
FASTER, SMALLER, CHEAPER LOOKING FORWARD TO NEW DISCOVERIES AT THE LHC

Department Colloquium, University of Hawaii

Jonathan Feng, UC Irvine, 4 February 2021



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OUTLINE

PARTICLE PHYSICS NOW

LIGHT, WEAKLY-INTERACTING PARTICLES

FORWARD PHYSICS

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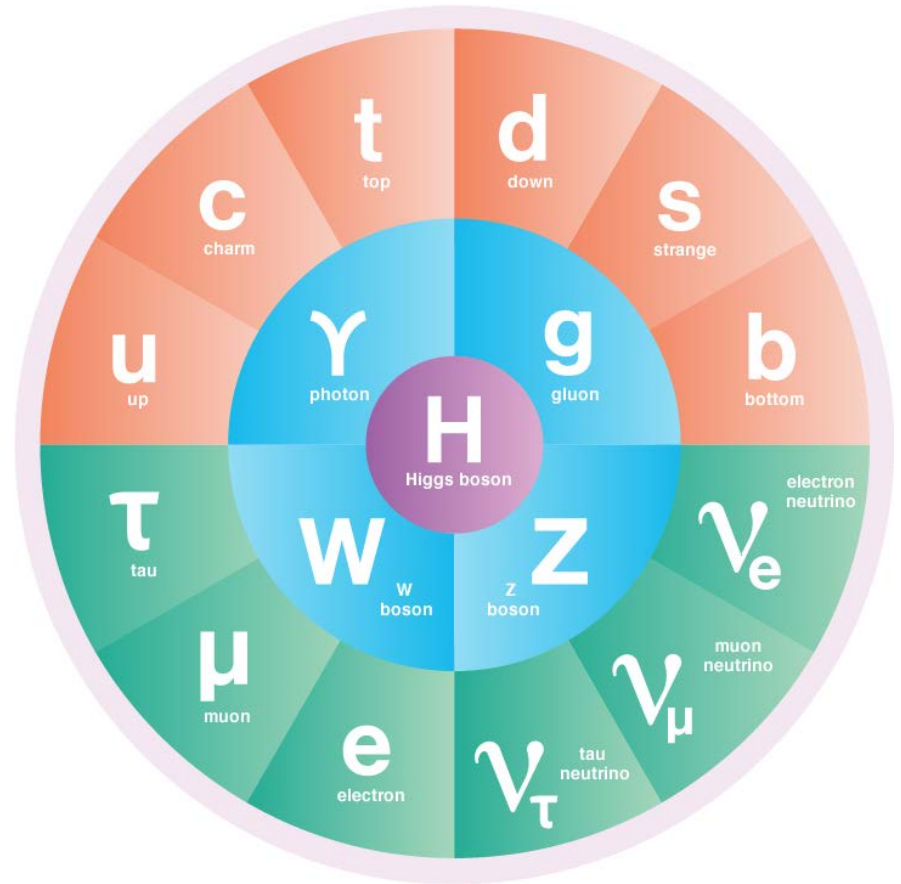
FORWARD PHYSICS FACILITY

SUMMARY

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



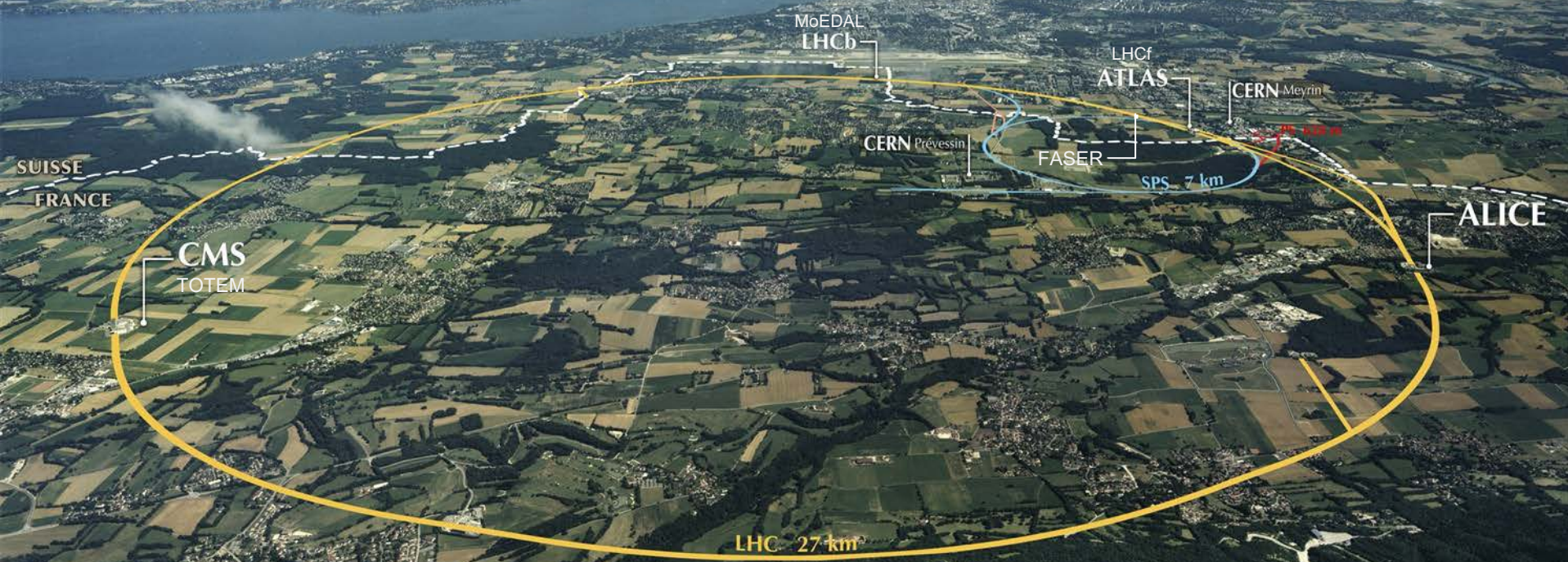
- In the 1930's, E. O. Lawrence made a cyclotron, which accelerated particles to higher velocities and energies.



- 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

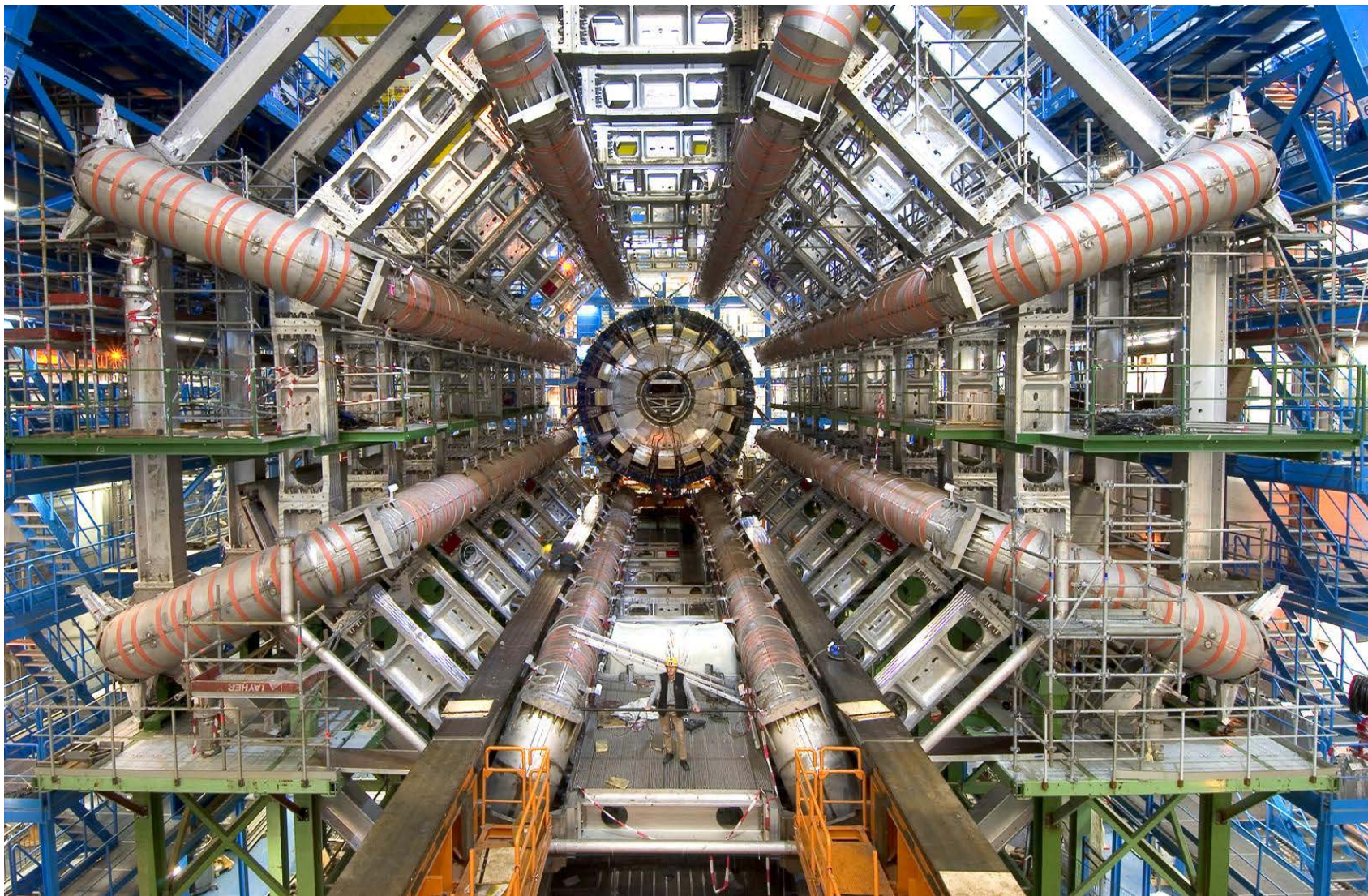
The latest realization of Lawrence's vision: the LHC in Geneva



