THE DAWN OF MULTI-MESSENGER COLLIDER PHYSICS

Maryland Johns Hopkins Joint Particle Physics Seminar

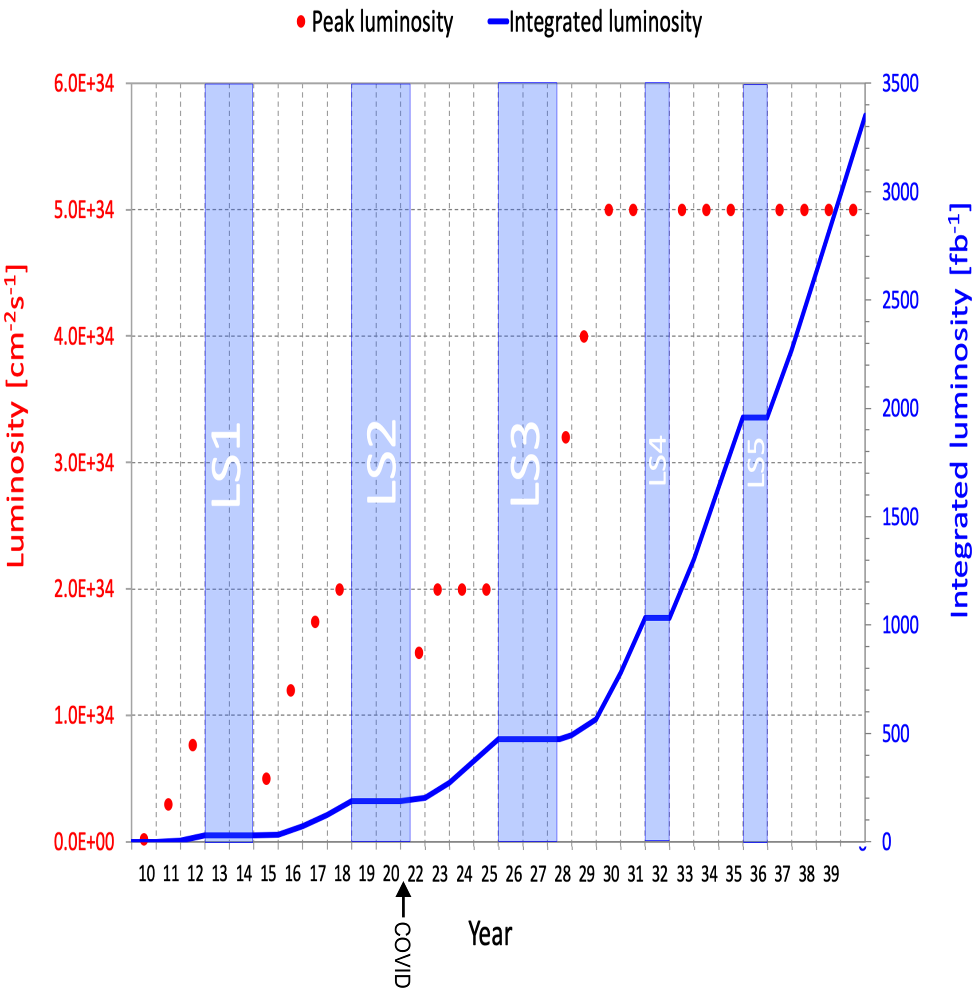
Jonathan Feng, UC Irvine, 8 May 2024

LIFETIME OF THE LHC

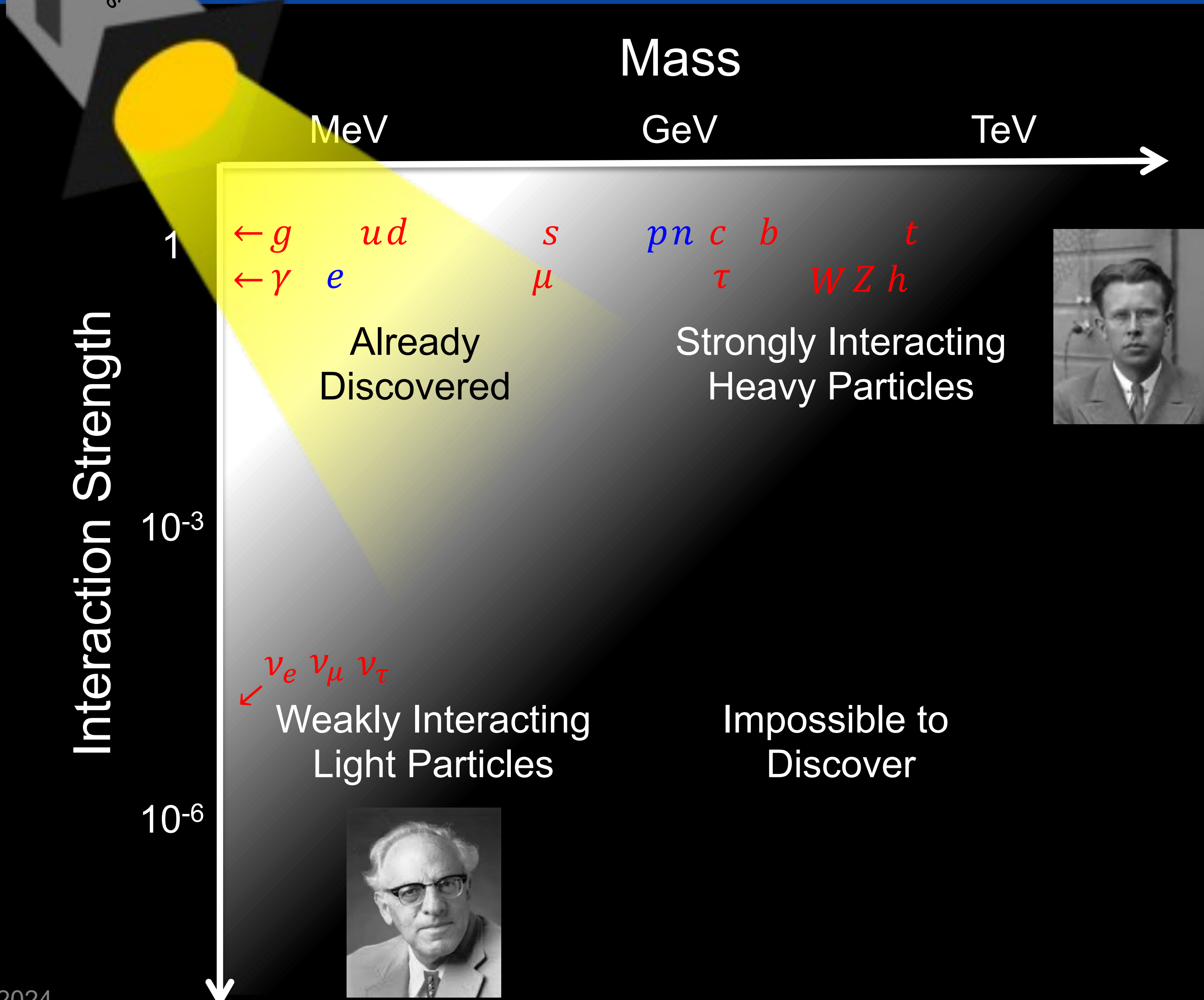
- The LHC has been a focus of particle physics for as long as most of us can remember. Its lifetime is my (professional) lifetime:
  - 1993 SSC canceled.
  - 2010: LHC starts.
  - 2040s: LHC ends.

- But the LHC is still in its youth!
  - a postdoc in terms of years
  - a kindergartener in terms of integrated luminosity

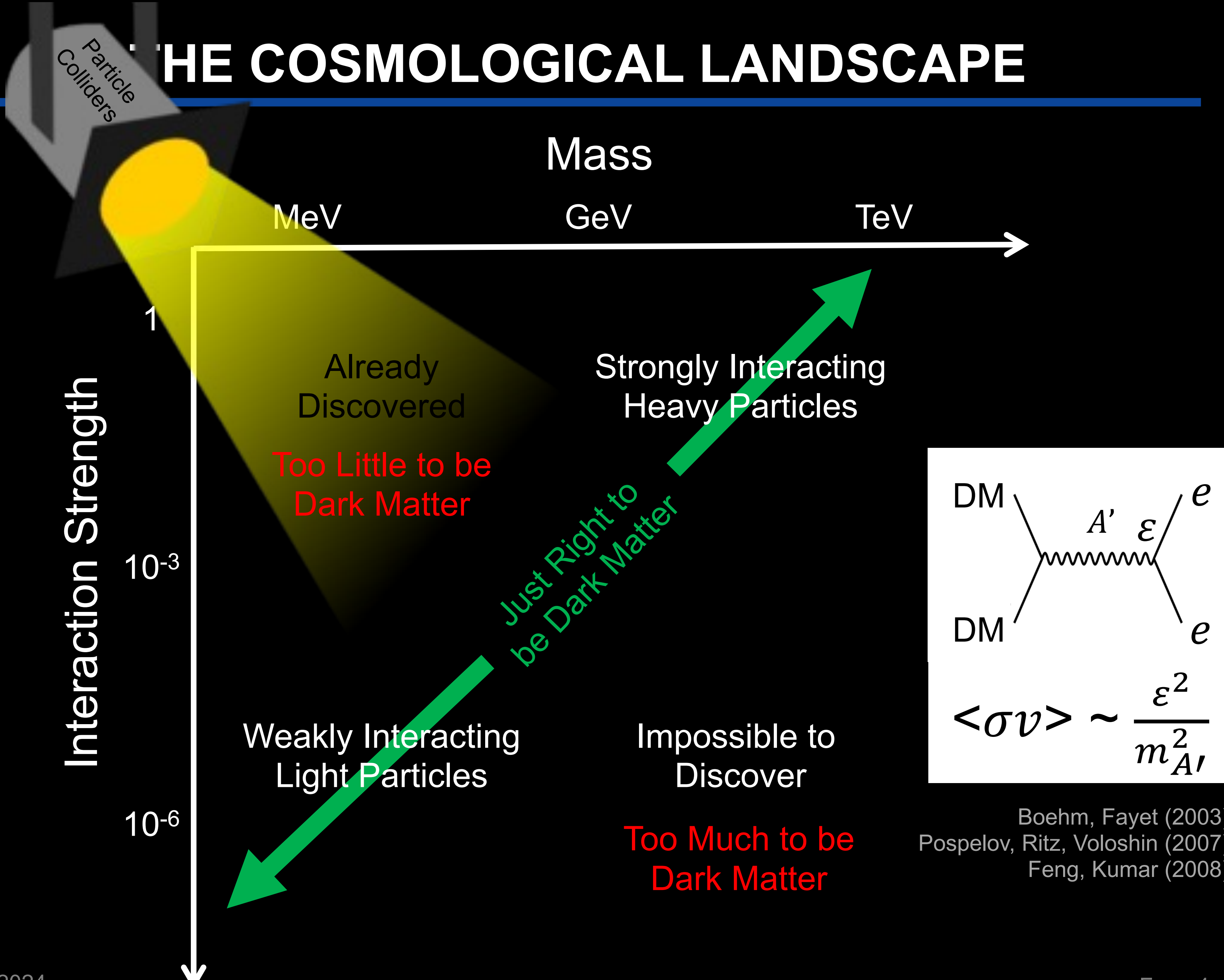
- Are we using the LHC to its full potential? If not, what can we do to enhance its discovery prospects?



THE PARTICLE LANDSCAPE



THE COSMOLOGICAL LANDSCAPE



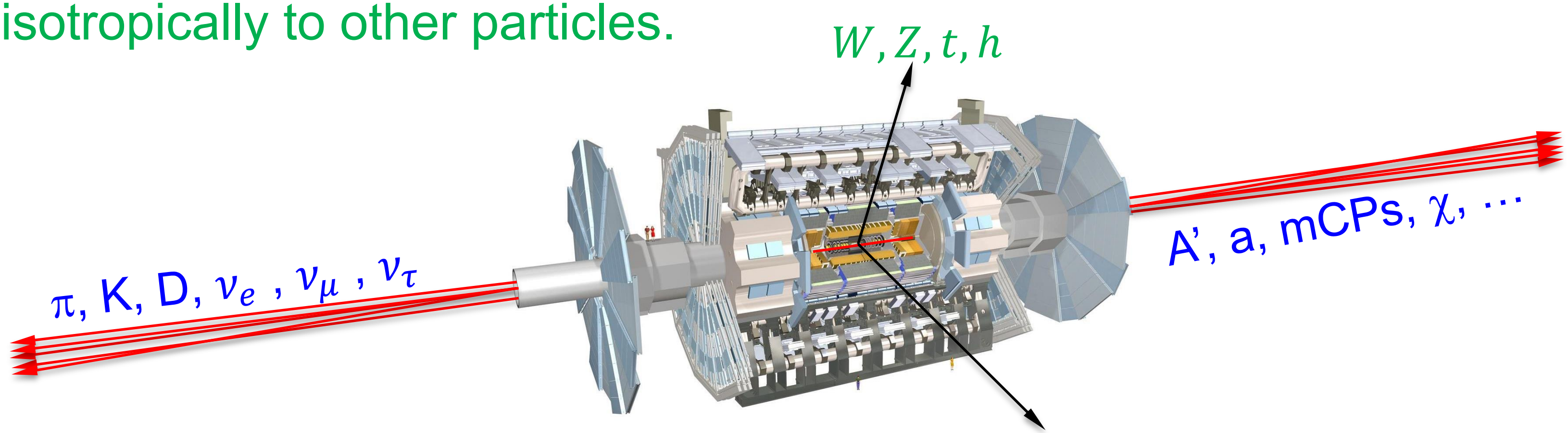
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

- In 2017, we realized that the large LHC detectors, while beautifully optimized to discover new heavy particles, are also perfectly 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.

