# BRIEF SUMMARY AND CURRENT STATUS

Jonathan Feng and Jamie Boyd

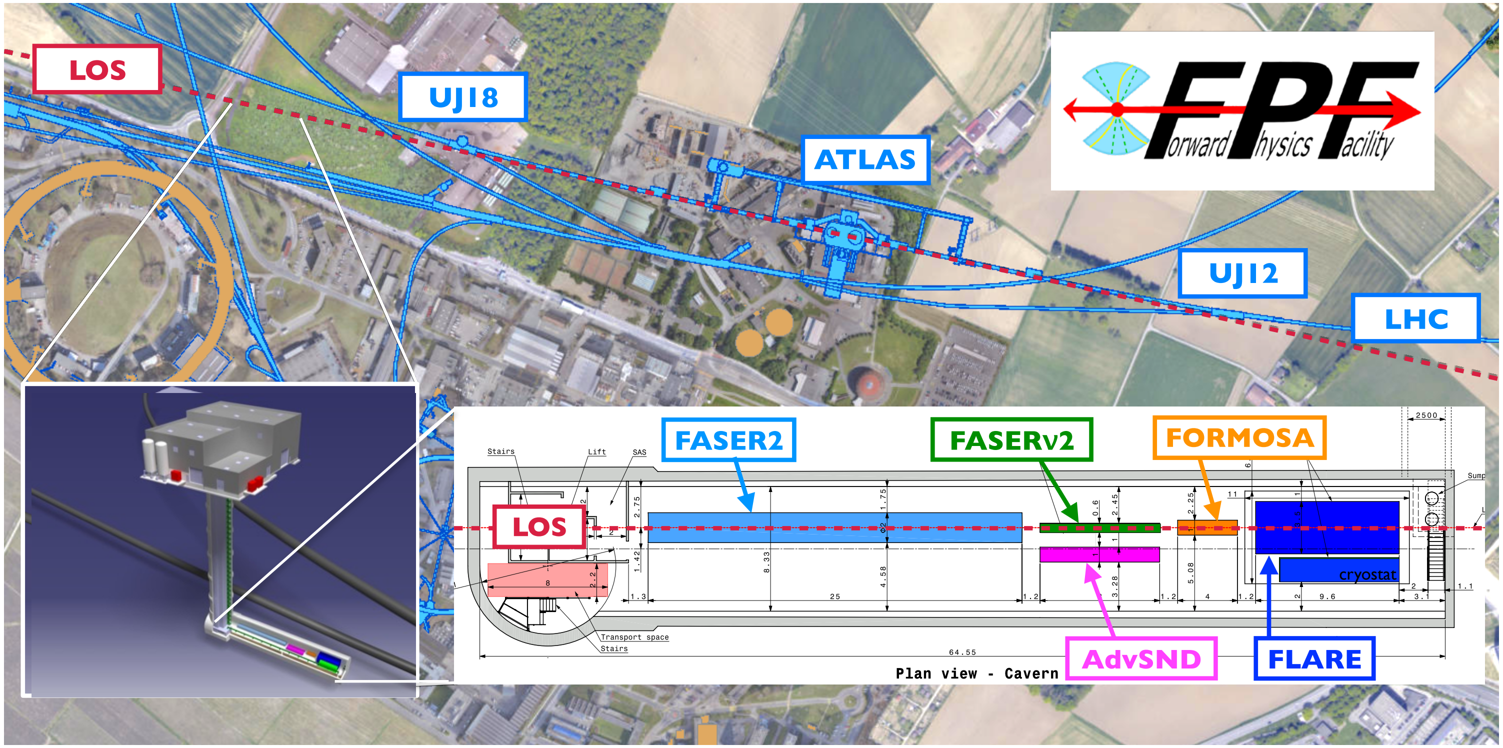
30 June 2022

# FPF TIMELINE SO FAR

- March 2020: COVID shuts down CERN. Fabiola encourages taking this opportunity to think about the future.
- May 2020: Jonathan presents basic idea of the FPF at a FASER Collaboration meeting.
- August 2020: Snowmass LoI signed by ~10% of Snowmass participants.
- September 2020: CERN PBC civil engineering studies begin (PBC FPF subgroup chaired by Jamie set up in March 2021).
- Nov 2020, May 2021, Oct 2021, Jan 2022: 4 dedicated, interdisciplinary (and highly interactive!) meetings to develop the FPF's potential. 5 exciting themes emerge: BSM physics, neutrinos, QCD, dark matter, and astroparticle physics.
- FPF Short Paper: 75 pages, 80 authors, 2109.10905, Phys. Rept. 968, 1 (2022).
- FPF Snowmass White Paper: A 429-page, 392-author+endorser summary, Feng, Kling, Reno, Rojo, Soldin et al., 2203.05090, to appear in J. Phys. G.

