FASER

AND THE FUTURE OF PARTICLE PHYSICS

UCLA Physics and Astronomy Colloquium

Jonathan Feng, UC Irvine, 2 November 2023

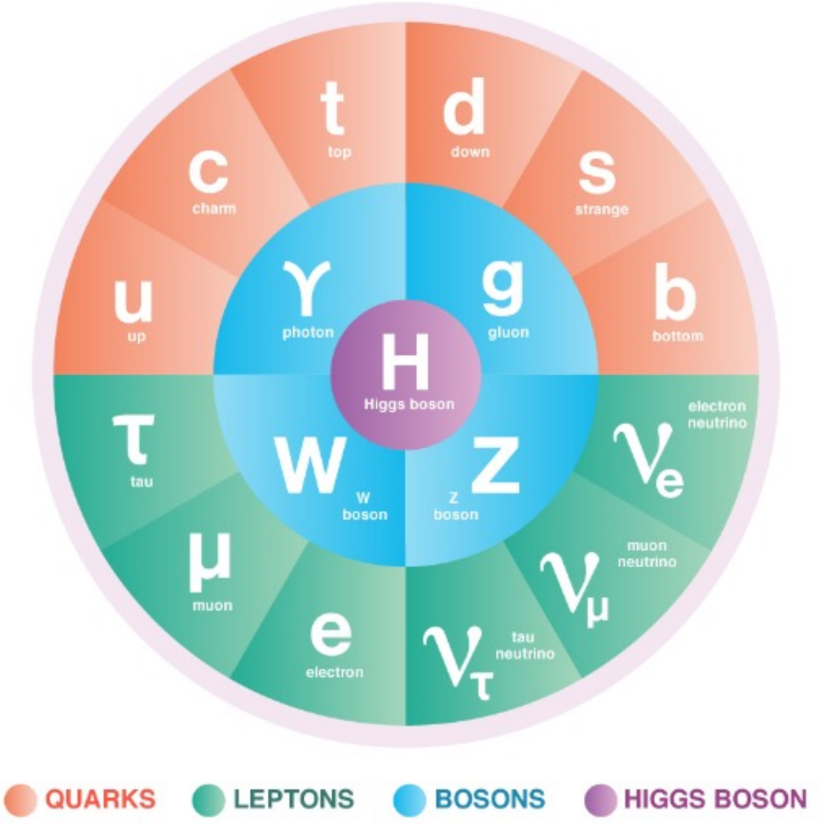
NSF SIMONS FOUNDATION HEISING-SIMONS FOUNDATION UC IRVINE CERN

THE STANDARD MODEL OF PARTICLE PHYSICS

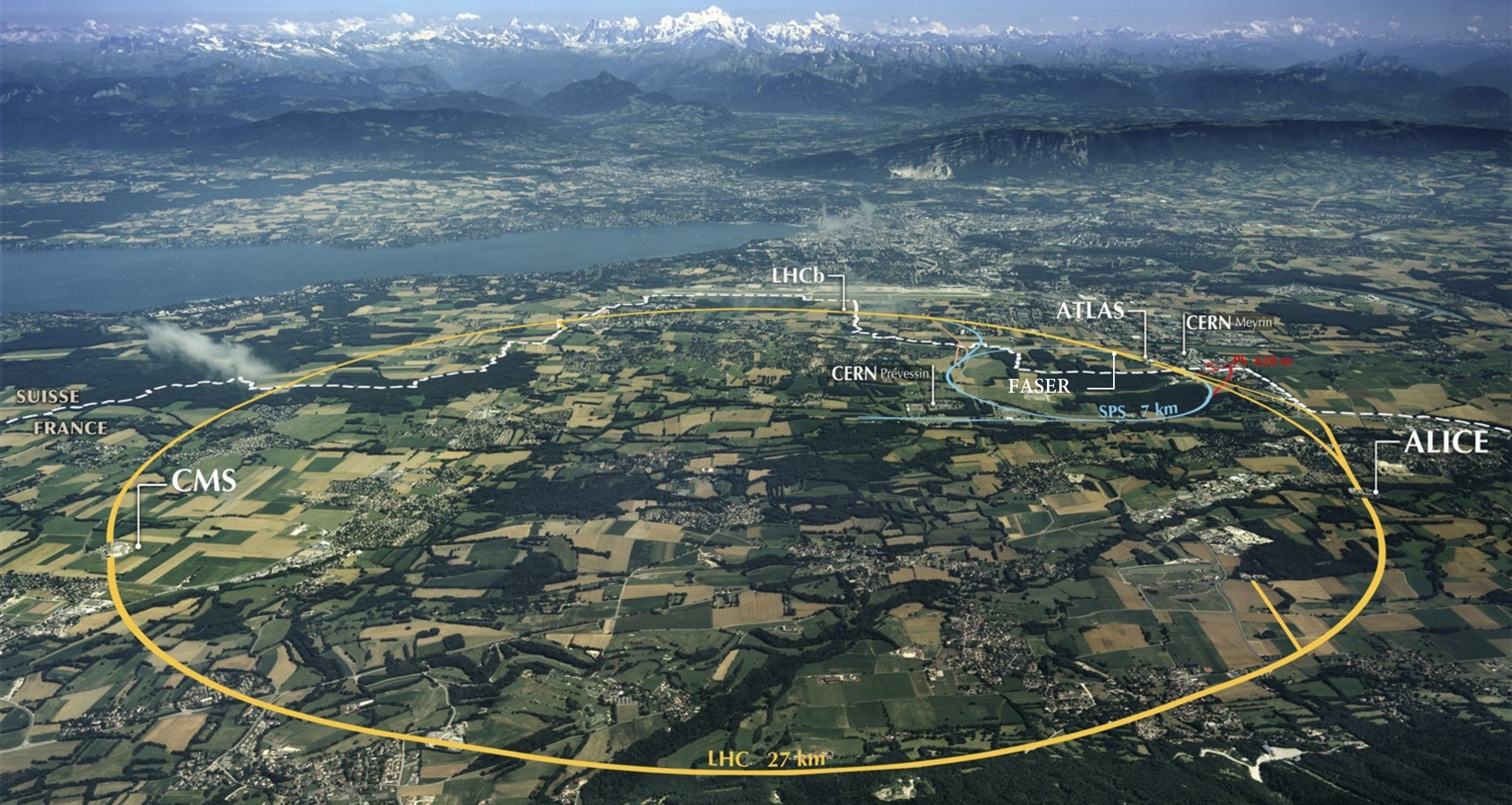
- The Standard Model is the reigning theory of fundamental particles and their interactions. The last particle predicted by the SM, the Higgs boson, was discovered at CERN in 2012.

- But the SM is not the last word, because many fundamental questions remain. For example:
  - Neutrino Masses: the SM predicts that neutrinos are massless, but they aren't.
  - Dark Matter: The particles of the SM make up only ~15% of the matter in the universe.

- These questions imply that there are likely (many) more particles left to discover.



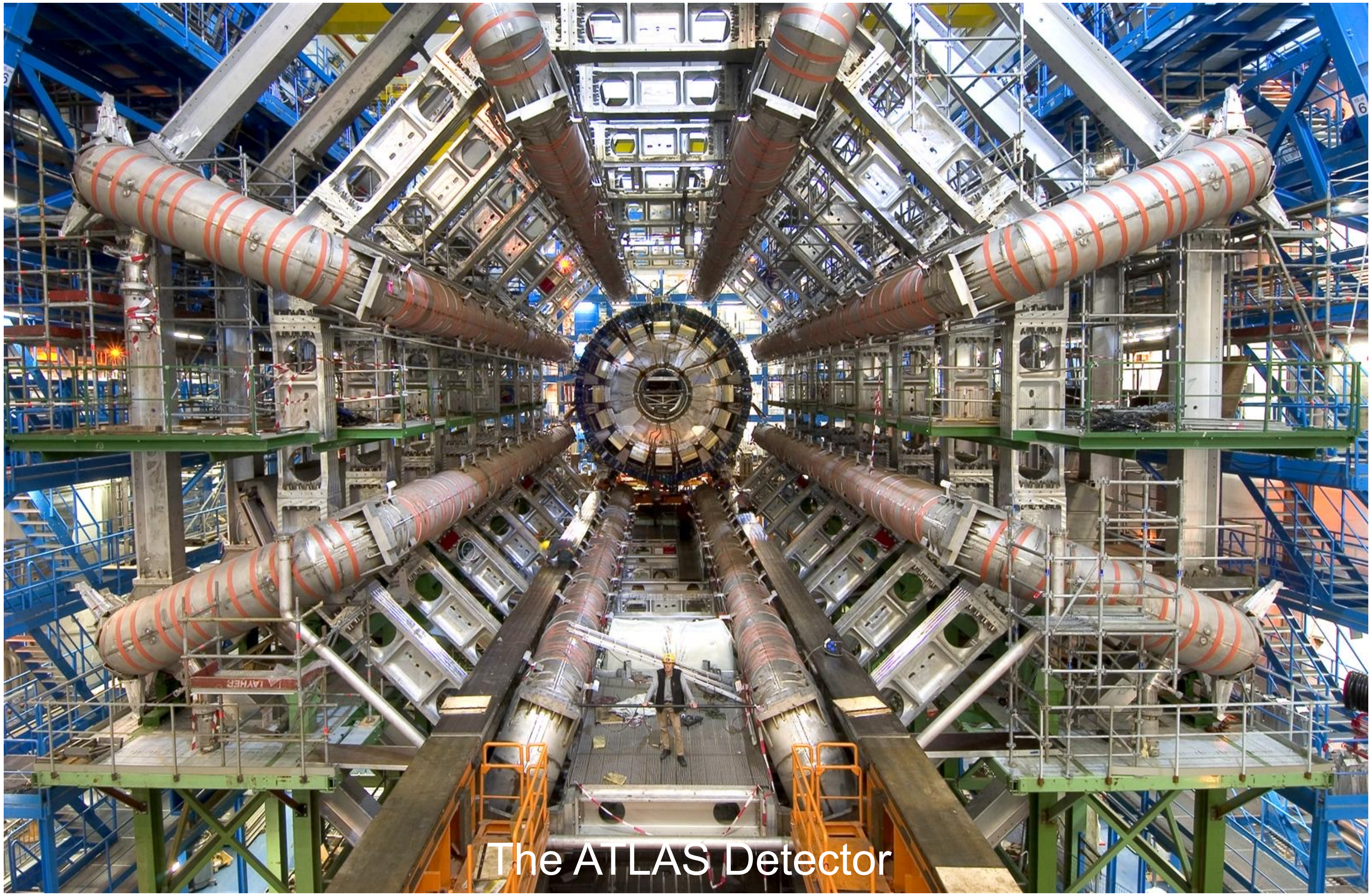
THE LARGE HADRON COLLIDER



Particle colliders have been key to progress for many decades. The state of the art is currently the LHC, accelerating protons to 0.99999999c and producing collisions at 13.6 TeV.

LHC DETECTORS

The protons collide at 4 points around the LHC, and each point is surrounded by a large detector to view the results of the collisions. These detectors cost ~$1B, and were constructed over decades by thousands of collaborators.