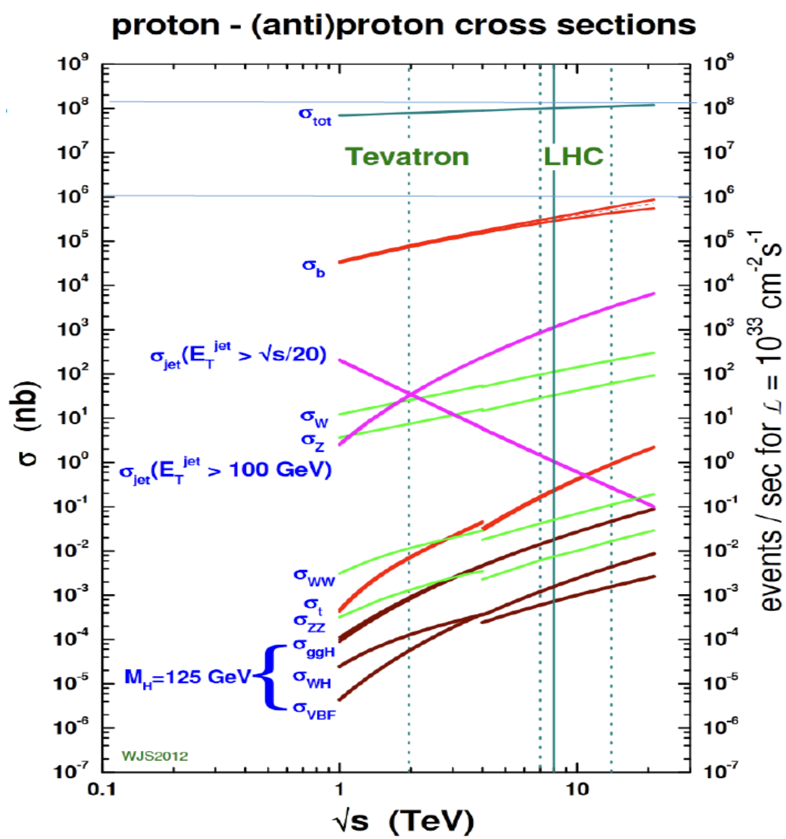


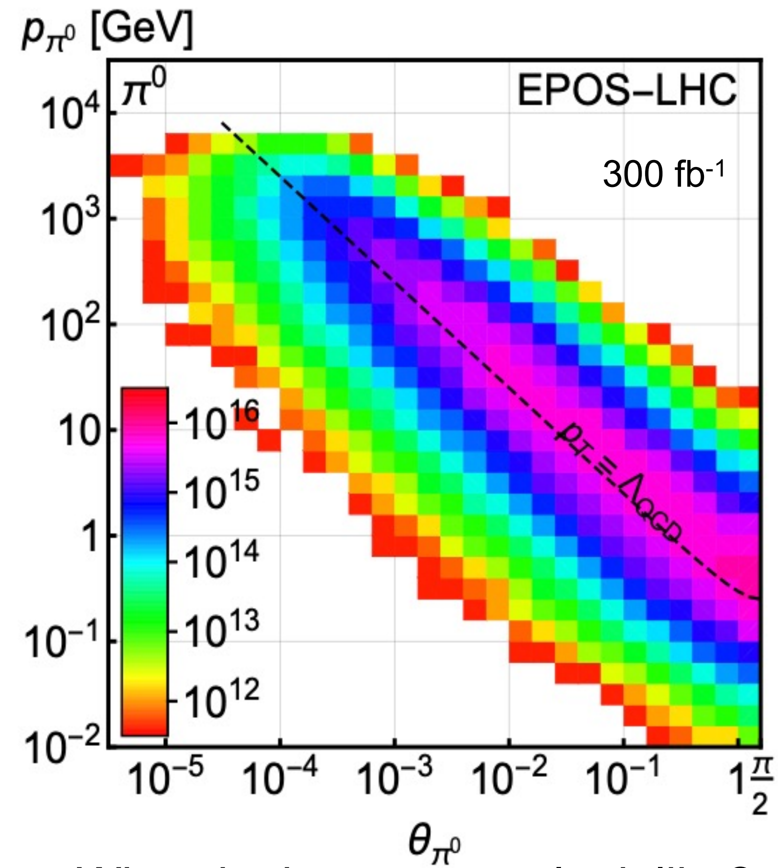
- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of existing detectors.
  - This is true for all known light particles: pions, kaons, D mesons, neutrinos.
  - It is also true for many hypothetical new particles, especially those motivated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

  De Rujula, Ruckl (1984)

- These blind spots are the Achilles heels of the large LHC detectors.

LIGHT PARTICLES AT THE LHC

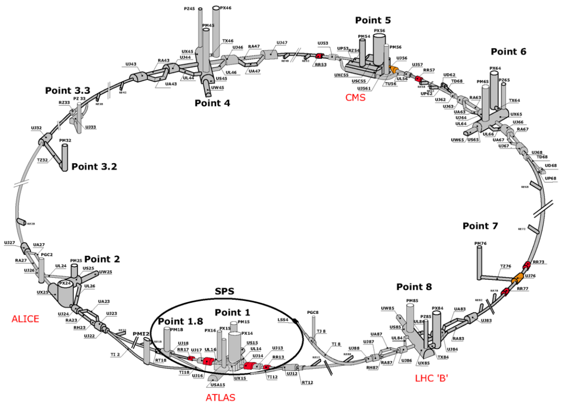




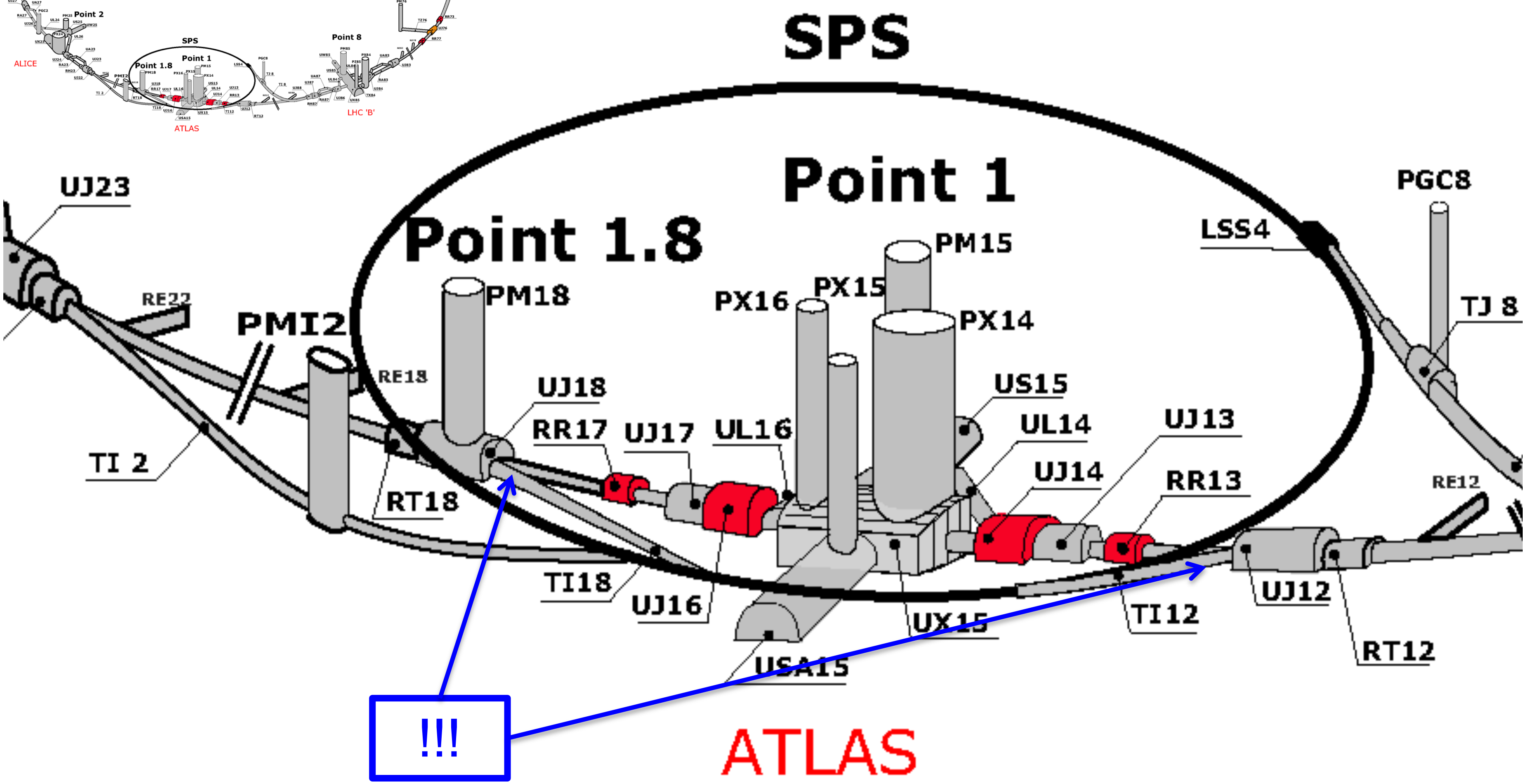
Feng, Galon, Kling, Trojanowski (2017)

- Most searches have focused on processes with σ ~ fb, pb.
- But the total cross section is σ_{tot} ~ 100 mb, which 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.

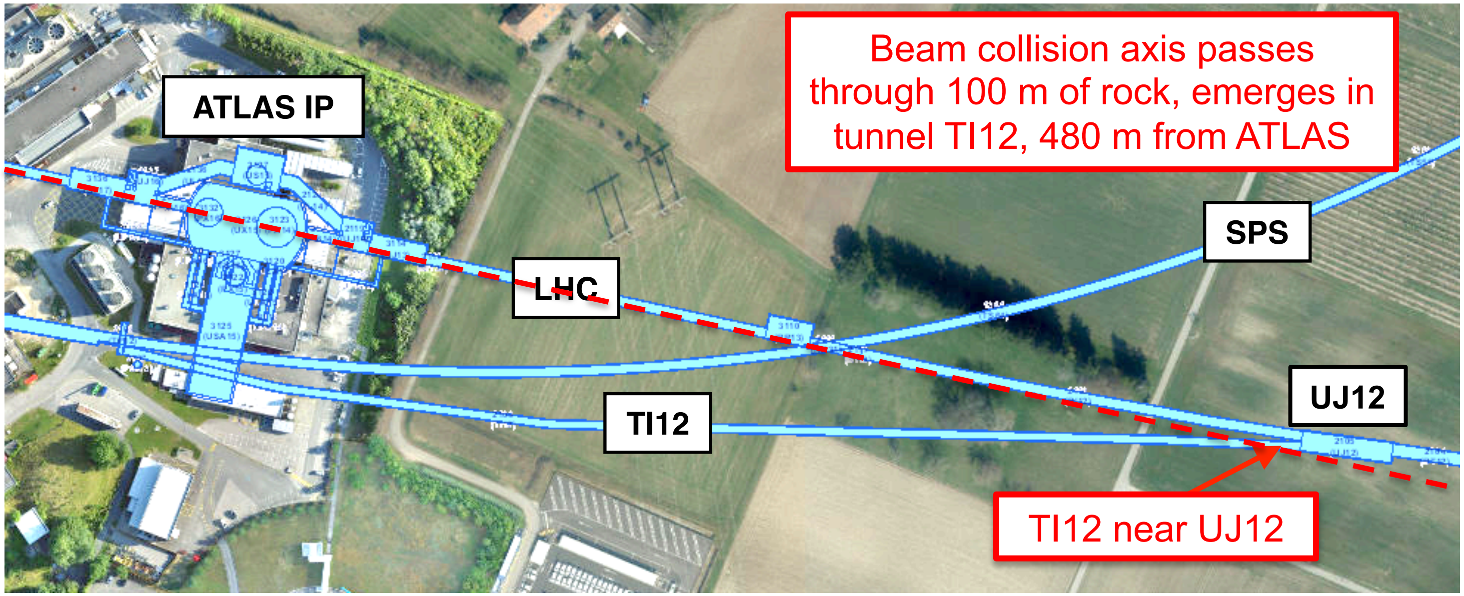
MAP OF THE LHC



To instrument the forward region, one can't simply plug up the holes – we need to let the protons in. But the LHC is a circular collider!



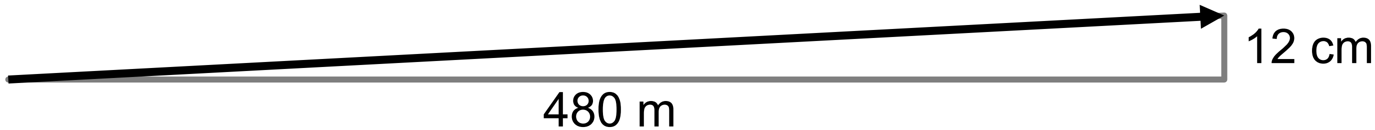
THE FORWARD REGION



HOW BIG DOES THE DETECTOR HAVE TO BE?

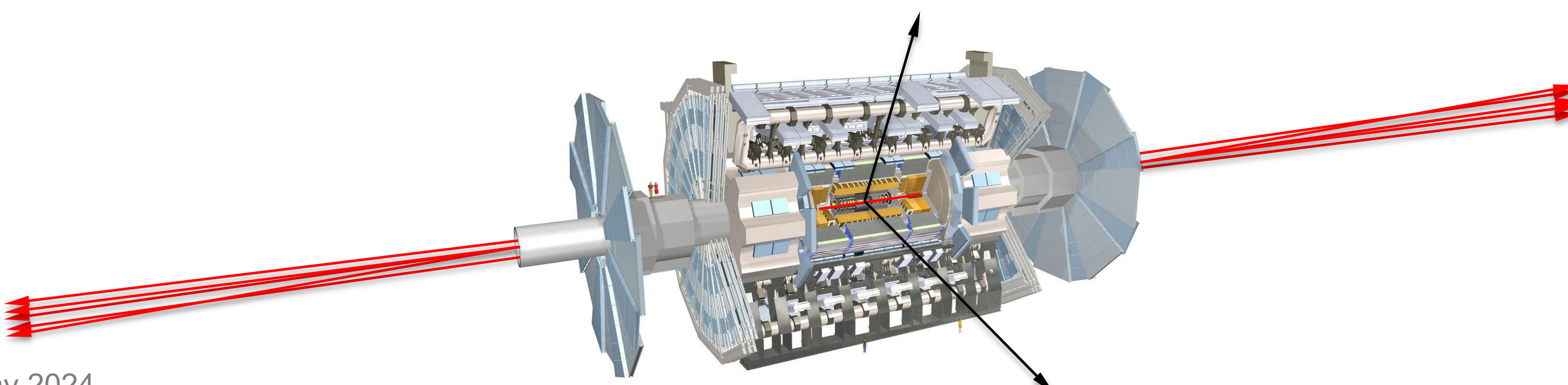
- Momentum:

- Space:

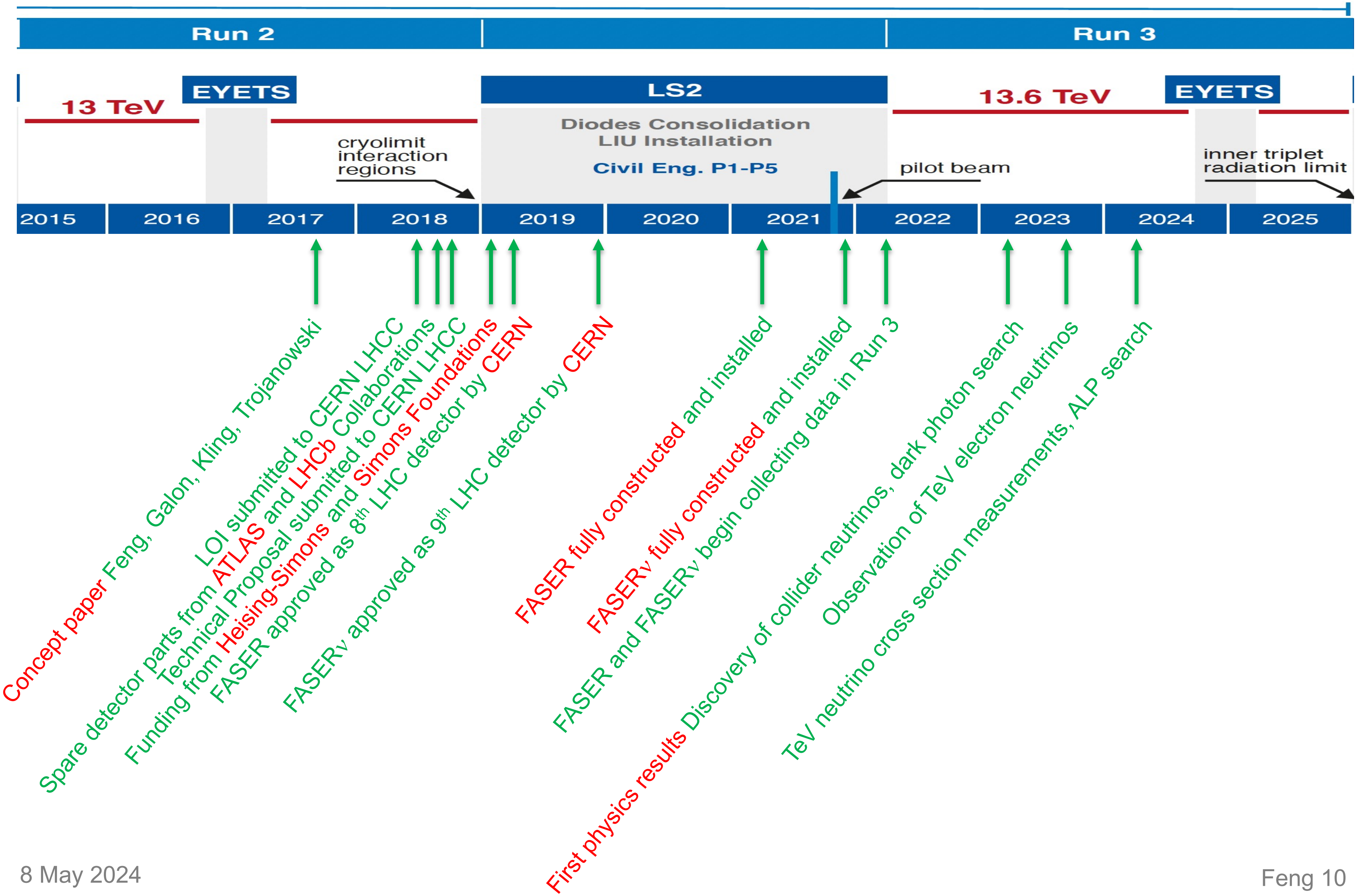


- The opening angle is 0.2 mrad (the moon is 7 mrad). Even 480 m away, most of the signal passes through an 8.5” x 11” (A4) sheet of paper.

- 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



THE FASER COLABORATION NOW

97 collaborators, 26 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 JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON

DESY.
INFN
International laboratory covered by a cooperation agreement with CERN
清華大学 Tsinghua University
ROYAL HOLLOWAY UNIVERSITY OF LONDON

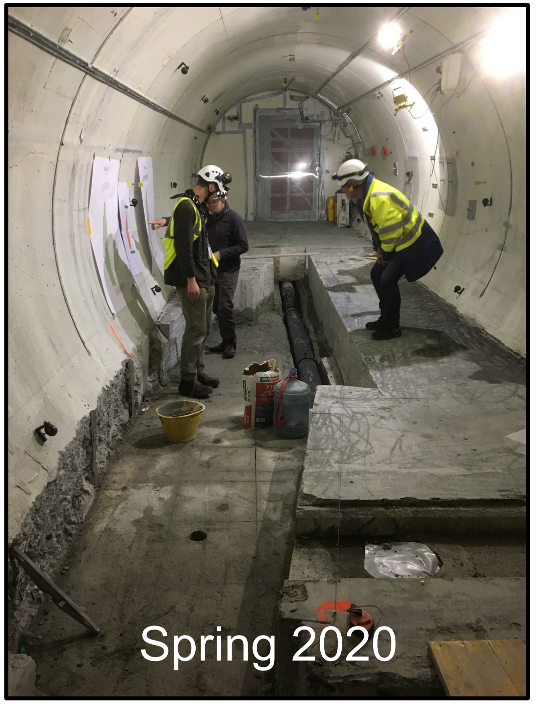
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
UNIVERSITY OF LIVERPOOL
ZHENGZHOU UNIVERSITY
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX

Nikhef
UNIVERSITÄT BONN
ETH zürich
MANCHESTER 1824 The University of Manchester

PREPARATION OF THE FASER LOCATION

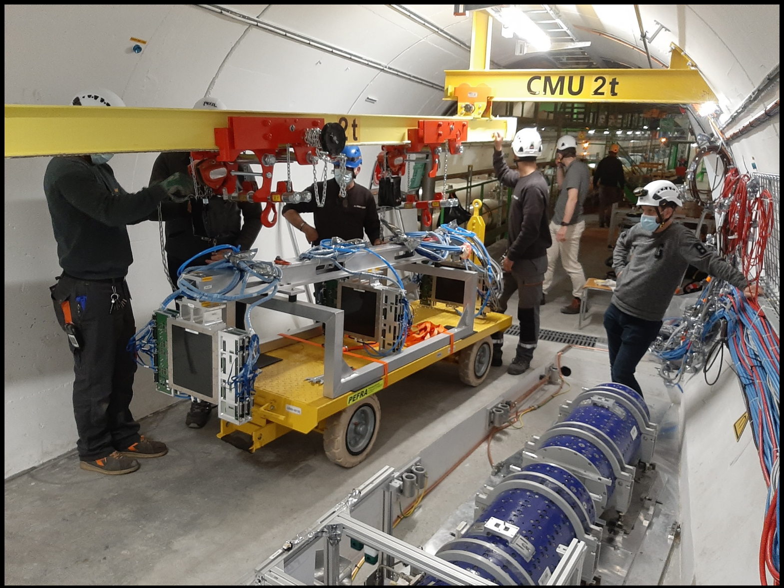
- The beam collision axis or line of sight (LOS) was located to mm accuracy by the CERN survey department. To place FASER on this axis, a trench was required to lower the floor by 46 cm.

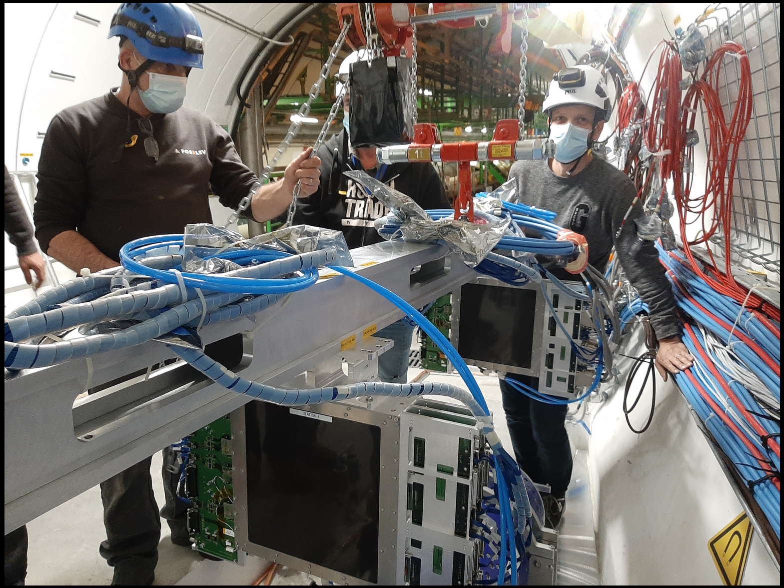
- The trench was completed by an Italian firm just hours before COVID shut down CERN in March 2020.

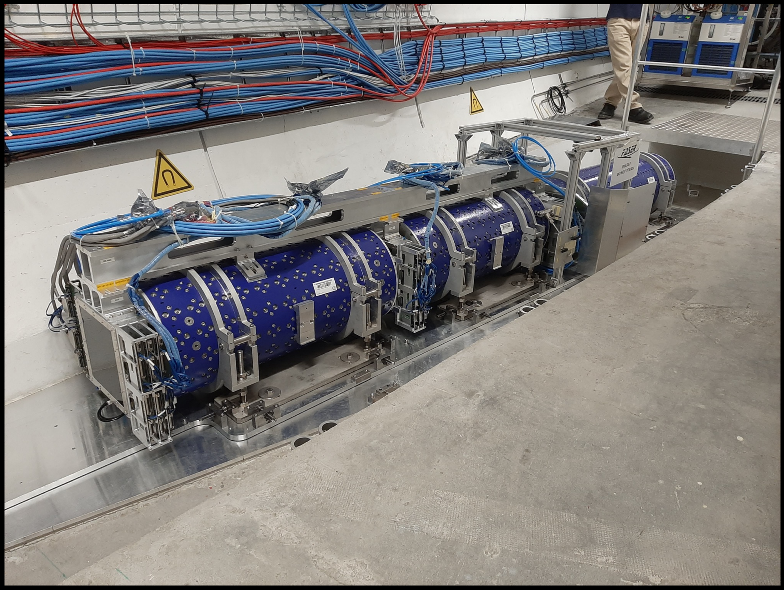


FASER AND THE LHC

FASER INSTALLATION



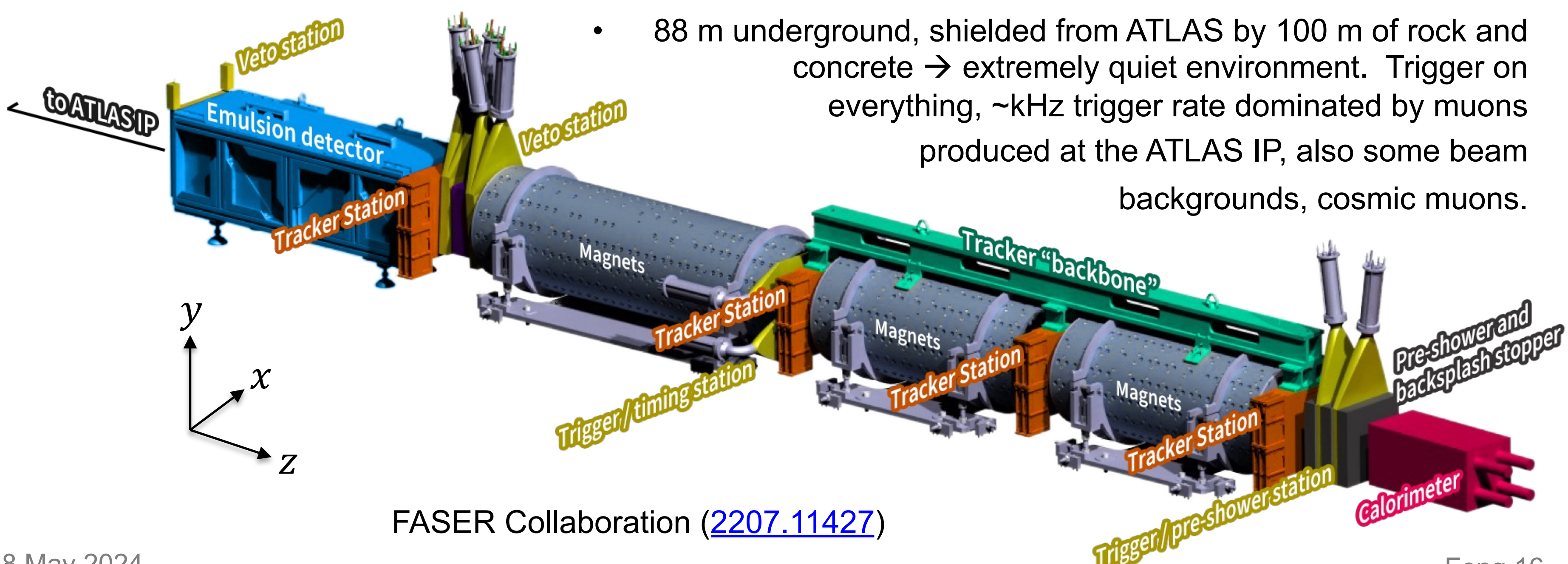




THE FASER DETECTOR

THE FASER DETECTOR

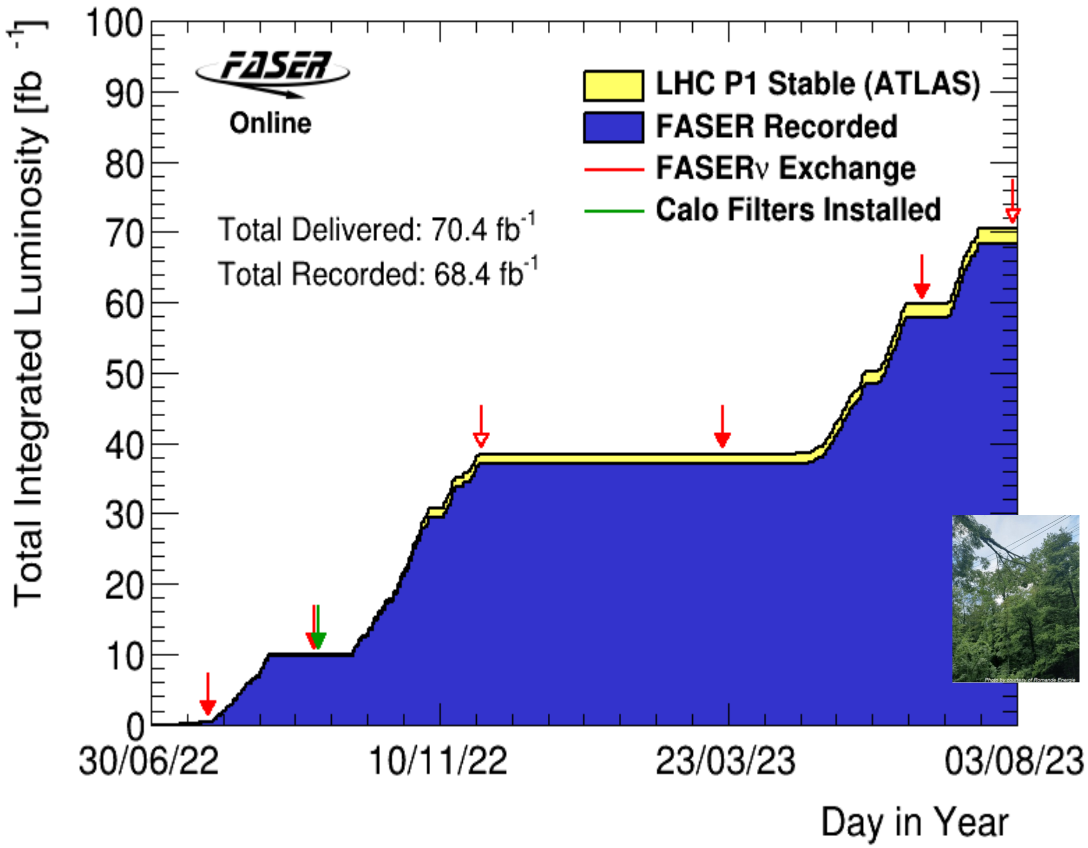
- Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.
- 3 permanent dipole magnets, Halbach design, constructed at CERN, 0.57 T, deflects charged particles in y.
- Tracker: 4 stations x 3 layers x 8 mod. = 96 ATLAS SCT modules. Resolution = 16 μm in y, 820 μm in x.
- Calorimeter: 2 x 2 LHCb ECAL modules.
- Scintillators: 4 stations, multiple layers, each 2 cm thick, >99.999% efficient. 4-layer veto ~ $(10^{-5})^4 \sim 10^{-20}$.
- FASERν: 770 interleaved sheets of tungsten + emulsion. 1 m long, 1.1 ton total mass. Micron-level spatial resolution, but no timing. Becomes over-exposed from muon tracks after ~20-30 fb^{-1}, must be replaced.
- 88 m underground, shielded from ATLAS by 100 m of rock and concrete → extremely quiet environment. Trigger on everything, ~kHz trigger rate dominated by muons produced at the ATLAS IP, also some beam backgrounds, cosmic muons.



