FASER AND THE FPF
NEW EYES FOR THE LHC

Brookhaven Physics Colloquium

Jonathan Feng, UC Irvine, 15 October 2024

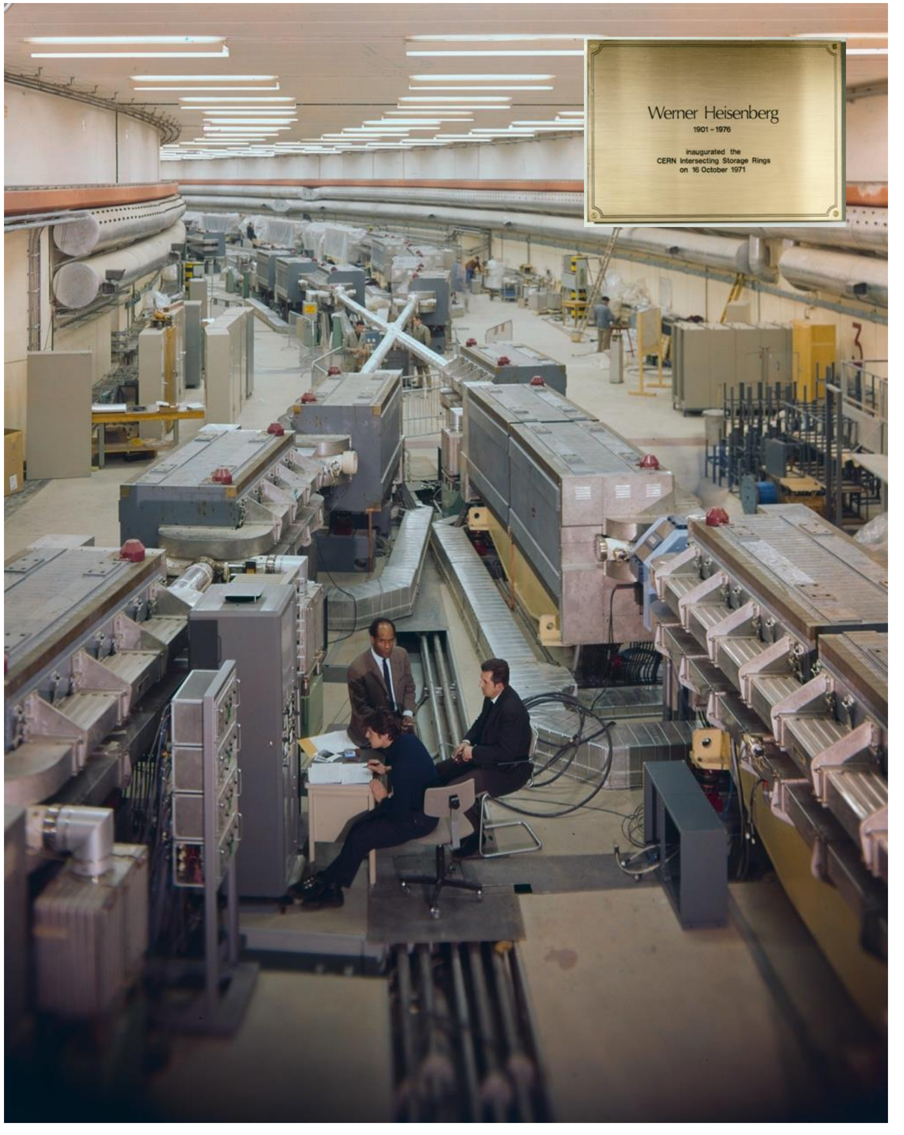
LESSONS FROM CHARM

- The charm quark was discovered here 50 years ago. What can we learn from that remarkable discovery?

- 3 years before, in 1971, the first hadron collider, CERN's Intersecting Storage Rings (ISR), began operation.

- It had a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.

- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists.



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 charm quarks, but, based on theoretical prejudice, experimentalists focused on the forward region and so missed them.

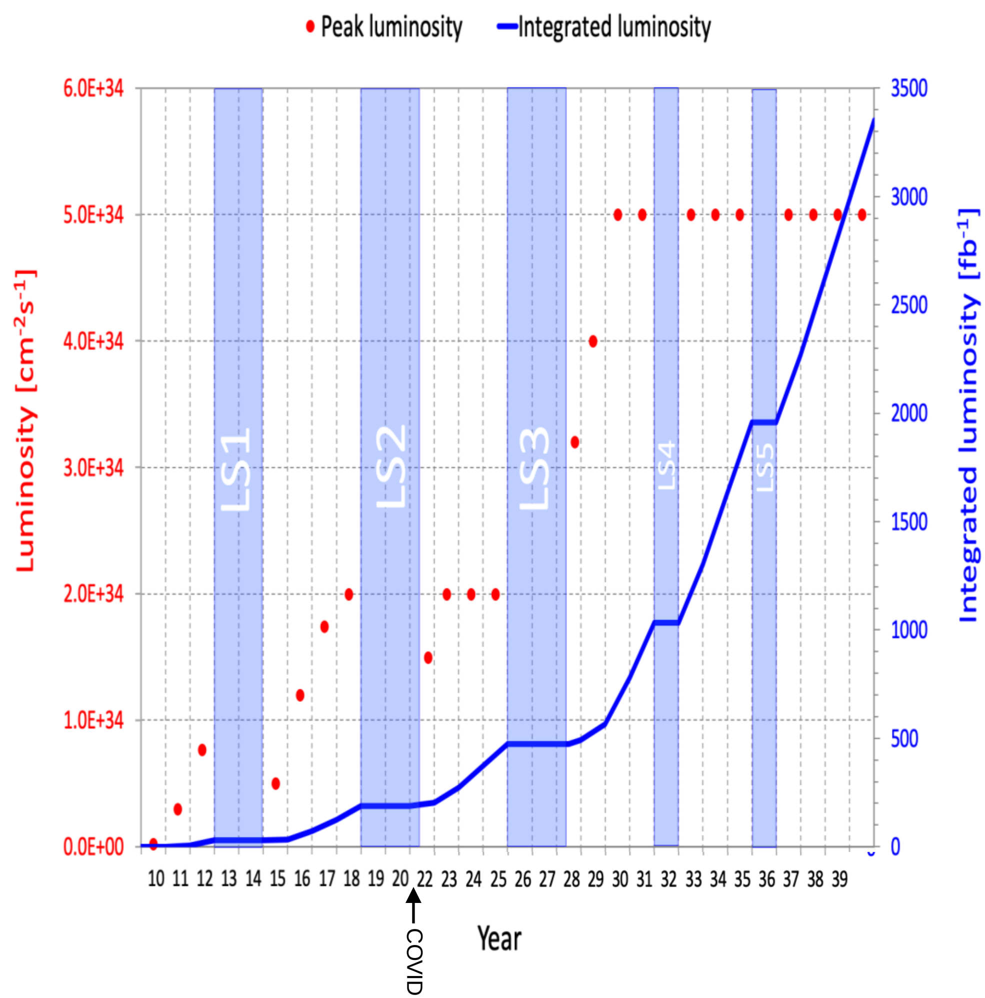
- Could we be making the same mistake now?
- If so, can we fix it?
- Could there be another November Revolution waiting for us at the LHC?

LIFETIME OF THE LHC

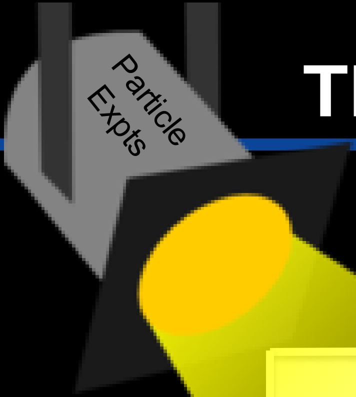
- Since their invention 70 years ago, particle colliders have been a steady source of discoveries, and the LHC is the latest example.

- The LHC started running in 2010. It is scheduled to run until the 2040s, but still has a long way to go
  - Middle-aged in terms of years
  - But a 4th grader 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



Mass

MeV GeV TeV

Interaction Strength

1

$\leftarrow g$ $u\,d$ s $p\,n$ c b t

$\leftarrow \gamma$ e μ τ $W\,Z\,h$

Already Discovered

Strongly Interacting Heavy Particles

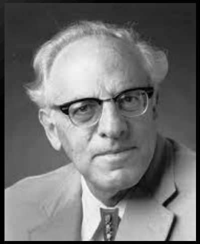
10^{-3}

$\swarrow$ $\nu_e\ \nu_\mu\ \nu_\tau$

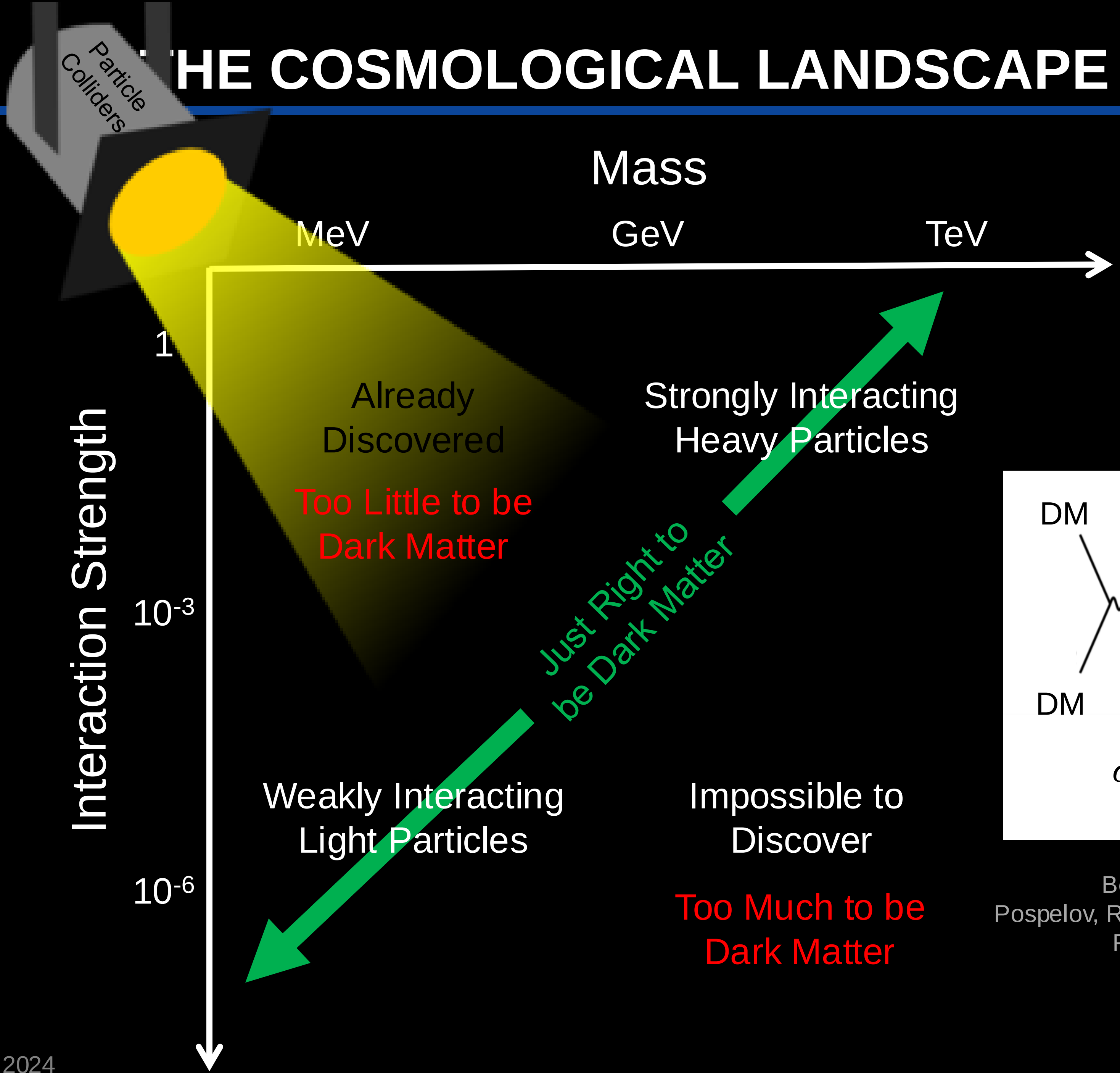
Weakly Interacting Light Particles

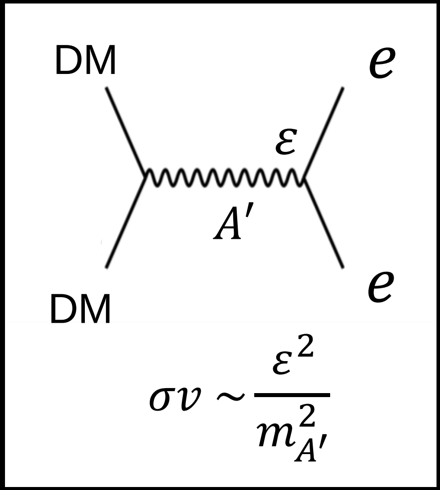
Impossible to Discover

10^{-6}



THE COSMOLOGICAL LANDSCAPE



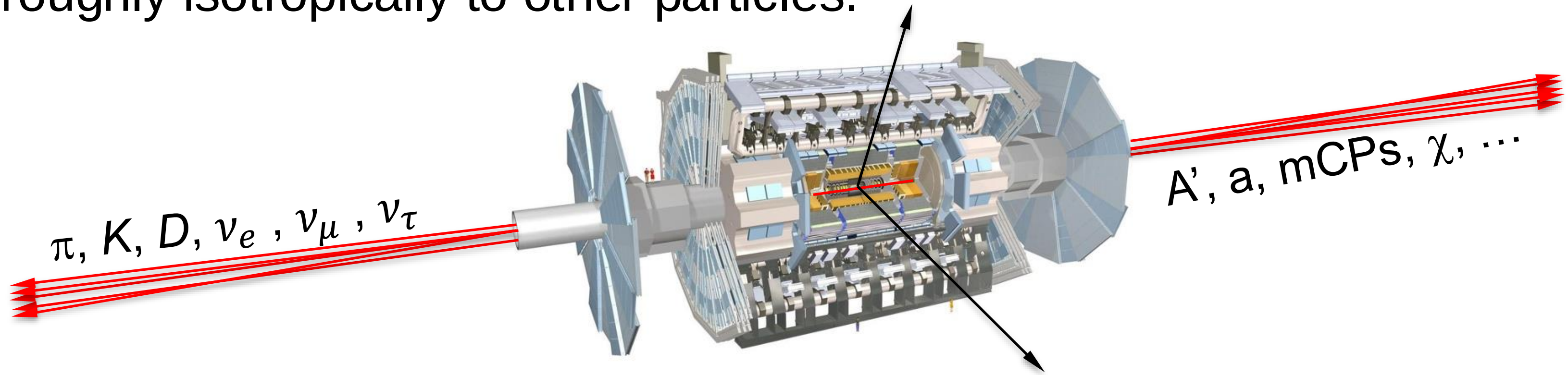


Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

FORWARD PHYSICS

- In 2017, we realized that the large LHC detectors, while beautifully optimized to discover new heavy particles, are also almost optimally configured not to find new light particles.
  Feng, Galon, Kling, Trojanowski (2017)

- Heavy particles (*W*, *Z*, *t*, *h*, …) are produced at low velocity and decay roughly isotropically to other particles.

