# FPF Forward Physics Facility

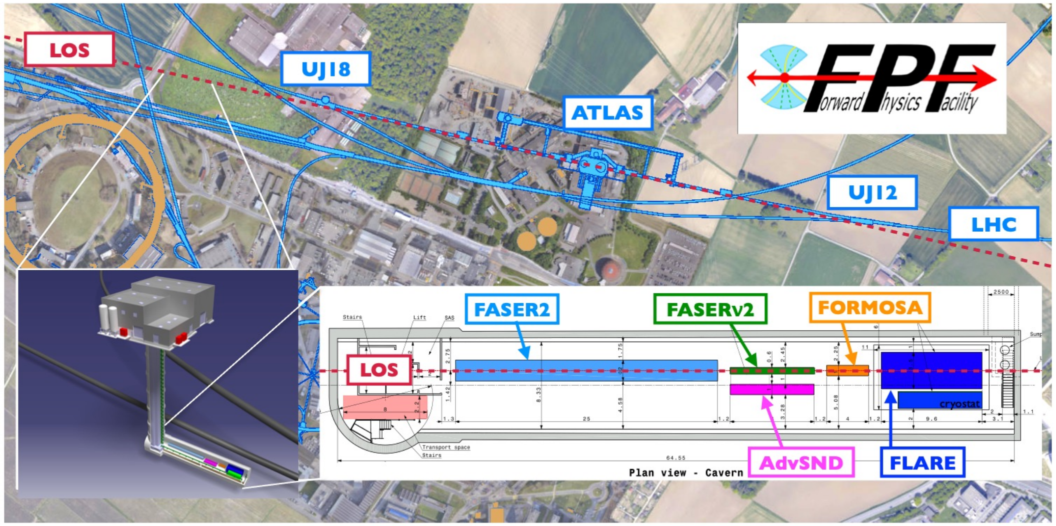
15th International Conference on Interconnections between
Particle Physics and Cosmology (PPC 2022)

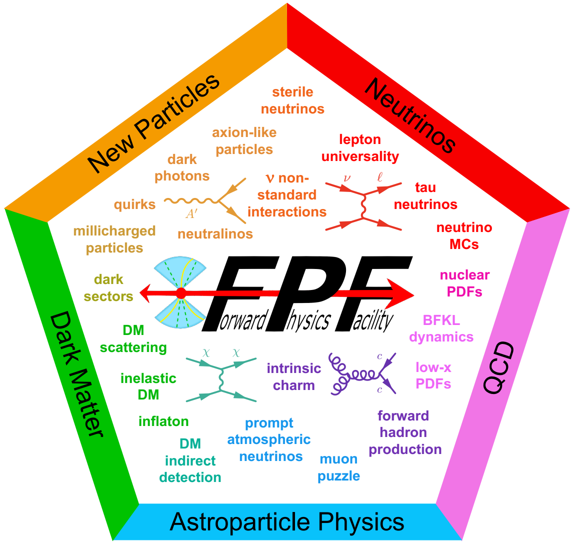
*Washington University, St. Louis*

Jonathan Feng, UC Irvine, 10 June 2022

# SUMMARY

- We are currently missing half of the physics opportunities at the LHC.
- This can be rectified by putting experiments in the far forward region to catch particles produced along the beamline.
- The Forward Physics Facility is a proposal to do exactly this for the HL-LHC era from 2029-40.



# PARTICLE PHYSICS: CURRENT STATUS

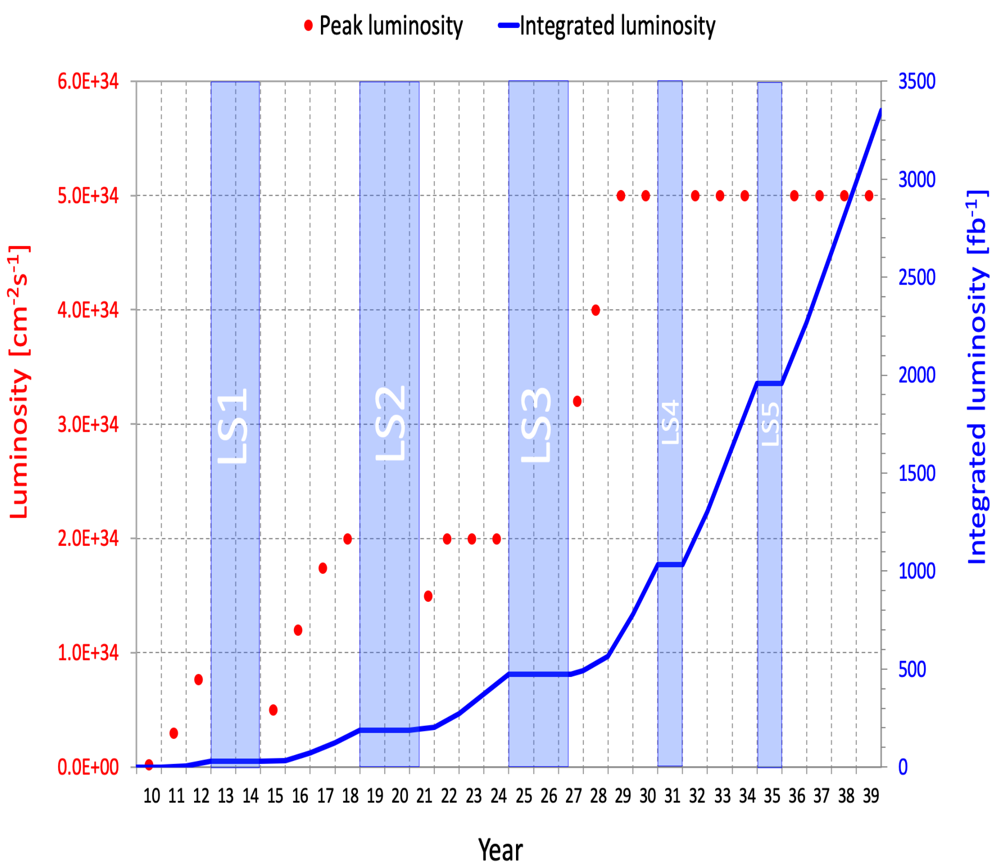
- This is a critical time in particle physics: the Higgs boson was discovered in 2012, but many fascinating problems remain (dark matter, neutrino masses, gauge and flavor hierarchy problems, …), and we have not discovered any other evidence of new particles.

- At the energy frontier, the LHC has just emerged from Long Shutdown 2.

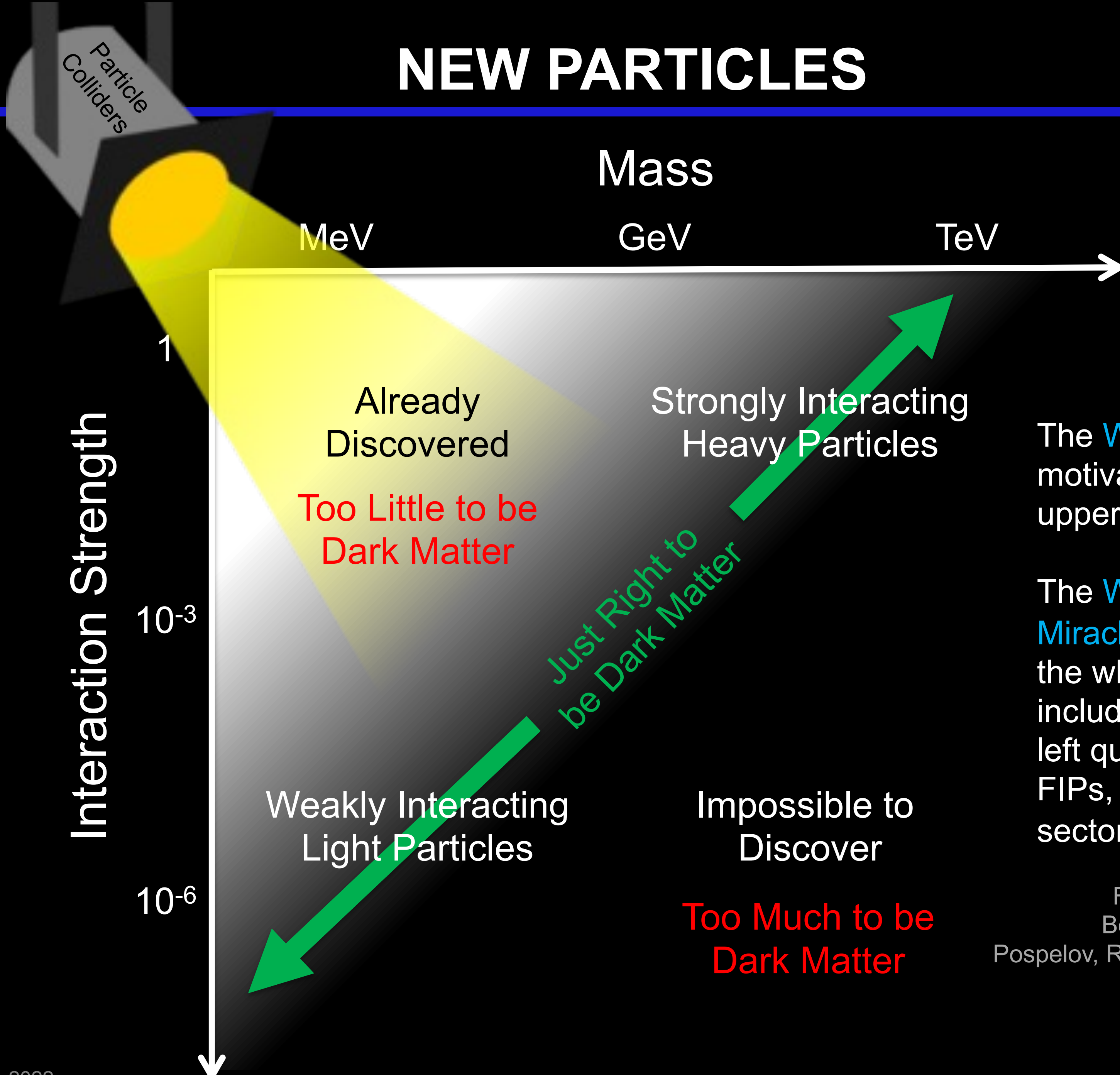
- Much more to come:
  Run 3, 2022-25, 150 $fb^{-1}$
  HL-LHC, 2029-40, 3000 $fb^{-1}$

- What can we do to enhance the prospects for discovering new physics?

[Askew, Han, Westhoff talks]



# NEW PARTICLES

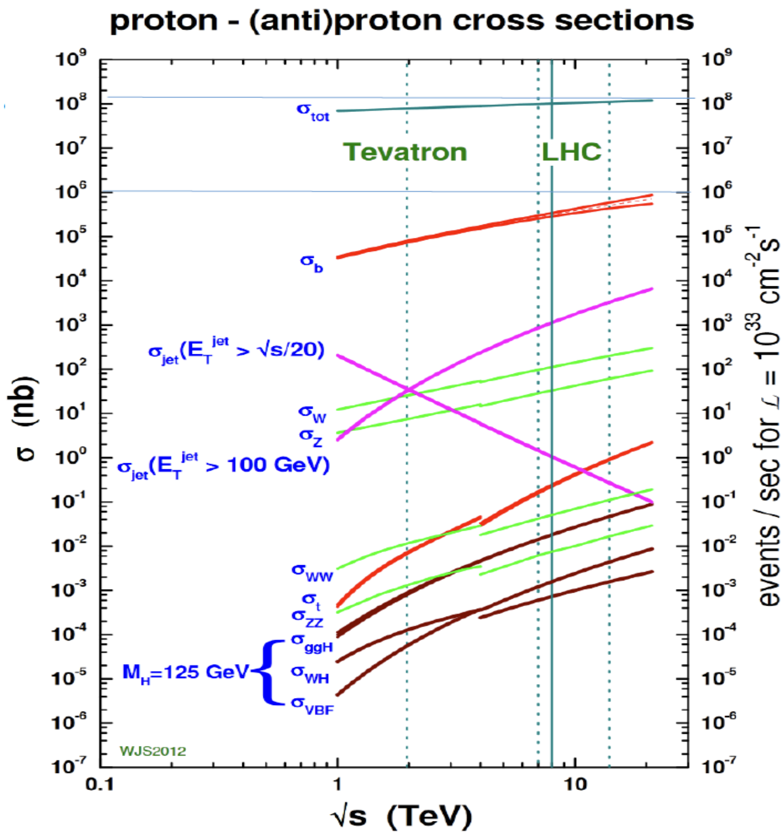


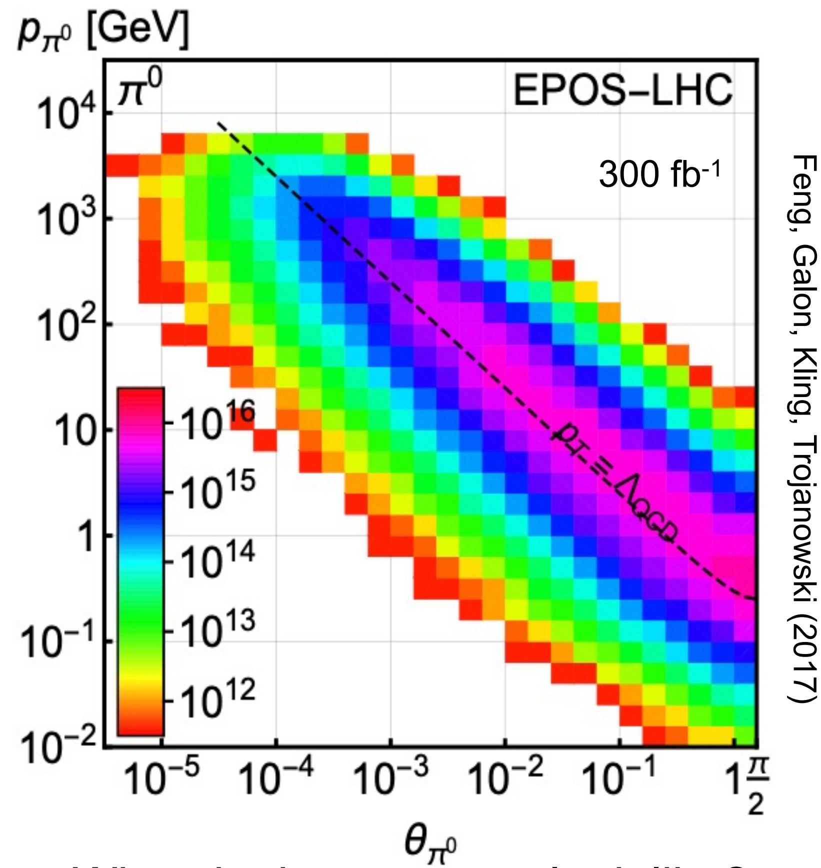

The WIMP Miracle motivates the upper right corner.