# 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 on CERN land in France: ~620-680 m west of the ATLAS IP, shielded by ~200 m of rock.
- Cavern is 60 m-long, 8 m-wide, disconnected and 10 m from the LHC.
- Preliminary costing (Class 4): 25 MCHF for CE, 13 MCHF for services.



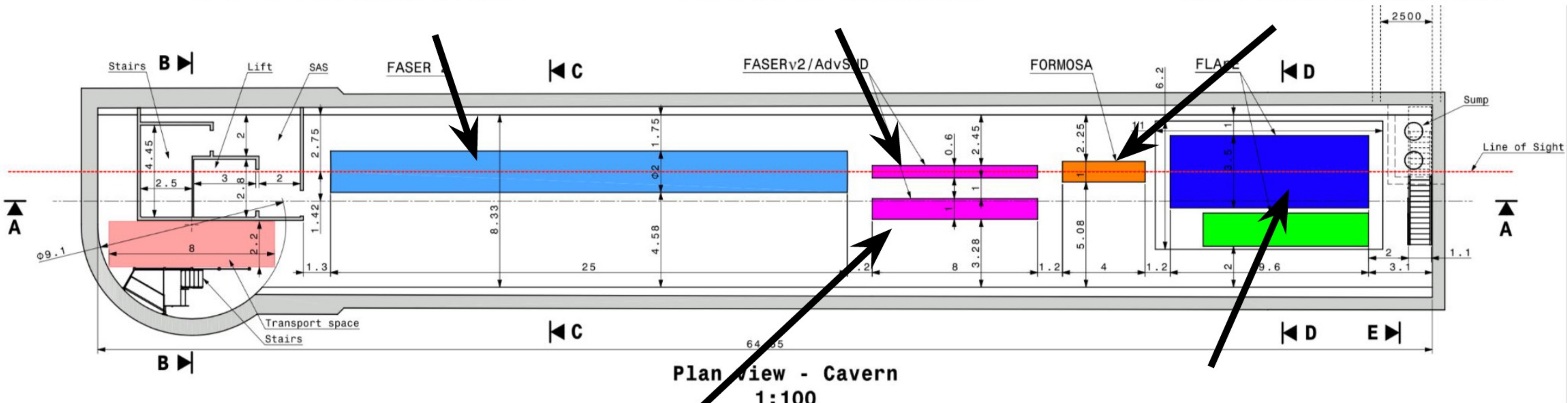
# FPF EXPERIMENTS

- 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

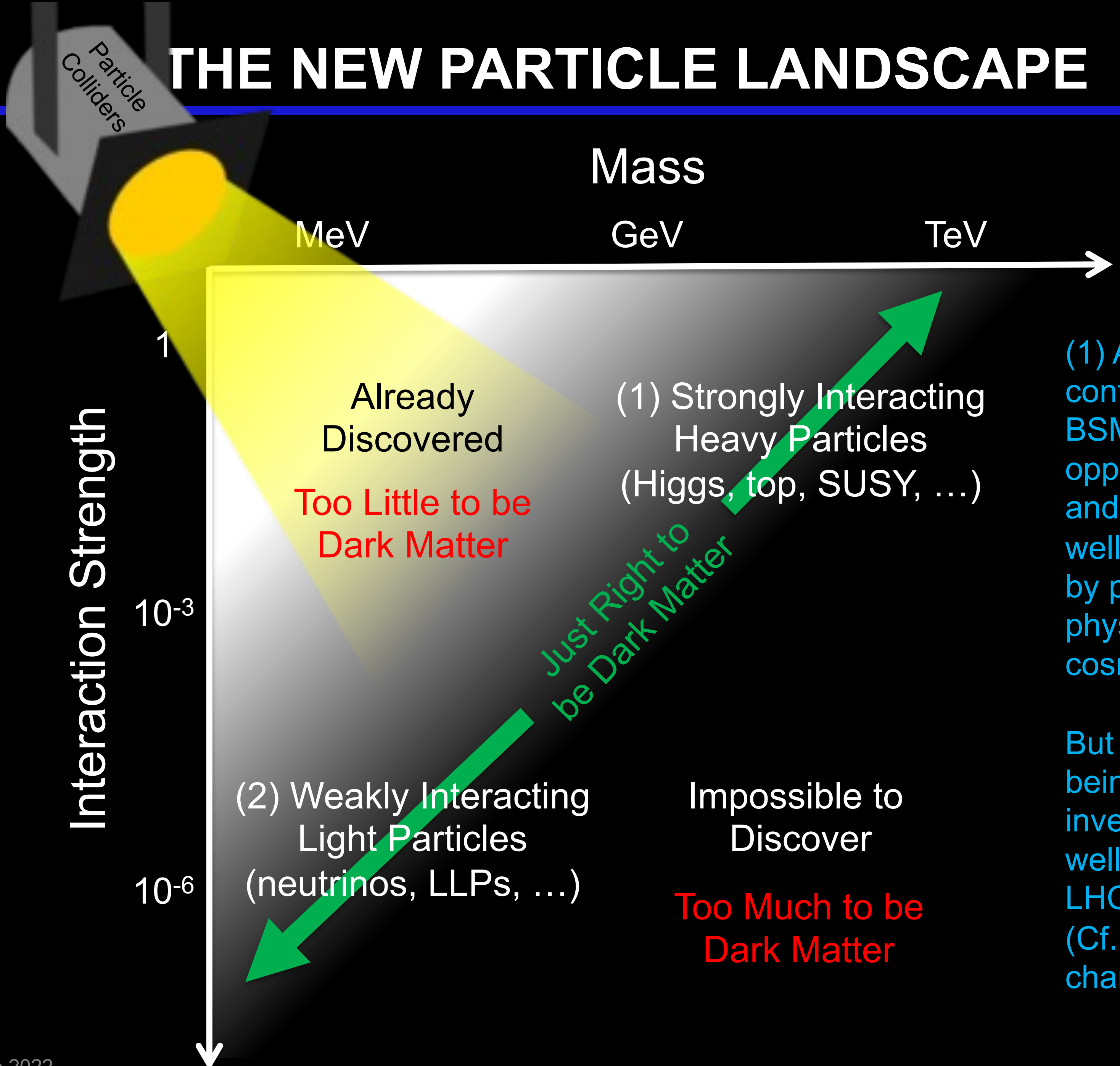



**AdvSND**
electronic
neutrino detector

**FLArE**
LAr based
neutrino detector

Kling (2022)