FASER Collaboration (2207.11427)

FASER DATA TAKING IN 2022 AND 2023

- FASER was ready to go in early 2021, and saw its first cosmic ray event on 18 March 2021.
- After LS2 from 2018-2021, the LHC started running again from Jul to Nov 2022 and Apr to Jul 2023.
- FASER began recording data immediately.
  - Recorded 97% of total lumi.
  - Largely automated: no control room, 2 shifters controlling and monitoring the expt from their laptops.

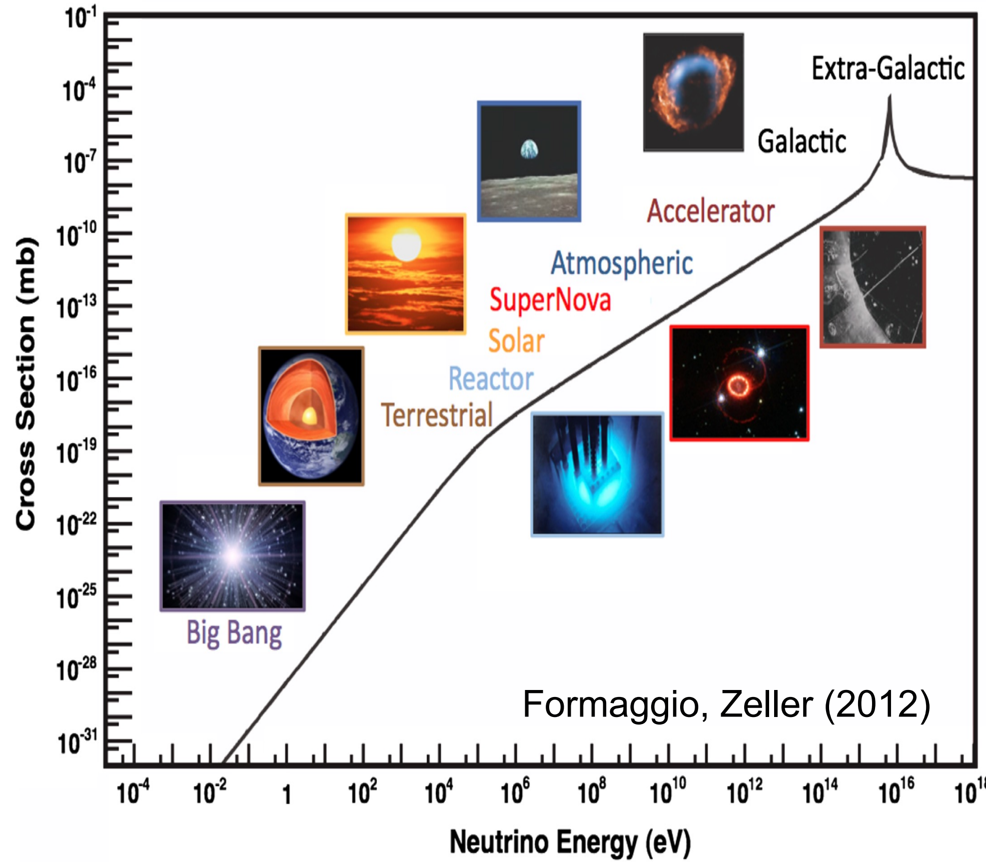


- FASERν emulsion exchanged periodically to prevent overexposure
  - 3 boxes in 2022 (0.5, 10, 30 fb^{-1})
  - 2 boxes in 2023 (20, 10 fb^{-1})

COLLIDER NEUTRINOS

- Neutrinos are the least understood of all known particles, and the only ones with confirmed BSM properties.

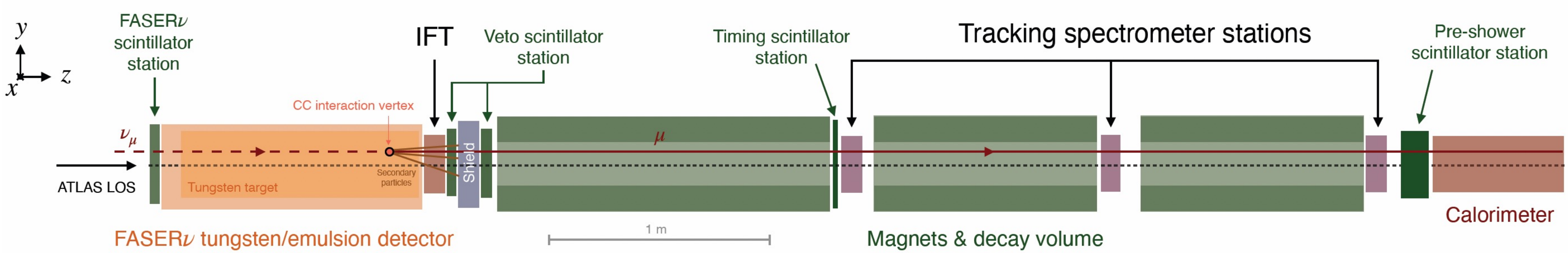
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.



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

COLLIDER NEUTRINO SEARCH

- Neutrinos produced at the ATLAS IP travel 480 m and pass through FASERν. Occasionally, they can interact through $\nu_\mu N \to \mu X$, producing a high-energy muon, which travels through the rest of the detector.



FASER Collaboration (2303.14185, PRL)

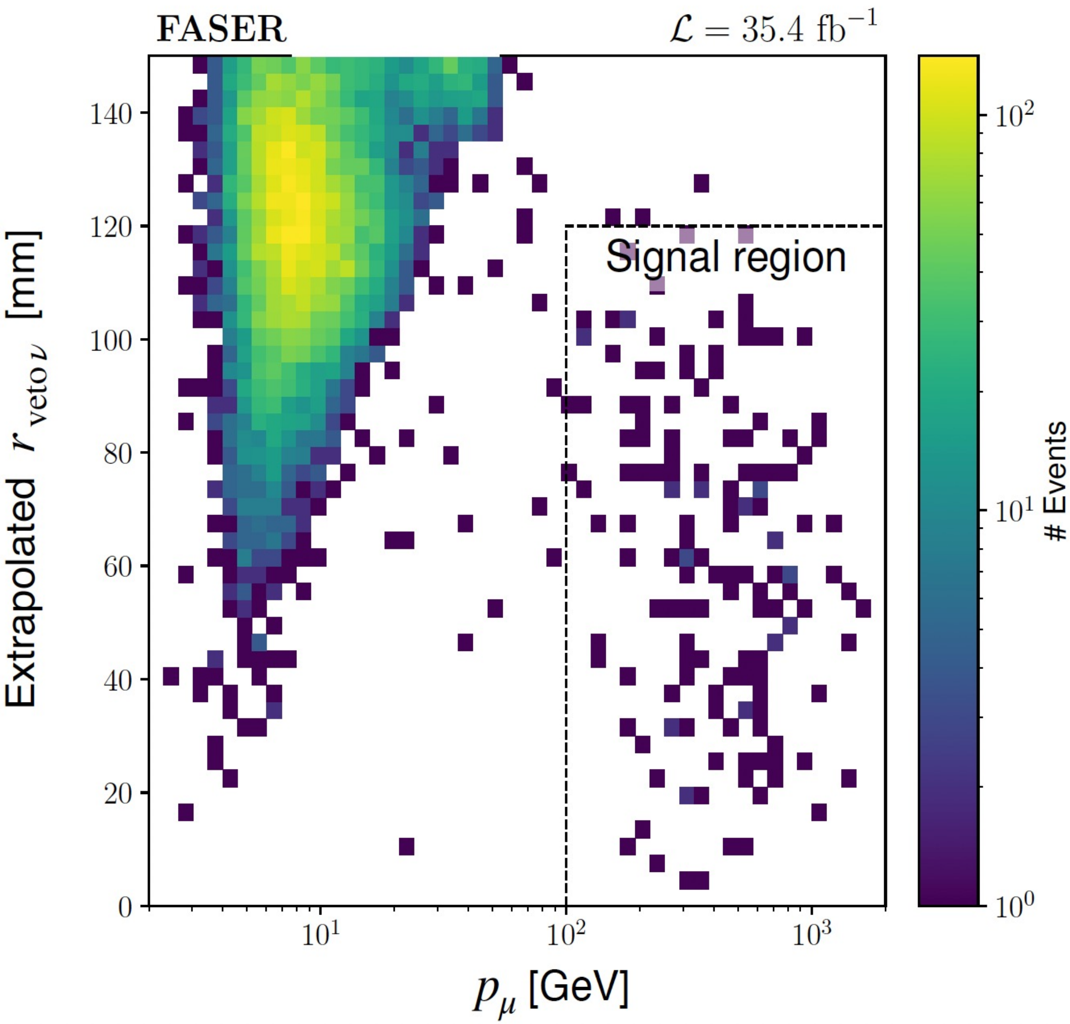
- The signal is no charged particle passing through the upstream veto scintillator detectors, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

- Leading backgrounds from neutral hadrons produced in the rock, muons that enter from the side, or beam 1 background contribute $\lesssim$ 1 event.

- 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
- 1st direct detection 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.



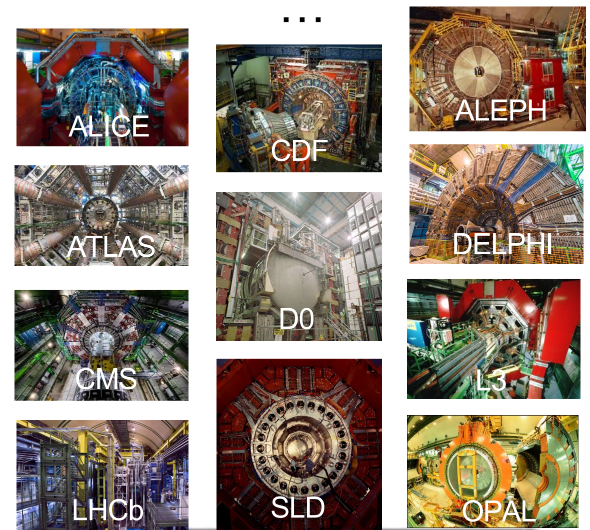
FASER Collaboration (2303.14185, PRL)

