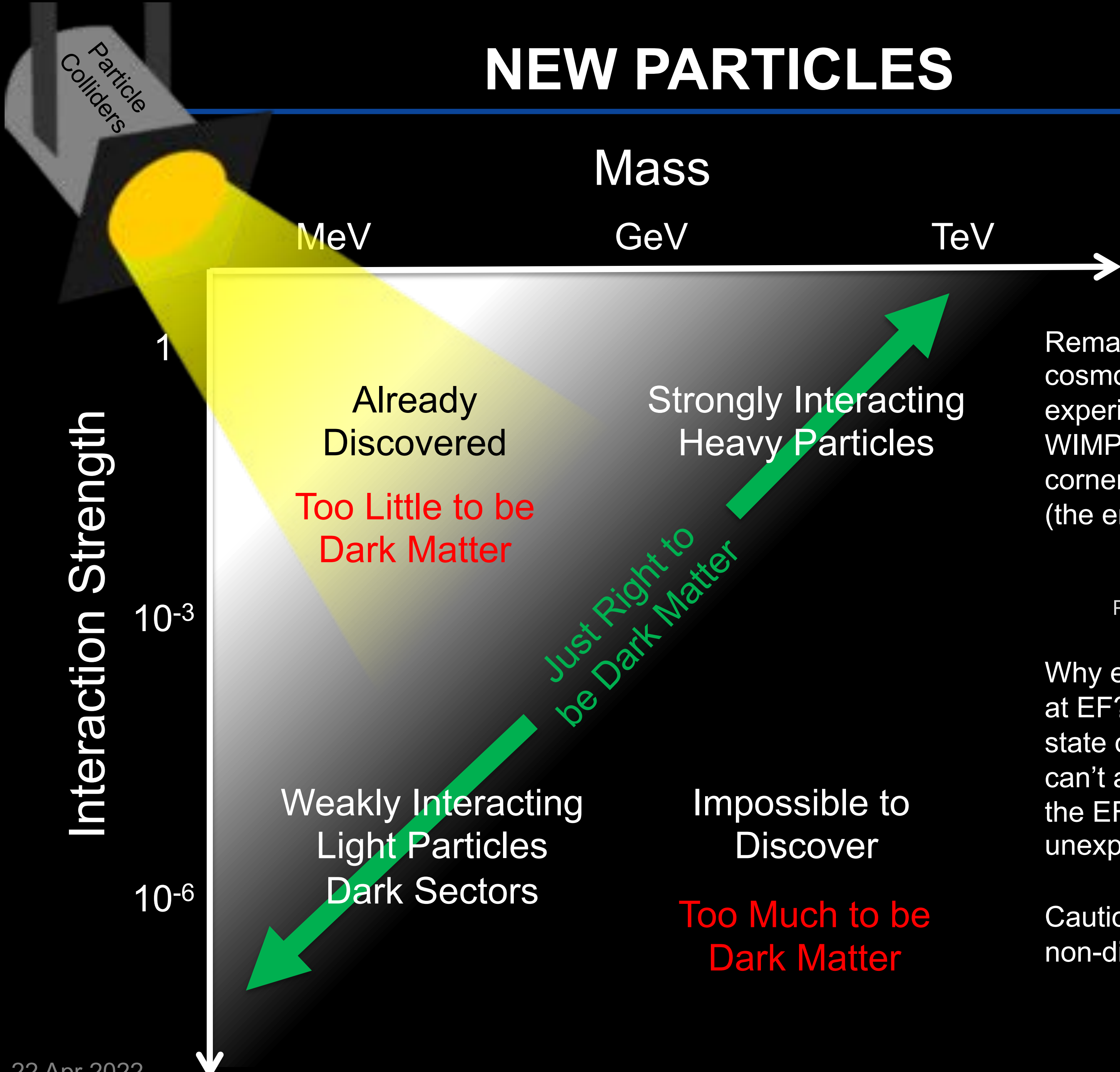
CONNECTION TO THE ENERGY FRONTIER

Accelerator-Based Dark Sector Searches Agora
Snowmass 2022

Jonathan Feng, UC Irvine, 22 April 2022

NEW PARTICLES



Remarkable overlap of cosmology and the current experimental frontier: the WIMP Miracle (upper right corner), WIMPless Miracle (the entire diagonal).

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

Why explore dark sectors at EF? Given the current state of particle physics, we can't afford to leave half of the EF's physics potential unexplored.

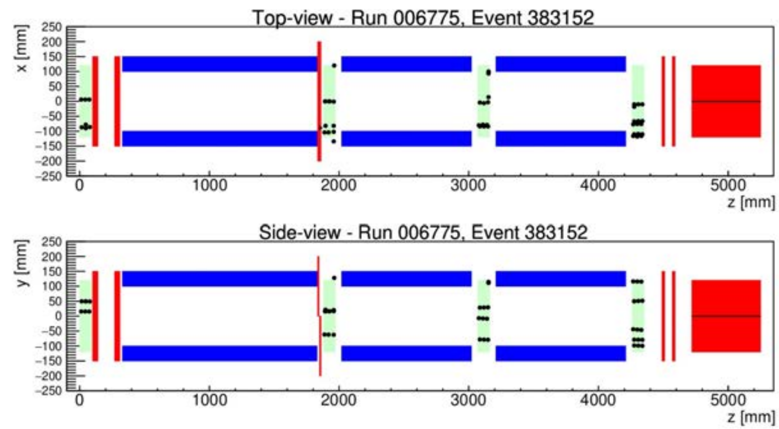
Cautionary tale: charm non-discovery at the ISR.

Myers (2021)
Evans, Jenni (2021)

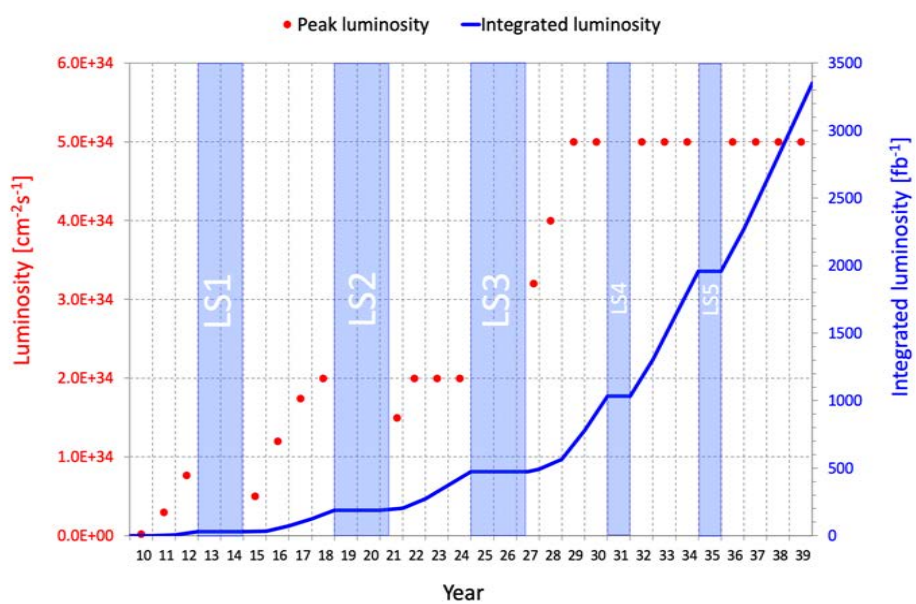
DARK SECTORS AT THE ENERGY FRONTIER

- Energy frontier colliders provide multiple avenues for probing dark sectors, given timely preparation and relatively small investments.

- LHC Run 3: Existing experiments will soon probe new parameter space. Beams started today! (Right: a beam splash event recorded by FASER 10 hours ago.)



- HL-LHC: More world-leading dark sector searches, with complementary neutrino and QCD studies.



- Future Colliders: Dark sector searches will be an integral part of any future collider program.