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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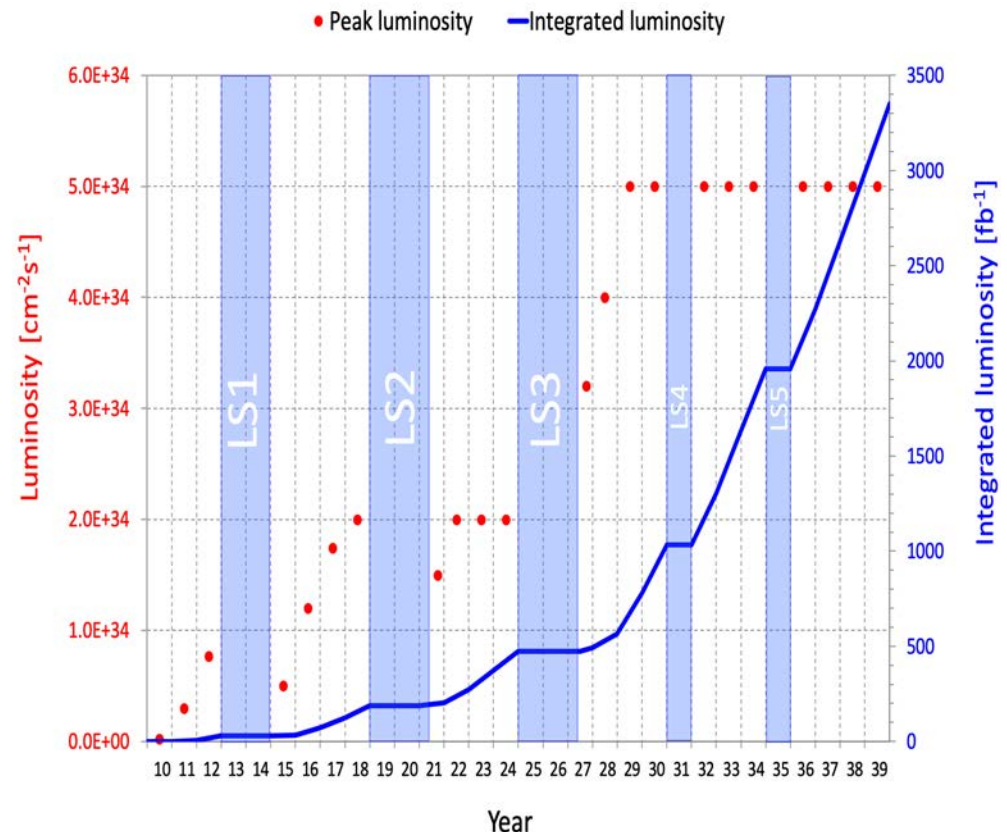
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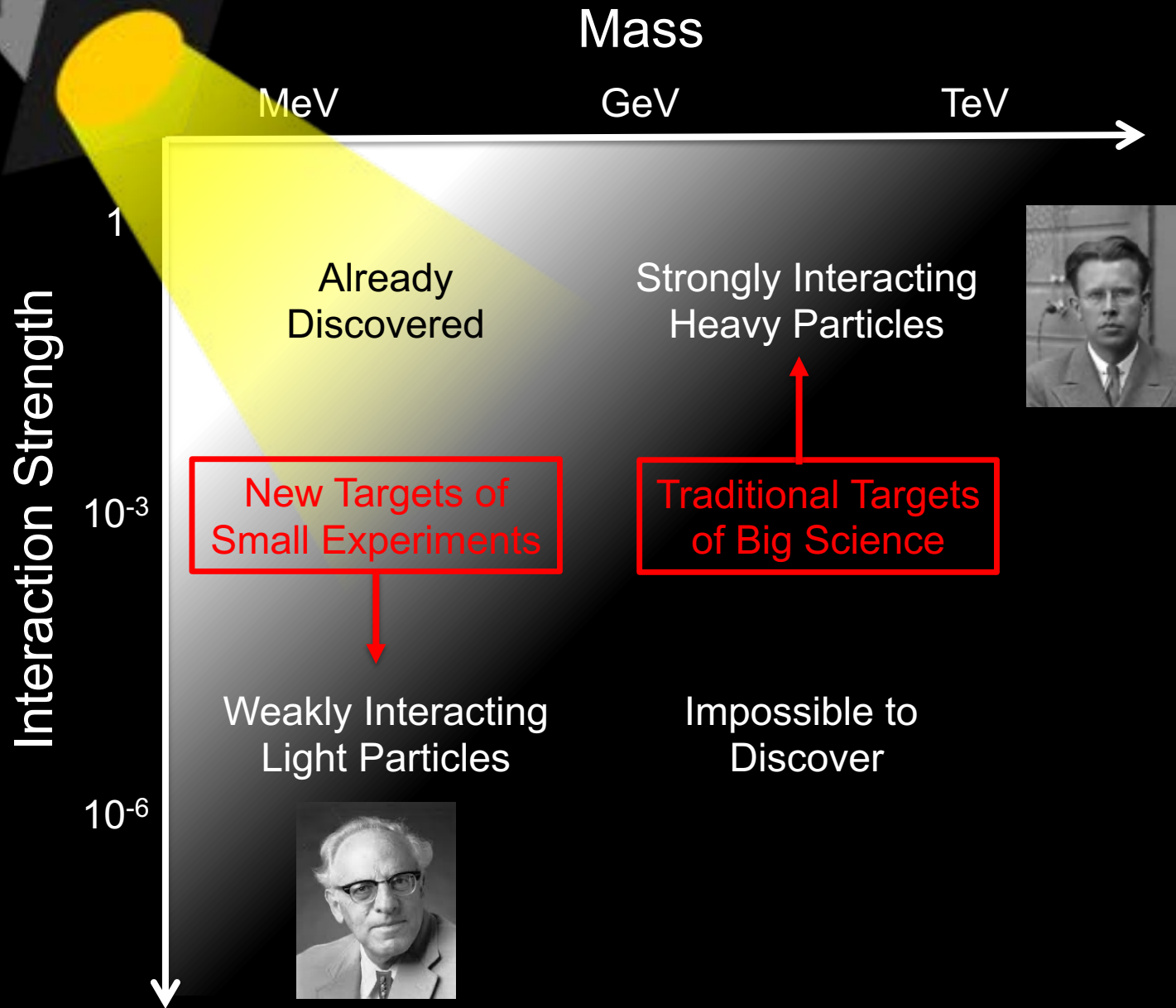
LHC: CURRENT STATUS

- 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?



LIGHT, WEAKLY- INTERACTING PARTICLES

THE NEW PARTICLE LANDSCAPE



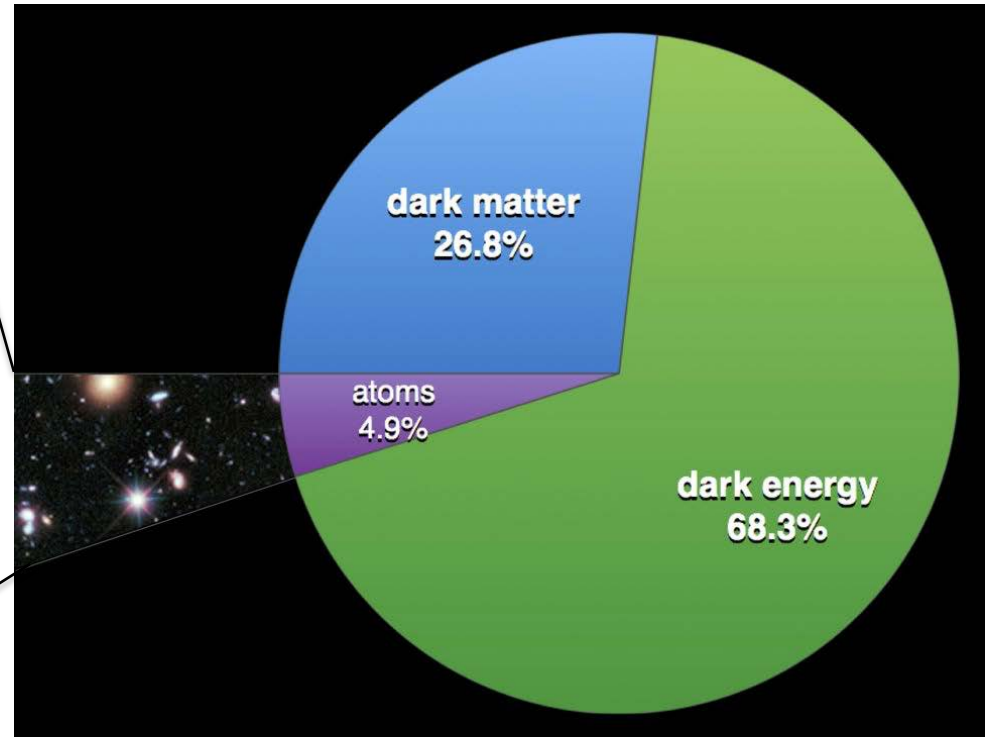
THE UNIVERSE TODAY

Periodic Table of Elements

The periodic table shows elements organized by atomic number (1 to 118). It includes color-coded regions for Metals, Nonmetals, and various groups like Lanthanoids and Actinoids. A legend indicates states: Solid (C), Liquid (Hg), Gas (H), and Unknown (Rt). A blue box highlights the first 10 elements (H to Ne). A blue box at the bottom left contains the text 'Ptable.com'.

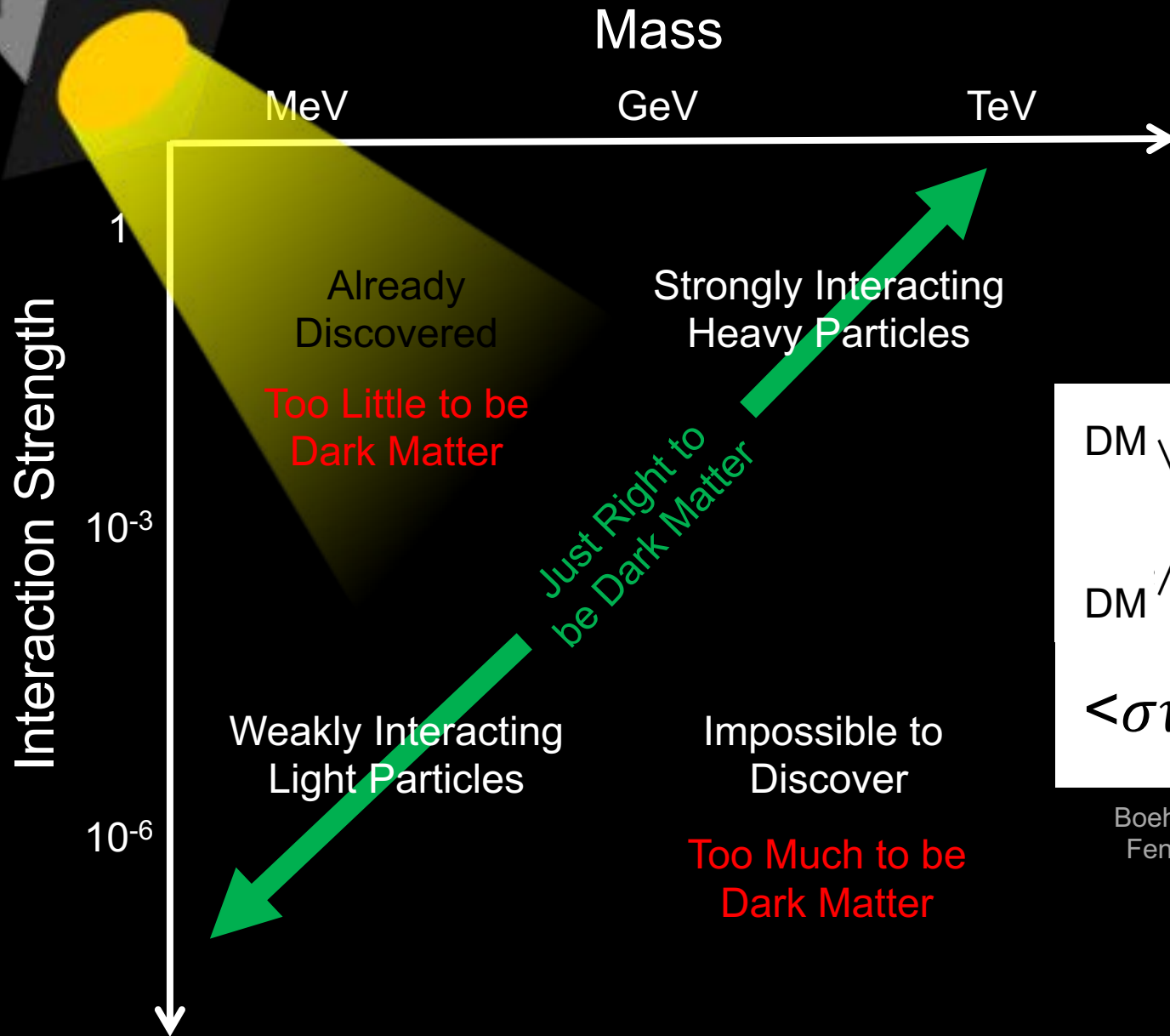
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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- 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%).
Dark matter provides a strong motivation for at least one new weakly-interacting particle.

THE THERMAL RELIC LANDSCAPE

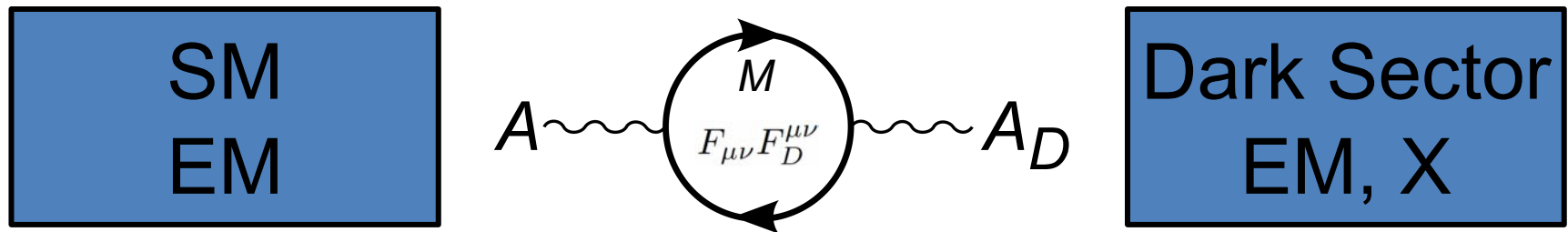


$$\langle \sigma v \rangle \sim \frac{\epsilon^2}{m_{A'}^2}$$

Boehm, Fayet (2003)
Feng, Kumar (2008)

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 A'** . 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**.

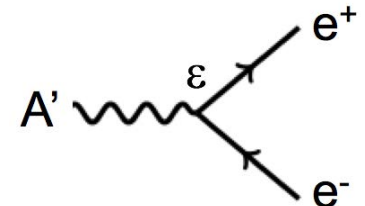
Holdom (1986)

- 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.