LOCATION, LOCATION, LOCATION

FASER

“Tabletop,” 18 months,
~$1M

153 neutrinos



All previous
collider detectors

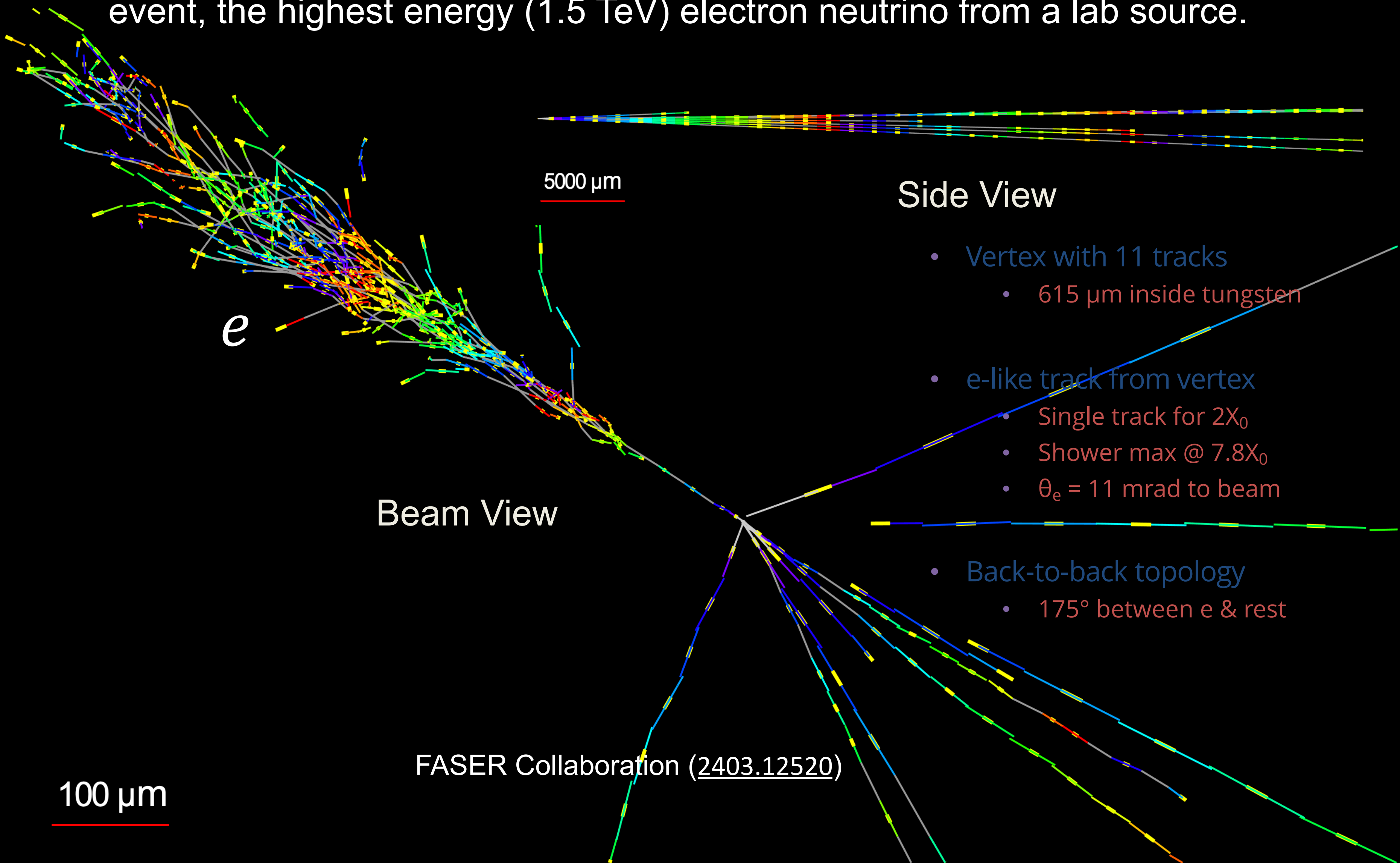
Building-size, decades,
~$1B

0 neutrinos

16σ discovery, opening a new window
at the high energy frontier

NEUTRINOS FROM EMULSION IN FASERν

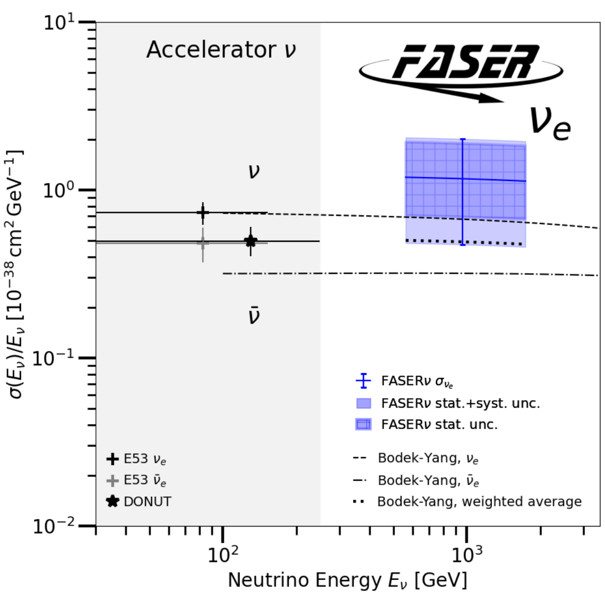
The discovery analysis did not even use the emulsion data! With the emulsion, we have now observed the first collider electron neutrinos, including the “Pika-ν” event, the highest energy (1.5 TeV) electron neutrino from a lab source.

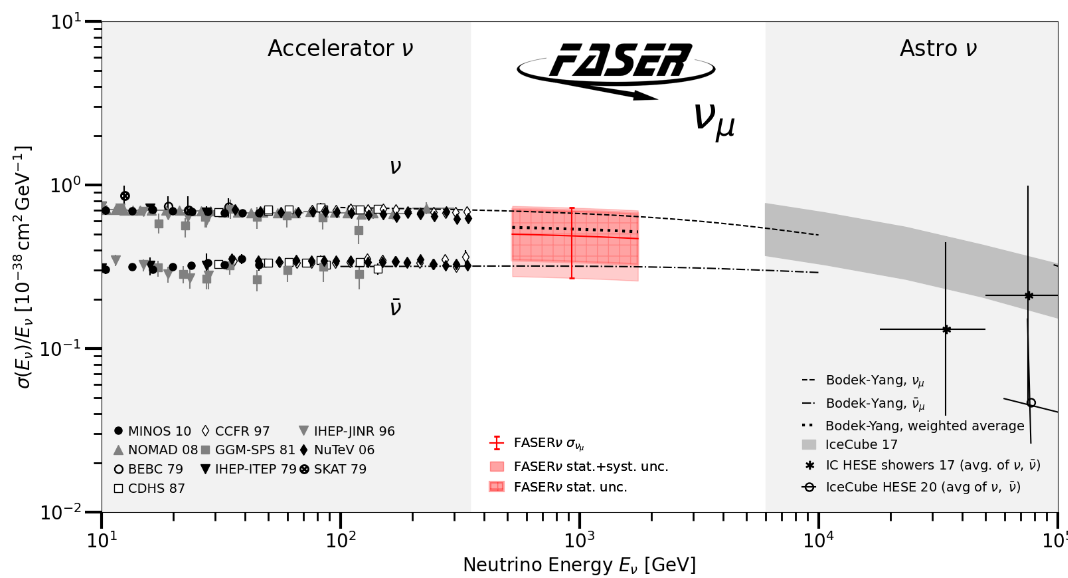


TEV NEUTRINO CROSS SECTIONS

- Following these discoveries, we can then move on to studies, including the first measurement of neutrino cross sections at TeV energies.

- Results are consistent with SM DIS predictions.



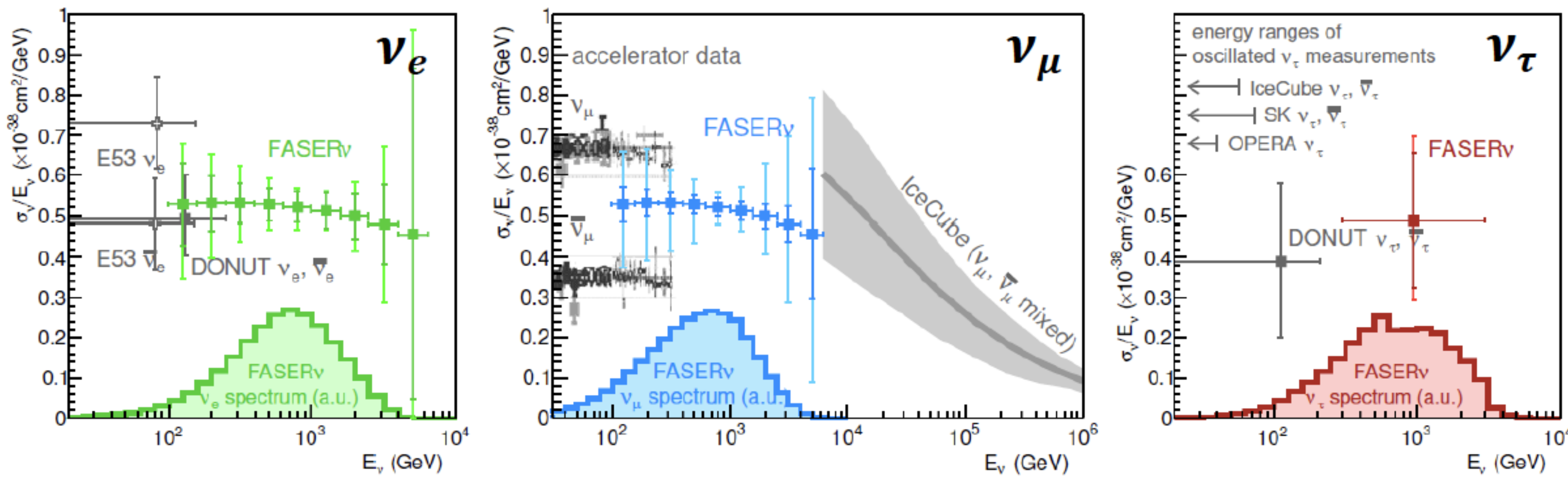


FASER Collaboration (2403.12520)

- These measurements use only 1.7% of the data already collected in 2022 and 2023.

NEUTRINO PROJECTIONS

- By the end of Run 3 (~300 fb^{-1}, 2025), we expect to
  - Record ~3000 ν_e, ~10,000 ν_μ, and ~50 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.
  - More than triple the world's supply of tau neutrinos, and detect the first ant-tau neutrino.

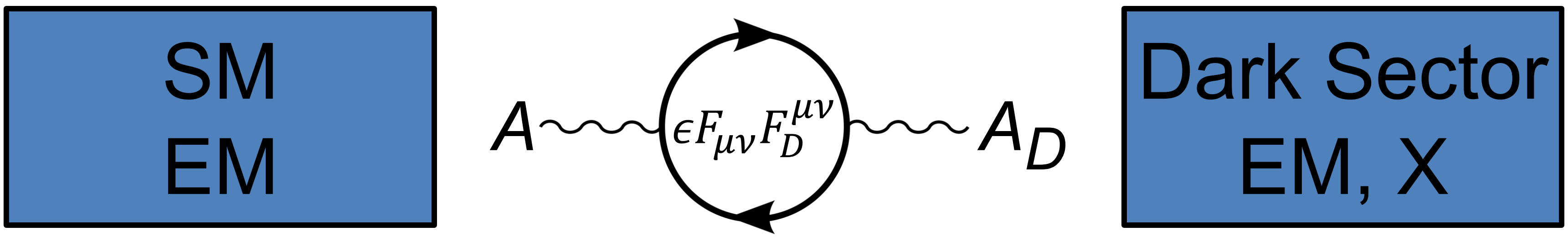


FASER Collaboration (1908.02310)

NEW PARTICLE SEARCHES

- Neutrinos are the only known light and weakly-interaction particles. But such particles appear generically in many BSM theories especially those addressing the neutrino mass and dark matter puzzles.

- For example: suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.



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

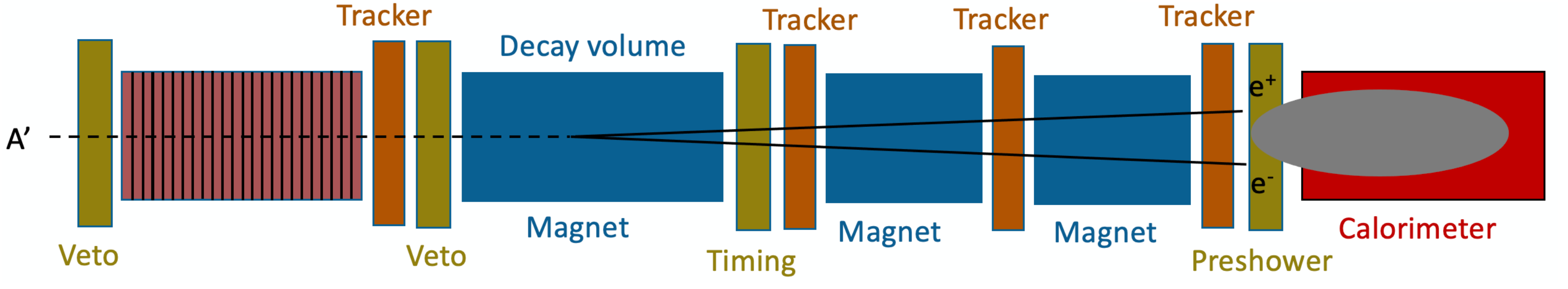
Holdom (1986)

- For low ϵ dark photons are long-lived particles (LLPs), can be produced in ATLAS, pass through rock and magnetic fields unhindered, and decay in FASER.

- Many other examples: sterile neutrinos, dark Higgs bosons, axion-like particles, light gauge bosons, light Binos, inflatons, …

DARK PHOTON SIGNAL

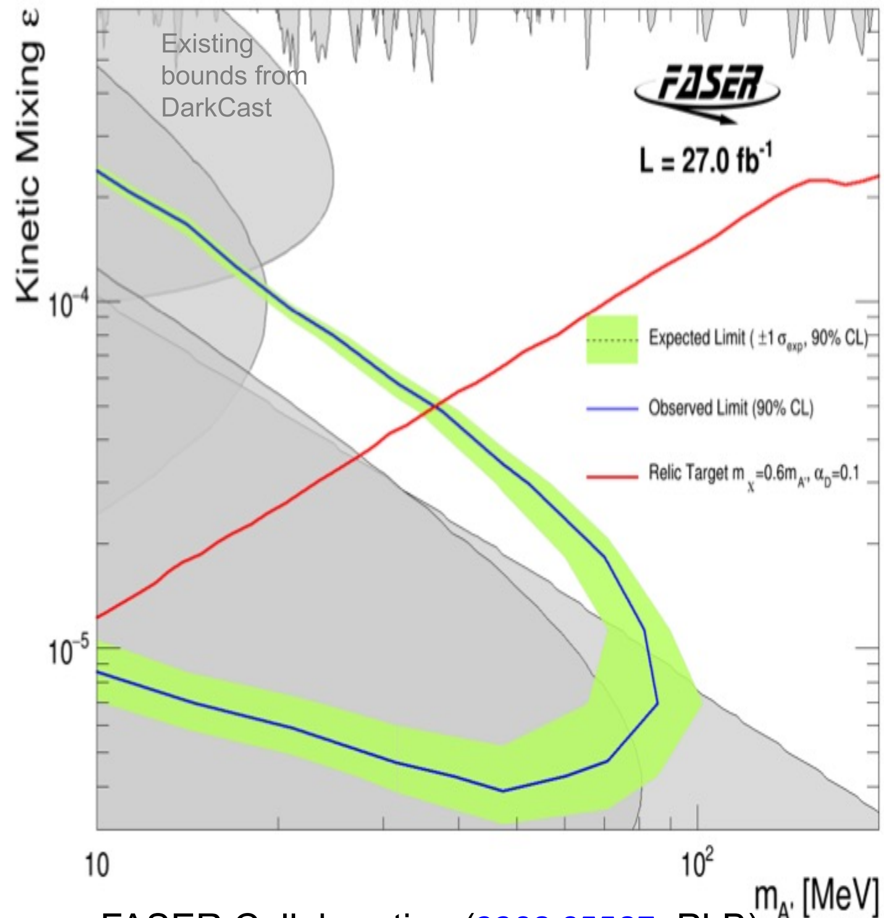
- Focus on masses in the 10-100 MeV range.
- Produced through meson decay $\pi/\eta \rightarrow A'\gamma$ or "dark bremsstrahlung" $pp \rightarrow ppA'$.
- Travel straight and unimpeded through 480 m of rock/concrete.
- Then decay through $A' \rightarrow e^+e^-$.



- The signal is no charged particle passing through the upstream veto scintillator detectors, followed by two very energetic (100s of GeV) charged tracks in downstream trackers. Tracks are very collimated, but magnet splits them sufficiently to be seen as 2 tracks in trackers.