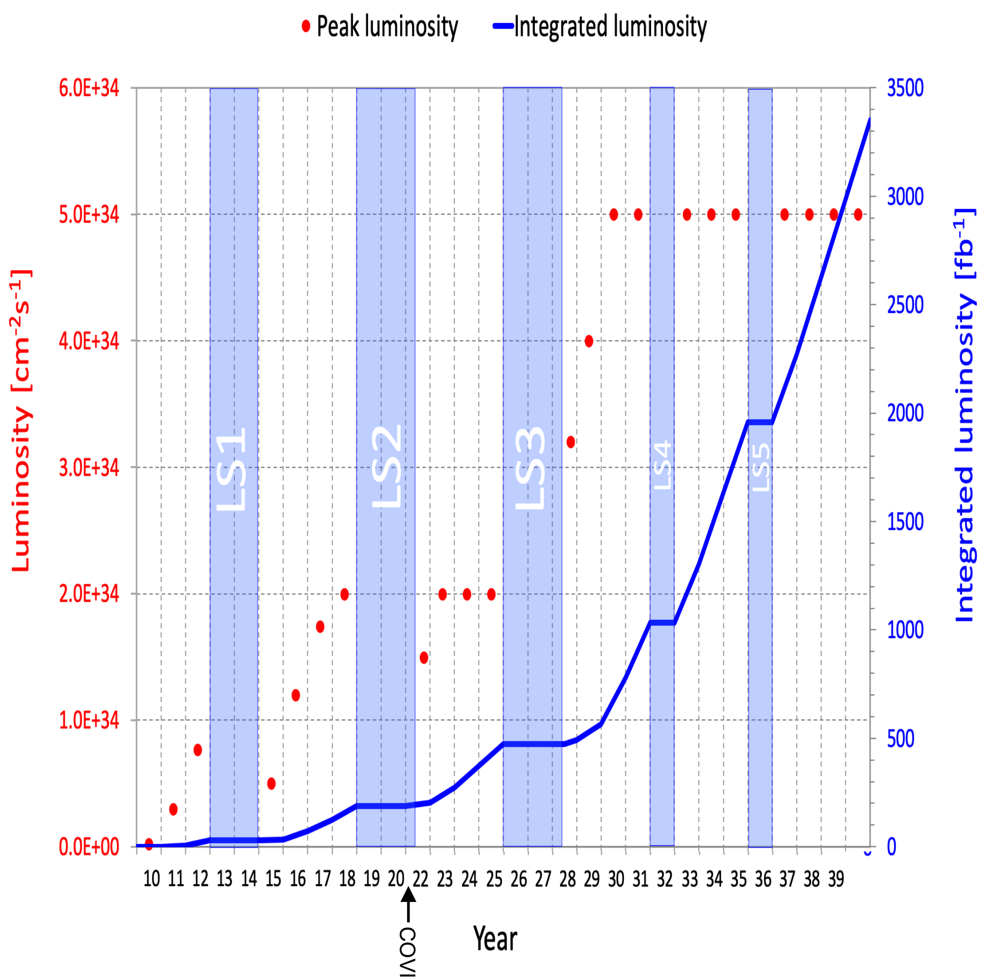


The ATLAS Detector

LIFETIME OF THE LHC

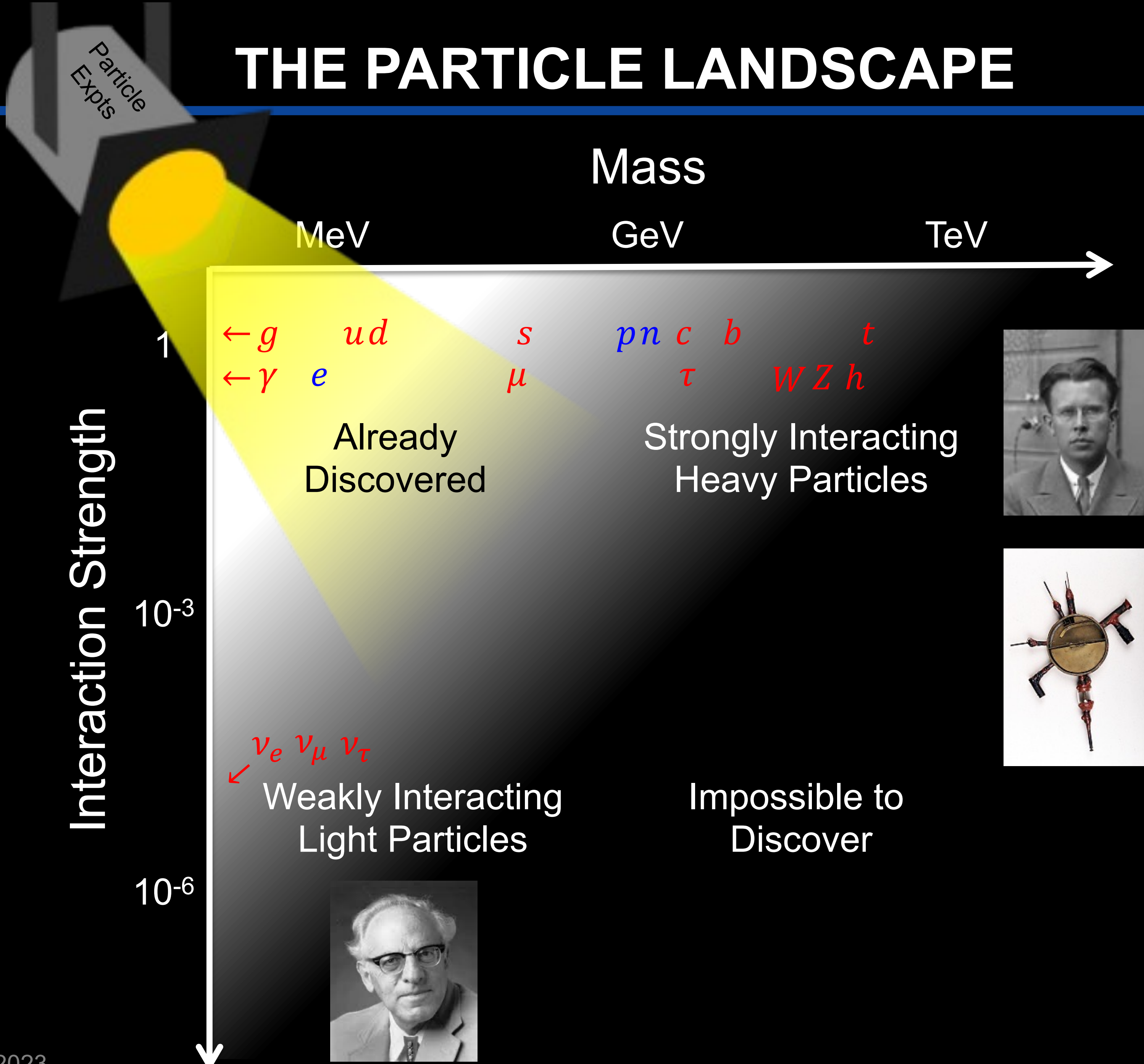
- The LHC became the future of particle colliders in 1993 when the US canceled the SSC, which was being built in Texas.

- But although the LHC started running in 2010, it is scheduled to run until ~2040s and is still in its youth
  - a postdoc in terms of years
  - a kindergartener in terms of number of collisions (integrated luminosity)

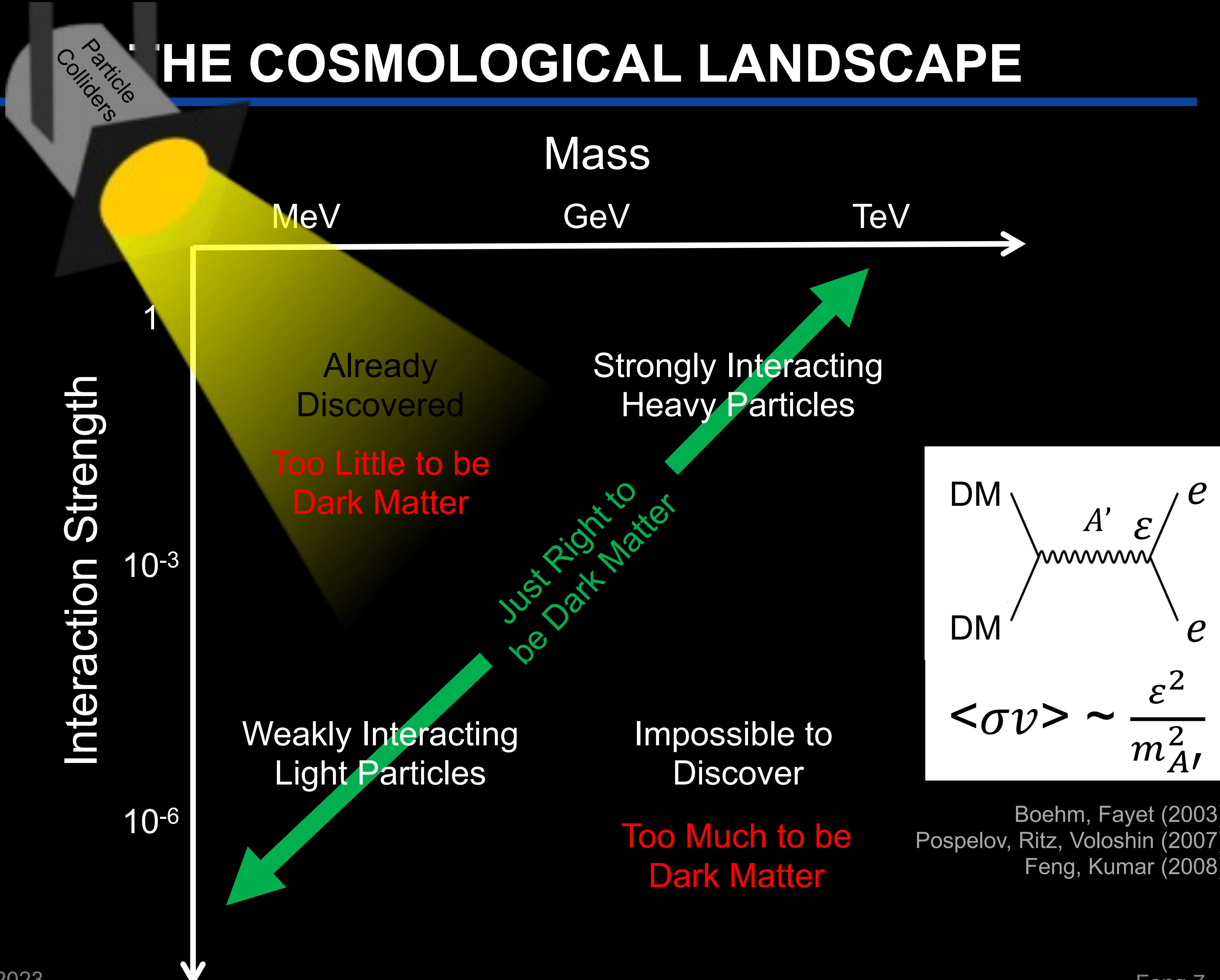


- Are we using the LHC to its full potential? If not, what can we do to enhance its discovery prospects?

THE PARTICLE LANDSCAPE



THE COSMOLOGICAL LANDSCAPE



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

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

LESSONS FROM THE PAST

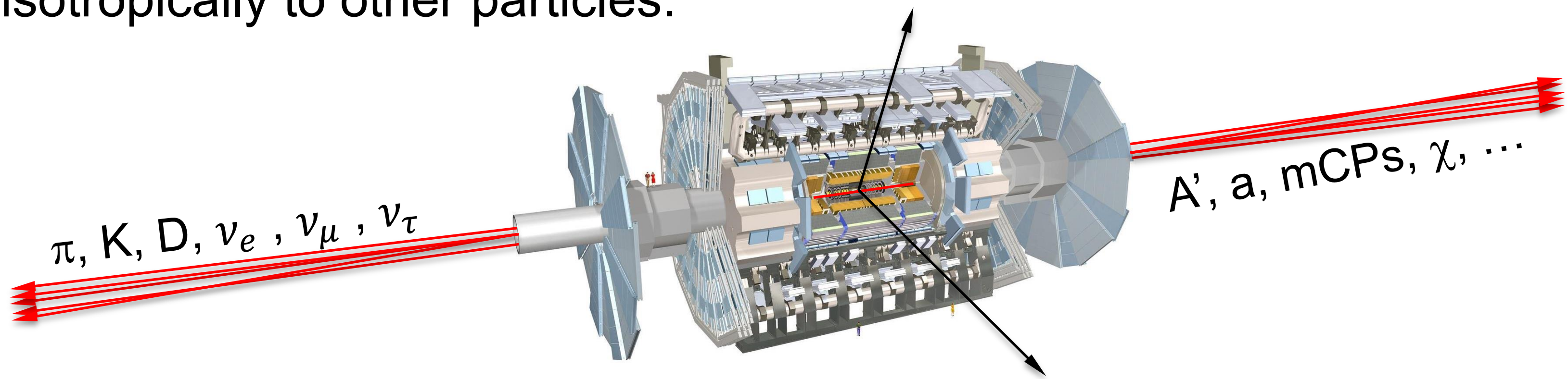
- We are not now in a golden age of particle physics.
- But particle physics is still fascinating, and the possibilities for deep connections to cosmology have never been stronger.
- The discovery of new particles is the gold standard for progress in particle physics. (Precision measurements are also very important.)
- Buoyed by past successes, we have been looking for strongly-interacting heavy particles, and this should continue.
- But typically, unless these are in a narrow window of masses (e.g., ~2-4 TeV for gluinos), we will not find them in the next two decades. And the most robust problems, neutrino masses and dark matter, naturally point toward very weakly-interacting particles.
- To bring us to a new golden age, we need to try new things now and diversify our searches for new particles without breaking the bank.

FORWARD PHYSICS

- In 2017, we realized that the large LHC detectors, while beautifully optimized to discover new heavy particles, are almost optimally configured to miss new light particles.

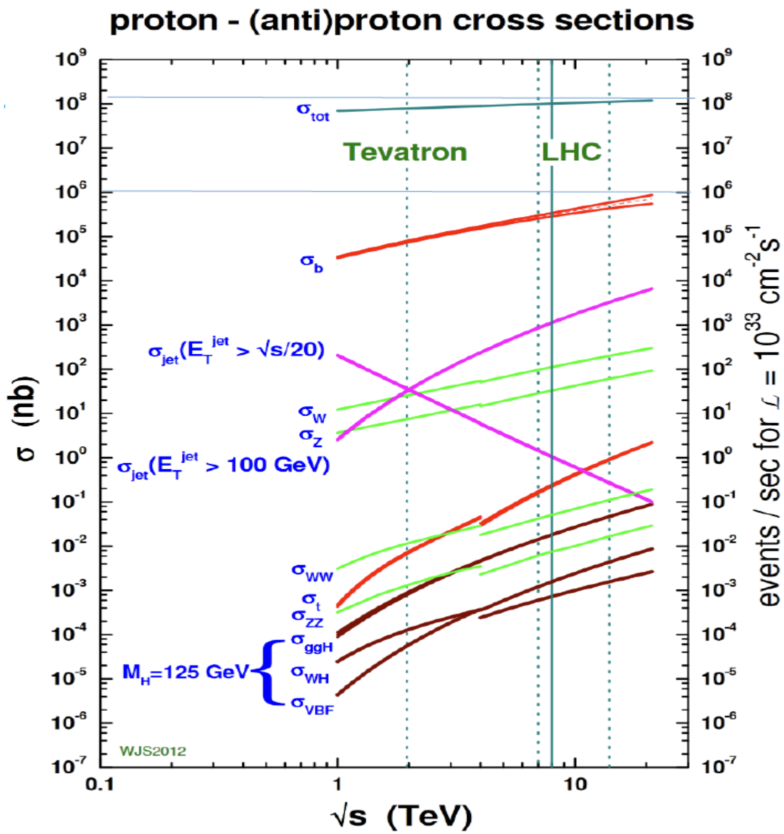
Feng, Galon, Kling, Trojanowski (2017)

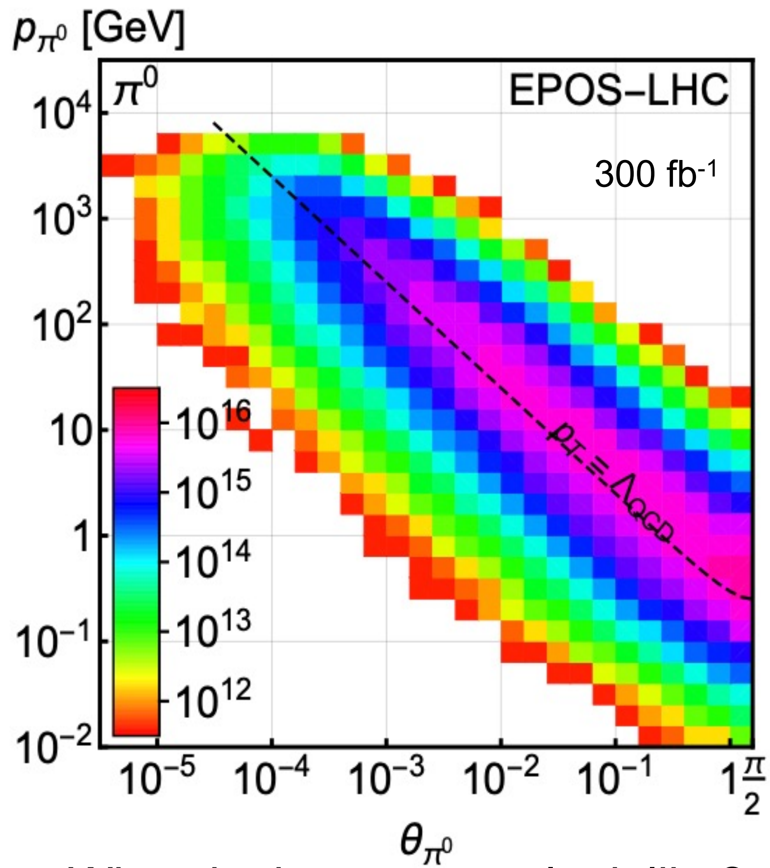
- Heavy particles are produced at low velocity and then decay roughly isotropically to other particles.



- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of existing detectors.
  - This is true for all known light particles: pions, kaons, D mesons, neutrinos.
  - It is also true for many hypothetical new particles, especially those motivated by neutrino mass and dark matter.
- These blind spots are the Achilles heels of the large LHC detectors.

