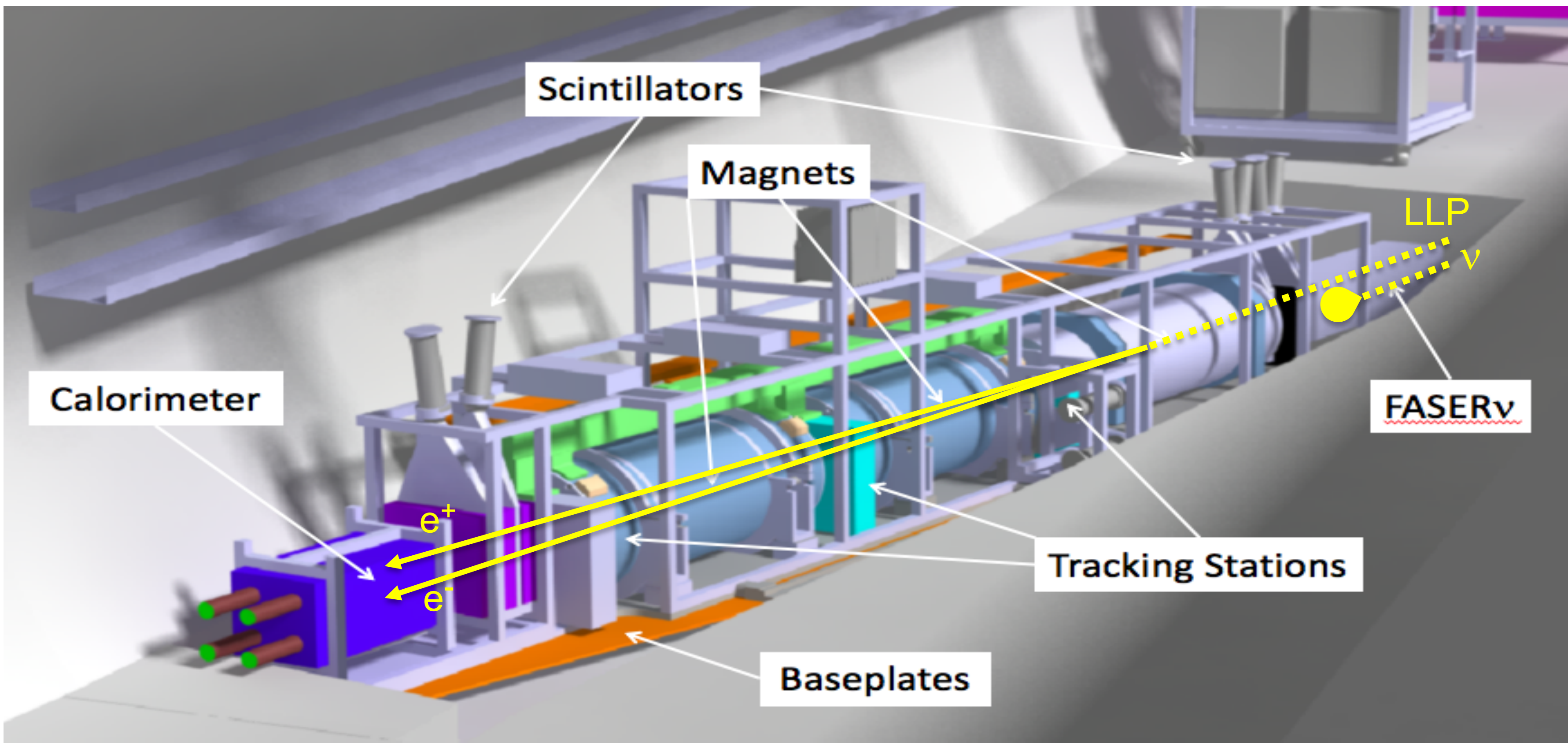
- In fact, we have probably already seen our first TeV collider neutrino.
- 2018: FASER pilot ~30 kg emulsion detectors collected 12.5 fb^{-1} on the beam collision axis (installed and removed during Technical Stops).
- Expect ~10 neutrino interactions. Several neutral vertices identified, likely to be neutrinos. Analysis ongoing.





