# NEW EYES FOR THE LHC

Wisconsin Physics Colloquium

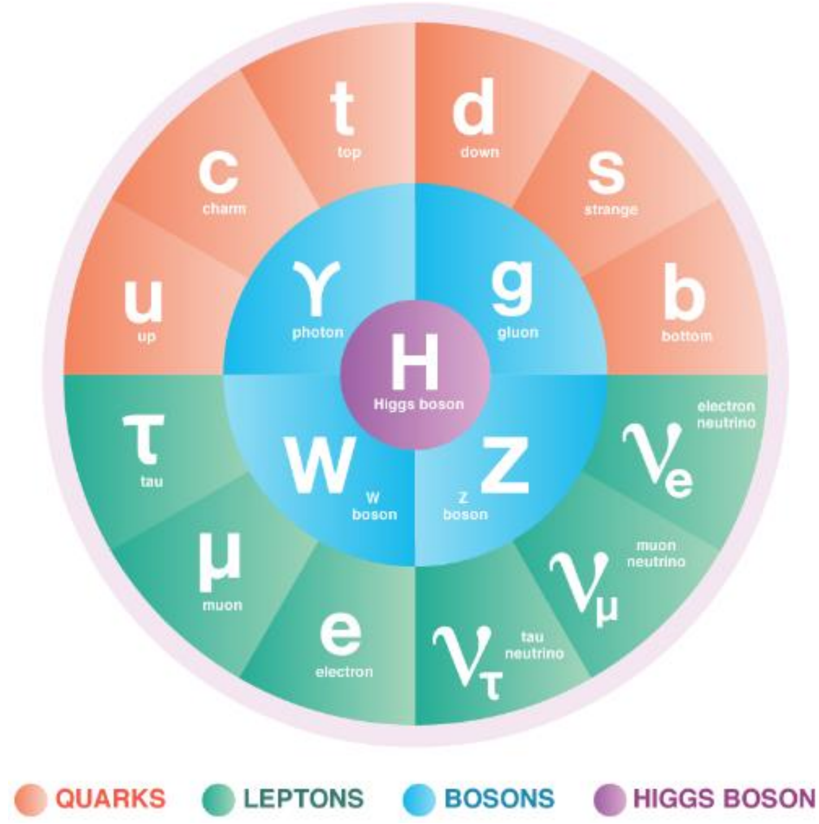
Jonathan Feng, UC Irvine, 27 September 2024

# THE STANDARD MODEL OF PARTICLE PHYSICS

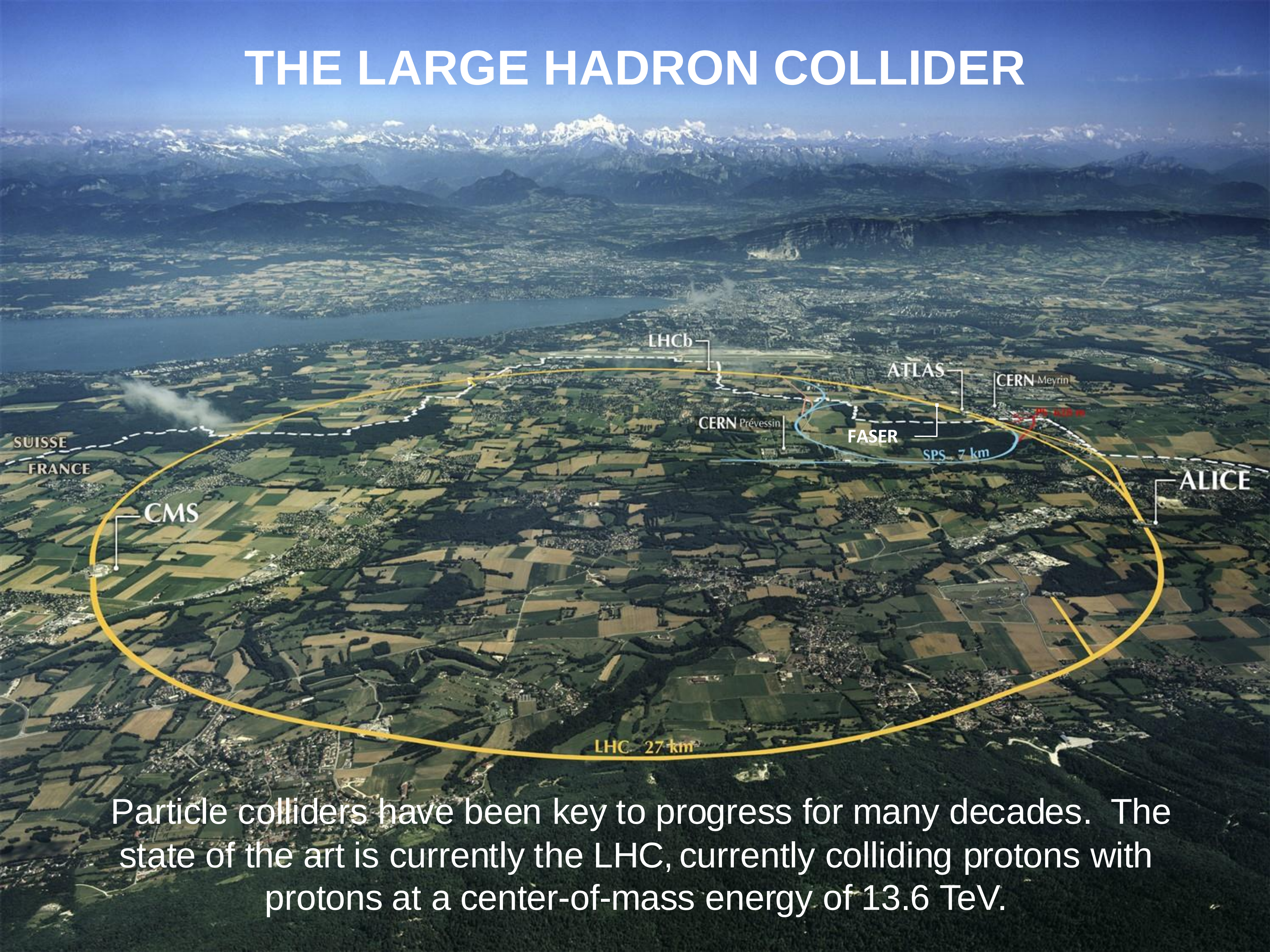
- The Standard Model is the reigning theory of fundamental particles and their interactions. The last particle predicted by the SM, the Higgs boson, was discovered at CERN in 2012.

- 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 more particles left to discover, and probably many more.



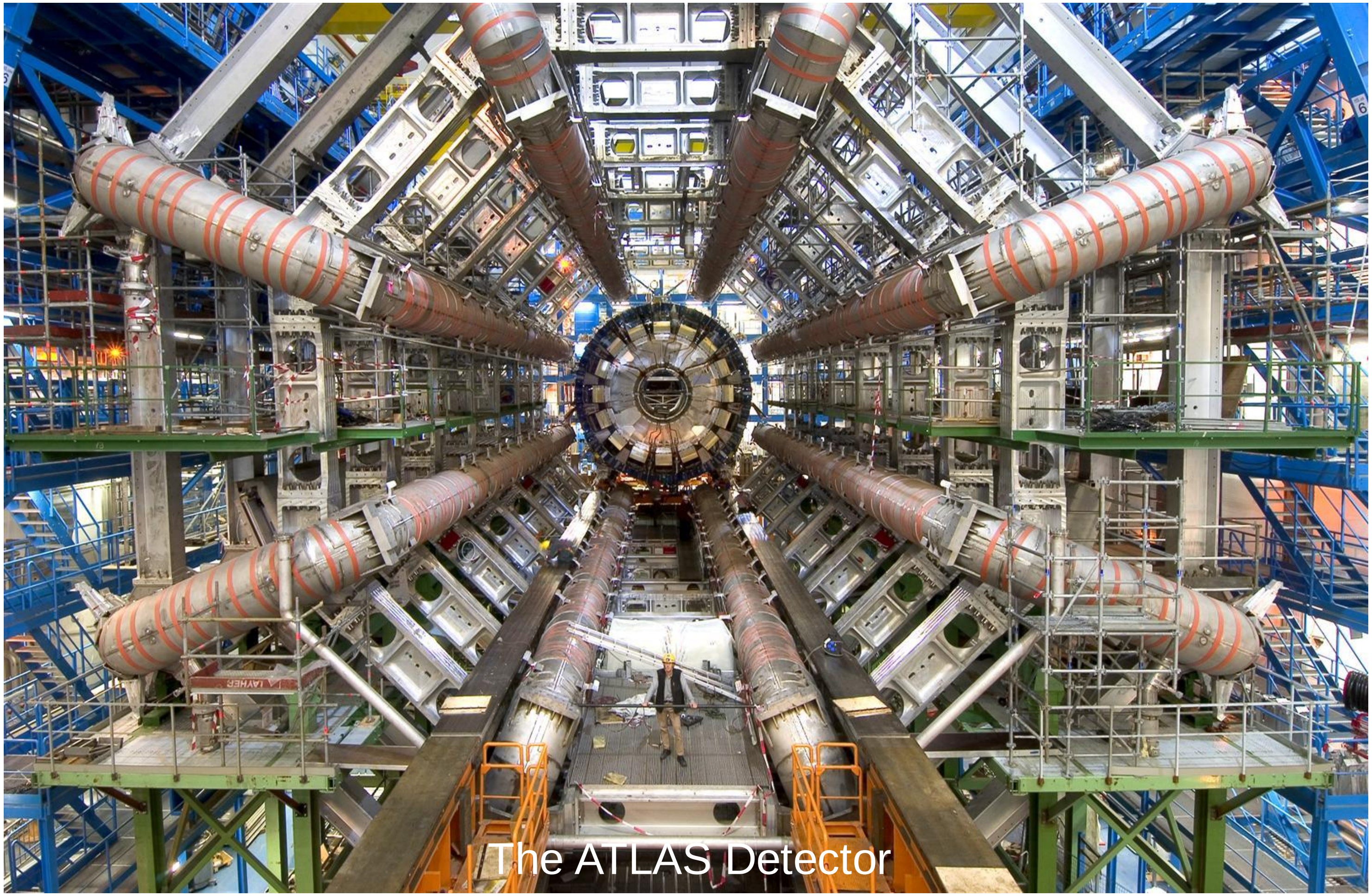
# THE LARGE HADRON COLLIDER




Particle colliders have been key to progress for many decades. The state of the art is currently the LHC, currently colliding protons with protons at a center-of-mass energy of 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 are were constructed over decades by thousands of collaborators.

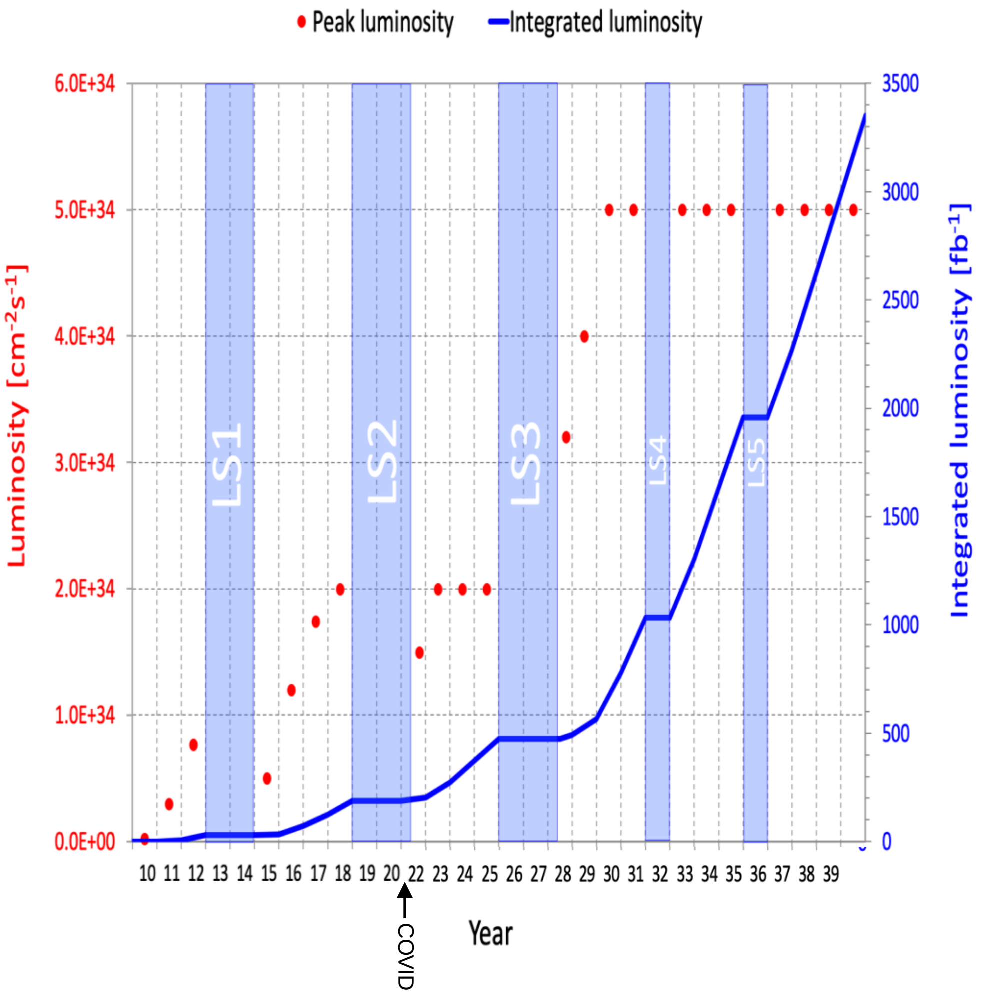

The ATLAS Detector

# LIFETIME OF THE LHC

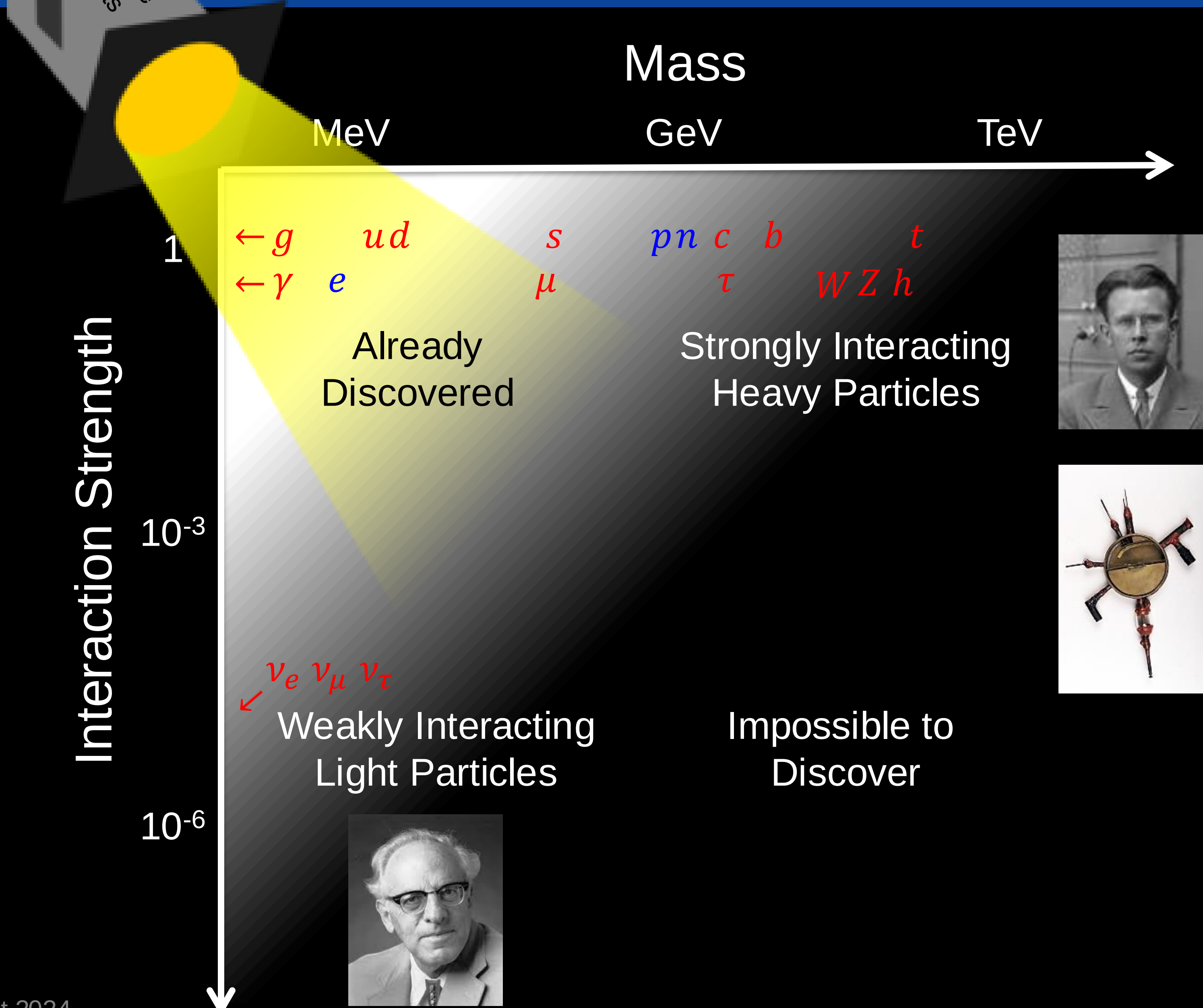
- The LHC became the future of particle colliders in 1993 when the US canceled the SSC, which was being built in Texas.