LIGHT PARTICLES AT THE LHC

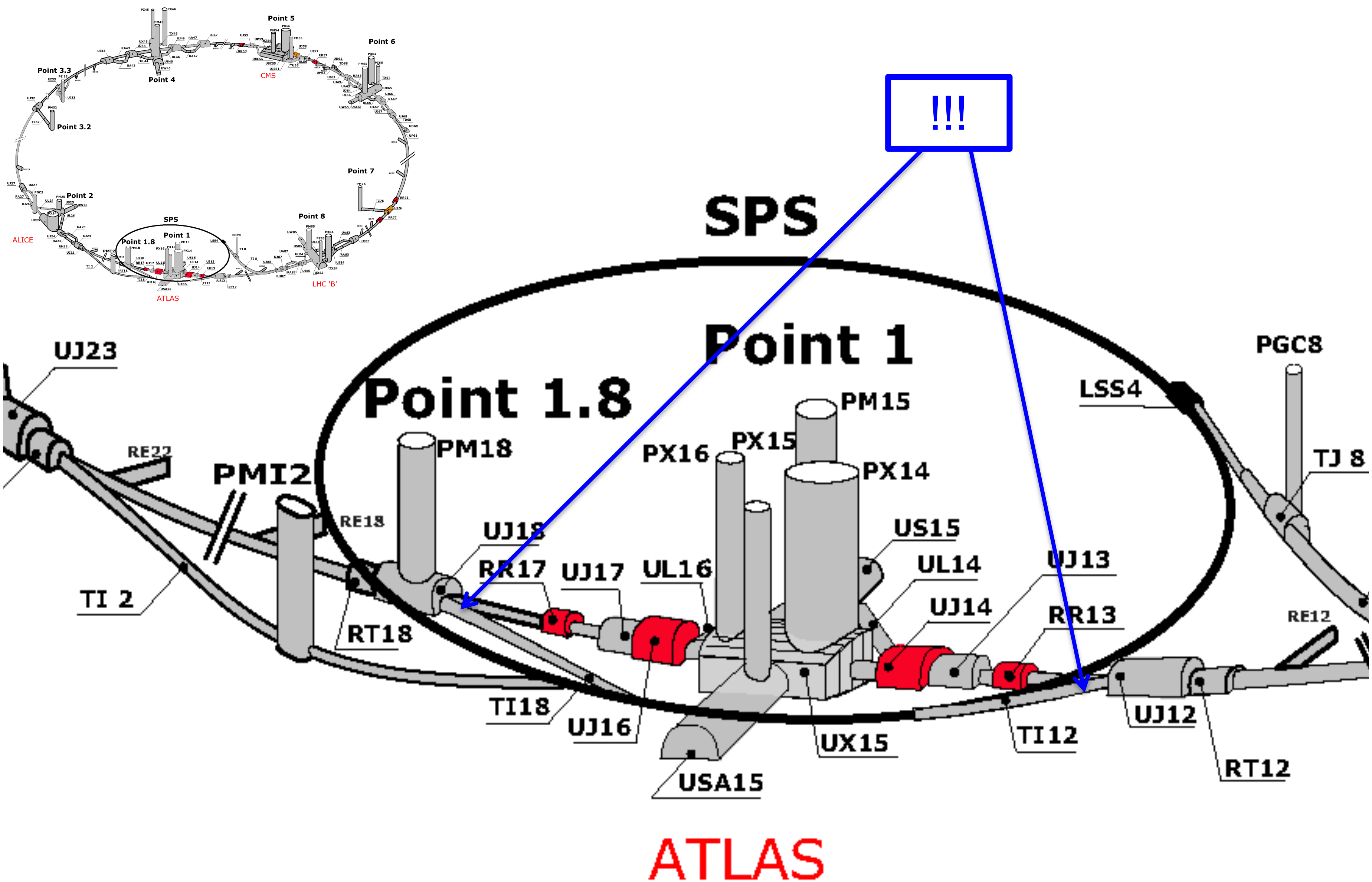




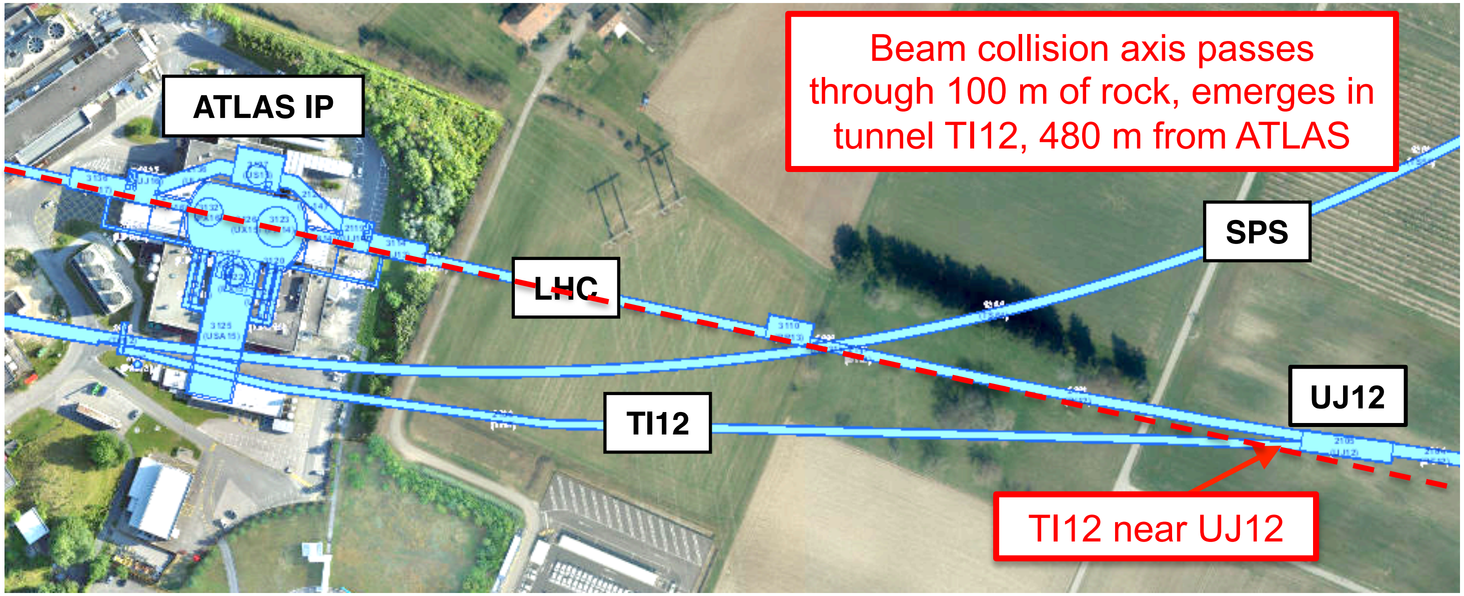
Feng, Galon, Kling, Trojanowski (2017)

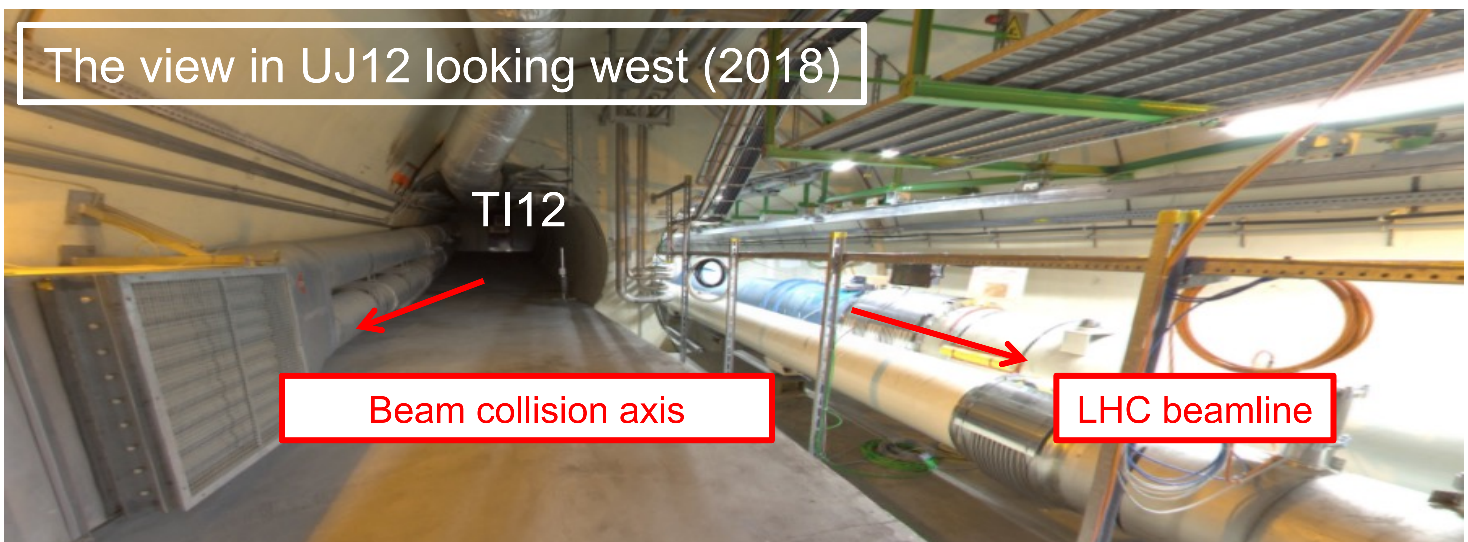
- Most searches have focused on processes with σ ~ fb, pb.
- But the total cross section is σ_{tot} ~ 100 mb and is typically wasted in new physics searches.
- What do these events look like? Consider pions.
- Enormous event rates. Typical p_T ~ 250 MeV, but many with p ~ TeV within 1 mrad (η > 7.6) of the beamline.

MAP OF THE LHC



THE FORWARD REGION



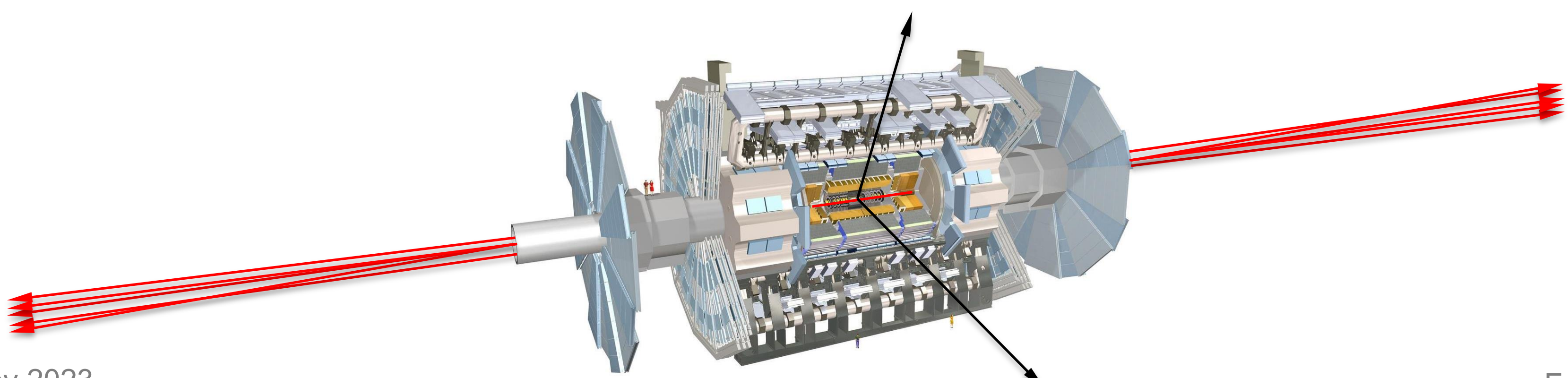


HOW BIG DOES THE DETECTOR HAVE TO BE?

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

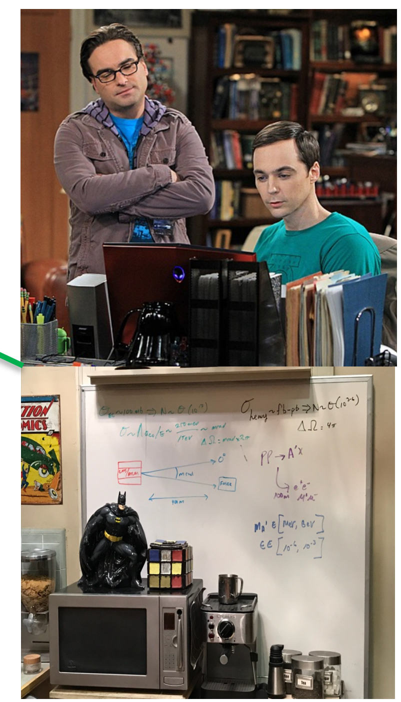
- The opening angle is 0.2 mrad (the moon is 7 mrad). Even 480 m away, most of the signal passes through an 8.5” x 11” (A4) sheet of paper.

- Neutrinos and many new particles are therefore far more collimated than shown below, motivating a relatively small, fast, and inexpensive experiment at the LHC: the ForwArd Search ExpeRiment (FASER).



FASER AND FASERν TIMELINE

- First paper: Feng, Galon, Kling, Trojanowski
- LOI submitted to CERN LHCC
- Spare detector parts from ATLAS and LHCb Collaborations
- Technical Proposal submitted to CERN LHCC
- Funding from Heising-Simons and Simons Foundations
- FASER approved as 8th LHC detector by CERN
- FASERν approved as 9th LHC detector by CERN
- FASER fully constructed and installed
- FASERν fully constructed and installed
- FASER and FASERν begin collecting data in Run 3
- FASER and FASERν announce first physics results



THE FASER COLLABORATION

89 collaborators, 25 institutions, 10 countries

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

UNIVERSITÄT BERN

Technion
Israel Institute of Technology

NAGOYA UNIVERSITY

UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
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מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

KEK

UNIVERSITY OF OREGON

DESY.