DARK PHOTON PROPERTIES

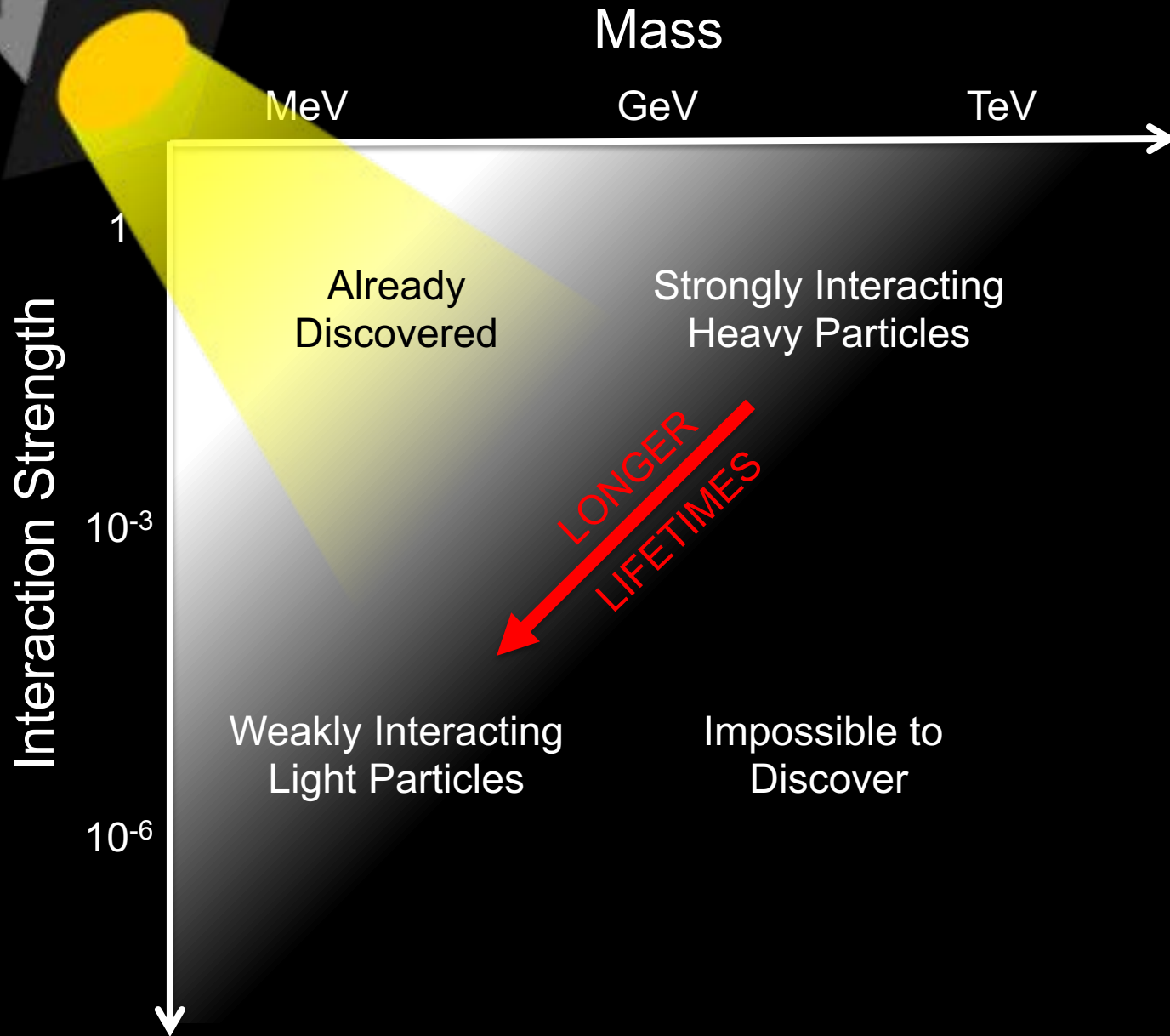
- Consider dark photons with
 - energy $E \sim \text{TeV}$, as can be produced at the LHC
 - mass between electron (0.5 MeV) and proton (1 GeV): take $m \sim 100 \text{ MeV}$
 - coupling between milli-charged and micro-charged: take $\epsilon \sim 10^{-5}$
- They pass through matter without interacting: radiation length is (10 cm) $\epsilon^{-2} \sim 10^9 \text{ m}$. 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:

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



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

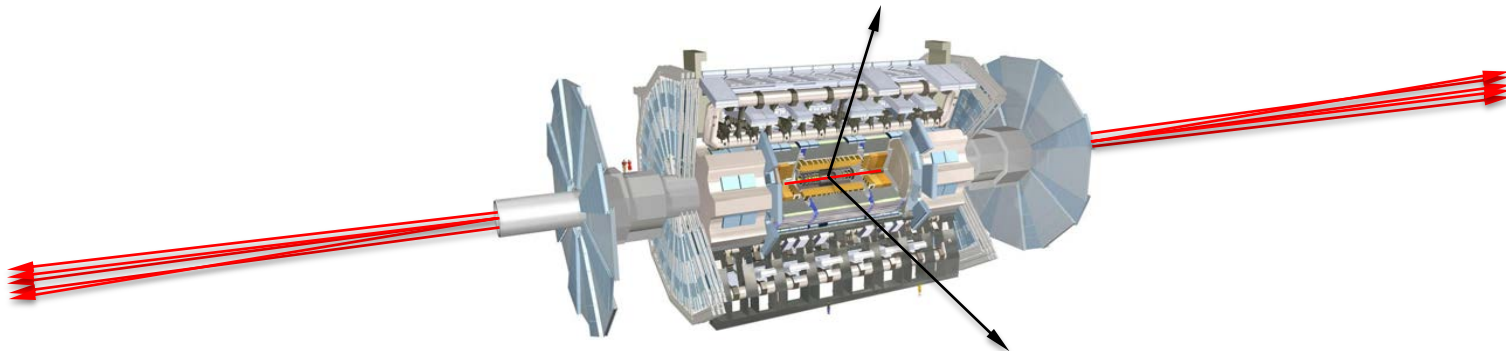
THE NEW PARTICLE LANDSCAPE



FORWARD PHYSICS

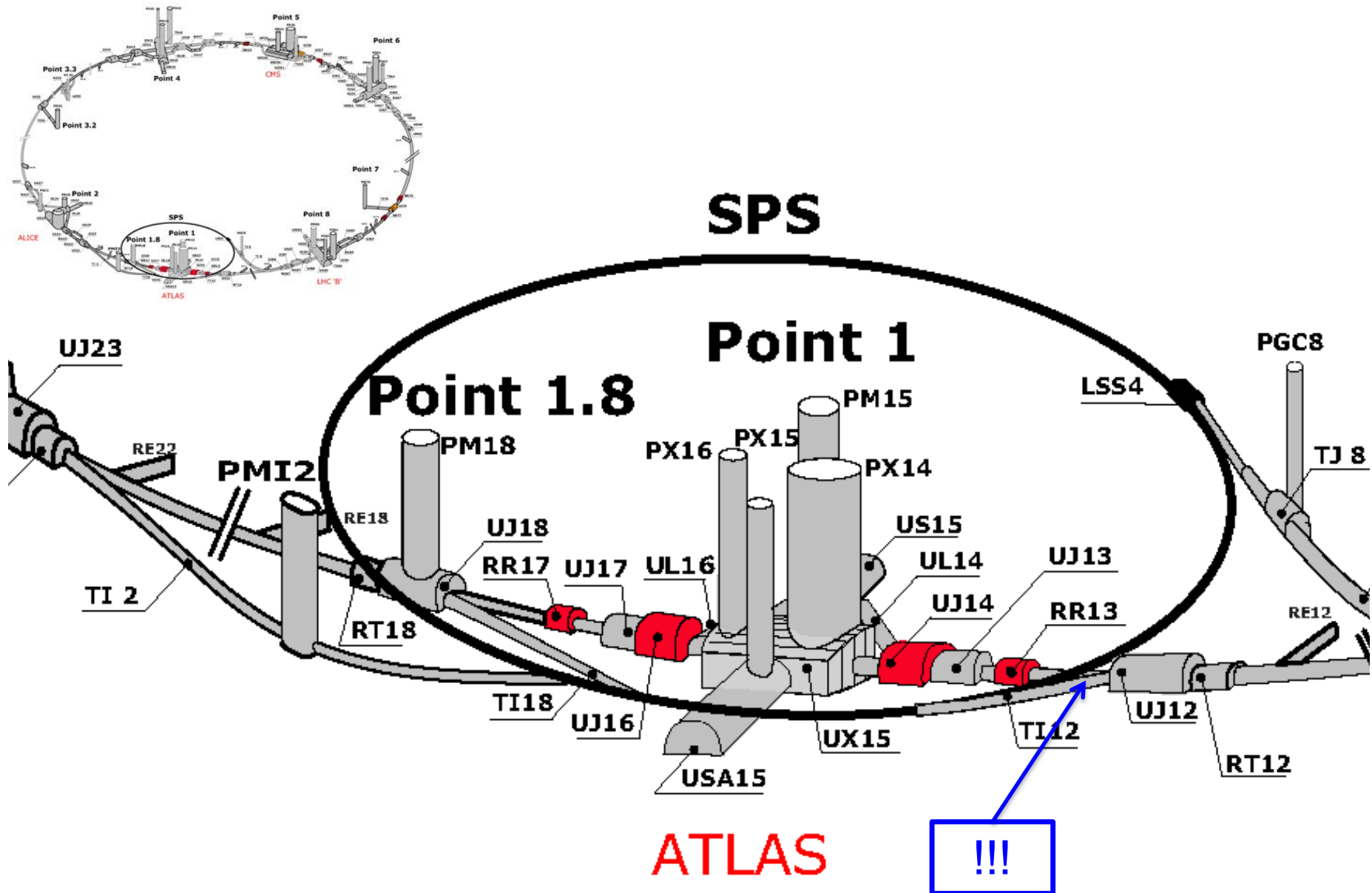
SEARCHES FOR NEW LIGHT PARTICLES

- 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. These particles are produced almost at rest and decay isotropically.

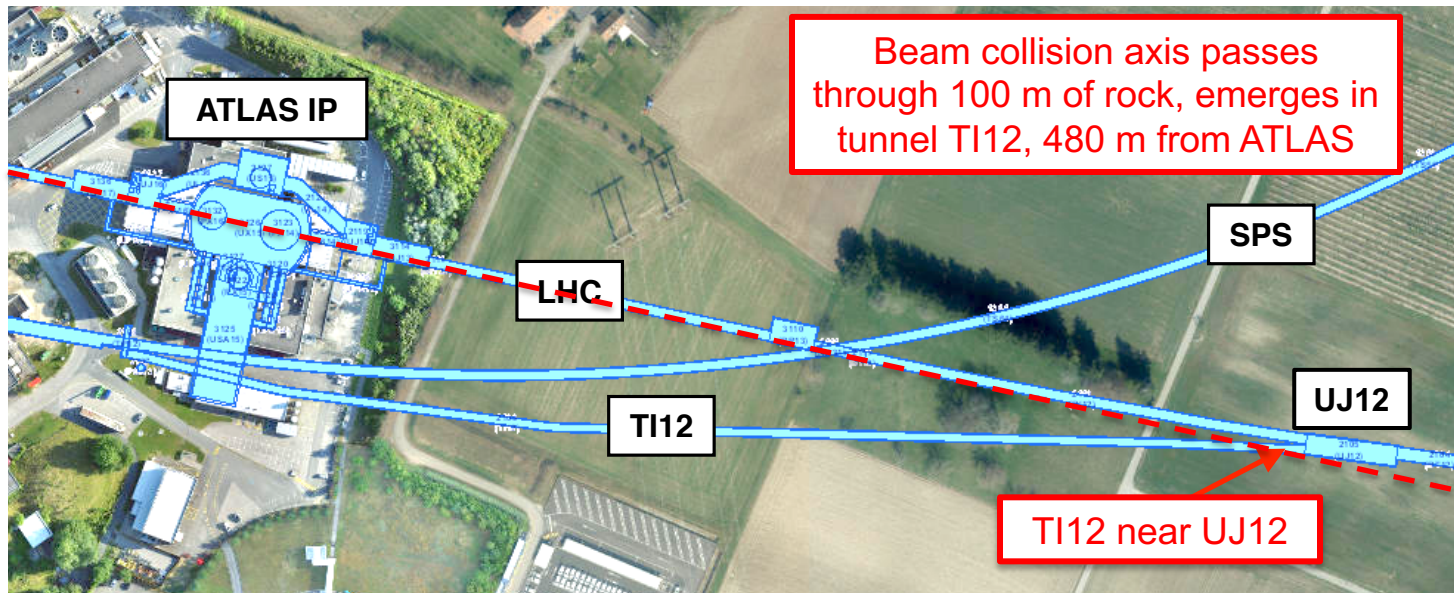


- But new **light** particles are mainly produced in the decays of light particles: π , K, D and B mesons. These are mainly produced along the beamline, and so the new particles disappear through the holes that let the beams in.
- Clearly what we need a detector to cover these “blind spots” in the **forward 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.

