Forward Physics Facility

Snowmass Energy Frontier Workshop, Brown University

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OUTLINE

Introduction

The Physics

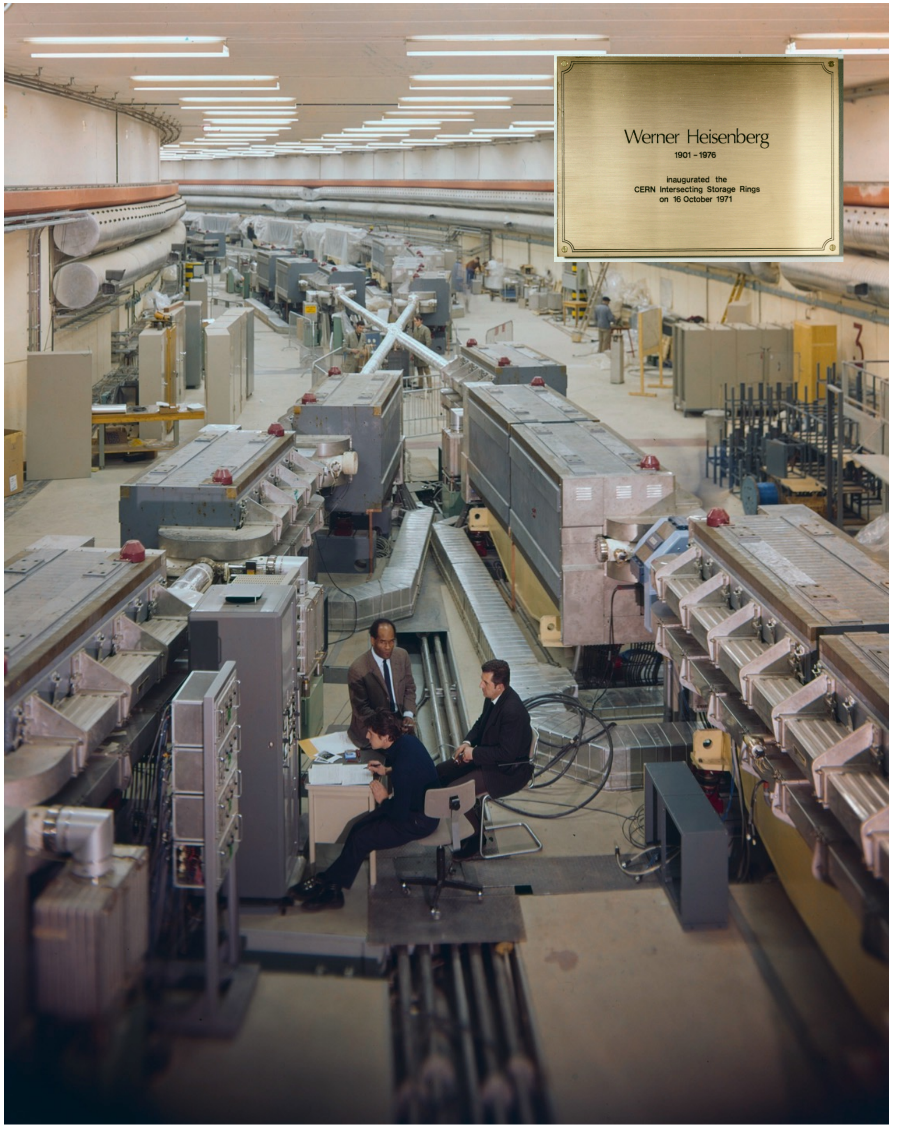
The Experiments

The Facility

Executive Summary

INTRODUCTION

- Snowmass is all about the future. But as we look forward, it also pays to look back.
- Last year was the 50^{th} anniversary of the birth of hadron colliders.
- In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, began colliding protons with protons at the center-of-mass energy of 30 GeV (later raised to 62 GeV).

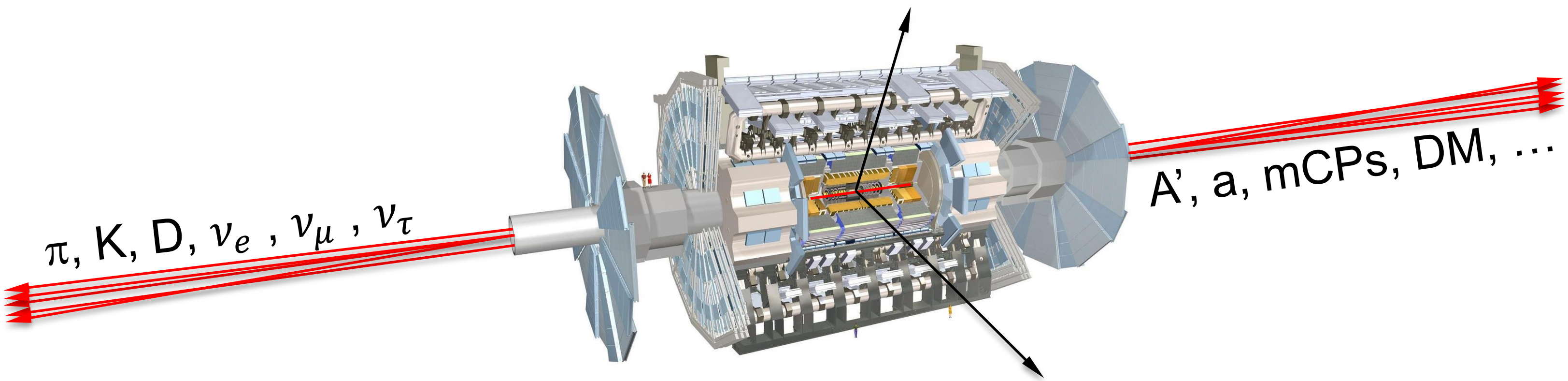


ISR'S LEGACY

- There have been 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).

AN OBVIOUS QUESTION

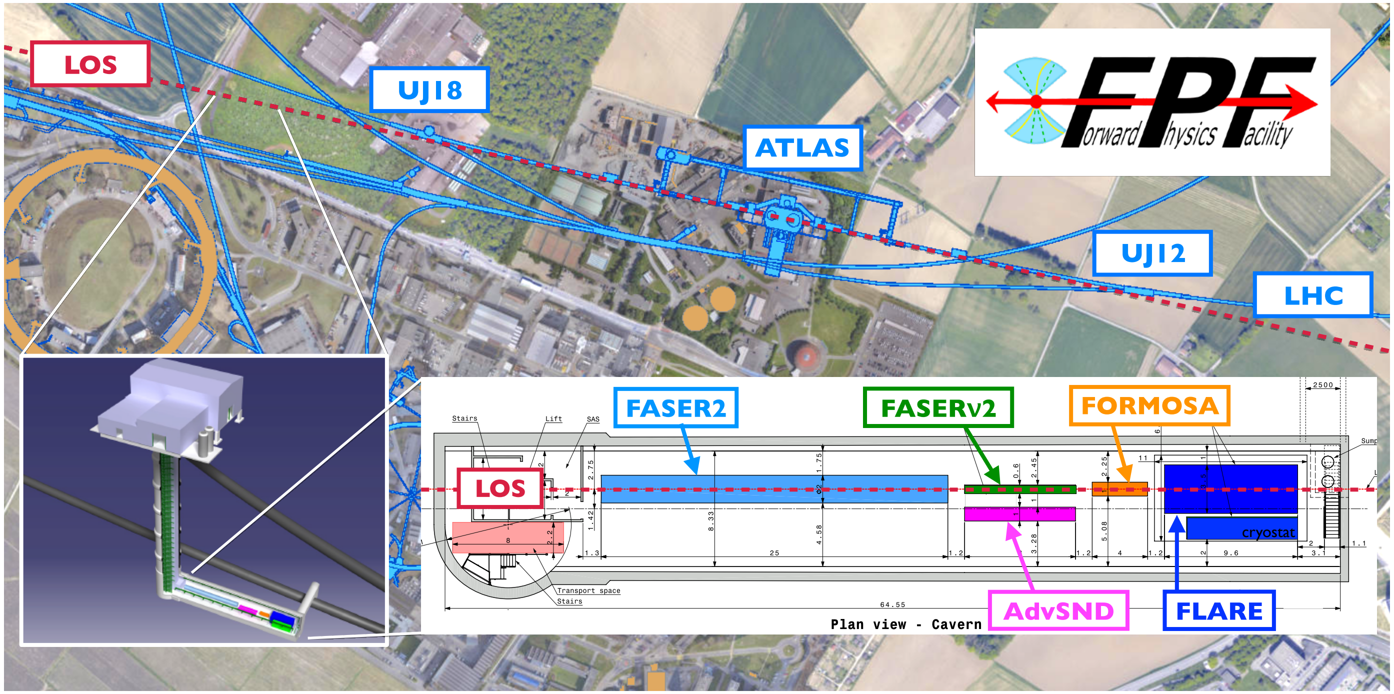
- Are we missing opportunities in a similar way at the LHC?
- The answer: Yes, but in the opposite way. In contrast to the ISR days, there is now broad belief that the most interesting physics is at high p_T . But we are now missing opportunities in the forward direction.
- By far the largest fluxes of high-energy light particles (e.g., pions, kaons, D mesons, neutrinos of all flavors) are in the far-forward direction.



- This may also be true of new particle candidates: dark photons, axion-like particles, millicharged particles, dark matter, and many others.
- All of these particles will pass through the "blind spots" of existing large LHC detectors and escape detection.

THE FORWARD PHYSICS FACILITY

- The FPF is a proposal to create an underground cavern to house a suite of far-forward experiments during the HL-LHC era. No modification to the LHC is needed.