The WIMPless Miracle motivates the whole diagonal, including the lower left quadrant (LLPs, FIPs, portals, dark sectors…)

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

# LHC PARTICLE PRODUCTION

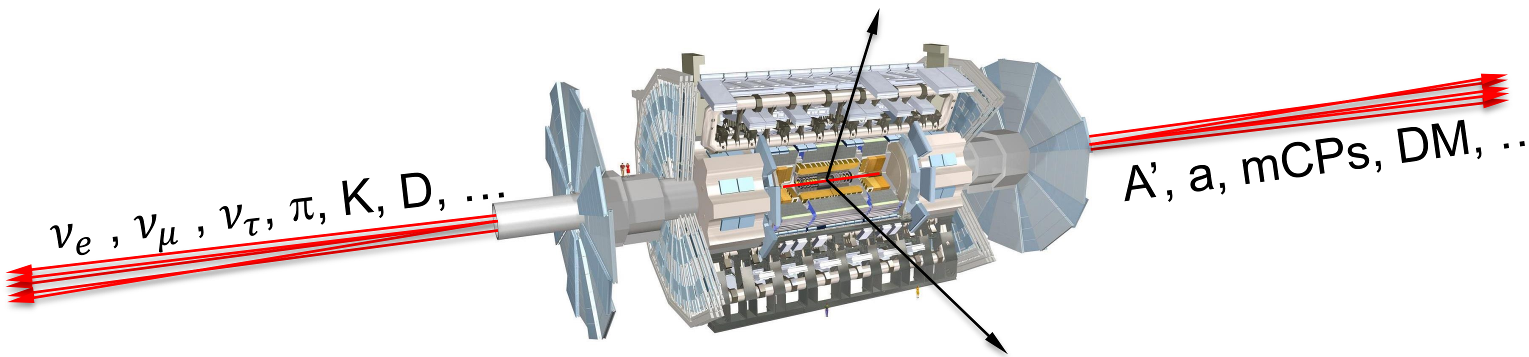



- Most searches have focused on processes with $\sigma$ ~ fb, pb.
- But $\sigma_{\text{tot}}$ ~100 mb, currently wasted in new physics searches.
- What do these events look like? Consider pions.
- Enormous event rates. Typical $p_T$ ~ 250 MeV, but many with $p$ ~ TeV within 1 mrad ($\eta$ > 7.6) of the beamline.

# SEARCHES FOR NEW LIGHT PARTICLES

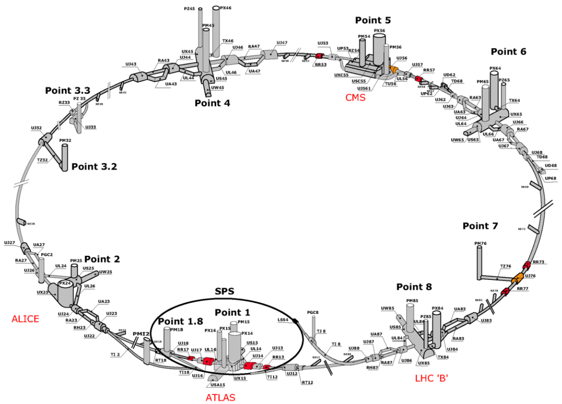
- Particles that close to the beamline are not seen by existing large LHC detectors. They were designed to find strongly-interacting heavy particles.



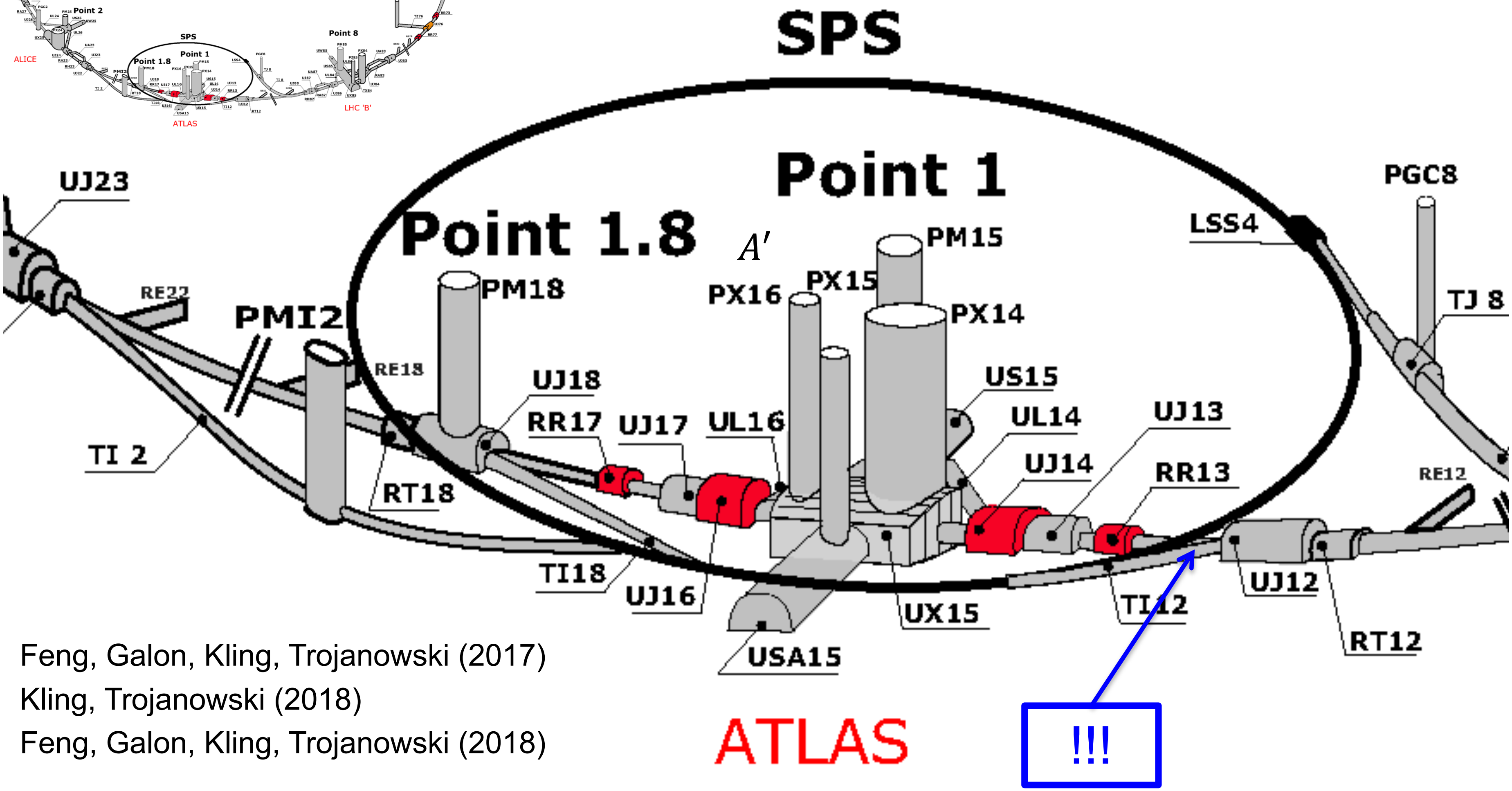

- But they are also perfectly designed to not find weakly-interacting light particles. These are dominantly produced in the rare decays of light particles (π, η, K, D, B, …) along the forward direction, and so the new particles escape through the blind spots down the beamline.

- There are both SM and BSM motivations to explore the "wasted" $\sigma_{tot}$ ~ 100 mb and cover these blind spots in the far forward region.

# THE BASIC IDEA

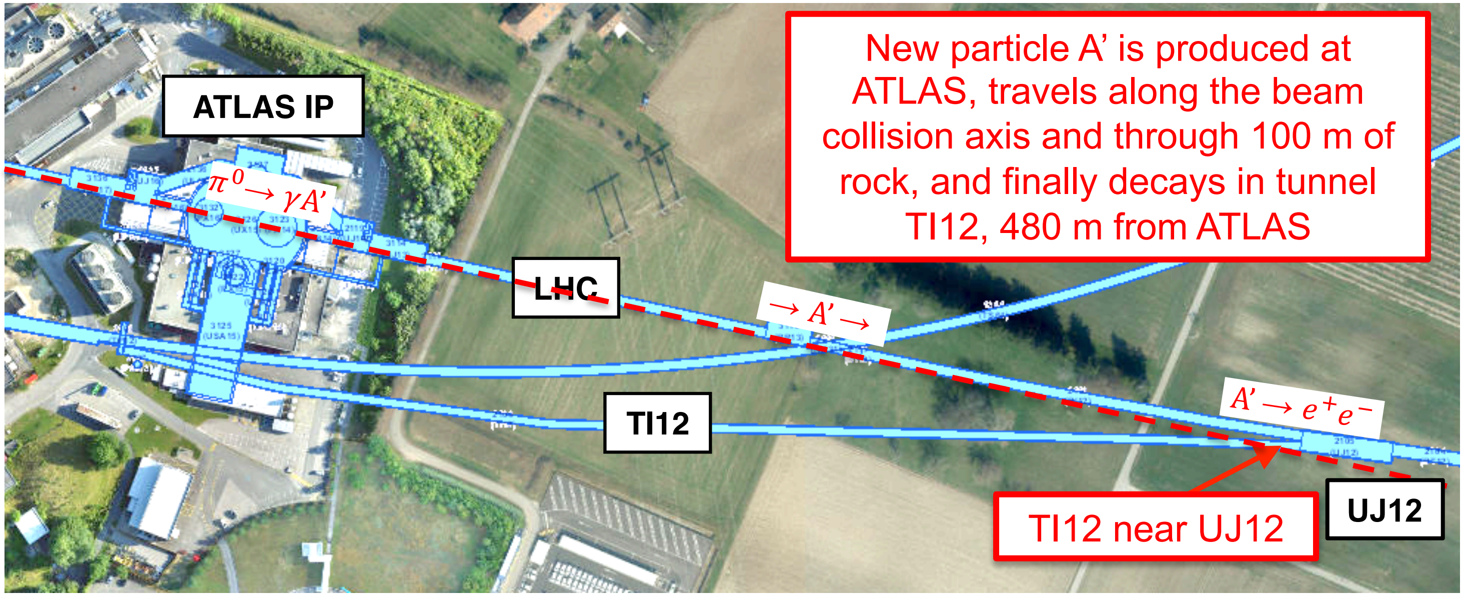


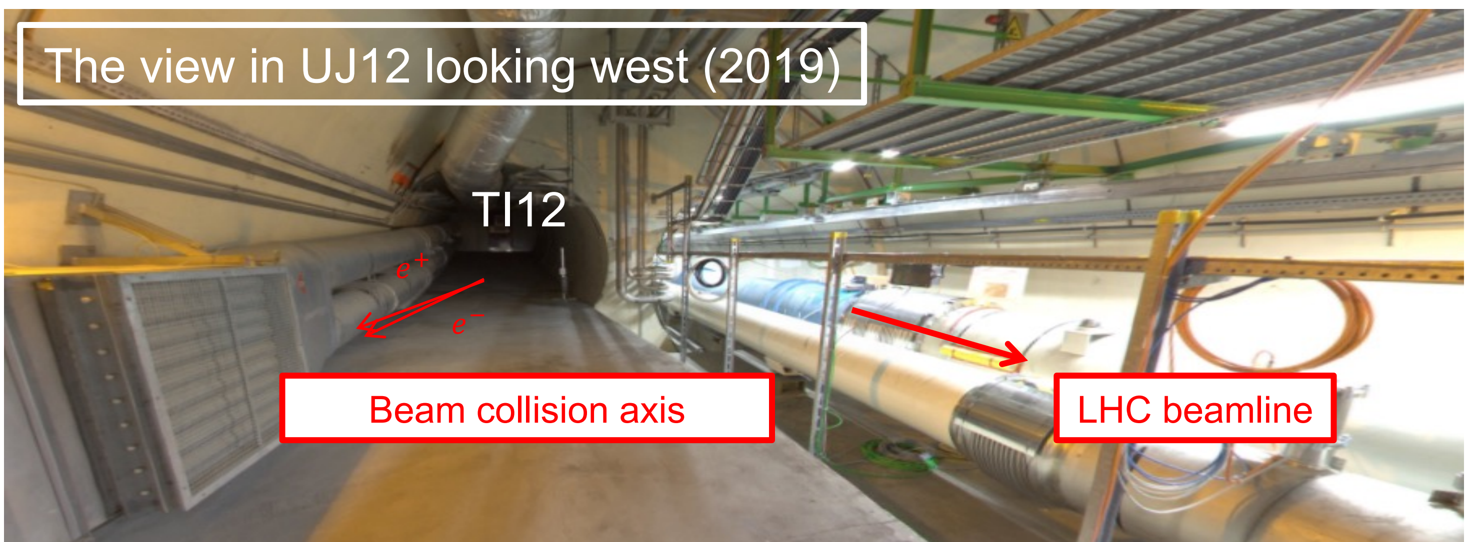

We cannot block the beams, but if we go far away, the proton beams are bent by magnets, whereas light, weakly-interacting particles go straight.