MAP OF LHC

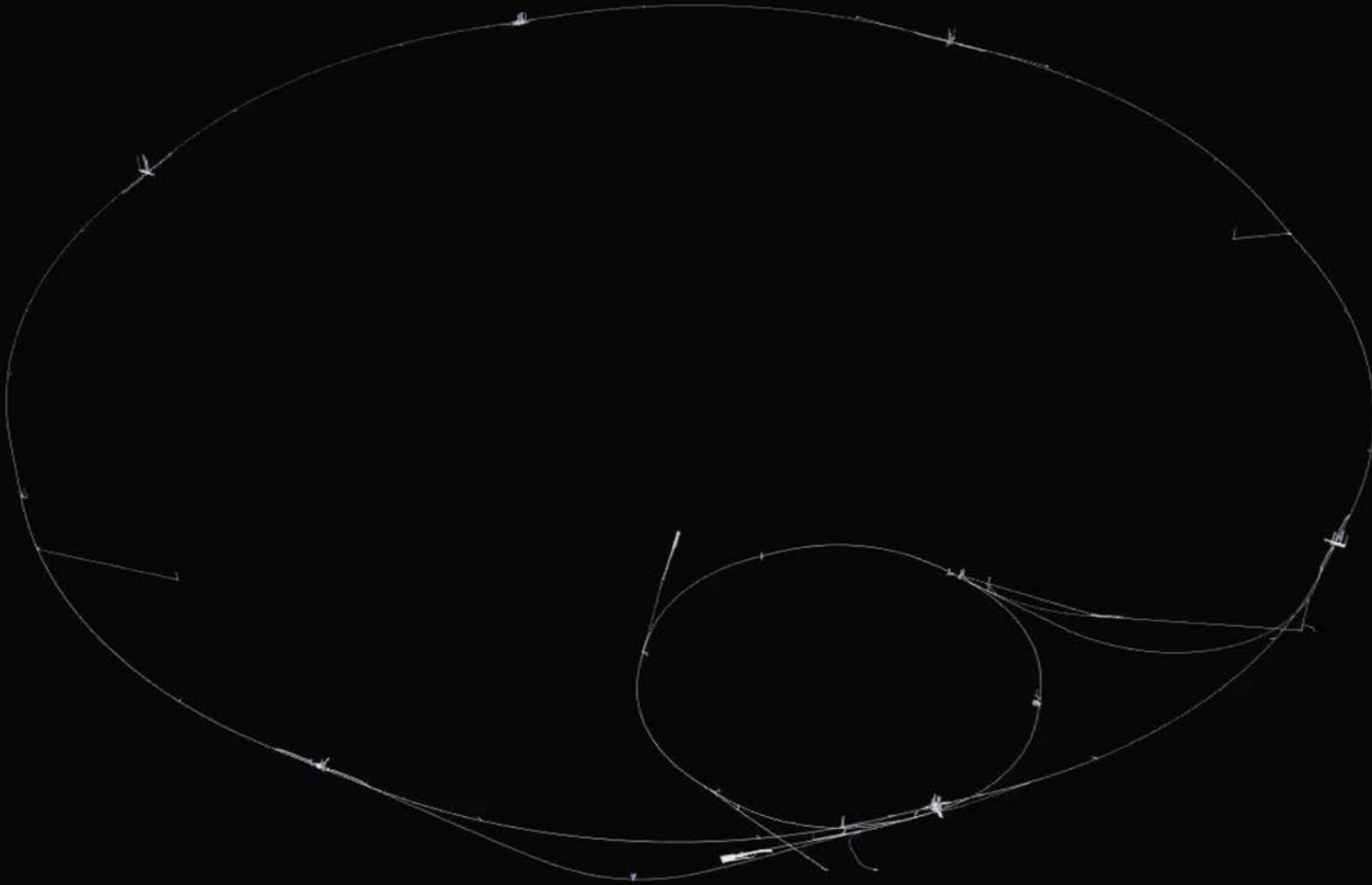


LOCATION, LOCATION, LOCATION



PARTICLE PATH FROM ATLAS TO T112

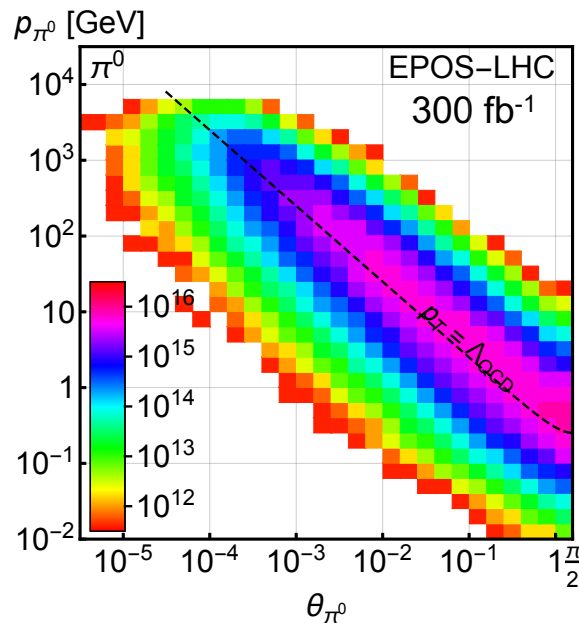
Dougherty, CERN Integration (2019)



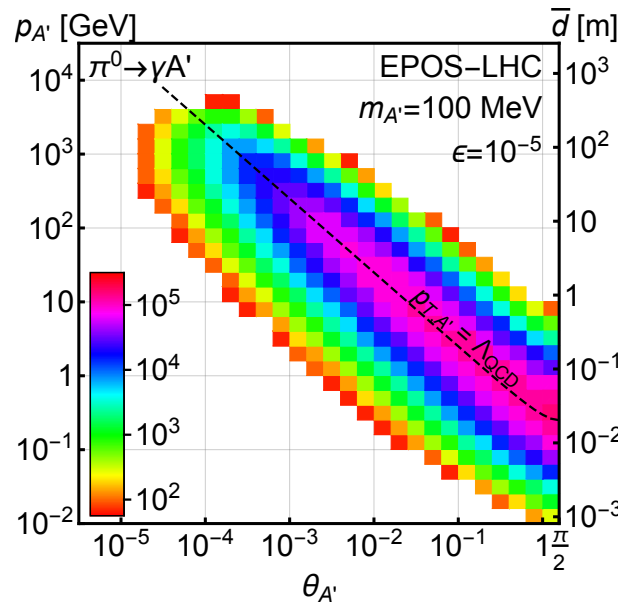
HOW BIG DOES THE DETECTOR HAVE TO BE?

Consider dark photons: $\pi^0 \rightarrow A' \gamma$, A' travels 480 m, then decays: $A' \rightarrow e^+ e^-$

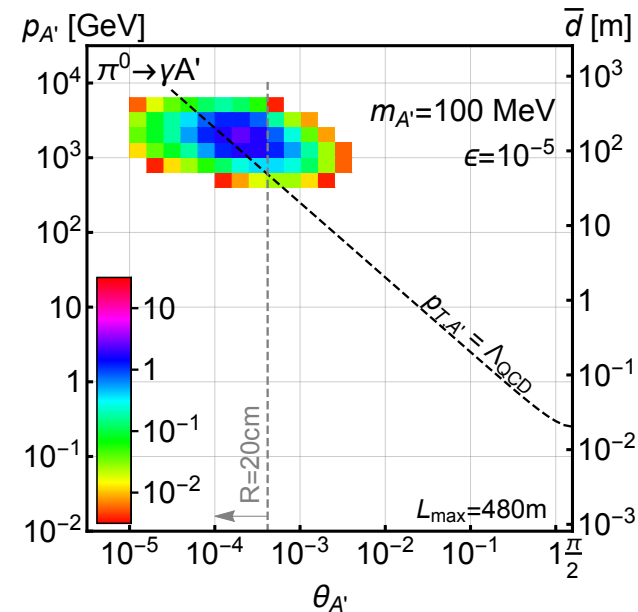
Pions at the IP



A' 's at the IP

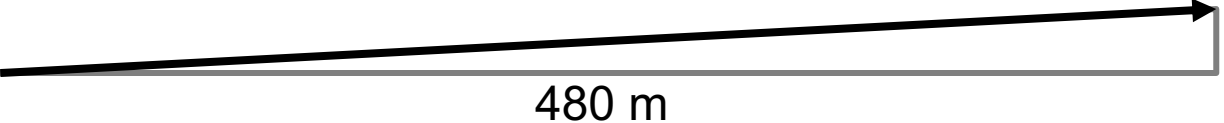


A' 's decay in [480m, 483m]

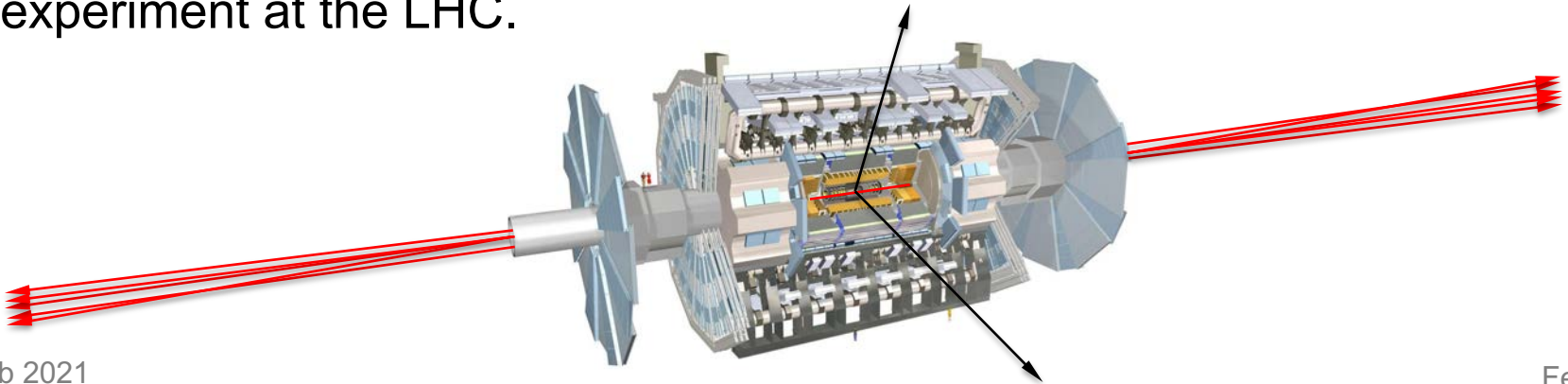


- Production is peaked at $p_T \sim m_\pi, \Lambda_{\text{QCD}} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin
- Rates highly suppressed by $\epsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin
- Only highly boosted $\sim \text{TeV}$ A' 's decay in FASER
- $N_{A'} \sim 100$ e^+e^- events, within 20 cm of “on axis”

HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:  200 MeV
1 TeV
- Space:  10 cm
480 m

- The opening angle is 0.2 mrad ($\eta \sim 9$); cf. the moon (7 mrad).
- TeV dark photons (or any other new particle produced in π , K, D, B decay) is far more collimated than shown below, motivating a new, small, fast, cheap experiment at the LHC.



FASER

FORWARD SEARCH EXPERIMENT



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

Feng, Galon, Kling, Trojanowski (2017)



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!