LHC RUN 3

SPECIFIC EXAMPLES

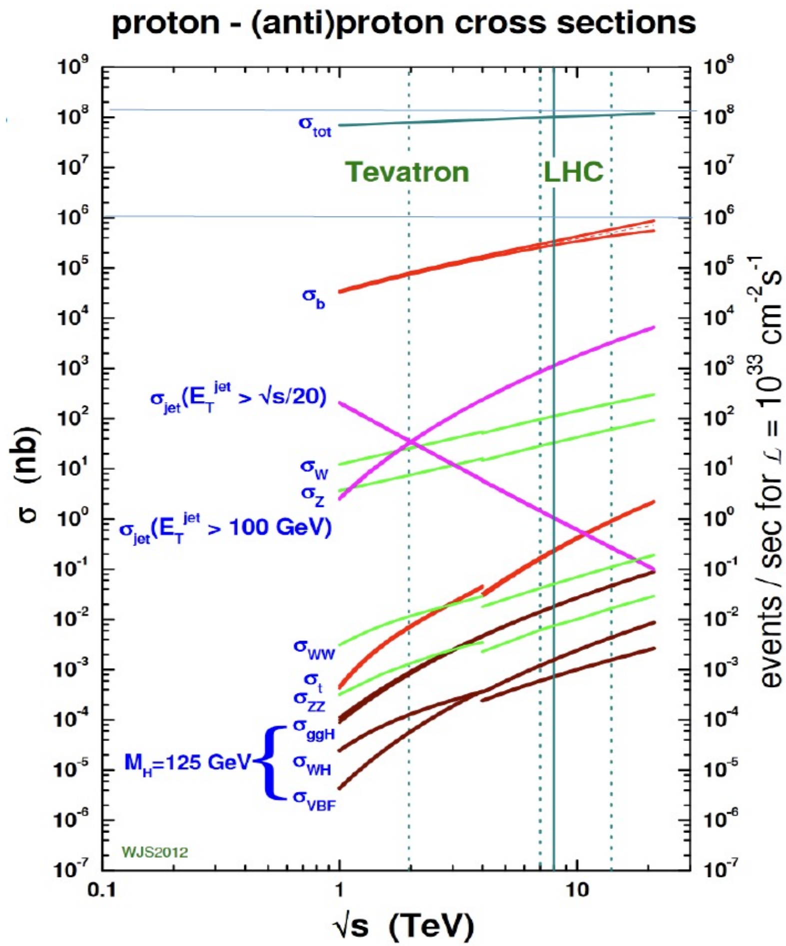
- Dark photon: like the photon, but with mass $m_{A'}$ and ε - suppressed couplings
  - SM process: $\pi^0 \rightarrow \gamma\,\gamma$
  - BSM process: $\pi^0 \rightarrow \gamma\, A'$, A' is long−lived, $A' \rightarrow e^+\, e^-$

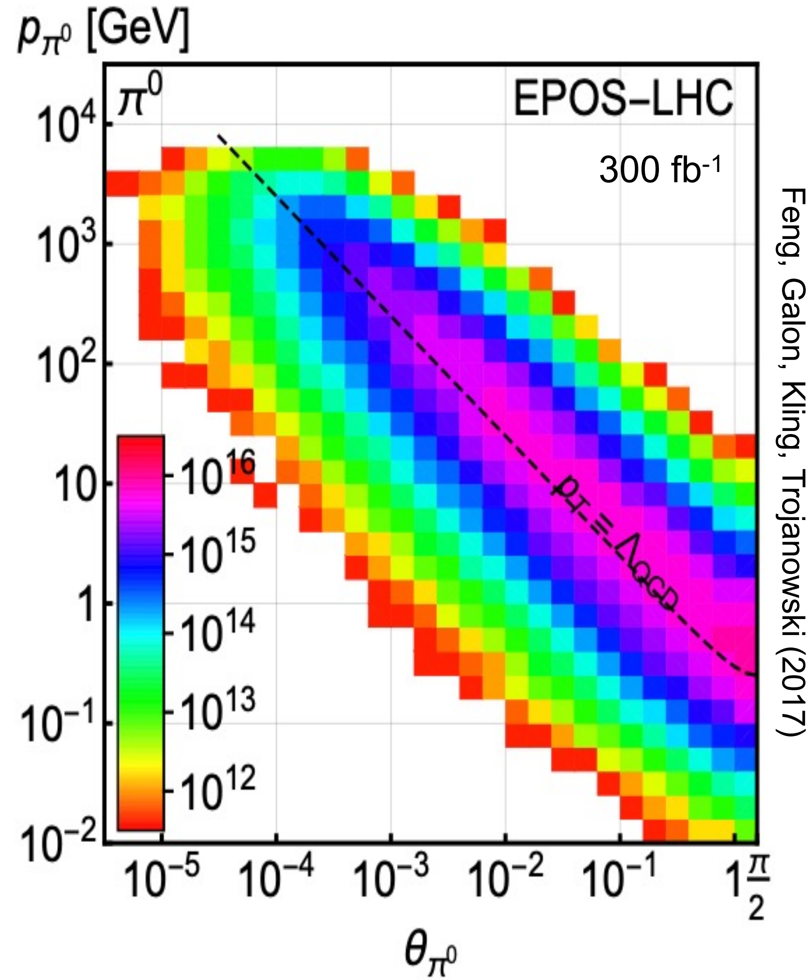
- Dark fermion (HNL, sterile neutrino): like a neutrino, but with mass m_N and U_{lN} - suppressed couplings
  - SM process: $\pi^+ \rightarrow \mu^+ \nu$
  - BSM process: $\pi^+ \rightarrow \mu^+ N$, N is long−lived, $N \rightarrow l^+\, l^-\, \nu$

- Clearly, one promising strategy is to exploit the large source of energetic neutral and charged pions at hadron colliders.

[Many other new particle examples (dark scalars; axion-like particles; light $U(1)_B$, $U(1)_{B\text{-}L}$, $U(1)_{\mu-\tau}$, protophobic gauge bosons, light neutralinos, …) and many other ways to find them (other accelerator probes, intensity frontier, cosmic frontier, …). See talks of Natalia, Stefania, Gaia, Rodolfo, and Brian.]