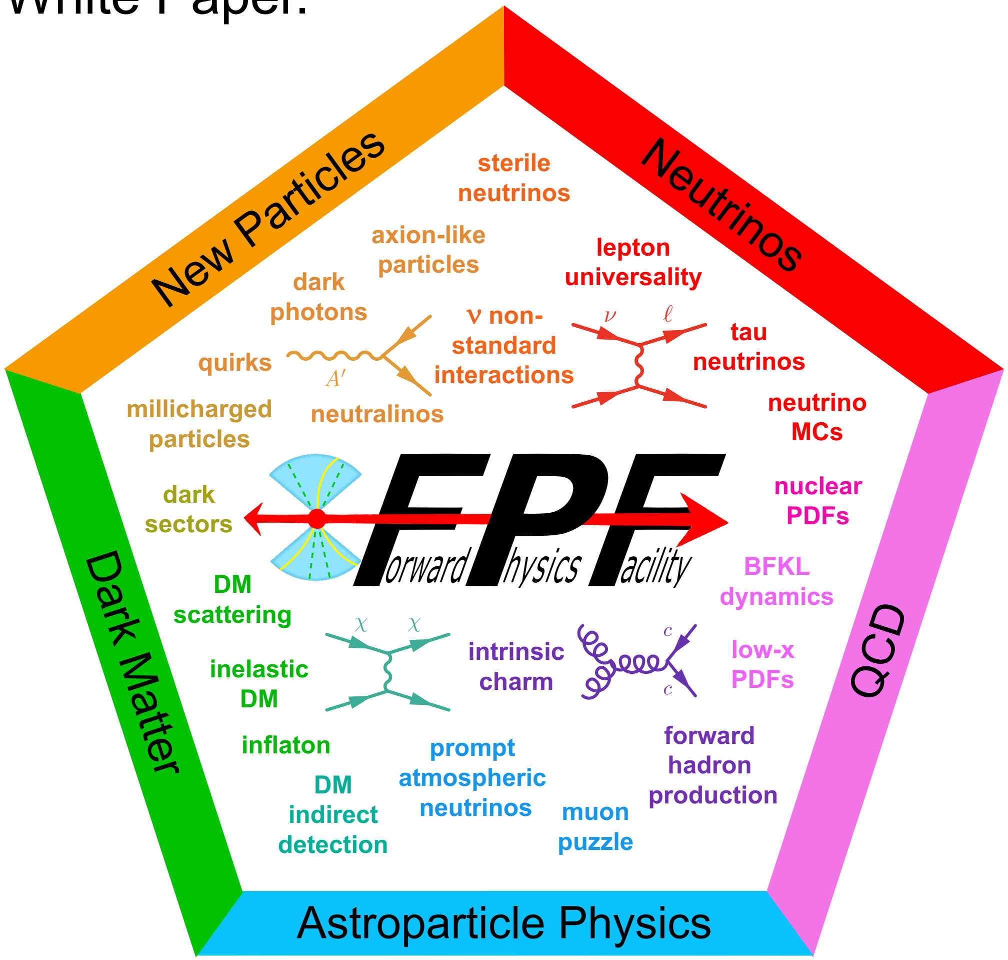
- The FPF is uniquely positioned to fully realize the LHC's physics potential for both SM and BSM physics in the far forward region, greatly extending the LHC physics program for relatively little cost.

FPF AND SNOWMASS

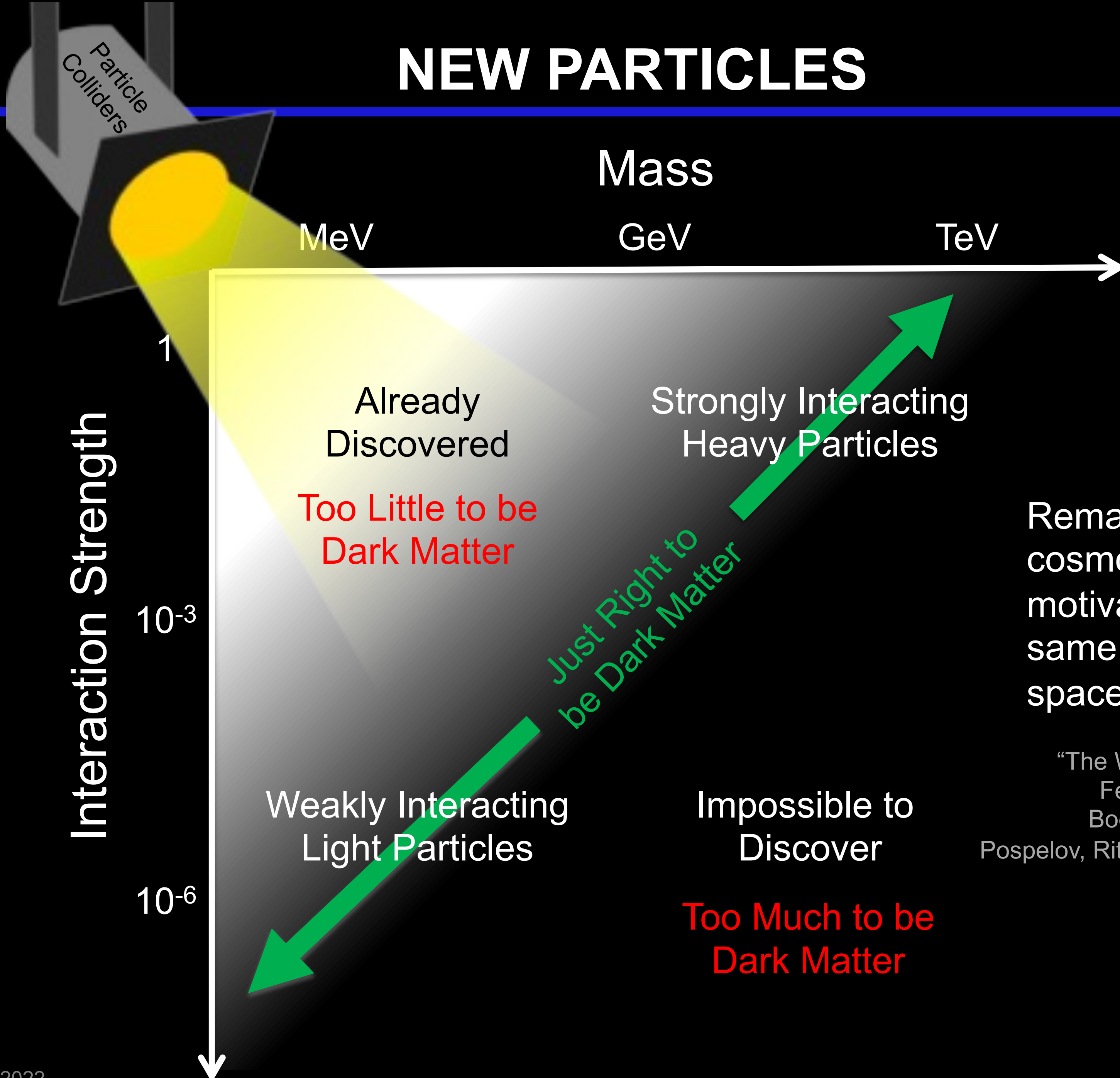
- The FPF was first proposed in May 2020 and has been the subject of 4 dedicated meetings
  - FPF1 Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733
  - FPF4 Meeting, 31 Jan-1 Feb 2022, https://indico.cern.ch/event/1110746
- These meetings have taken place within the frameworks of
  - Snowmass 2021: https://snowmass21.org
  - Physics Beyond Colliders: https://pbc.web.cern.ch
- FPF1 and FPF2 led to "The Forward Physics Facility: Sites, Experiments, and Physics Potential" (2109.10905), a 75-page, 80-author document distilling key progress on the FPF.
- The FPF Snowmass White Paper, Feng, Kling, Reno, Rojo, Soldin et al. (2203.05090), is now out. It is a comprehensive, 429-page, 392-author+ endorser summary of the status. Additional endorsers are welcome here.

THE PHYSICS

- The FPF is a general purpose facility with a broad SM and BSM physics program that spans all of the Snowmass frontiers. Here I will just give a few (not even representative) examples. For more details, see the FPF White Paper.



NEW PARTICLES

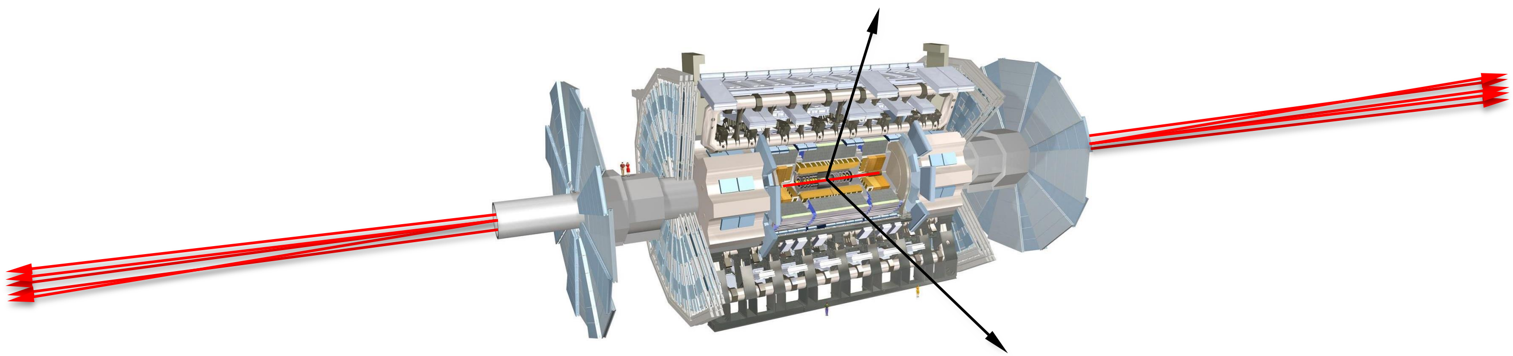


Remarkably, cosmology motivates the same parameter space.