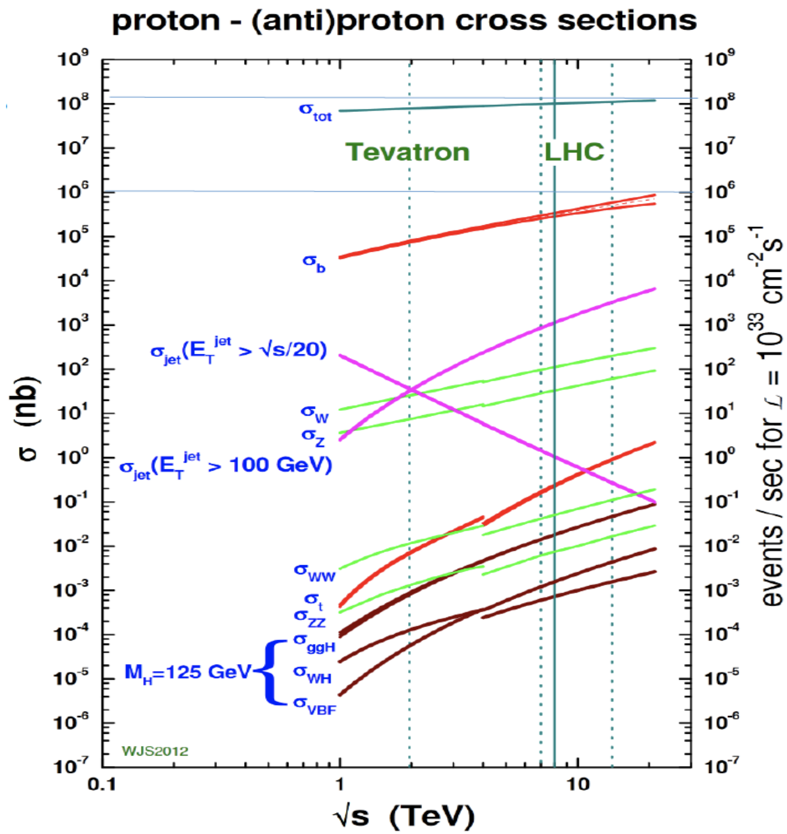


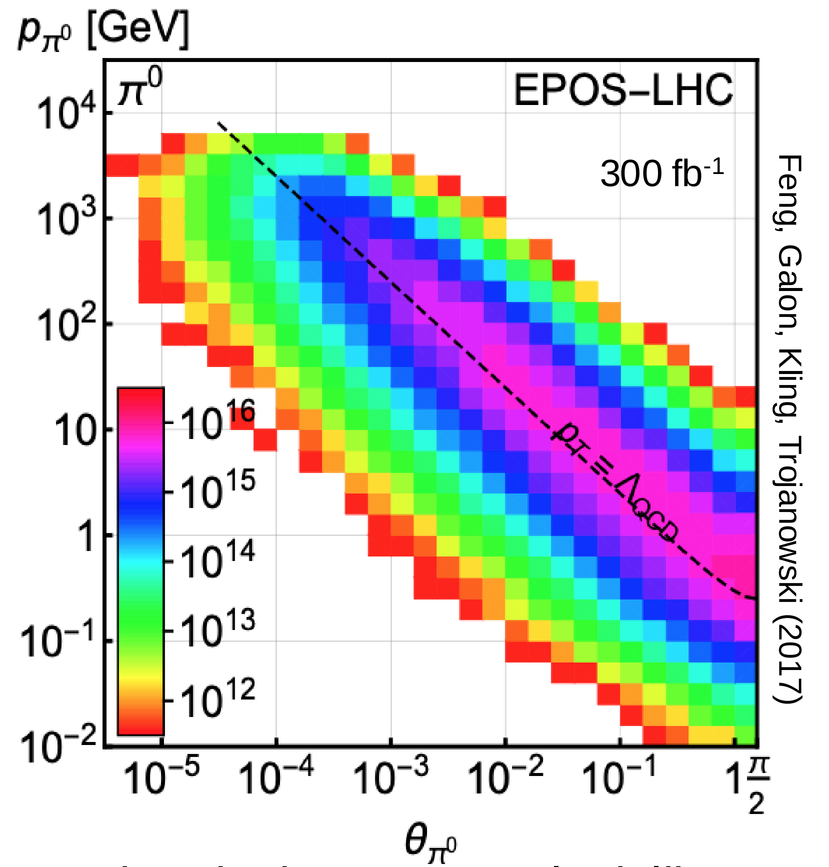
- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles: pions, kaons, *D* mesons, all neutrinos.
  - It is also true for many proposed new particles, especially those 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



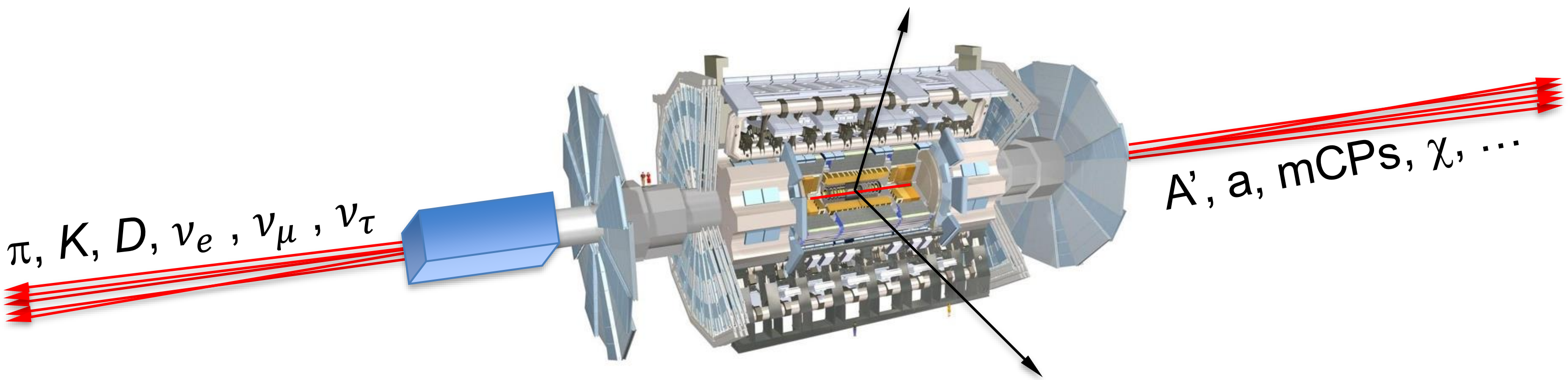


- Most searches have focused on processes with σ ~ fb, pb.
- But the total cross section is σ_{tot} ~ 100 mb and most of it is typically treated as useless.
- What do these events look like? Consider pions (decays to ν, BSM).
- Enormous event rates. Typical p_T ~ 250 MeV, but many with p ~ TeV within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

DETECTING FORWARD PARTICLES

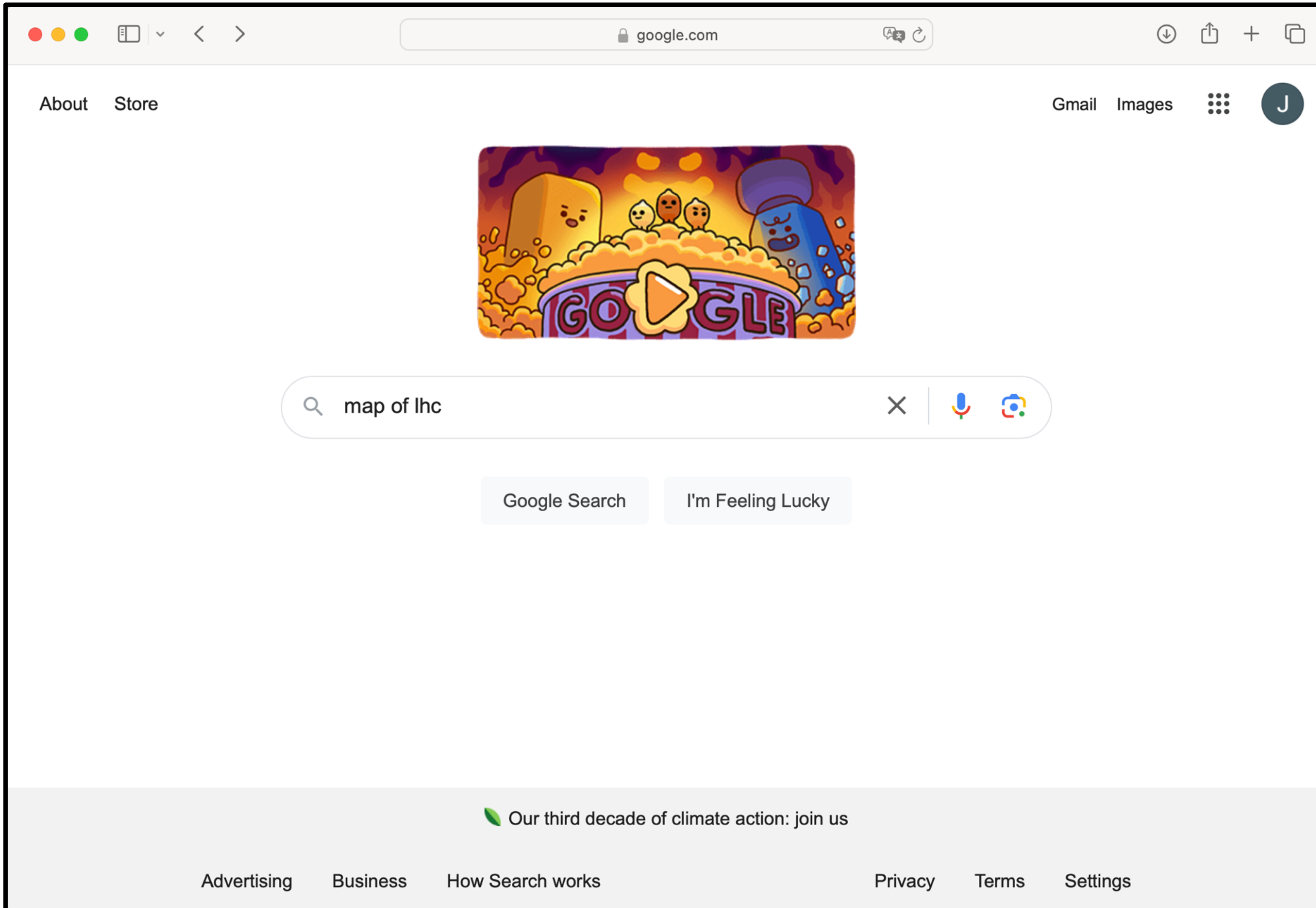
- To capture the enormous forward flux, we need to detect particles that are produced in the forward direction along the beamline.

- Problem: we can't just put the detector there: they will block the protons from coming in.

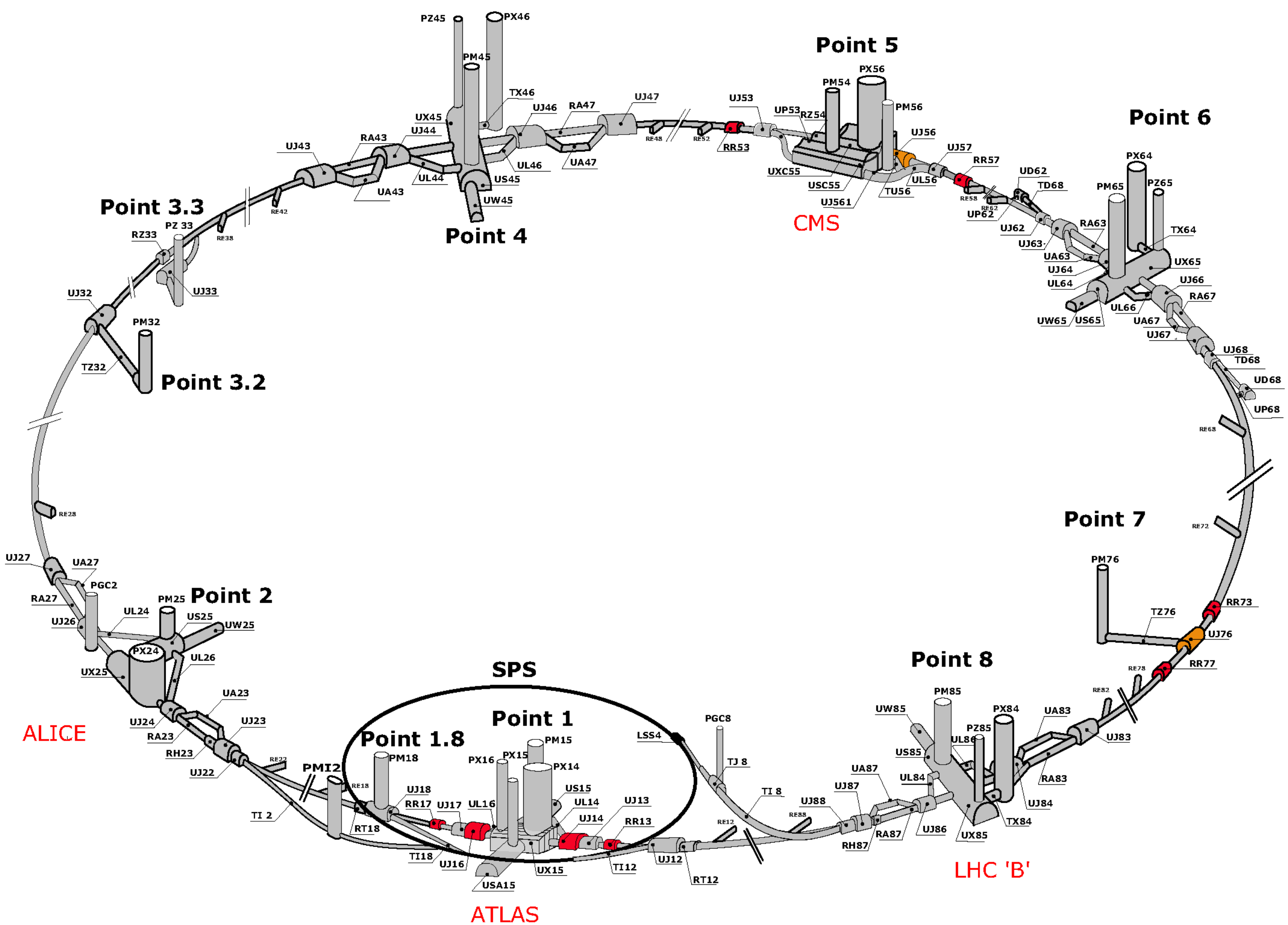


- Solution: the LHC is a circular collider! If we go far enough away, the LHC proton beam will curl away, while all the light, weakly-interacting particles we are looking for will go straight.