Feng, Galon, Kling, Trojanowski (2017)
Kling, Trojanowski (2018)
Feng, Galon, Kling, Trojanowski (2018)

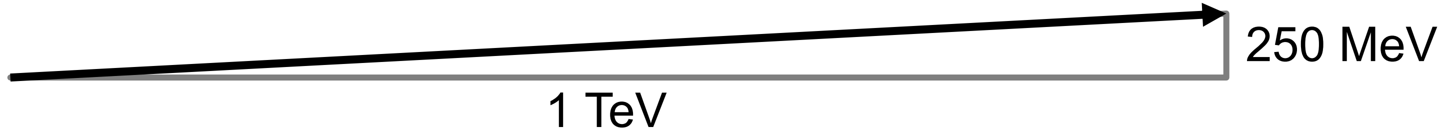
# THE FAR-FORWARD REGION



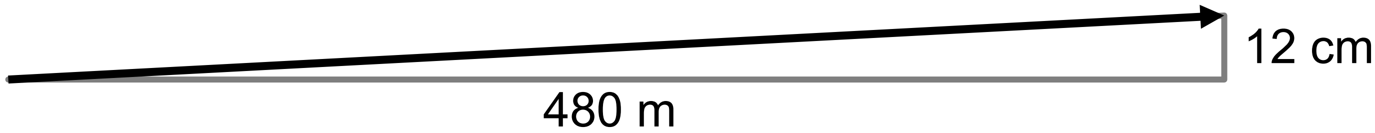



# HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:

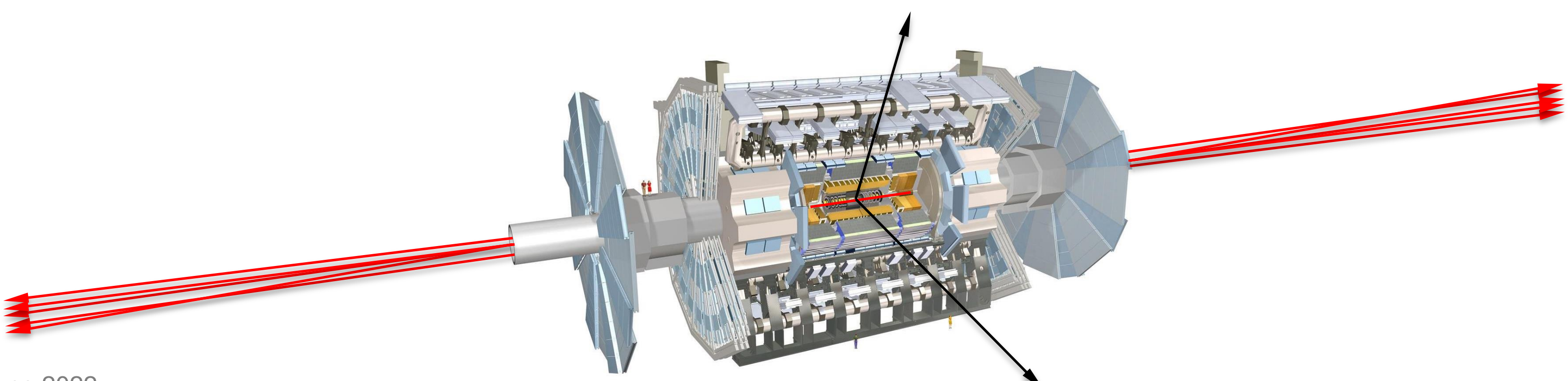



- Space:




- Particles produced in pion decays have $\theta$ ~ 0.2 mrad ($\eta$ ~ 9); cf. the moon (7 mrad).

- Particles produced in $\pi$, $\eta$, K, D, B decay are therefore far more collimated than shown below, motivating new, small, fast, and cheap experiments at the LHC.

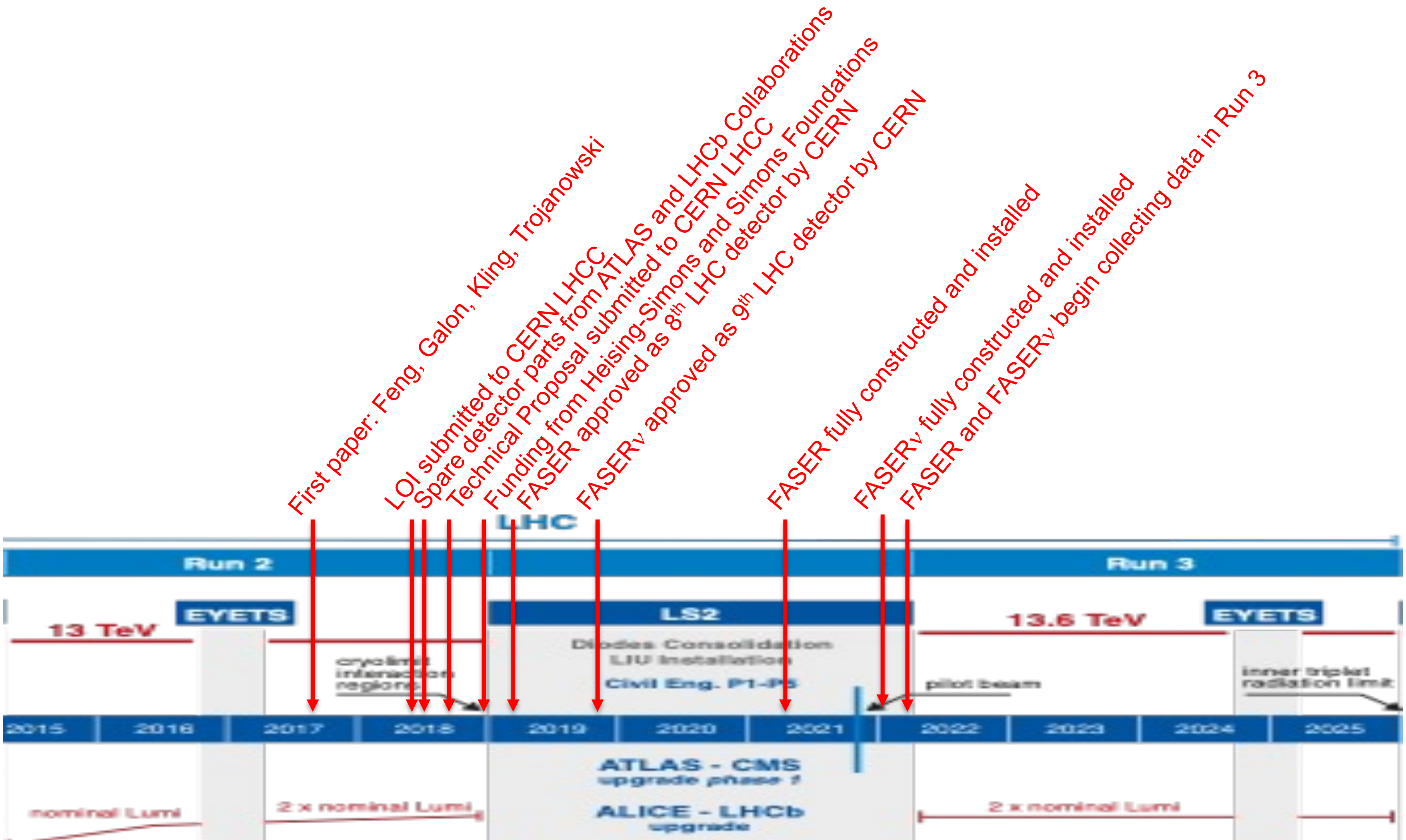


# CURRENT FAR FORWARD DETECTORS

3 far forward detectors have been constructed and installed and are currently taking data in LHC Run 3: FASER, FASERν, and SND@LHC.