"The WIMPless Miracle"
Feng, Kumar (2008)
Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)

SEARCHES FOR NEW LIGHT PARTICLES

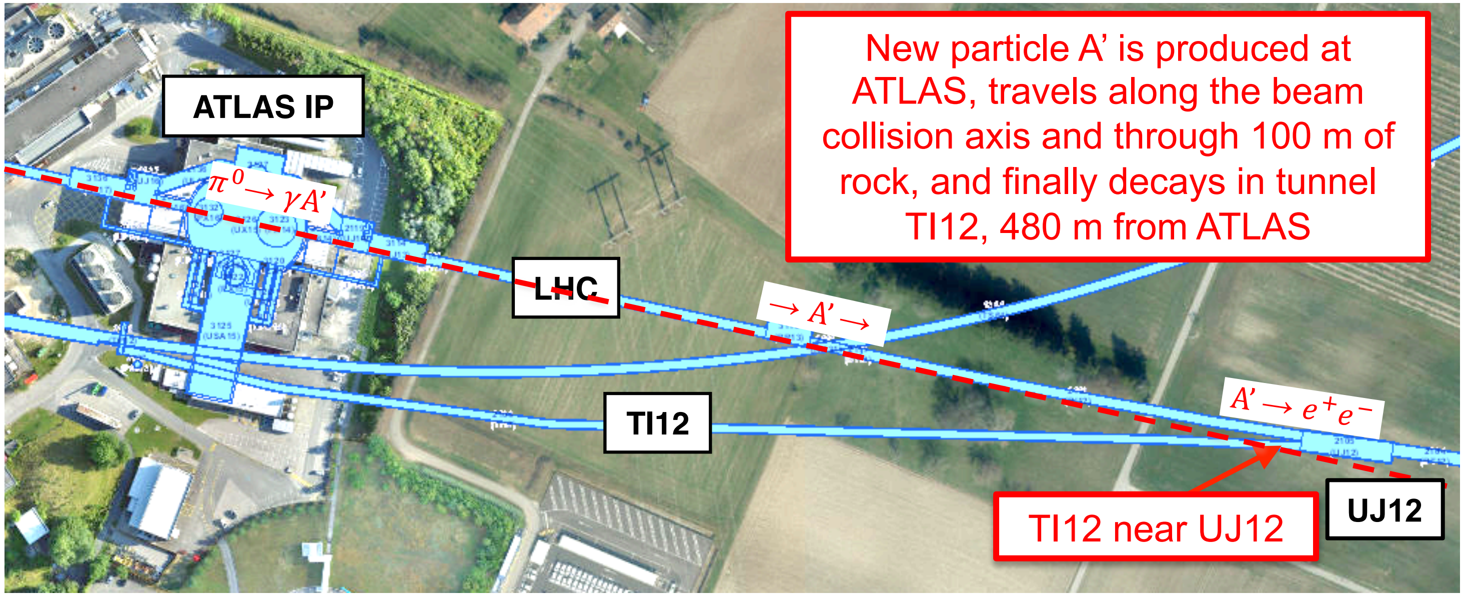
- The existing large LHC detectors are beautifully designed to find strongly-interacting **heavy** particles.

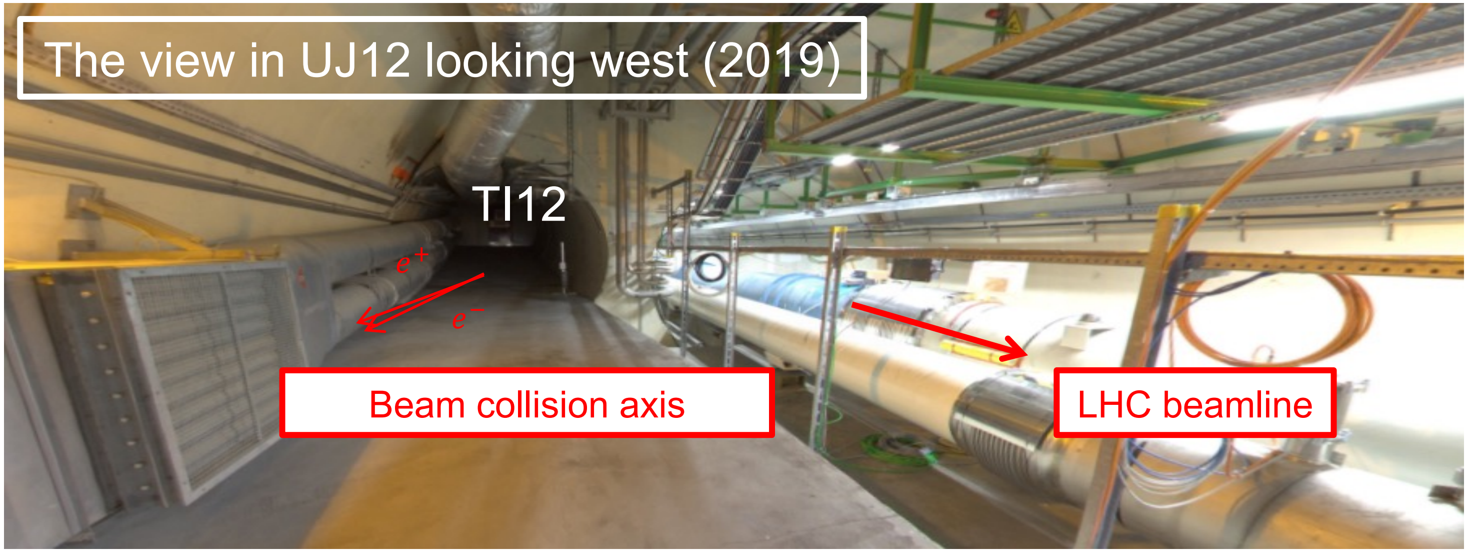


- But weakly-interacting light particles are dominantly produced in the rare decays of light particles: π, η, K, D and B mesons. These are mainly produced along the beamline, and the new particles also escape down the beamline.

- Clearly we need to exploit the "wasted" σ_{inel} ~ 100 mb and cover these blind spots in the forward region. If we go far enough away, the proton beams are bent by magnets (it's a circular collider!), whereas the new light particles will go straight.

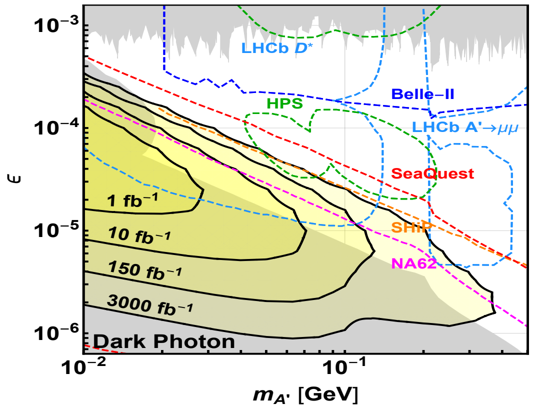
THE FAR-FORWARD REGION





FASER

FASER has been built to look for these signals. It was approved, constructed, installed, and commissioned from 2019-21. In a few months, it will begin probing new parameter space with discovery prospects starting with the first fb^{-1}.