# THE NEW PARTICLE LANDSCAPE

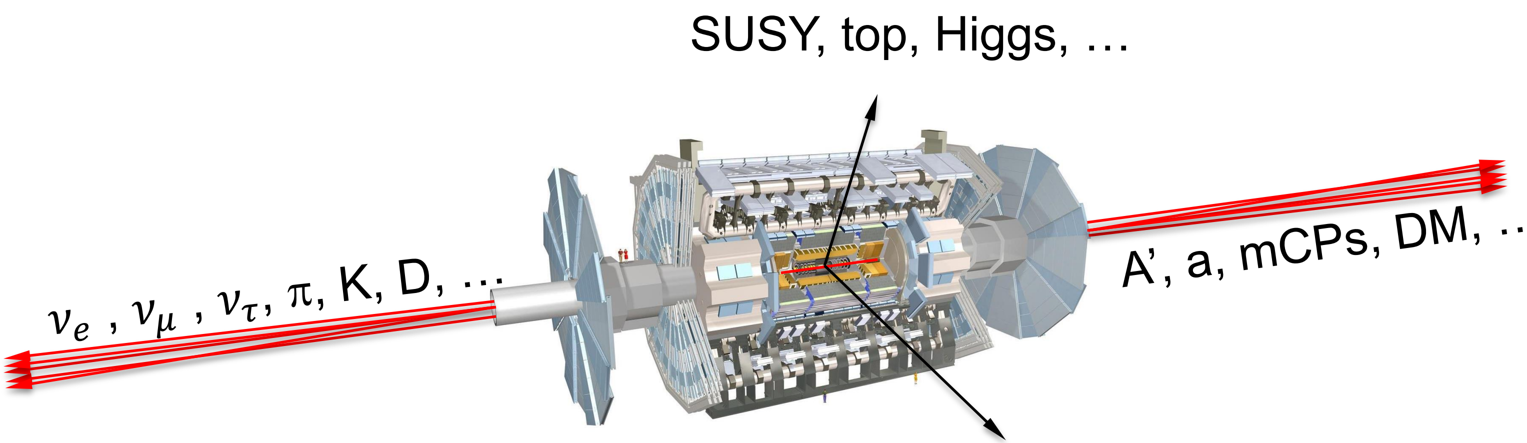



(1) And (2) both contain SM and BSM opportunities, and both are well motivated by particle physics and cosmology.

But only (1) is being investigated well by current LHC detectors. (Cf. ISR and charm.)

# SEARCHES FOR NEW LIGHT PARTICLES

- The existing large LHC detectors were designed to find strongly interacting heavy particles. Particles with $\eta > 4.5$ escape down the beampipe.

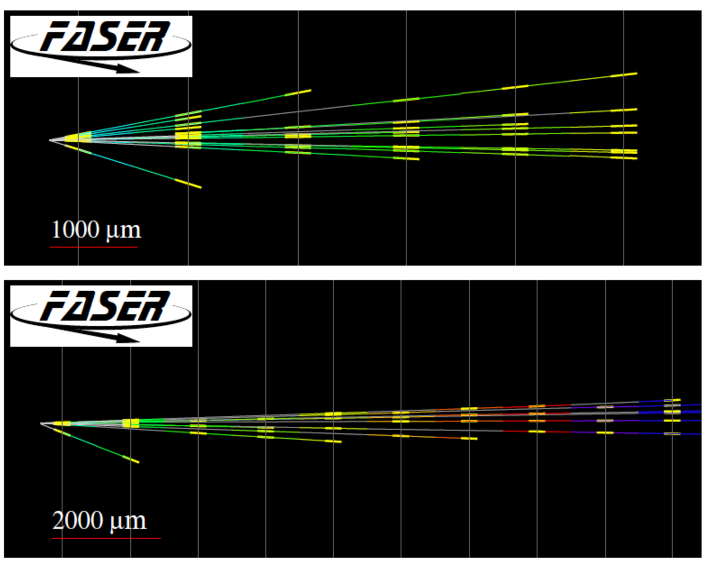



- There is therefore a rich and unexplored physics program in the far forward direction for weakly interacting light particles.
  - SM: TeV neutrinos of all flavors at the highest energyies from a human-made source. Neutrinos also enable probes of QCD, proton and nuclear structure.
  - BSM: world-leading sensitivities to LLPs, FIPs, dark sectors, including dark photons, axion-like particles, milli-charged particles, dark matter, …

# PROOF OF PRINCIPLE: $1^{ST}$ COLLIDER NEUTRINOS

- In 2018 an 11 kg emulsion detector was placed on the beam collision axis for 4 weeks, collecting 12.2 $fb^{-1}$ (installed and removed during TSs).

- In May 2021, the FASER Collaboration announced the direct detection of 6 candidate neutrinos above the expected neutral hadron background events ($2.7\sigma$).