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

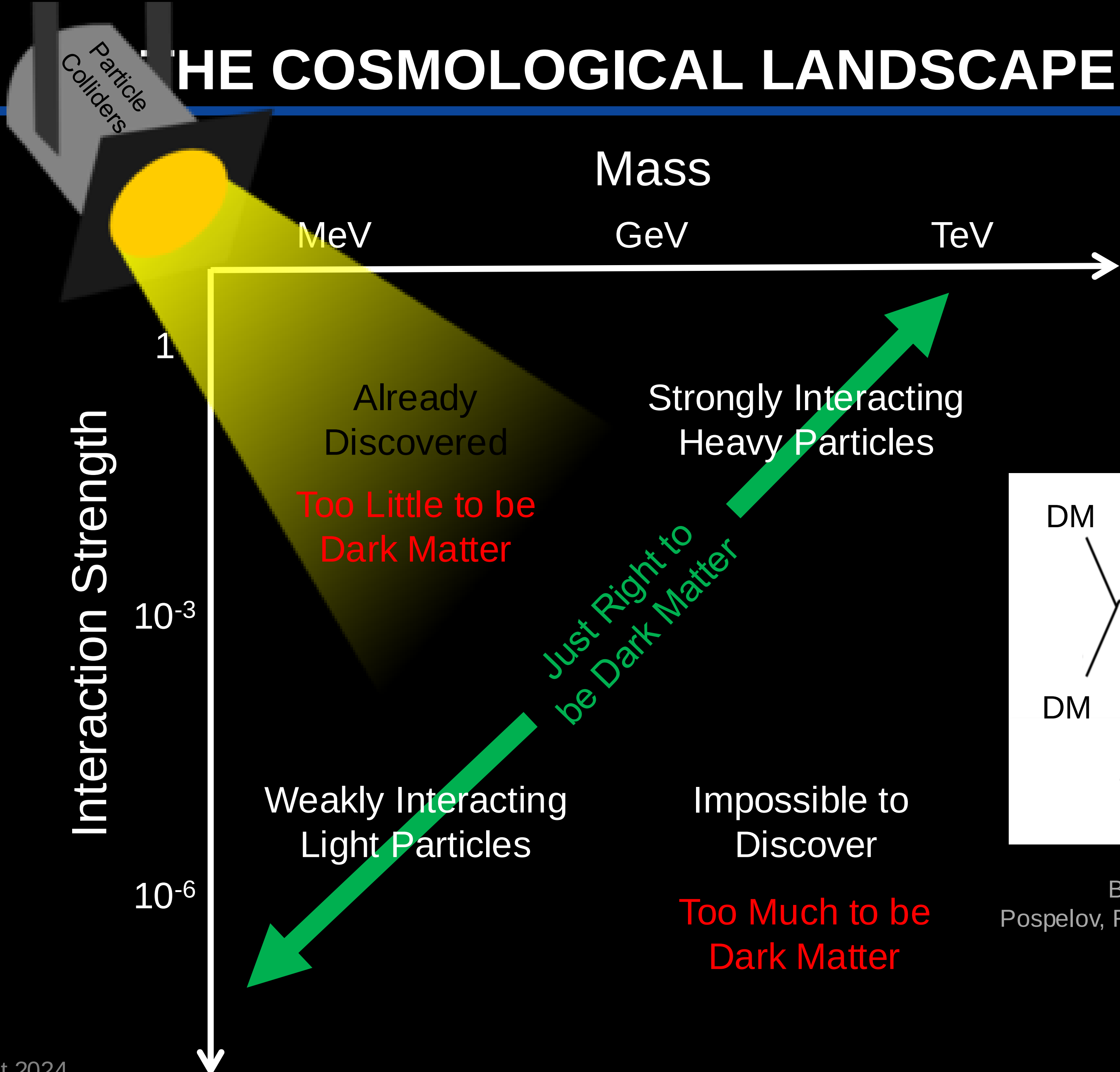
- Are we using the LHC to its full potential? If not, what can we do to enhance its discovery prospects?

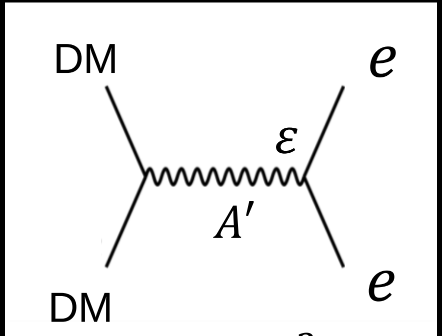


# THE PARTICLE LANDSCAPE



# THE COSMOLOGICAL LANDSCAPE




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

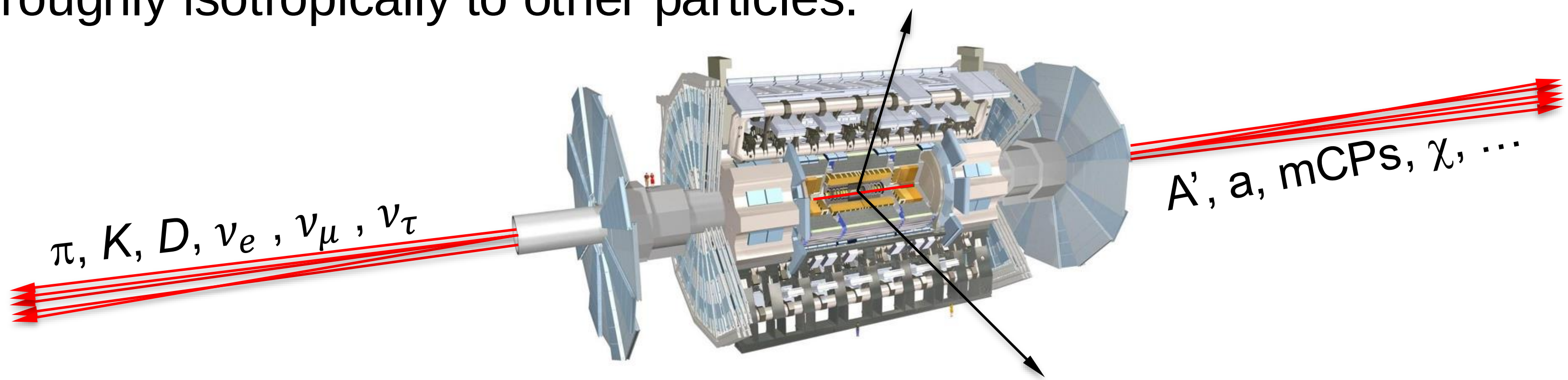
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

# 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.

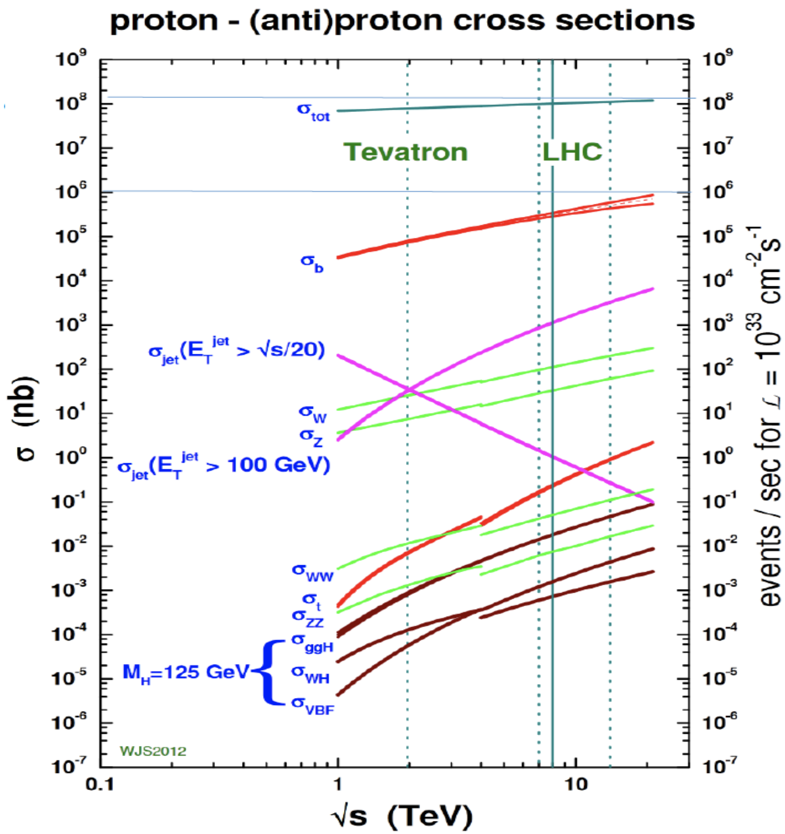


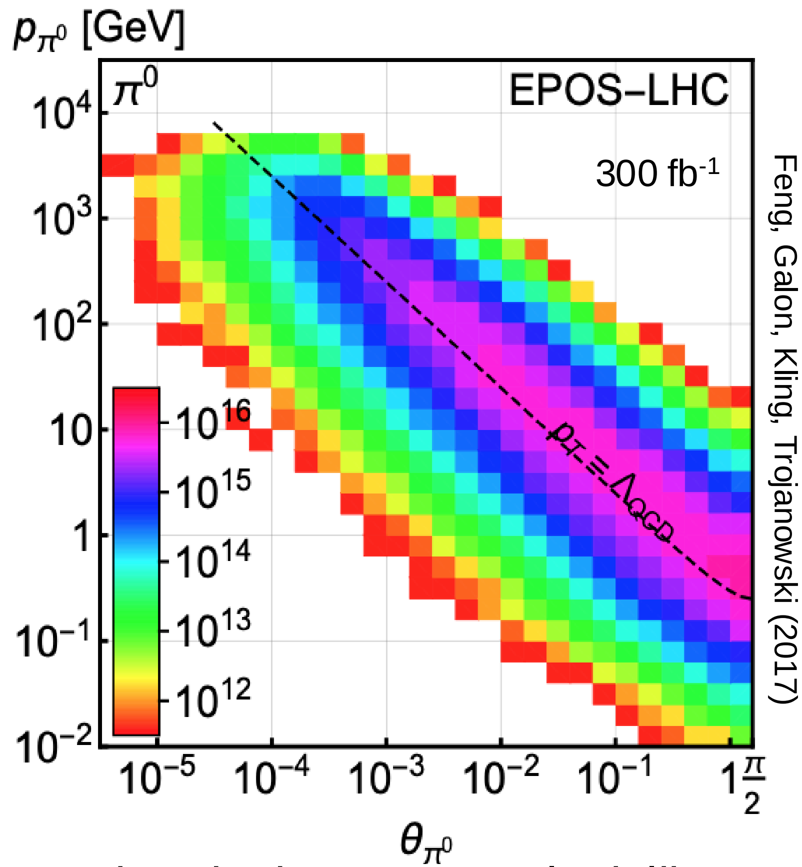

- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of these large detectors.
  - This is true for all known light particles: pions, kaons, *D* mesons, all neutrinos.
  - It is also true for many proposed new particles, especially those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



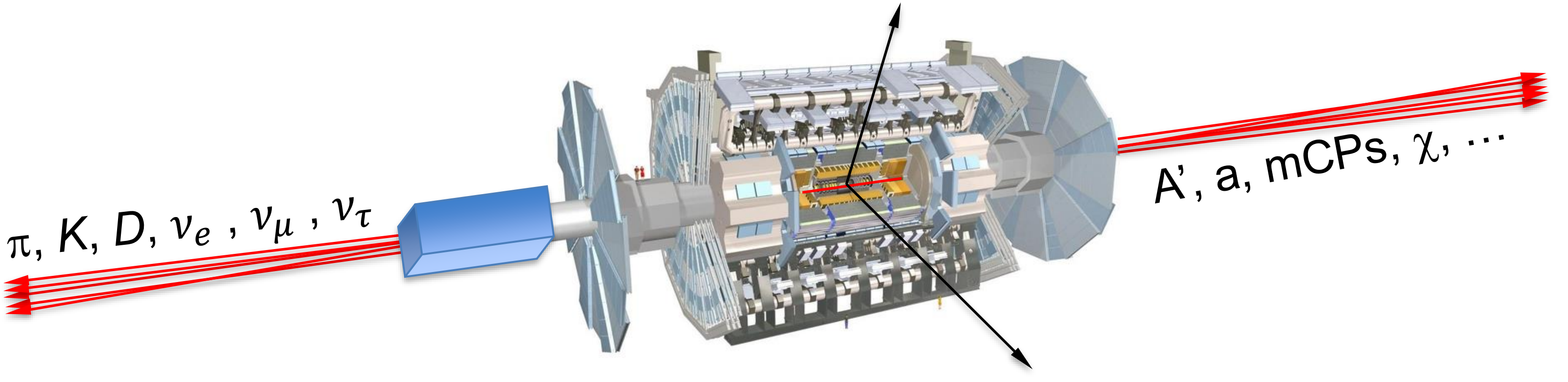




- Most searches have focused on processes with $\sigma$ ~ fb, pb.
- But the total cross section is $\sigma_{tot}$ ~ 100 mb and most of it is typically treated as useless.
- What do these events look like? Consider pions (decays to $\nu$, BSM).
- Enormous event rates. Typical $p_T$ ~ 250 MeV, but many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

# DETECTING FORWARD PARTICLES

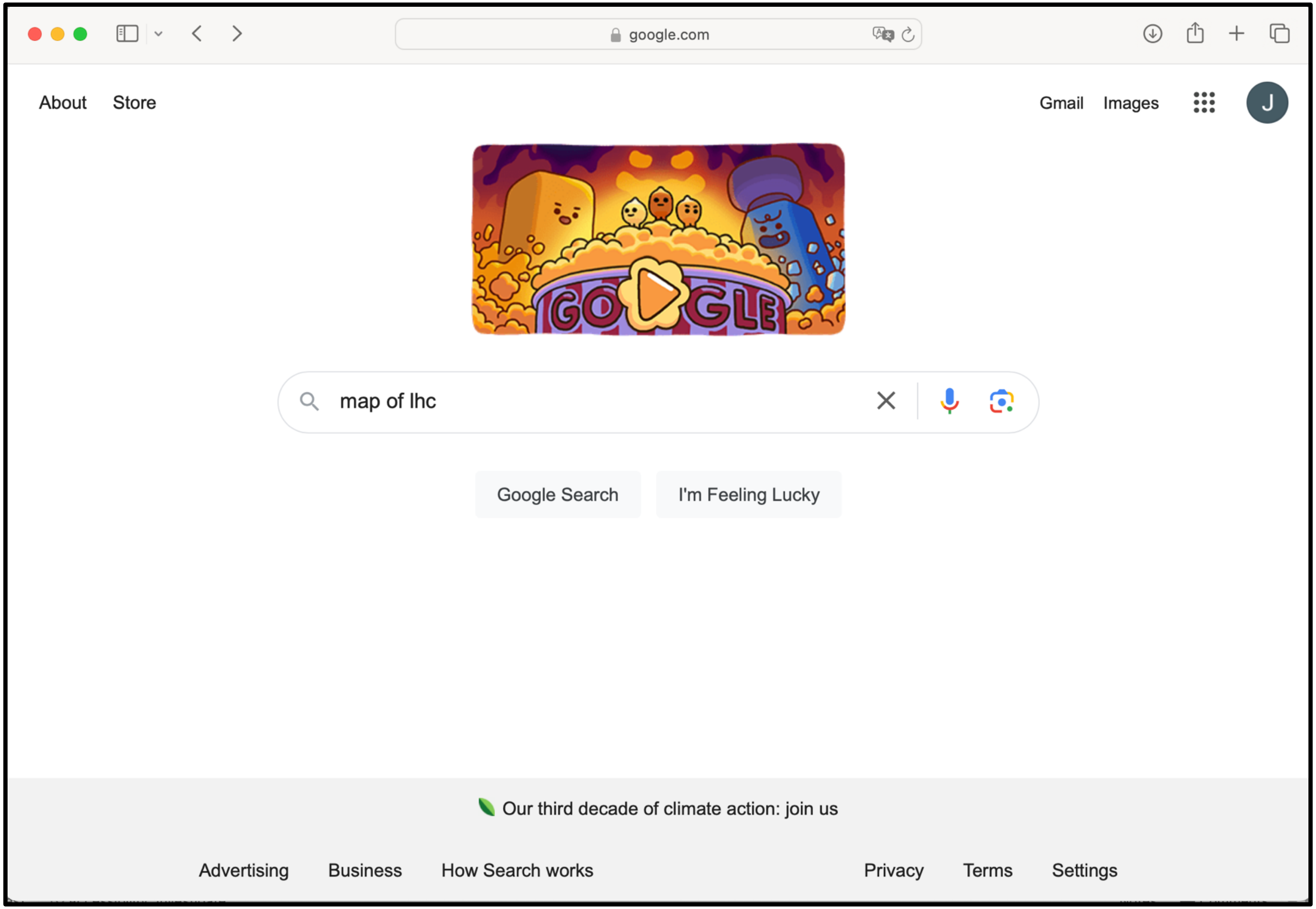
- To capture the enormous forward flux, we need to detect particles that are produced in the forward direction along the beamline.

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

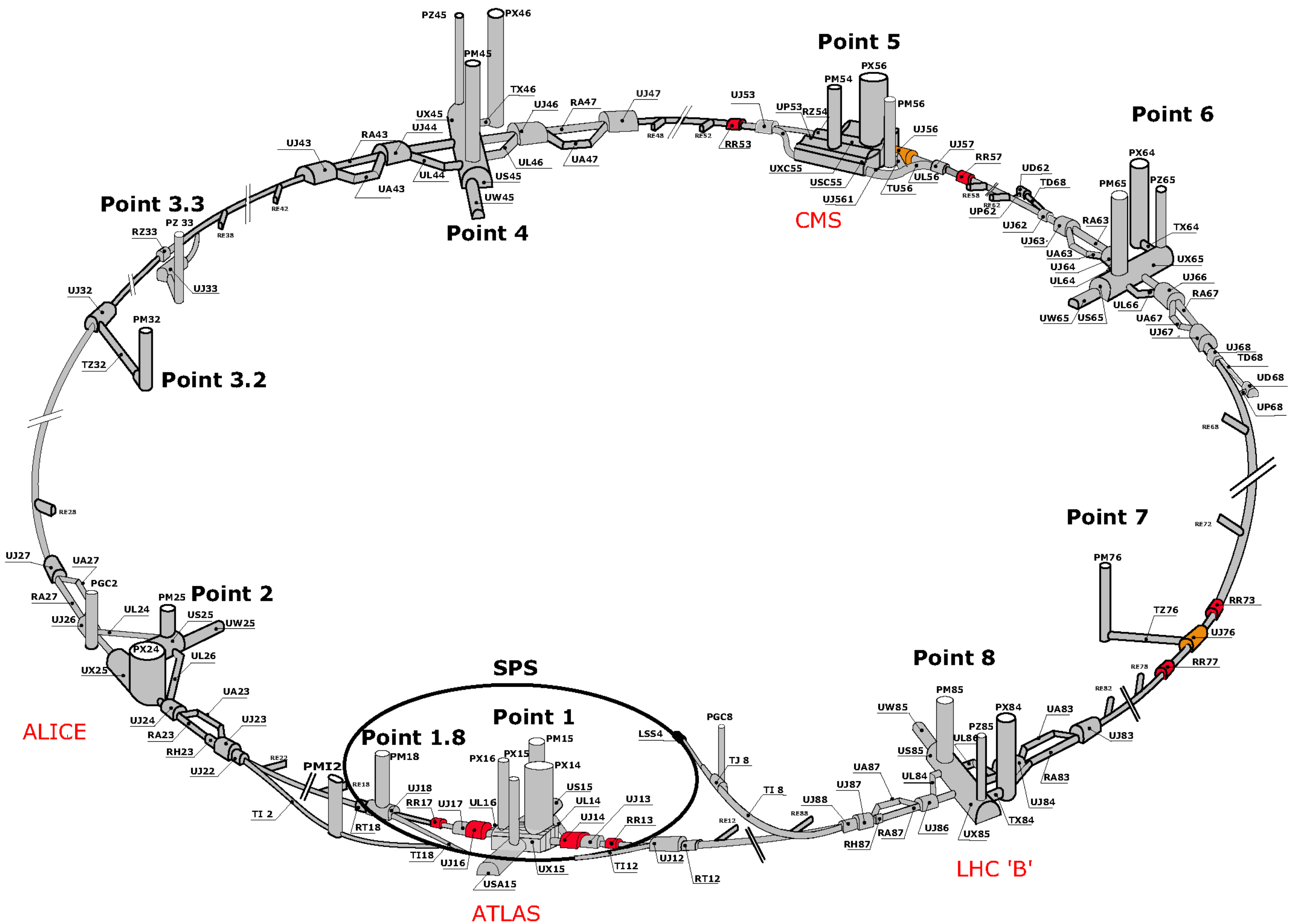



- Solution: the LHC is a circular collider!  If we go far enough away, the LHC proton beam will curl away, while all the light, weakly-interacting particles we are looking for will go straight.