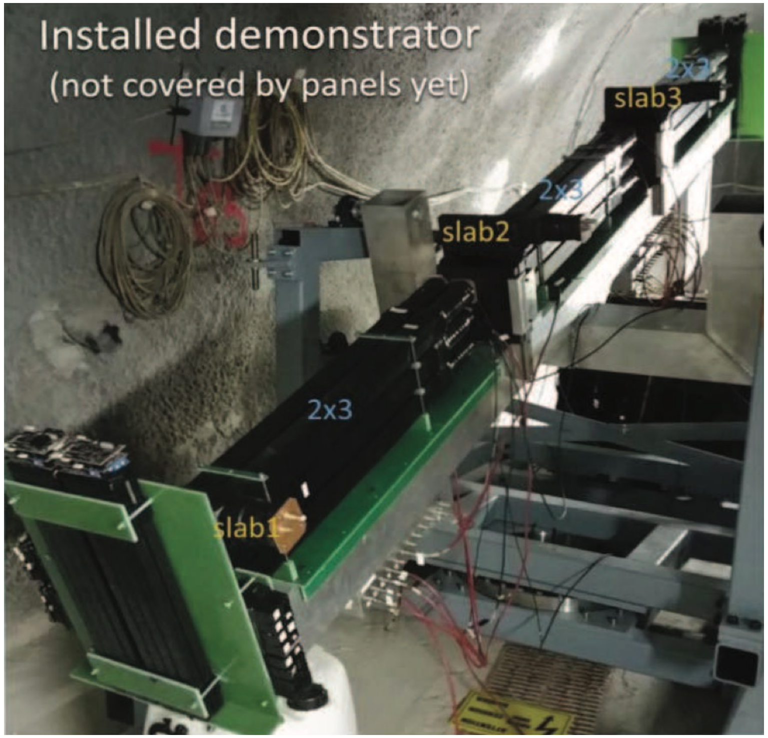
NEW PARTICLES AT THE FPF

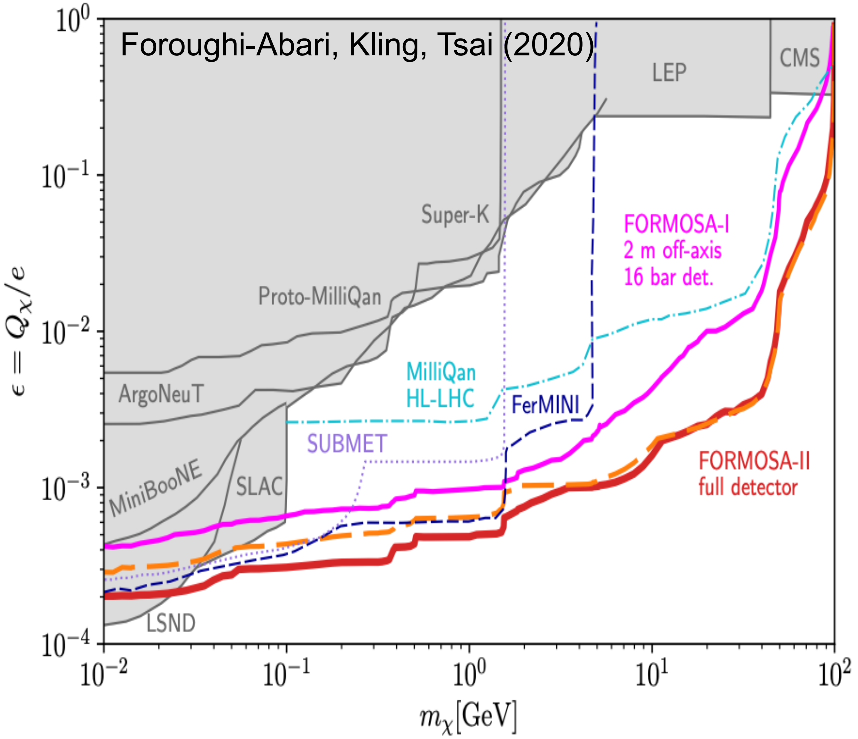
- The FPF will extend the current BSM program by housing larger and a more diverse array of experiments.
- FASER 2, with R = 1 m, L = 20 m, can discover all portal particles with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and many other particles.
- Other experiments can discover mCPs, dark matter, and many other interesting ideas.

Benchmark Model	Underway	FPF
BC1: Dark Photon	FASER	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2
BC2: Dark Matter	–	FLArE
BC3: Milli-Charged Particle	–	FORMOSA
BC4: Dark Higgs Boson	–	FASER 2
BC5: Dark Higgs with hSS	–	FASER 2
BC6: HNL with e	–	FASER 2
BC7: HNL with μ	–	FASER 2
BC8: HNL with τ	–	FASER 2
BC9: ALP with photon	FASER	FASER 2
BC10: ALP with fermion	FASER	FASER 2
BC11: ALP with gluon	FASER	FASER 2

MILLI-CHARGED PARTICLES

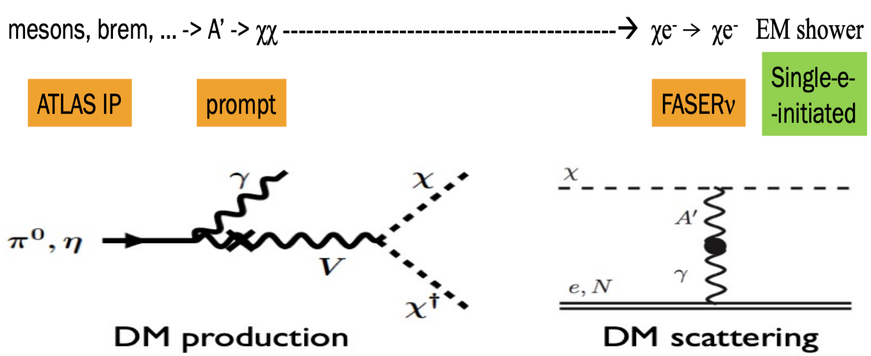
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a non-forward tunnel.
- Full MilliQan can also run in this location in the HL-LHC era, but the sensitivity may be improved greatly by moving it to the FPF (FORMOSA).



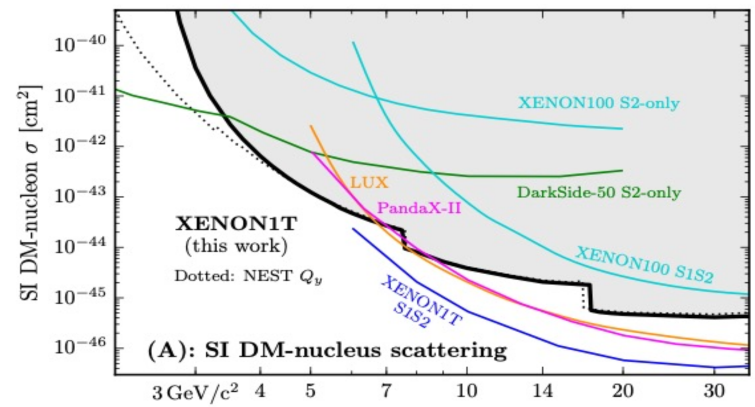


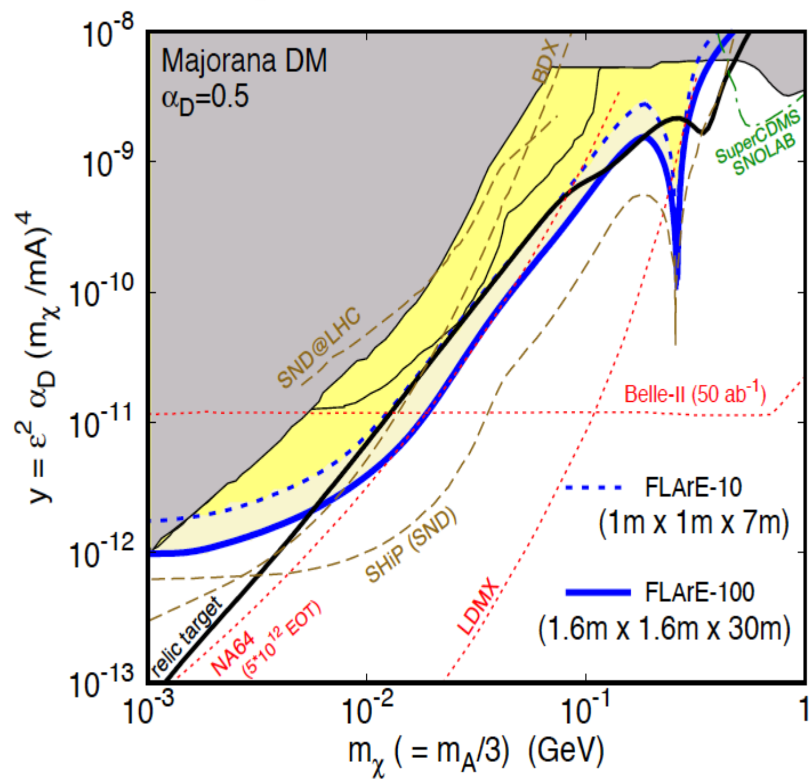
DARK MATTER

- Light DM with masses below the GeV scale is famously hard to detect, since galactic DM has v ~ 10^{-3} c.
- 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 tonne LArTPC.



- FLArE probes most of the region favored by thermal freezeout.



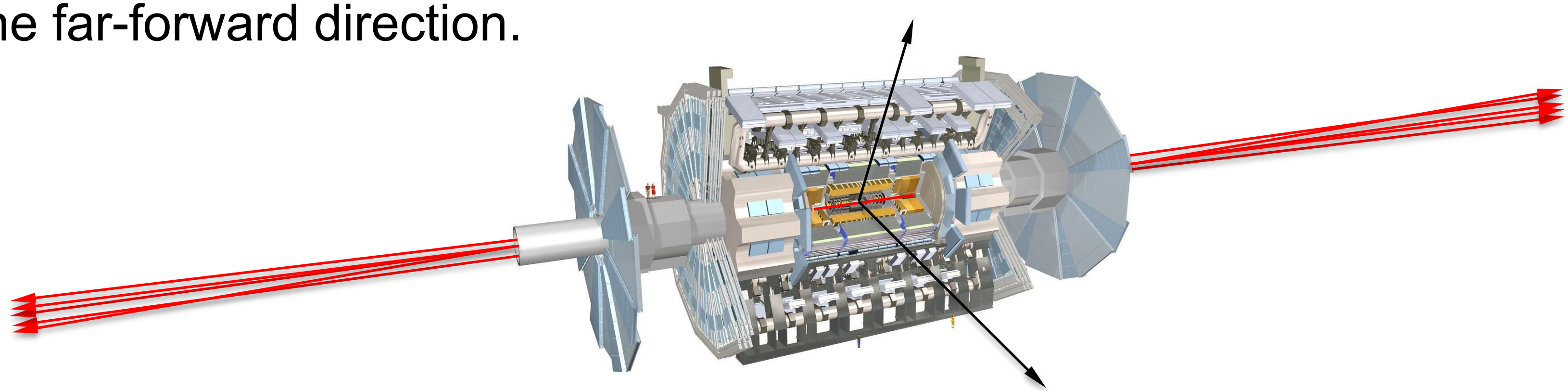


Batell, Feng, Trojanowski (2021)

NEUTRINOS

- Before May 2021, no collider neutrino candidate had ever been detected.

- Why? They are very weakly-interacting of course. But also, the high-energy ones, which interact most strongly, are overwhelmingly produced in the far-forward direction.



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

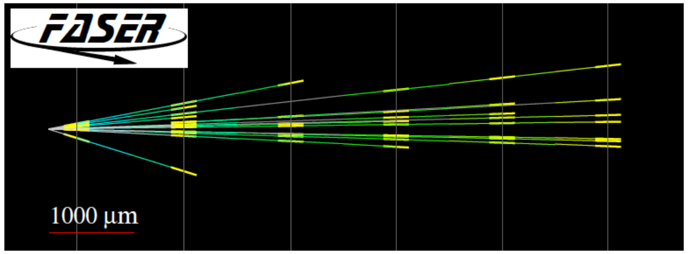
De Rujula, Ruckl (1984); Winter (1990); Vannucci (1993)

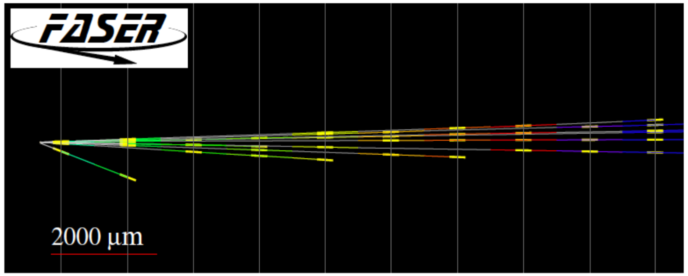
FIRST COLLIDER NEUTRINOS

- 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 (2.7σ).