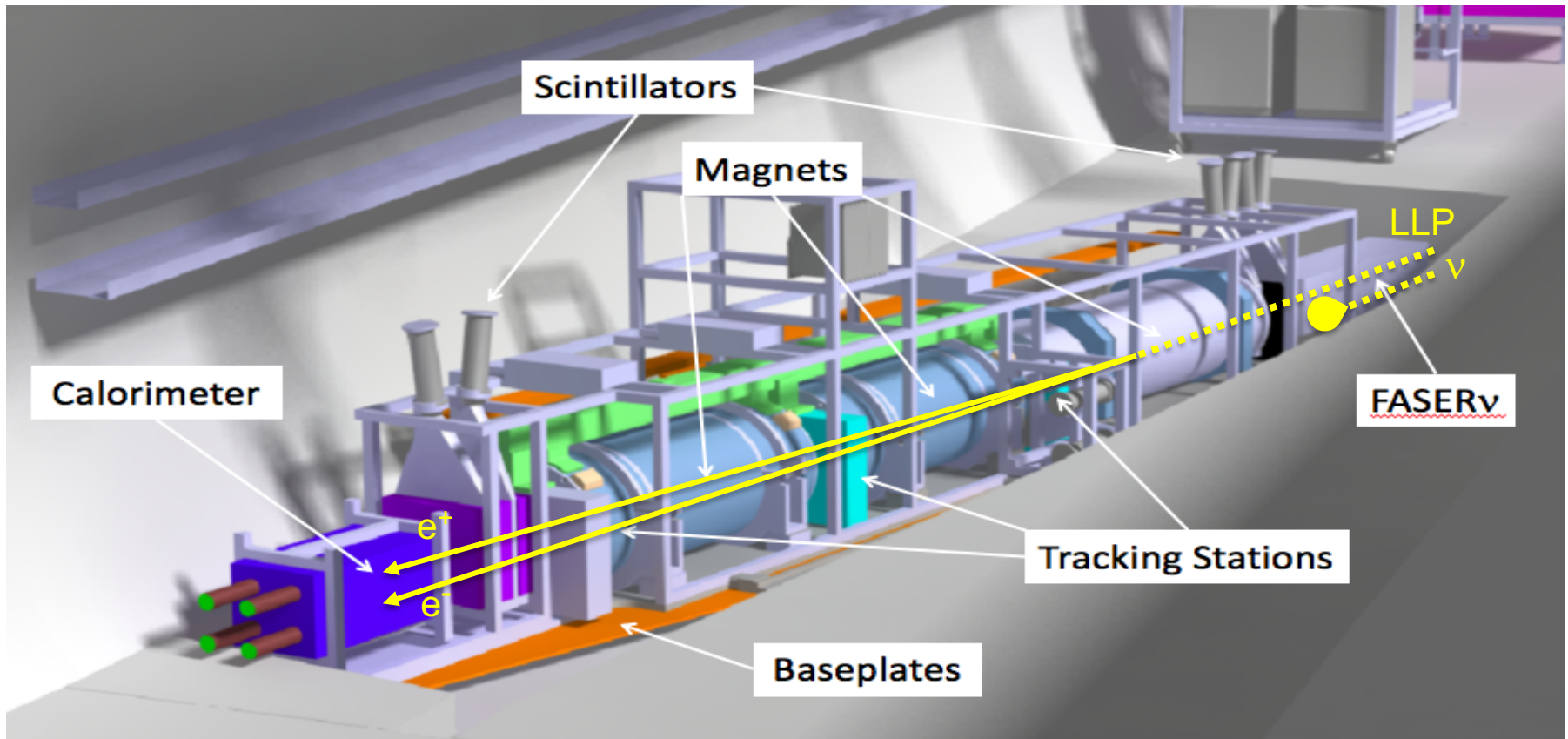
FASER IN TUNNEL T112

- 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.



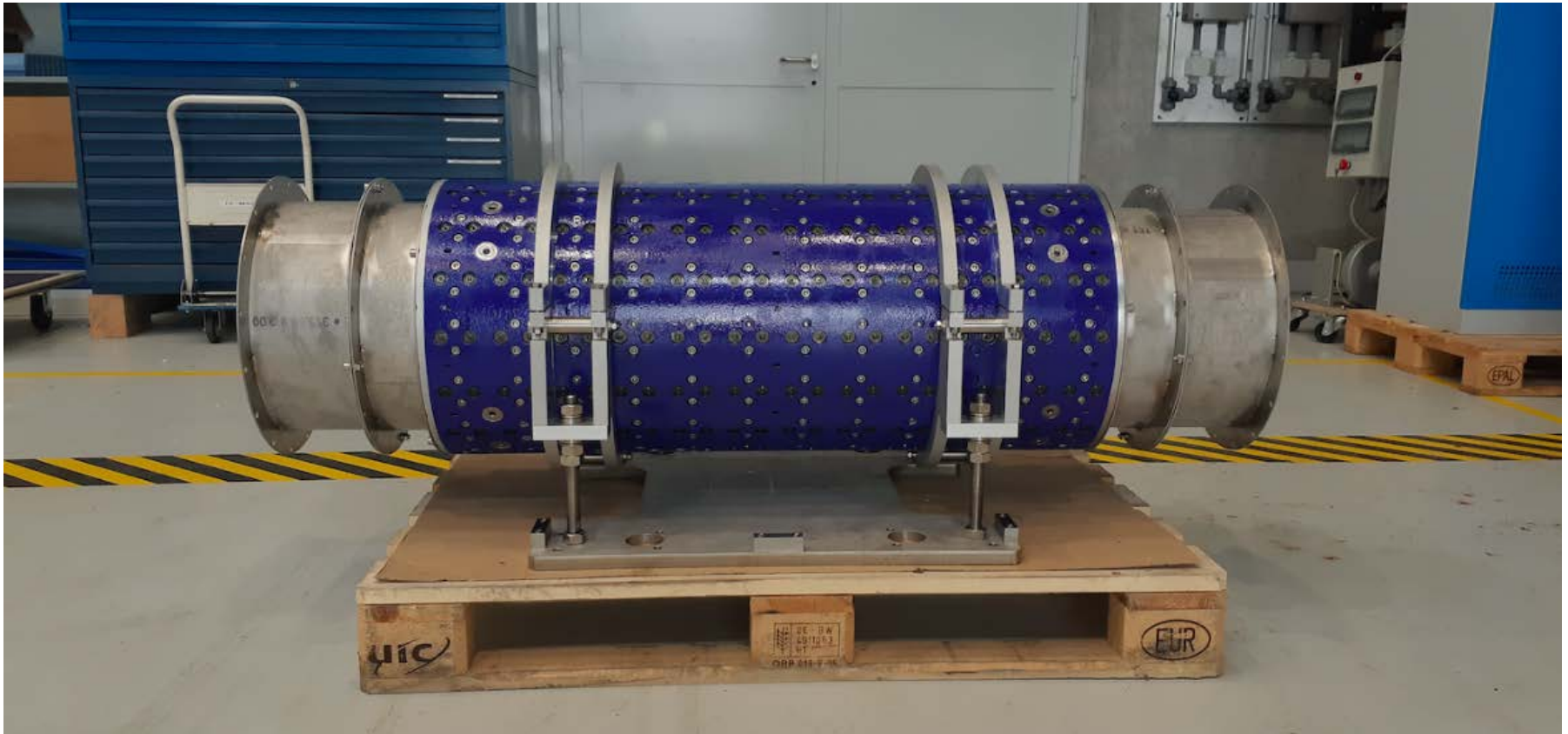
THE FASER DETECTOR

- 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.



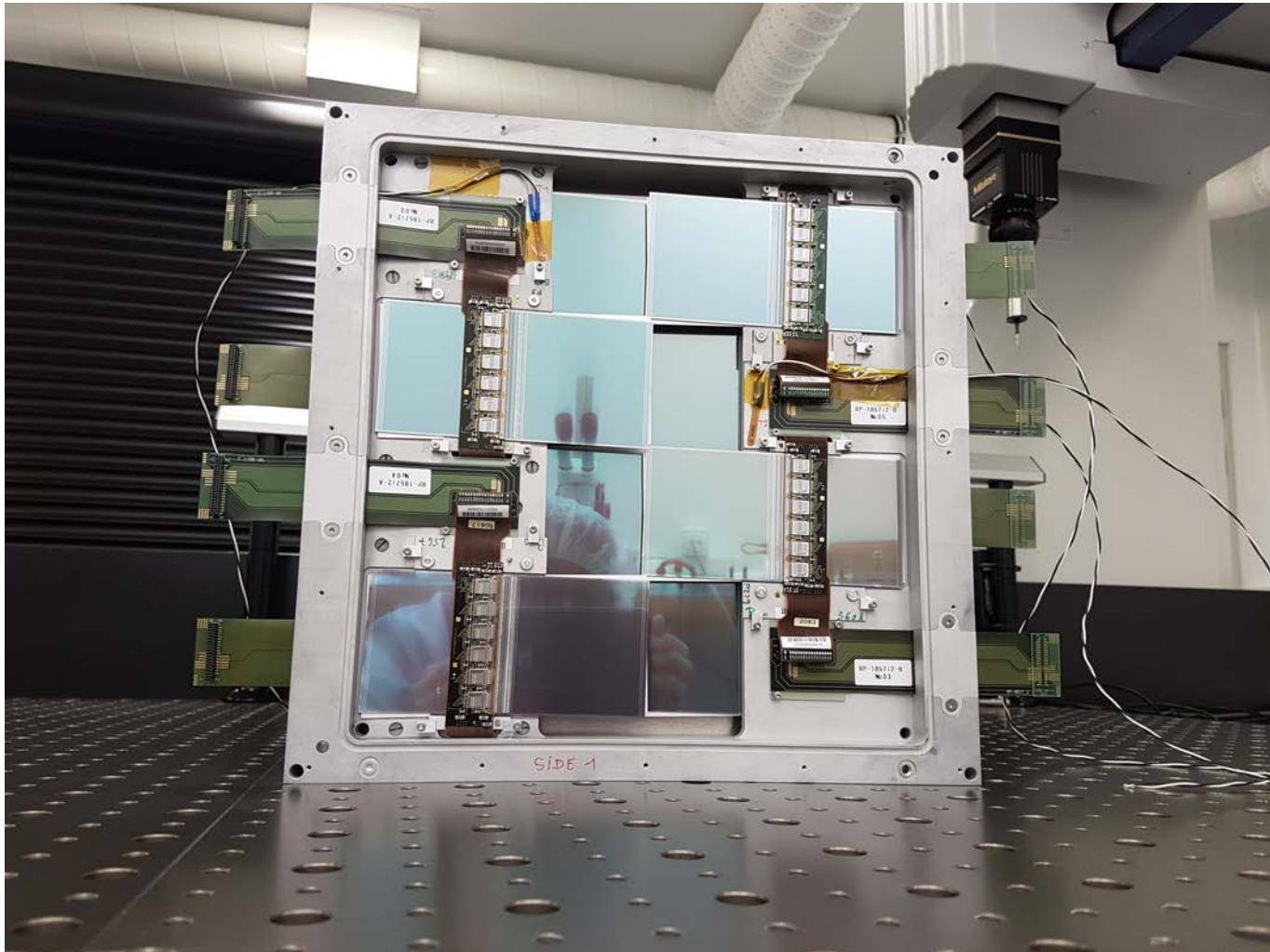
MAGNETS

- 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.

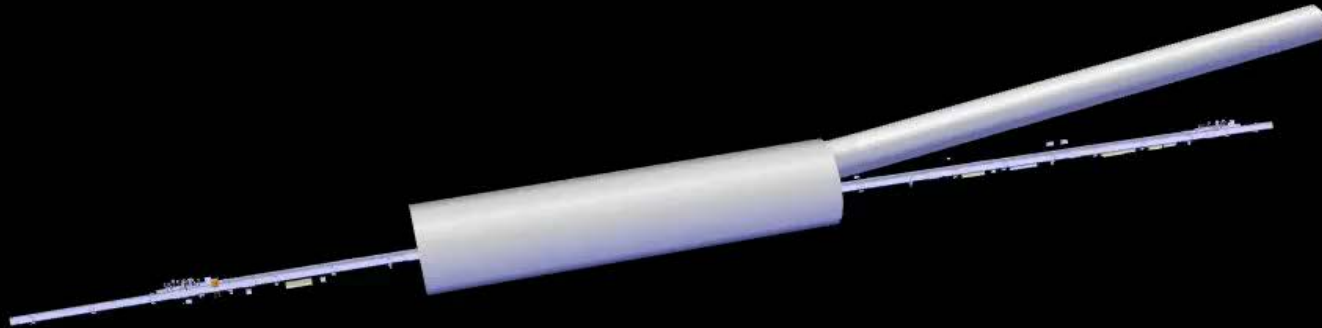


FASER COMMISSIONING ON SURFACE

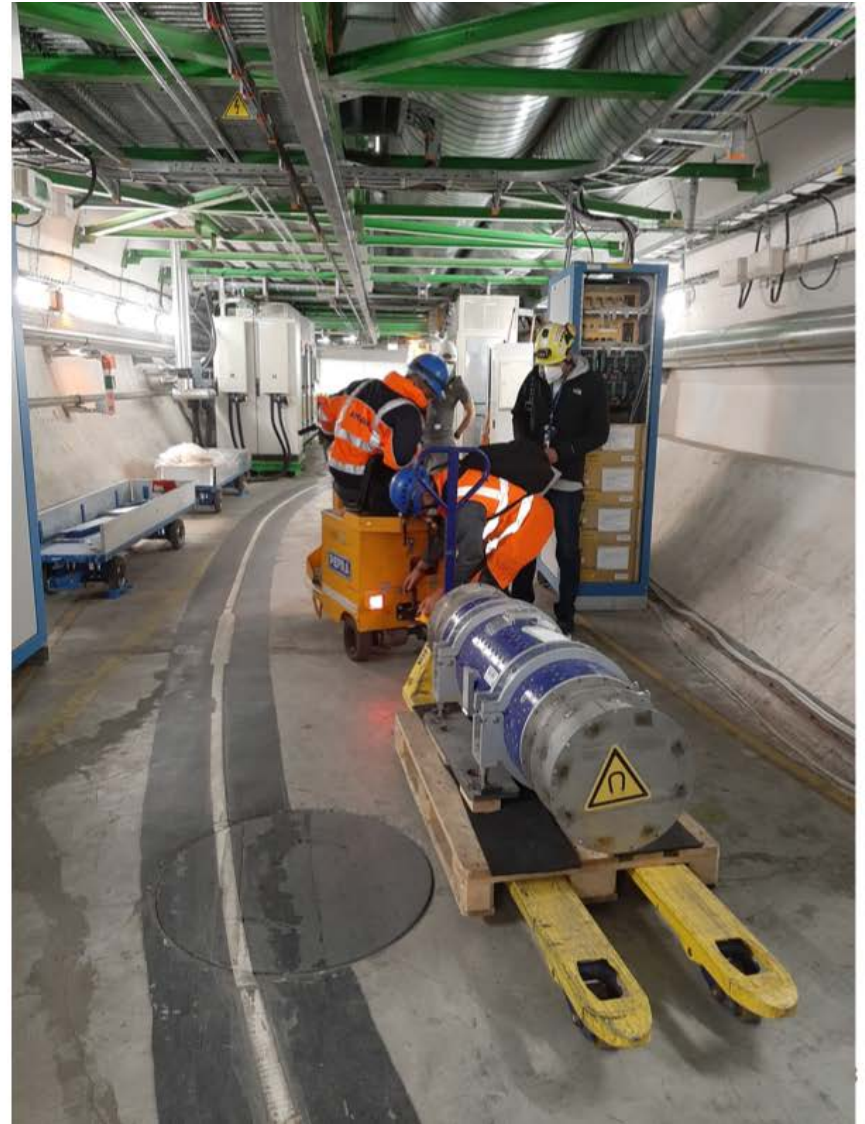


FASER INSTALLATION

Dougherty, CERN Integration (2019)