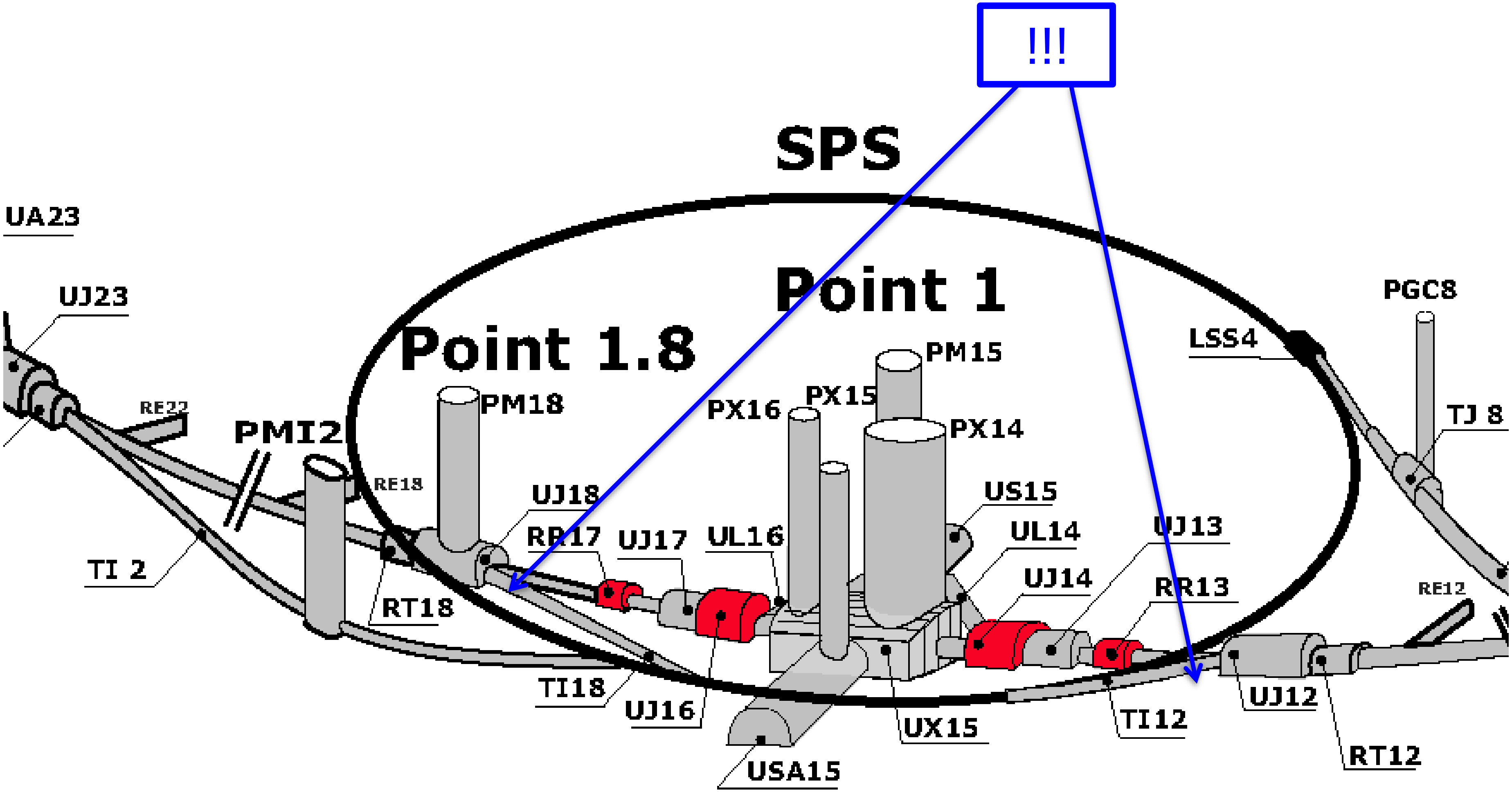
SOPHISTICATED RESEARCH



MAP OF LHC

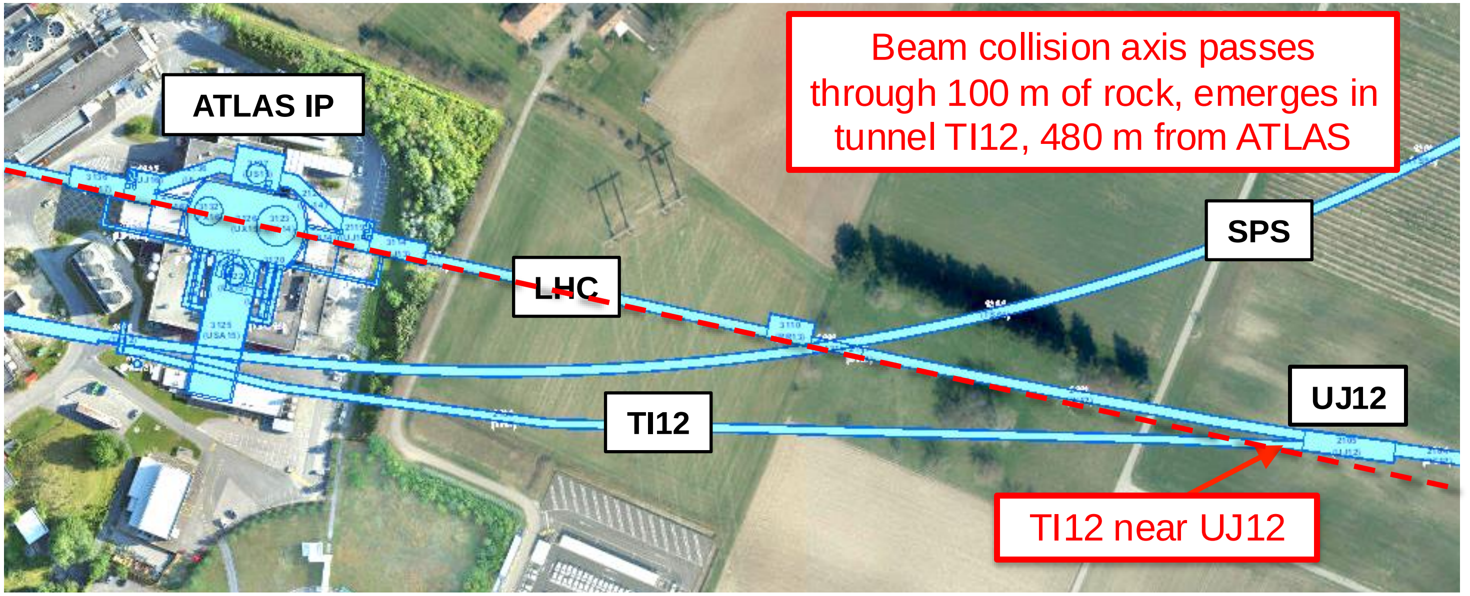

Point 5
CMS
Point 6
Point 4
Point 3.3
Point 3.2
Point 7
Point 2
ALICE
SPS
Point 1
Point 1.8
ATLAS
Point 8
LHC 'B'

MAP OF LHC



ATLAS

THE FORWARD REGION

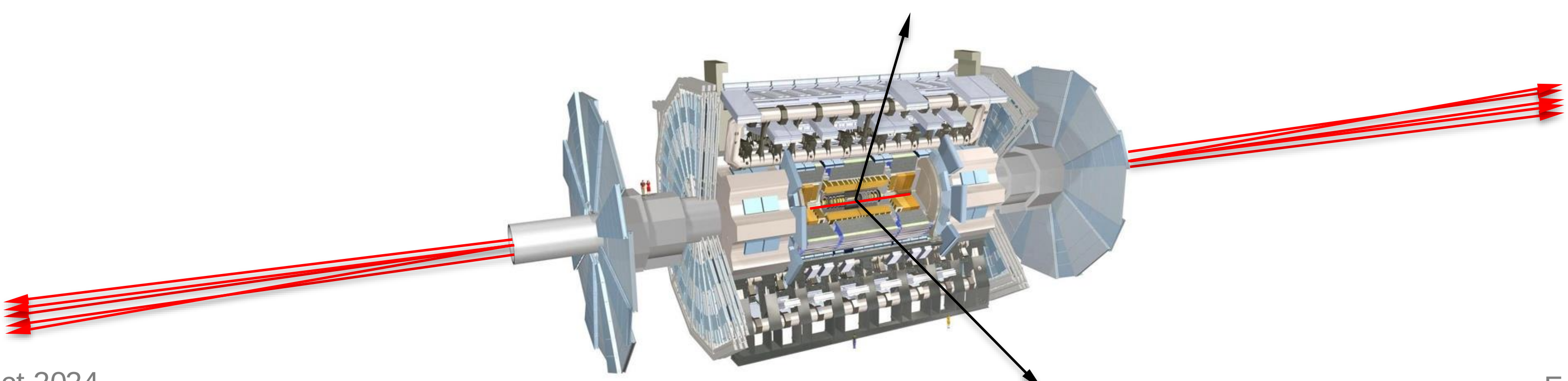


HOW BIG DOES THE DETECTOR HAVE TO BE?

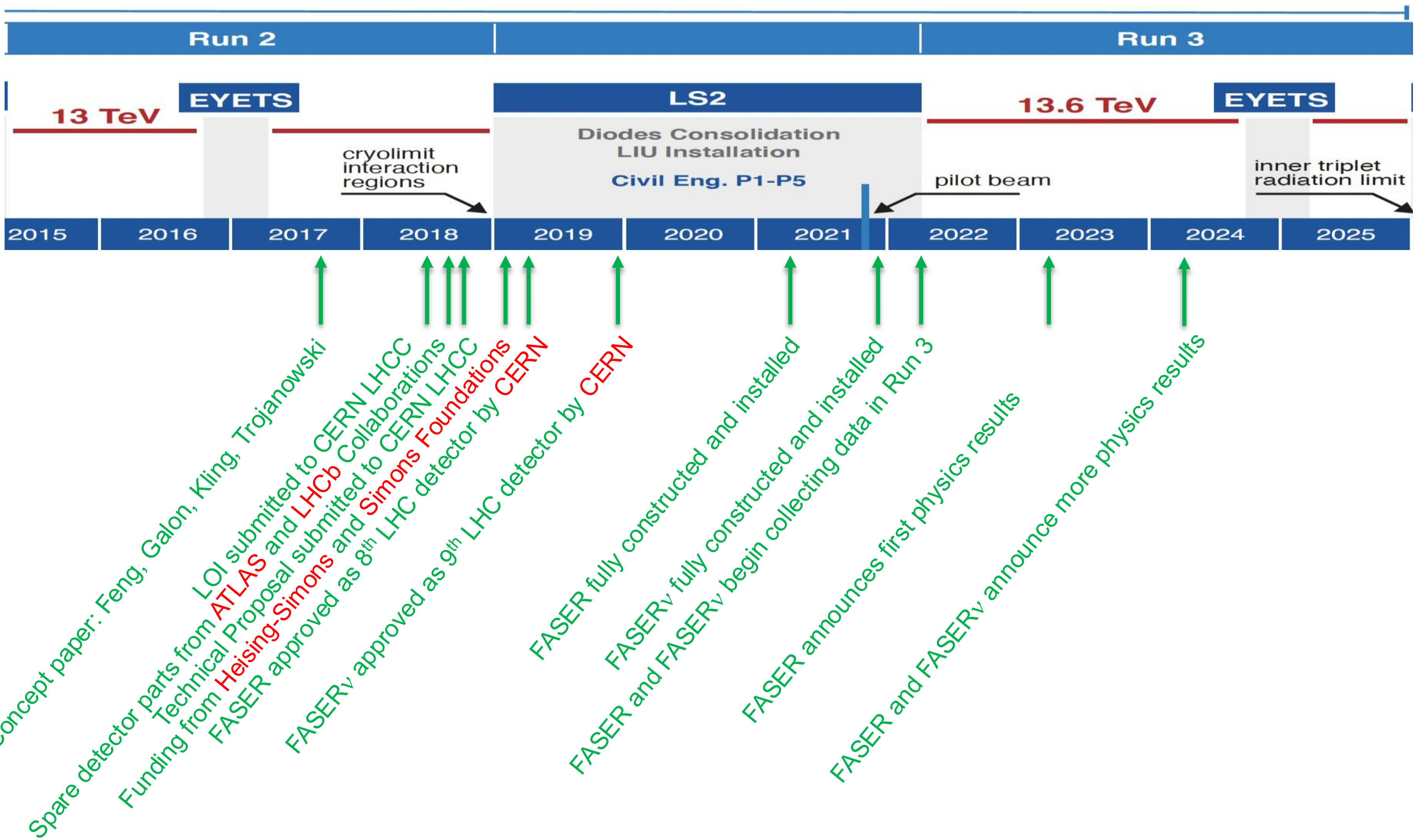
- Momentum: 1 TeV, 250 MeV
- Space: 480 m, 12 cm

- 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 much 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



FASER COLLABORATION

111 collaborators, 28 institutions, 11 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

CHIBA UNIVERSITY

UNIVERSITY OF OREGON

DESY.

INFN

ISS

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

ZHENGZHOU UNIVERSITY

NATIONAL INSTITUTE OF TECHNOLOGY (KOSEN), NIIHAMA COLLEGE

UNIVERSITY OF SUSSEX

Nikhef

UNIVERSITÄT BONN

ETH zürich

UKRI Science and Technology Facilities Council
Rutherford Appleton Laboratory

MANCHESTER 1824
The University of Manchester

PREPARATION OF THE FASER LOCATION

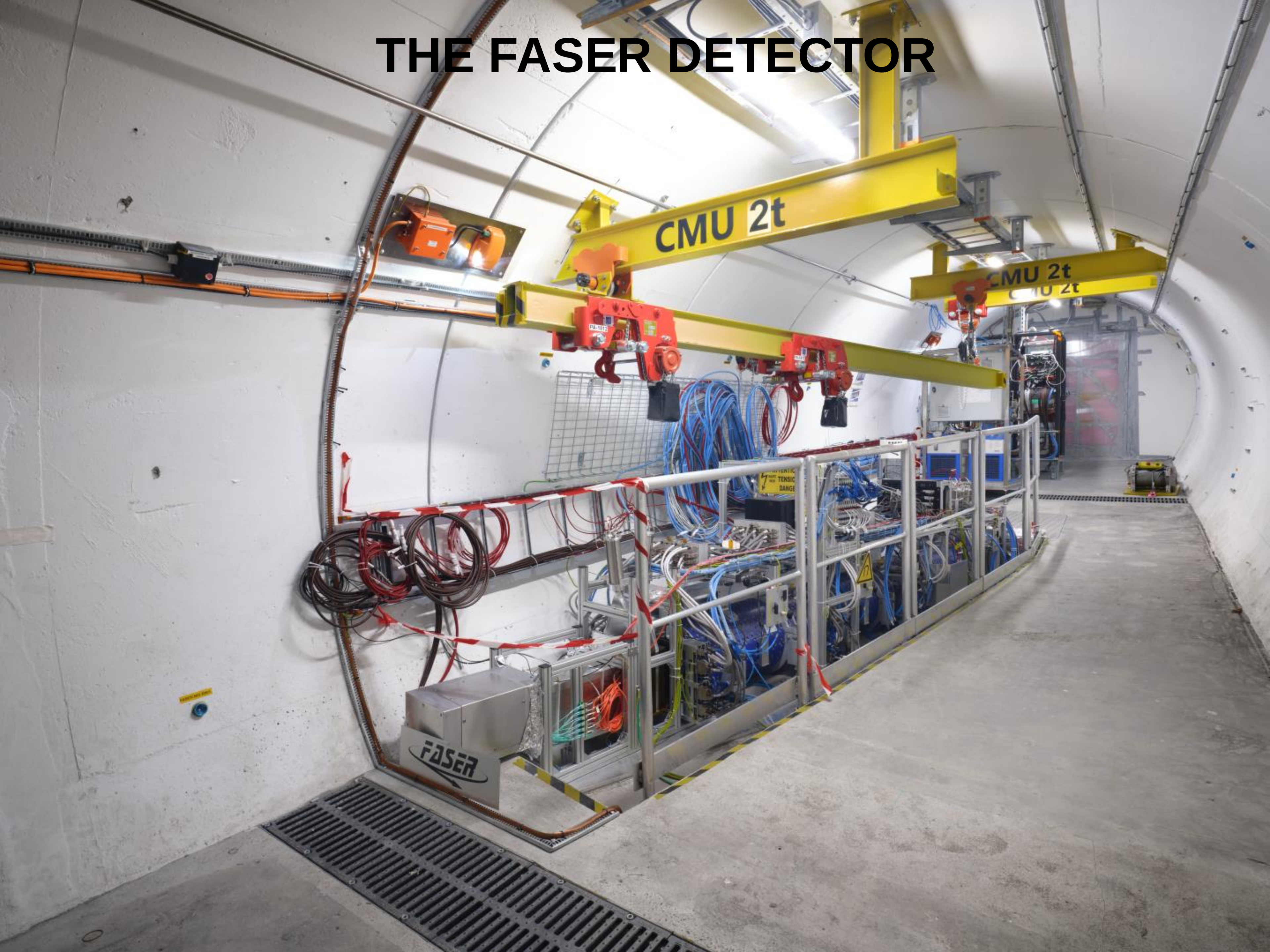
- The nominal beam collision axis was located to mm accuracy by the CERN survey department. (In fact, it goes moves around by several cm, depending on the beam crossing angle and orientation.) To place FASER on this axis, a trench was required to lower the floor by 46 cm.