- At Run 3, FASERν and SND@LHC will open up a completely new field: neutrino physics at the LHC.



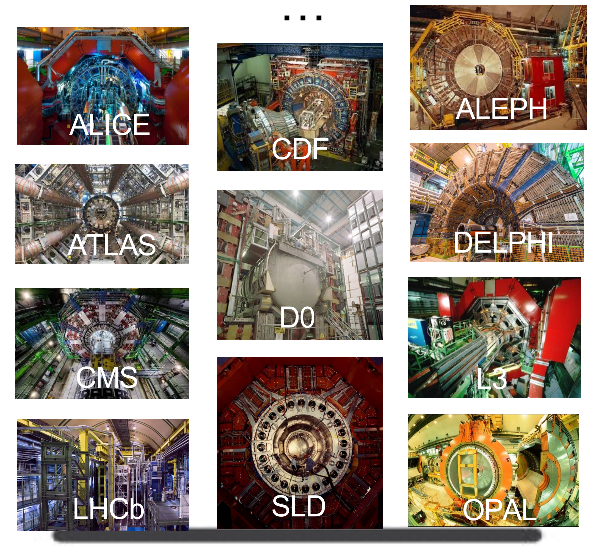


LOCATION, LOCATION, LOCATION

FASER Pilot Detector

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

6 candidate neutrinos



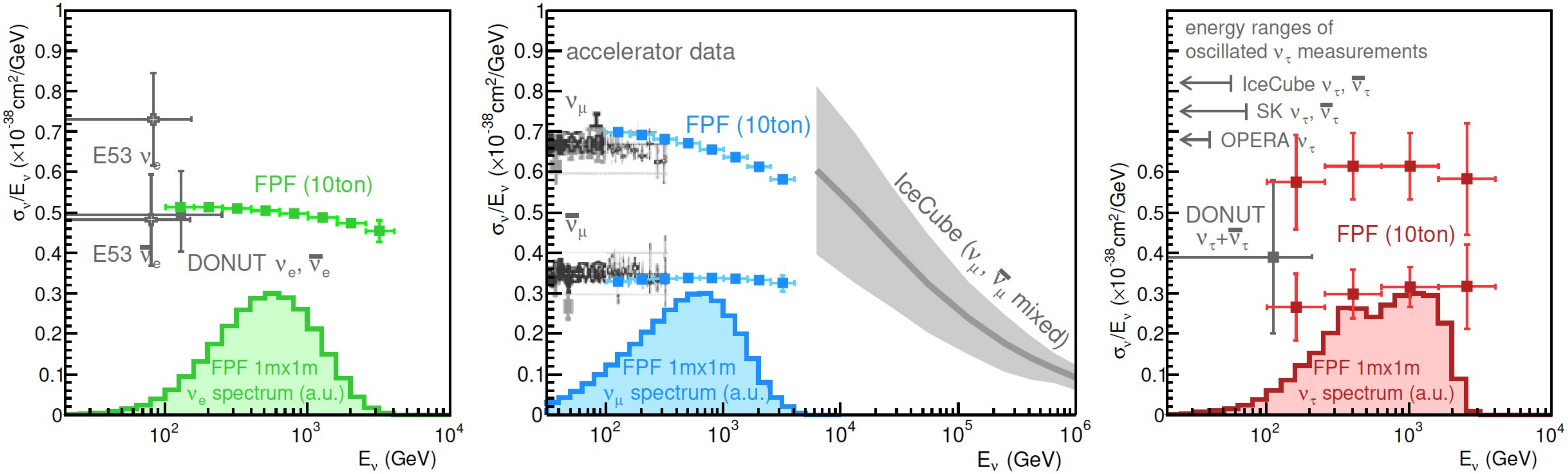
All previous
collider detectors

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

0 candidate neutrinos

NEUTRINO PHYSICS AT THE FPF

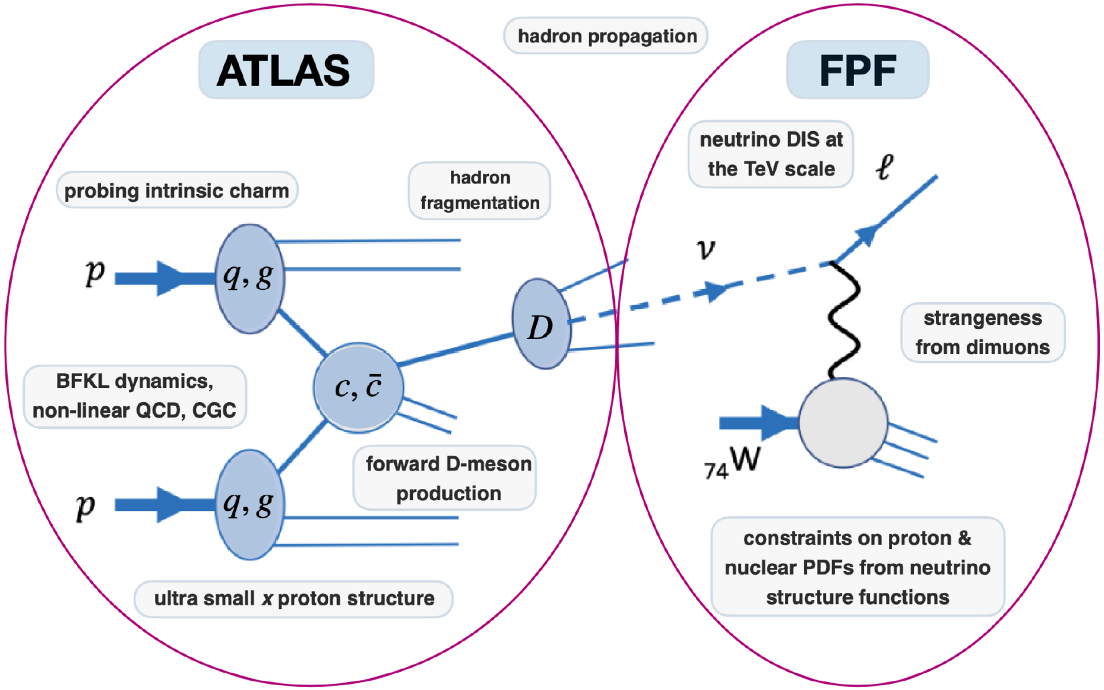
- At the FPF, three proposed ~10 tonne detectors FASERν2, Advanced SND, and FLArE will each detect ~100,000 ν_e, ~1,000,000 ν_μ, and ~1000 ν_τ interactions at TeV energies, providing high statistics samples for all three flavors in an energy range that has never been directly explored.
- First precision 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.

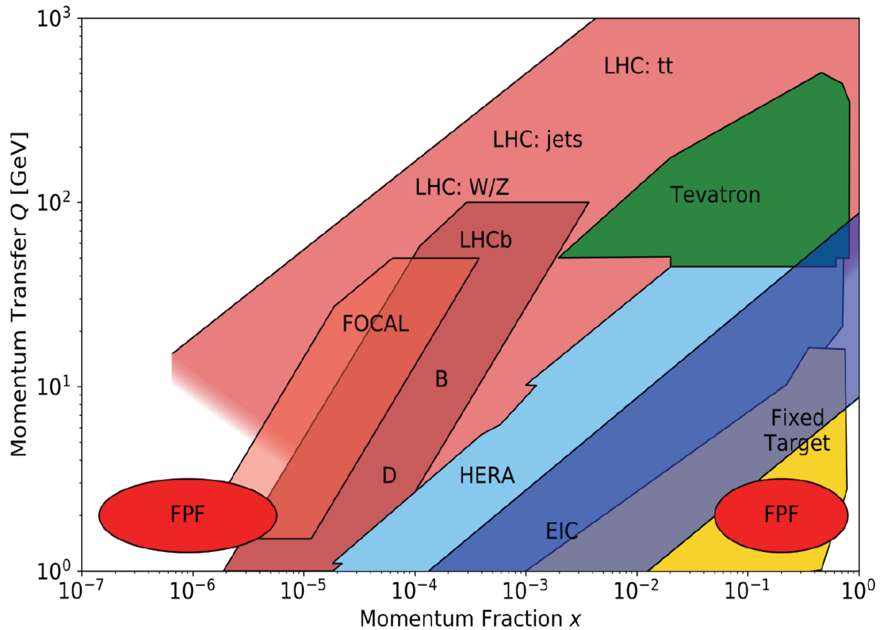


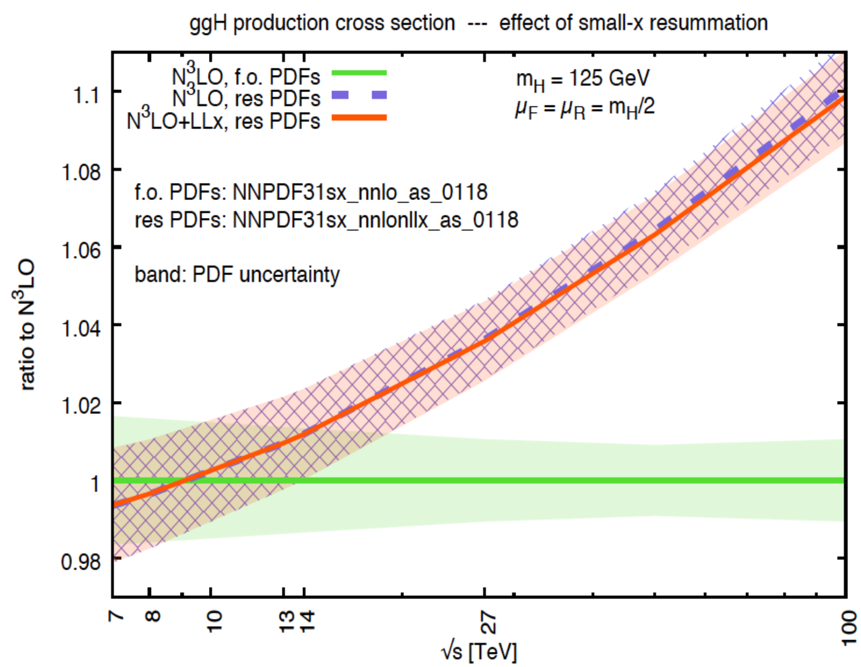
FASER White Paper (2022)

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.