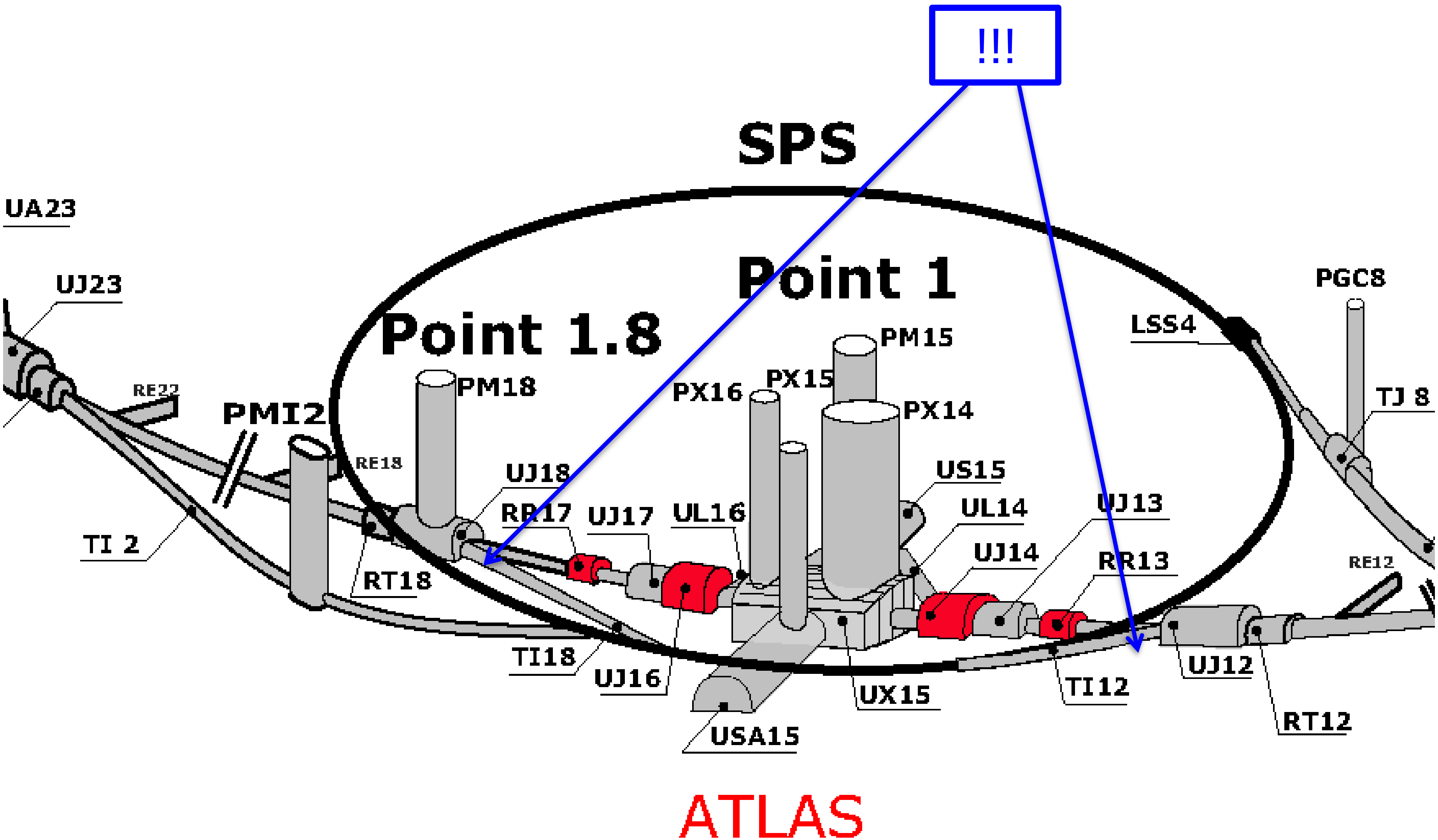
# SOPHISTICATED RESEARCH



# SOPHISTICATED RESEARCH

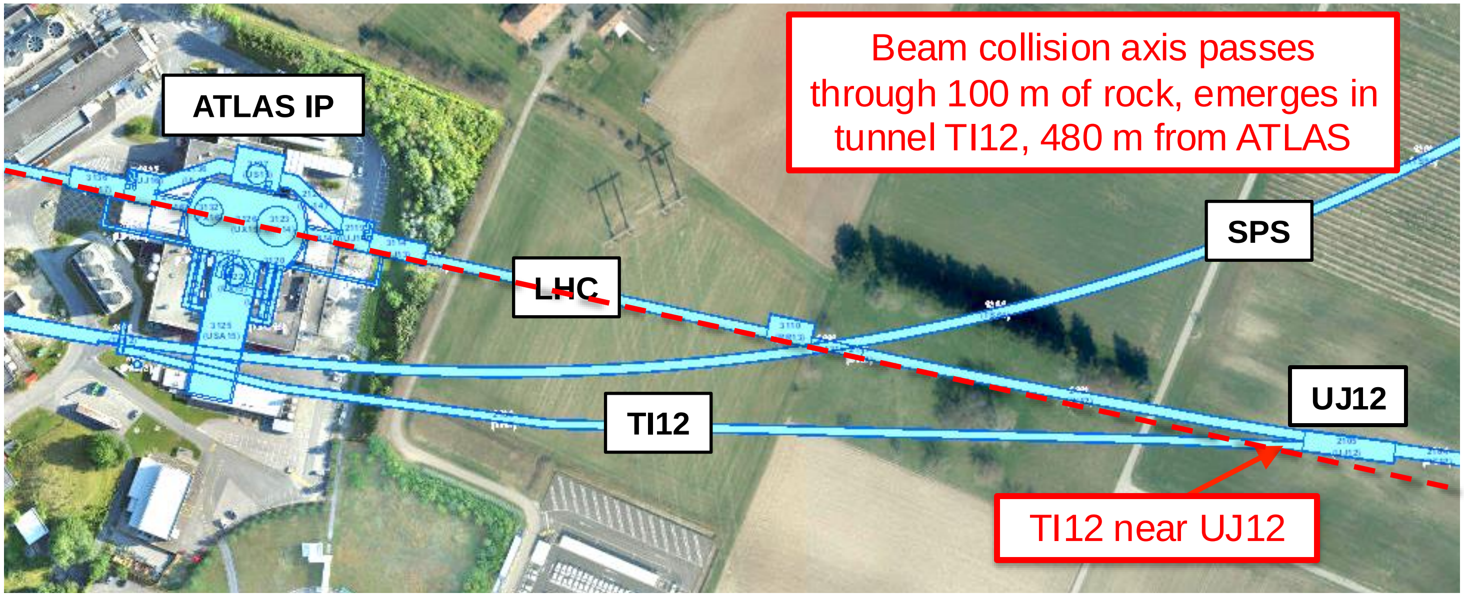


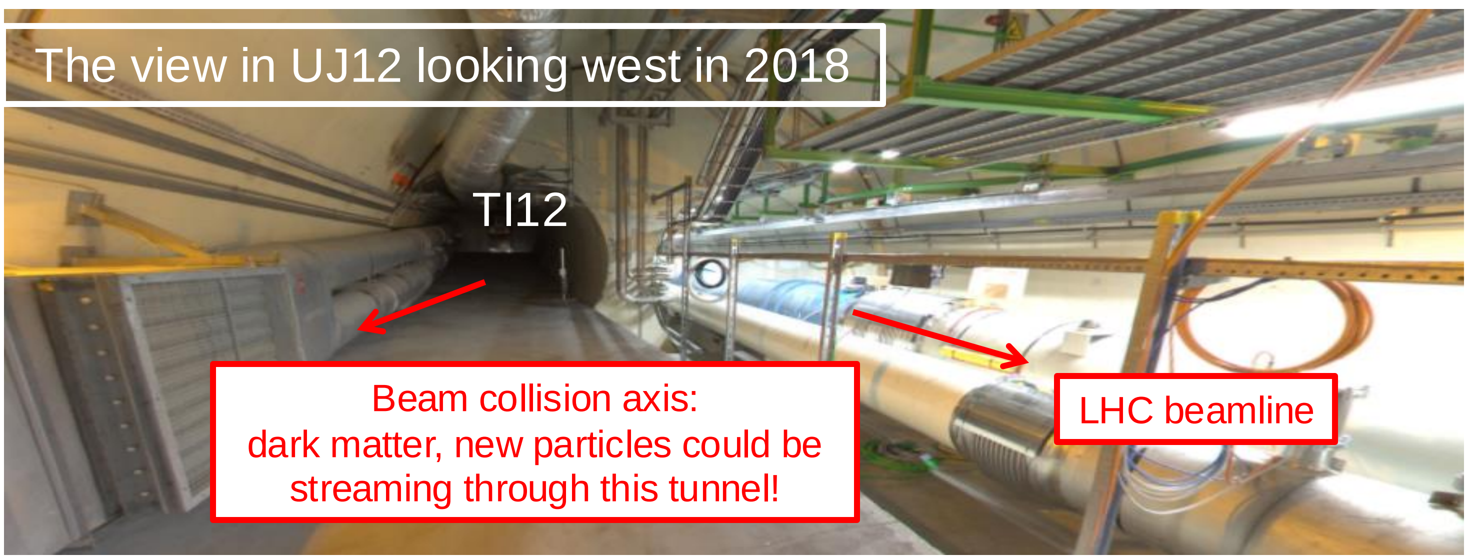
# MAP OF LHC



!!!
SPS
Point 1
Point 1.8
UA23
UJ23
RE22
PMI2
PM18
PX16
PX15
PM15
PX14
LSS4
PGC8
TJ 8
RE18
UJ18
RR17
UJ17
UL16
US15
UL14
UJ13
UJ14
RR13
RE12
TI 2
RT18
TI18
UJ16
USA15
UX15
TI12
UJ12
RT12
ATLAS

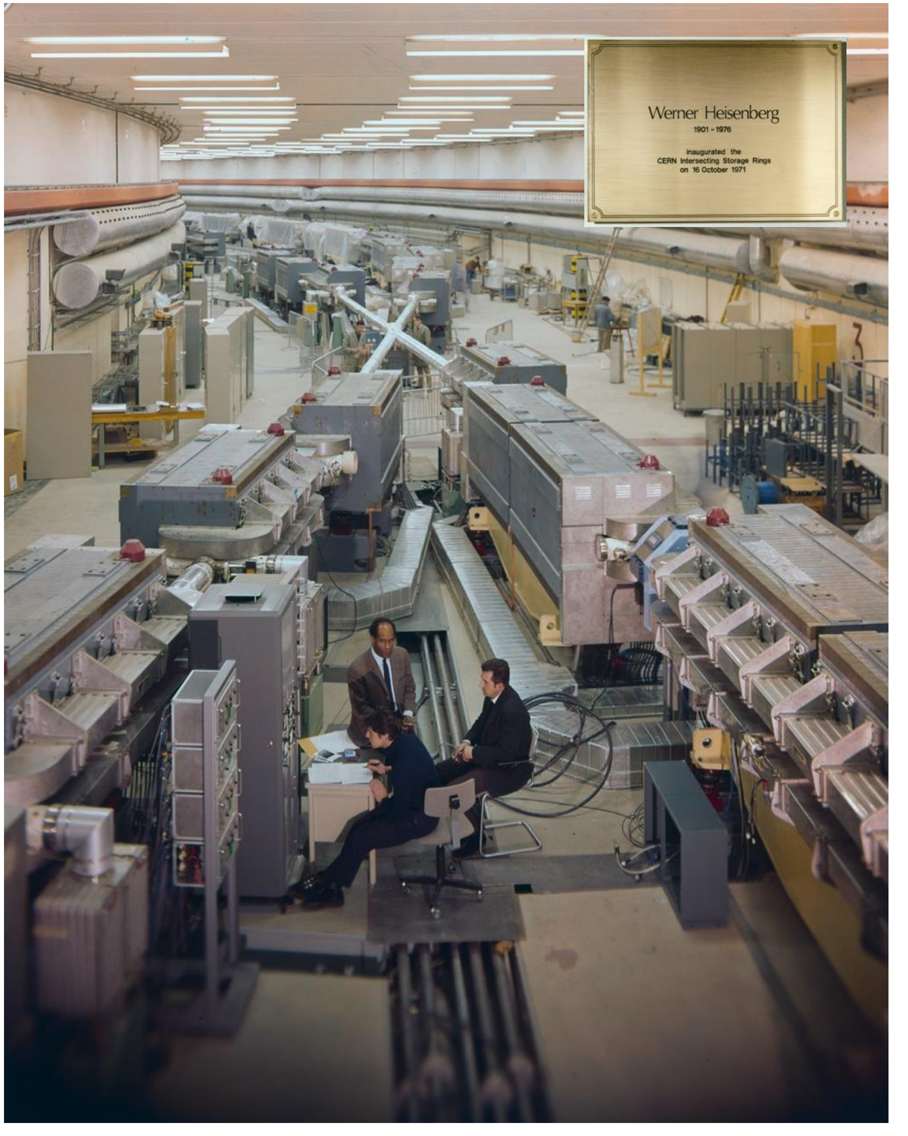
# THE FORWARD REGION



# HISTORICAL ASIDE

- Is it really possible that a collider is making new particles, and we are missing them simply because we are looking in the wrong place?
- Yes.  In fact, it happened before at CERN.
- 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.

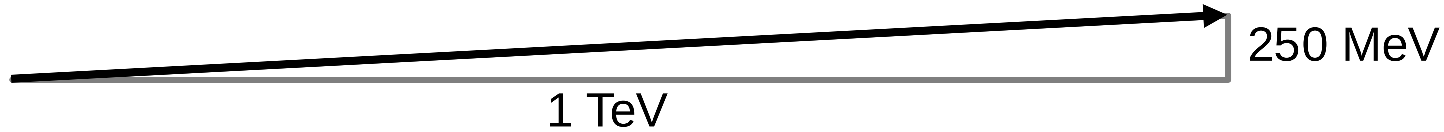


# ISR'S LEGACY

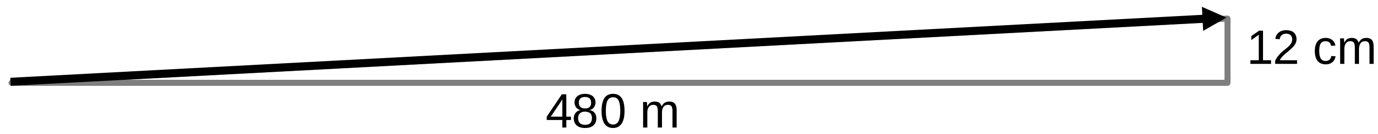
- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.
  - "There was initially 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, but in reverse?

# HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:

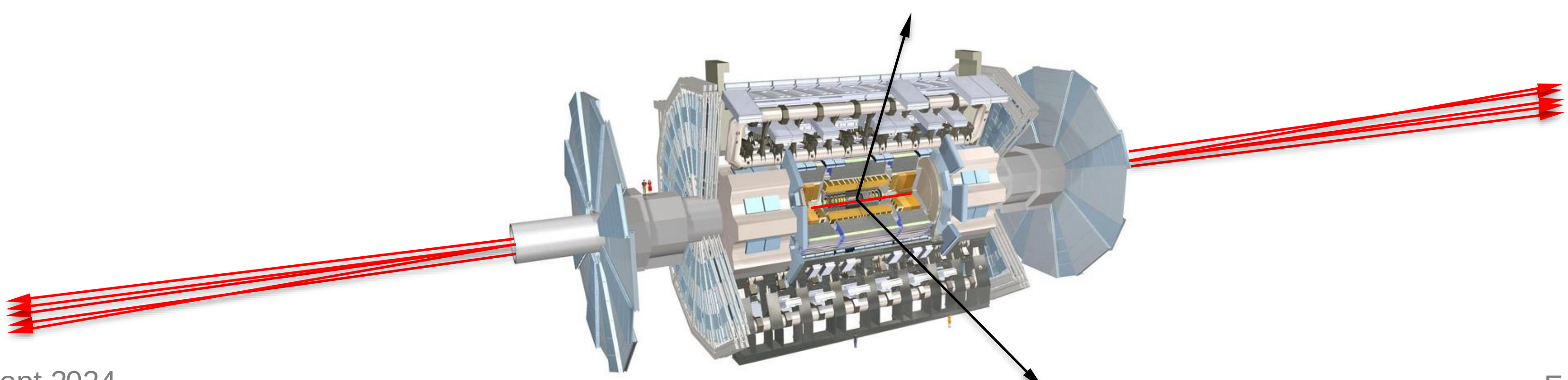



- Space:

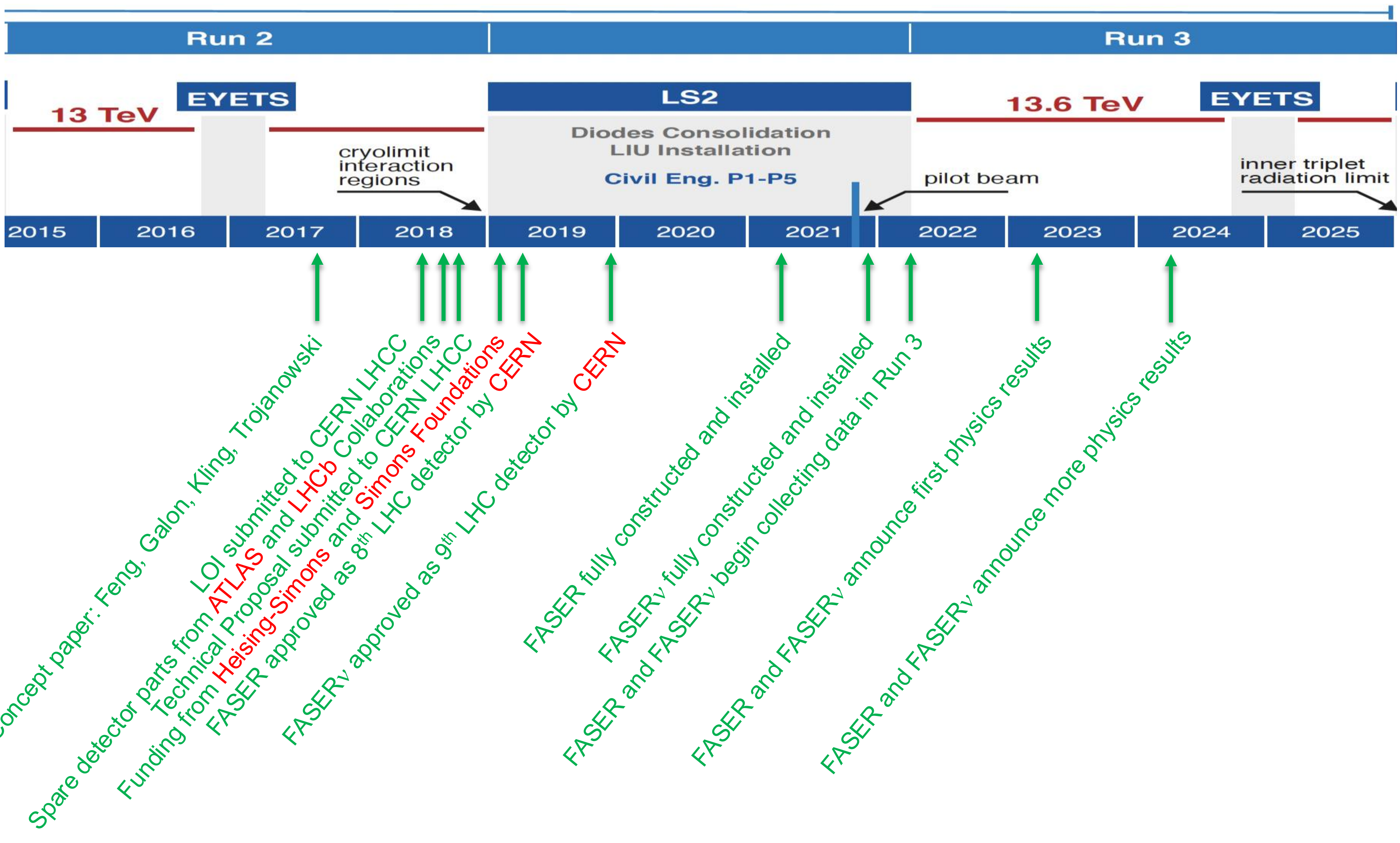



- The opening angle is 0.2 mrad (the moon is 7 mrad). Even 480 m away, most of the signal passes through an 8.5” x 11” (A4) sheet of paper.

- Neutrinos and many new particles are therefore 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

108 collaborators, 27 institutions, 11 countries

International laboratory covered by a cooperation agreement with CERN

# PREPARATION OF THE FASER LOCATION

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

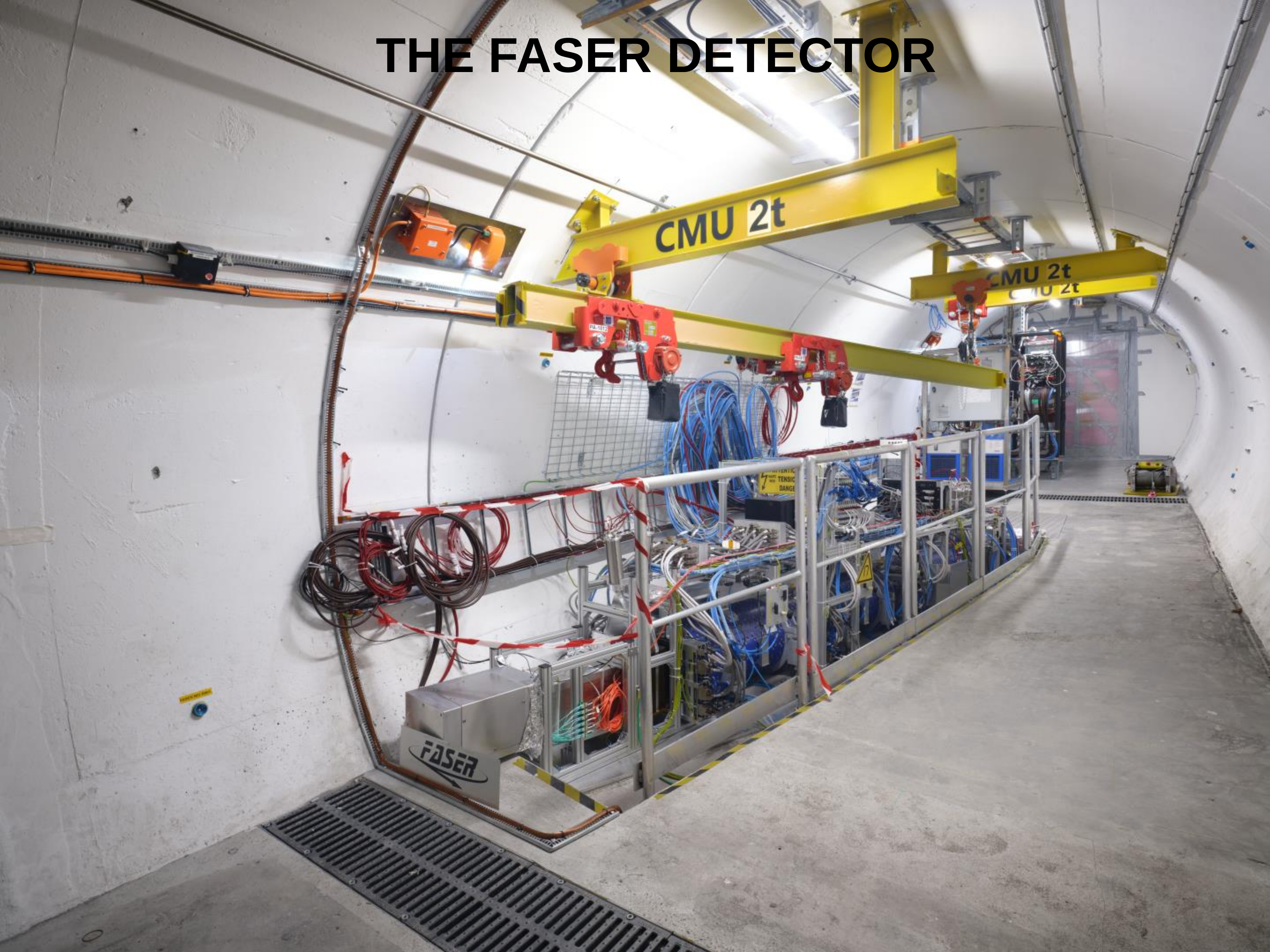
- The trench was completed by an Italian firm just hours before COVID shut down CERN in March 2020.



# FASER AND THE LHC

# FASER INSTALLATION


# THE FASER DETECTOR

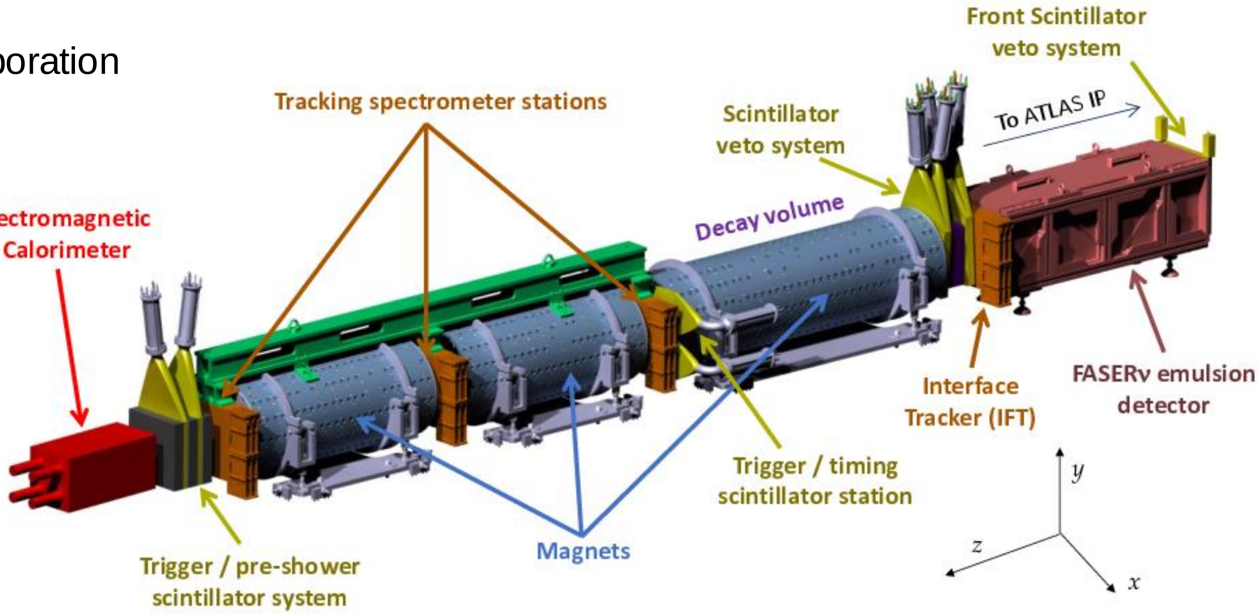


# THE FASER DETECTOR

- 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 ~ $(10^{-5})^4 \sim 10^{-20}$.
  - FASER$\nu$: 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 $fb^{-1}$.

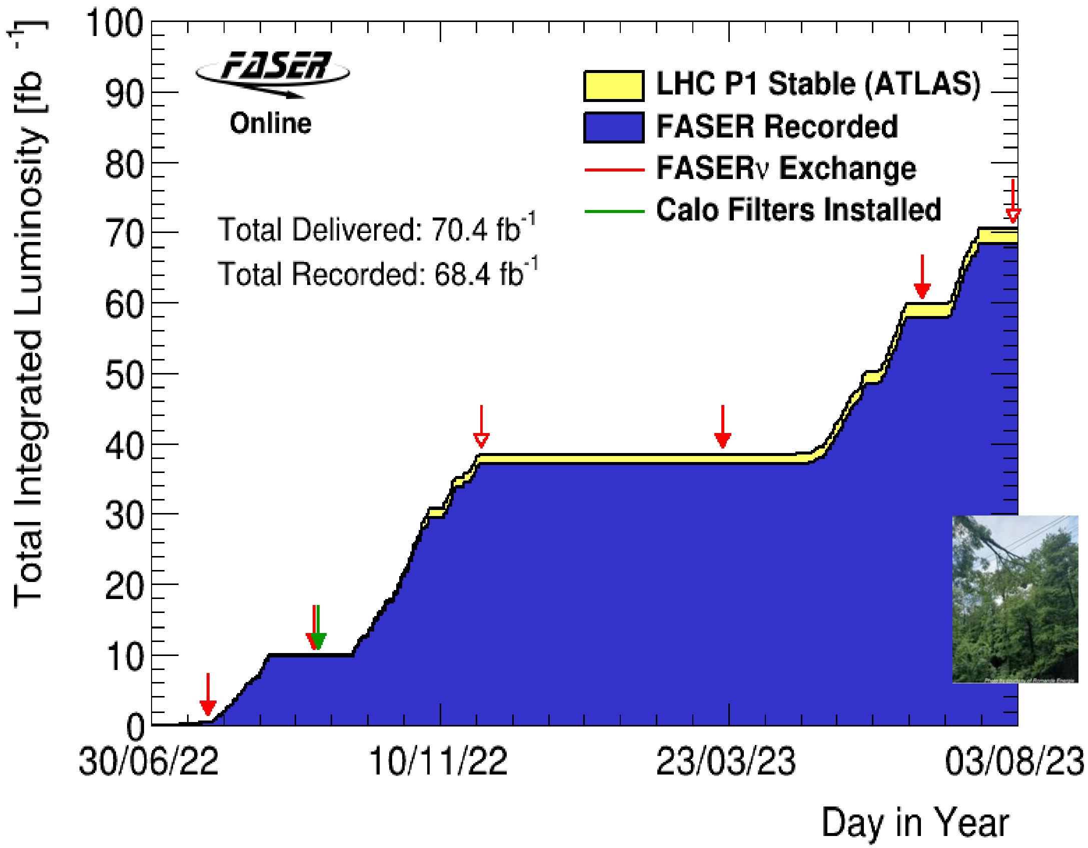
- The experimental environment: 88 m underground, shielded from ATLAS by 100 m of rock → extremely quiet. Trigger on everything, ~kHz trigger rate dominated by muons from ATLAS.

FASER Collaboration
([2207.11427](2207.11427))



# FASER DATA TAKING IN 2022 AND 2023

- 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 from Jul to Nov 2022 and Apr to Jul 2023.
- 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

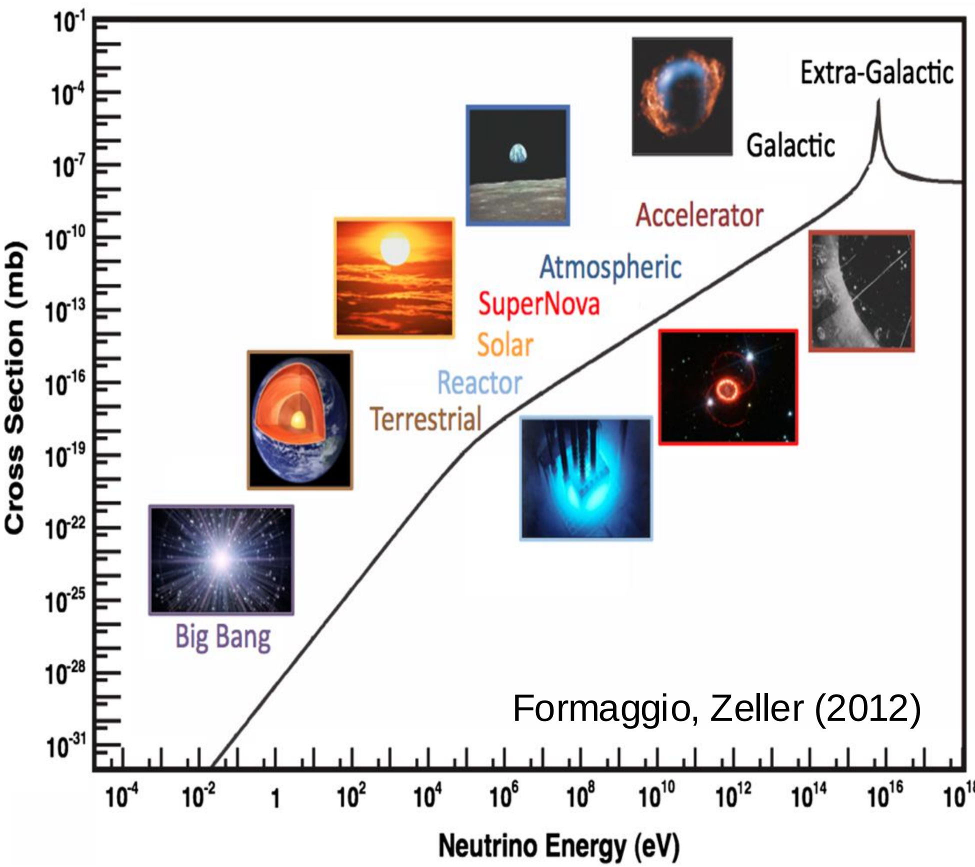



- FASERν emulsion exchanged periodically to prevent overexposure
  - 3 boxes in 2022 (0.5, 10, 30 $fb^{-1}$)
  - 2 boxes in 2023 (20, 10 $fb^{-1}$)

# COLLIDER NEUTRINOS

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

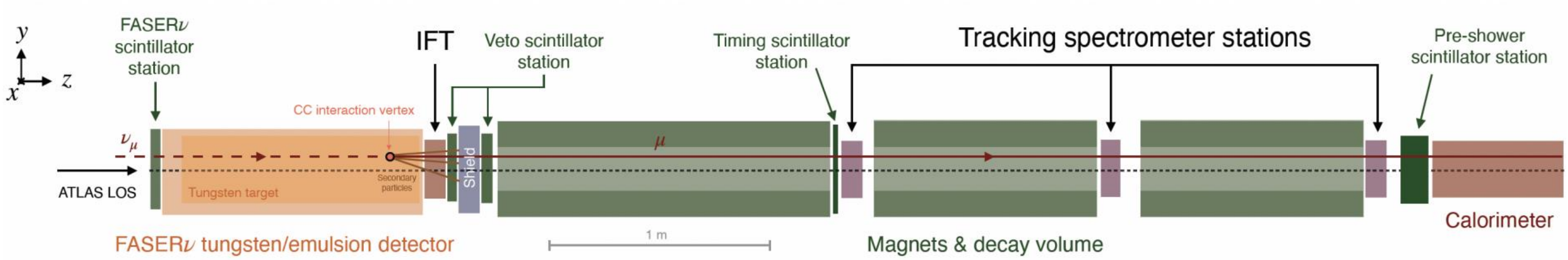
- They have been discovered from many sources, each time with stunning implications for particle physics, astrophysics, and cosmology.