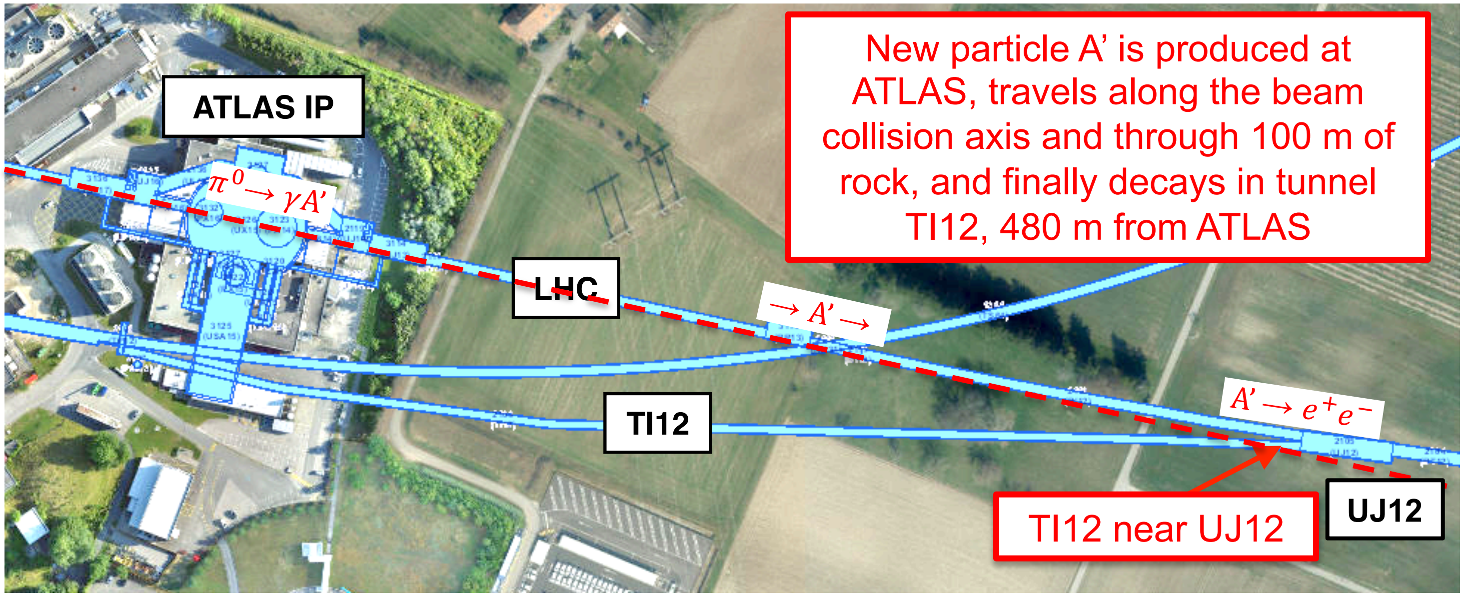
WHERE THE PIONS ARE

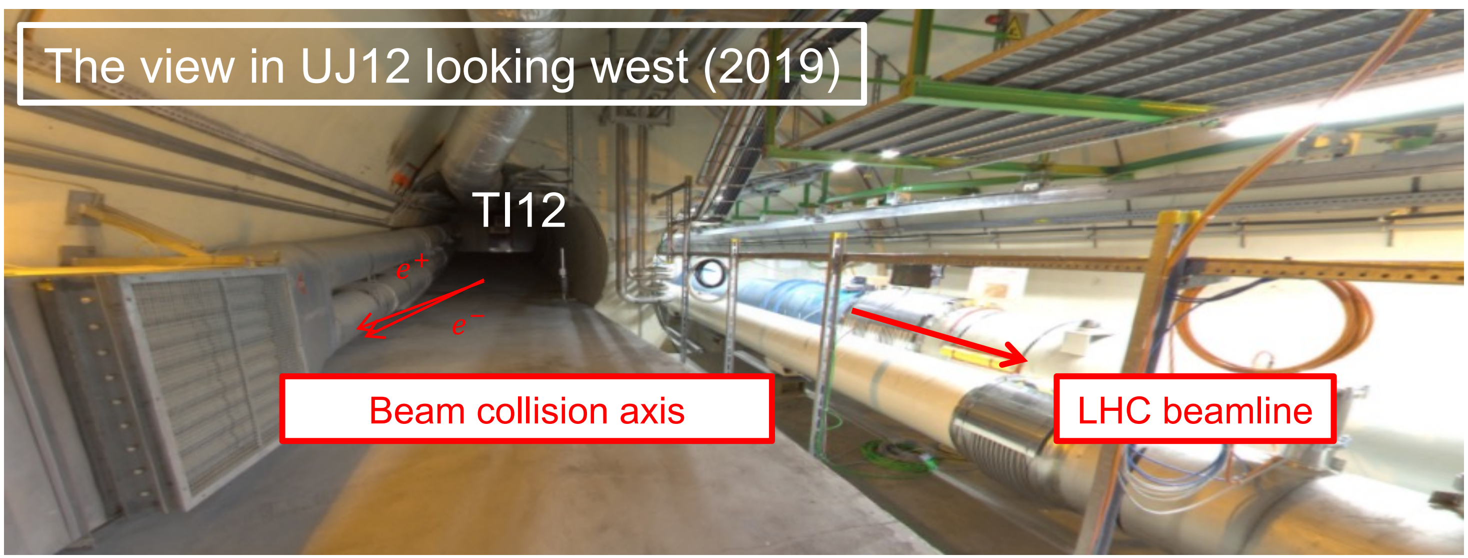




- Enormous σ_{tot} ~100 mb, currently wasted in BSM searches.
- Pions typically have p_T ~ 250 MeV, but large flux with p ~ TeV within 1 mrad (η > 7.6) of the beamline.

THE FAR-FORWARD REGION

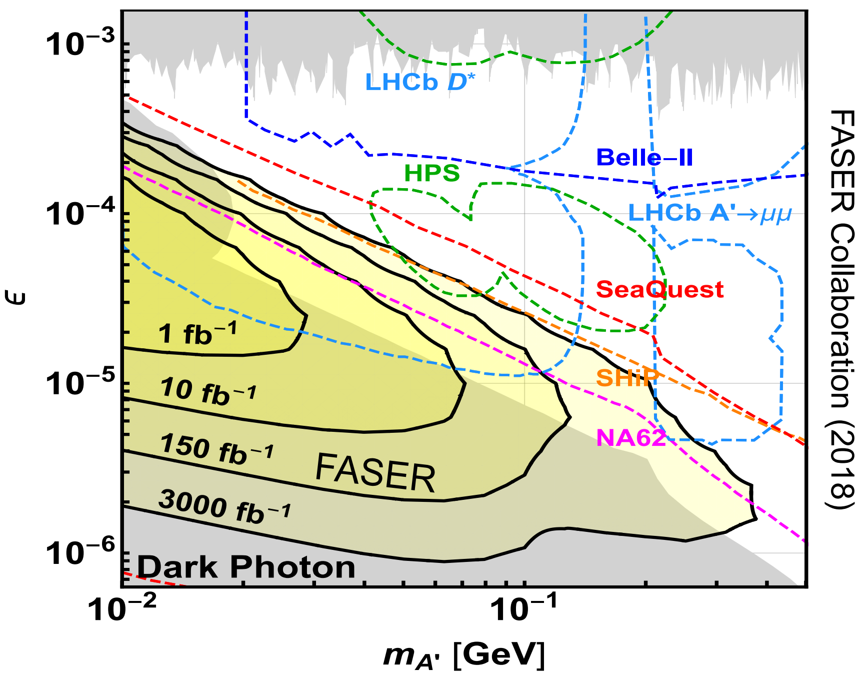


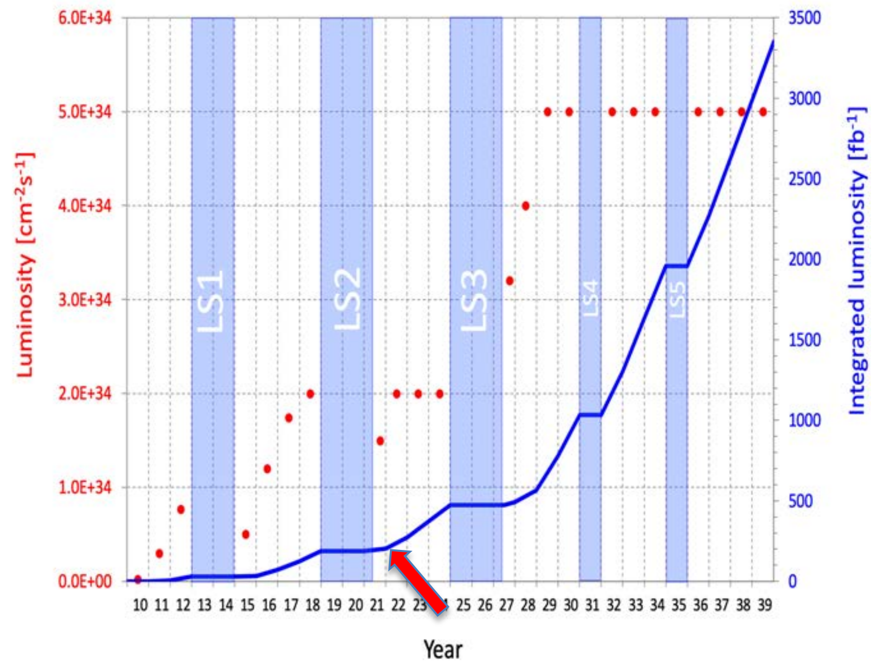


FASER COMPLETED IN 2021

1st Cosmic Ray
18 March 2021

DARK PHOTON SENSITIVITY REACH





- Energy frontier experiments are among the most promising probes of dark photons in the coming years.
- LHCb probes new parameter space starting at larger couplings.

Ilten, Soreq, Thaler, Williams, Xue (2016)

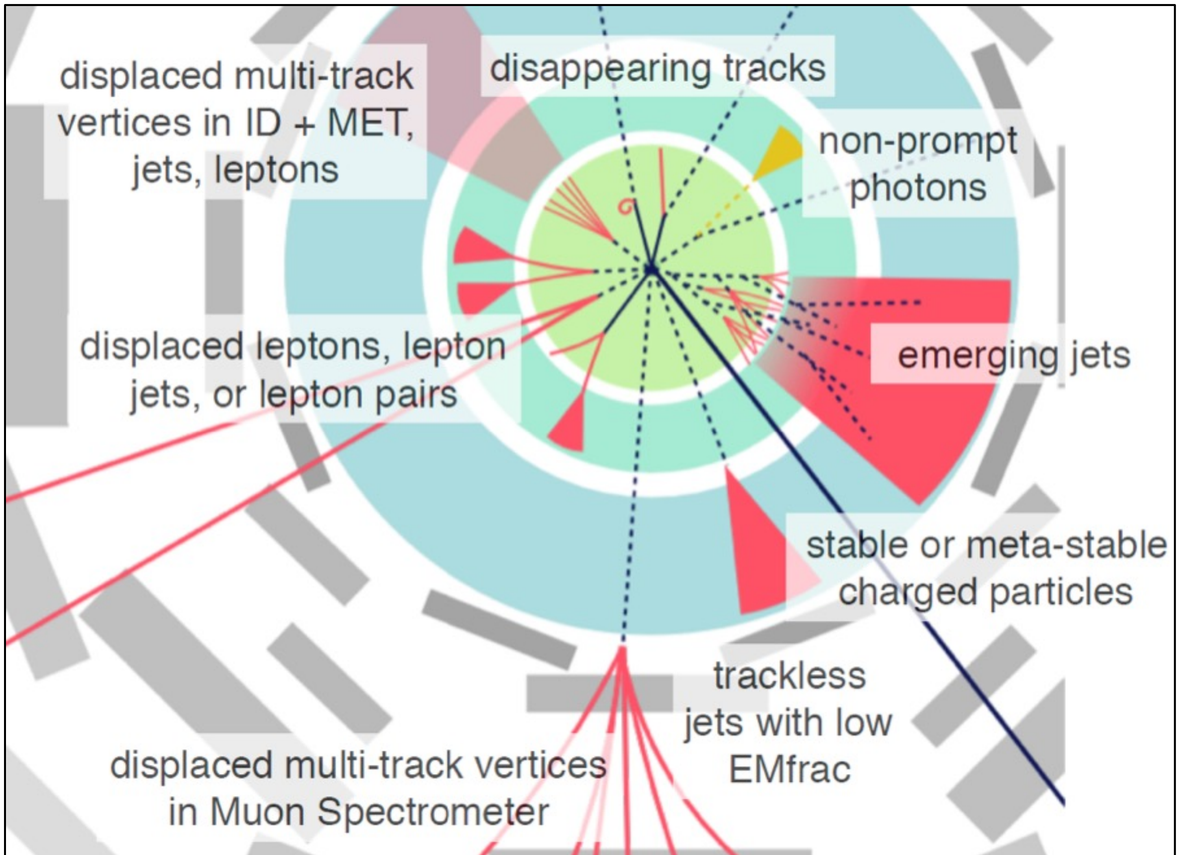
- FASER probes new parameter space starting at smaller couplings, with discovery or new limits with just 1 fb^{-1} starting in June 2022.