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. Started probing new parameter space with the first day of data, ended up ~100 times more sensitive than previous experiments.
- Background-free analysis; contrary to conventional wisdom, $N = 3$ contours are conservative.



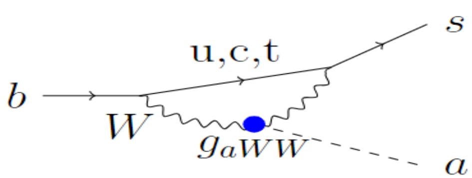
FASER Collaboration (2308.05587, PLB)

- For the future, factor of ~10 more luminosity and other improvements in Run 3 from 2023-25 data.

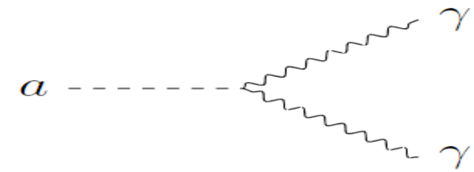
ALP-W SEARCH RESULTS

- Can also look for LLPs with purely photonic final states. E.g., ALP-Ws

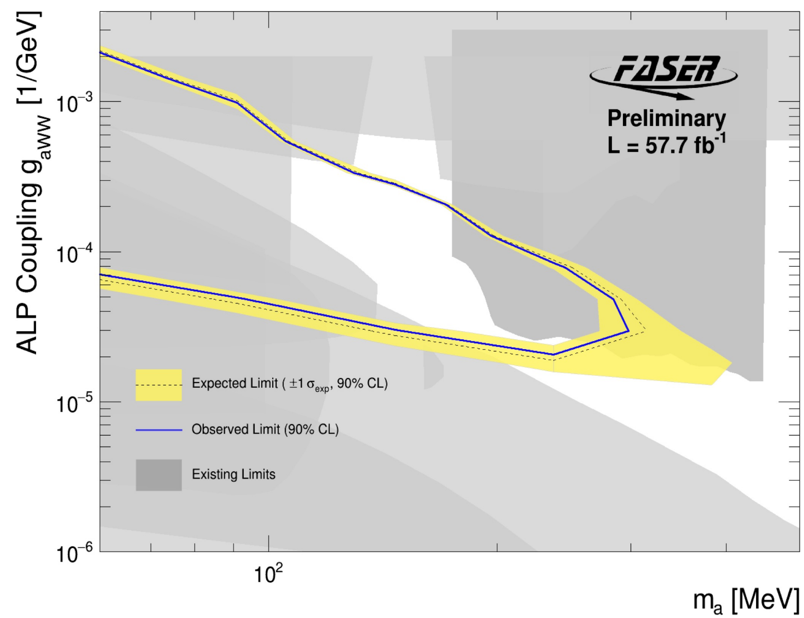
production



decay



- Signal is no hits in veto scintillators, >1 TeV energy deposit in ECAL.
- Background: Expect 0.42 ± 0.32 from ν interactions in 58 fb^{-1}.
- 1 event seen, excludes new parameter space. Benefits from LHC's high energy, lots of B's.



FASER Collaboration (CERN-FASER-CONF-2024-001)

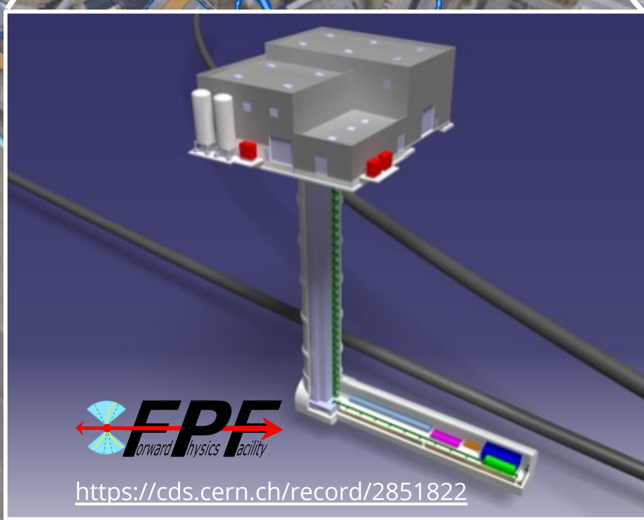
- Future BSM searches: factor of ~10 more luminosity, improved analyses, hardware upgrades (high resolution preshower calorimeter).
- Improved sensitivity for all of these models, as well as many more particles to look for: $U(1)_B$, protophobic gauge bosons, ALP-γ, ALP-g, up-philic scalar, light-shining through walls axions, 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.

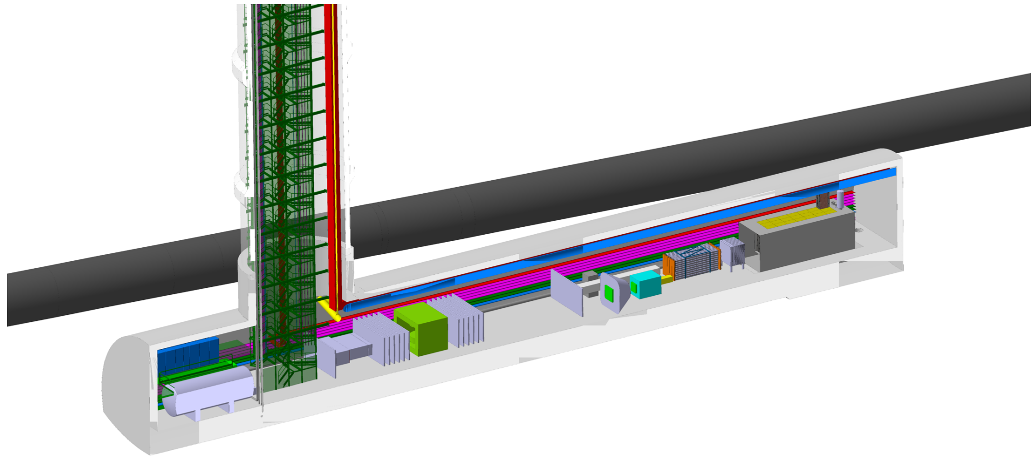


FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

CERN GIS

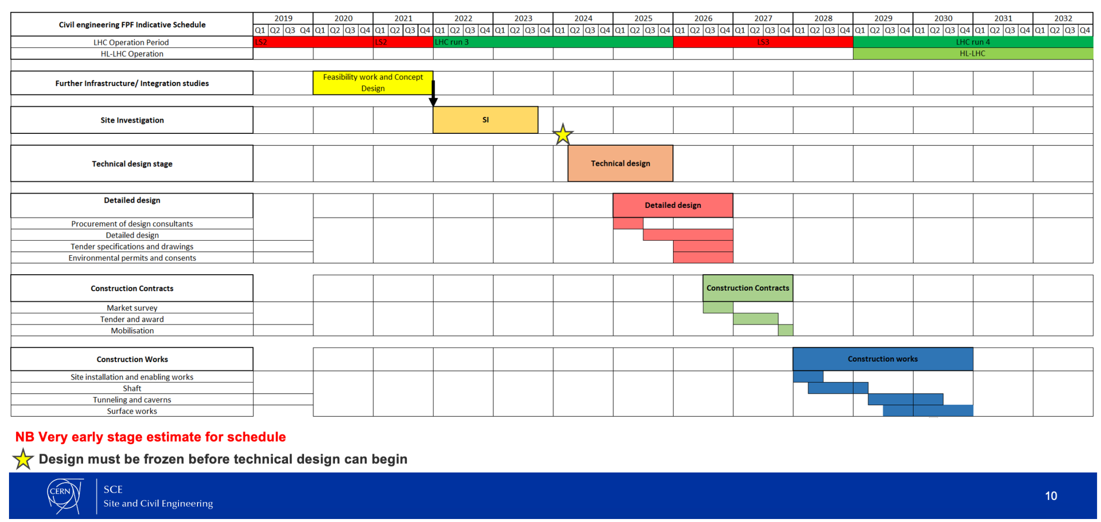
THE FACILITY

- A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.
- 75 m long, 12.5 m in diameter, covers $\eta > 5.1$.
- Preliminary (Class 4) cost estimate: 30 MCHF.
- Can be constructed independently of the LHC, does not disrupt LHC running.
- Timeline: construct in LS3/early Run 4, physics starts in late Run 4/Run5.



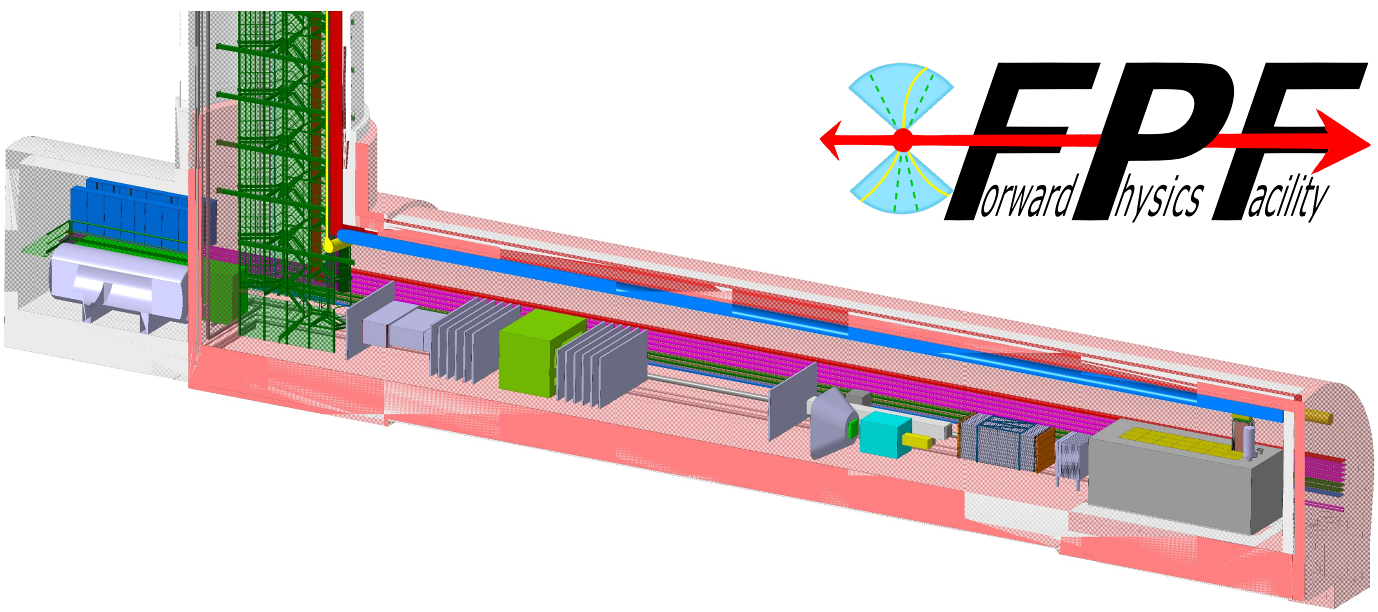
Bud, Magazinik, Pál, Osborne, et al. CERN CE (2024)

Proposed Civil Engineering Schedule



FPF EXPERIMENTS

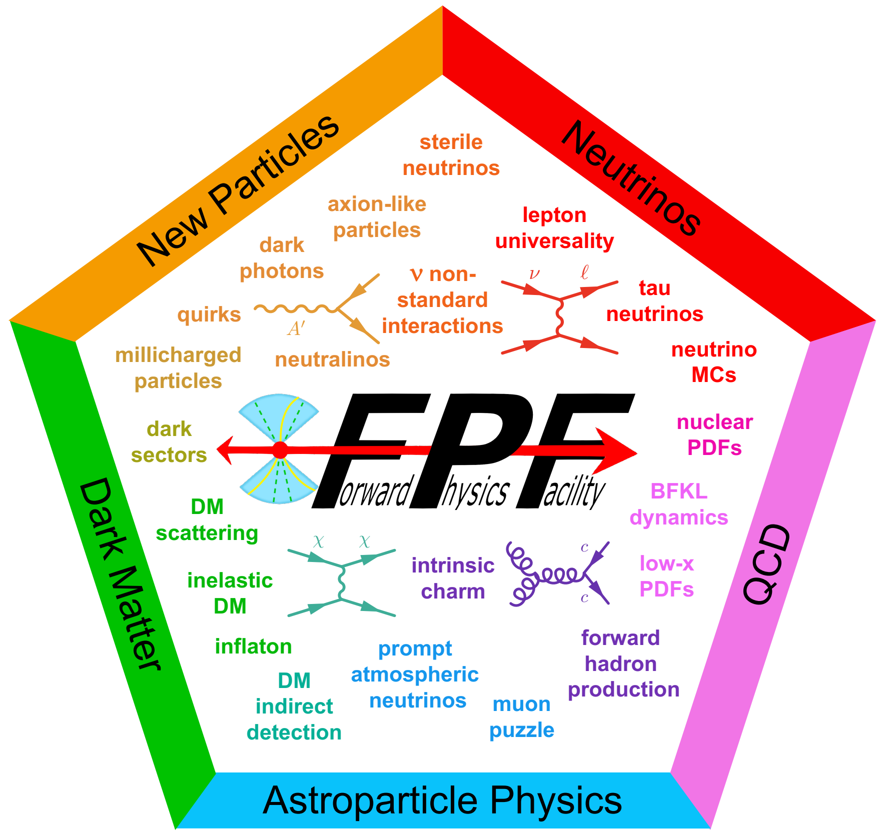
- At present there are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASERν2: emulsion-based neutrino detector
  - FLArE: LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)



- These represent a huge jump relative to the existing experiments:
  - 10,000 times greater (decay volume * luminosity) for BSM searches.
  - Will detect miilions of TeV neutrinos (~1000 neutrinos/day).