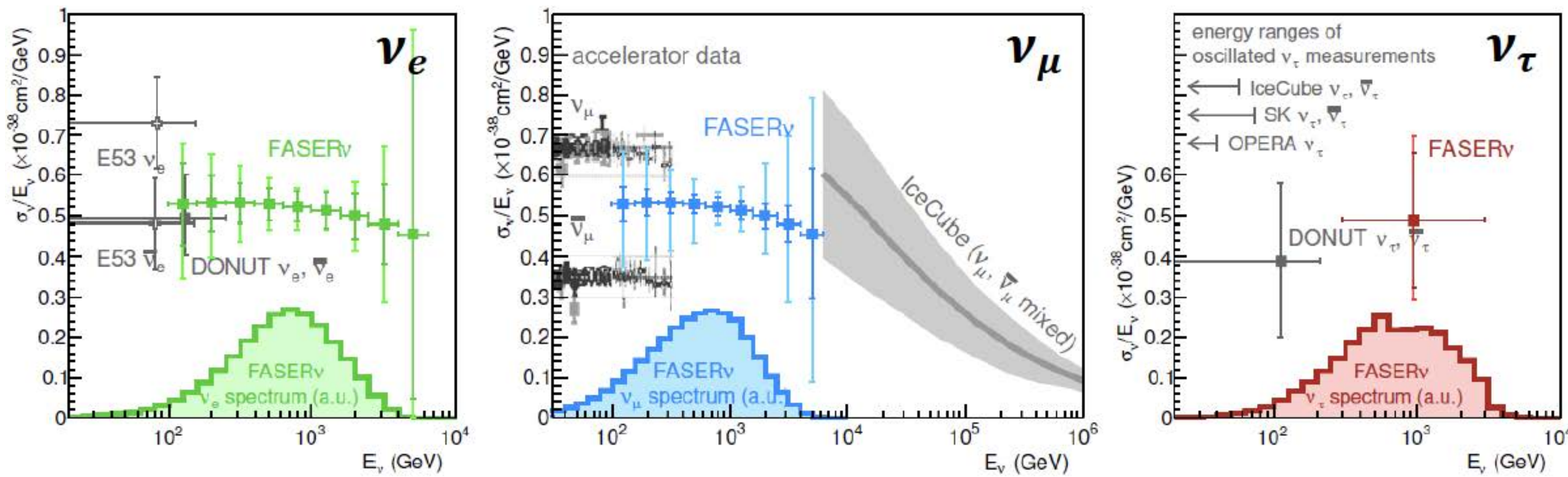
THE FASERν DETECTOR

- FASERν is designed to detect neutrinos of all flavors.
  - 25cm x 30cm x 1.1m detector consisting of 770 emulsion layers interleaved with 1mm-thick tungsten plates.
  - Emulsion is swapped out every ~10-30 fb^{-1}, total 10 sets of emulsion for Run 3.



NEUTRINO PHYSICS

- 2022-24: FASERν will collect data with 1.1-tonne detector in Run 3
  - Will detect the first collider neutrino.
  - Will 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.
  - Will double the world's supply of tau neutrinos.
  - Will be able to distinguish muon neutrinos from anti-neutrinos by combining FASER and FASERν data, and so measure their cross sections independently.



FASER Collaboration 1908.02310 (2019)

SUMMARY AND OUTLOOK

- A new target for particle physics experiments: light and weakly-interacting particles at the lifetime frontier.

- Fast, small, cheap experiments can provide world-leading sensitivities.

- FASER: 18 months from theory paper to beginning of construction, fits on a tabletop, ~$2M. Data-taking begins 2022 with new neutrino measurements and discovery prospects for a host of proposed new particles.

Branigan, Symmetry Magazine (2019)

- More info: https://faser.web.cern.ch.