HL-LHC

GENERAL PURPOSE DETECTORS

- Dark sectors motivate long-lived particles, which, if produced transverse to the beam, can lead to a dizzying array of spectacular signatures at ATLAS and CMS.

See LLP WG study, Alimena et al. (1903.04497)

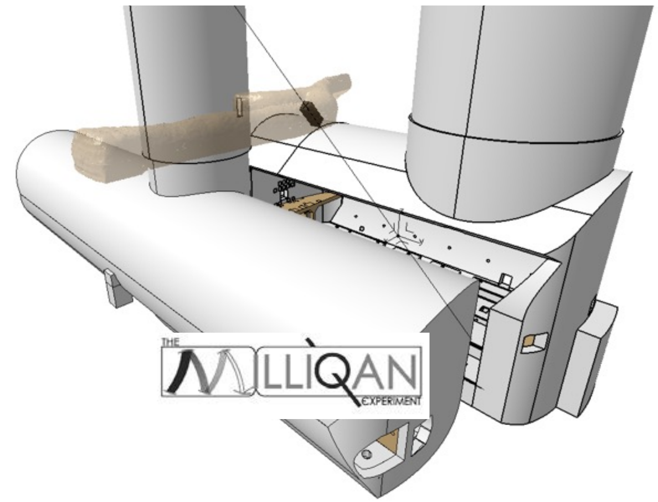


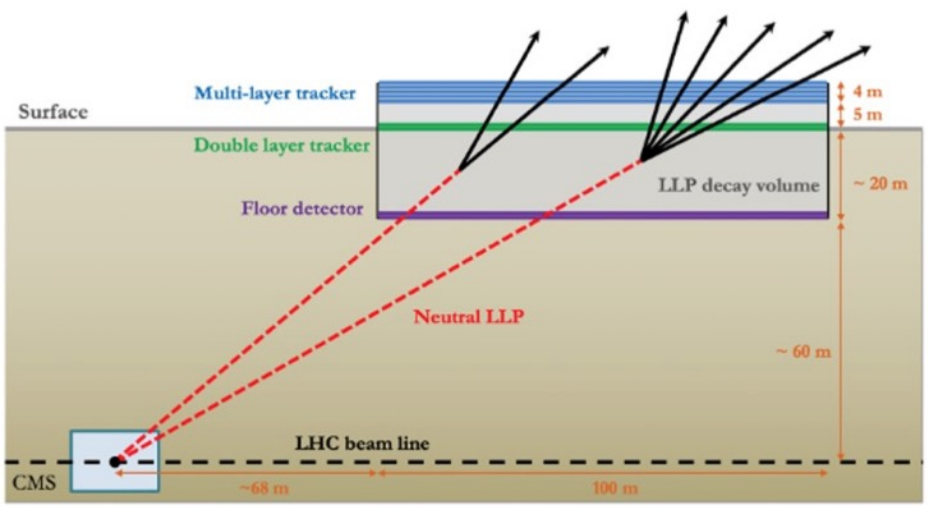
Credit: Heather Russell

DEDICATED TRANSVERSE DETECTORS

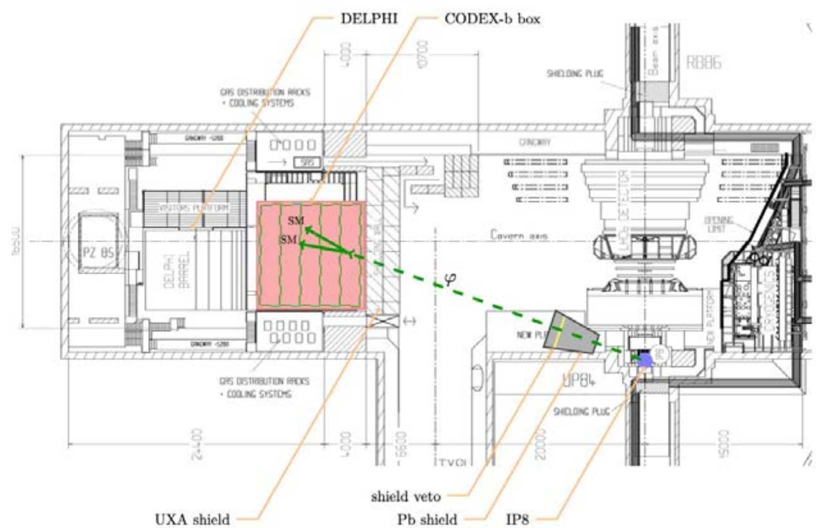
- Many ongoing and proposed detectors dedicated to searching for LLPs and milli-charged particles at large angles to the beamline.

- MoeDAL/MAPP, MilliQan, MATHUSLA, Codex-b, ANUBIS, …





MATHUSLA White Paper (2203.08126)



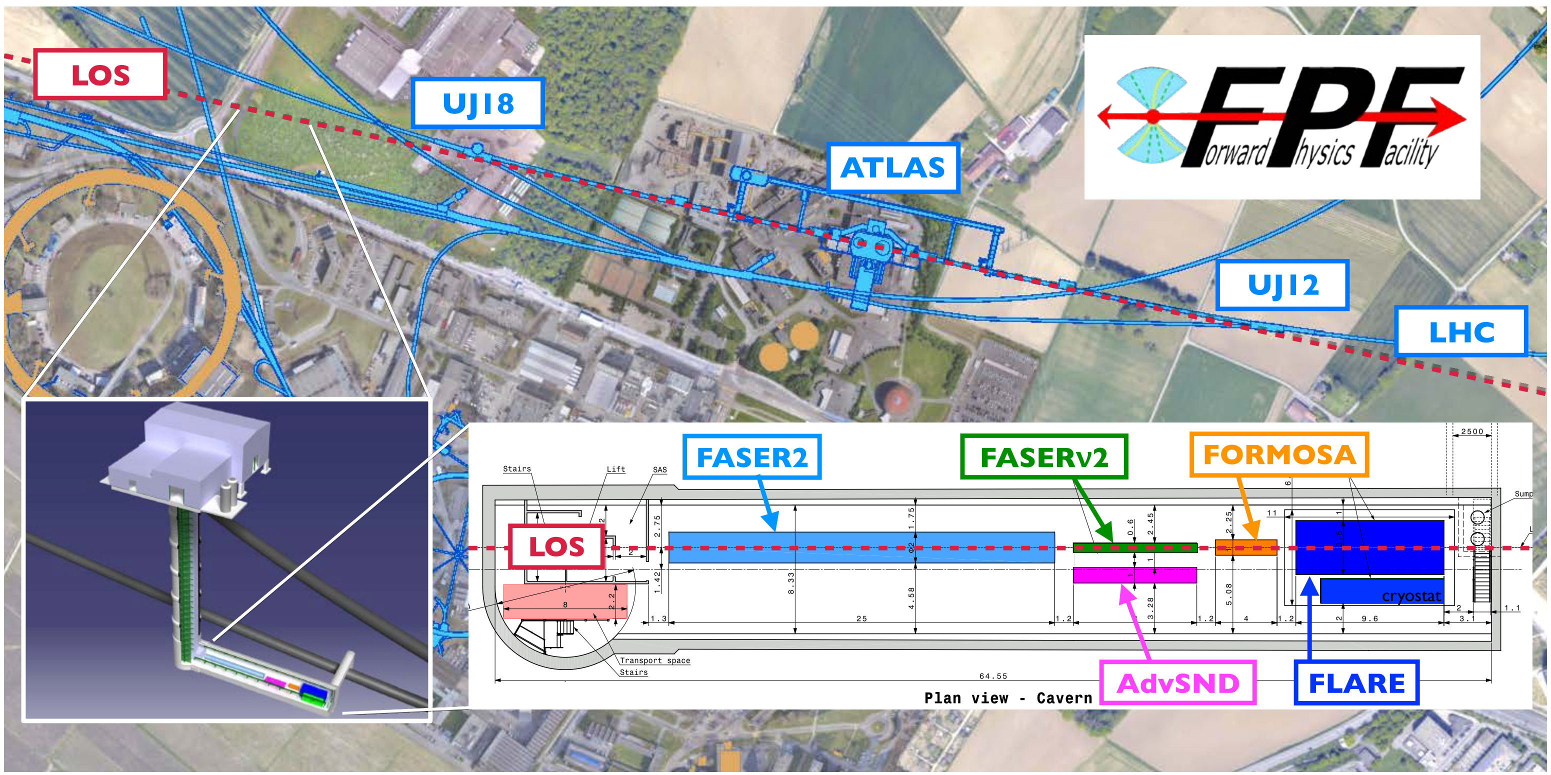
CODEX-b White Paper (2203.07316)

DEDICATED FORWARD DETECTORS

- A suite of dedicated far-forward detectors are proposed to be housed in the Forward Physics Facility. (See also FACET.)