- But before FASER, neutrinos produced at a particle collider (since 1971) had never been directly observed: they interact very weakly, and 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 FASER$\nu$. 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)

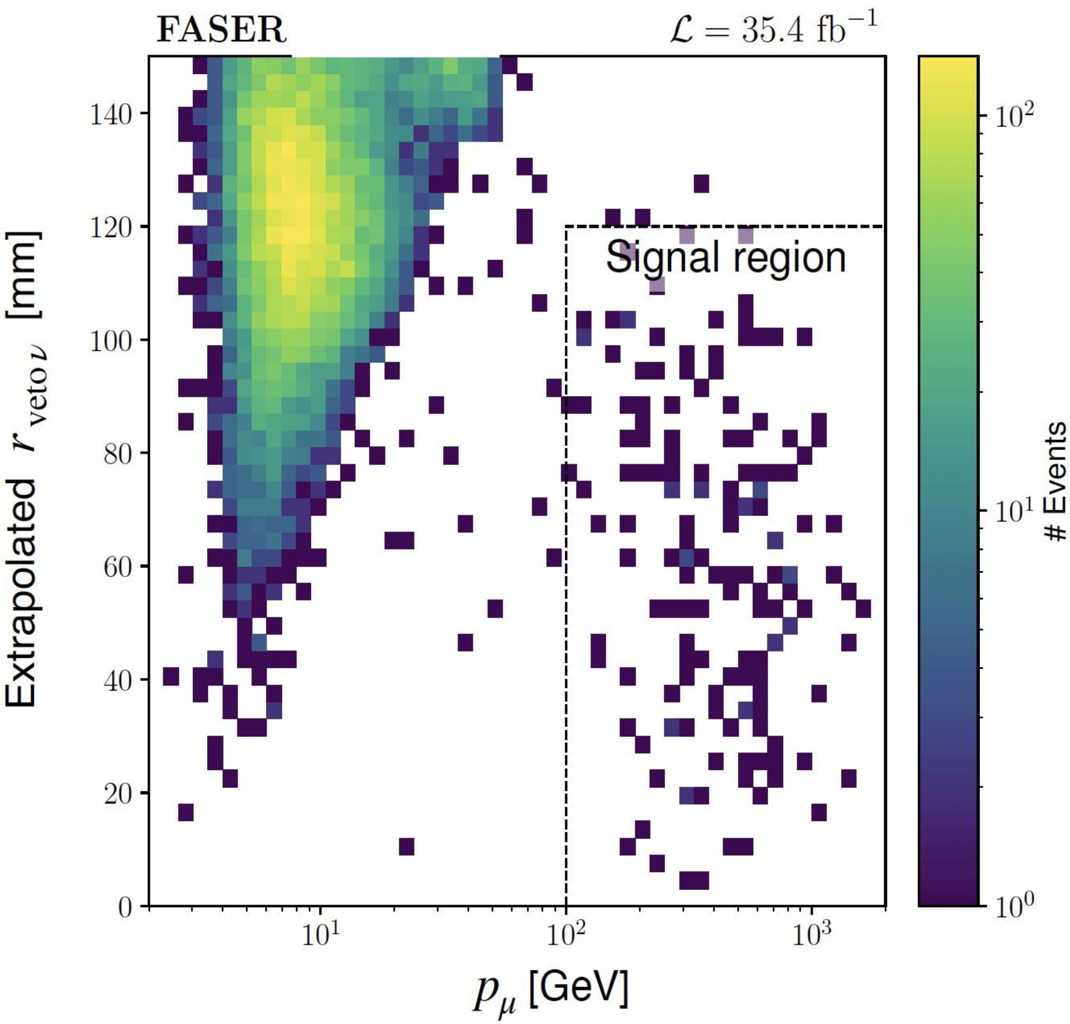
- The signal is no charged particle passing through the upstream veto scintillators, hits in the downstream scintillators, and a single charged track, >100 GeV, in the central region of downstream trackers.

- 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 → $\nu$ and $\bar{\nu}$
  - These include the highest energy $\nu$ 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)

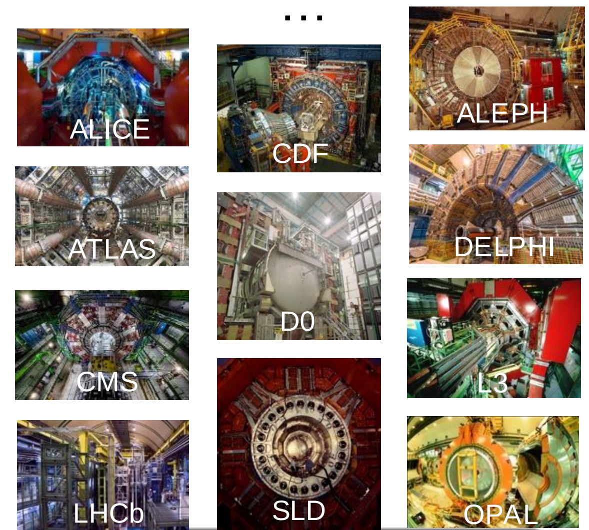
# DISCOVERY OF COLLIDER NEUTRINOS

# LOCATION, LOCATION, LOCATION

FASER

"Tabletop," 18 months,
~$1M

153 neutrinos




All previous
collider detectors

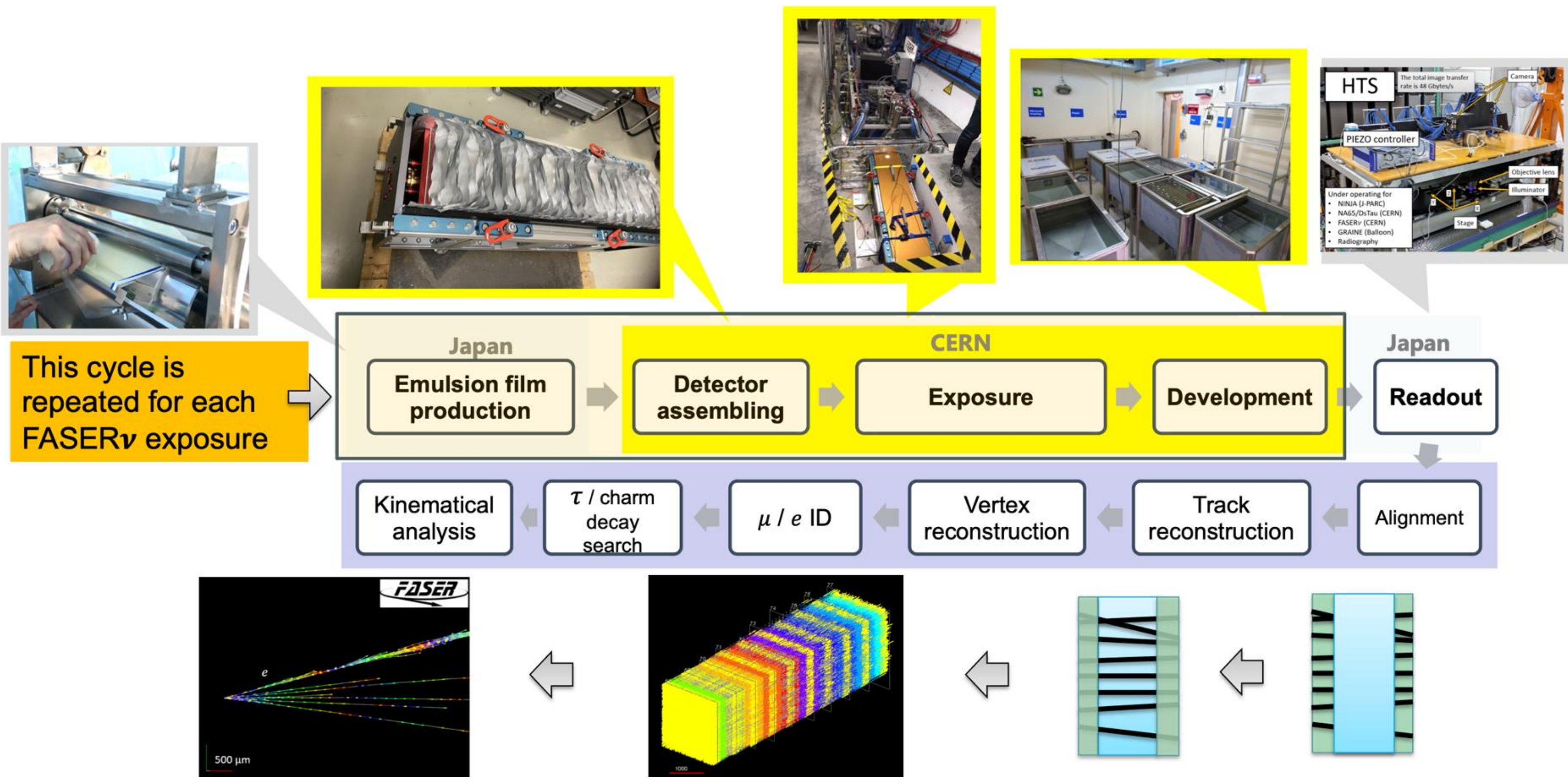
Building-size, decades,
~$1B

0 neutrinos

$16\sigma$ discovery, opening a new window
at the high energy frontier

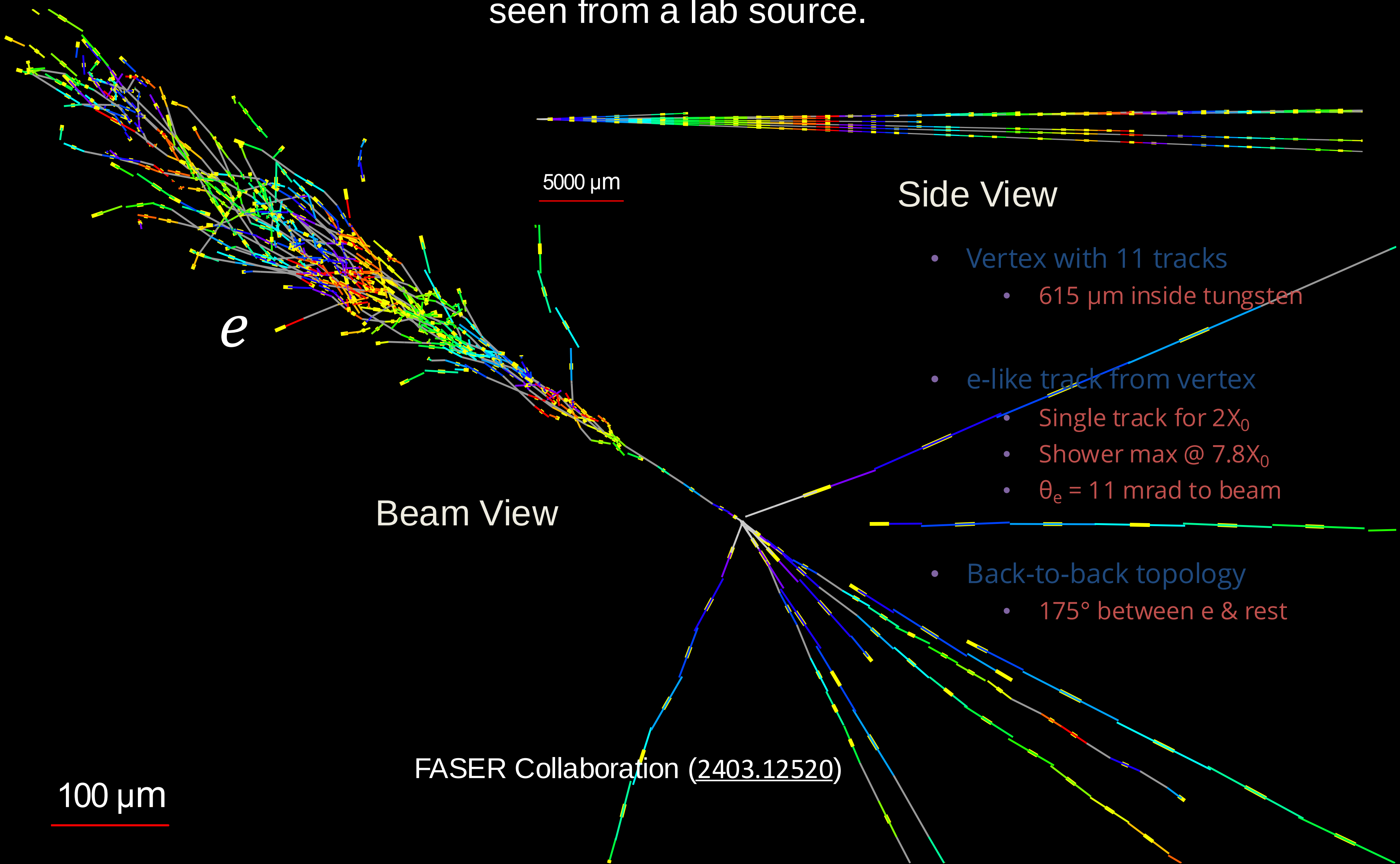
# NEUTRINOS IN FASERν

- 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 FASER$\nu$

With the emulsion, we have now observed the first collider electron neutrinos, including the "Pika-$\nu$" 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 @ $7.8X_0$
  - $\theta_e$ = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

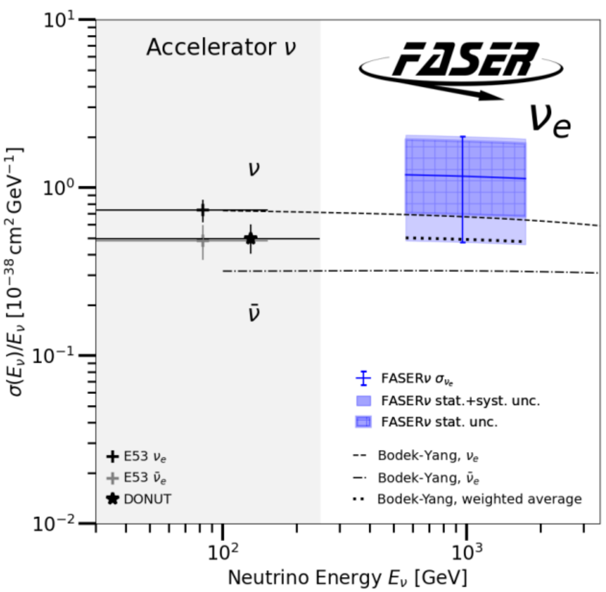
FASER Collaboration (2403.12520)

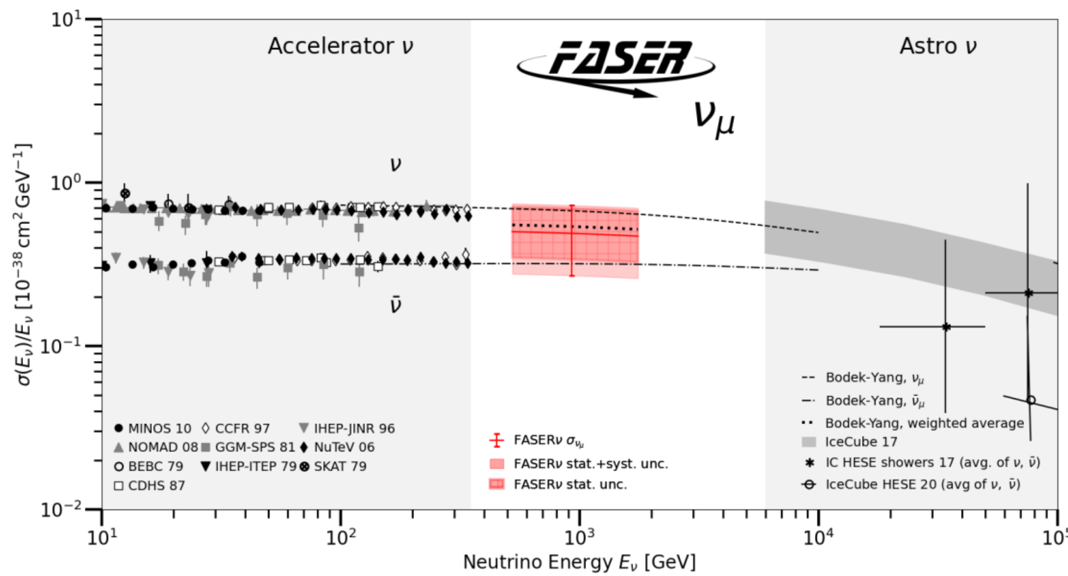
# TEV NEUTRINO CROSS SECTIONS

- 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.

Xie, Gao, Hobbs, Stump, Yuan (2024)



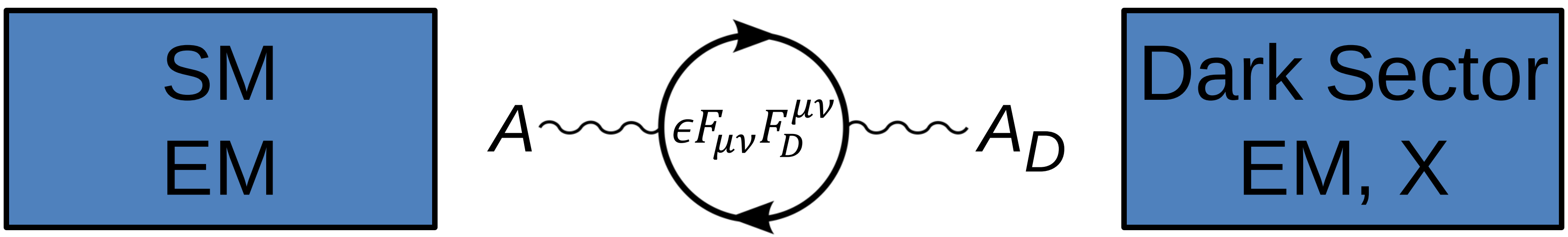




FASER Collaboration (2403.12520)

- These measurements use only 1.7% of the data already 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.