- 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

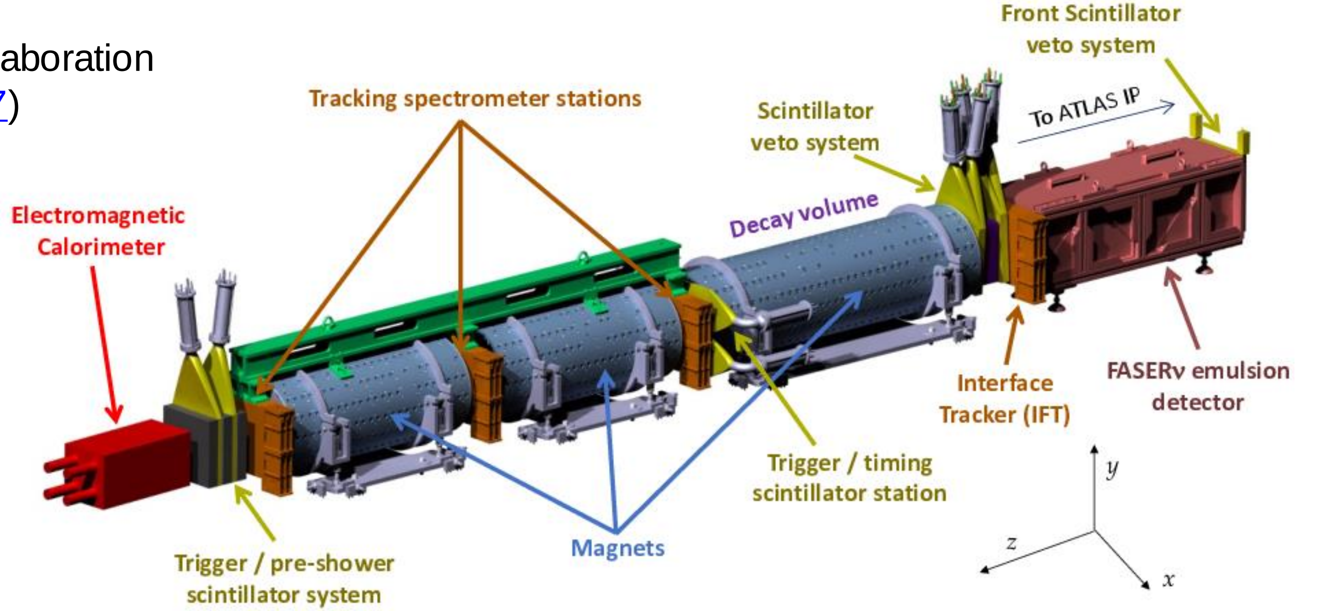


THE FASER DETECTOR

- Design challenges: small (no room), low maintenance (no access), fast (no time).
  - Size: Total length ~ 5 m, decay volume: R = 10 cm, L = 1.5 m.
  - Magnets: 3 permanent dipoles (Halbach design), 0.57 T, deflect charged particles in y.
  - Tracker: composed of 4 stations x 3 layers x 8 mod. = 96 ATLAS SCT modules.
  - Calorimeter: composed of 2 x 2 LHCb ECAL modules.
  - Scintillators: 4 stations, each 1-2 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 muons, must be replaced after ~30 fb^{-1}.

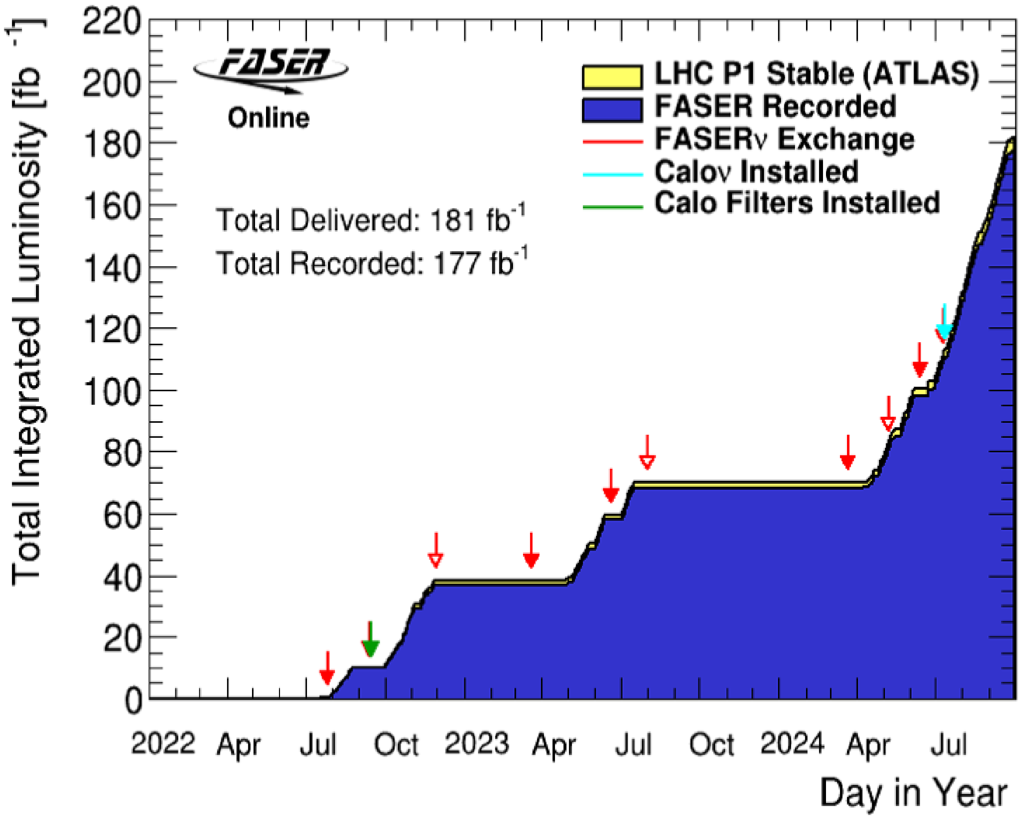
- The experimental environment: 88 m underground, shielded from ATLAS by 100 m of rock → extremely quiet. Trigger on everything, ~kHz trigger rate dominated by muons from ATLAS.

FASER Collaboration
(2207.11427)



FASER DATA TAKING 2022 - PRESENT

- FASER was constructed in 18 months. We saw our first cosmic ray event on 18 March 2021.
- After LS2 from 2018-2021, the LHC started running again in Jul 2022, and again in 2023 and in 2024.
- FASER began recording data immediately.
  - Recorded 97% of delivered luminosity
  - Largely automated: no control room, 2 shifters controlling and monitoring the expt from their laptops

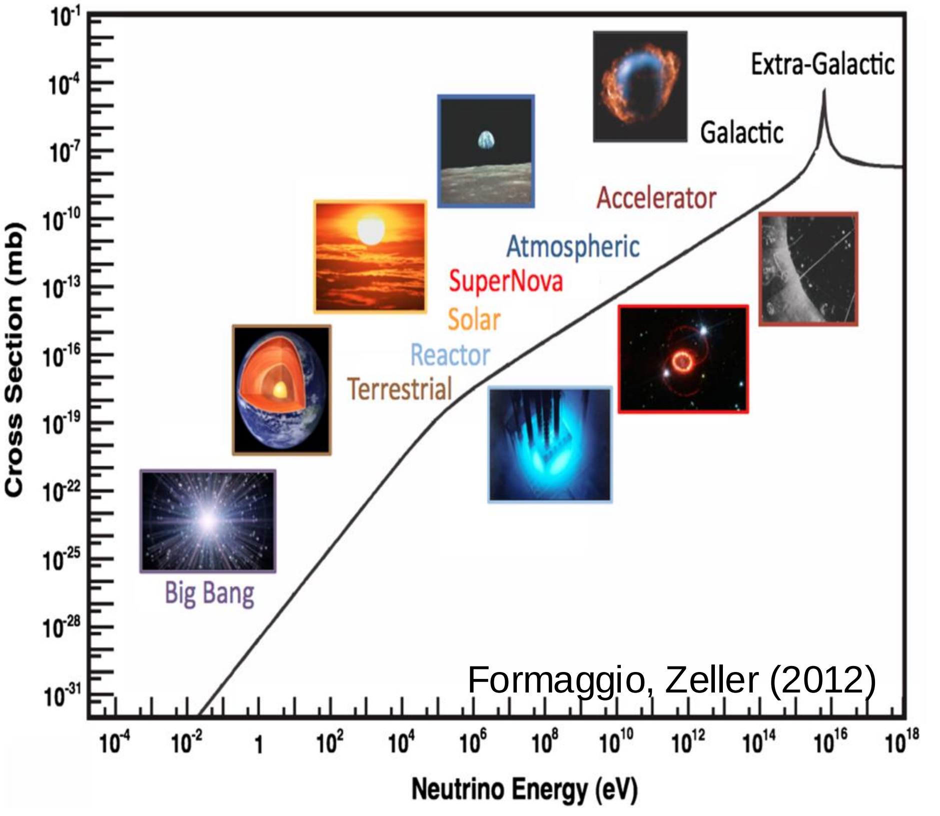


- FASERν emulsion exchanged periodically to prevent overexposure
  - 3 boxes in 2022 (0.5, 10, 30 fb^{-1})
  - 2 boxes in 2023 (20, 10 fb^{-1})
  - 2 boxes in 2024 (10, 10 fb^{-1})

COLLIDER NEUTRINOS

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

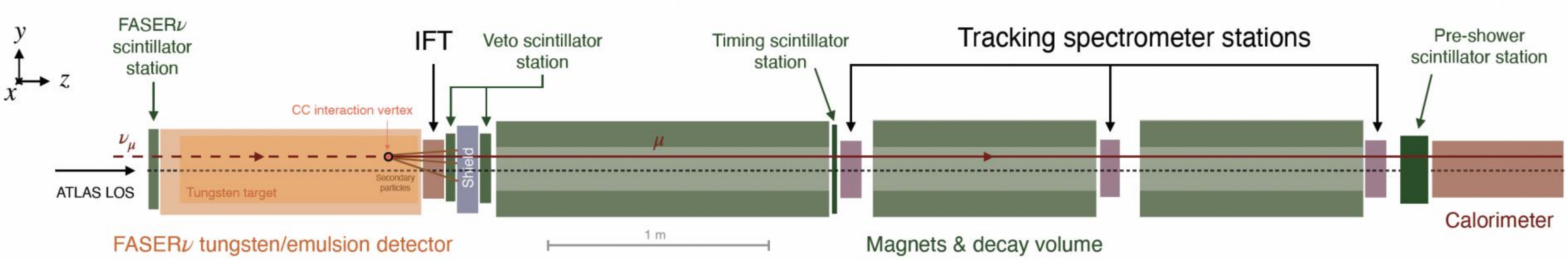
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.



- But before FASER, neutrinos produced at a particle collider had never been directly observed
  - Conventional wisdom: neutrinos interact very weakly so cannot be detected.
  - The reality: the highest energy ones, which are most likely to interact, 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)

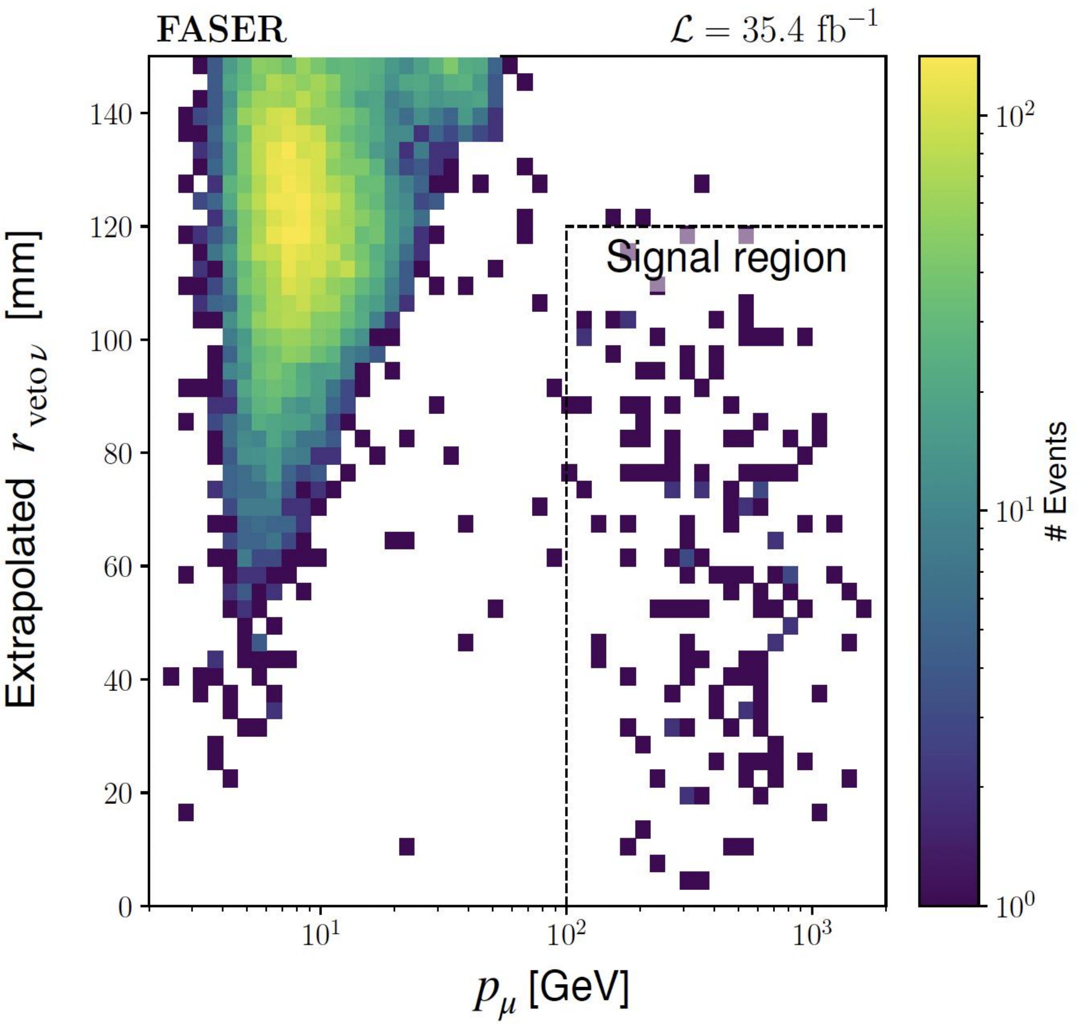
- The signal is no charged particle passing through the upstream veto scintillators, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

- 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.