FASER INSTALLATION



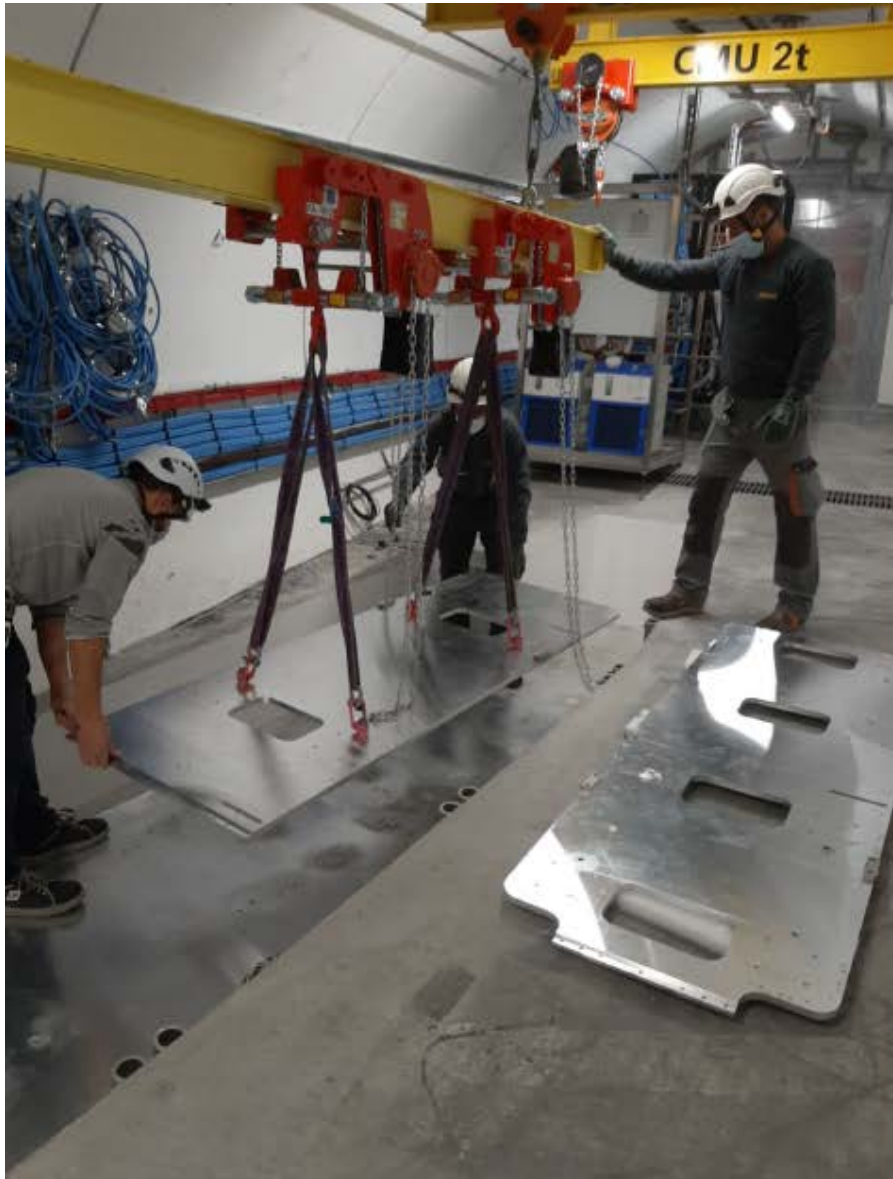
FASER INSTALLATION



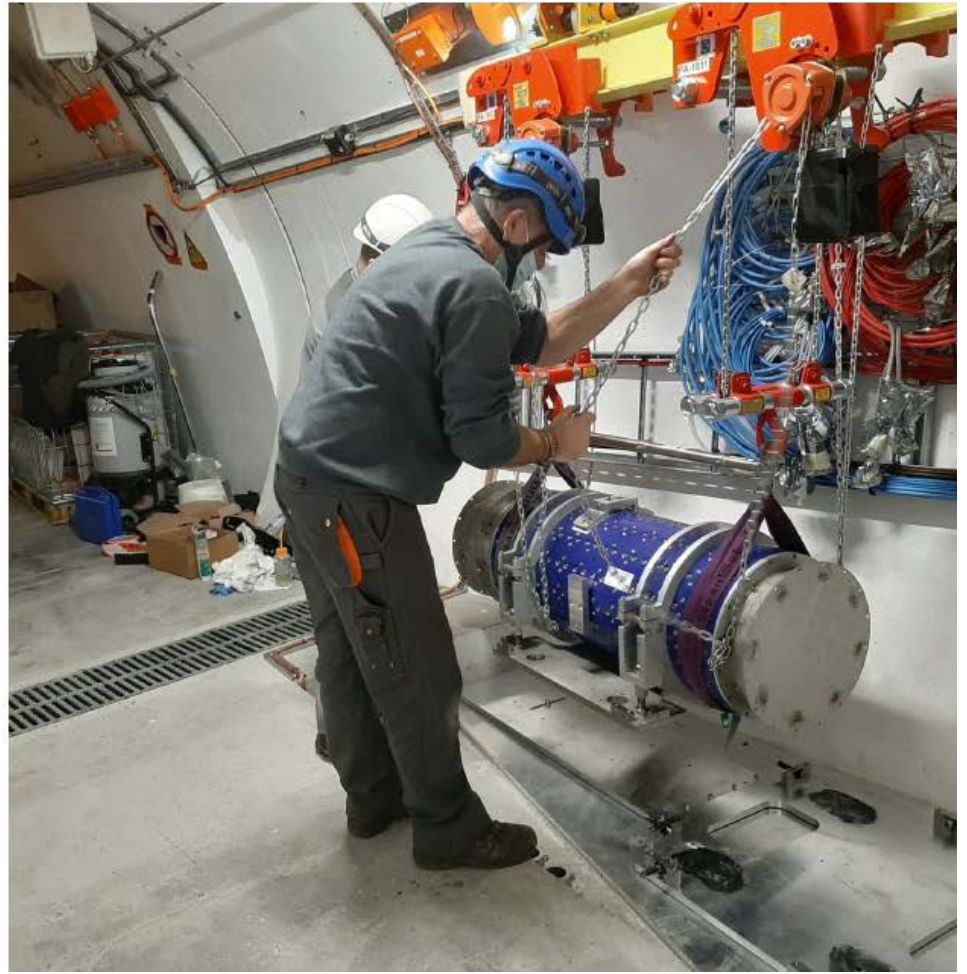
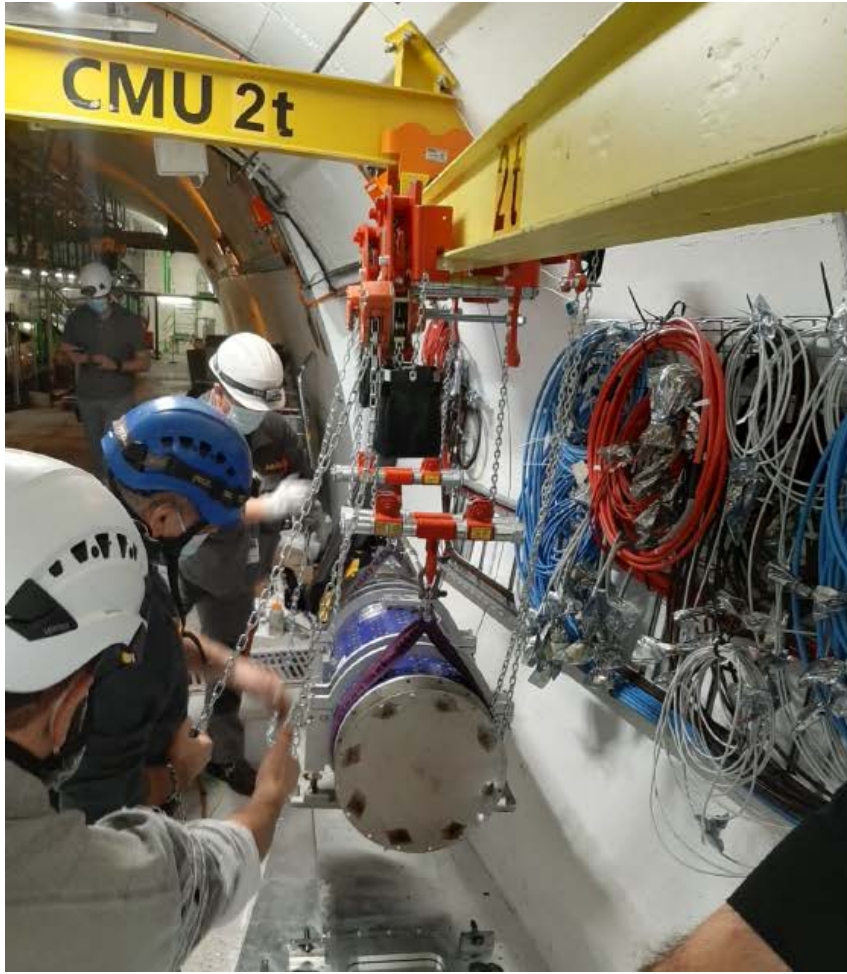
FASER INSTALLATION



FASER INSTALLATION



FASER INSTALLATION



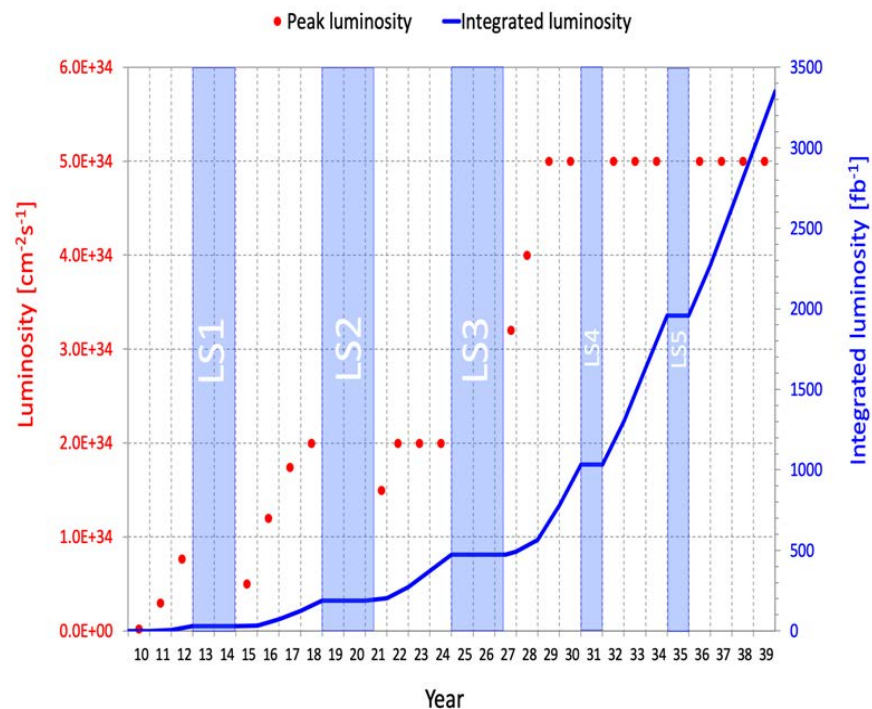
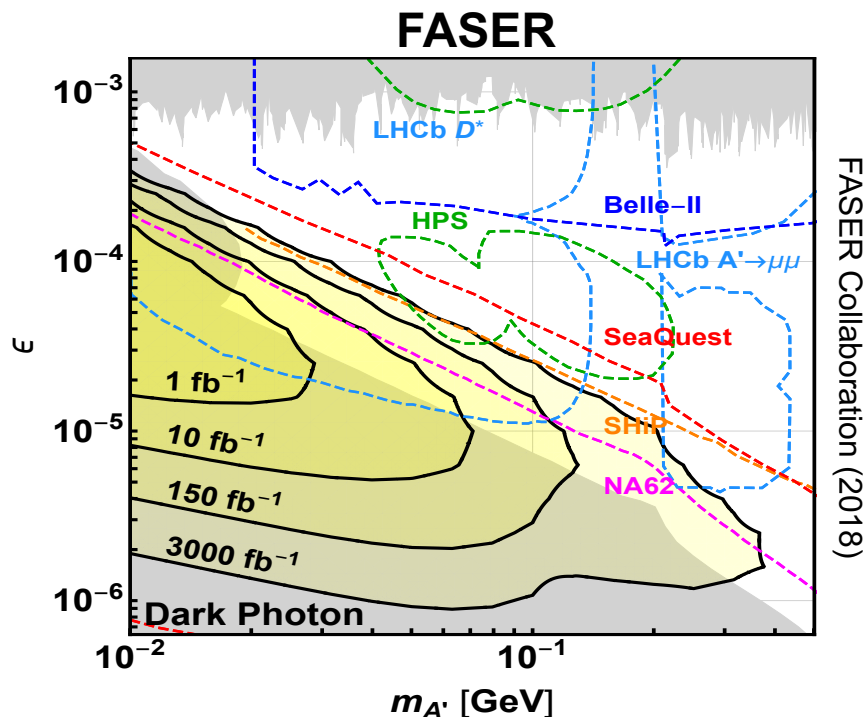
FASER CURRENT STATUS