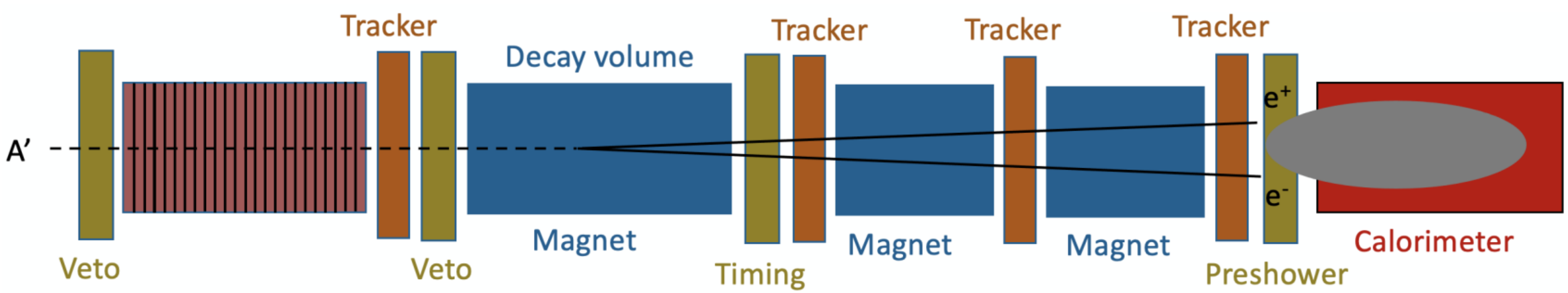

- The result? Dark photons $A'$ , like photons, but with mass $m_{A'}$, couplings suppressed by $\epsilon$.

Holdom (1986)

- For low $\epsilon$, 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 $\pi/\eta \to A'\gamma$ or “dark bremsstrahlung” $pp \to ppA'$.
- Travel straight and unimpeded through 480 m of rock/concrete.
- Then decay through $A' \to \ e^+e^-$.



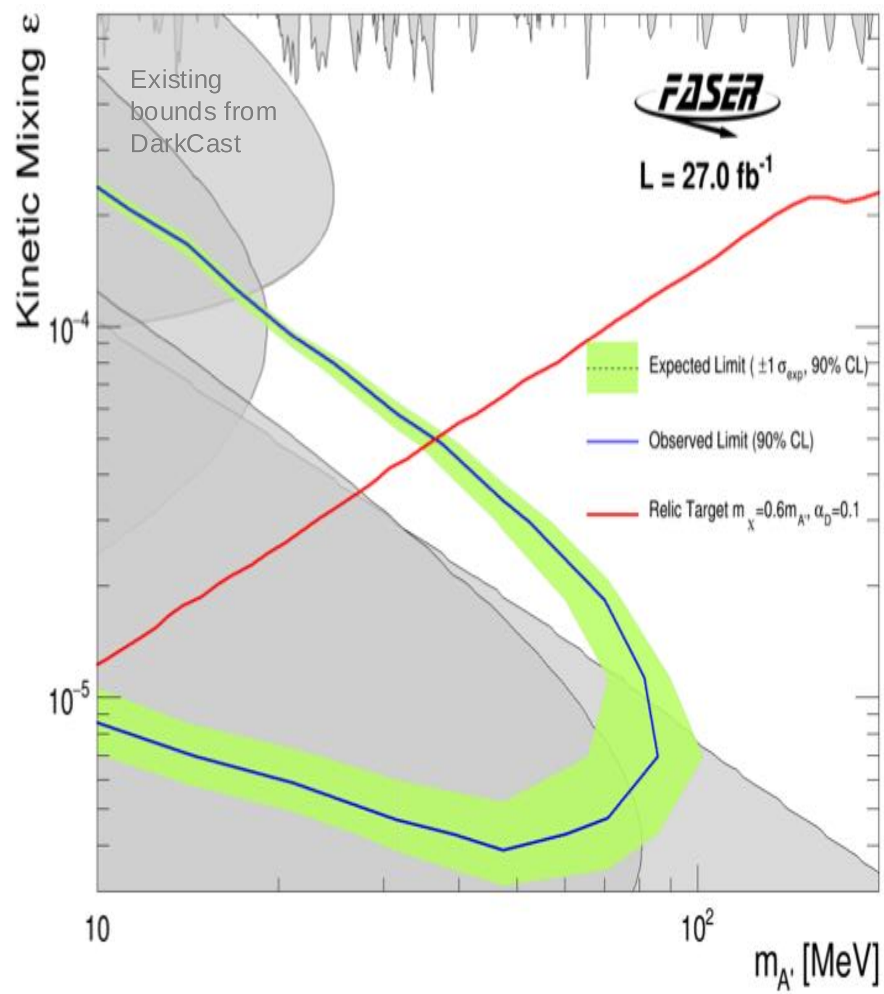

- The signal is no charged particle passing through the upstream veto scintillator detectors, followed by two very energetic (100s of GeV) charged tracks in downstream trackers. Tracks are very collimated, but magnet splits them sufficiently to be seen as 2 tracks in trackers.

# 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.

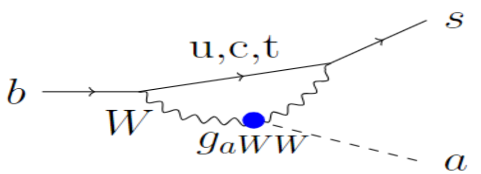
- Bodes well for the future
  - Background-free analysis
  - Started probing new parameter space with the first day of data
  - Ended up ~100 times more sensitive than previous experiments
  - Improvements in analysis and 40 times more data to come



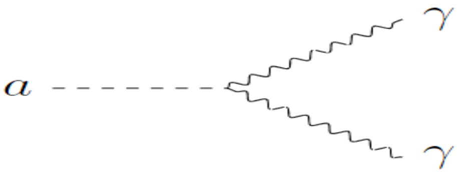

FASER Collaboration (2308.05587, PLB)

# ALP-W SEARCH RESULTS

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

production 



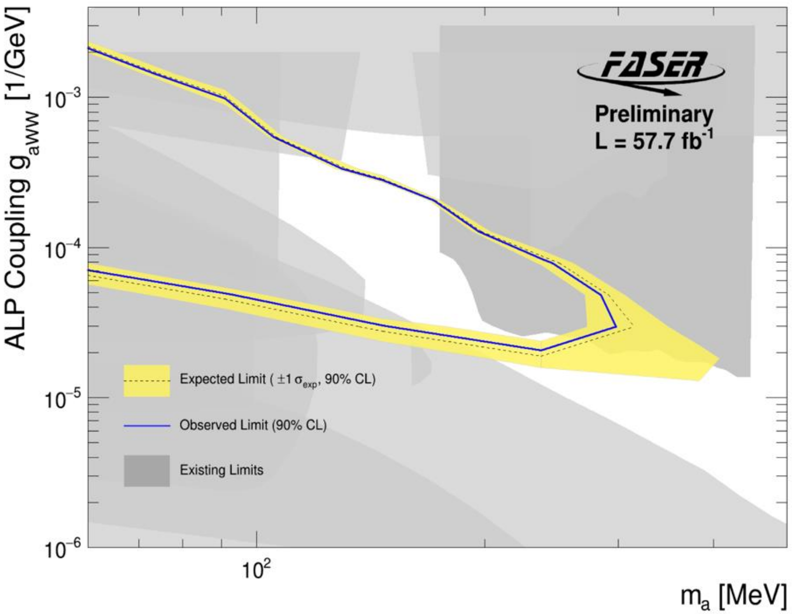
decay 



- Signal is no hits in veto scintillators, >1 TeV energy deposit in ECAL.

- Background: Expect $0.42 \pm 0.32$ from $\nu$ 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)

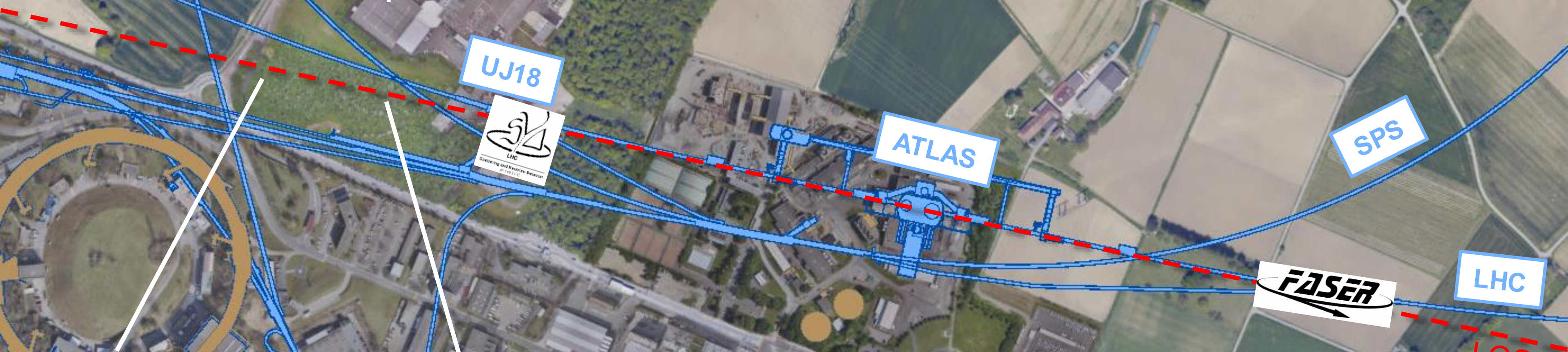
- FASER is approved to run through Run 4 (-2031), with improvements in analysis, hardware upgrades (high granularity pre-shower). We will be testing many other new ideas, e.g., other new force carriers ($U(1)_{B-L}$, $U(1)_B$, protophobic), ALP-$\gamma$, ALP-g, light-shining-through-walls axions, dark Higgs bosons, sterile neutrinos, light neutralinos, inflatons, quirks, etc., all with world leading sensitivities.

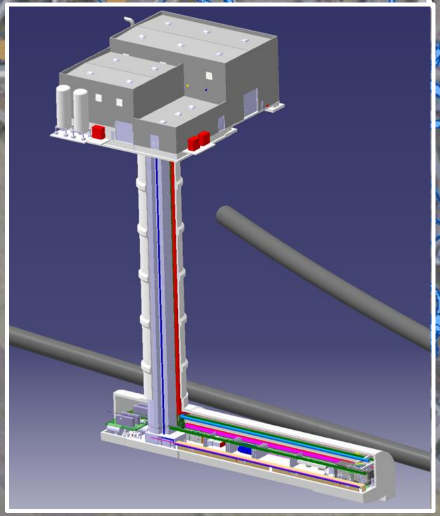
FPF

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 2028-2040s.



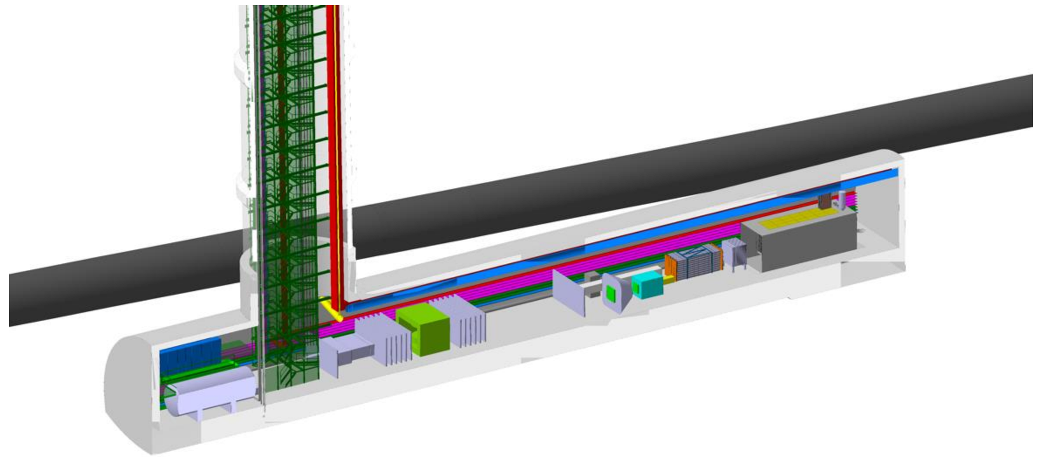



FPF site selection study and core study have identified an ideal site in France just outside the CERN main gate

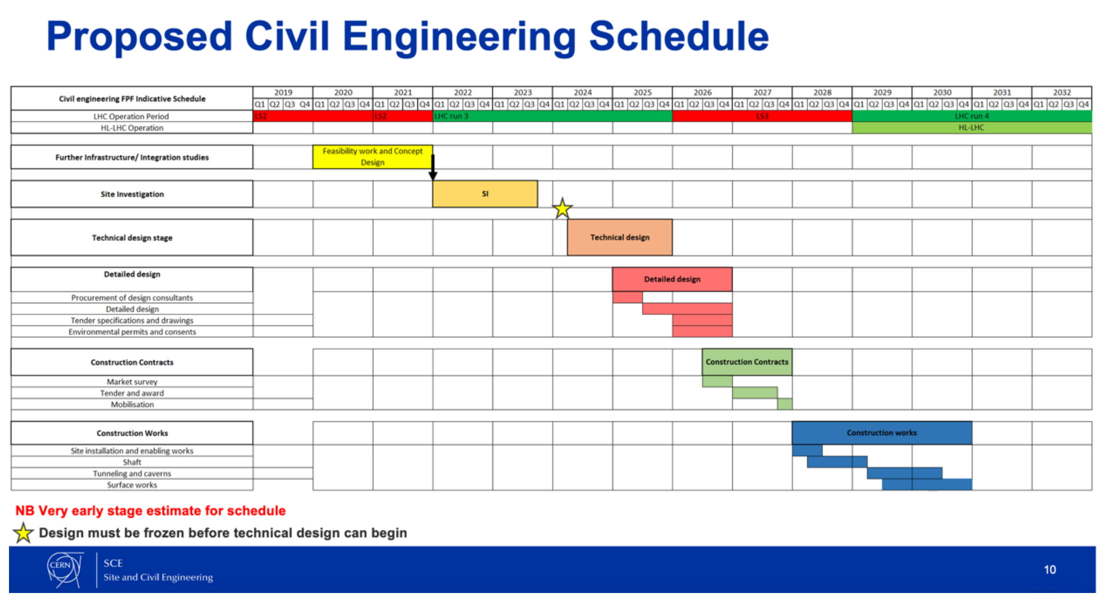
CERN GIS

# THE FACILITY

- A cylindrical cavern surrounding the LOS, 620-695 m west of the ATLAS IP.
- 75 m long, 12 m in diameter, covers $\eta > 5.1$.
- Preliminary (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/Run5.

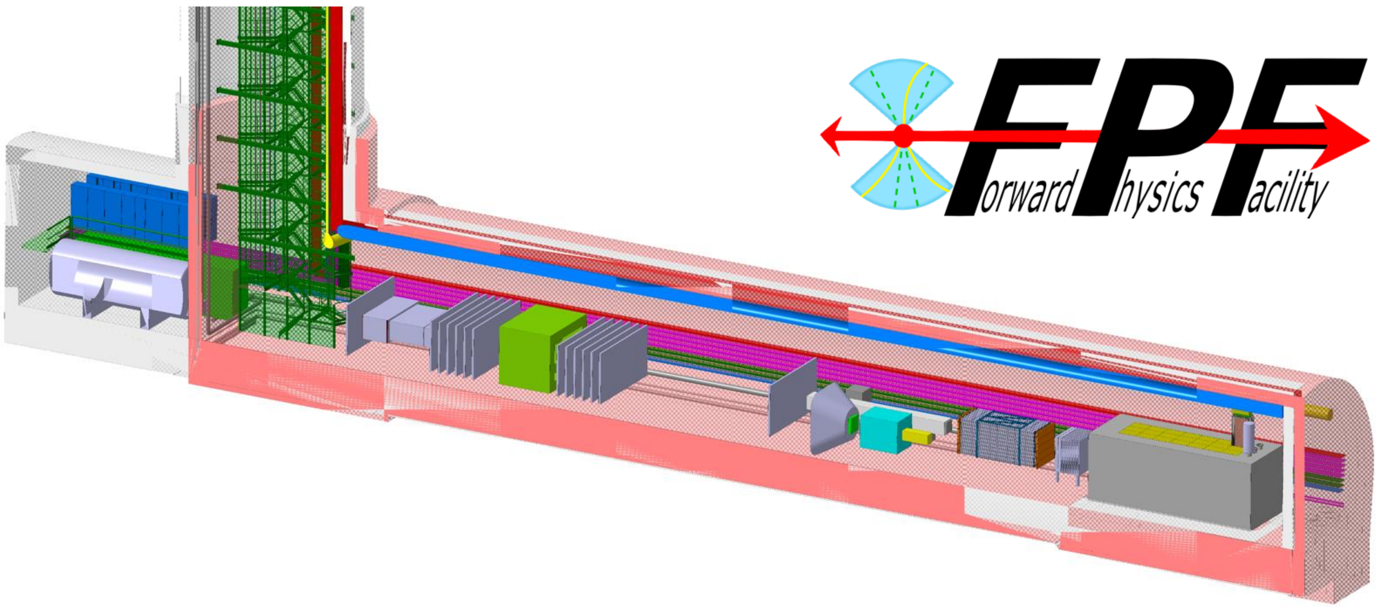


Bud, Magazinik, Pál, Osborne, et al. CERN CE (2024)