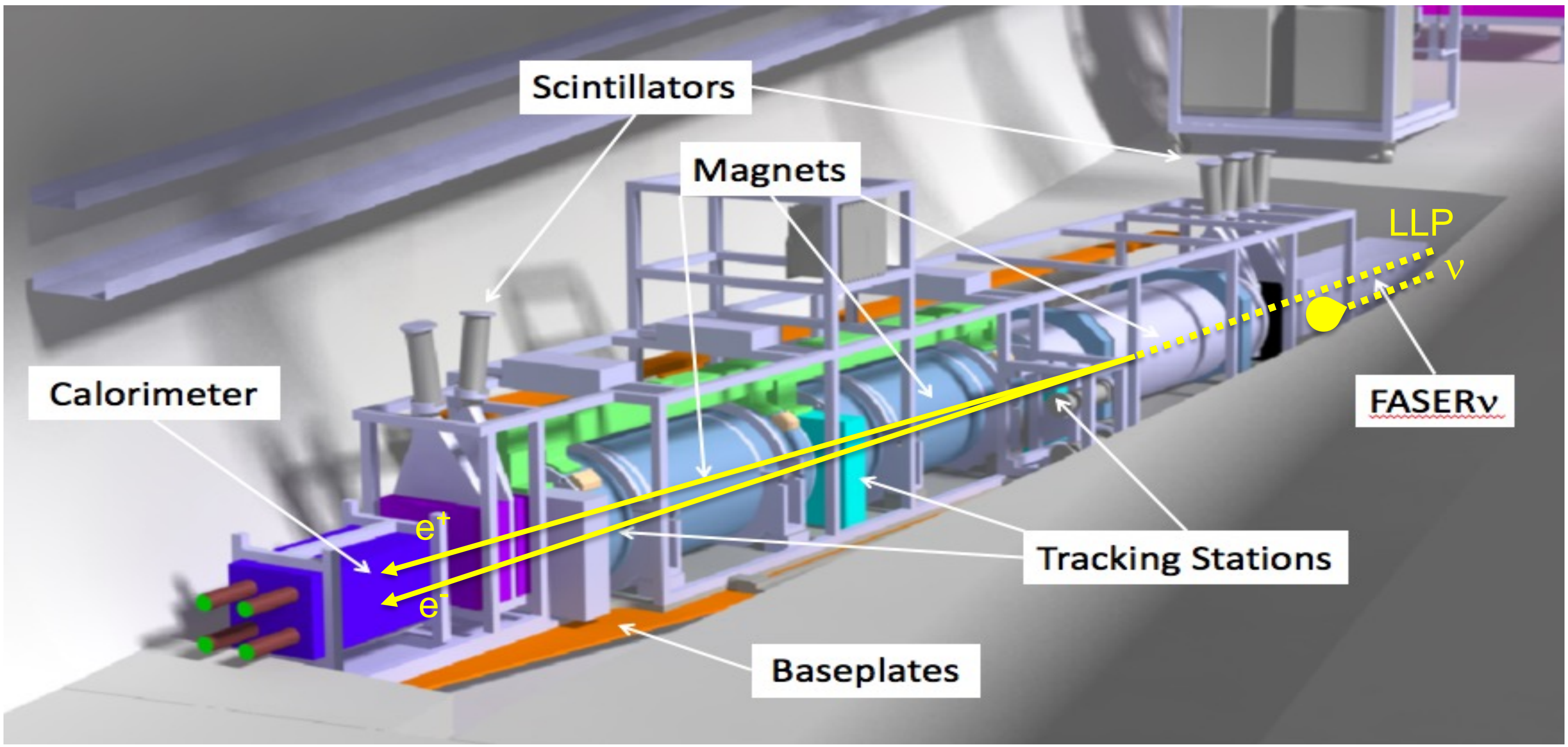

CERN GIS

# FASER AND FASERν TIMELINE

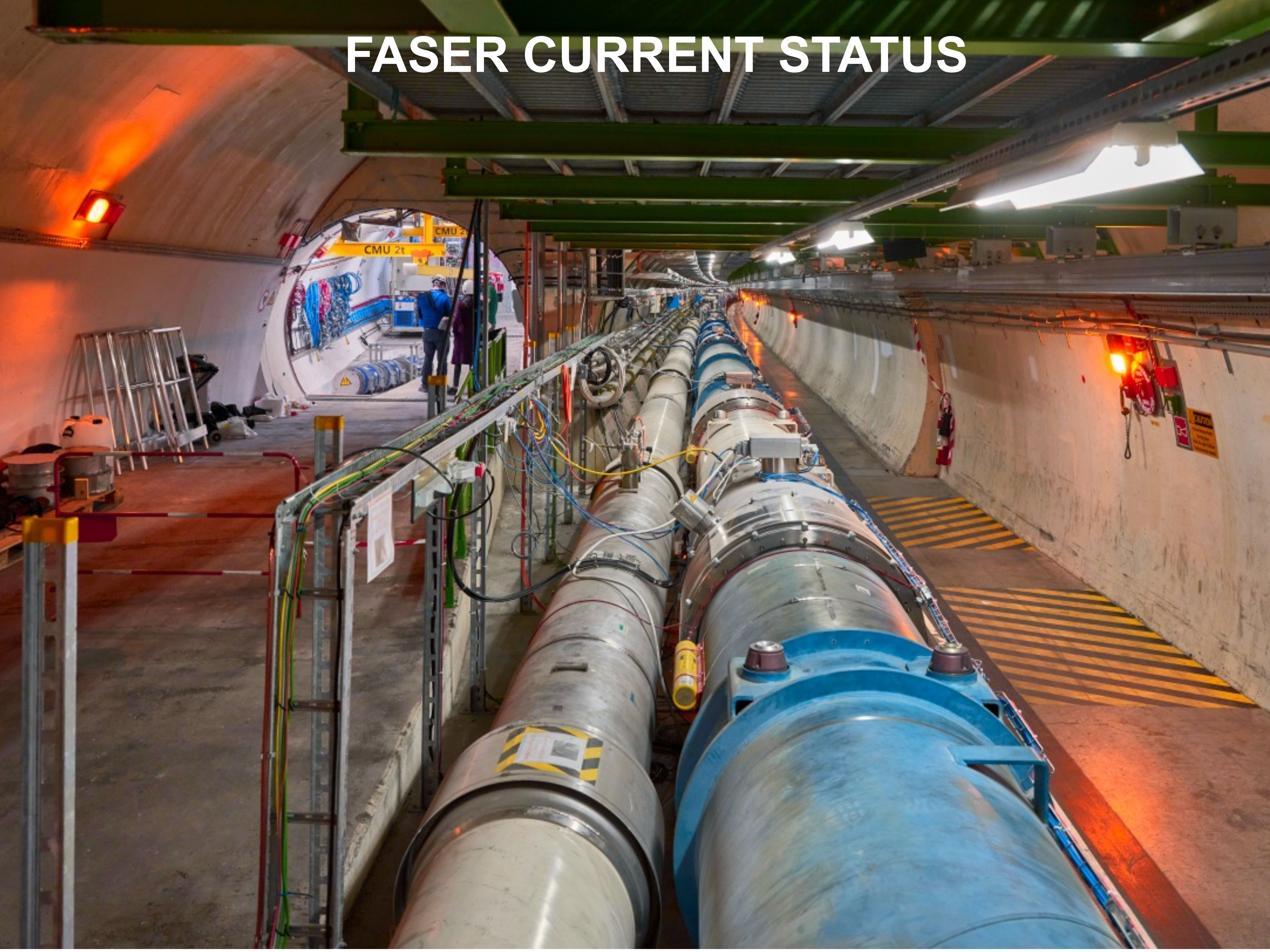


# THE FASER DETECTOR

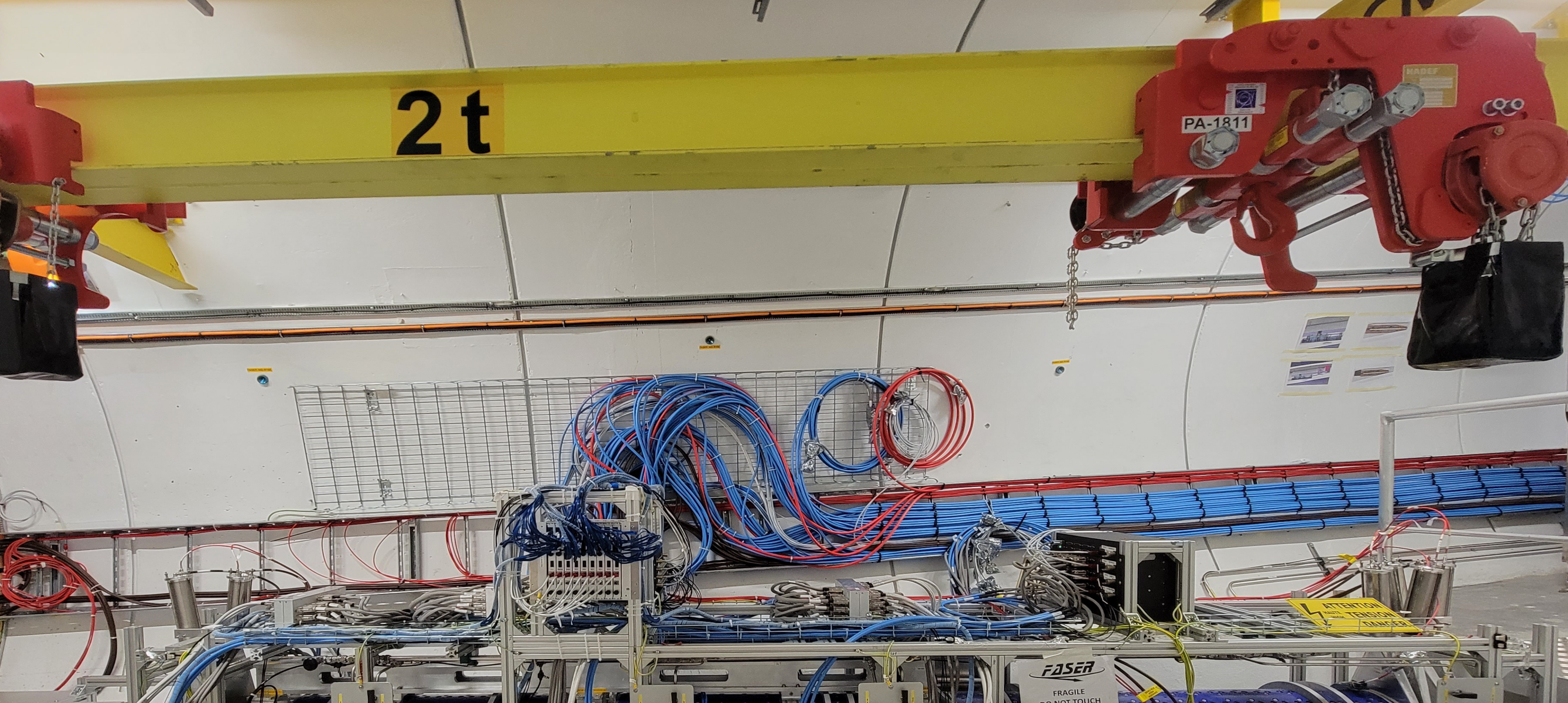
- Nothing incoming and 2 ~TeV, opposite-sign charged tracks pointing back to the ATLAS IP: a “light shining through (100 m-thick) wall” experiment.
- Scintillators veto incoming charged tracks (muons), magnets split the charged tracks, which are detected by tracking stations and a calorimeter.

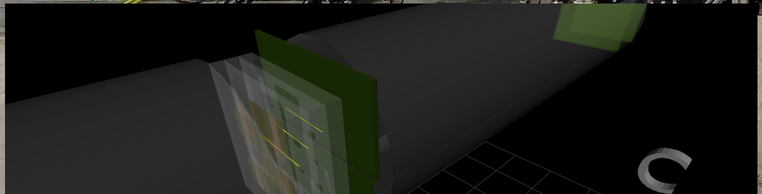


# FASER CURRENT STATUS

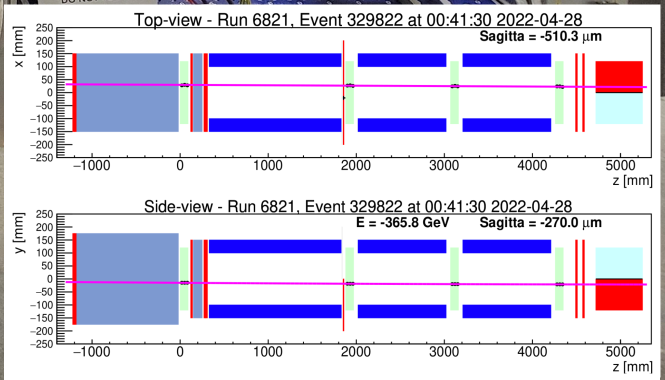


# FASER CURRENT STATUS



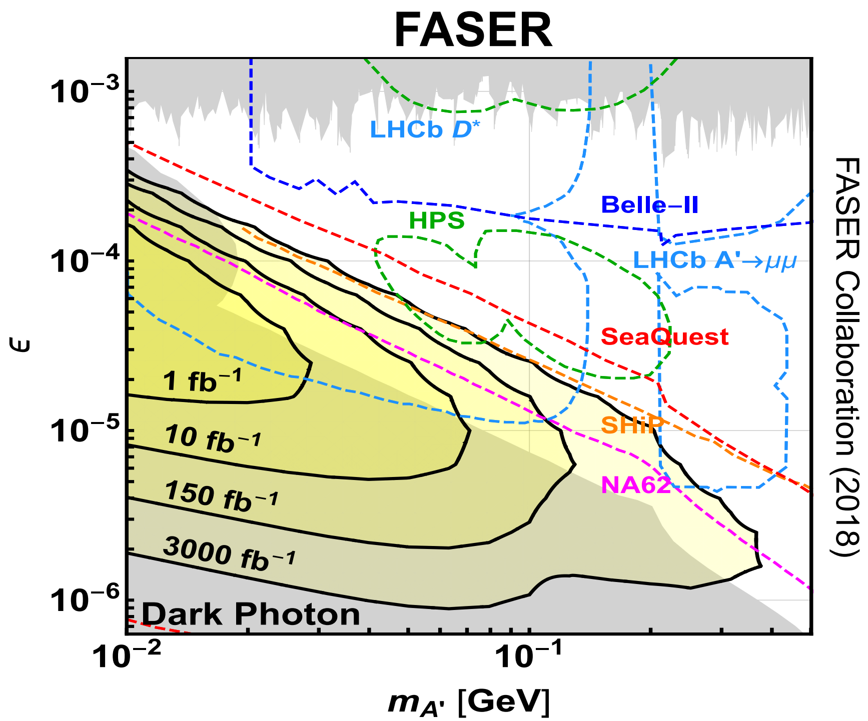



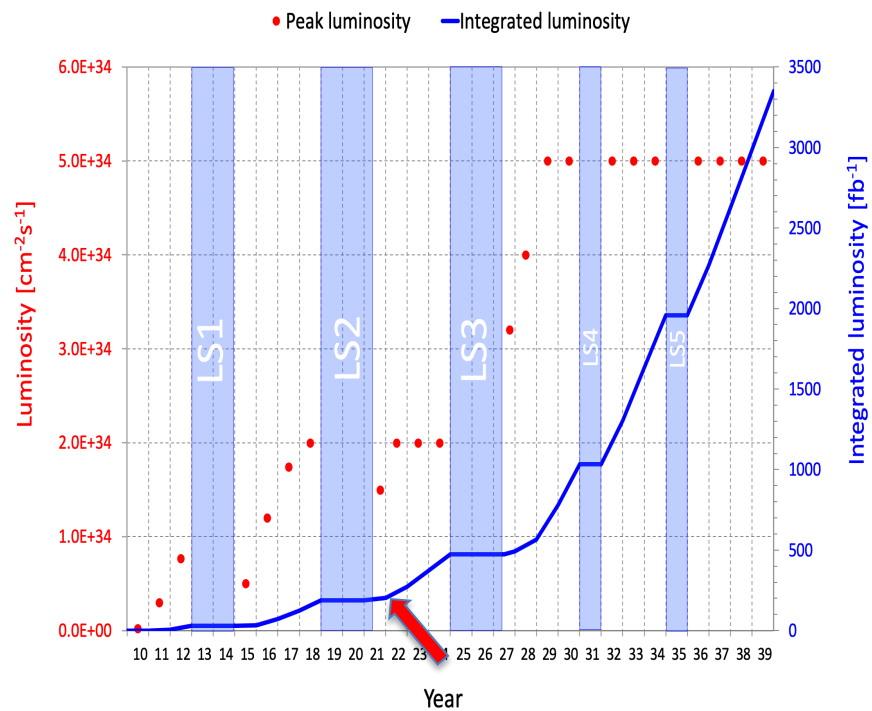
1st Cosmic Ray
18 March 2021




Beam splash event 28 April 2022

# DARK PHOTON SENSITIVITY REACH



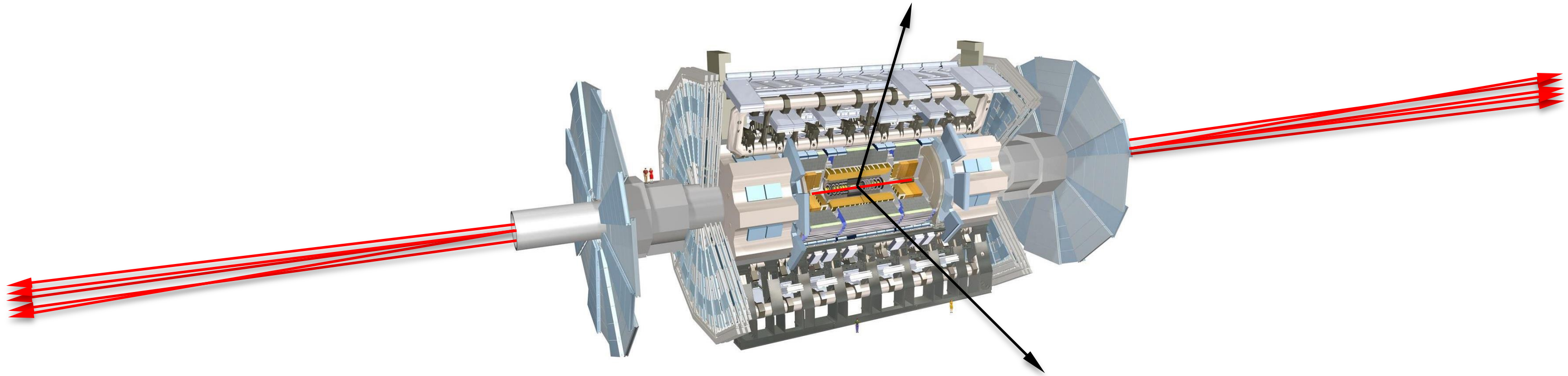




- FASER probes new parameter space with just 1 $fb^{-1}$ starting in July 2022.
- In Run 3, will probe the MeV-GeV region favored by WIMPless miracle considerations, muon g-2 explanations, SIDM, ATOMKI anomalies, …
- Even without a detector upgrade, the HL-LHC extends (Luminosity*Vol) by factor of 3000 – could detect as many as 10,000 dark photons.