FASER CURRENT STATUS



DARK PHOTON SENSITIVITY REACH



- 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 $\sim 10^6$.

PHYSICS SUMMARY

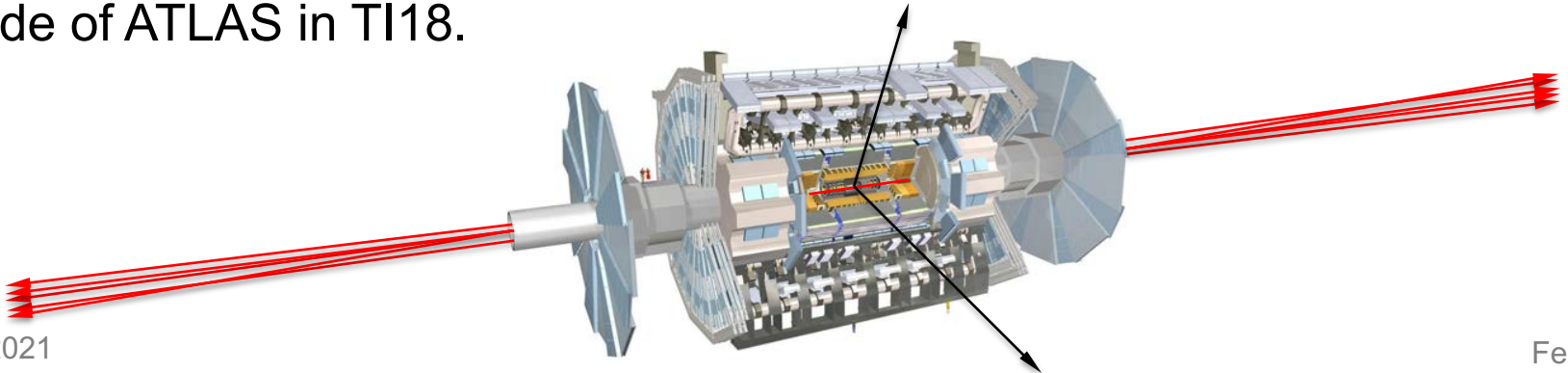
- Many other studies: FASER has discover prospects for all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ , f , g); and many other examples; see 1811.12522.

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_v

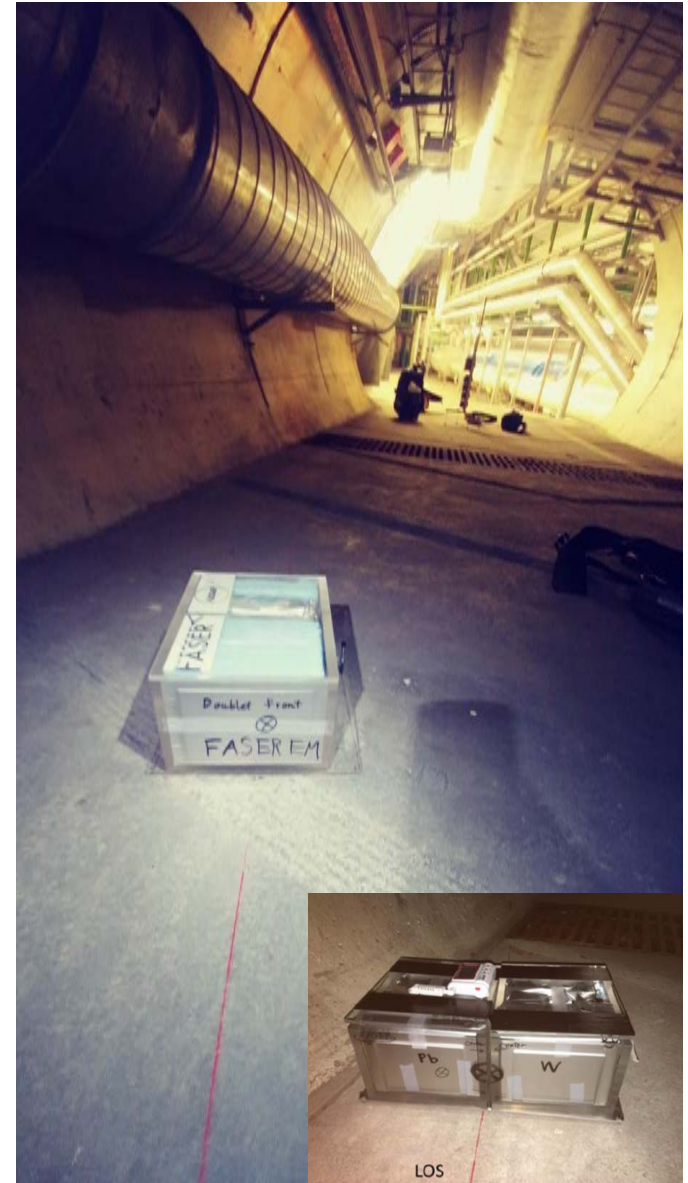
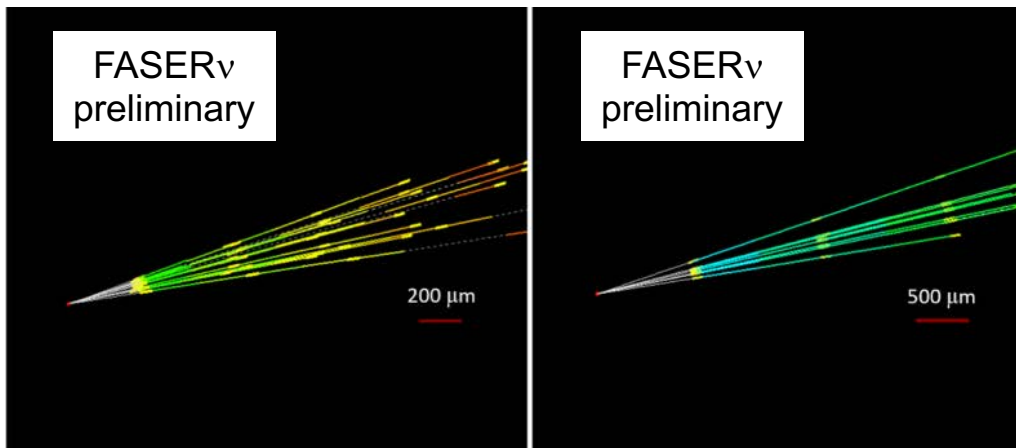
COLLIDER NEUTRINOS

- 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 ($\pi \rightarrow \nu_\mu$, $K \rightarrow \nu_e$, $D \rightarrow \nu_\tau$) and both neutrinos and anti-neutrinos.
- De Rujula, Ruckl (1984); Winter (1990)
- Currently two experiments targeting this opportunity: FASER ν , to be located just in front of FASER in TI12, and SND, proposed for the opposite side of ATLAS in TI18.



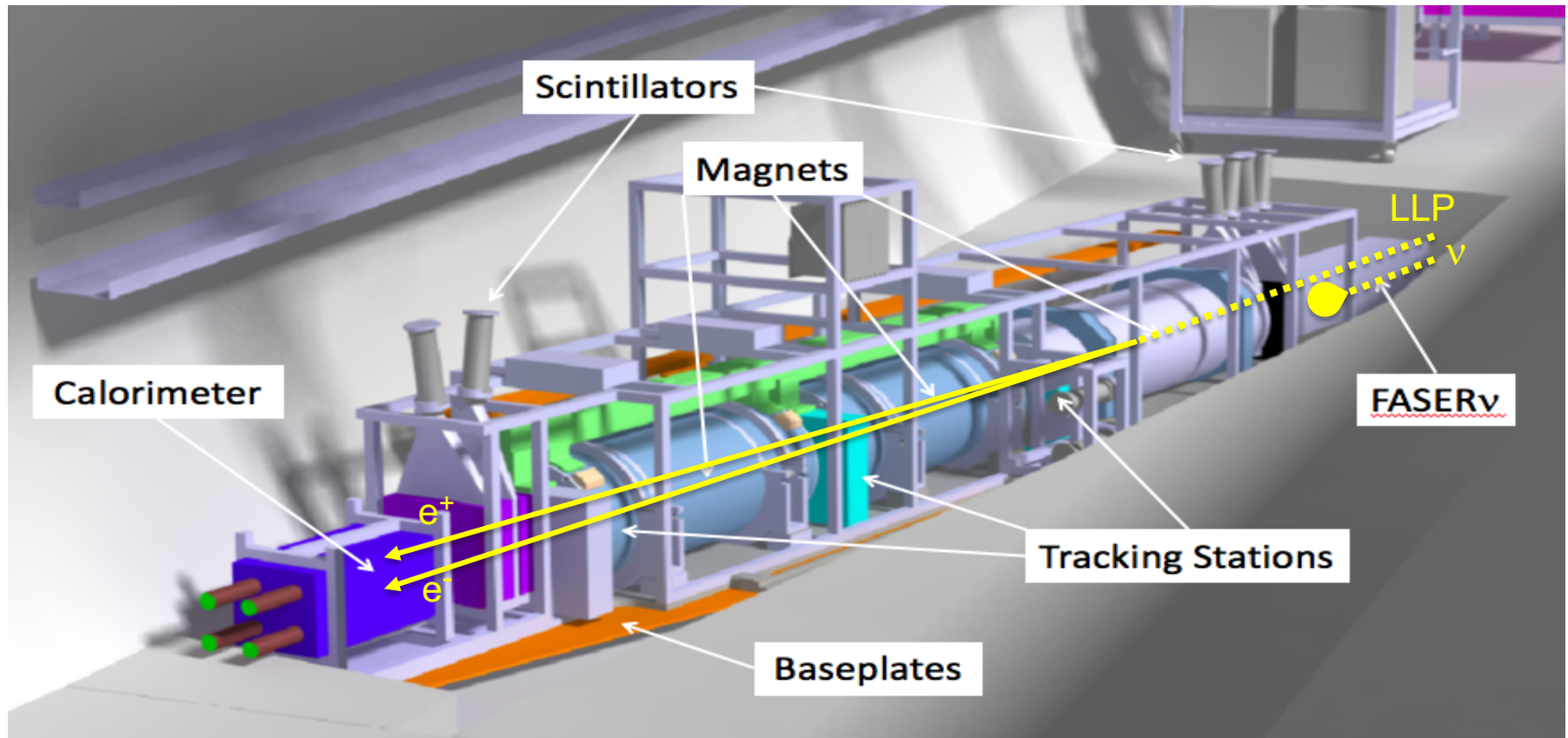
NEUTRINO FLUXES

- In fact, we have probably already seen our first TeV collider neutrino.
- In 2018 a 29 kg FASER pilot 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.