FORWARD PHYSICS FACILITY

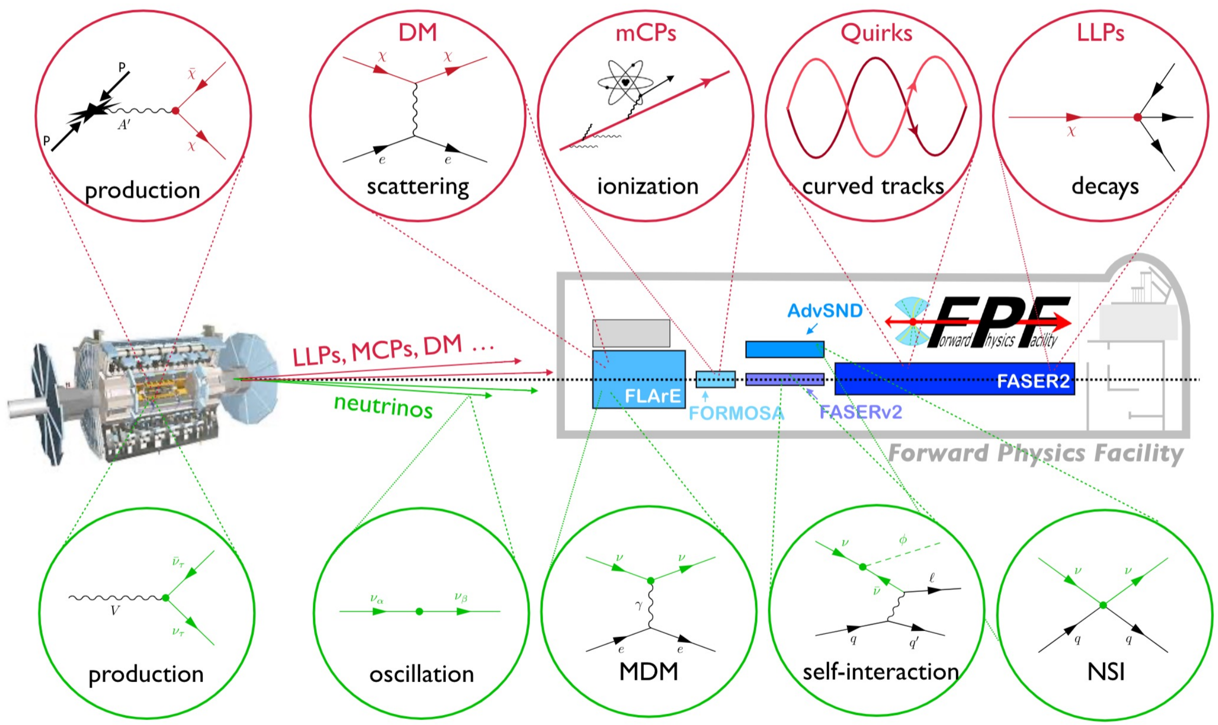
- The physics program in the far-forward region has been developed in a series of meetings and papers.
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020
  - FPF2 Meeting, 27-28 May 2021
  - FPF3 Meeting, 25-26 Oct 2021
  - FPF4 Meeting, 31 Jan - 1 Feb 2022
  - FPF5 Meeting, 15-16 Nov 2022
  - FPF6 Meeting, 8-9 Jun 2023
  - FPF7 Meeting, 29 Feb – 1 Mar 2024
- 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."

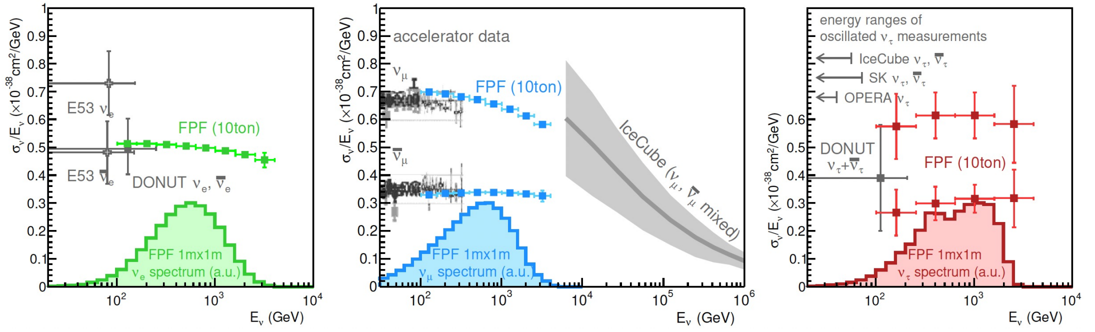
NEW PHYSICS AT THE FPF

- 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, …

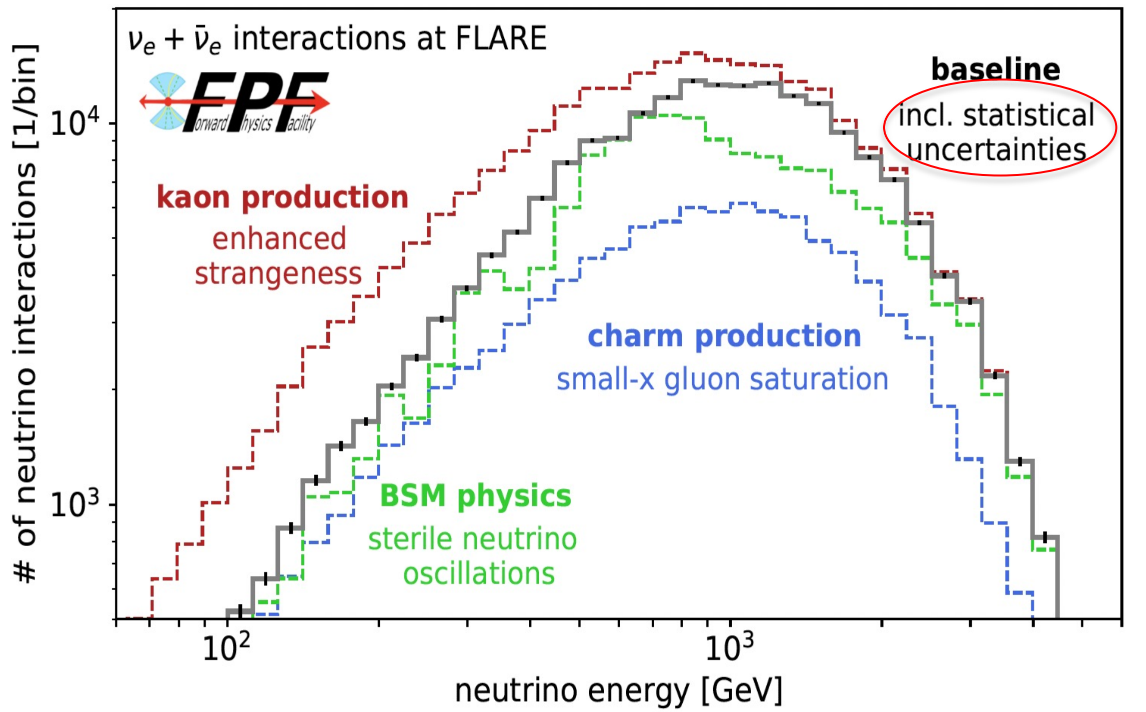


NEUTRINOS AT THE FPF

- 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.

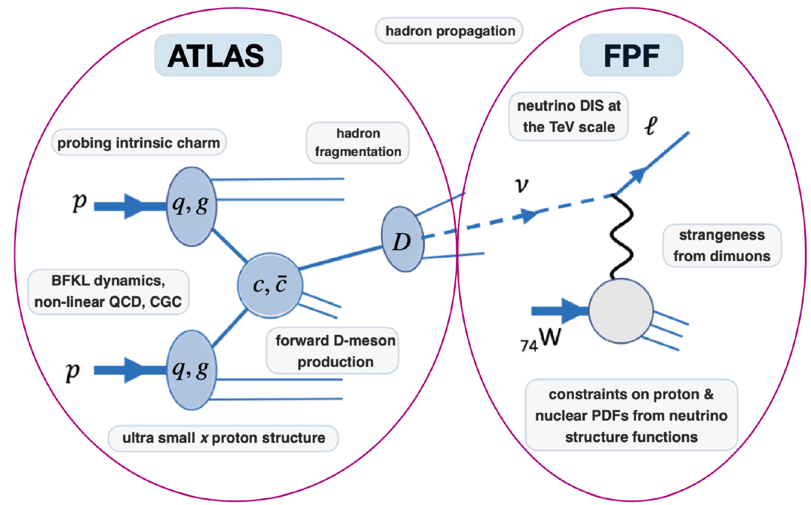


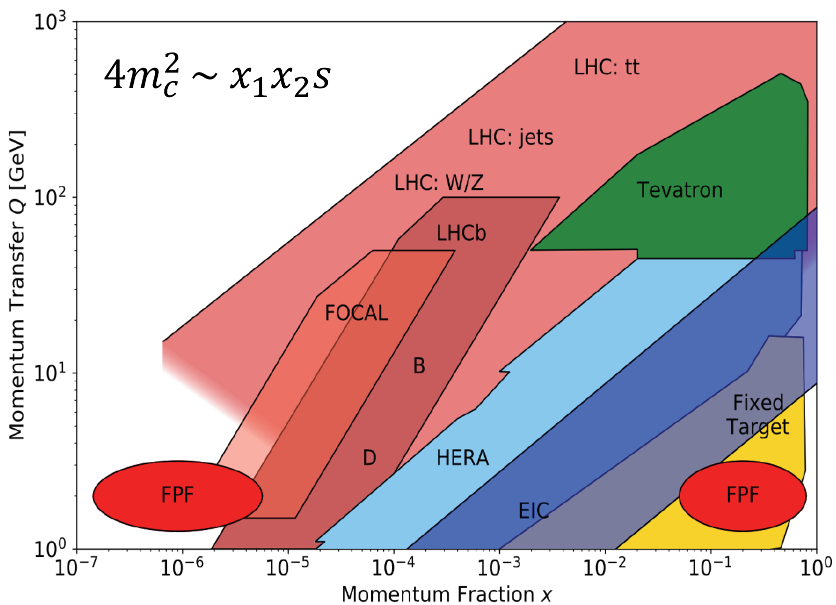
- Neutrinos are produced by forward hadron production: $\pi, K, D, \ldots$. Dependence on E, η will inform
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x ~ 10^{-1}, x ~ 10^{-7} , intrinsic charm, small-x gluon saturation, …
  - Neutrino oscillations: ν_s with $\Delta m^2 \sim 10^3\ \mathrm{eV}^2$

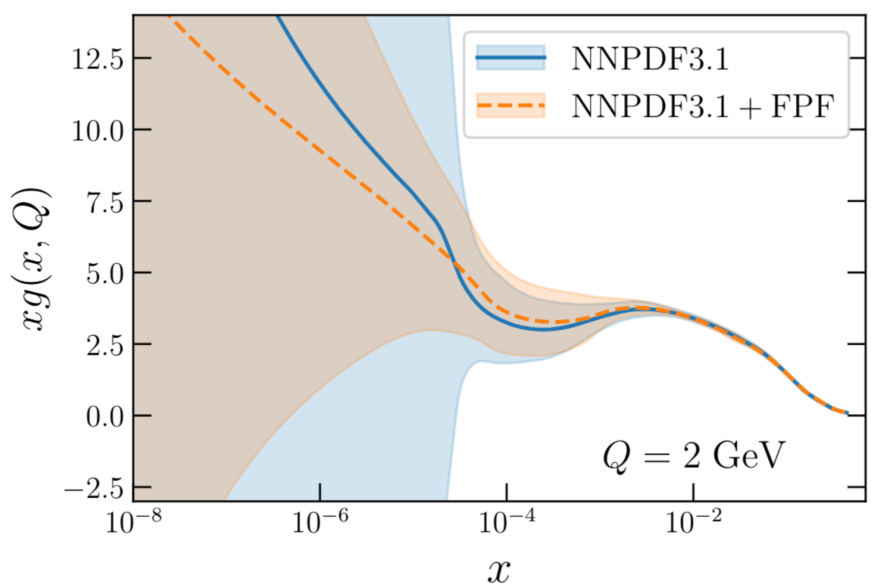


QCD AT THE FPF

- The FPF will enable 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, ATLAS/CMS at HL-LHC, …





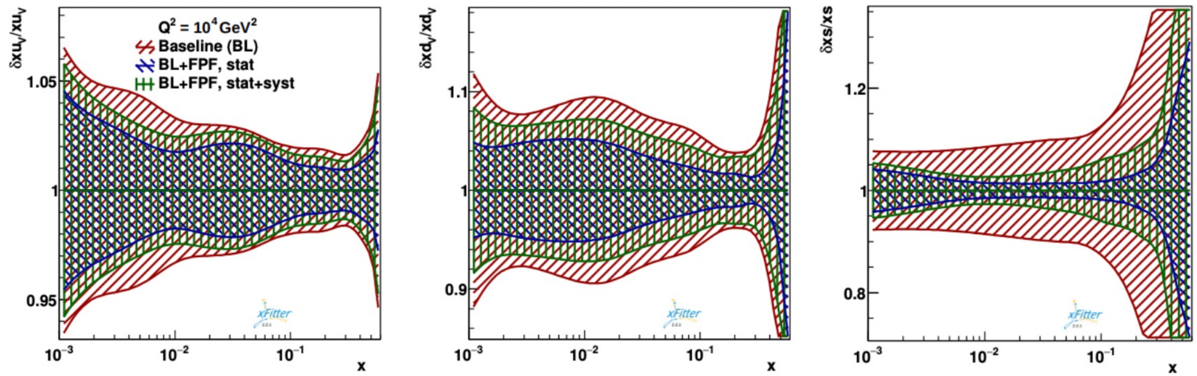


FASER White Paper (2022); Rojo et al. (2024)

COMPLEMENTARITY WITH HIGH PT PHYSICS

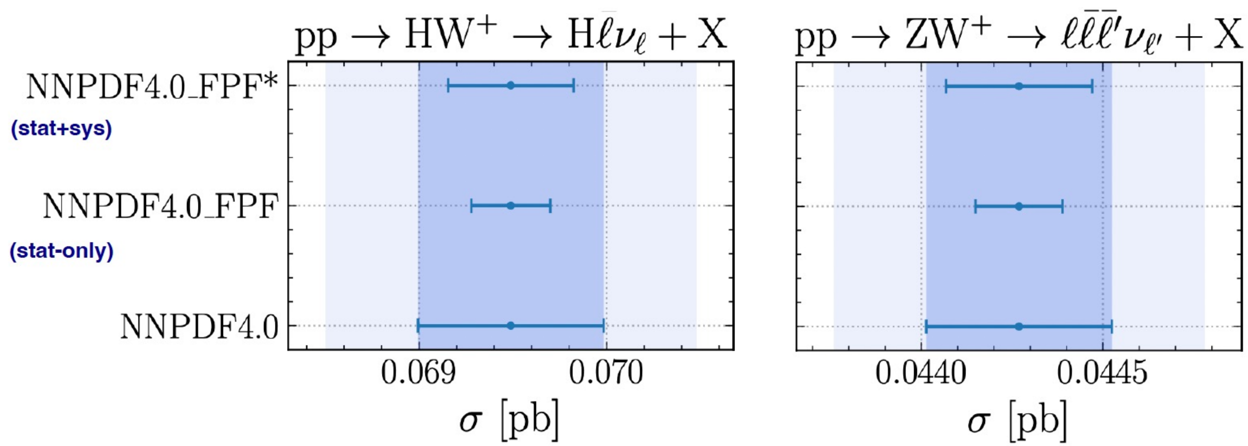
- The FPF will provide new constraints on pdfs that will sharpen studies at ATLAS and CMS.