INFN

International laboratory covered by a cooperation agreement with CERN

清華大學
Tsinghua University

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

UNIVERSITY OF LIVERPOOL

CHIBA UNIVERSITY

UNIVERSITY OF SUSSEX

Nikhef

UNIVERSITÄT BONN

ETH zürich

MANCHESTER 1824
The University of Manchester

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PREPARATION OF THE FASER LOCATION

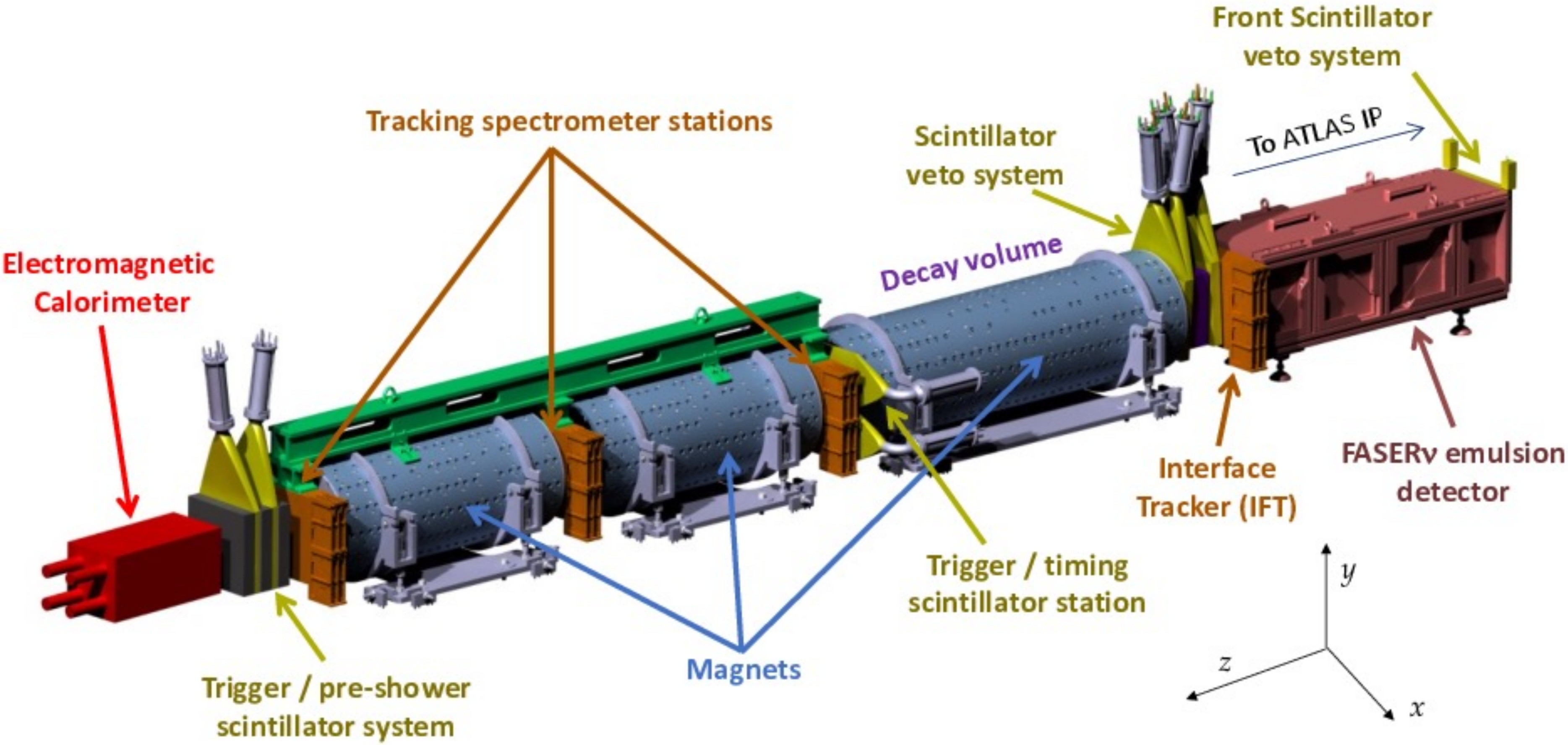
- The beam collision axis was located to mm accuracy by the CERN survey department. To place FASER on this axis, a trench was required to lower the floor by 46 cm.
- The trench was completed by an Italian firm just hours before COVID shut down CERN in March 2020.


2019

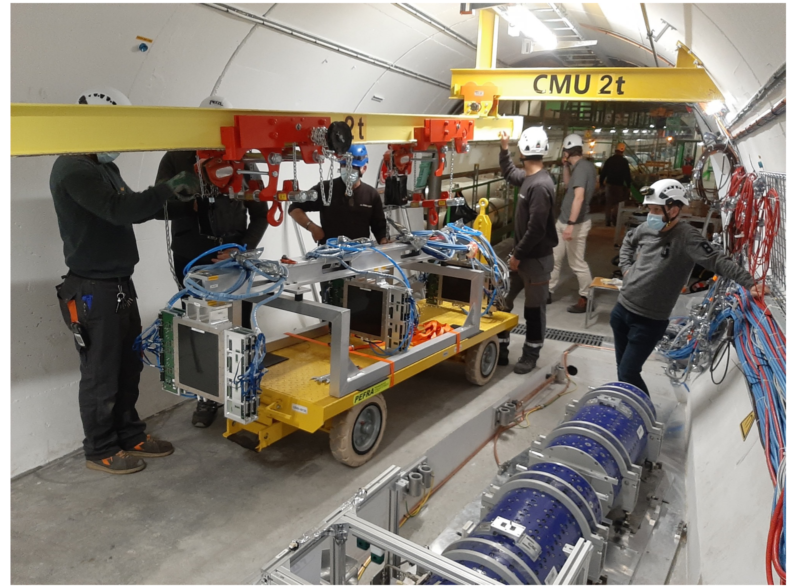

Spring 2020

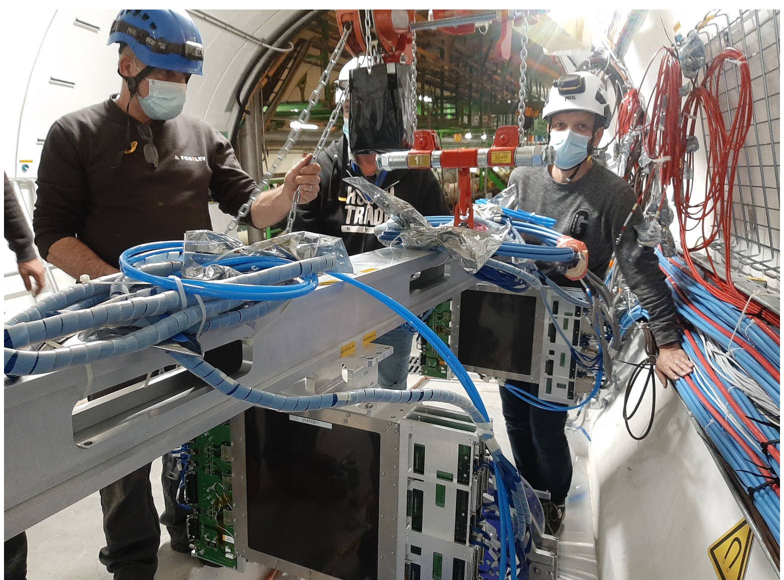

Summer 2020

FASER DETECTOR

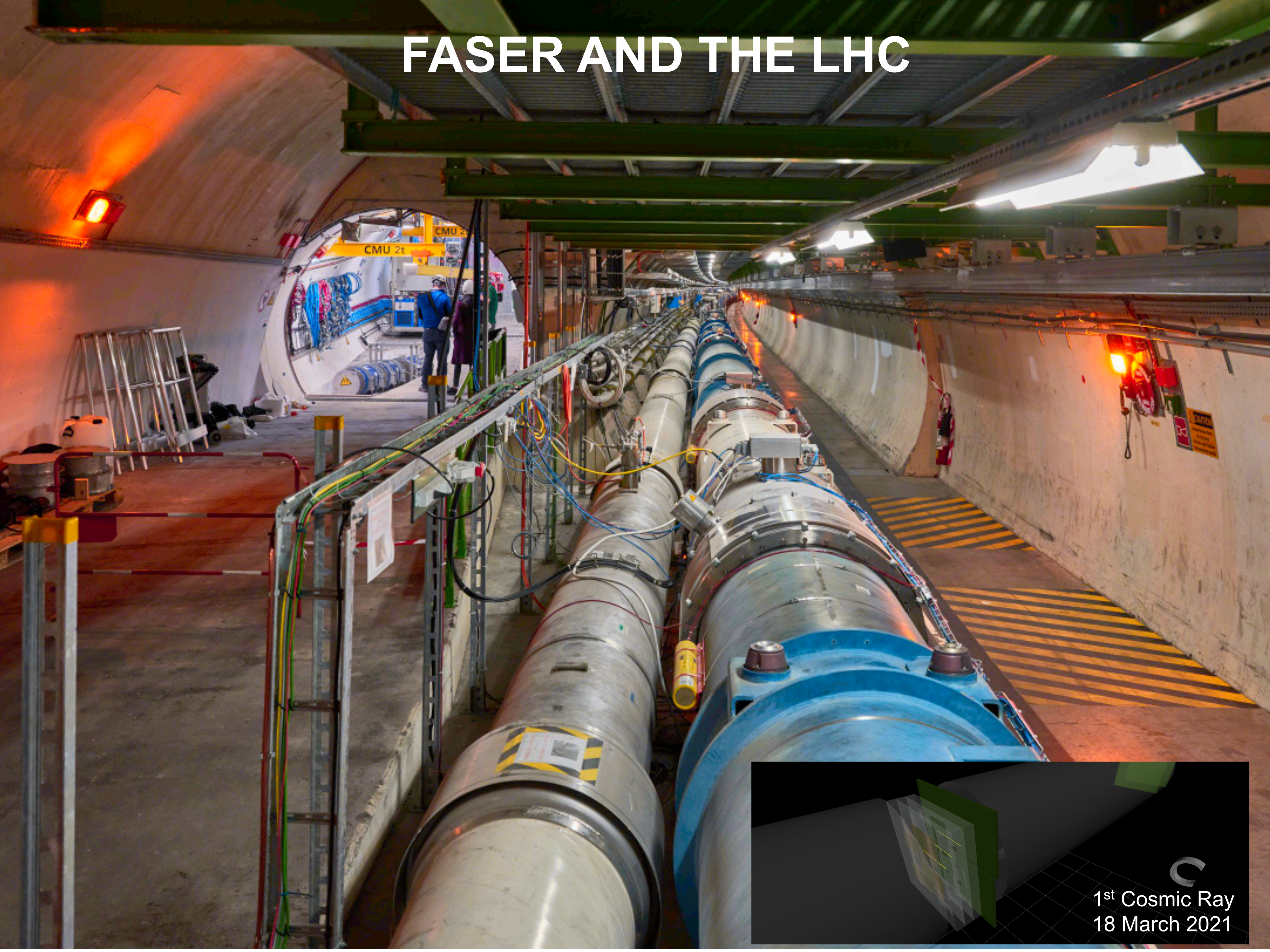


FASER INSTALLATION



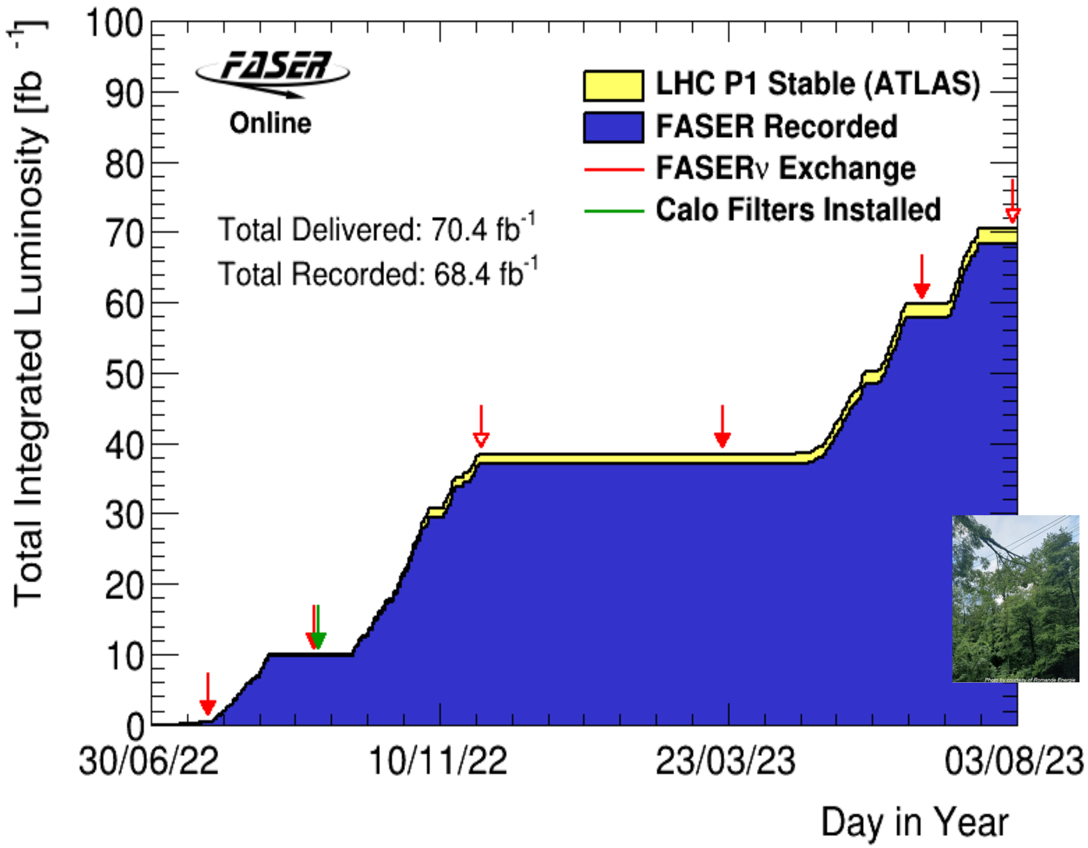


FASER AND THE LHC



FASER DATA TAKING IN 2022 AND 2023

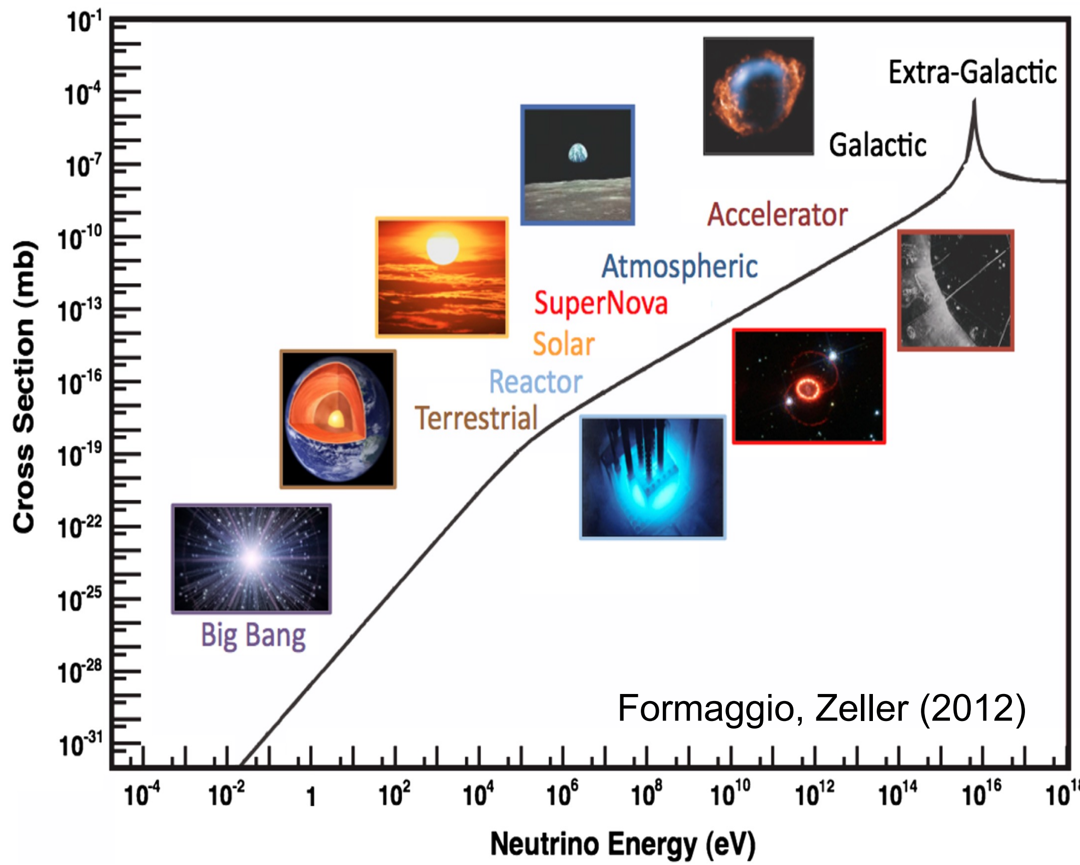
- After Long Shutdown 2 from 2018-2021, the LHC started running again from July to November 2022 and April to July 2023.
- FASER began recording data immediately after beam turn on and operated beautifully after that.
  - Recorded 97% of delivered luminosity
  - Largely automated: no control room, 2 shifters controlling and monitoring the experiment from their laptops.