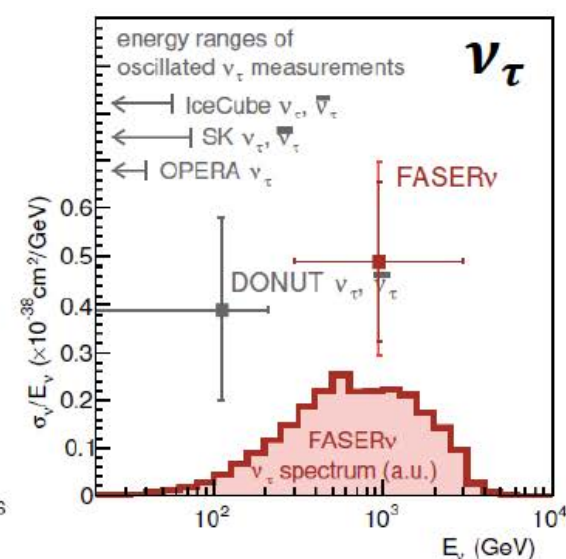
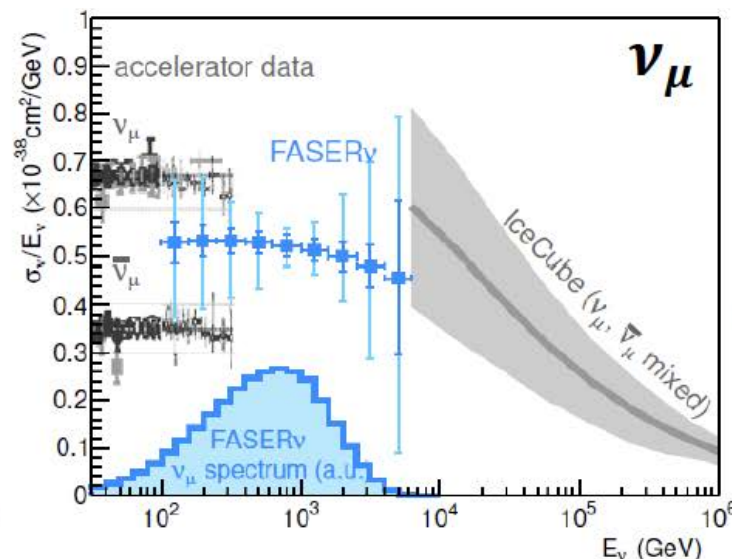
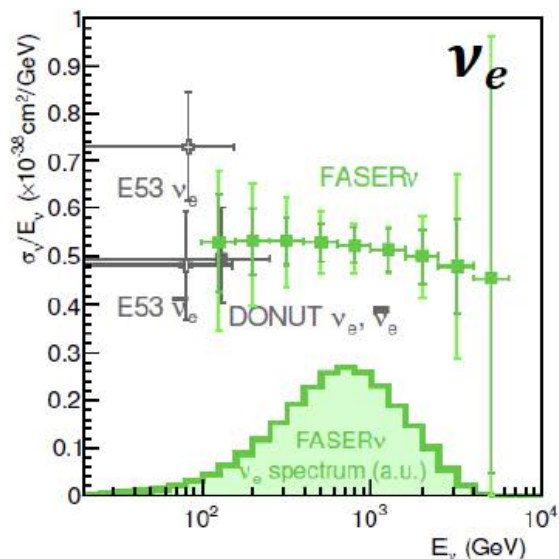
THE FASER _{ν} DETECTOR

- FASER _{ν} 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 $\sim 10\text{-}30 \text{ fb}^{-1}$, total 10 sets of emulsion for Run 3.



NEUTRINO PHYSICS

- 2022-24: FASER ν will collect data with 1.1-tonne detector in Run 3
 - Will detect the first collider neutrino.
 - Will record ~ 1000 ν_e , $\sim 10,000$ 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 FASER ν data, and so measure their cross sections independently.



FASER Collaboration 1908.02310 (2019)

FORWARD PHYSICS FACILITY

FORWARD PHYSICS FACILITY

- FASER, FASER ν , and other proposed detectors are currently highly constrained by 1980's infrastructure that was never intended to support experiments.
- At the same time, it is becoming clear that there is a rich physics program in the far-forward region.
 - New particle searches, neutrinos, QCD, MC event generators, milli-charged particles, dark matter, dark sector, cosmic rays, and cosmic neutrinos.
- Strongly motivates creating a dedicated facility to house far-forward experiments for the HL-LHC era from 2027-37.
 - Snowmass LOI: 240 authors from many different communities
 - FPF Kickoff Meeting: 9-10 November 2020. 40 talks, lots of fascinating discussion. For talk slides and Zoom recordings, see <https://indico.cern.ch/event/955956>.

FPF LOCATION: NEW SHAFT AND CAVERN



Jonathan Gall, work in progress

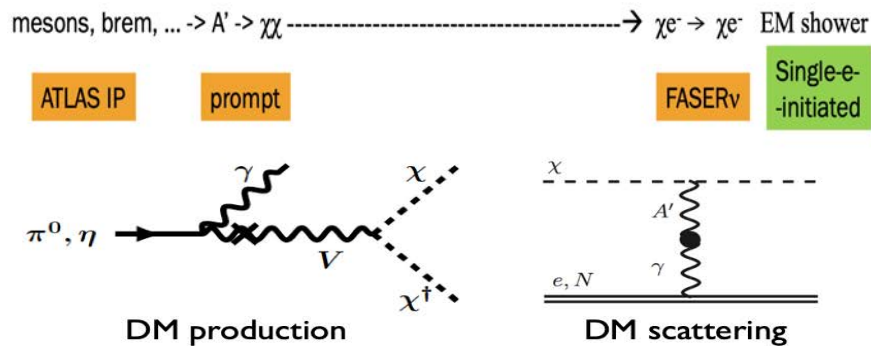
NEW PHYSICS SEARCHES AT THE FPF

- The FPF will house a number of experiments
- FASER 2, an upgraded FASER with $R = 1$ m, $L = 10$ m, can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ , f , g); and many other particles.
- Other experiments that can probe neutrinos and many other interesting ideas.

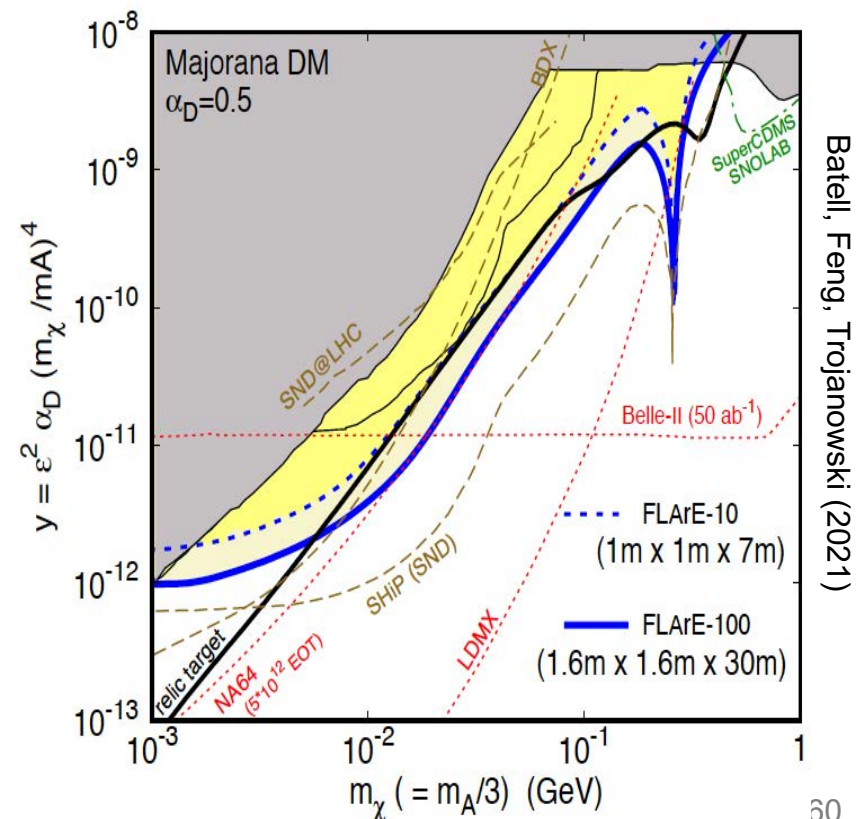
Benchmark Model	Underway	FPF
BC1: Dark Photon	FASER	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2
BC2: Dark Matter	–	FLArE
BC3: Milli-Charged Particle	–	FORMOSA
BC4: Dark Higgs Boson	–	FASER 2
BC5: Dark Higgs with hSS	–	FASER 2
BC6: HNL with e	–	FASER 2
BC7: HNL with μ	–	FASER 2
BC8: HNL with τ	FASER	FASER 2
BC9: ALP with photon	FASER	FASER 2
BC10: ALP with fermion	FASER	FASER 2
BC11: ALP with gluon	FASER	FASER 2

FLArE: DARK MATTER AT THE FPF

- If $m_{\text{LLP}} > 2m_{\text{DM}}$, the LLP will typically decay in the dark sector to dark matter, leading to invisible decays.
- Can look for the resulting DM to scatter off electrons at FLArE, a proposed LArTPC. Dominant background from neutrinos reduced for $1 < E_e < 20$ GeV.

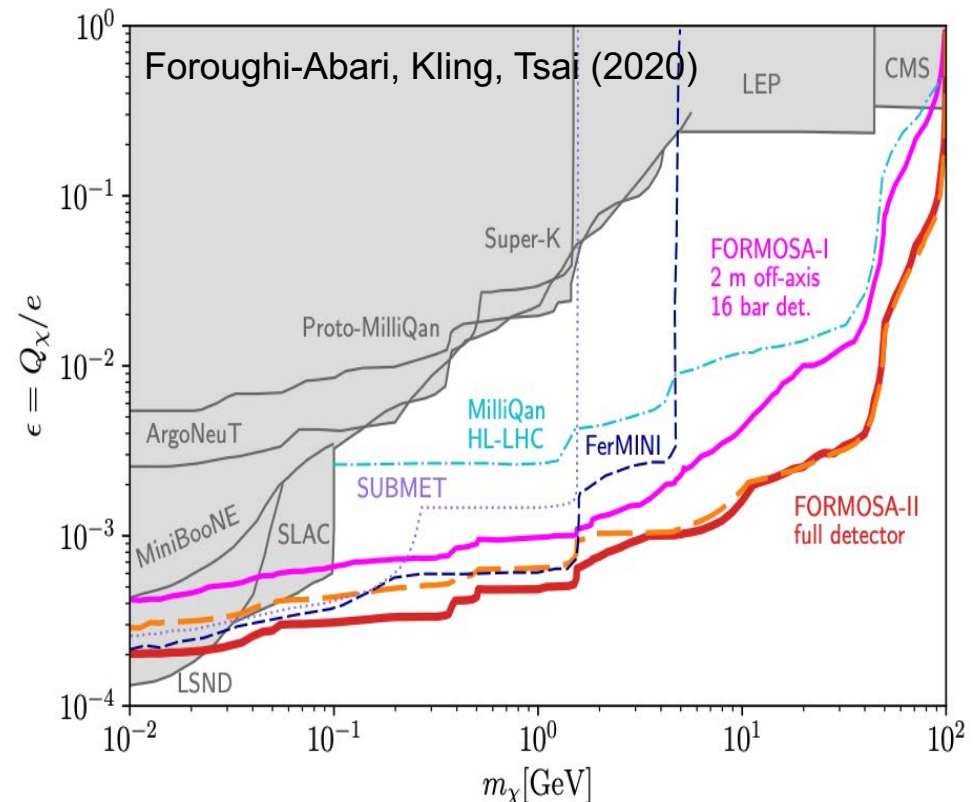


- FLArE will probe much of the favored/allowed relic target region. Complementary to missing energy experiments that probe the “too large $\Omega_\chi h^2$ ” region), but don’t detect DM scattering.



FORMOSA:MILLICHARGED PARTICLES AT THE FPF

- Currently the target of the MilliQan experiment near the CMS IP.
- MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan planned to run in this location at HL-LHC, but the sensitivity can be improved greatly by moving it to the FPF (FORMOSA).



SUMMARY

SUMMARY

- A new target for discovery: light and weakly-interacting particles probed by fast, small, and cheap experiments with world-leading sensitivities.
- FASER: 18 months from theory paper to beginning of construction, fits on a tabletop, ~\$2M. Data-taking starts 2022 with rich physics program.
 - New particles: searches for dark photons, dark Higgs bosons, HNLs, ALPs, milli-charged particles, dark matter, new forces, ...
 - Known particles: guaranteed discovery of the first collider neutrino, $\sim 1000 \nu_e$, $\sim 10,000 \nu_\mu$, $\sim 10 \nu_\tau$ at TeV energies where there are no or few existing measurements. Implications for neutrino properties, forward hadron production, cosmic ray and cosmic neutrino physics.
- Forward Physics Facility: proposed to house a suite of far-forward experiments for the HL-LHC era from 2027-37.