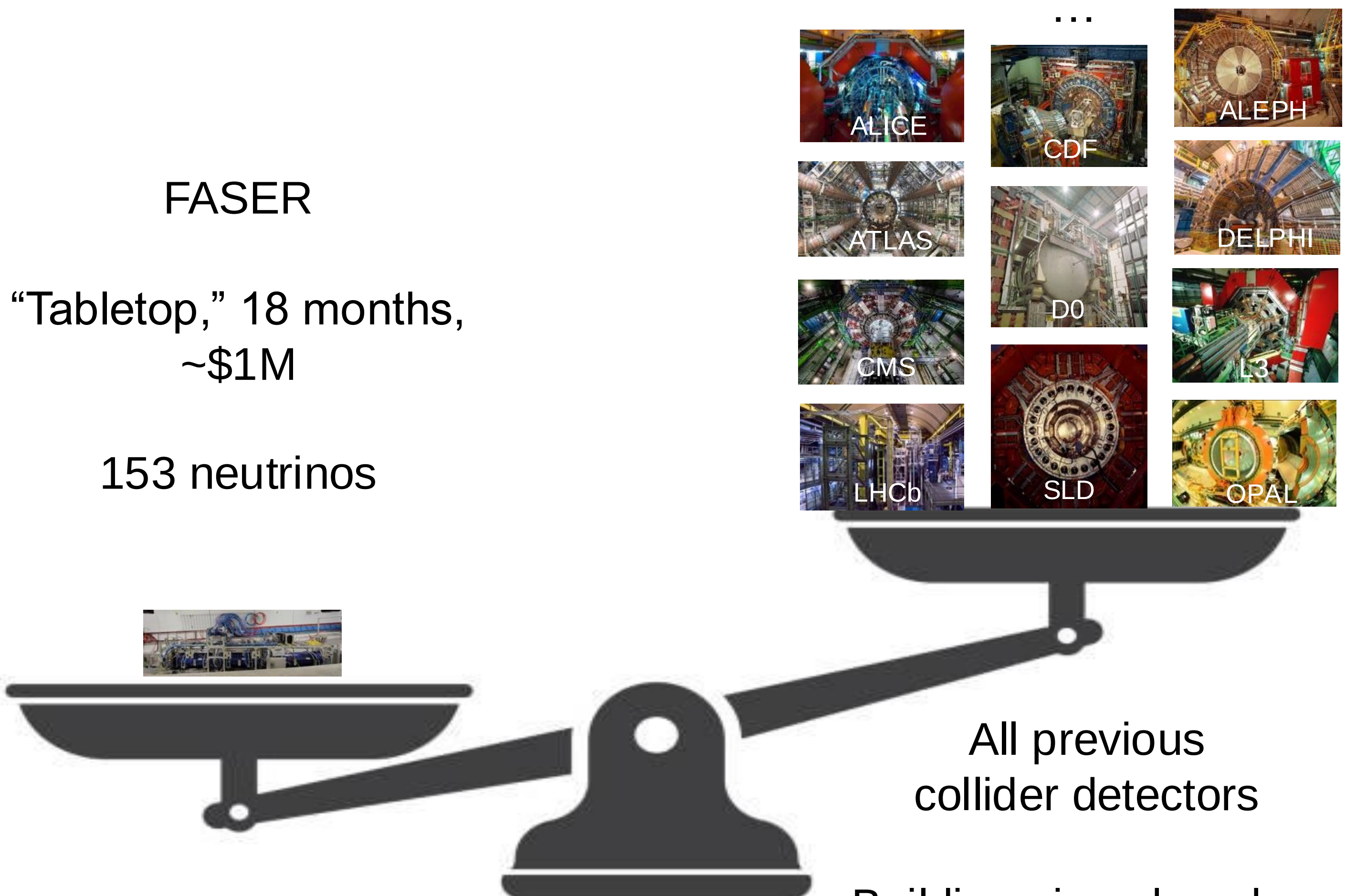
FASER Collaboration (2303.14185, PRL)

LOCATION, LOCATION, LOCATION

FASER

"Tabletop," 18 months,
~$1M

153 neutrinos



All previous
collider detectors

Building-size, decades,
~$1B

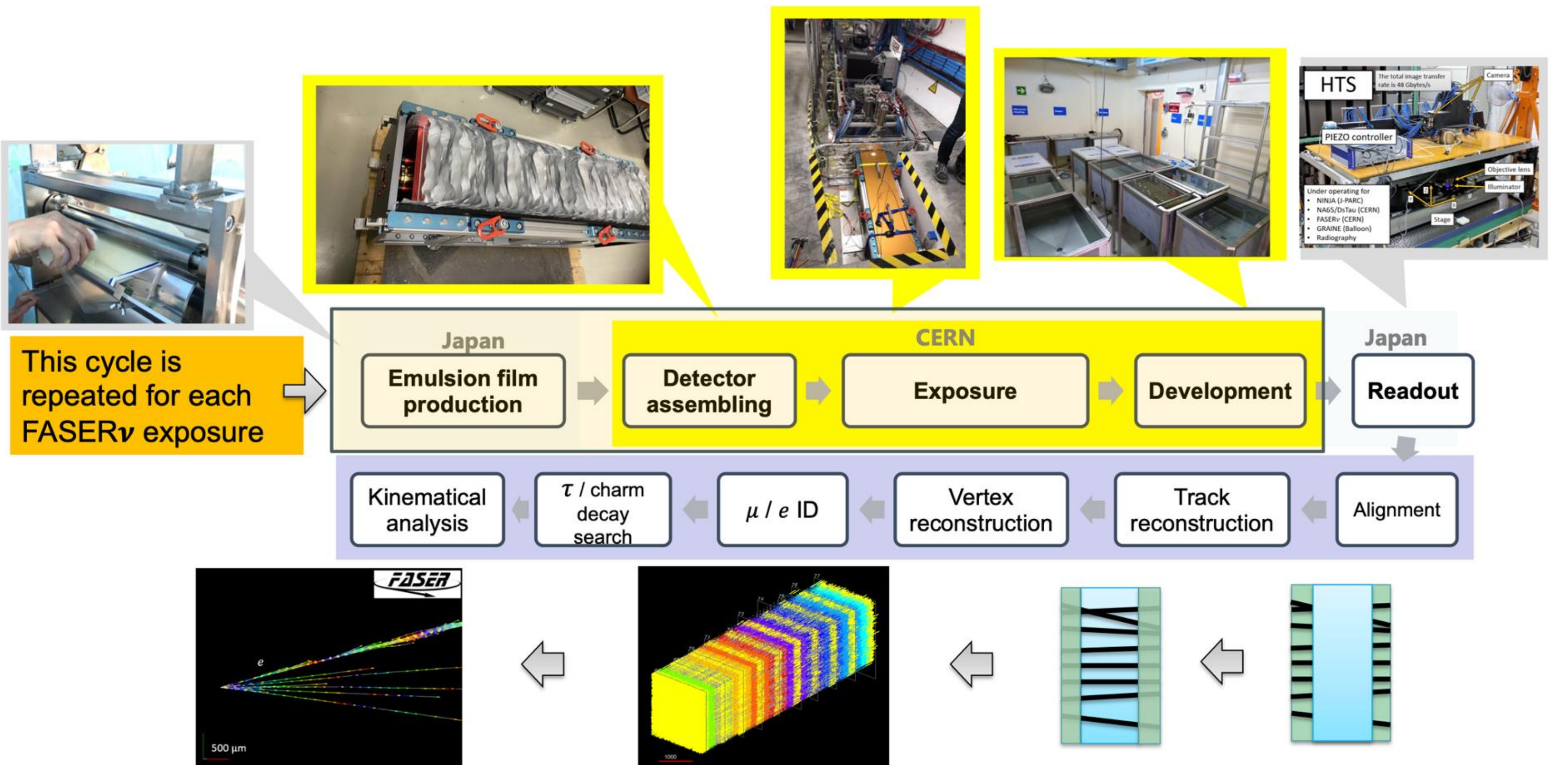
0 neutrinos

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

DISCOVERY OF COLLIDER NEUTRINOS

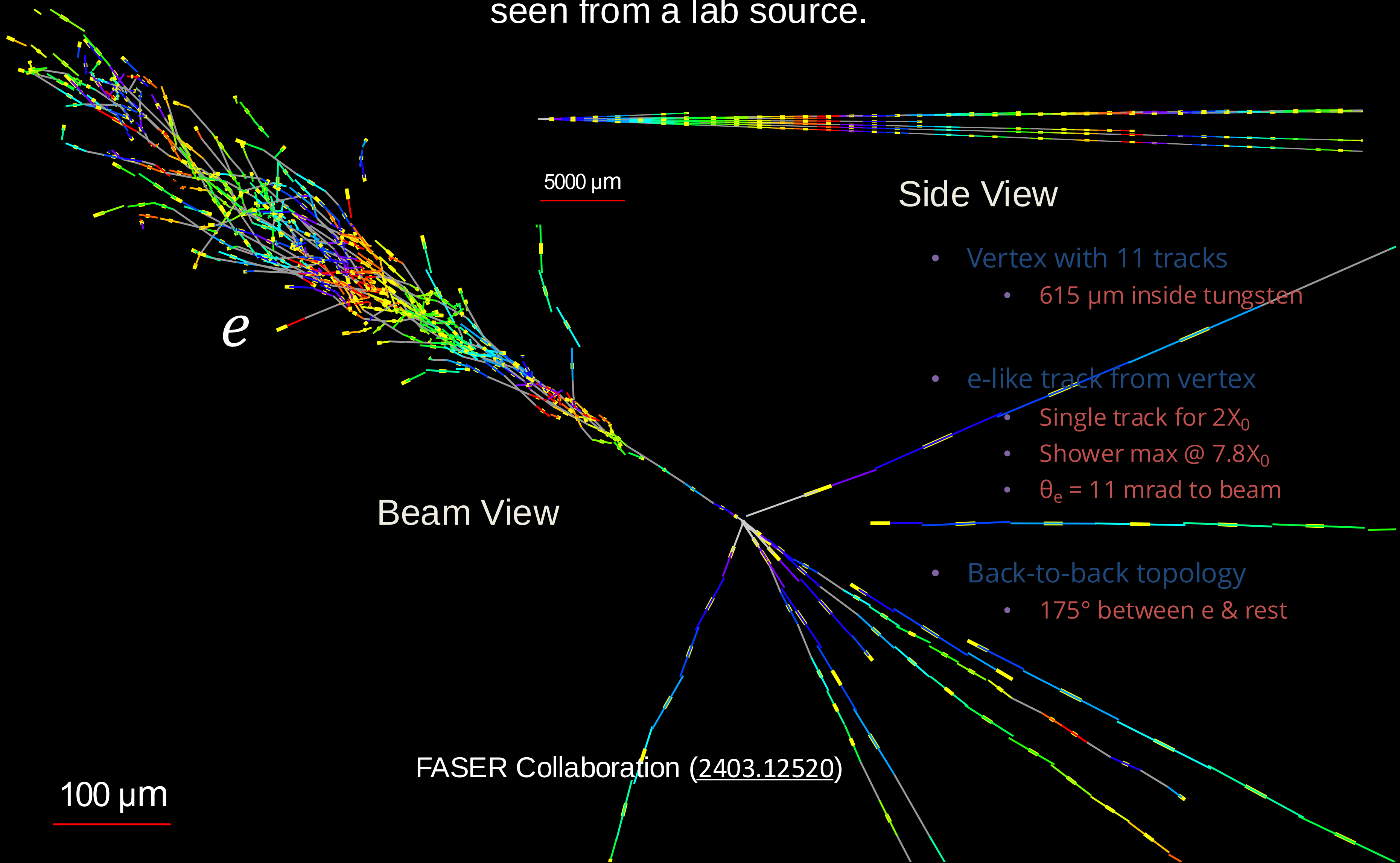
NEUTRINOS IN FASERν

- At the front of FASER is FASERν, a 1.1-ton block of interleaved tungsten and emulsion plates. The first neutrino analysis treated this as a big block of matter, but the emulsion provides far more detailed information.
- Emulsion is essentially old-fashioned photographic film, has unmatched spatial resolution (~0.5 microns).



NEUTRINOS IN FASERν

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 ever seen from a lab source.



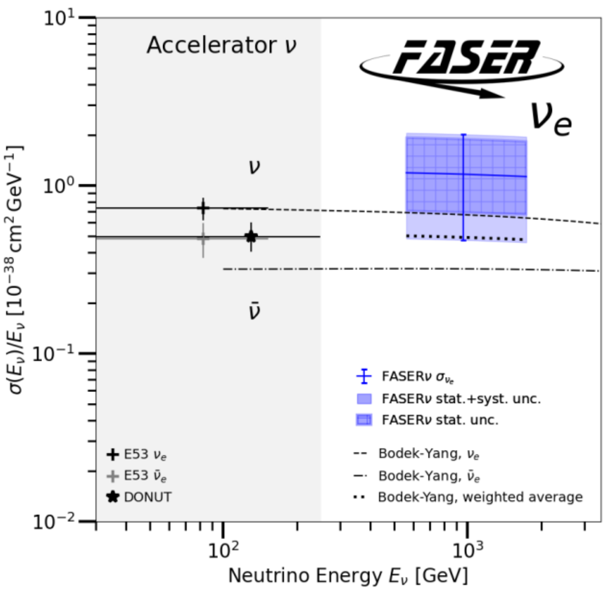
- Vertex with 11 tracks
  - 615 µm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

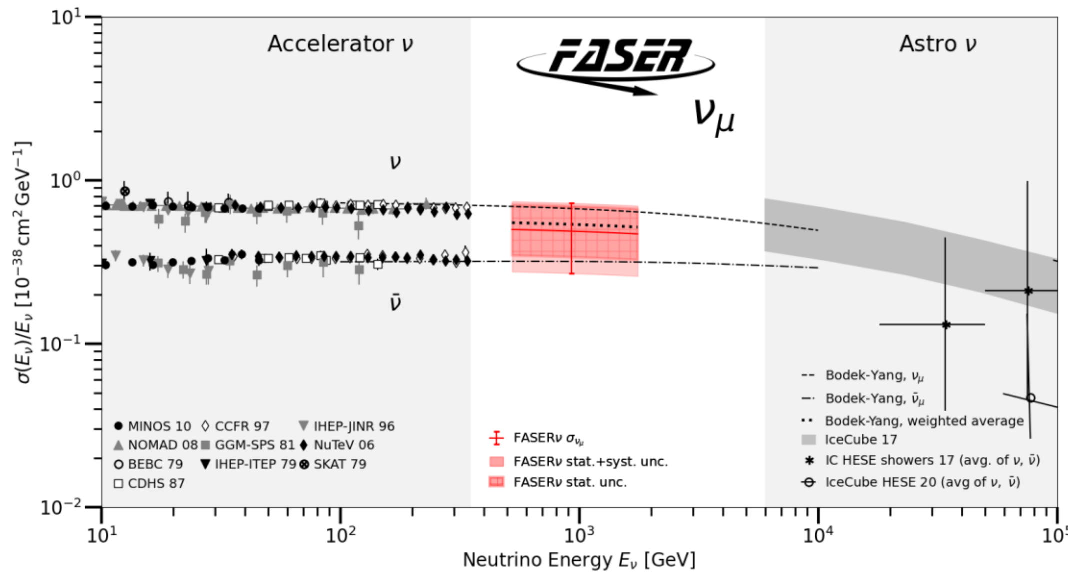
FASER Collaboration (2403.12520)

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.