- FASERν emulsion exchanged periodically to prevent overexposure
  - 3 boxes in 2022 (0.5, 10, 30 fb^{-1})
  - 2 boxes in 2023 (20, 10 fb^{-1})

COLLIDER NEUTRINOS

- Neutrinos are the least understood of all known particles.
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.

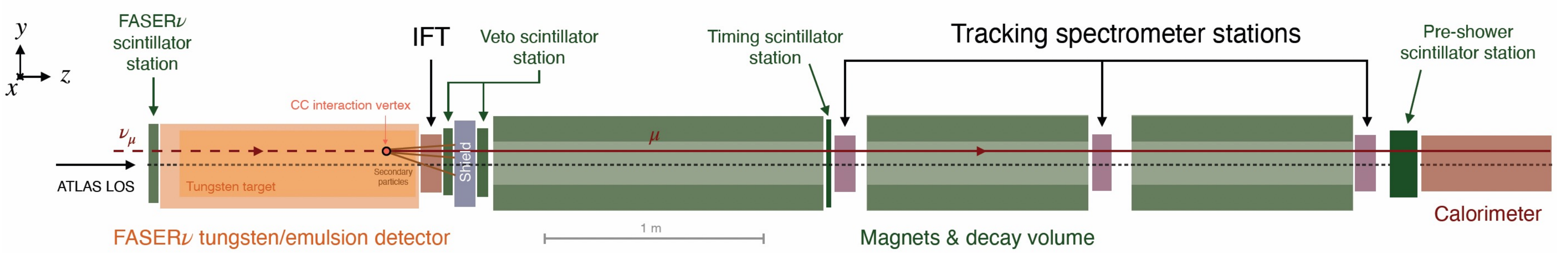


- But before FASER, neutrinos produced at particle colliders had never been direct observed before, because they interact very weakly, and the highest energy ones, which are the most strongly interacting, pass through the blind spots of existing detectors.

COLLIDER NEUTRINO SEARCH

- Neutrinos produced at the ATLAS interaction point travel 480 m and pass through FASERν. Occasionally, they can interact through $\nu_\mu N \to \mu X$, producing a high-energy muon, which can be observed.

De Rujula, Ruckl (1984)



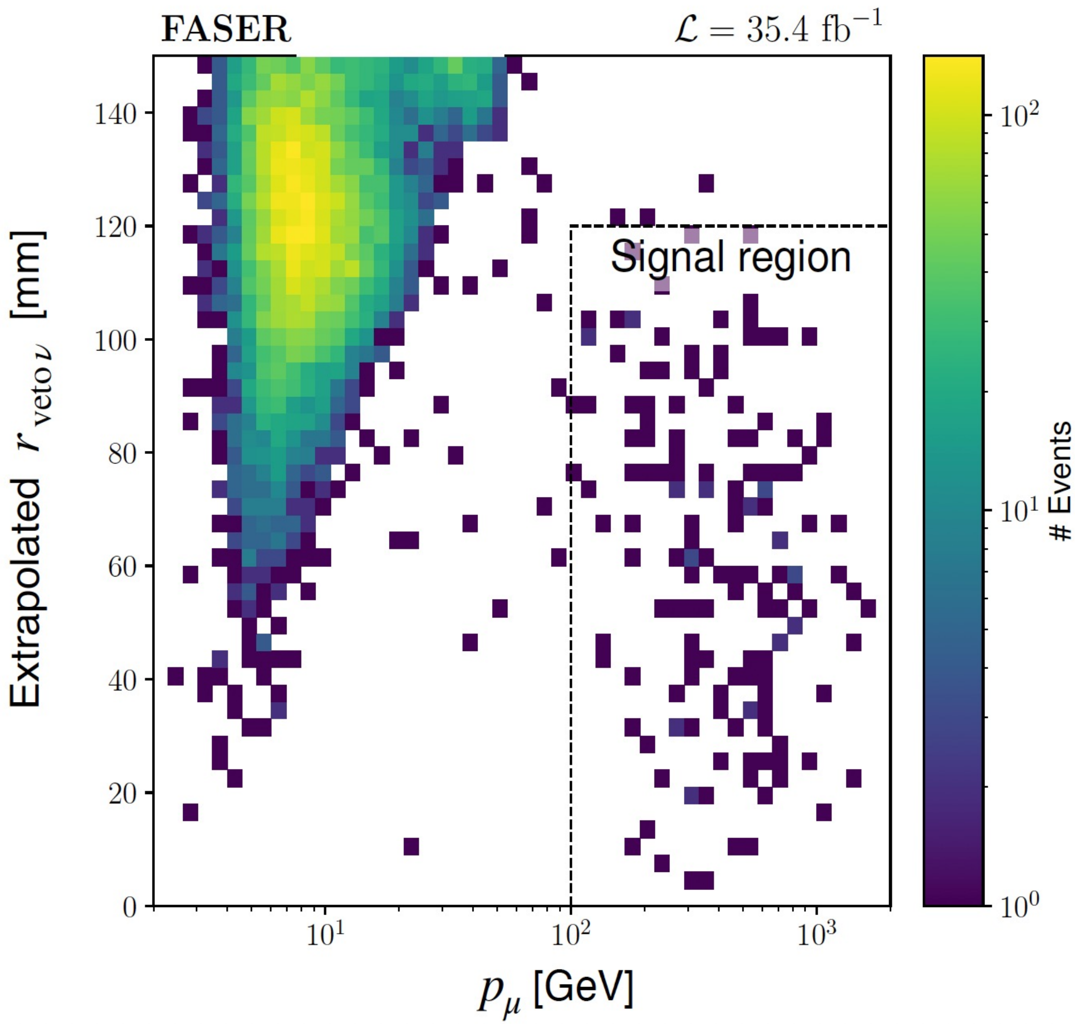
FASER Collaboration (2303.14185, PRL)

- The signal is no charged particle passing through the upstream "veto" scintillator detectors, followed by a single charged particle in downstream detector components.

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

COLLIDER NEUTRINO RESULTS

- After unblinding, we found 153 signal events
  - Background $\lesssim$ 1 event
- 1st direct observation of collider neutrinos
  - Signal significance of ~16σ
  - Muon charge → ν and $\bar{\nu}$
  - These include the highest energy ν and $\bar{\nu}$ interactions ever observed from a human source
- Following the FASER observation, SND@LHC, a complementary experiment in the "other" forward direction, discovered an additional 8 neutrinos

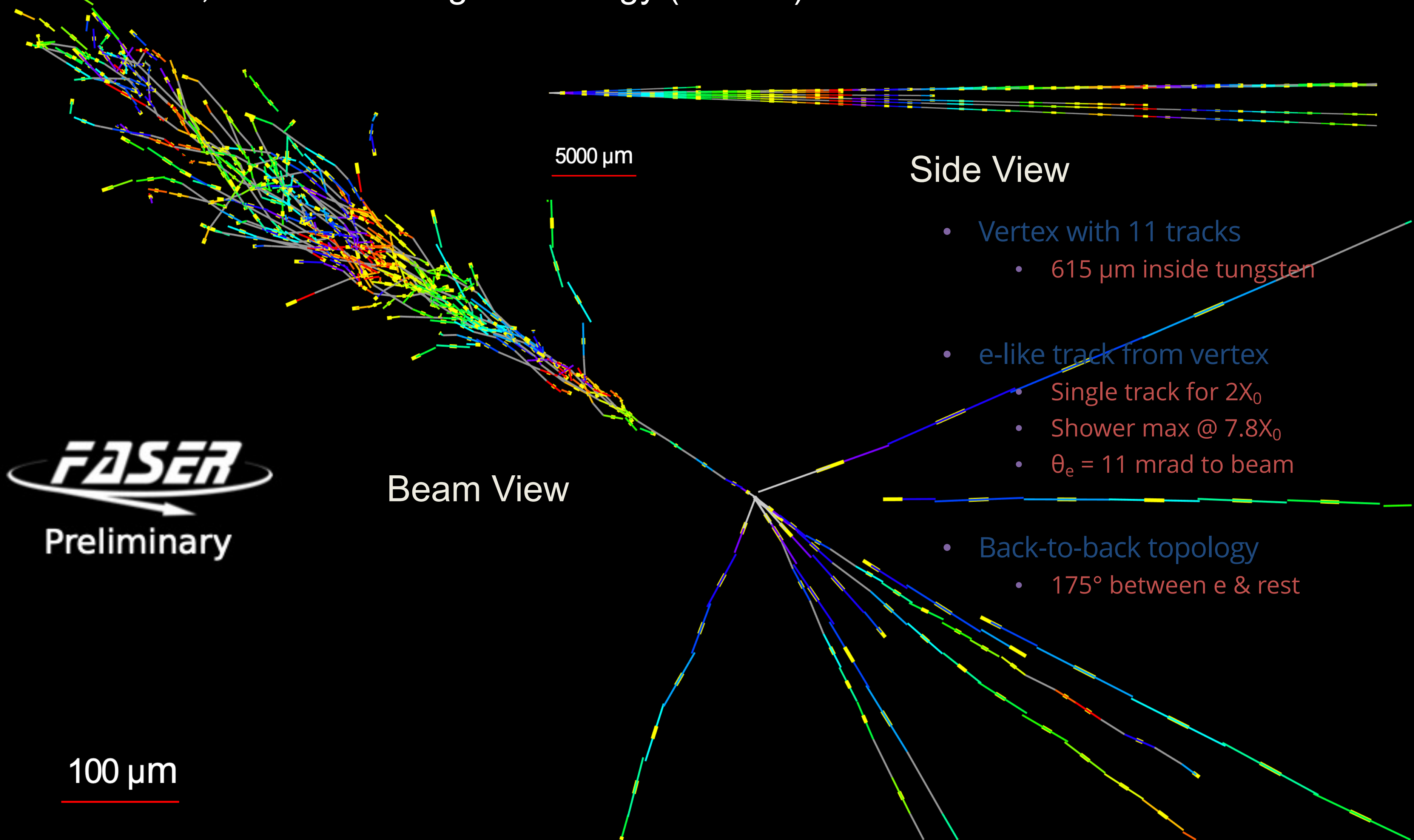


FASER Collaboration (2303.14185, Physical Review Letters)

DISCOVERY OF COLLIDER NEUTRINOS

NEUTRINOS FROM EMULSION IN FASERν

Much more to come: the discovery analysis did not even use the emulsion data! With the emulsion, we have now observed many additional neutrinos, including this event, which is the highest energy (~2 TeV) electron neutrino ever observed.