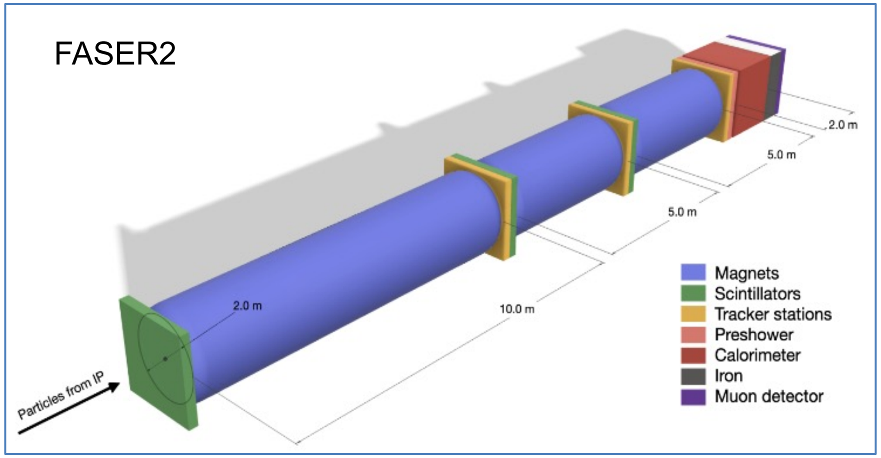


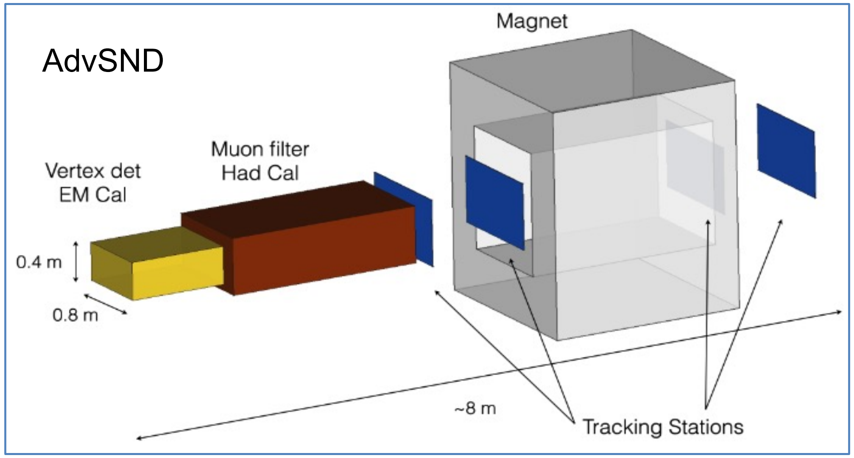


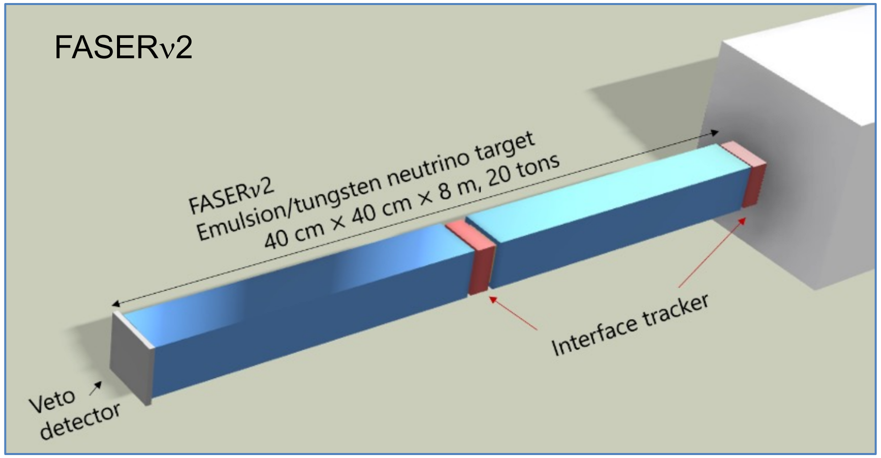
FASER White Paper (2022)

THE EXPERIMENTS

- At present there are 5 experiments being developed for the FPF; these are works in progress, with much more work to be done.
- FASER2: upgraded FASER (tracker + magnetic spectrometer) 20 m long, targeting LLPs.
- AdvSND, FASERν2: successors to SND@LHC and FASERν, ~10 tonne detectors to study TeV neutrinos and differentiate flavors.

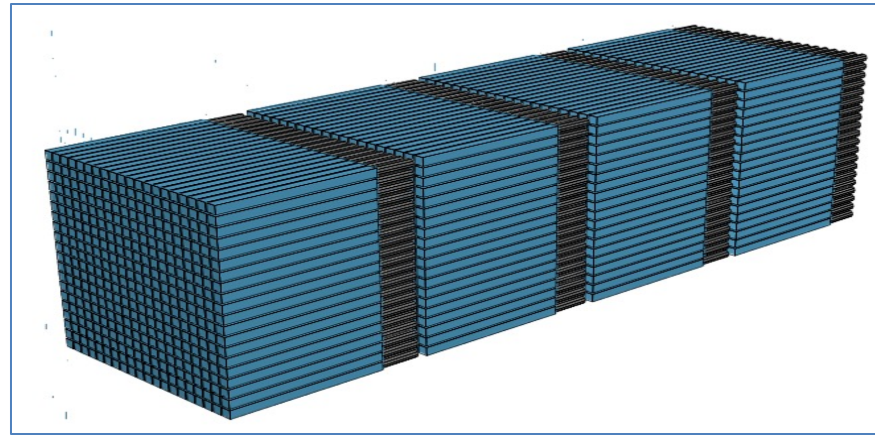




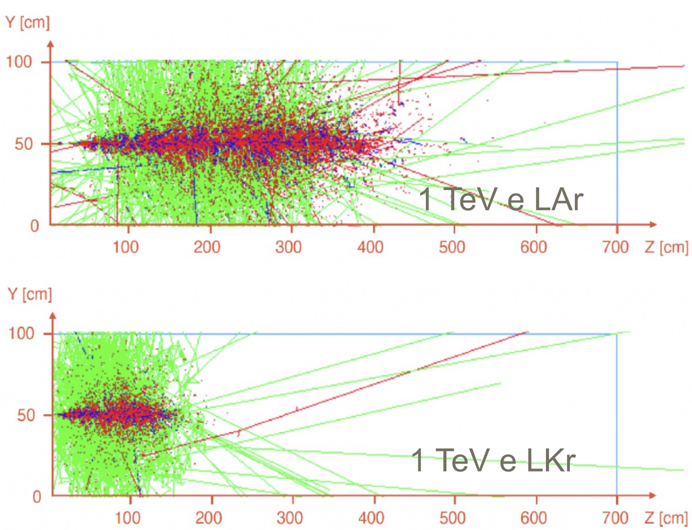


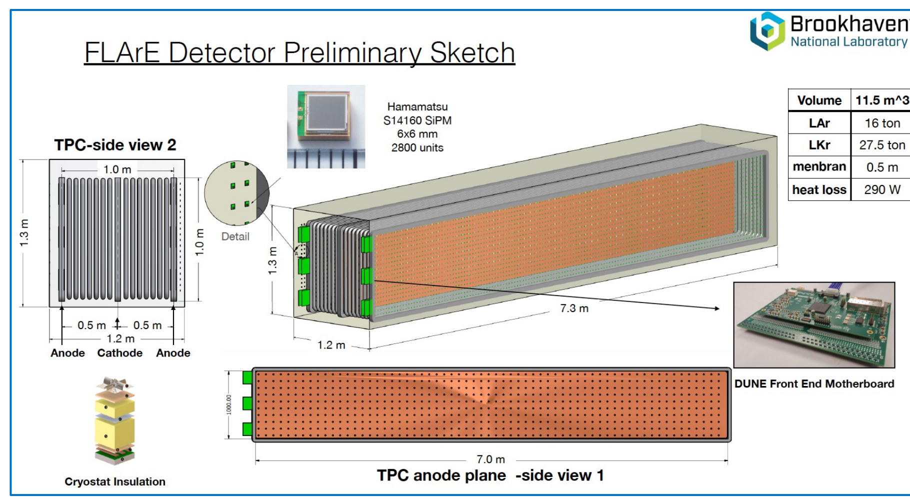
THE EXPERIMENTS

- FORMOSA: 1m x 1m x 5m scintillator bars+ PMTs looking for milli-charged particles, particles with EDMs, MDMs, and similar signatures.