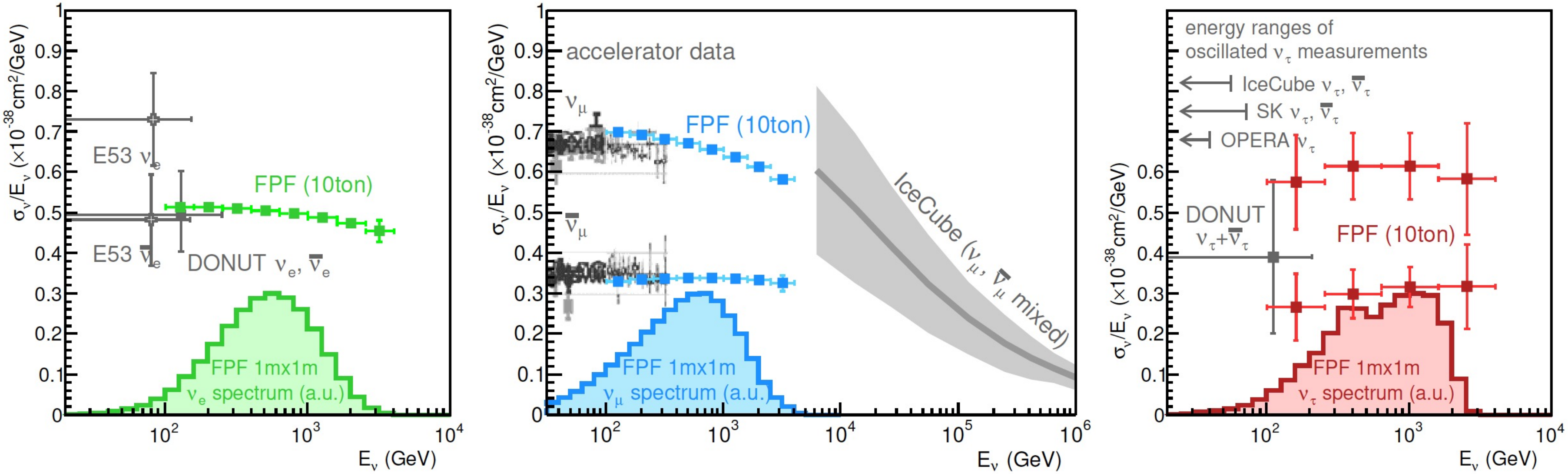

FASER Collaboration (2105.06197)

# 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.

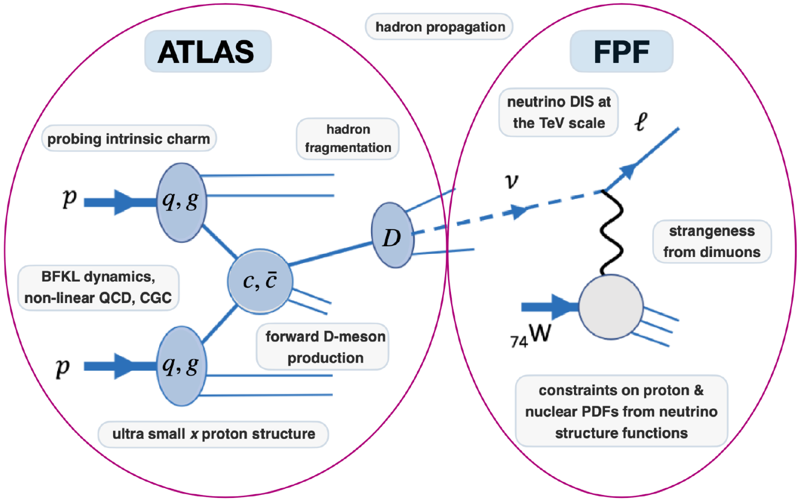
- Can also distinguish neutrinos and anti-neutrinos for muon and tau.