# FPF EXPERIMENTS

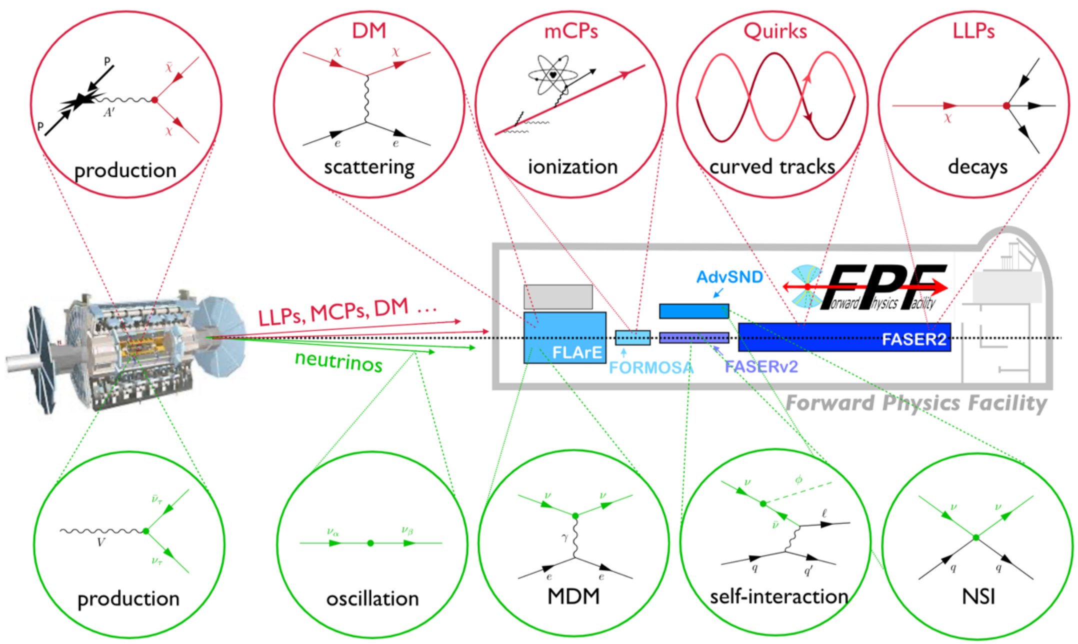
- At present there are 4 experiments being designed for the FPF
  - FASER2: magnetized spectrometer for BSM searches
  - FASER$\nu$2: emulsion-based neutrino detector
  - FLArE: LArTPC neutrino detector
  - FORMOSA: scintillator array for BSM searches (successor to MilliQan)

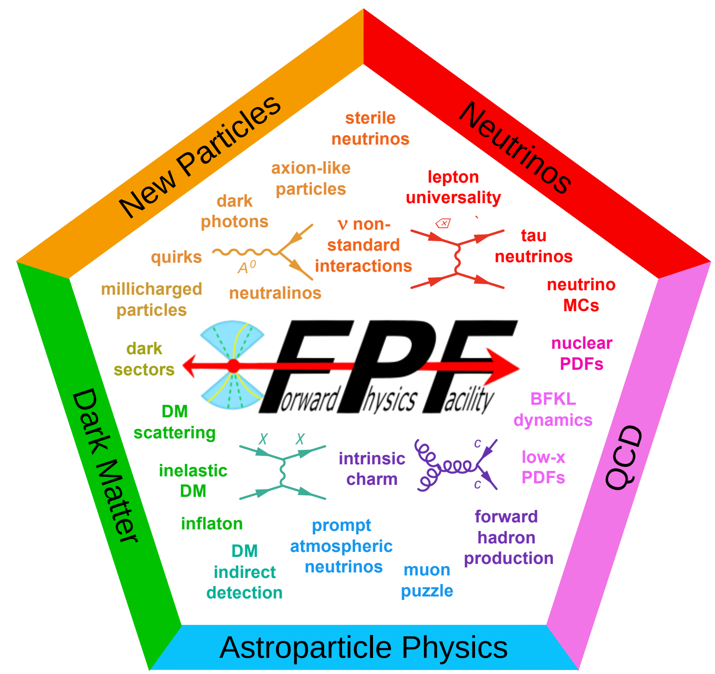



- These represent a huge jump relative to the existing experiments:
  - 10,000 times greater (decay volume * luminosity) for BSM searches.
  - Will detect miilions of TeV neutrinos, ~1000 neutrinos/day!

# NEW PHYSICS AT THE FPF

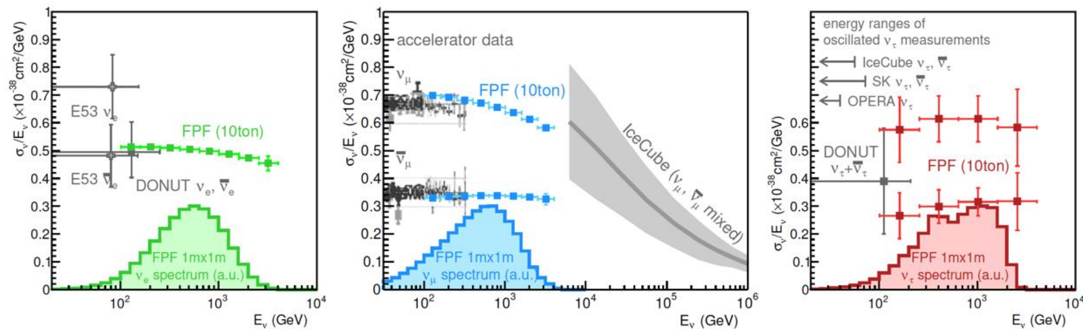
- The FPF is proposed to run at the HL-LHC with unique probes of
  - New physics in neutrino properties: neutrino blind → neutrino factory ($10^6$ neutrinos at the highest human-made energies ever).
  - New particles: dark matter, dark sectors, milli-charged particles, new force particles, new Higgs-like particles, sterile neutrinos, quirks, …



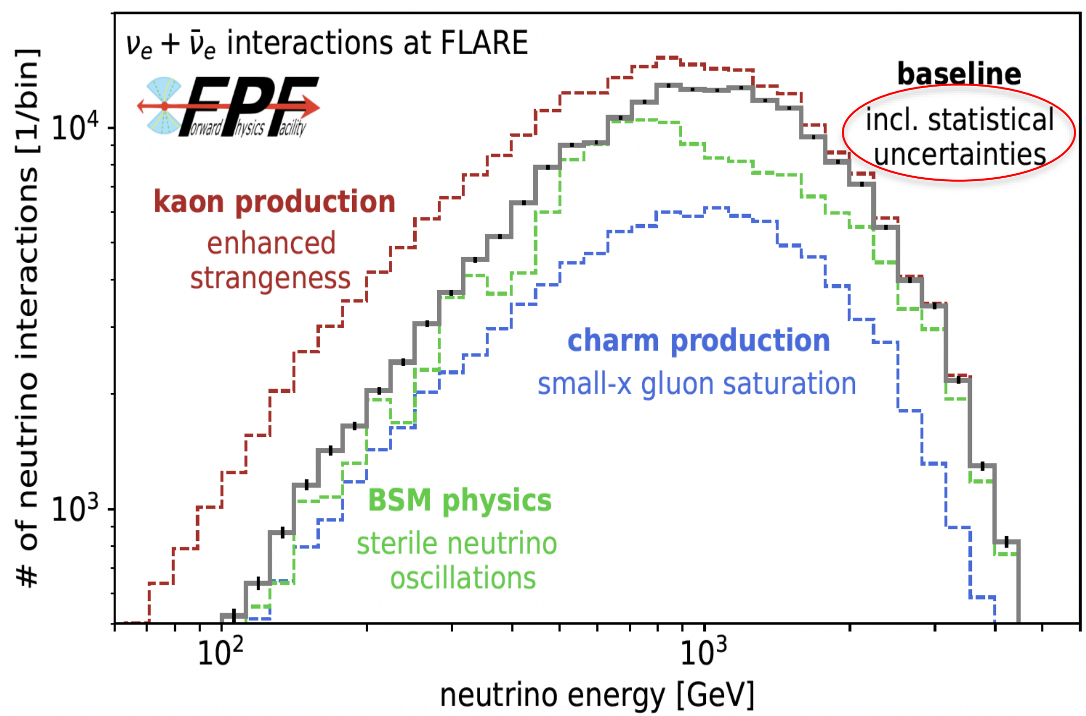



# NEUTRINOS AT THE FPF

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




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



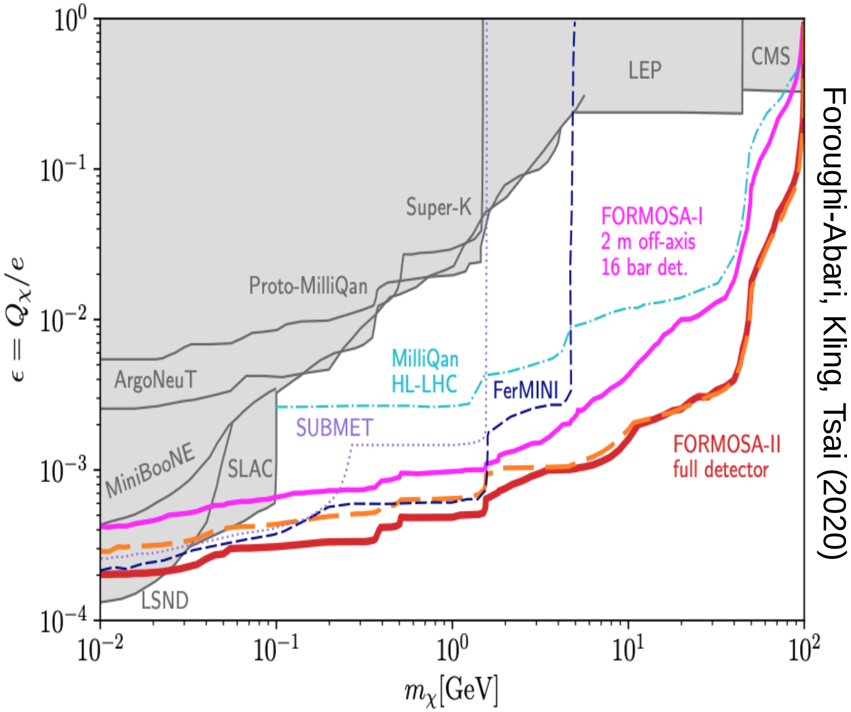
# UNIQUE DISCOVERY OPPORTUNTIES

- FPF experiments will enhance the LHC's discovery potential, looking somewhere new where no other LHC experiments (or any other experiments) can look. 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.

- FORMOSA is 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 explored 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, …)

$m_1$

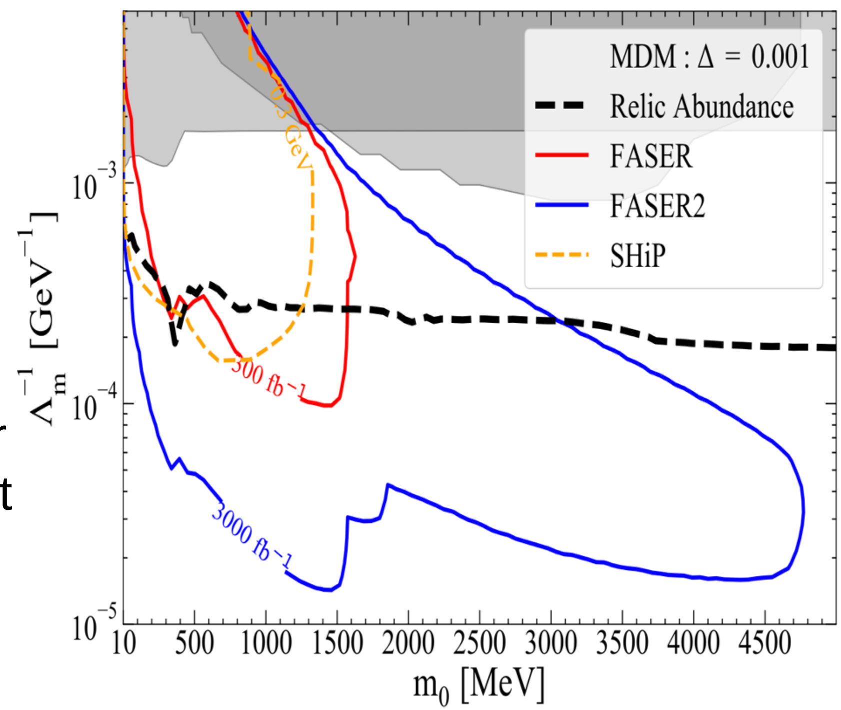
$m_0$

$\chi_1 \to \chi_0 \gamma$

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

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

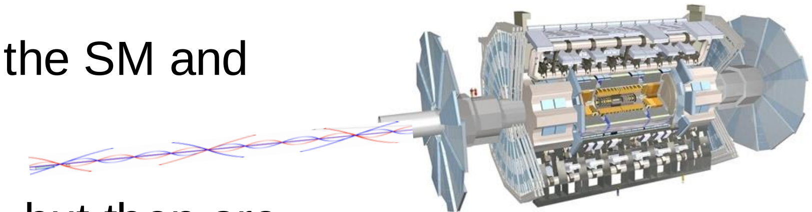
0



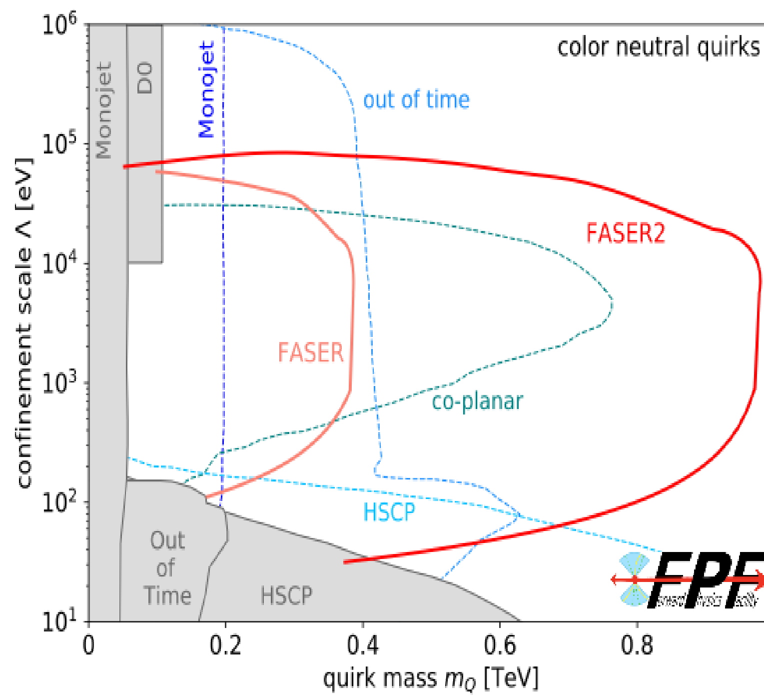

Dienes et al. (2023)

# QUIRKS

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



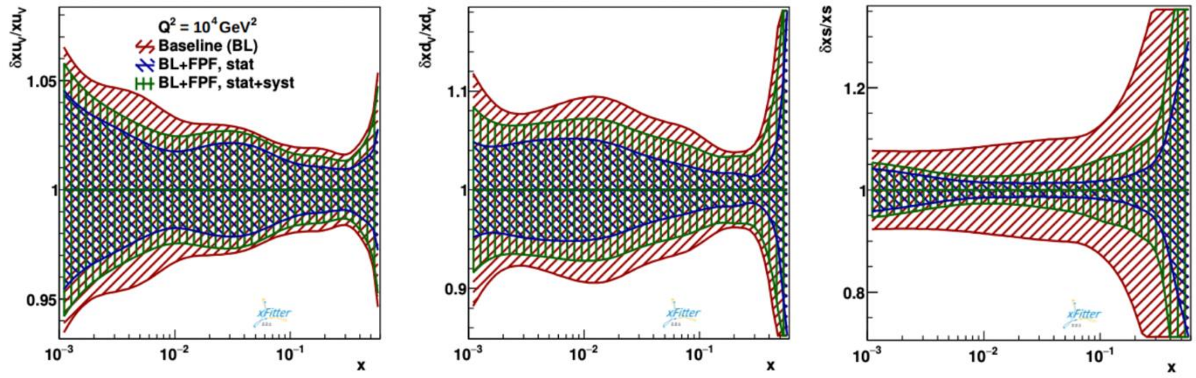
- Quirks can be pair-produced at the LHC, but then are bound by a color string, oscillate about their center-of-mass and travel down the beamline.
- By looking for 2 coincident slow or delayed tracks (out of time with the bunch crossing), FPF experiments can discover quirks with masses up to ~TeV, as motivated by neutral naturalness solutions to the gauge hierarchy problem.
- Unique discovery potential at the FPF: very challenging at ATLAS/CMS, not possible at fixed target experiments.



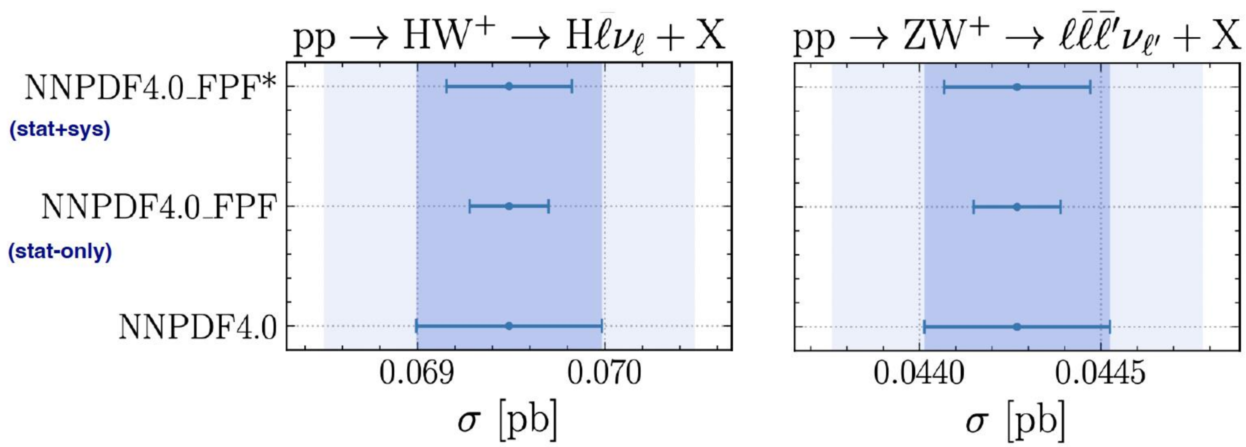

Feng, Li, Liao, Ni, Pei (2024)

# COMPLEMENTARITY WITH HIGH $P_T$ 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.
- Will also remove degeneracies between pdfs and new physics ("fitting away new physics"), enhancing the reach for new particle searches.




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




Ubiali et al., in progress

# SUMMARY

- The forward region, previously thought of as uninteresting, is in fact a treasure trove of interesting physics.
    - Collider neutrinos at TeV energies, with implications for neutrino properties, QCD, astroparticle physics, and high $p_T$ physics.
    - Possibly also 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 coming months and years.
- The Forward Physics Facility is being considered to enable the LHC to fully realize its physics potential before it shuts down in 2042.