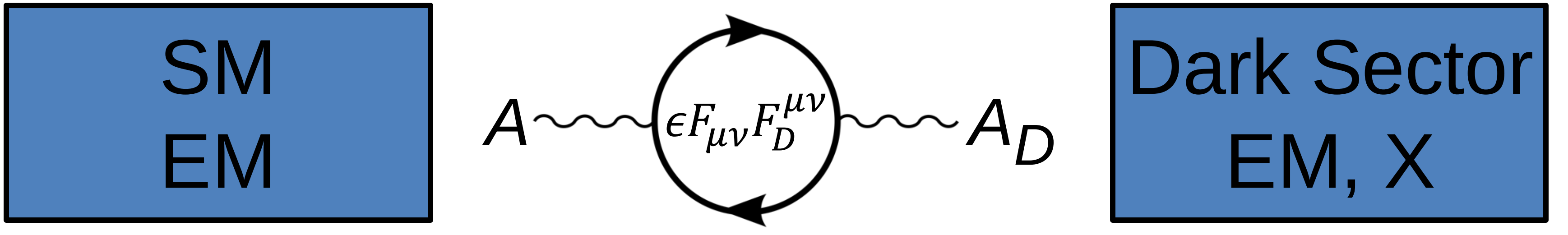


FASER Collaboration (2403.12520)

- These measurements use only 1.7% of the data collected in 2022 and 2023. Much more to come; we expect to triple the world's supply of tau neutrinos, identify the first anti-tau neutrino, ….

NEW PARTICLE SEARCHES

- FASER can also look for 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.



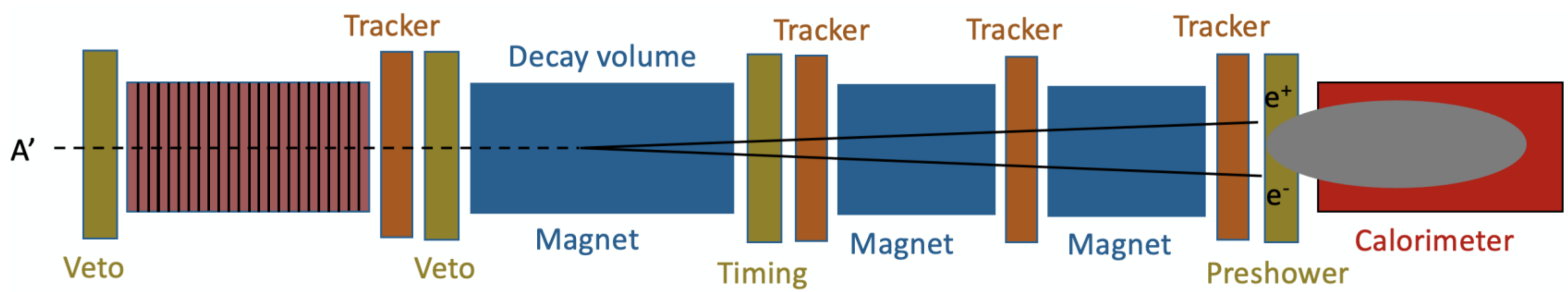
- The result? Dark photons A' , like photons, but with mass $m_{A'}$, couplings suppressed by ϵ.

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.

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 $A' \rightarrow e^+e^-$.



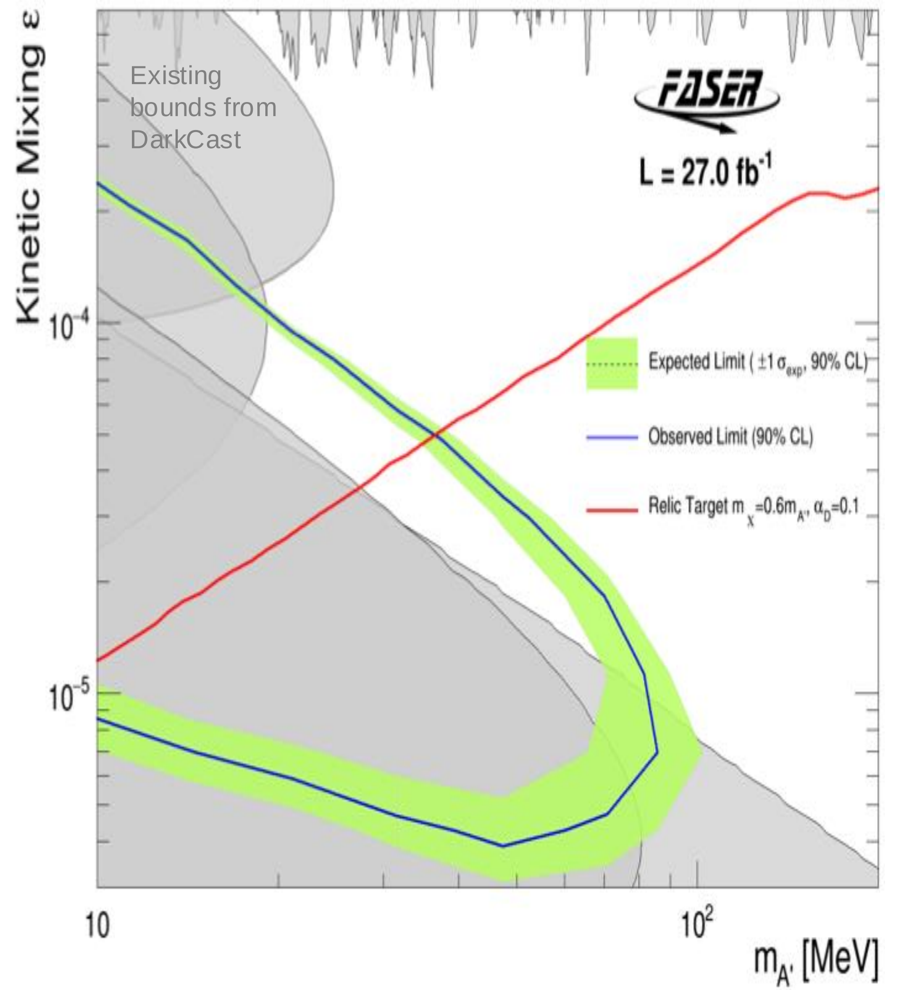
- The signal is no charged particle passing through the upstream veto scintillator detectors, followed by two very energetic (100s of GeV) charged tracks in downstream trackers. Tracks are very collimated, but magnet splits them sufficiently to be seen as 2 tracks in trackers.

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.

- Bodes well for the future
  - Background-free analysis
  - Started probing new parameter space in the first day of running
  - Ended up ~100 times more sensitive than previous experiments
  - Improvements in analysis and 40 times more data to come

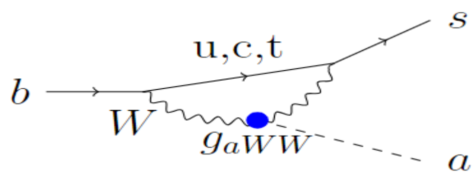


FASER Collaboration (2308.05587, PLB)

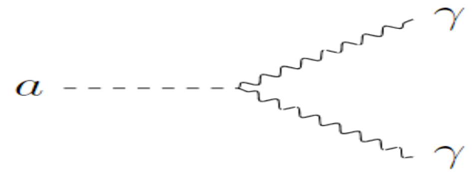
ALP-W SEARCH RESULTS

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

production



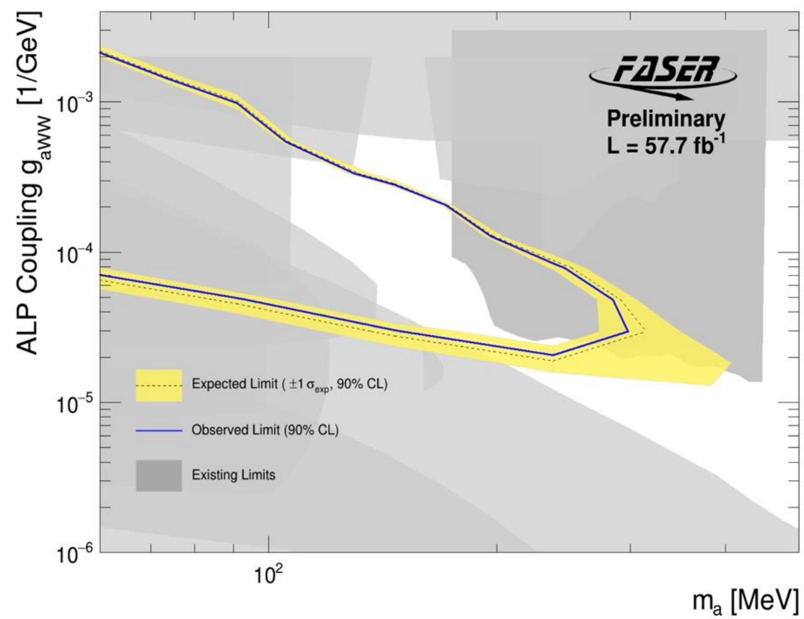
decay



- 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} (yesterday's signal, today's background)

- 1 event seen, excludes new parameter space. Benefits from LHC's high energy, lots of B's.



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

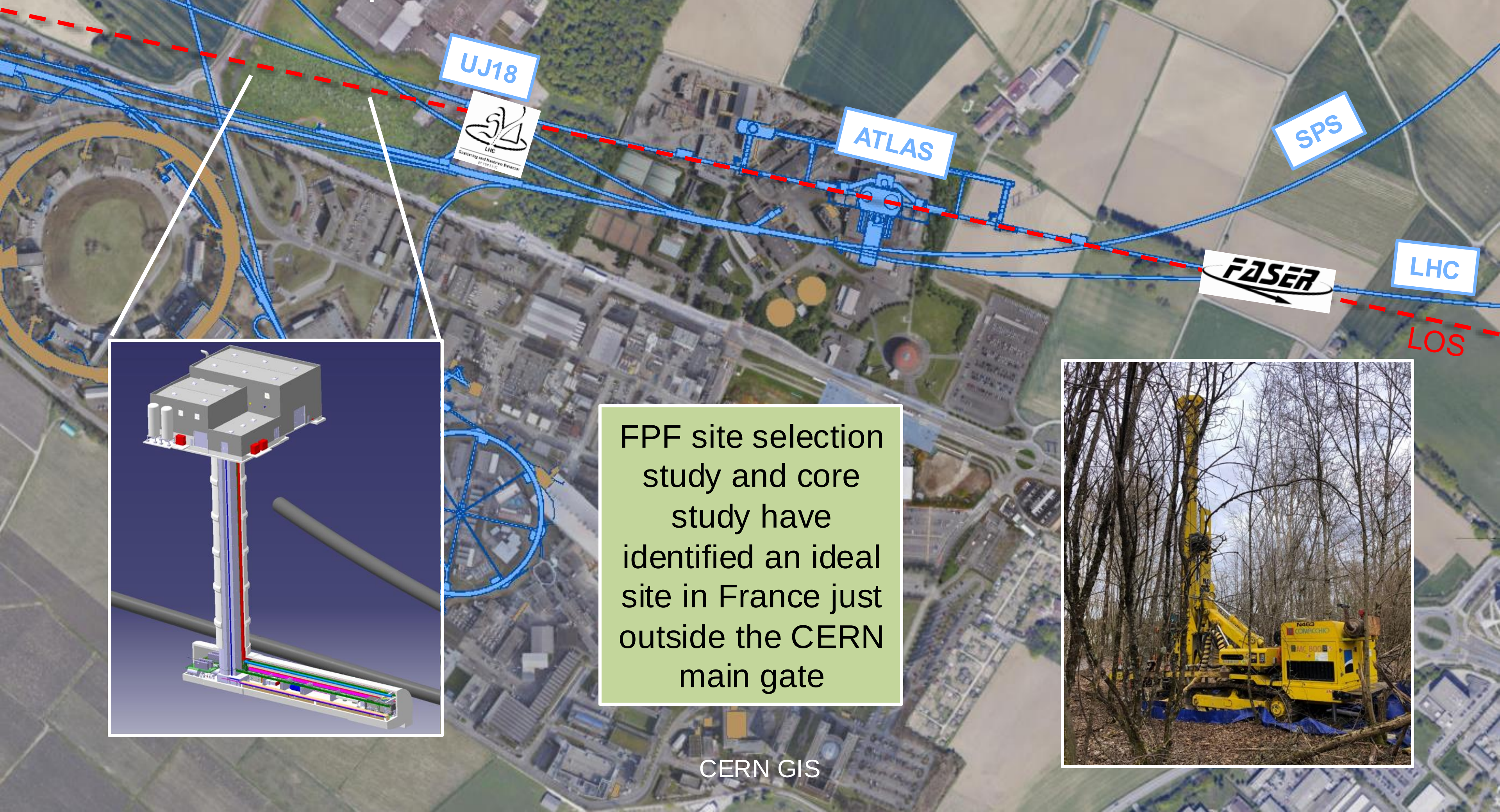
- FASER is approved to run through Run 4 (2030-33), with hardware upgrades, improvements in analysis. We will be testing many other new ideas, e.g., other new force carriers ($U(1)_{B-L}$, $U(1)_B$, protophobic), ALP-γ, ALP-g, light-shining-through-walls axions, dark Higgs bosons, sterile neutrinos, light neutralinos, inflatons, quirks, etc., all with world leading sensitivities.

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 2029-2040s.