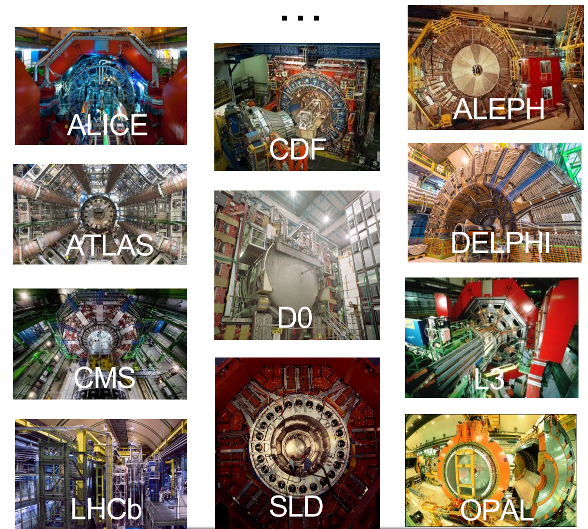


LOCATION, LOCATION, LOCATION

FASER

"Tabletop," 18 months, ~$1M

153 neutrinos



All previous collider detectors

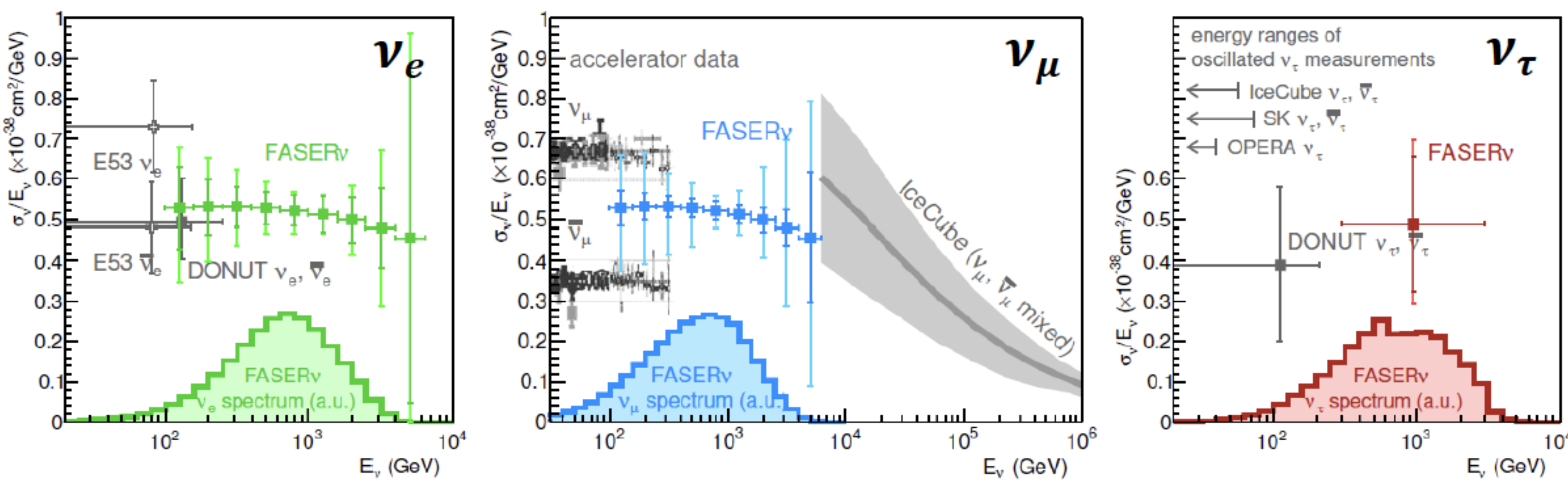
Building-size, decades, ~$1B

0 neutrinos

□□σ discovery, opening a new field: collider neutrino physics

NEUTRINO PHYSICS

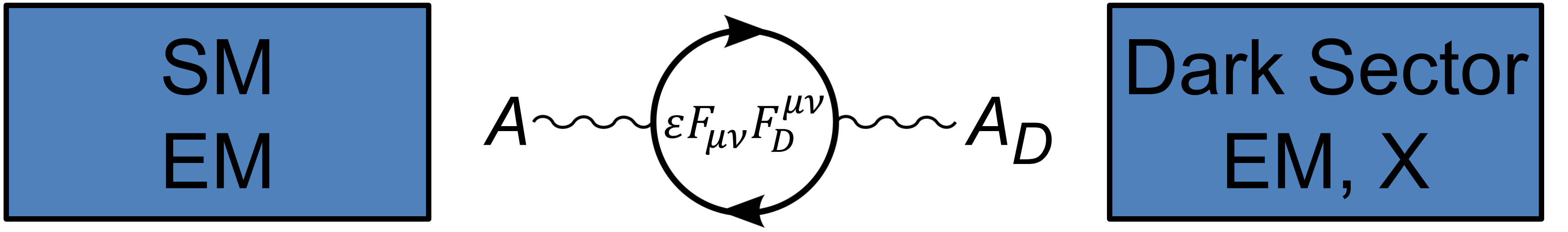
- In Run 3 (2022-25), FASER's goals are to
  - Record ~3000 ν_e , ~10,000 ν_μ, and ~70 ν_τ interactions at TeV energies, the first direct exploration of this energy range for all 3 flavors.
  - Distinguish muon neutrinos from anti-neutrinos by combining FASER and FASERν data, and so measure their cross sections independently.
  - Add significantly to the number of ν_τ detected and detect the first anti-ν_τ



FASER Collaboration 1908.02310 (2019)

NEW PARTICLE SEARCHES

- FASER can also search for many types of new light and weakly-interacting particles.
- For example: 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



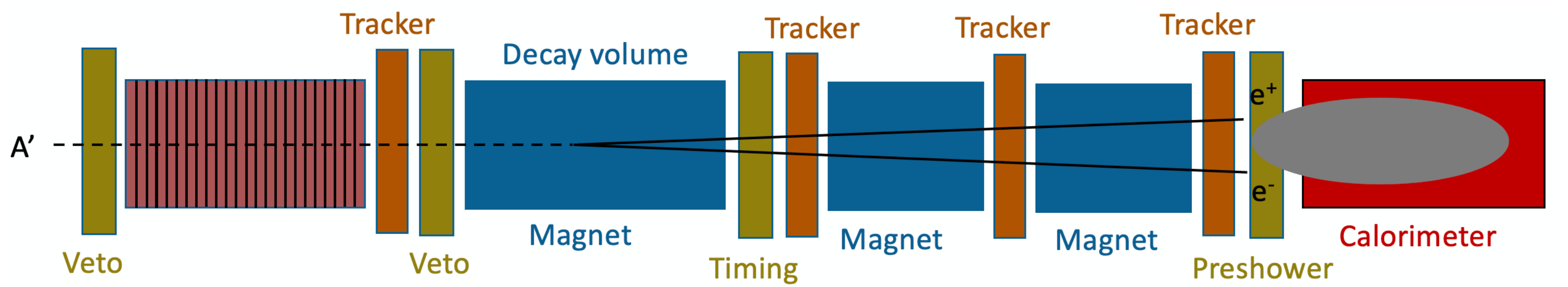
- The result? Dark photons A', like photons, but with mass $m_{A'}$, couplings suppressed by ε.

Holdom (1986)

- Finding a dark photon would imply a new fundamental force and possibly a "portal" to the dark sector.

DARK PHOTON SIGNAL

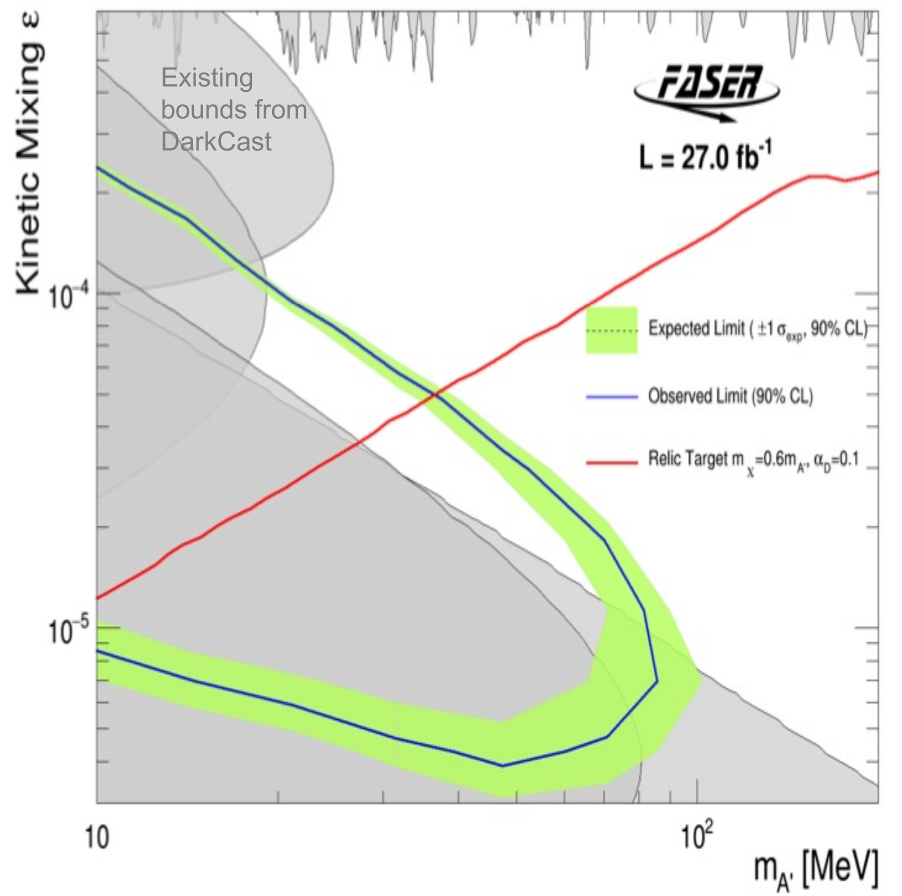
- Produced through meson decay $\pi/\eta \to A'\gamma$ or "dark bremsstrahlung" $pp \to ppA'$.
- Travels straight and unimpeded through 480 m of rock/concrete.
- Then decays, e.g., through $A' \to\ e^+e^-$.



- The signal is no charged particle passing through the upstream veto scintillator detectors, followed by two very energetic (100s of GeV) charged particles in downstream detector components.

DARK PHOTON RESULTS

- After unblinding, no events seen, FASER sets limits on previously unexplored parameter space.
- First new probe of the parameter space favored by dark matter from low coupling since the 1990's; with 2022 data alone, ~100 times the sensitivity of previous experiments.
- Background-free analysis bodes well for the future. Factor of ~10 more luminosity and other improvements in Run 3 from 2023-25 data.



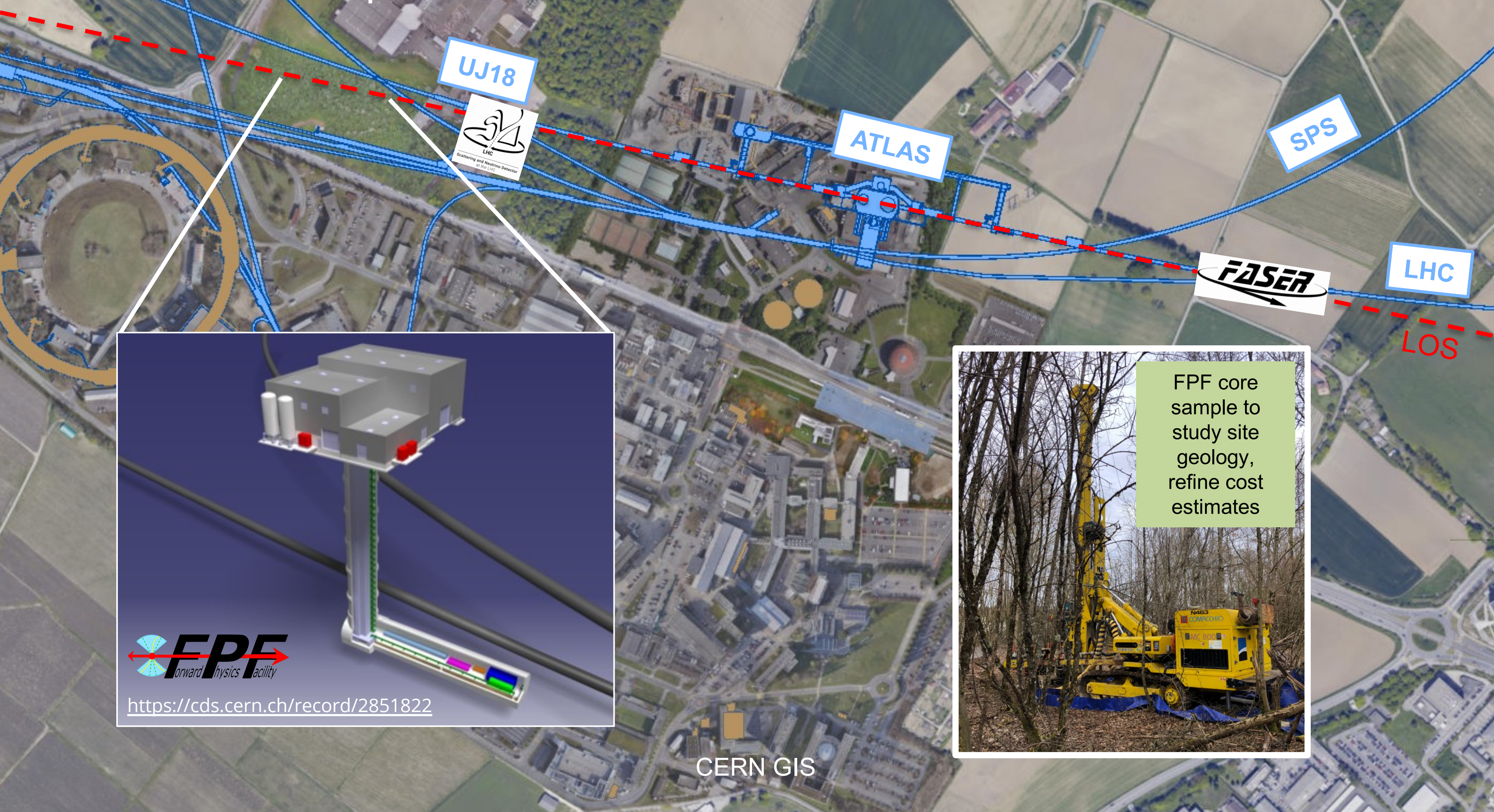
- Searches also underway for many other new particles: other light force carriers ($U(1)_{B-L}$, $U(1)_B$, protophobic), sterile neutrinos/heavy neutral leptons, dark Higgs bosons, axion-like particles with photon/W/gluon couplings, up-philic scalars, quirks, etc.

FPF

Forward Physics Facility

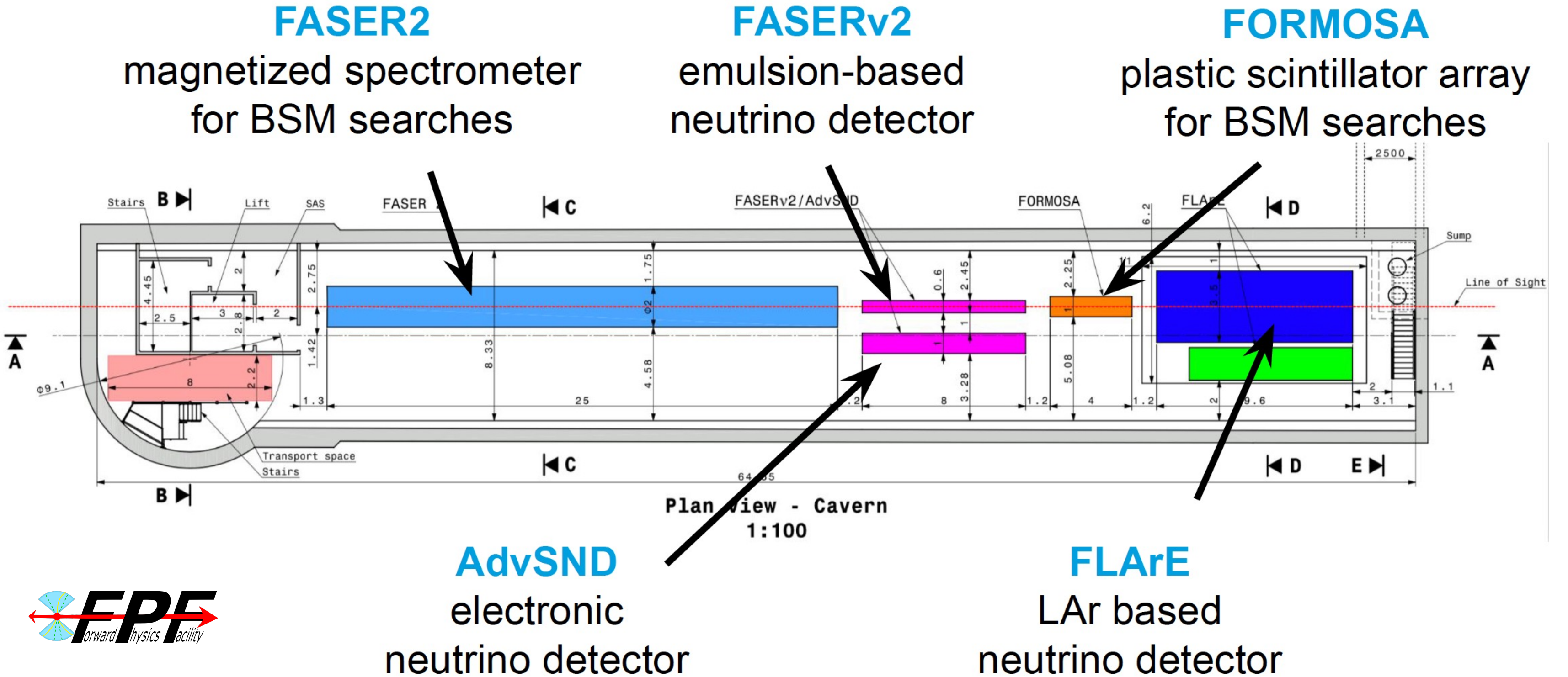
FORWARD PHYSICS FACILITY

- Following the results of FASER and SND@LHC, CERN is considering the possibility of creating a dedicated Forward Physics Facility to house far-forward experiments for the rest of the LHC era from 2028-2040s.