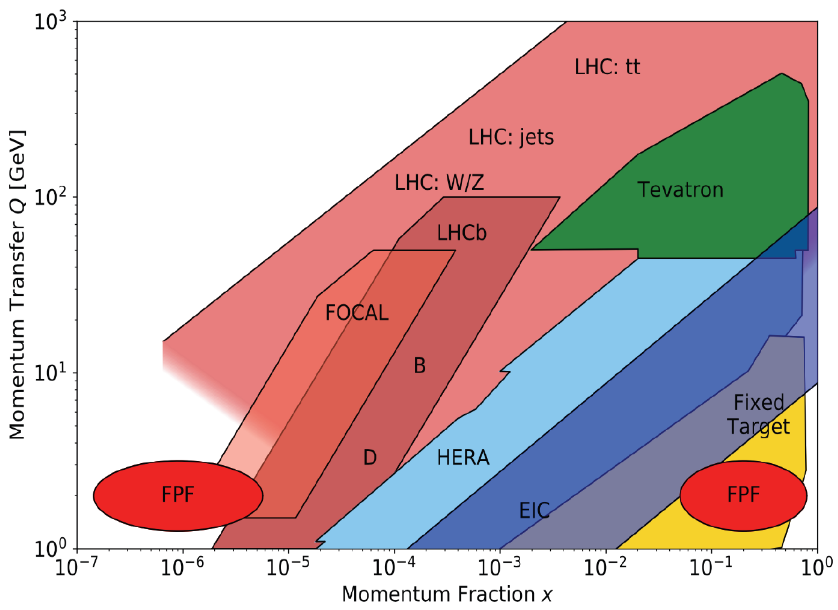


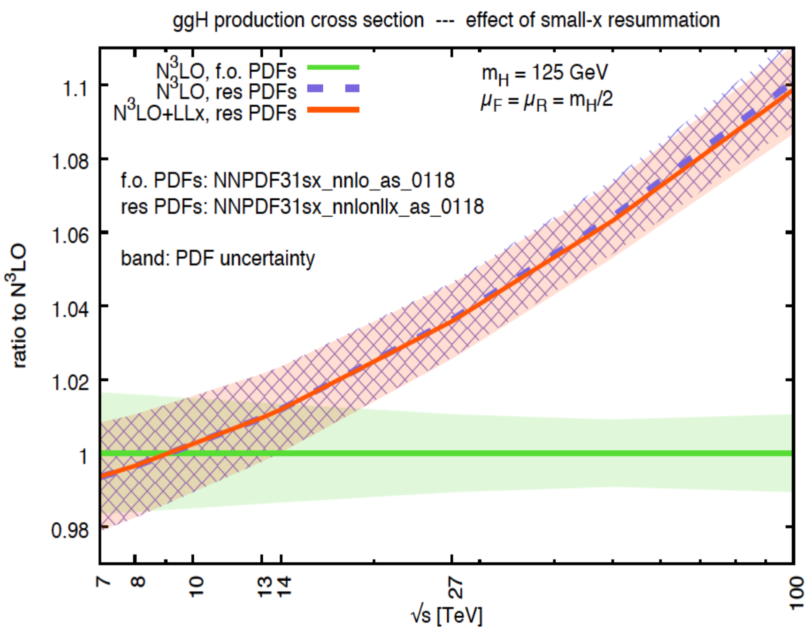

FASER White Paper (2022)

# QCD

- The FPF will also support a rich program of QCD and hadron structure studies.
- Forward neutrino production is a 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, 100 TeV pp collider, …



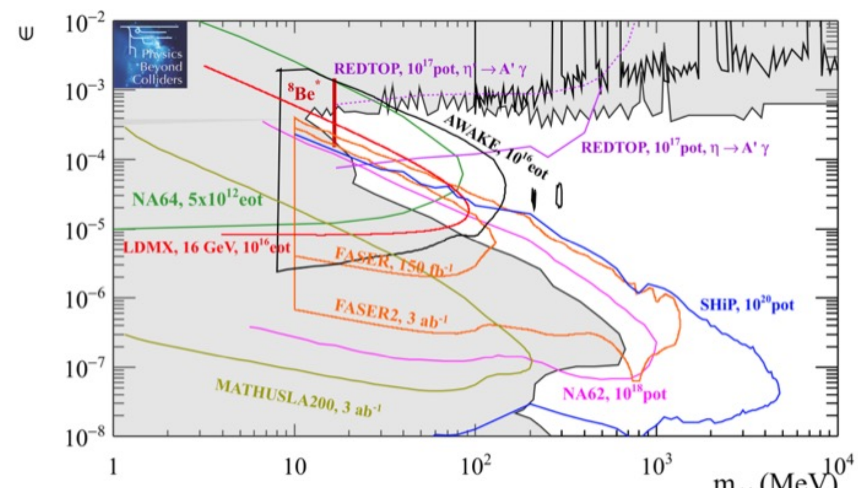




FASER White Paper (2022)