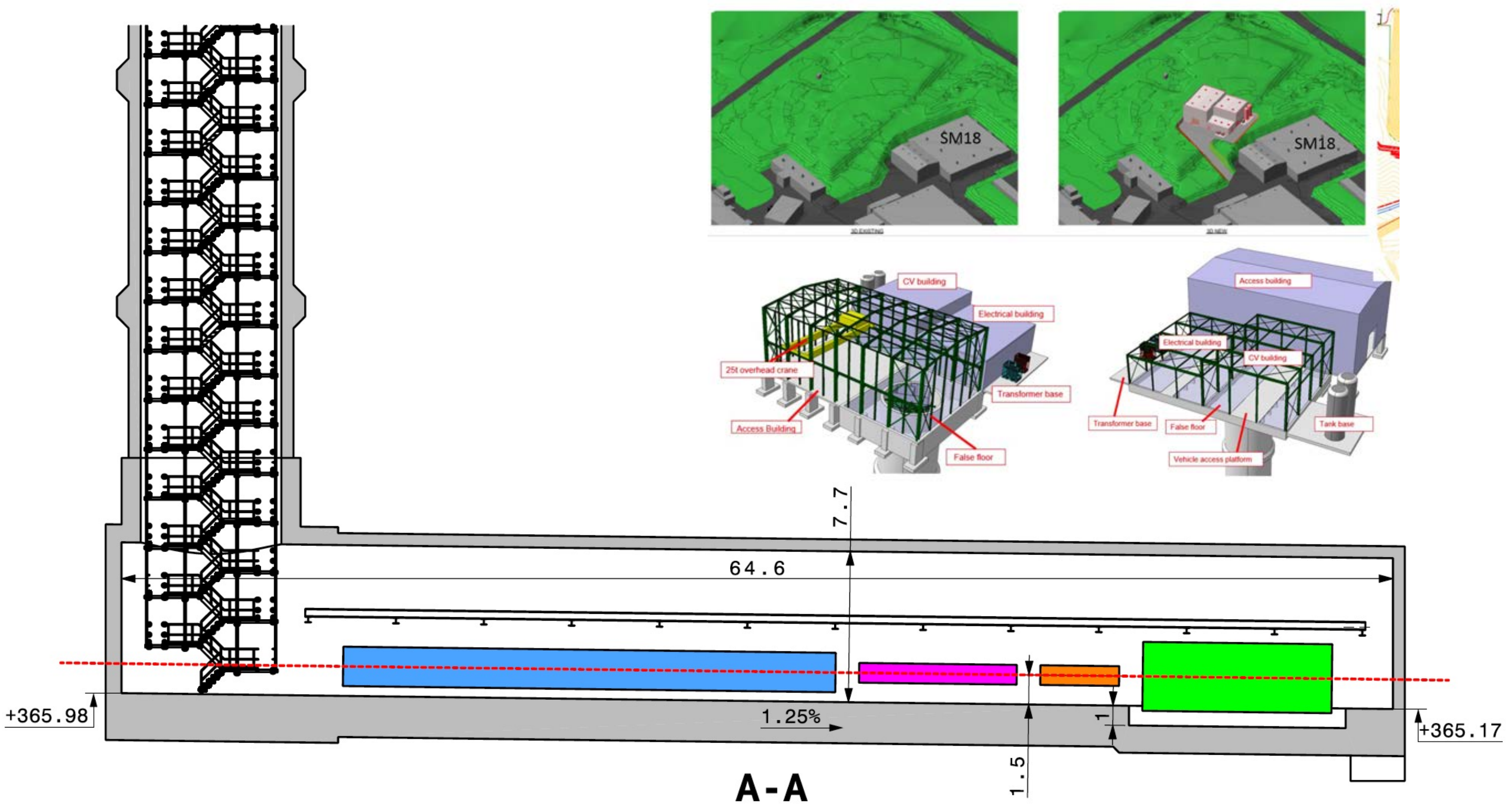
FPF "Short" Paper (2109.10905) and White Paper (2203.05090)

- 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

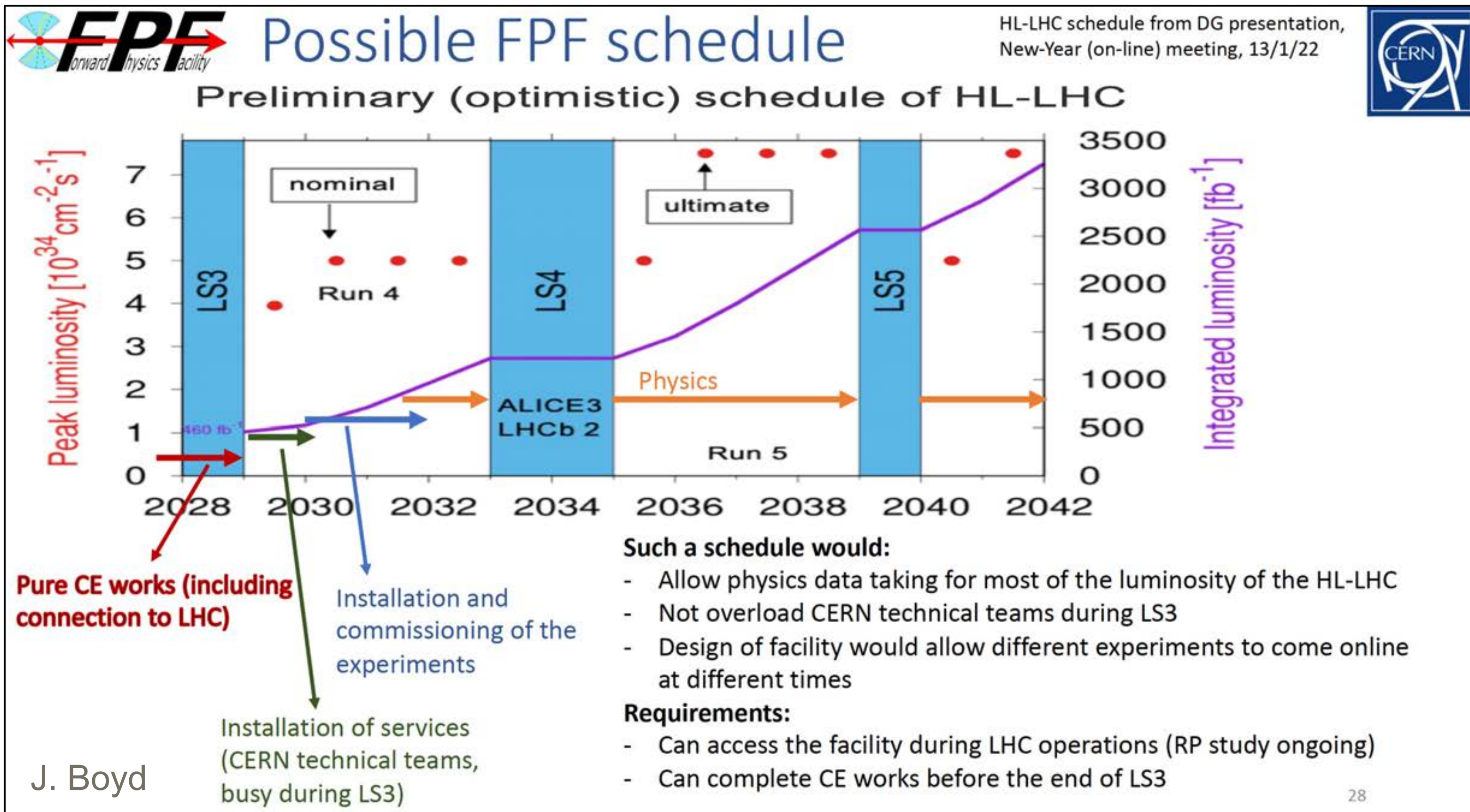
- Cavern: 65m long, 8m wide/high. Shaft: 88m deep, 9.1m diameter.
- The FPF is completely decoupled from the LHC (no connecting tunnel), requires no modifications to the LHC.



COST AND TIMELINE

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

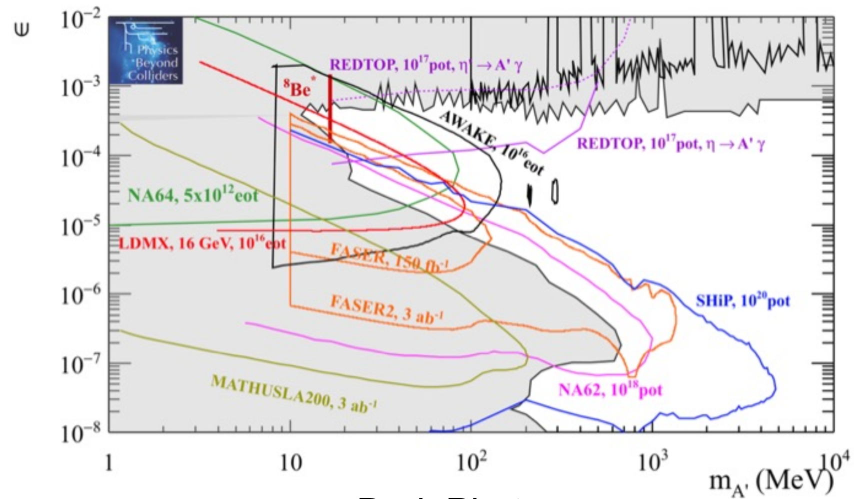
- Possible timeline presented at Chamonix workshop in February 2022.