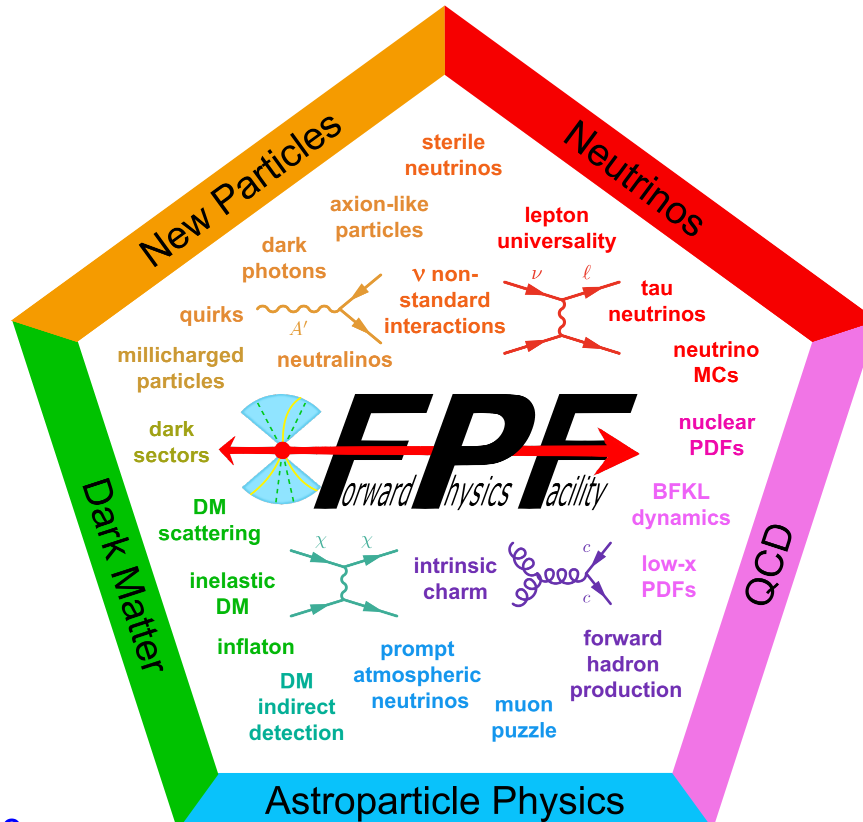
FORWARD PHYSICS FACILITY EXPERIMENTS

- At present there are 5 experiments being designed to explore the breadth of physics topics.
  - Millions of TeV-energy neutrinos will provide new probes of neutrino properties, quantum chromodynamics, and astroparticle physics.
  - Roughly 10,000 times greater sensitivity for new particles (new force carriers, axion-like particles, light dark matter, millicharged particles, …)



FORWARD PHYSICS FACILITY

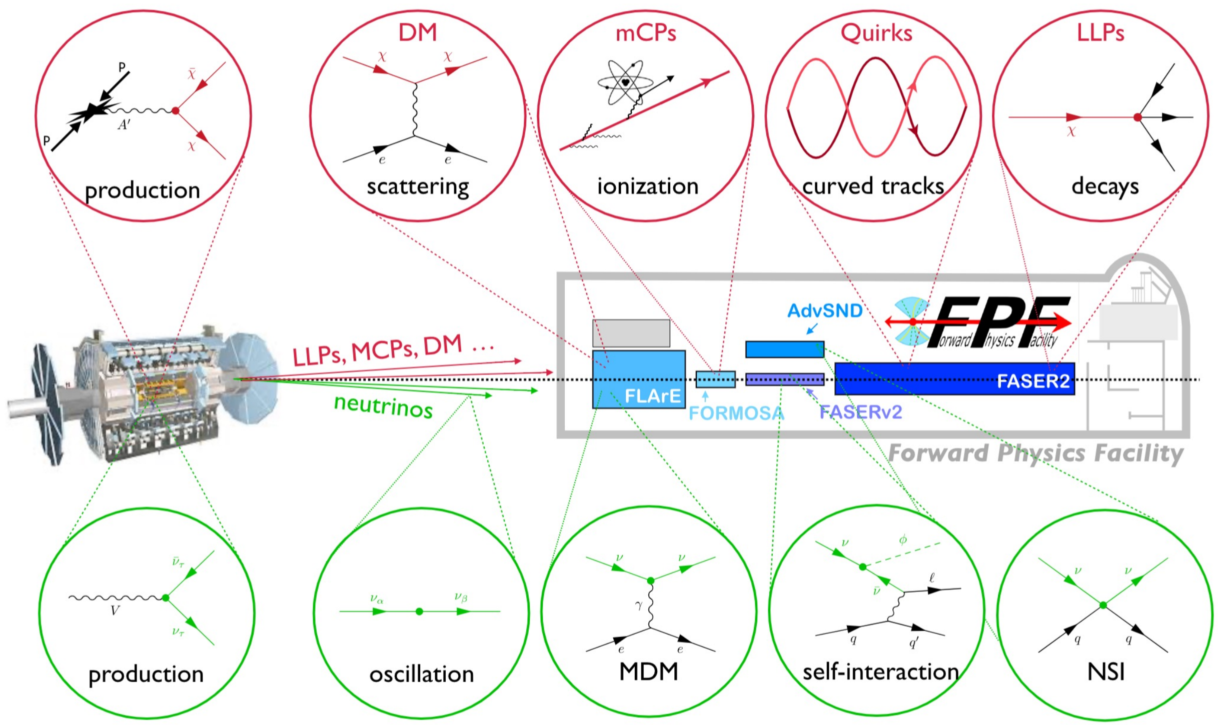
- The physics program in the far-forward region has been developed in a series of meetings and papers.
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020
  - FPF2 Meeting, 27-28 May 2021
  - FPF3 Meeting, 25-26 Oct 2021
  - FPF4 Meeting, 31 Jan-1 Feb 2022
  - FPF5 Meeting, 15-16 Nov 2022
  - FPF6 Meeting, 8-9 June 2023



- FPF Papers
  - FPF “Short” Paper: 75 pages, 80 authors, Phys. Rept. 968, 1 (2022), 2109.10905.
  - FPF White Paper: 429 pages, 392 authors+endorsers representing over 200 institutions, J. Phys. G (2023), 2203.05090.
- Snowmass 2022: “Our highest immediate priority accelerator and project is the HL-LHC, … including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.”

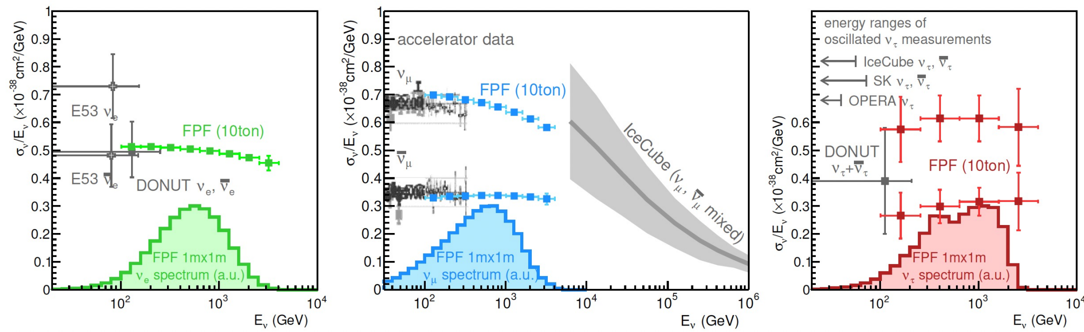
NEW PHYSICS AT THE FPF

- The FPF is proposed to run at the HL-LHC with implications for
  - New physics in neutrino properties: 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, …

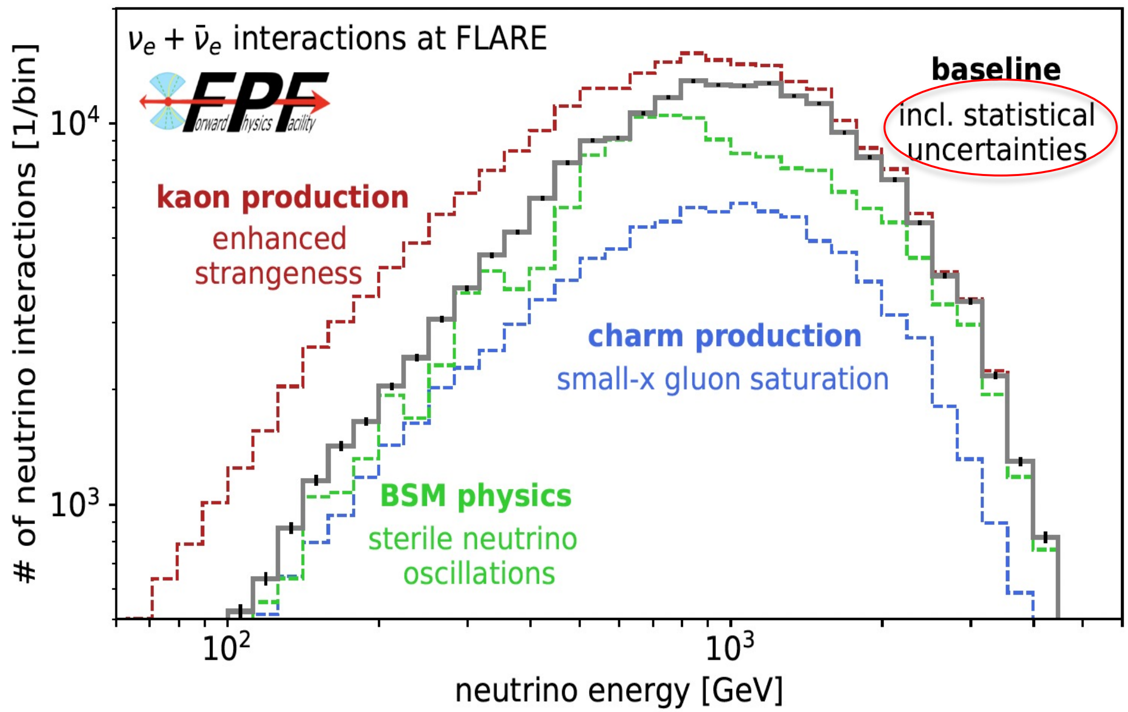


NEUTRINOS AT THE FPF

- The FPF experiments will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^4\ \nu_\tau$ interactions at ~ TeV energies where there is currently almost no data.

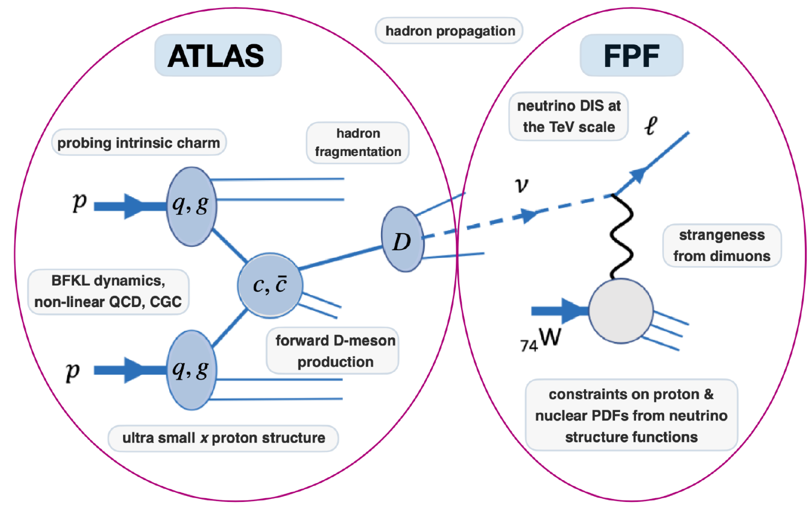


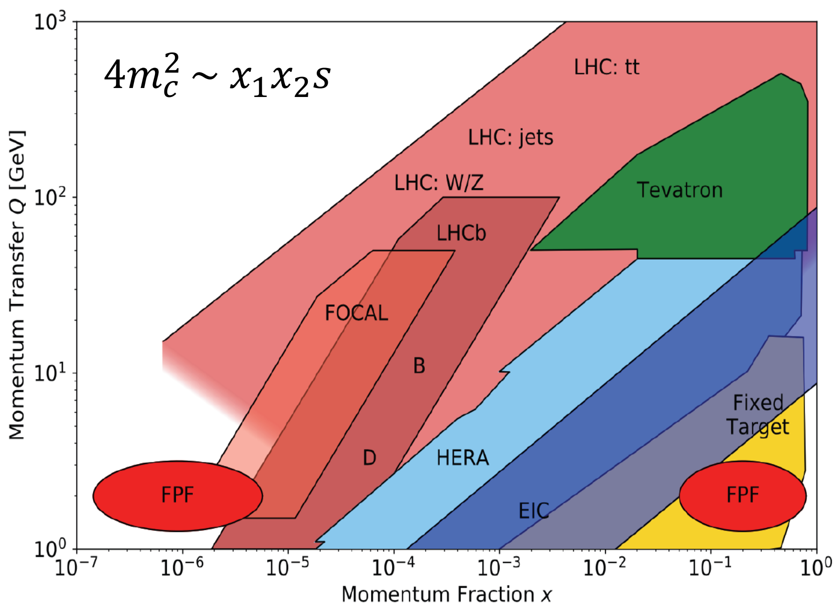
- Neutrinos are produced by forward hadron production: $\pi, K, D, \ldots$. Energy spectra will inform
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x ~ 10^{-1}, x ~ 10^{-7} , intrinsic charm, small-x gluon saturation, …
  - Neutrino oscillations: ν_s with $\Delta m^2 \sim 10^3\ \mathrm{eV}^2$