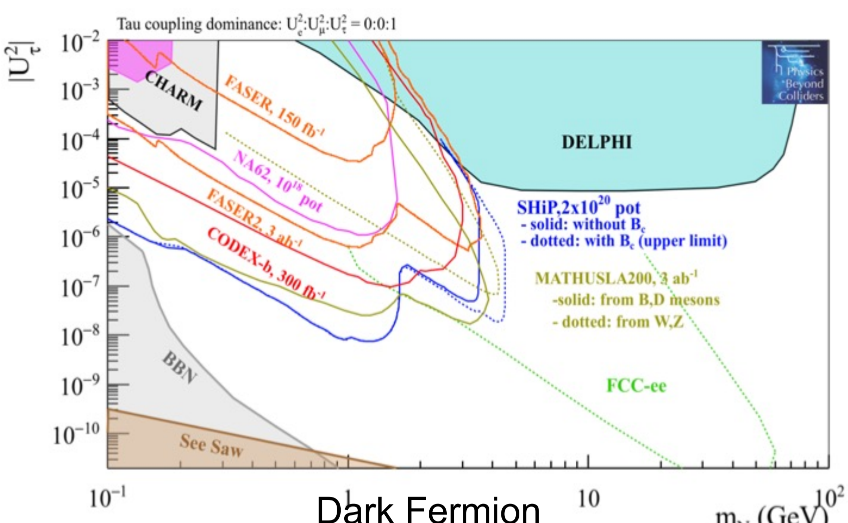
# DARK SECTOR SEARCHES

- 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, inflatons, relaxions, and many others.

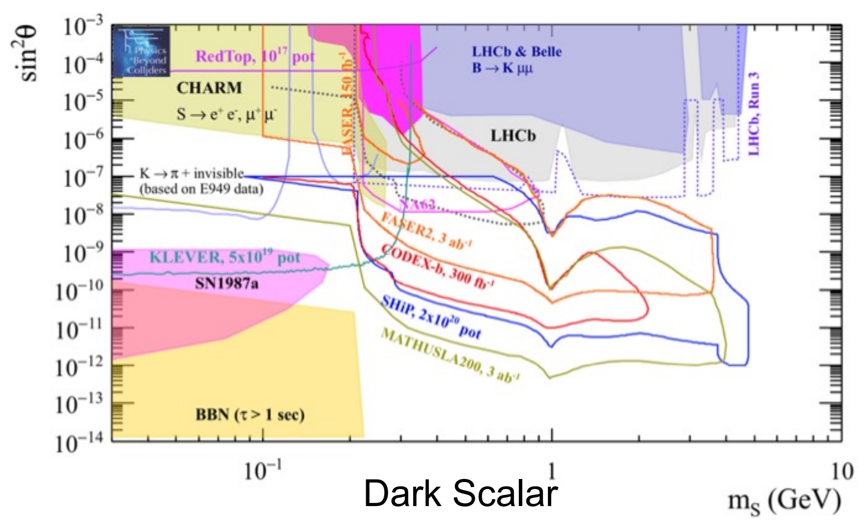
FPF White Paper (2022)