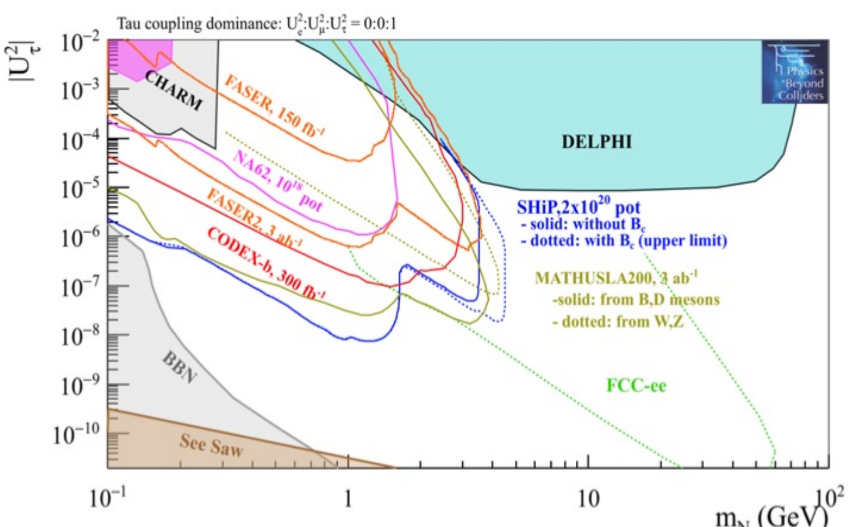
DARK SECTOR SEARCHES

- The dedicated detectors have significant discovery potential for a wide variety of dark sector models.
- See Physics Beyond Colliders and LLP WG studies (and previous talk of Gaia).

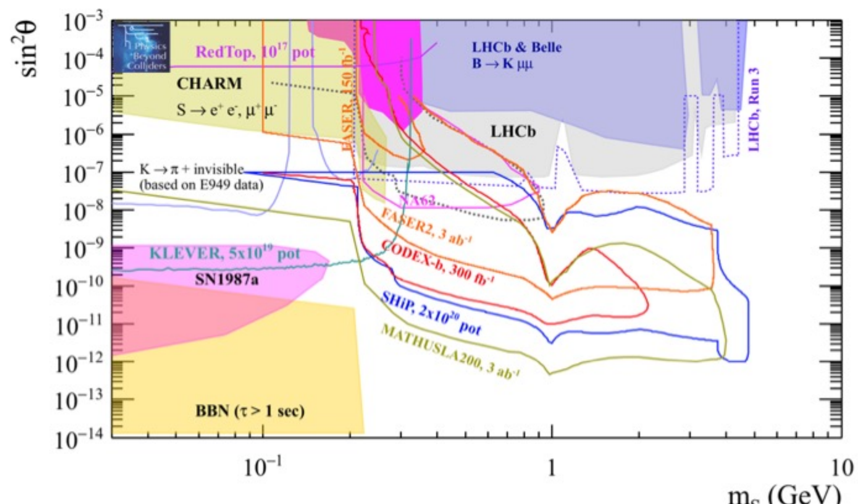
Beacham et al. ([1901.09966](https://arxiv.org/abs/1901.09966))
Alimena et al. ([1903.04497](https://arxiv.org/abs/1903.04497))



Dark Photon



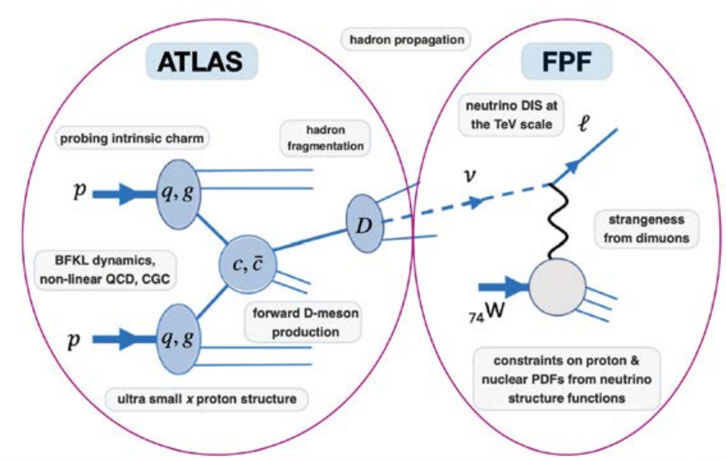
Dark Fermion



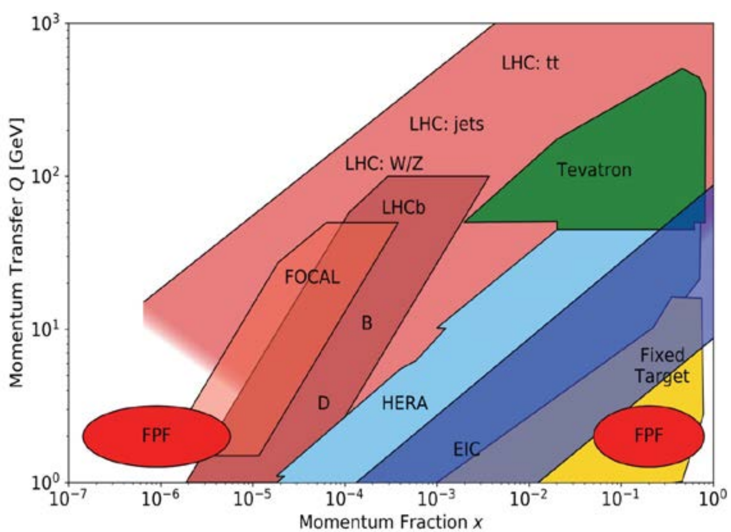
Dark Scalar

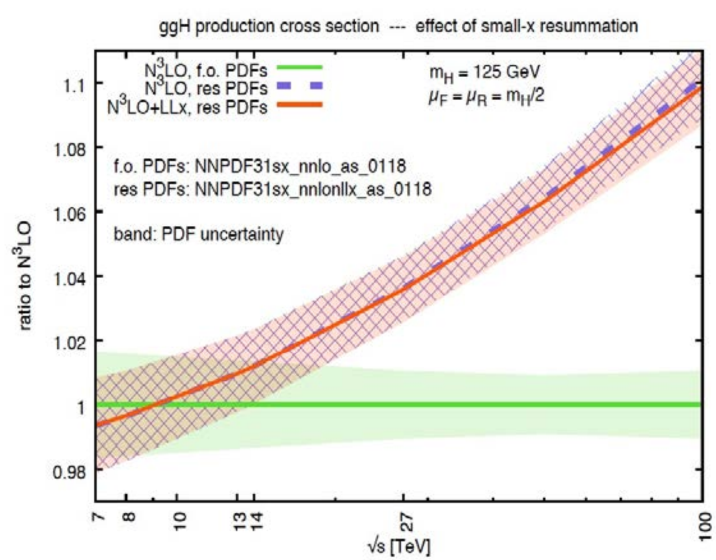
NEUTRINO AND QCD PHYSICS

- Focused here on dark sectors, but there is a rich, complementary SM physics program.
- Neutrinos: see previous talk of Brian.
- QCD: FPF will probe proton structure at ultra small x ~ 10^{-7} and also high x ~ 1.
- Of great interest for astroparticle physics and future colliders, e.g., in making precise predictions for $\sigma(gg \to h)$ at a 100 TeV.



FPF White Paper (2203.05090)

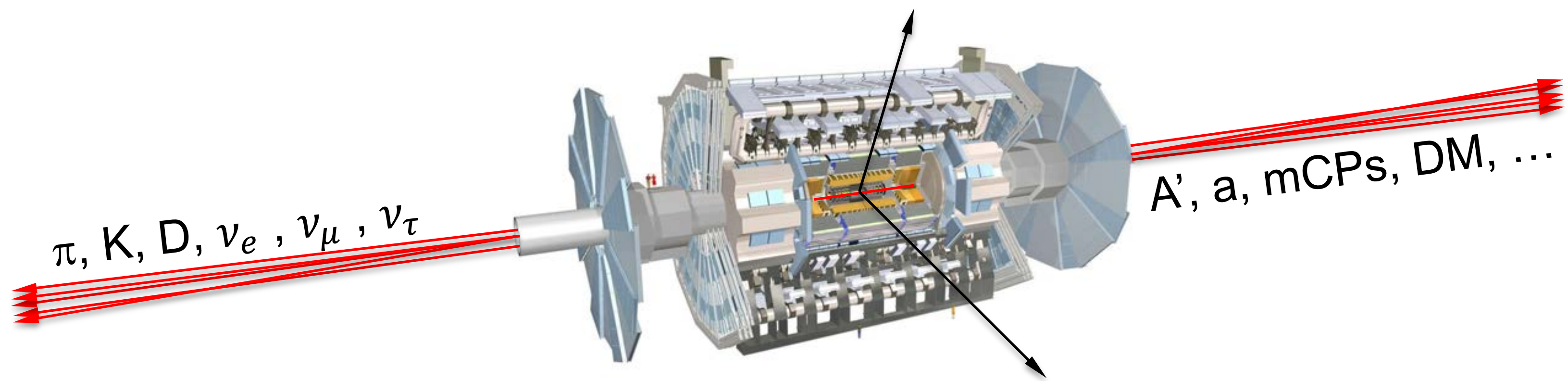




SUMMARY

- Dark sectors, and weakly-interacting light particles in general, represent half of the discovery potential at the energy frontier.