# FASER$\nu$

- In addition to the possibility of hypothetical new light, weakly-interacting particles, there are also known light, weakly-interacting particles: neutrinos.

- The high-energy ones, which interact most strongly, are overwhelmingly produced in the far forward direction. Before May 2021, no candidate collider neutrino had ever been detected.

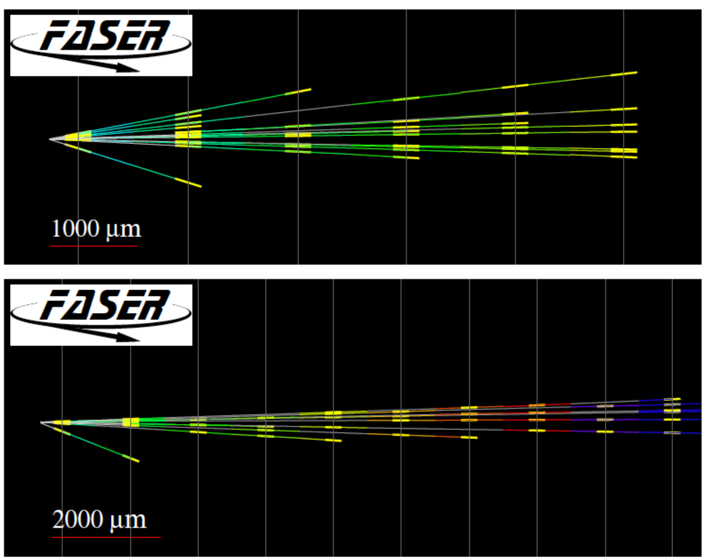


- If they can be detected, there is a fascinating new world of LHC neutrinos that can be explored.
  - The neutrino energies are ~TeV, highest human-made energies ever.
  - All flavors are produced ($\pi \rightarrow \nu_\mu$, $K \rightarrow \nu_e$, $D \rightarrow \nu_\tau$) and both neutrinos and anti-neutrinos.

De Rujula, Ruckl (1984); Winter (1990); Vannucci (1993)

# FIRST COLLIDER NEUTRINO CANDIDATES

- In 2018 a FASER pilot emulsion detector with 11 kg fiducial mass collected 12.2 $fb^{-1}$ on the beam collision axis (installed and removed during Technical Stops).
- In May 2021, the FASER Collaboration announced the direct detection of 6 candidate neutrinos above 12 expected neutral hadron background events (2.7$\sigma$).

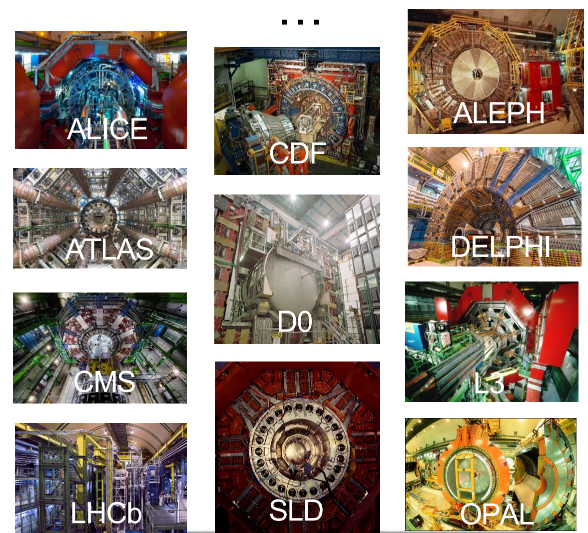



# LOCATION, LOCATION, LOCATION

FASER Pilot Detector

Suitcase-size, 4 weeks
\$0 (recycled parts)

6 candidate neutrinos




All previous
collider detectors

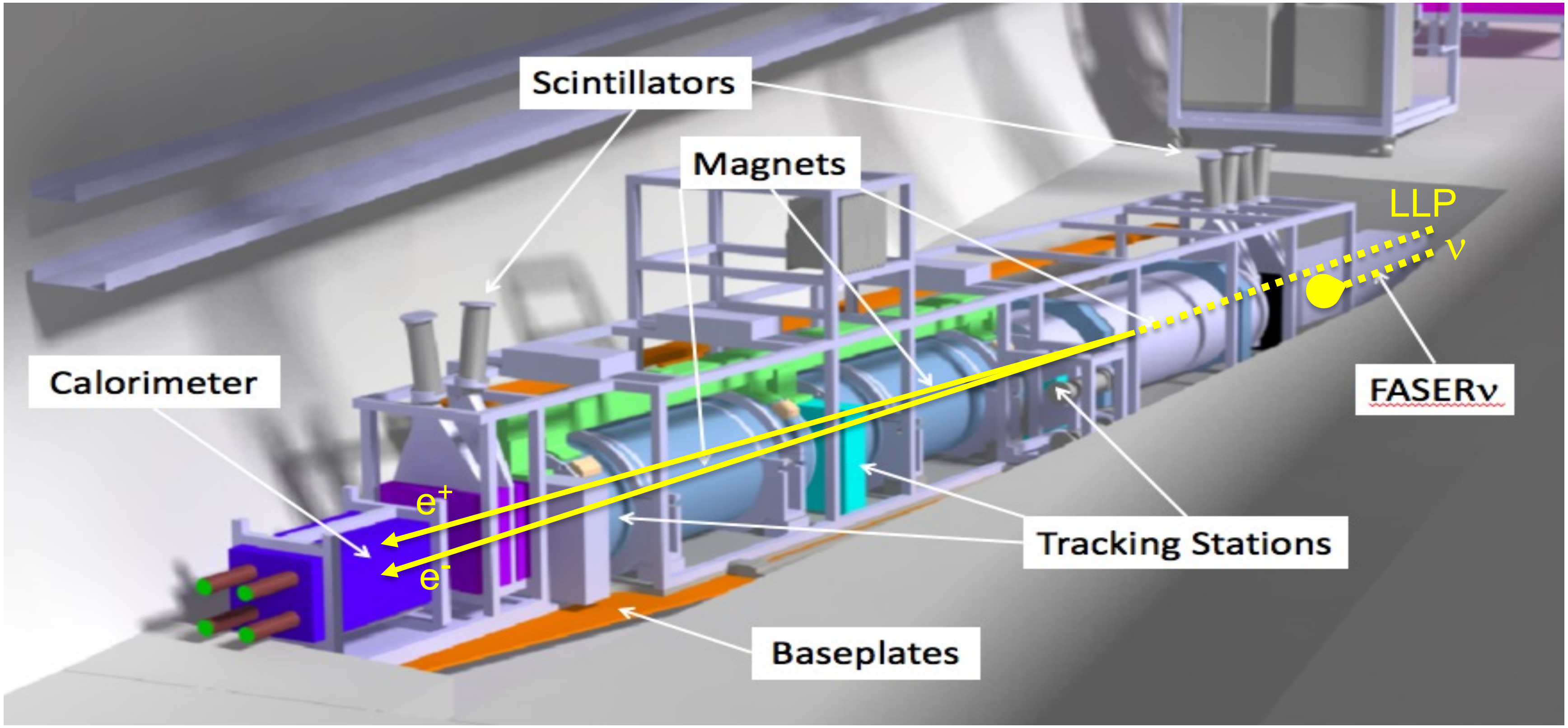
Building-size, decades
~\$$10^9$

0 candidate neutrinos

This opens up a new field:
neutrino physics at colliders

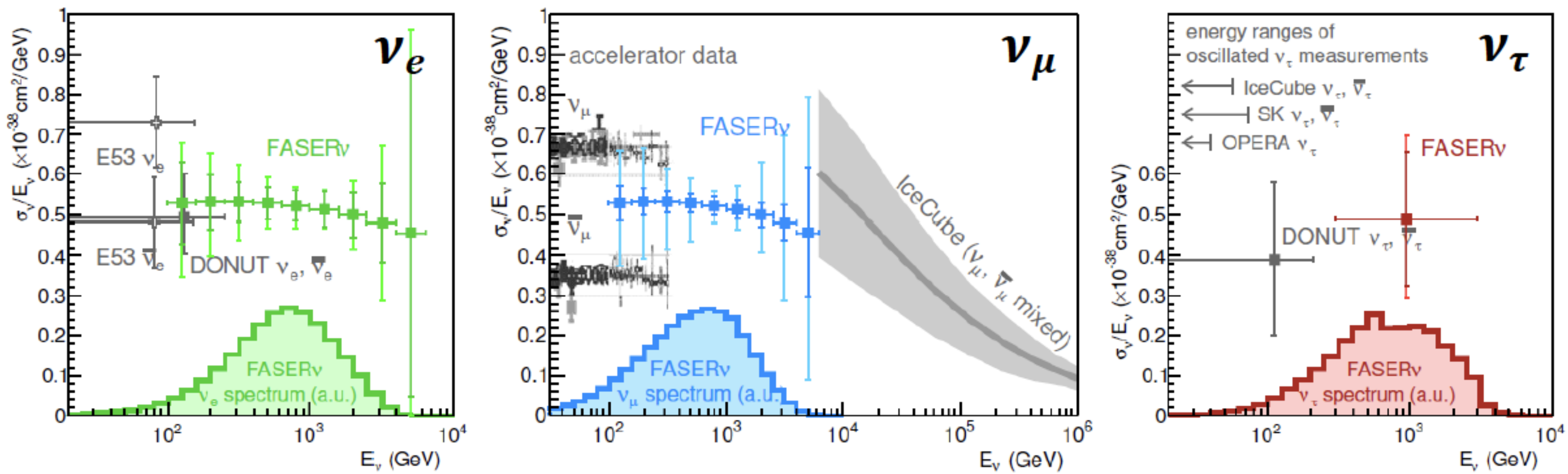
# THE FASERν DETECTOR

- FASERν will detect neutrinos of all flavors; also SND@LHC, a complementary, slightly off-axis experiment on the other side of ATLAS.
  - 25cm x 30cm x 1.1m detector consisting of 770 emulsion layers interleaved with 1 mm-thick tungsten plates; target mass = 1.1 tonnes.
  - Emulsion swapped out every ~10-30 $fb^{-1}$, total 10 sets of emulsion for Run 3.



# NEUTRINO PHYSICS

- In Run 3, the goals of FASERν are to
  - 5σ discovery of collider neutrinos.
  - Record ~1000 $\nu_e$, ~10,000 $\nu_\mu$, and ~10 $\nu_\tau$ 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 $\nu_\tau$ and identify the first anti-$\nu_\tau$ .




FASER Collaboration 1908.02310 (2019)

# FPF

Forward Physics Facility

# FORWARD PHYSICS FACILITY

- FASER, FASER$\nu$, and SND@LHC are currently highly constrained by 1980's (LEP!) infrastructure that was never intended to support experiments.

- The rich physics program in the far-forward region therefore strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2029-2040.