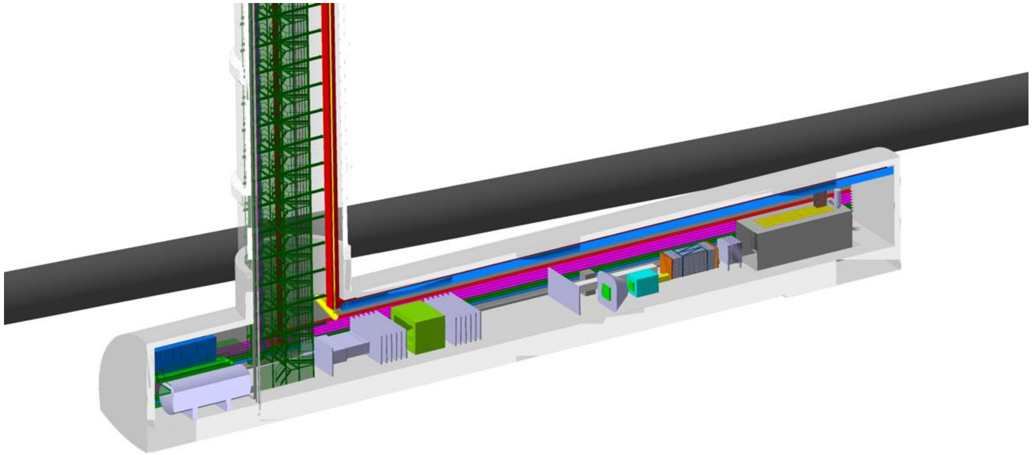


FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

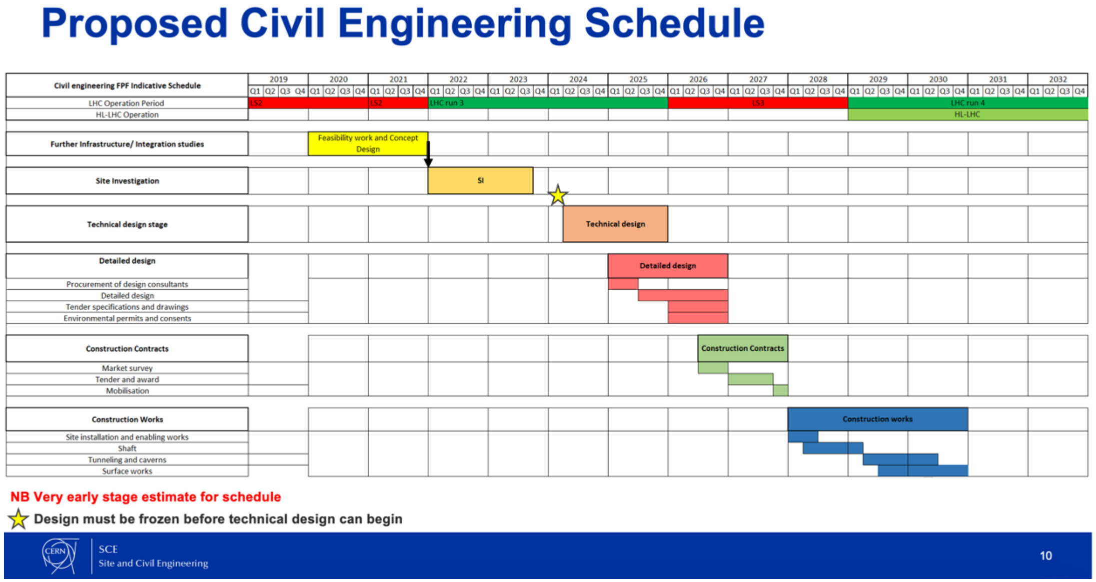
CERN GIS

THE FACILITY

- A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.
- 75 m long, 12 m in diameter, covers $\eta > 5.1$.
- Class 4 cost estimate: 35 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.



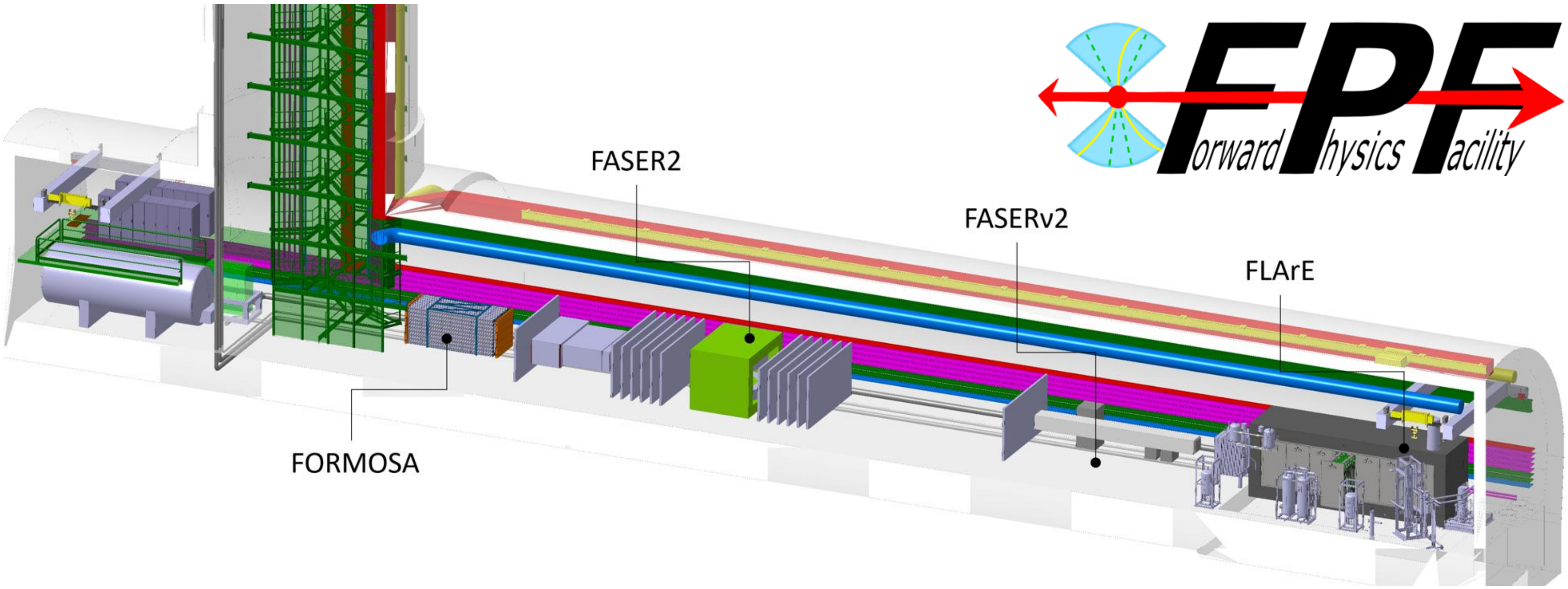
Bud, Magazinik, Pál, Osborne, et al. CERN CE (2024)



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)

- The total of core costs for the 4 experiments is ~40 MCHF.

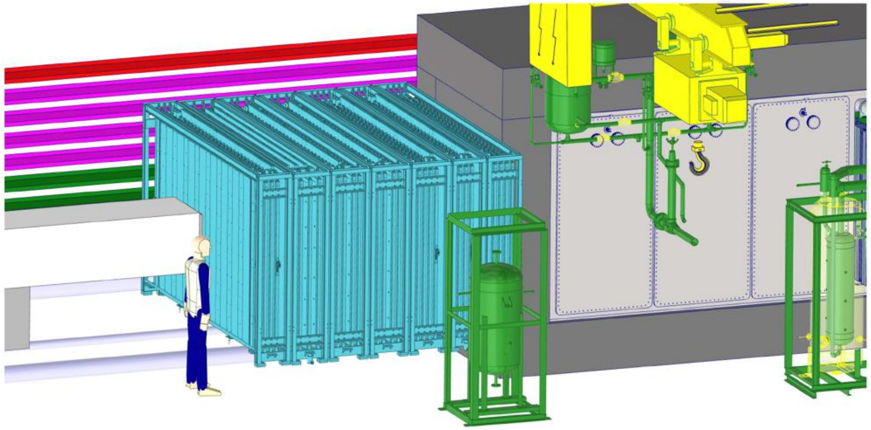


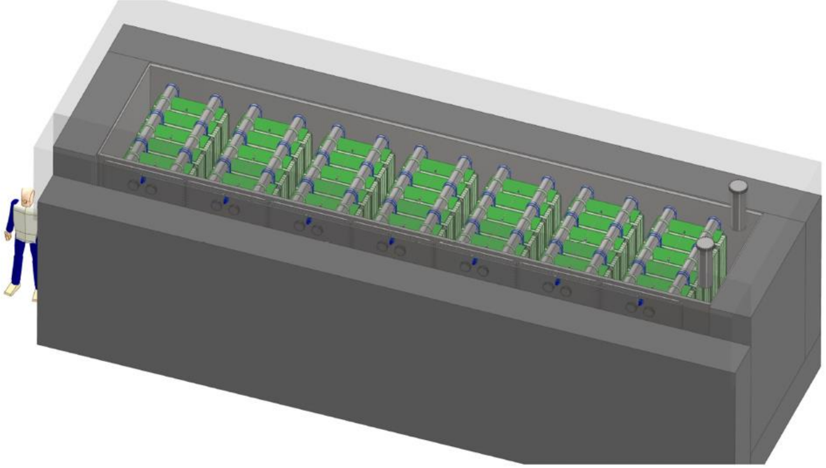
FPF EXPERIMENTS

- The FPF experiments will deliver a huge jump in physics reach relative to the existing experiments:
  - 10,000 times greater (decay volume * luminosity) for BSM searches.
  - Will detect miilions of TeV neutrinos, ~1000 neutrinos/day!
  - Highly flexible program: In the event of a discovery at FPF or elsewhere, FPF experiments will be able to adapt, measure the properties of the new particles, explore possible connections to dark matter, dark sectors.

- FASER2, FASERν2, FORMOSA are based on experience with the corresponding "pathfinder" experiments (FASER, FASERν, milliQan).

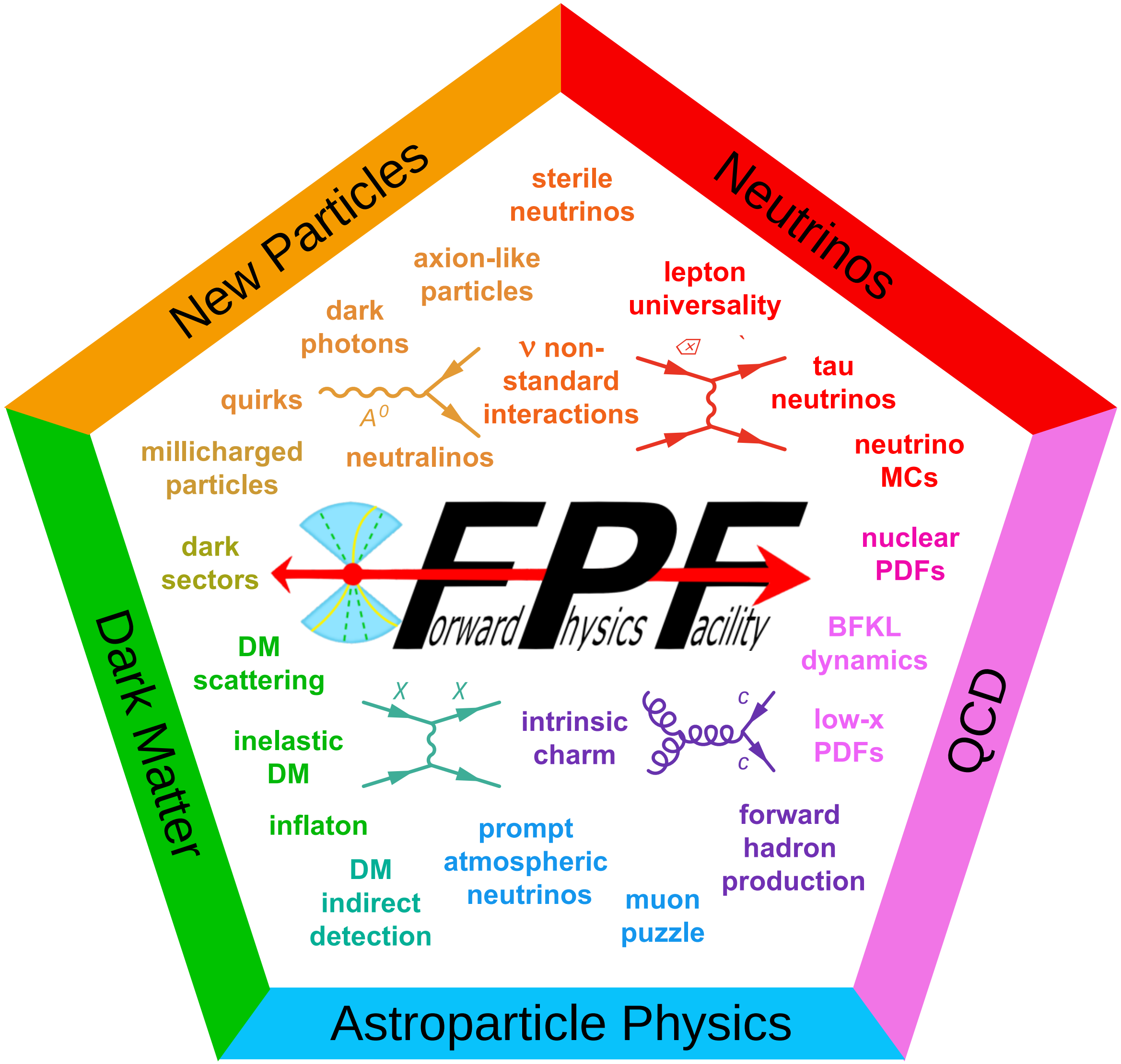
- FLArE does not benefit from a pathfinder experiment, but there has been impressive progress, led by BNL.





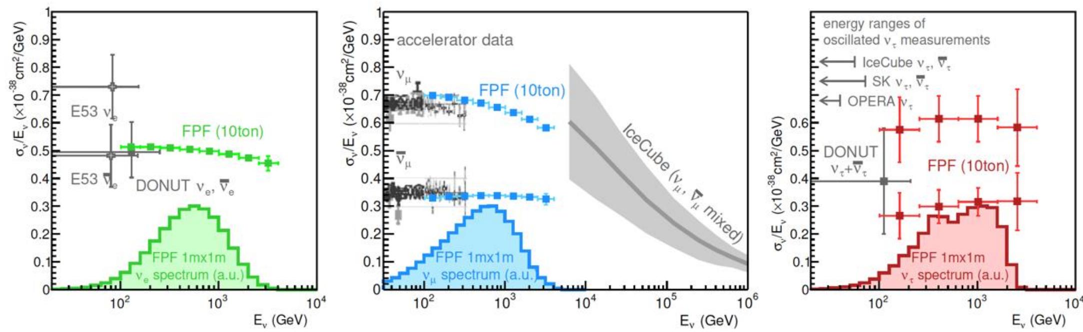
PHYSICS AT THE FPF

- The FPF at the HL-LHC will have many unique capabilities:
  - New physics in neutrino properties: neutrino blind → neutrino factory: 10^6 neutrinos at the highest human-made energies ever.
  - New particles: enhancement of conventional LHC searches, and many searches for particles that cannot be round anywhere else.