- We are currently missing physics opportunities at the LHC: neutrinos and QCD for sure, and maybe also the discovery of BSM physics.

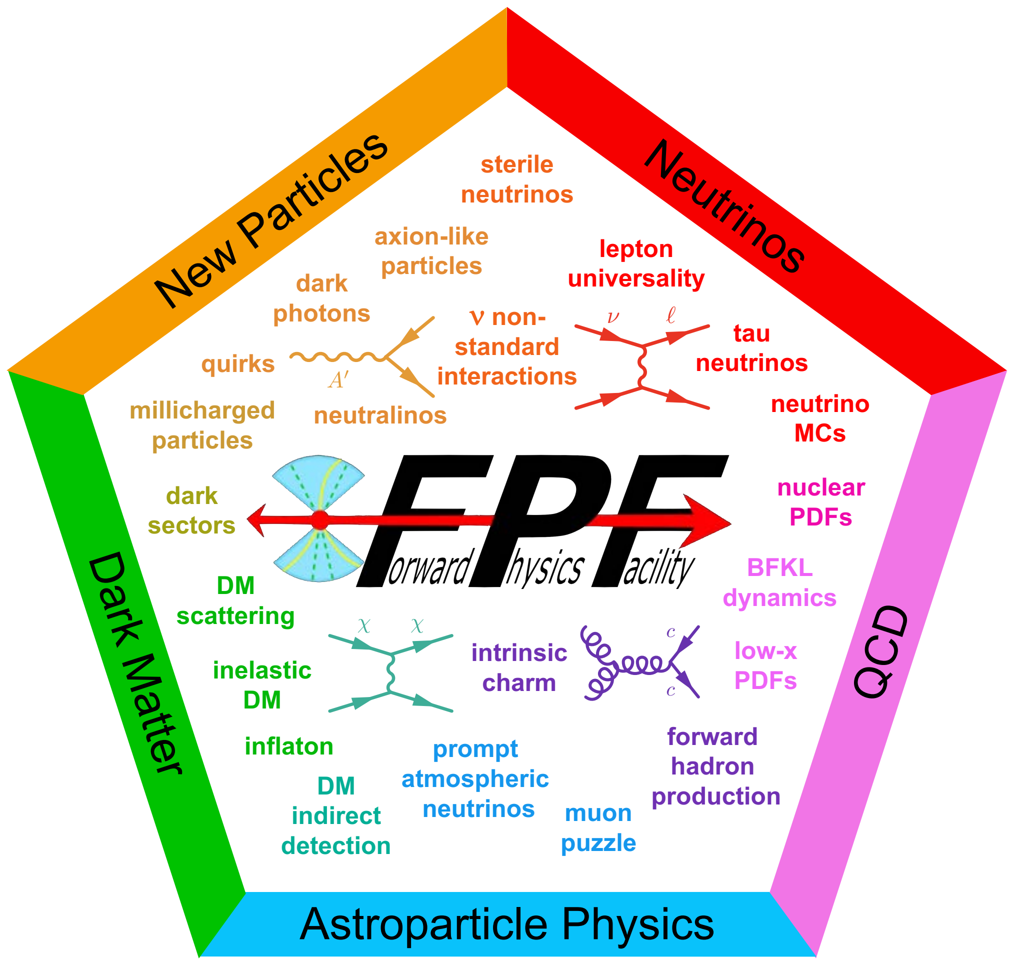


- With timely preparation and relatively small investments, we can cover these blind spots, with potentially strong implications for future plans for all of particle physics.

BACKUP

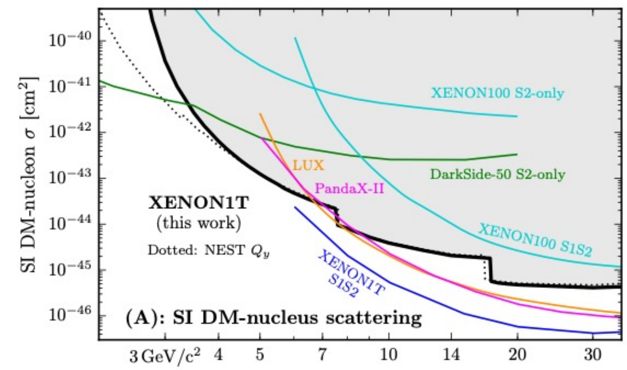
FPF PHYSICS

- The FPF is a general purpose facility with a broad SM and BSM physics program that expands on the physics of the current experiments FASER, FASERν, and SND@LHC. See the FPF White Paper (2203.05090) .

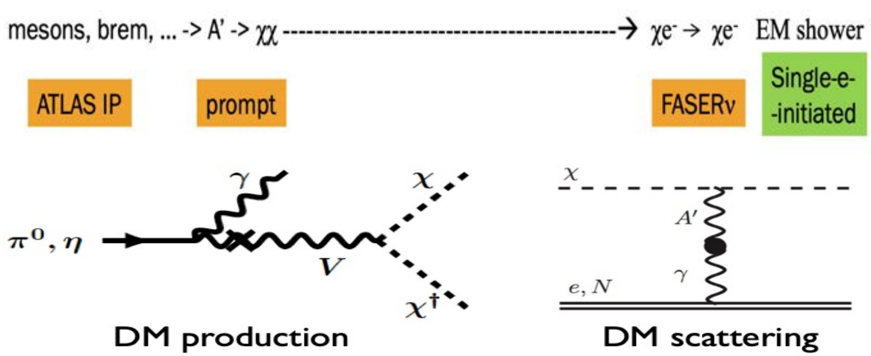


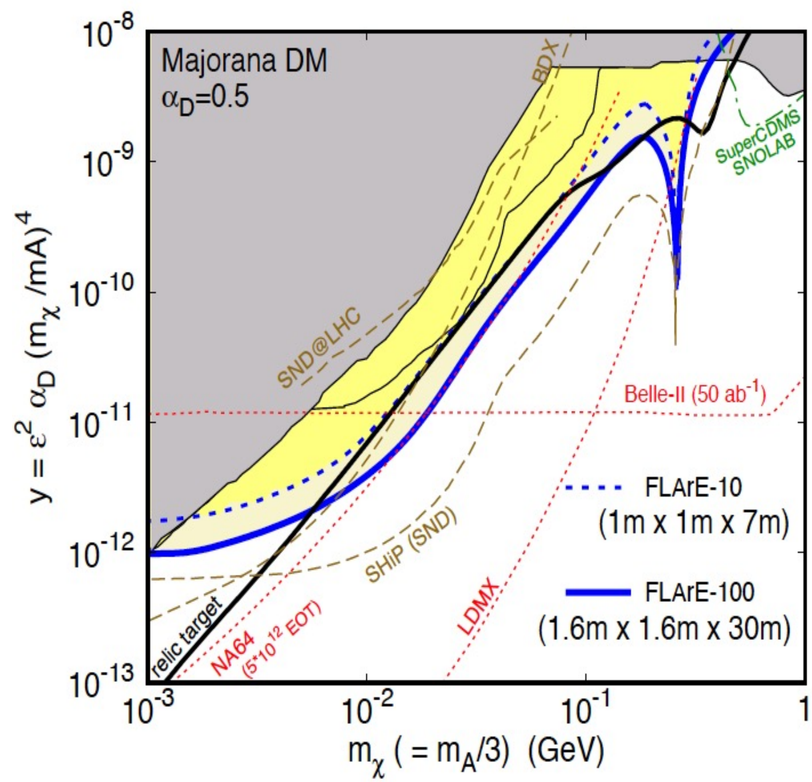
DARK MATTER

- 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.