# ACKNOWLEDGEMENTS


SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

NSF

CERN

Swiss National Science Foundation

erc

科研費 KAKENHI

国家自然科学基金委员会 National Natural Science Foundation of China

We also thank

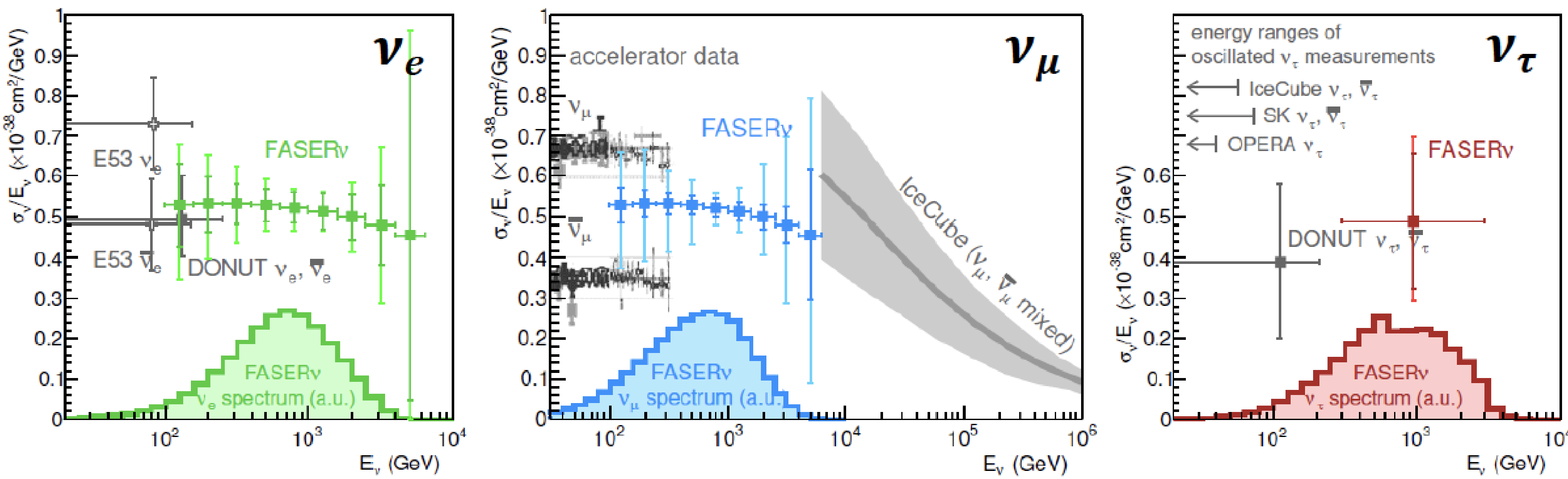
- The LHC for excellent performance in 2022
- ATLAS for luminosity information
- ATLAS for use of ATHENA s/w framework
- ATLAS SCT for spare tracker modules
- LHCb for spare ECLA modules
- CERN FLUKA team for bkgrd simulations
- CERN PBC and technical infrastructure groups for excellent support during FASER's design, construction, installation



THE FASER COLLABORATION
108 collaborators, 27 institutions, 11 countries
FASER Collaboration Meeting, Bonn, 25-27 June 2024

# NEUTRINO PHYSICS

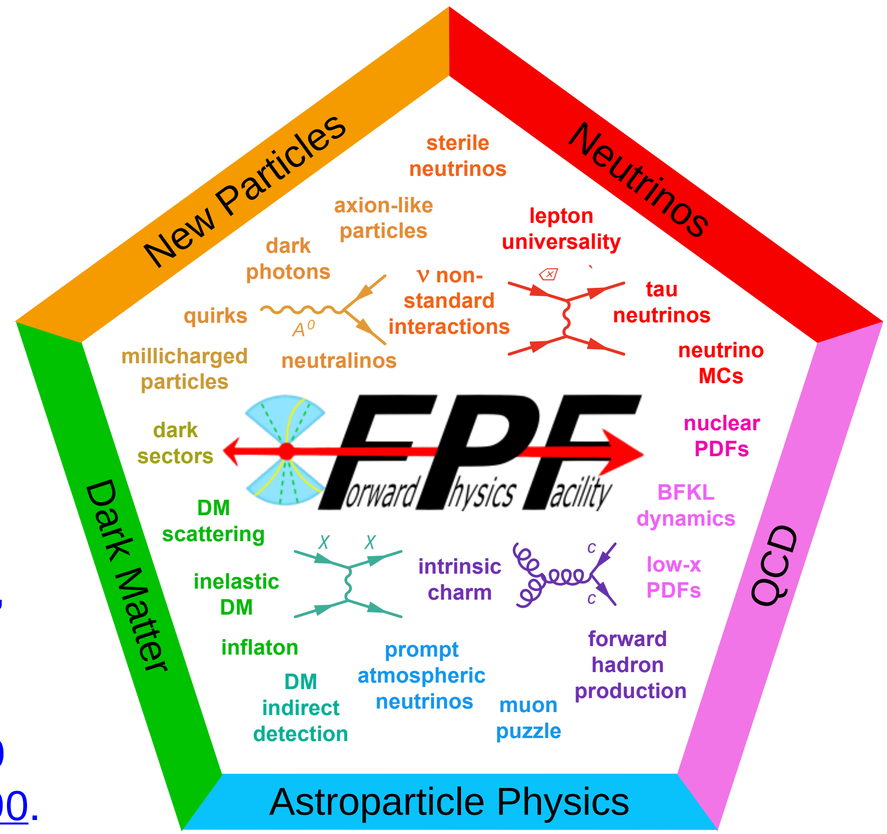
- In Run 3 (2022-25), FASER's goals are to
  - Record ~3000 $\nu_e$, ~10,000 $\nu_\mu$, and ~70 $\nu_\tau$ interactions at TeV energies, the first direct exploration of this energy range for all 3 flavors.
  - Distinguish muon neutrinos from anti-neutrinos by combining FASER and FASERν data, and so measure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




FASER Collaboration 1908.02310 (2019)

# FORWARD PHYSICS FACILITY

- The physics program has been defined by a large and broad community.
- 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.

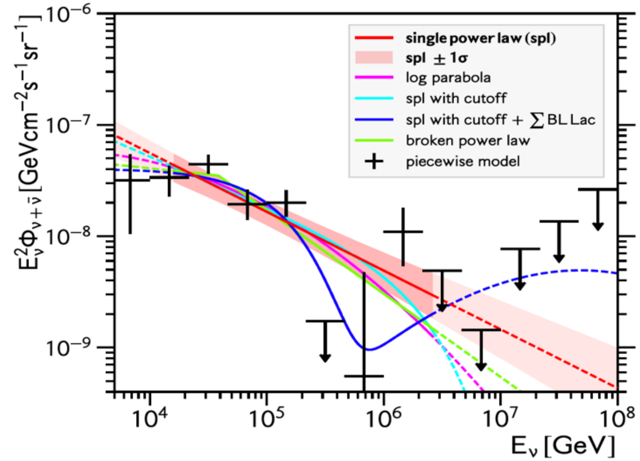



- Snowmass 2022: "Our highest immediate priority accelerator and project is the HL-LHC, … including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades."

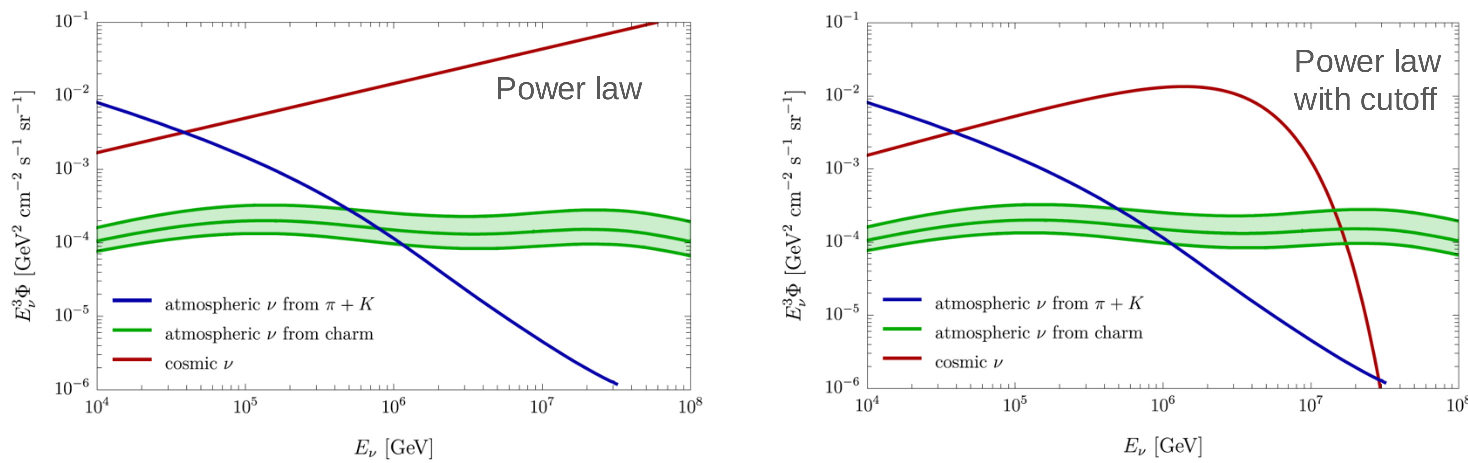
# ASTROPARTICLE PHYSICS AT THE FPF

- 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



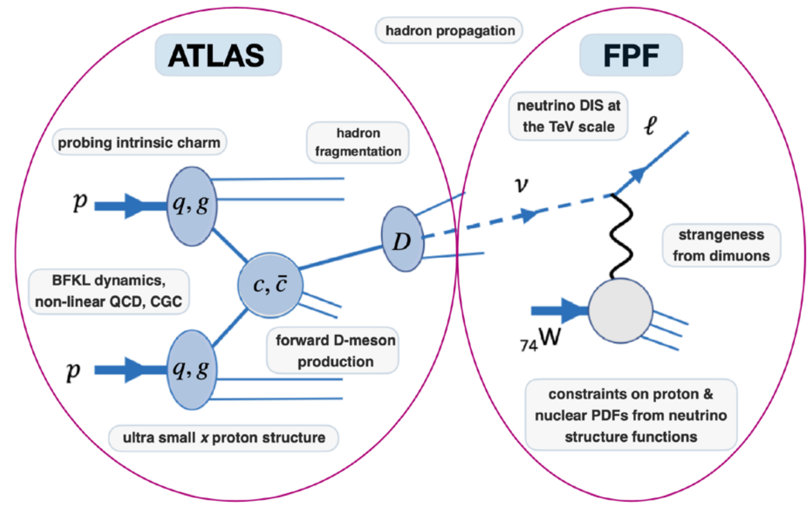

Bhattacharya et al. (1502.01076)

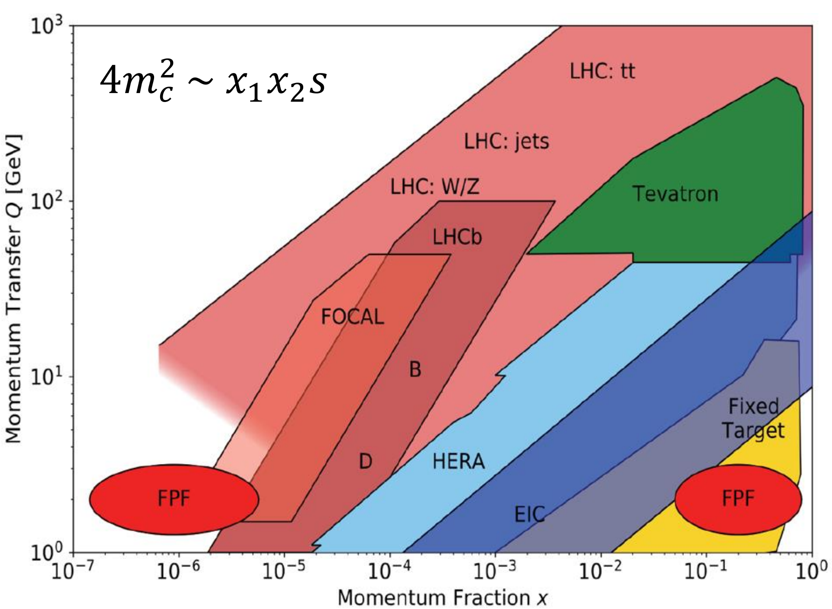
- This can be measured in the controlled environment of a particle collider if
  - $\sqrt{s} \sim \sqrt{2 E_\nu m_p} \sim 10$ TeV for $E_\nu \sim 10^7$ GeV: Requires the energy of the LHC
  - $x_{1,2} \sim \frac{m_c}{\sqrt{s}} e^{\pm\eta} \Rightarrow \eta \sim 7$ to $9$: Requires the far forward angular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

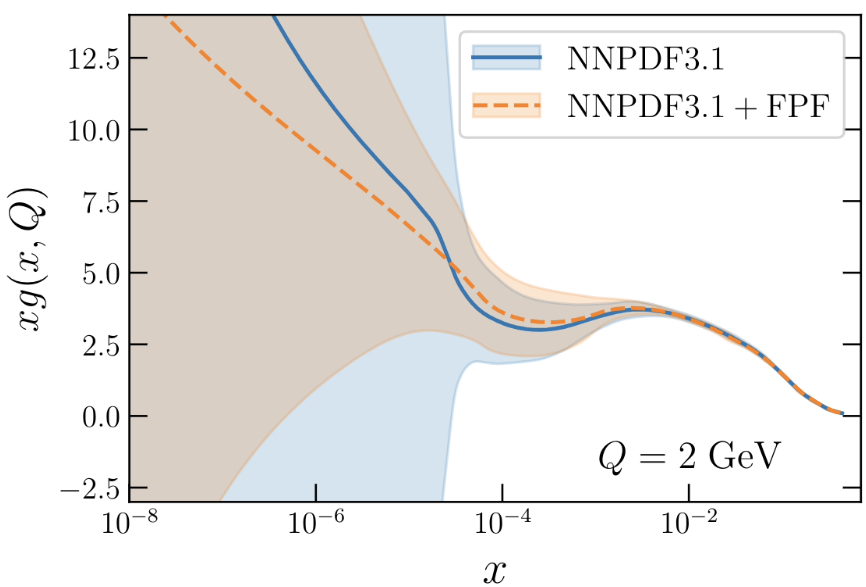
Anchordoqui (2022)

# 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, …



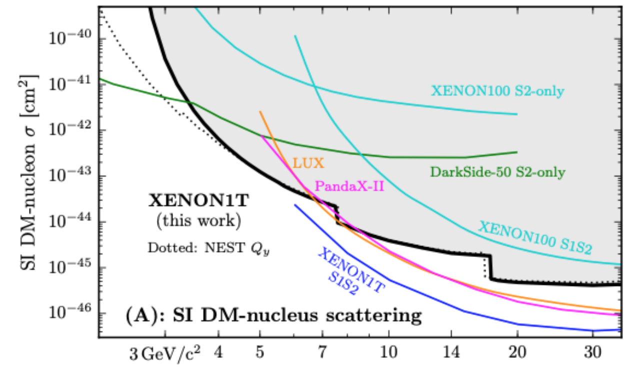



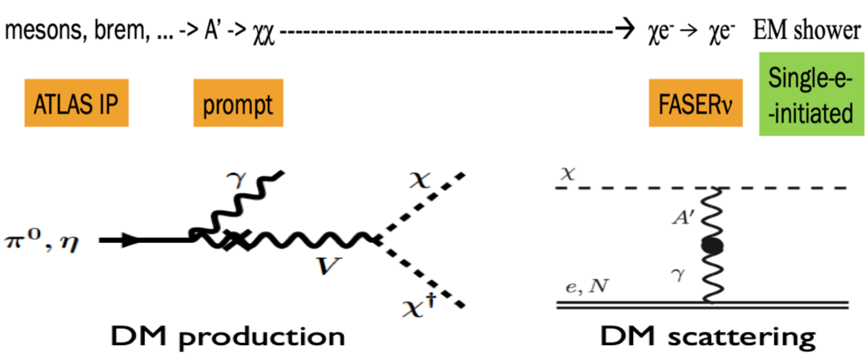

FASER White Paper (2022); Rojo et al. (2024)

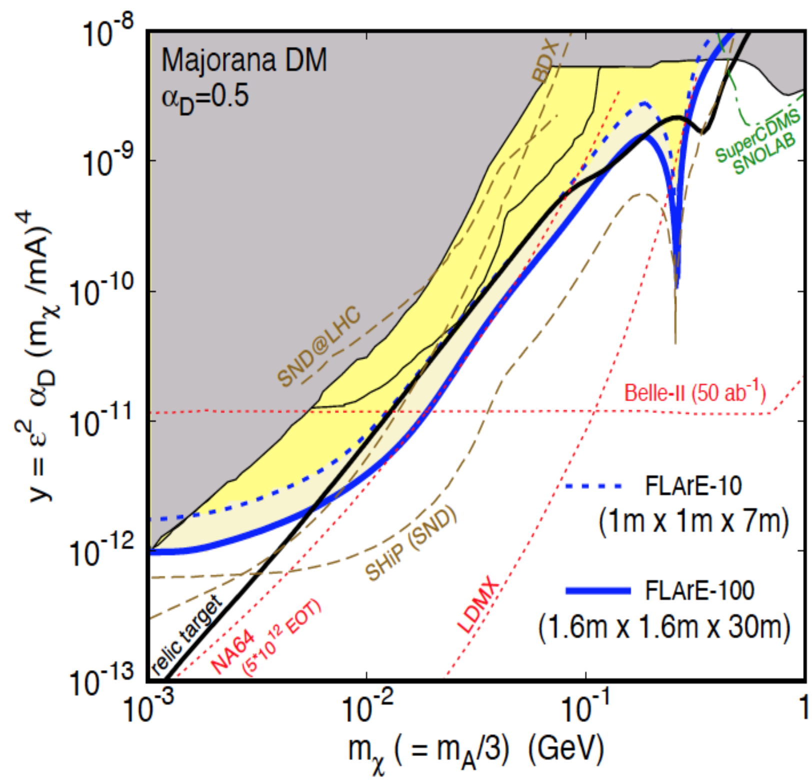
# DARK MATTER DIRECT DETECTION AT THE FPF

- 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

- 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).