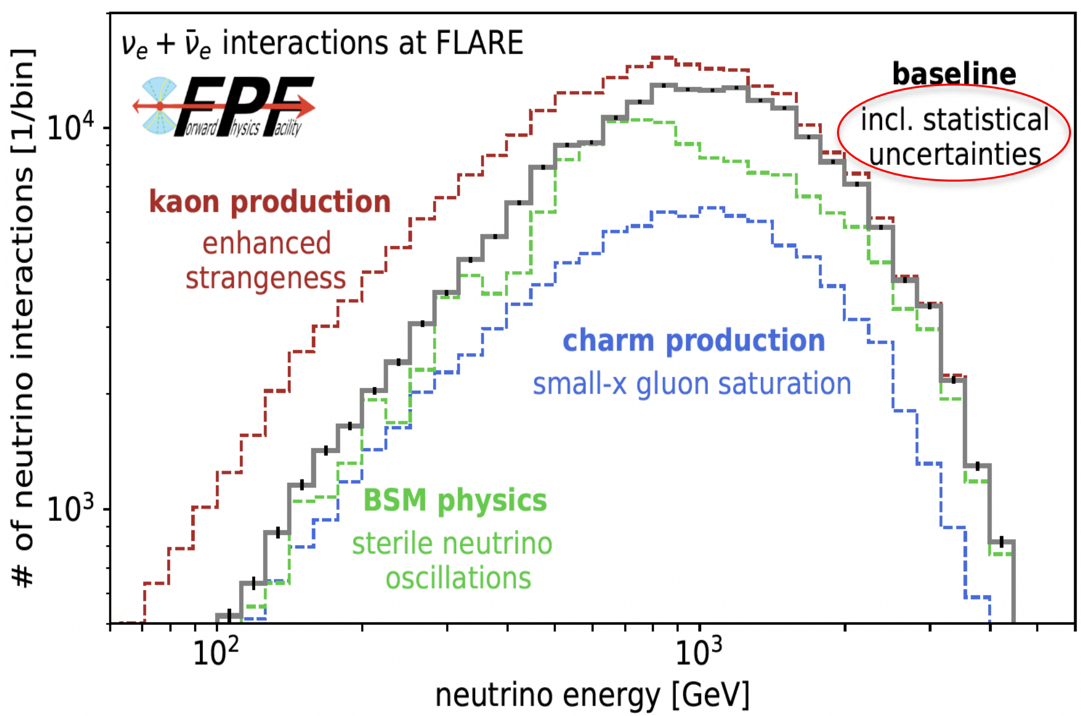


NEUTRINOS AT THE FPF

- The FPF experiments will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^4\ \nu_\tau$ interactions at TeV energies. The last chance to probe this in a controlled environment for at least 50 years.

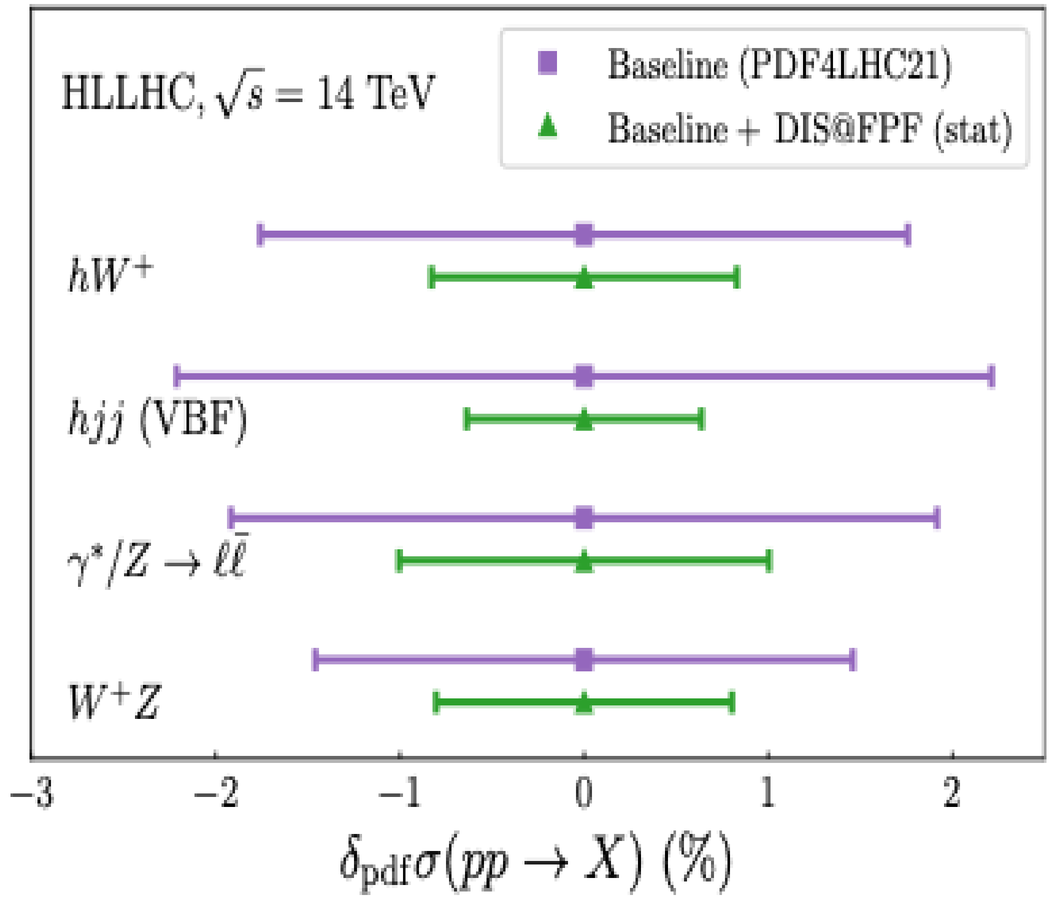


- Neutrinos are produced by forward hadron production: π, K, D, ... Dependence on E, η will inform
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x ~ 10^{-1}, x ~ 10^{-7} , intrinsic charm, small-x gluon saturation, …
  - Neutrino oscillations: ν_s with $\Delta m^2 \sim 10^3\ \mathrm{eV}^2$



ENHANCEMENT OF HIGH P_T SEARCHES

- The FPF will provide new constraints on pdfs that will sharpen studies at ATLAS and CMS.
- For example, W, Z, and Higgs boson studies.
- Will also remove degeneracies between pdfs and new physics ("fitting away new physics"), extending the reach for new particle searches (e.g., ~10 TeV W', Z').



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

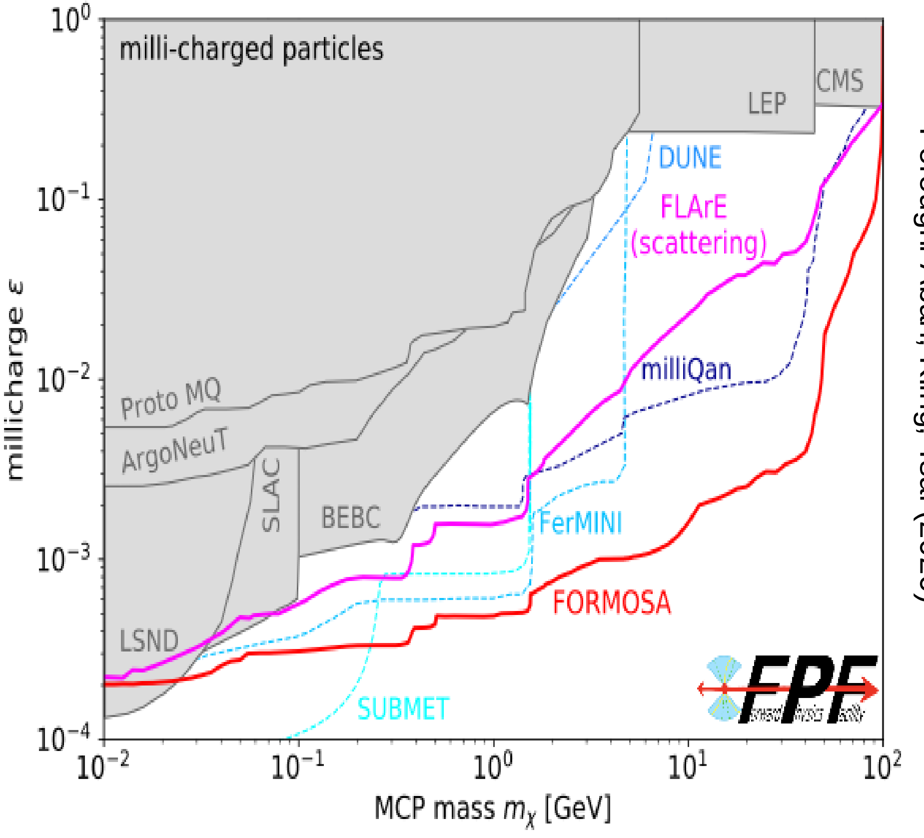
UNIQUE DISCOVERY OPPORTUNTIES

- FPF experiments have the potential to discovery BSM physics that cannot be seen anywhere else. Many examples:

- Millicharged particles: 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.

- Can be explored at the FPF with both FLArE and FORMOSA, a dedicated experiment in the forward region with much greater sensitivity for a wide range of masses from 10 MeV to 100 GeV.

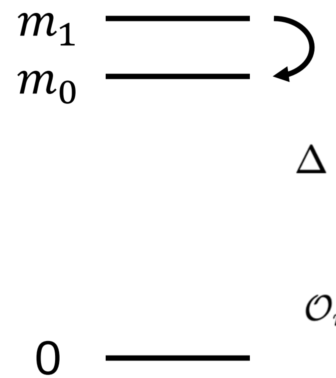
- Currently being investigated with the FORMOSA Demonstrator behind FASER.



Foroughi-Abari, Kling, Tsai (2020)

DARK MATTER

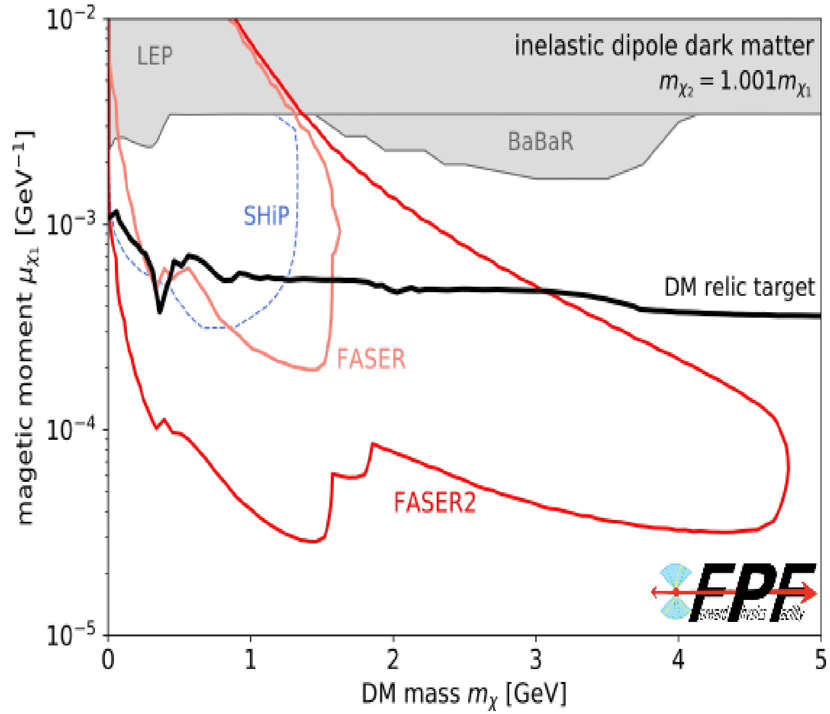
- In the last few decades, there has been an intense effort to detect dark matter through non-gravitational couplings, all yielding null results.
- One generic possibility that is infamously hard to detect: inelastic dark matter, where there are two nearly-degenerate dark states with off-diagonal couplings to the SM.
- These generically lead to long-lived particles, but with soft decay products, but these are highly boosted to observable levels at the FPF.
- Bottom line: the FPF can discover DM (or any compressed spectrum), which cannot be seen anywhere else (ATLAS/CMS, SHiP and other fixed target expts, direct and indirect DM searches, …)



$$\chi_1 \to \chi_0 \gamma$$

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

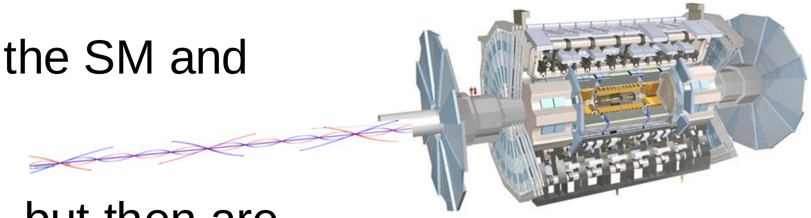
$$\mathcal{O}_m = \frac{1}{\Lambda_m} \overline{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$



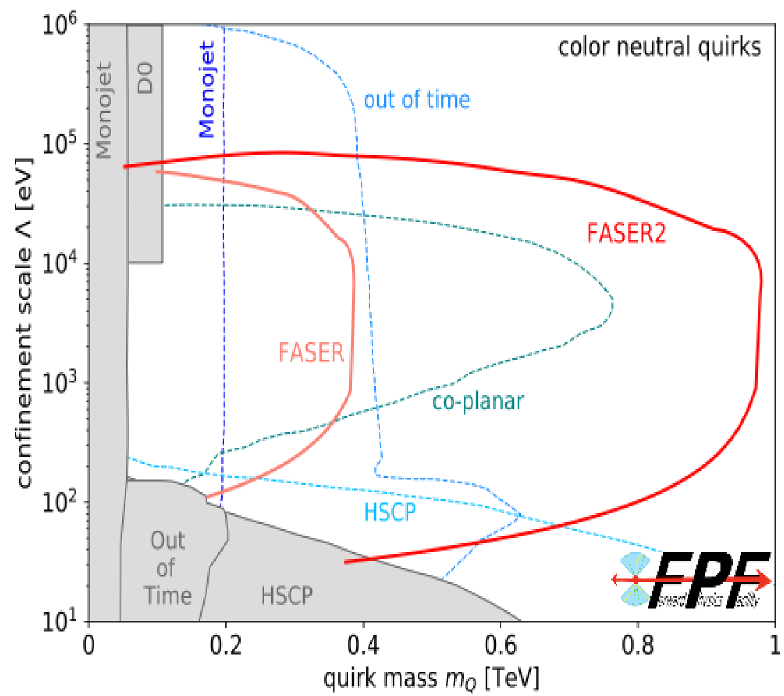
Dienes, Fieg, et al. (2023)

QUIRKS

- There may be another strong (non-Abelian) force.
- Quirks are particles charged under both the SM and another strong force, with $m \gg \Lambda$.



- Quirks can be pair-produced at the LHC, but then are bound by a color string, oscillate about their center-of-mass and travel down the beamline.
- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FPF experiments can discover quirks with masses up to ~TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.
- Unique discovery potential at the FPF: very challenging at ATLAS/CMS, impossible at fixed target experiments.



Feng, Li, Liao, Ni, Pei (2024)

SUMMARY

- The forward region is a treasure trove of interesting physics.
  - Collider neutrinos at TeV energies, with implications for neutrino properties, QCD, astroparticle physics, and high p_T physics.
  - Opportunities for breakthrough discoveries of light (and also heavy), weakly-interacting BSM particles, including many motivated by dark matter.
- FASER has shown that this dataset can be mined by small, fast, and inexpensive detectors. Many more results coming in the next few days, months, and years.
- The Forward Physics Facility will enable the LHC to fully realize its physics potential before it shuts down in the 2040s.

see the FPF status report for EPPSU, on arxiv soon