- For example, W, Z, and Higgs boson studies.



Cruz-Martinez, Fieg, Giani, Krack, Makela, Rabemananjara, Rojo (2023)

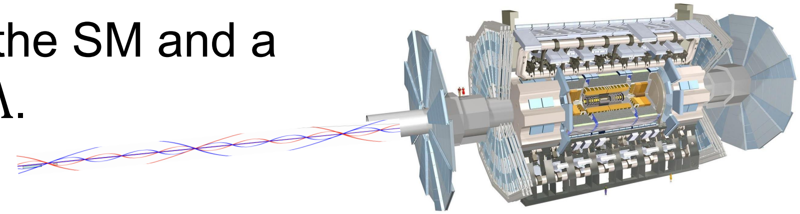
- Will also remove degeneracies between pdfs and new physics (fitting away new physics), enhancing the reach for, e.g., new resonance searches.



Ubiali et al., in progress

QUIRKS: STRONGLY-INTERACTING DARK SECTORS

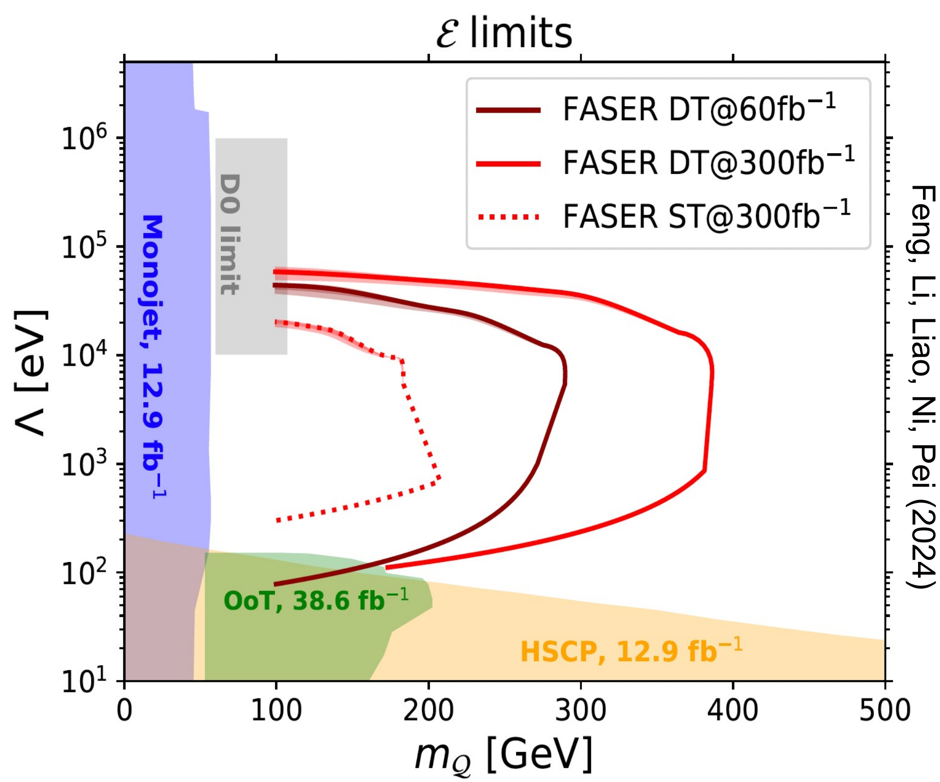
- Quirks are particles charged under both the SM and a strong-interacting dark force, with $m \gg \Lambda$.



- Quirks can be pair-produced at the LHC, but the quirk-anti-quirk pair is bound together and has $p_T \approx 0$. They therefore preferentially travel down the beampipe, and may pass through FPF detectors.

- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FASER and FASER2 can discover quirks with masses up to ~ hundreds of GeV to TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.

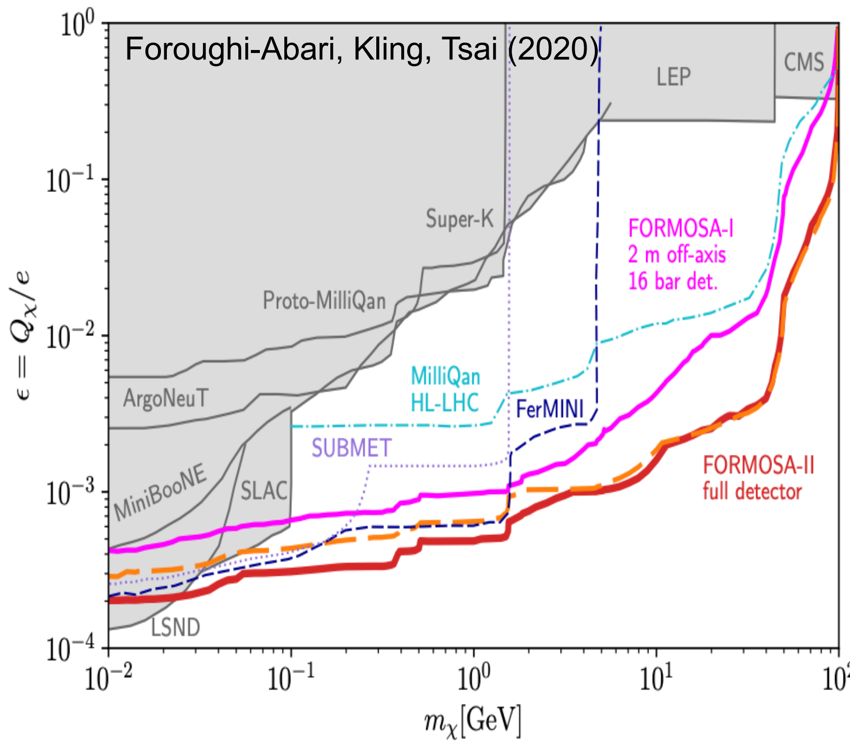
- Only possible at the EF, not at fixed target experiments.



MILLI-CHARGED PARTICLES AT THE FPF

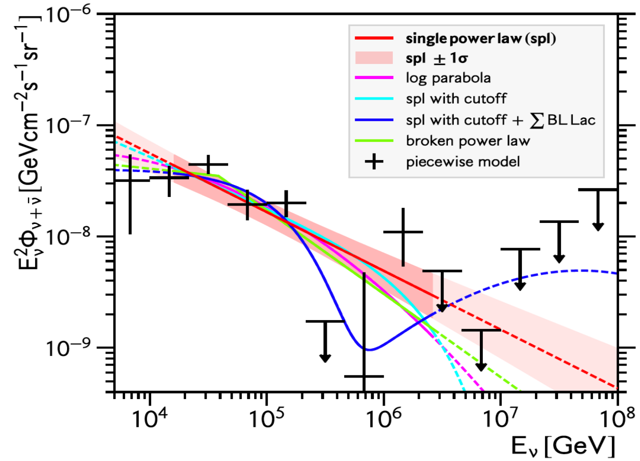
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a "non-forward" tunnel.

- 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).

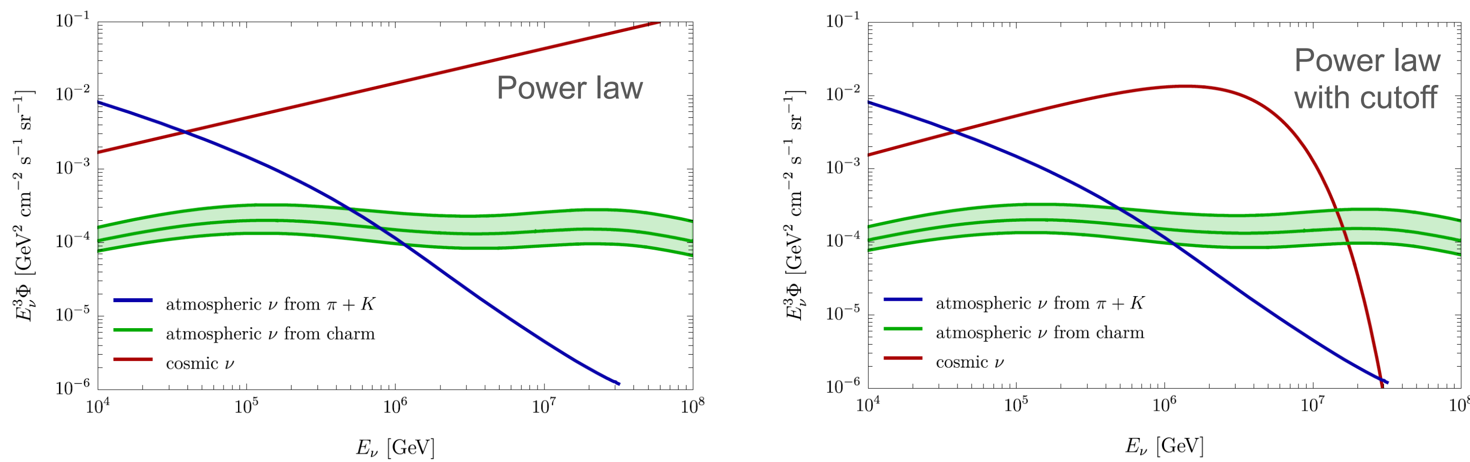


ASTROPARTICLE PHYSICS AT THE FPF

- 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



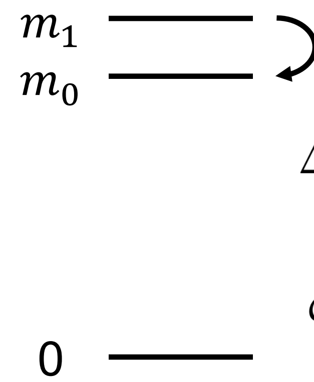
Bhattacharya et al. (1502.01076)

- 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)

LLPS FROM COMPRESSED SPECTRA

- LLPs can result from weak couplings.
- But they can also arise generically from compressed spectra (e.g., inelastic DM), where decays are phase-space suppressed by degeneracies.

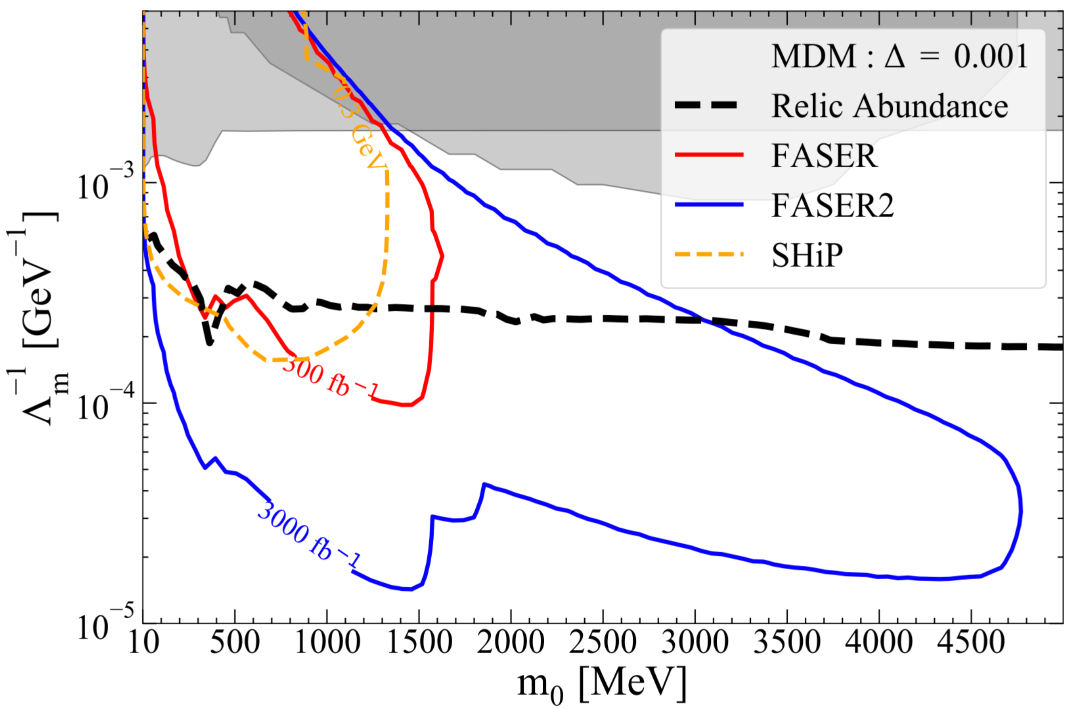


$\chi_1 \to \chi_0 \gamma$

$$\Delta \equiv \frac{\Delta m}{m_0} \equiv \frac{m_1 - m_0}{m_0}$$

$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$

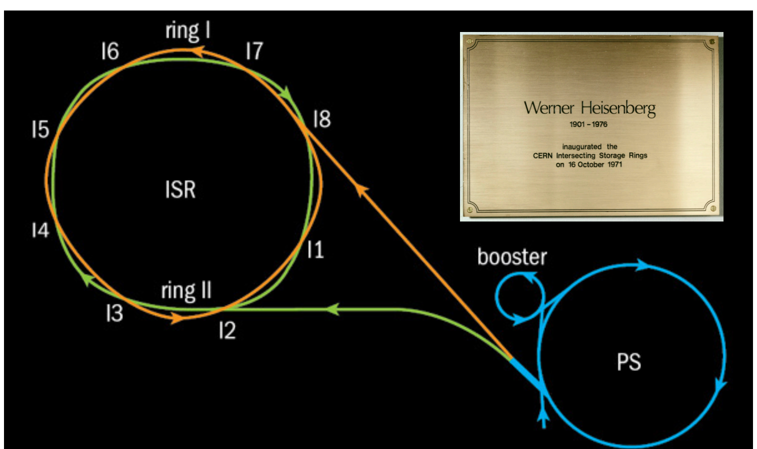
- In this case, decays $\chi_1 \to \chi_0 \gamma$ lead to very soft photons that can be difficult to detect.
- But these are boosted at the LHC by $\gamma \sim 1000$, FASER2 can detect GeV particles with even ~MeV mass splittings, thermal relic target.
- Difficult at SHiP (sensitivity contour assumes E_γ threshold of 300 MeV, 2 10^{20} POT).



Dienes et al. (2023)

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!

CONCLUSIONS

- In the last year, we have directly detected collider neutrinos for the first time, opening up a new window at the energy frontier.

- Forward experiments have a broad physics program
  - The study of collider neutrinos at TeV energies, with implications for neutrinos, QCD, astroparticle physics, and high p_T physics.
  - Searches for light (and also heavy), weakly-interacting BSM particles, including many motivated by dark matter.

- I have no doubt that neutrino detectors will be included in all future collider plans, just like trackers and calorimeters. It would be good to do this for the HL-LHC as well. The Forward Physics Facility is now being considered for the HL-LHC (2028-2040s).