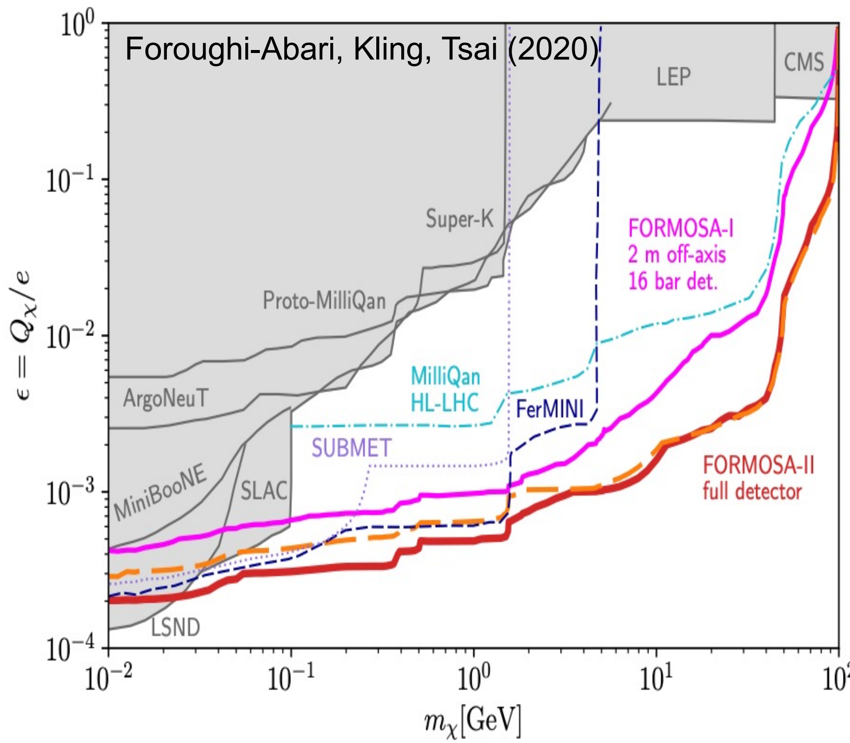


Batell, Feng, Trojanowski (2021)

- FLArE is powerful in the region favored/allowed by thermal freezeout.

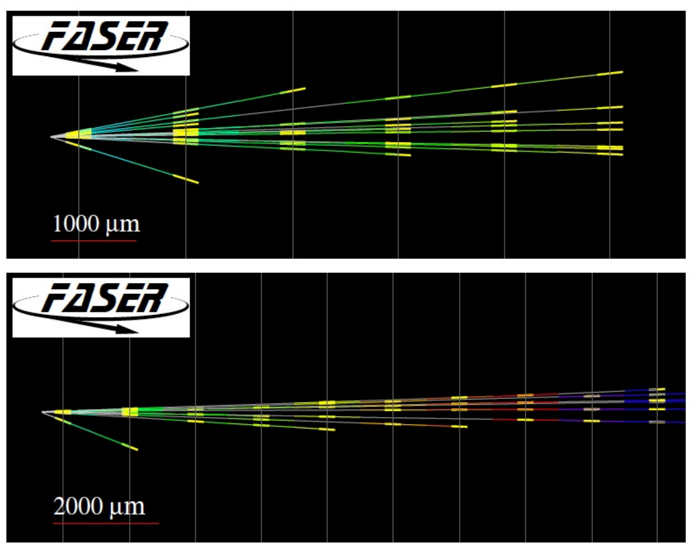
MILLI-CHARGED PARTICLES

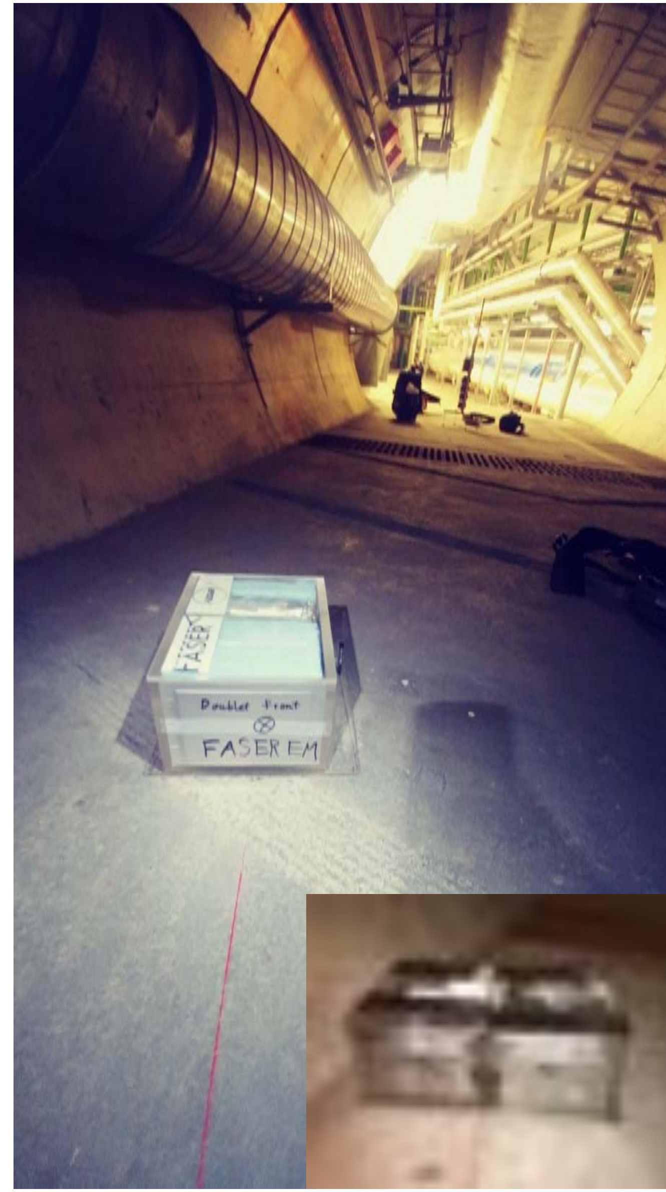
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a “non-forward” tunnel.
- The MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan can also run in this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



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.





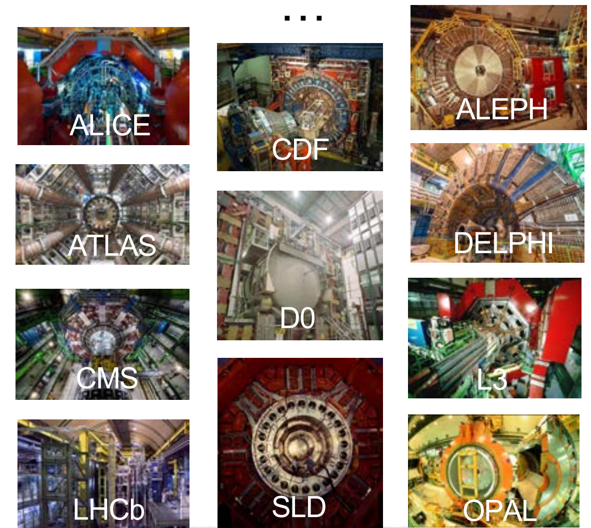
LOCATION, LOCATION, LOCATION

FASER Pilot Detector

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

6 candidate neutrinos

…



All previous
collider detectors

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

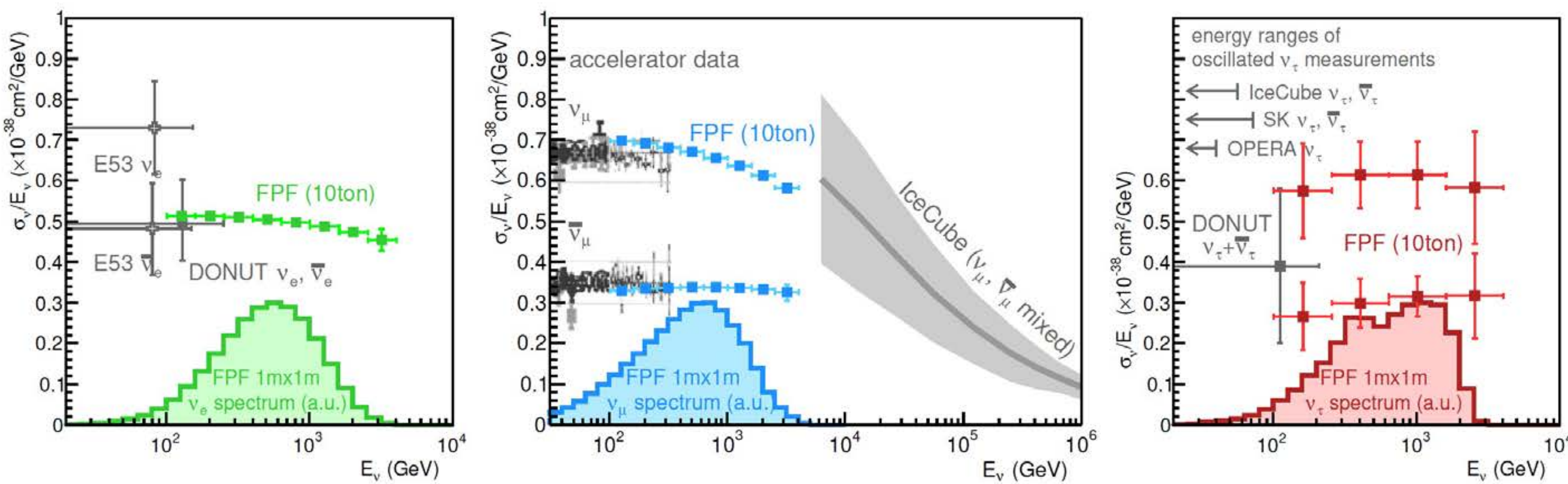
0 candidate neutrinos

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)