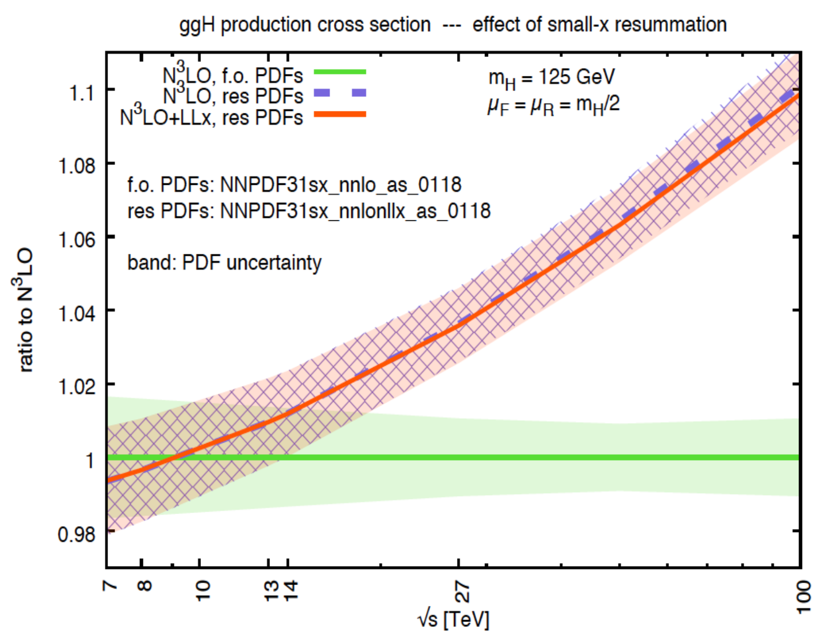


QCD AT THE FPF

- The FPF will also support a rich program of QCD and hadron structure studies.
- Forward neutrino production is a probe of forward hadron production, BFKL dynamics, intrinsic charm, and proton structure at ultra small x ~ 10^{-7} to 10^{-6}.
- Important implications for UHE cosmic ray experiments, 100 TeV pp collider, …



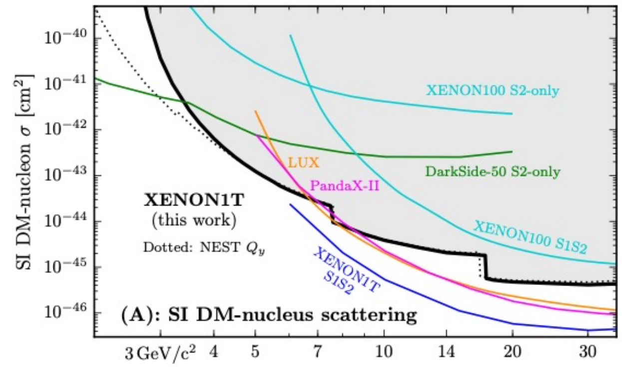




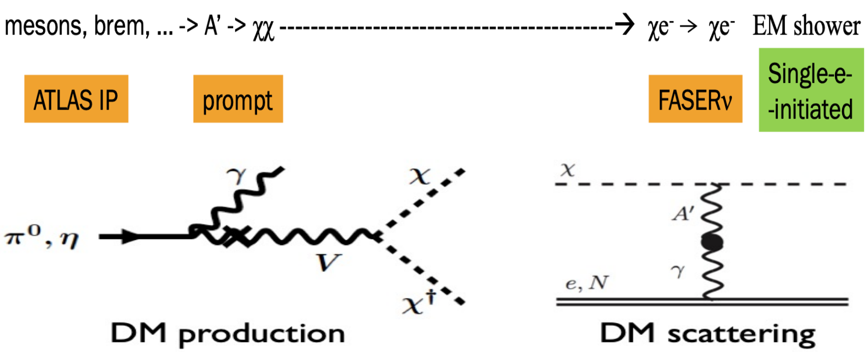
FASER White Paper (2022)

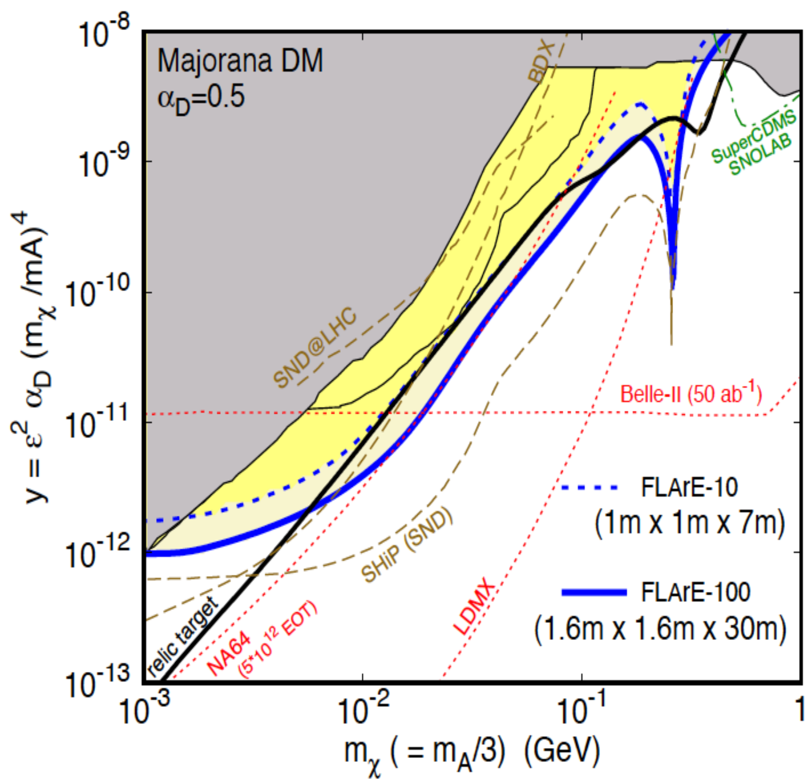
DARK MATTER DIRECT DETECTION AT THE FPF

- Light DM with masses at the GeV scale and below is famously hard to detect.
  - Galactic halo velocity ~ 10^{-3} c, so kinetic energy ~ keV or below.



- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.





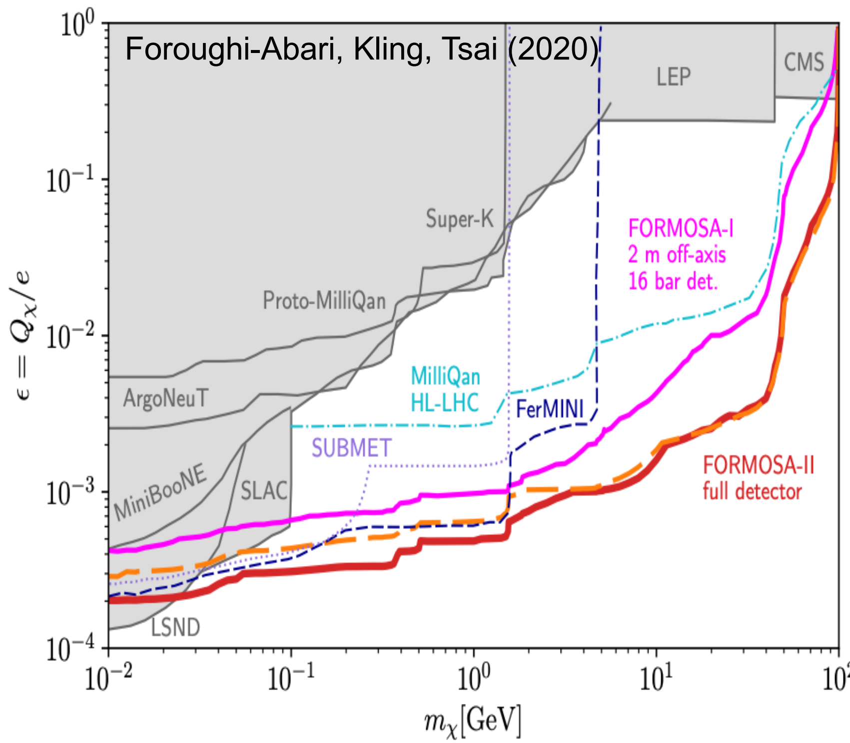
Batell, Feng, Trojanowski (2021)

- FLArE is powerful in the region favored/allowed by thermal freezeout.

MILLI-CHARGED PARTICLES AT THE FPF

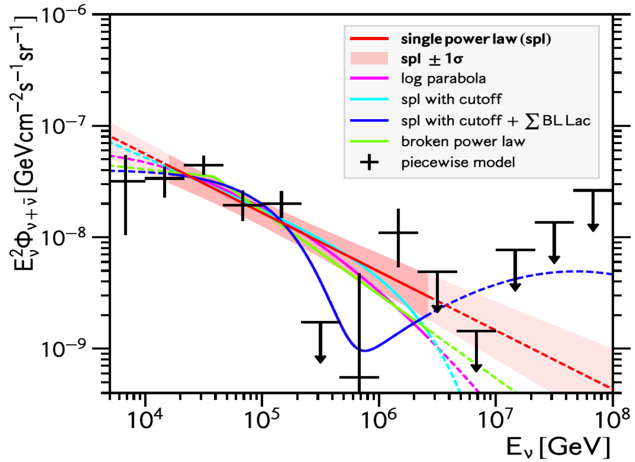
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a "non-forward" tunnel.

- The MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan can also run in this location in the HL-LHC era, but the sensitivity may be improved significantly by moving it to the FPF (FORMOSA).

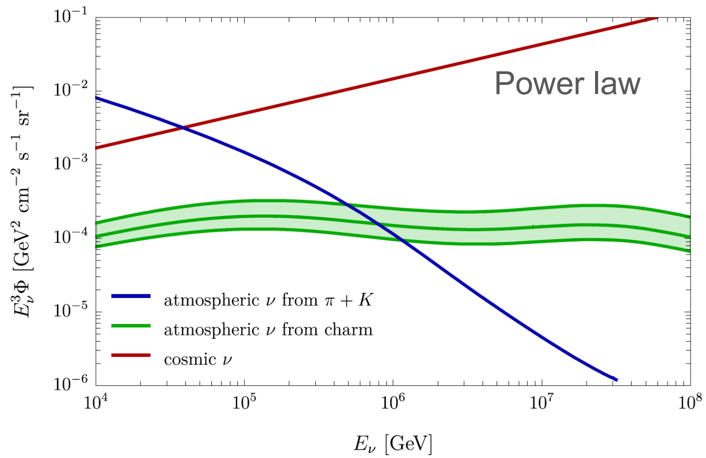


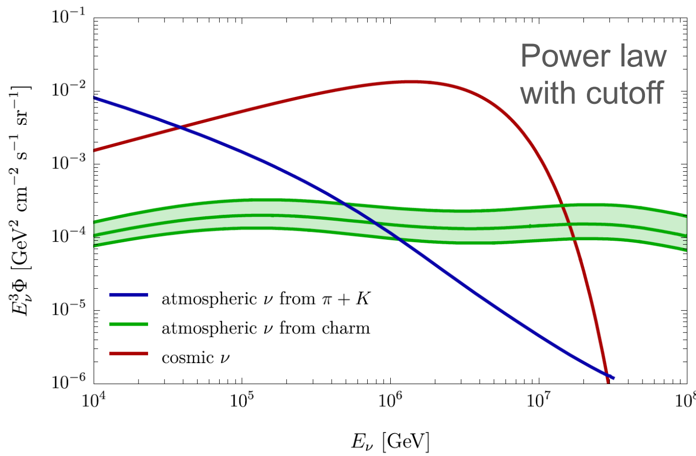
ASTROPARTICLE PHYSICS AT THE FPF

- The current IceCube cosmic nu flux can be fit by a power law, a power law with cutoff, ...
- More data may be able to distinguish these, but only if the atmospheric neutrino background from charm is better determined.



IceCube 2001.09520





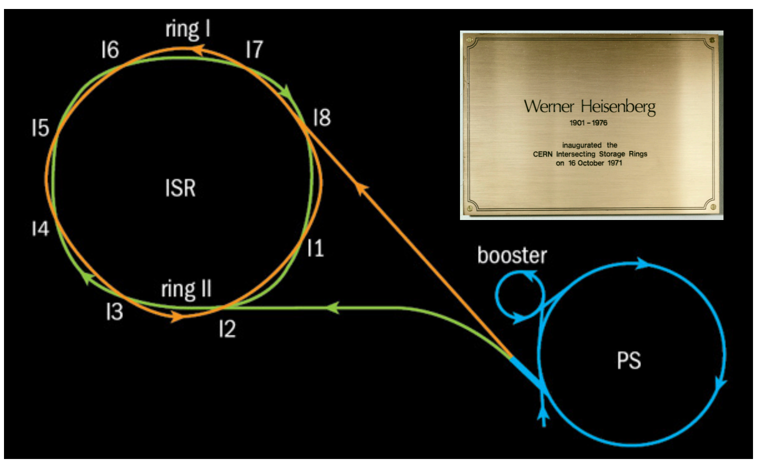
Bhattacharya et al. (1502.01076)

- This can be measured in the controlled environment of a particle collider if
  - $\sqrt{s} \sim \sqrt{2E_\nu m_p} \sim$ 10 TeV for $E_\nu \sim 10^7$ GeV: Requires the energy of the LHC
  - $x_{1,2} \sim \frac{m_c}{\sqrt{s}} e^{\pm\eta} \Rightarrow \eta \sim$ 7 to 9: Requires the far forward angular coverage of the FPF

Anchordoqui (2022)

A CAUTIONARY TALE

- Sometimes to look forward, it pays to first look back.
- 2021 was the 50th anniversary of the birth of hadron colliders.
- In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.



ISR'S LEGACY

- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists looking back on the ISR's legacy.
  - "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, "Discovery Machines," CERN Courier (2021).
- Bottom line: The collider was creating new forms of matter (charm), but the detectors focused on the forward region (along the beamline) and so missed them. Let's not follow this precedent!

SUMMARY

- The FASER experiment is a new way of studying collisions at the LHC to probe fundamental physics.
  - Discovery and study of collider neutrinos, interacting at the highest human-made energies ever observed.
  - Searches for light, weakly-interacting new particles, including many motivated by dark matter.

- Compared to other LHC experiments, FASER is inexpensive, small, and fast.
  - The detector was designed, constructed, and installed in ~2 years.
  - First physics data taken in 2022, first physics results in March 2023, many more to come.

- Following the success of FASER, the Forward Physics Facility is now being considered to fully exploit the forward region of the LHC collisions through the rest of the LHC's lifetime (2028-2040s).

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