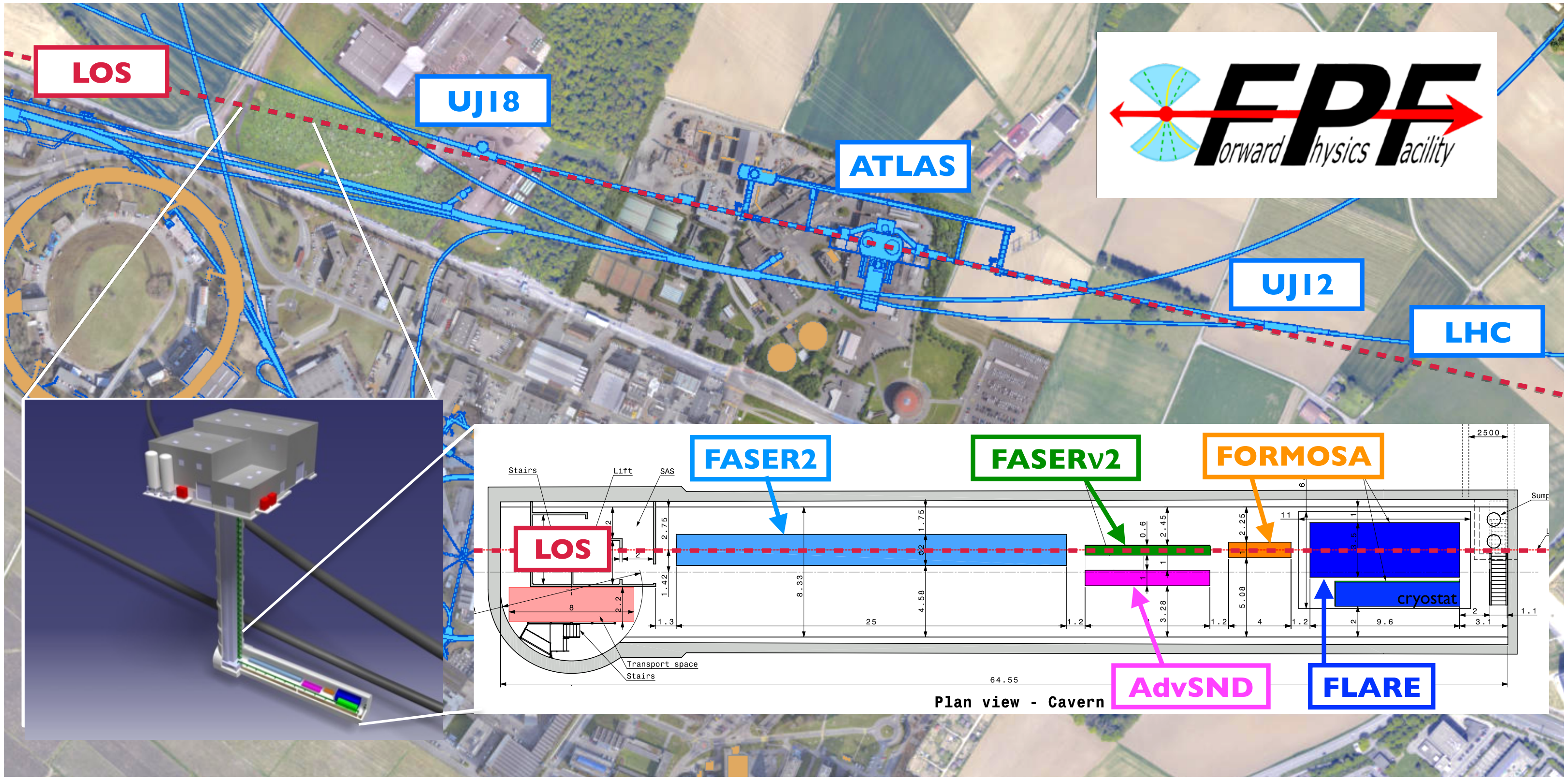
- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733
  - FPF4 Meeting, 31 Jan-1 Feb 2022, https://indico.cern.ch/event/1110746

- FPF Short Paper: 75 pages, 80 authors completed in Sep 2021 (2109.10905, Physics Reports 968, 1 (2022)).

- FPF Snowmass White Paper: Feng, Kling, Reno, Rojo, Soldin et al. A comprehensive, 429-page, 392-author+endorser summary (2203.05090).

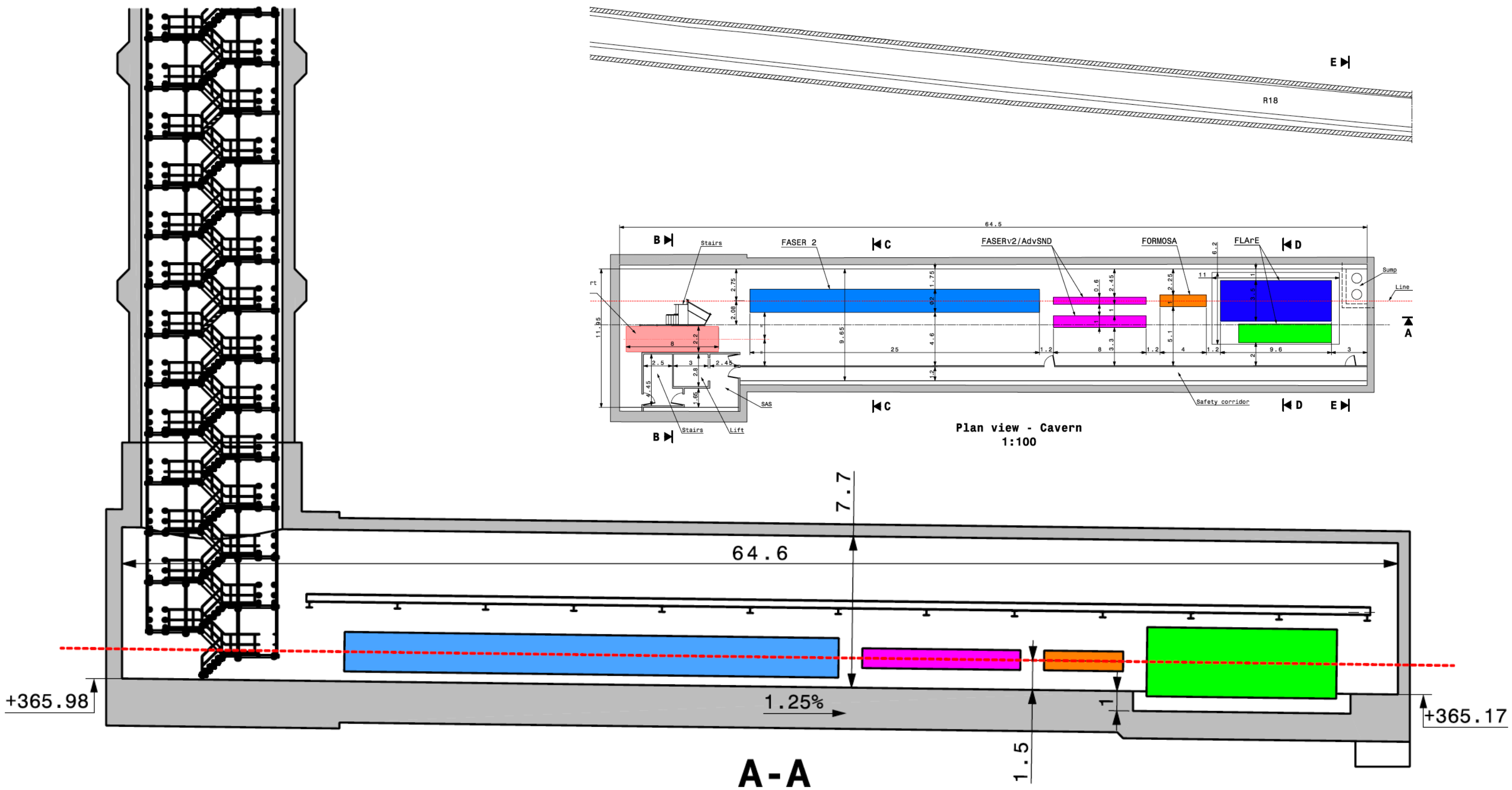
# THE LOCATION

- The CERN civil engineering team has considered many sites around the LHC ring that are on the beam collision axis of an IP.
- A preferred location has been identified ~620-680 m west of the ATLAS IP, shielded by ~200 m of rock. The site is on CERN land in France.

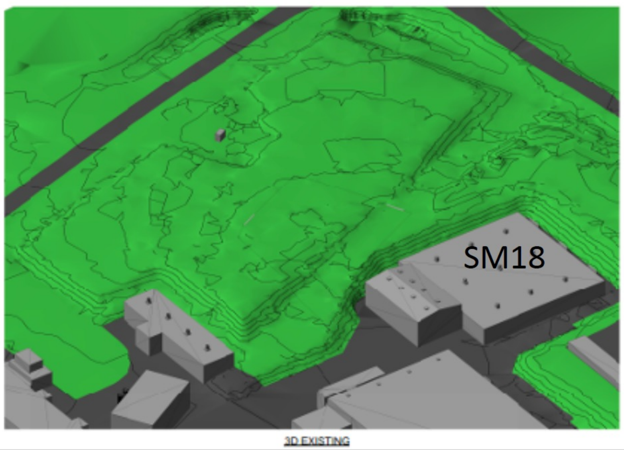


# CAVERN AND SHAFT

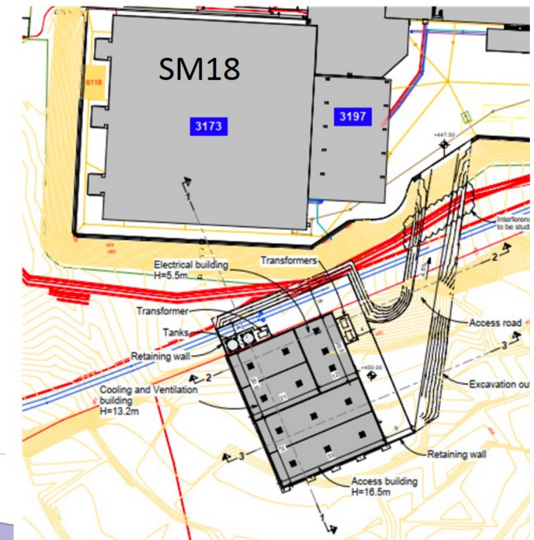
- Cavern: 65m long, 8m wide/high. Shaft: 88m-deep, 9.1m-diameter.
- The FPF is completely decoupled from the LHC: no need for a safety corridor connecting the FPF to the LHC, preliminary RP and vibration studies indicate that FPF construction will have no significant impact on LHC operation.

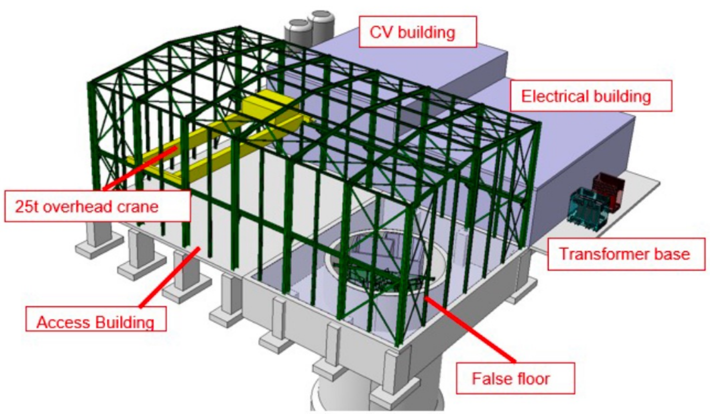


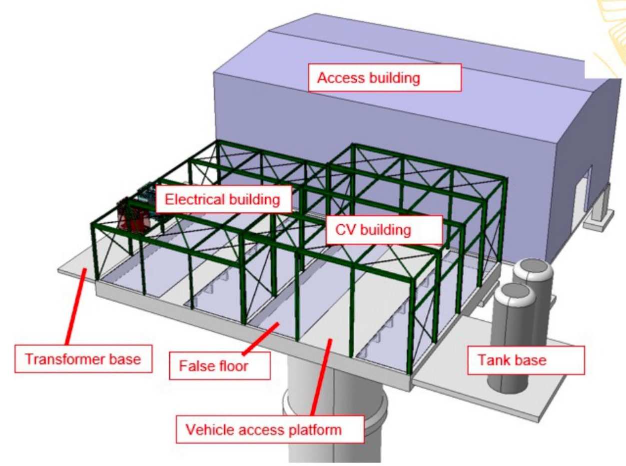
# SURFACE BUILDINGS







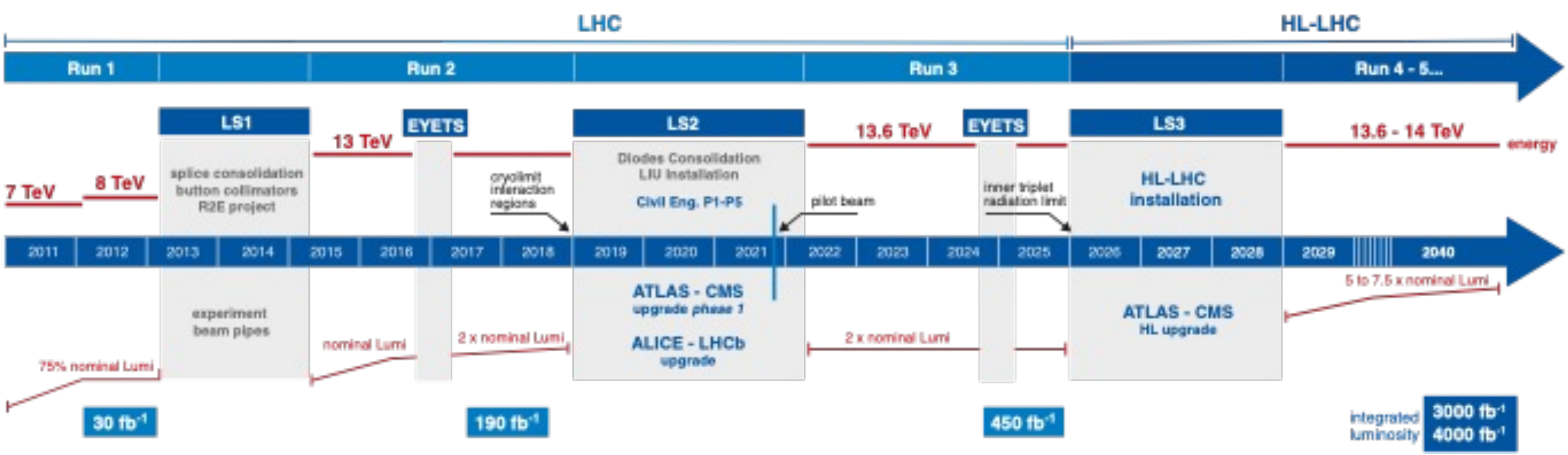




Kincso Balazs,
John Osborne,
CERN CE (2022)

# COST AND TIMELINE

- Very preliminary (class 4) cost estimate: 23 MCHF (CE) + 15 MCHF (services) ≈ 40 MCHF (+50%/-30%), not including experiments.
- Timeline presented at Chamonix workshop (Jamie Boyd, Feb 2022).
- Expect CDRs for FPF and its experiments in the coming 6-12 months.
- Begin CE works, installation of services in LS3, followed by installation and commissioning of experiments in early Run 4. Physics begins in Run 4 and continues to the end of the HL-LHC era.