- FLArE: ~1m x 1m x 7m noble liquid (Ar or Kr) TPC for neutrino studies, light DM searches.

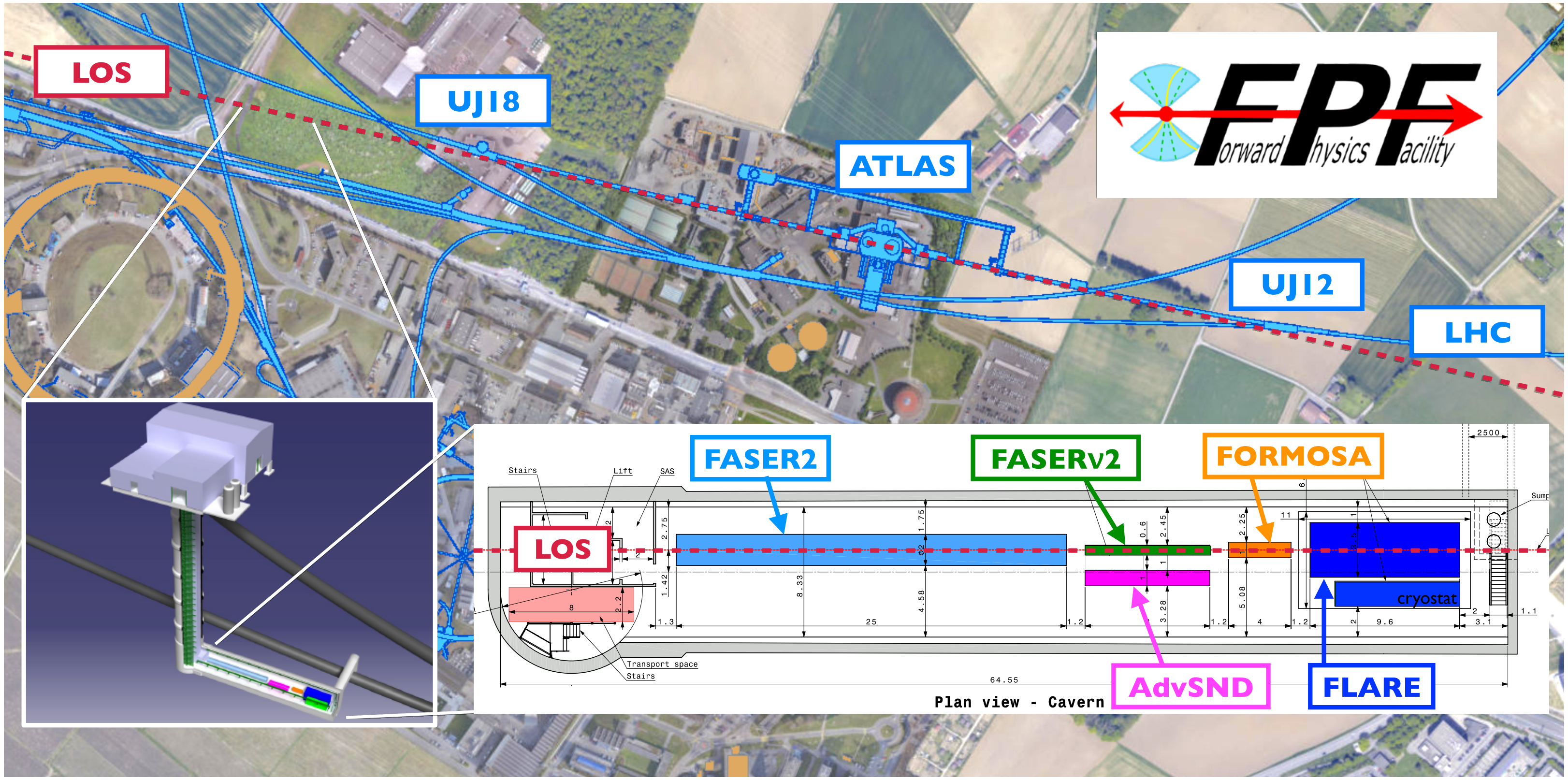




THE FACILITY

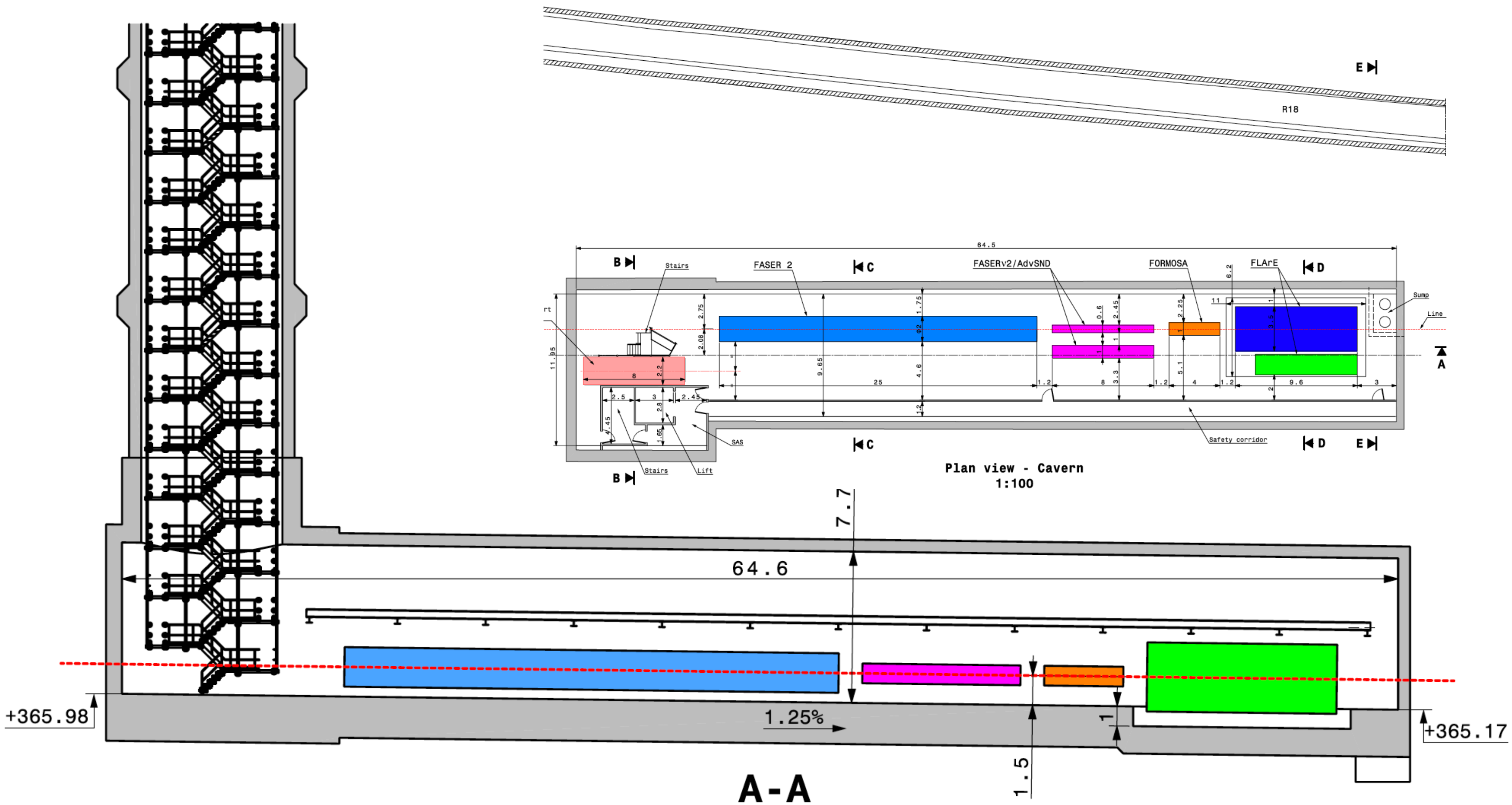
- The CERN civil engineering team has considered many sites around the LHC ring that are on the beam collision axis of an IP.

- 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.

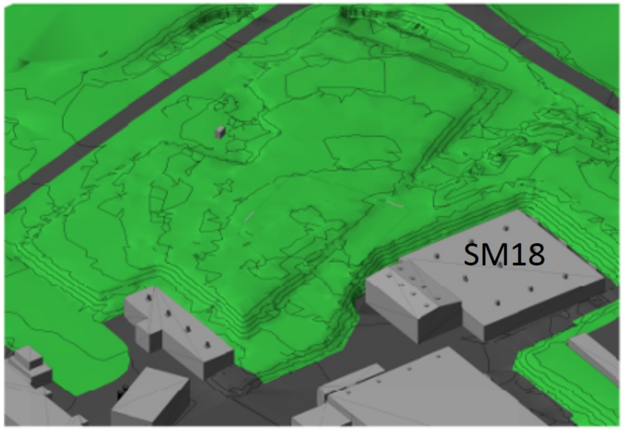


CAVERN AND SHAFT

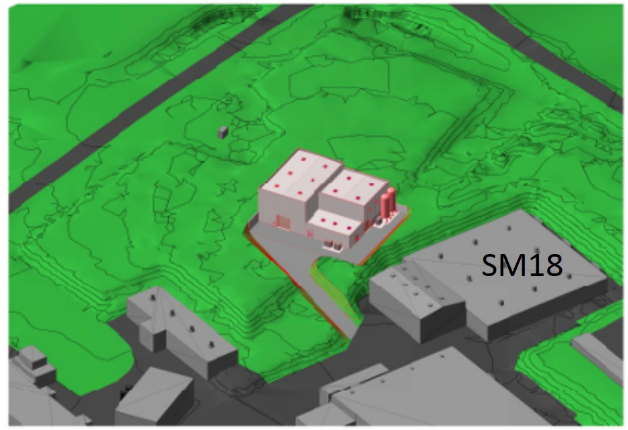
- Cavern: 65m long, 8m wide/high. Shaft: 88m-deep, 9.1m-diameter.
- The FPF is completely decoupled from the LHC (as of today, no need for a safety corridor connecting FPF to the LHC).



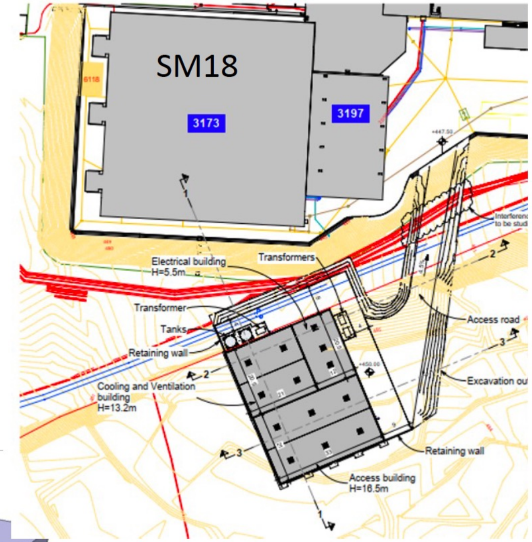
SURFACE BUILDINGS

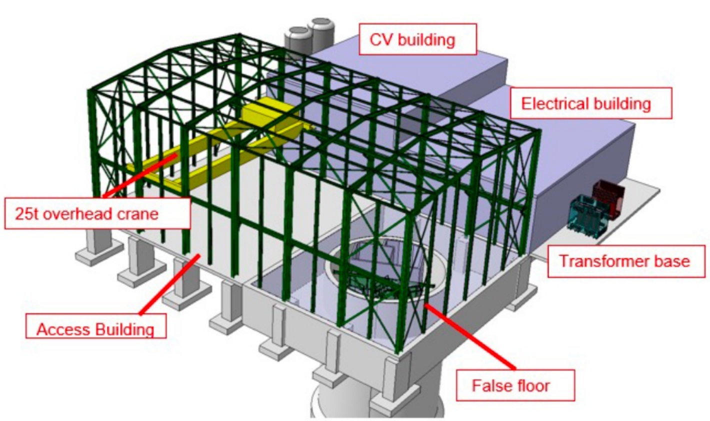


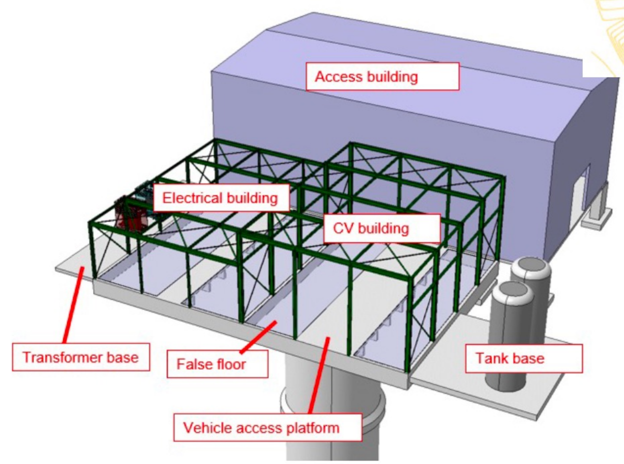
3D EXISTING



3D NEW





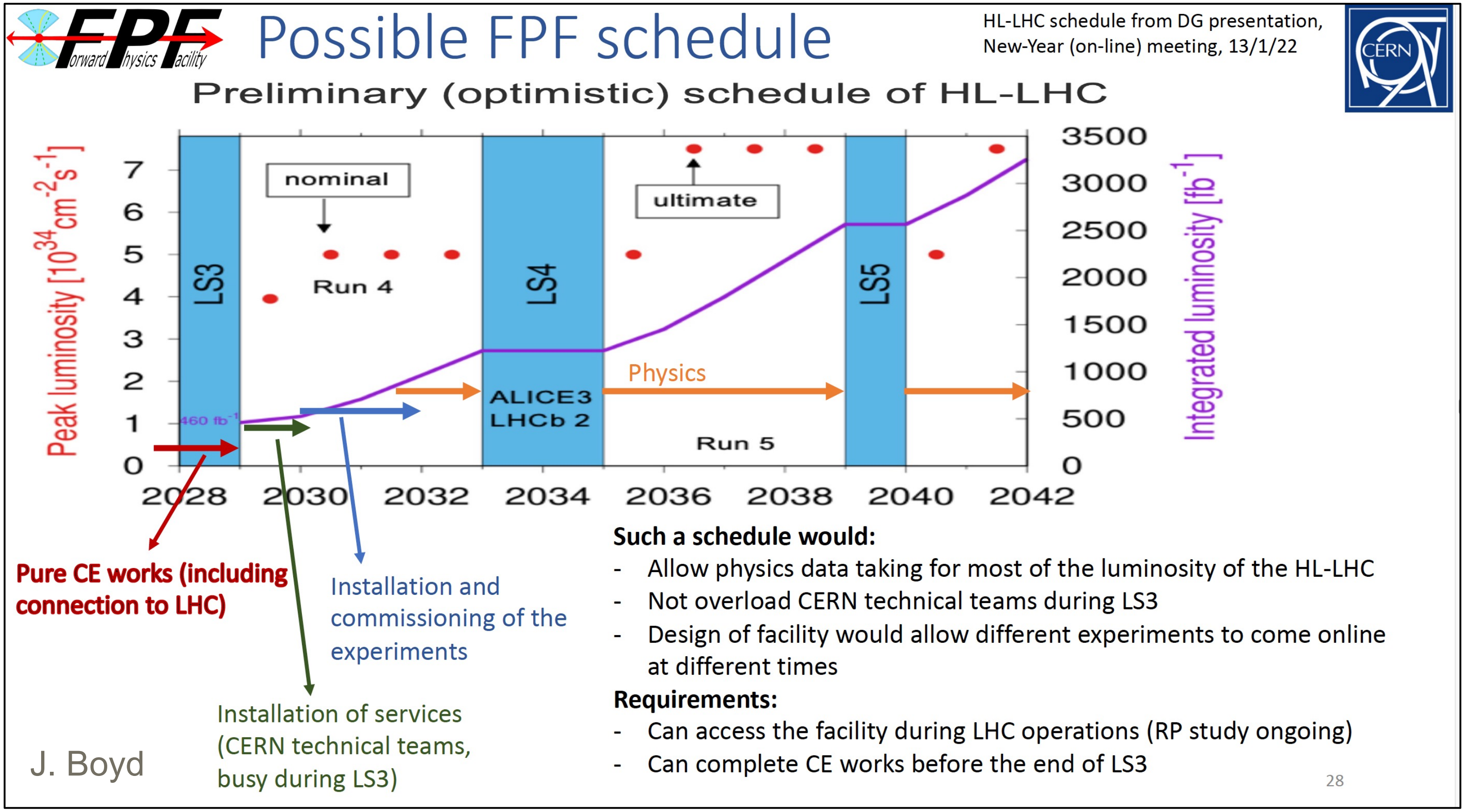


24

COST AND TIMELINE

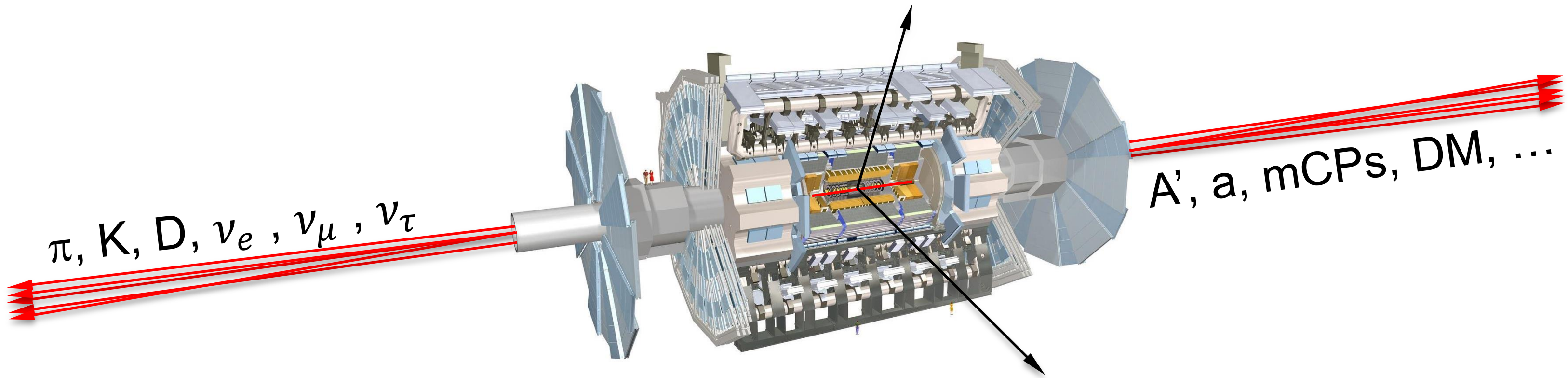
- Very preliminary (class 4) cost estimate: 23 MCHF (CE) + 15 MCHF (services) ≈ 40 MCHF (+50%/-30%), not including experiments.

- Timeline presented at Chamonix workshop (Feb 2022)



EXECUTIVE SUMMARY

- Physics opportunities are currently being missed in the far-forward region at the LHC.



- The proposed FPF will be an underground cavern constructed to house a suite of far-forward experiments for the HL-LHC era.

- The FPF is uniquely positioned to fully realize the LHC's physics potential for both SM and BSM physics in the far-forward region.

- A very preliminary cost estimate is 40 MCHF + experiments. The construction can take place separate from the LHC, and no modifications to the LHC are needed.