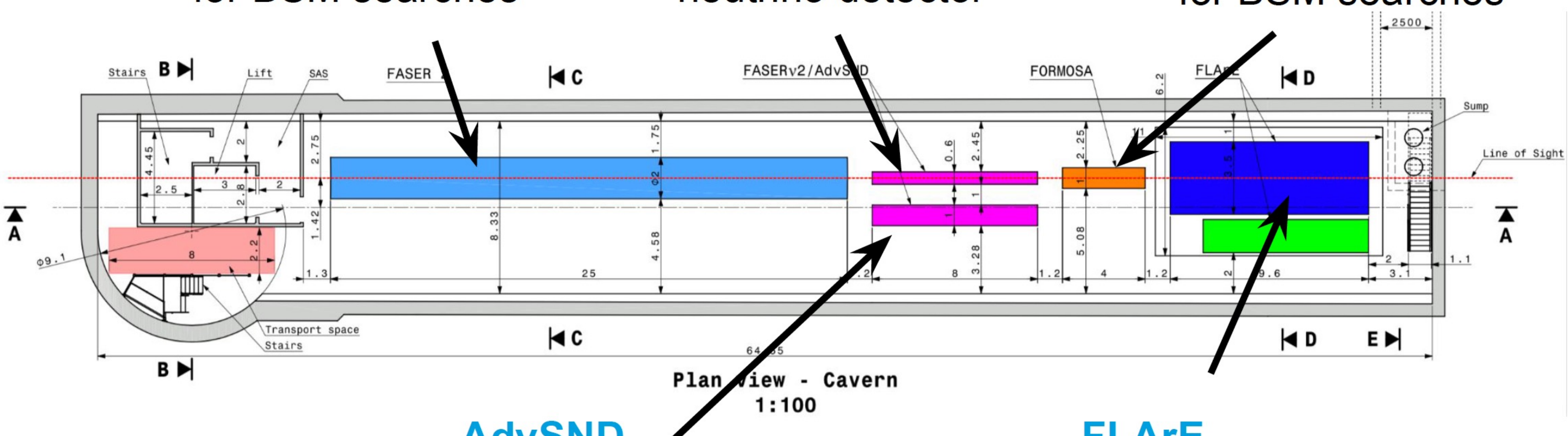
# FPF EXPERIMENTS

- At present there are 5 experiments being developed for the FPF.
- Pseudo-rapidity coverage in the FPF is $\eta > 5.5$, with most experiments on the LOS covering $\eta > 7$.

**FASER2**
magnetized spectrometer
for BSM searches

**FASERν2**
emulsion-based
neutrino detector

**FORMOSA**
plastic scintillator array
for BSM searches



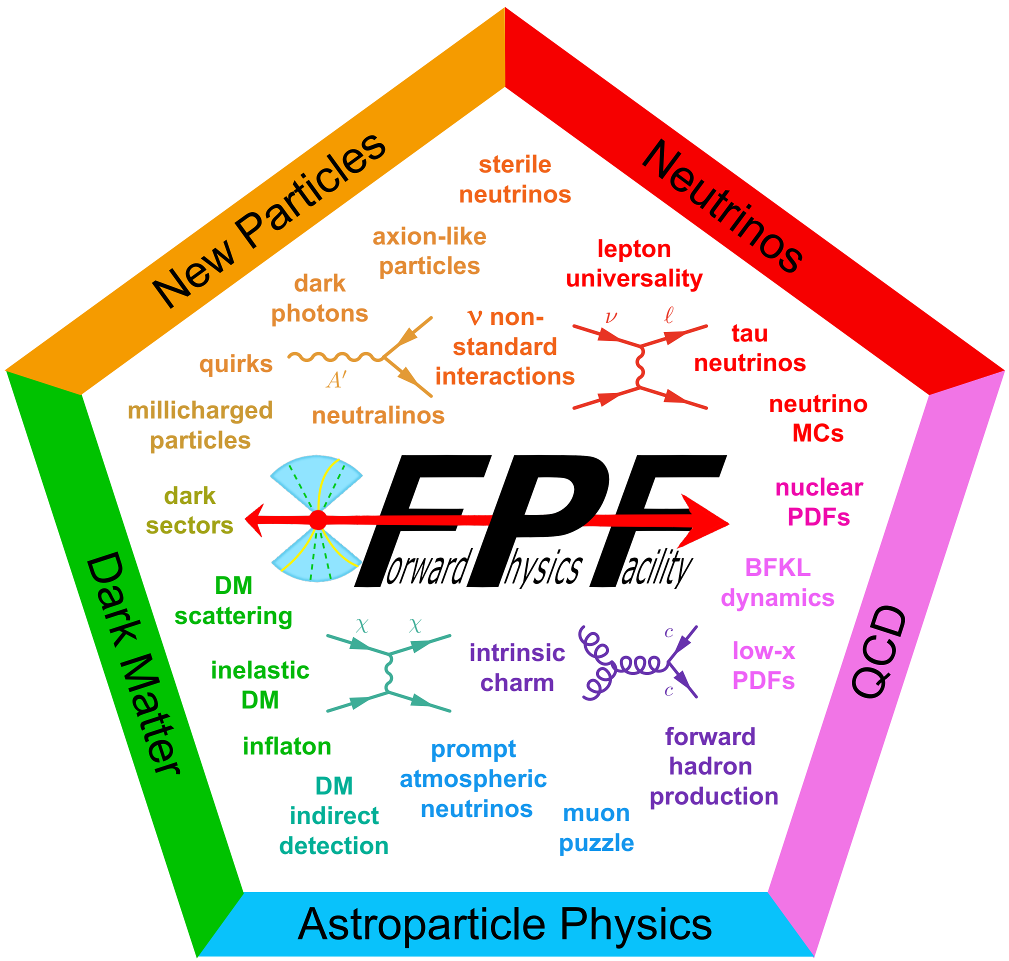

**AdvSND**
electronic
neutrino detector

**FLArE**
LAr based
neutrino detector

Kling (2022)

# FPF PHYSICS

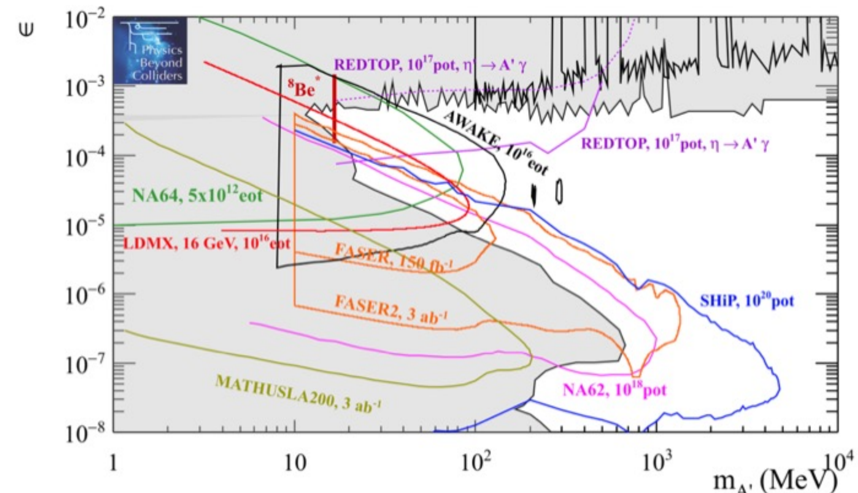
- The FPF is a general purpose facility with a broad SM and BSM physics program that expands on the physics of FASER and FASERν. Here I will just give a few examples. For more, see the FPF White Paper.



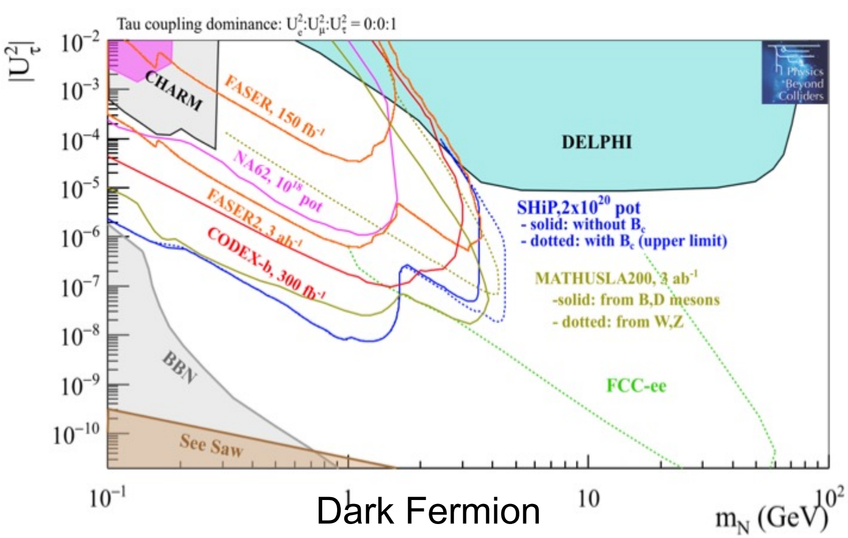
# DARK SECTOR SEARCHES

- The dedicated detectors have significant discovery potential for a wide variety of BSM/LLP models: dark photons; B-L and related gauge bosons; dark Higgs bosons; HNLs with couplings to e, mu, tau; ALPs with photon, gluon, fermion couplings; light neutralinos, inflaton, relaxion, and many others.

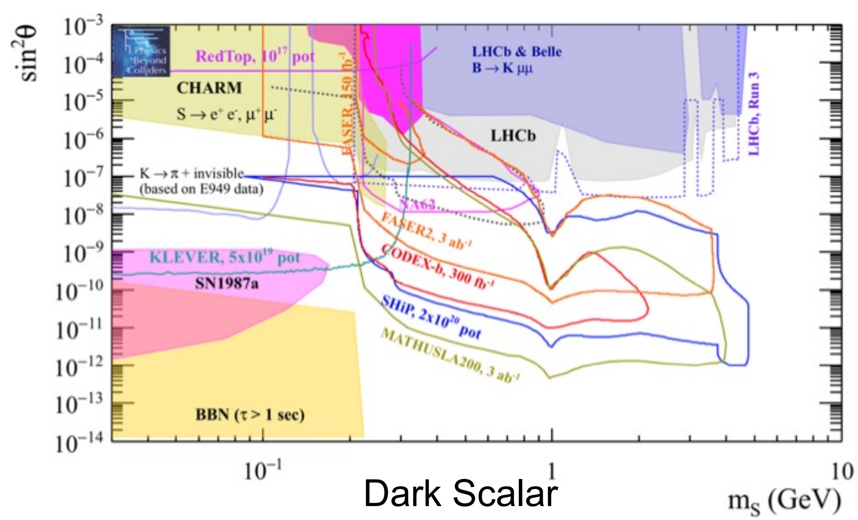
FPF White Paper (2022)




Dark Photon



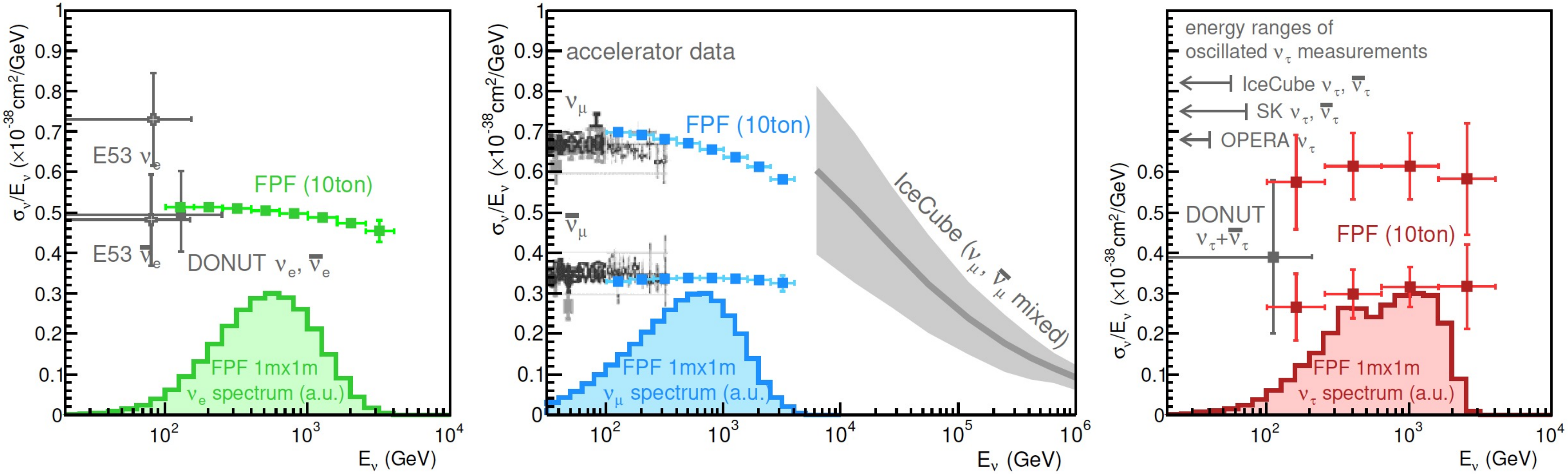

Dark Fermion




Dark Scalar

# NEUTRINOS

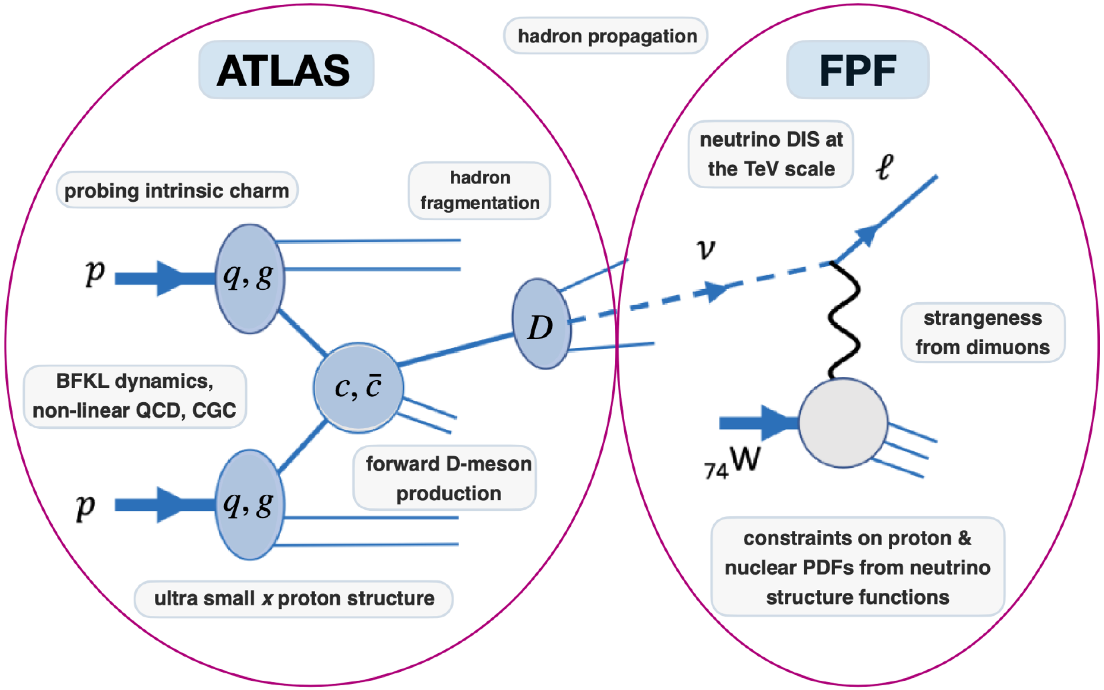
- At the FPF, three proposed ~10-ton detectors FASER$\nu$2, AdvSND, and FLArE will each detect ~100,000 $\nu_e$, ~1,000,000 $\nu_\mu$, and ~1000 $\nu_\tau$ interactions at TeV energies, providing high statistics samples for all three flavors in an energy range that has never been directly explored.
- Will enable precision studies of the tau neutrino.
- Can also distinguish neutrinos and anti-neutrinos for muon and tau.




FASER White Paper (2022)

# QCD

- The FPF will also support a rich program of QCD and hadron structure studies.
- Forward neutrino production is a a probe of forward hadron production, BFKL dynamics, intrinsic charm, ultra small x proton structure, with important implications for UHE cosmic ray experiments.
- Neutrino interactions will probe DIS at the TeV-scale, constrain proton and nuclear structure, pdfs.

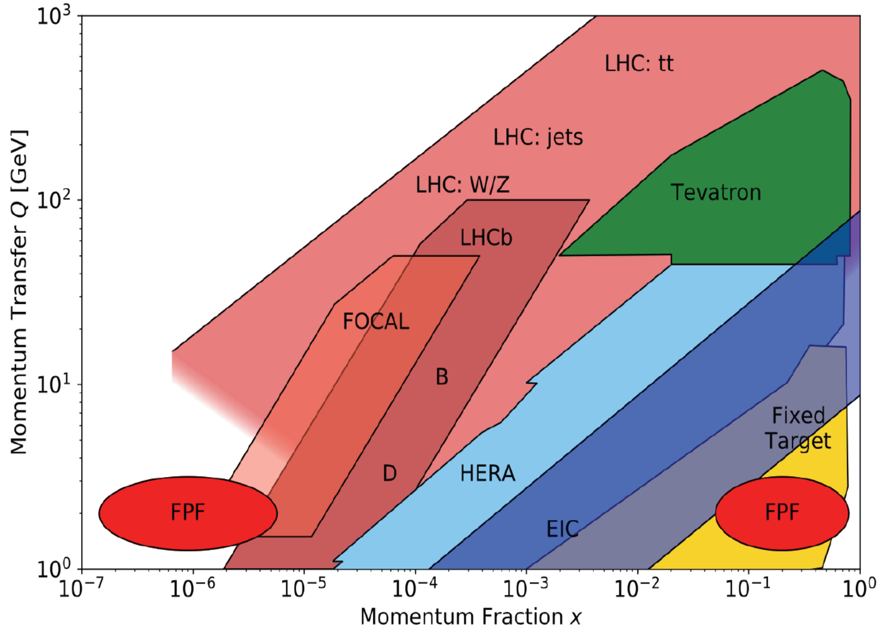


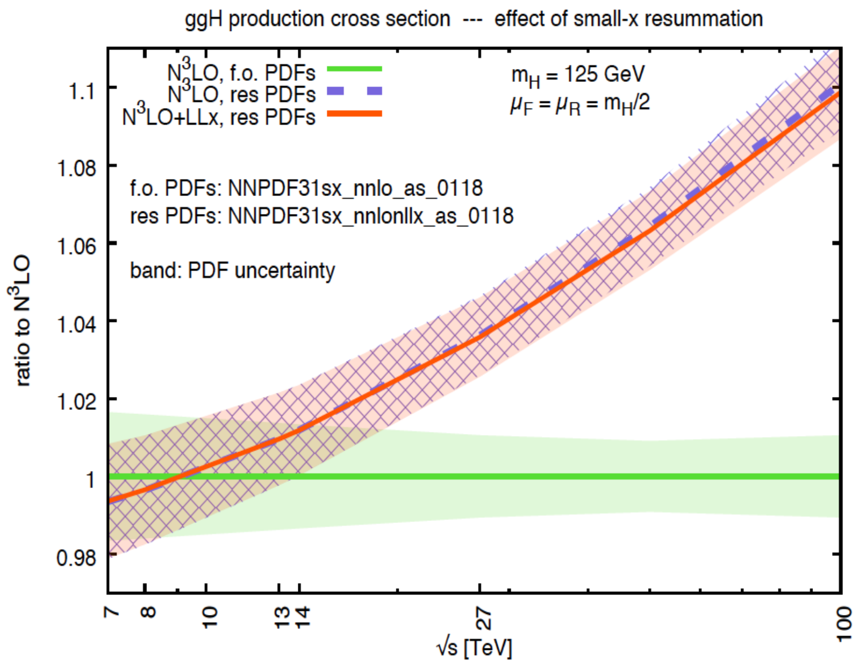

FASER White Paper (2022)

# QCD

- The FPF will probe proton structure at ultra small $x \sim 10^{-7}$ (and also high $x \sim 1$).

- In addition to the intrinsic interest in QCD, ultra small-x physics will become more and more important at higher energies, for example, in making precise predictions for $\sigma(gg \to h)$ at a 100 TeV pp collider.



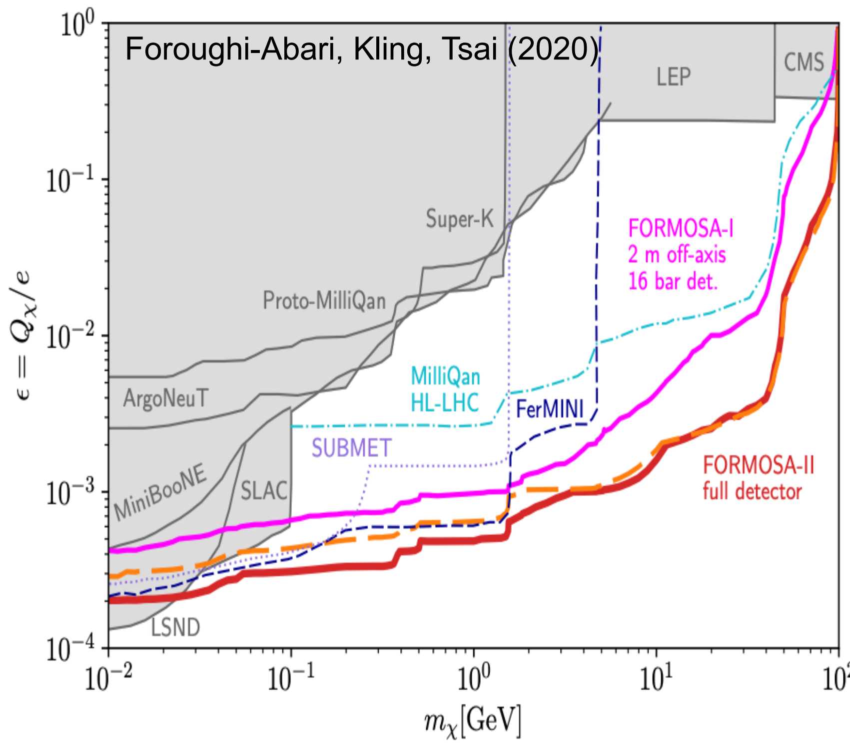




FPF White Paper (2022)

# MILLI-CHARGED PARTICLES

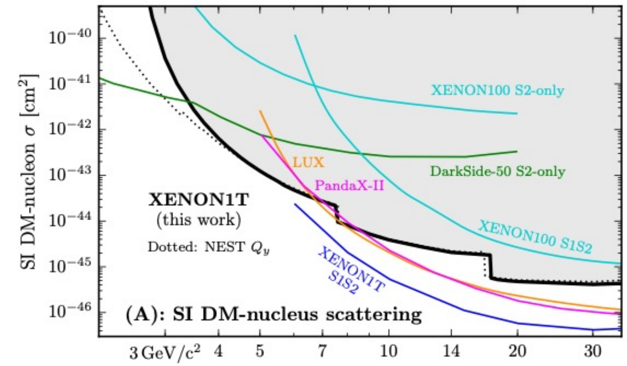
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a "non-forward" tunnel.

- 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).

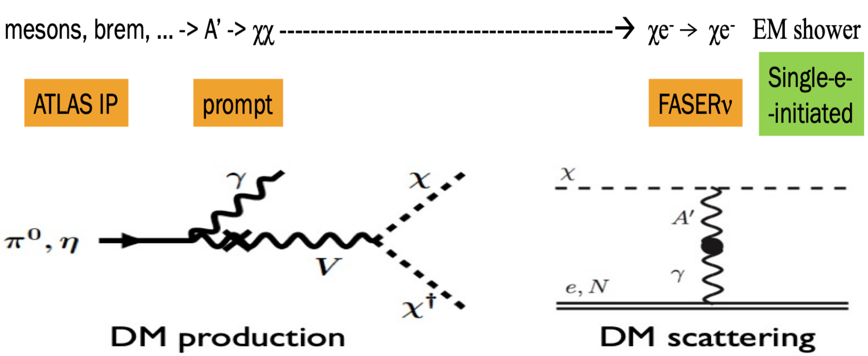



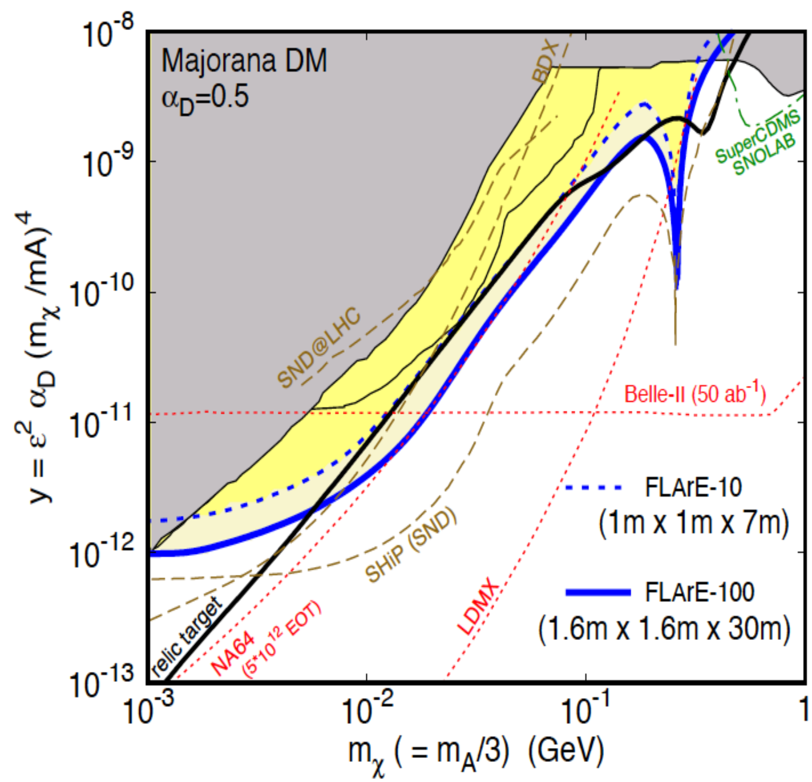
# DARK MATTER DIRECT DETECTION

- 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.

# SUMMARY

- Half of the physics opportunities at the LHC are currently being missed.
- This can be rectified by putting experiments in the far forward region to catch particles produced along the beamline.
- The Forward Physics Facility is a proposal to do exactly this for the HL-LHC era (2029-40).