Dark Photon



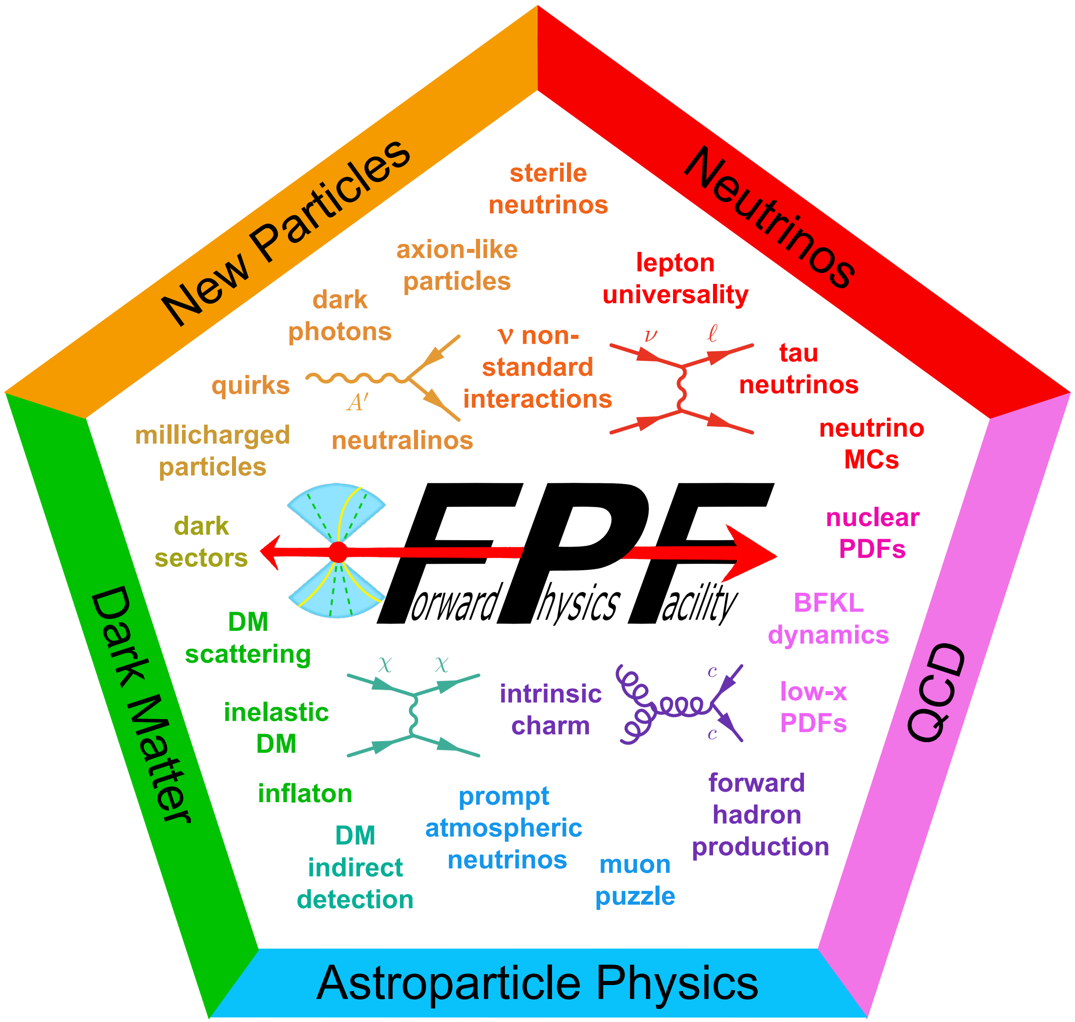

Dark Fermion




Dark Scalar

# FPF PHYSICS SUMMARY

- The FPF is a general purpose facility with a broad SM and BSM physics program. Additional examples are in the White Paper and backup slides.



# FUNDING AND TIMELINE

- A possible split: CERN supports construction of the facility…
  - Very preliminary (class 4) cost estimate: 23 MCHF (CE) + 15 MCHF (services) ≈ 40 MCHF (+50%/-30%), not including experiments.

- …US DOE, NSF, other funding agencies support R&D and construction of the experiments
  - Recently received 1st funding from the NSF for FASER operations.
  - Recently received 1st funding from Heising-Simons Foundation and Brookhaven LDRD for FLArE R&D.

- Timeline considerations presented by Jamie at Chamonix workshop (Feb 2022):
  - Can access FPF while LHC is running (no connector, RP studies ongoing).
  - Experiments can come online a different times with relatively little interference.
  - Possible timeline
    - LS3: pure CE works
    - Beginning of Run 4: installation of services (CERN teams busy during LS3).
    - Middle of Run 4: installation and commissioning of experiments.
    - End of Run 4 to end of HL-LHC: Physics in time to benefit from most of HL-LHC luminosity, impact planning for FCC and future colliders.

# NEAR-TERM GOALS

- CDRs for FPF and the 5 experiments in the next 6-12 months
  - FASER2, FASERnu2, AdvancedSND, and FORMOSA (advanced MilliQan) build on existing experiments and existing collaborations.
  - FLArE, the most novel experiment, has recently received 1st funding for R&D from the Heising-Simons Foundation and Brookhaven LDRD.
  - CE studies for the Facility can progress quickly once experiments are better defined.

- Support from US Snowmass and P5
  - There is already a significant and growing potential users community for the FPF (400 authors/endorsers for the FPF white paper).
  - Strong recommendations from many Snowmass subgroups: Energy Frontier QCD, Energy Frontier BSM, Neutrino Frontier, Rare Process Frontier, Cosmic Frontier, …
  - But are facing bias of Snowmass organizers toward “US projects,” questions about CERN interest.

- Support from CERN
  - Organizational structure (proto-collaborations) put in place in the next few months: would be very helpful to have CERN’s blessing to move from current PBC structure to a more formal level of organization.
  - Submit expression of interest to LHCC?
  - Set timeline and structure for review and possible approval of the FPF, include FPF in discussions of ECN3 and related projects.  HL-LHC sets a hard deadline.

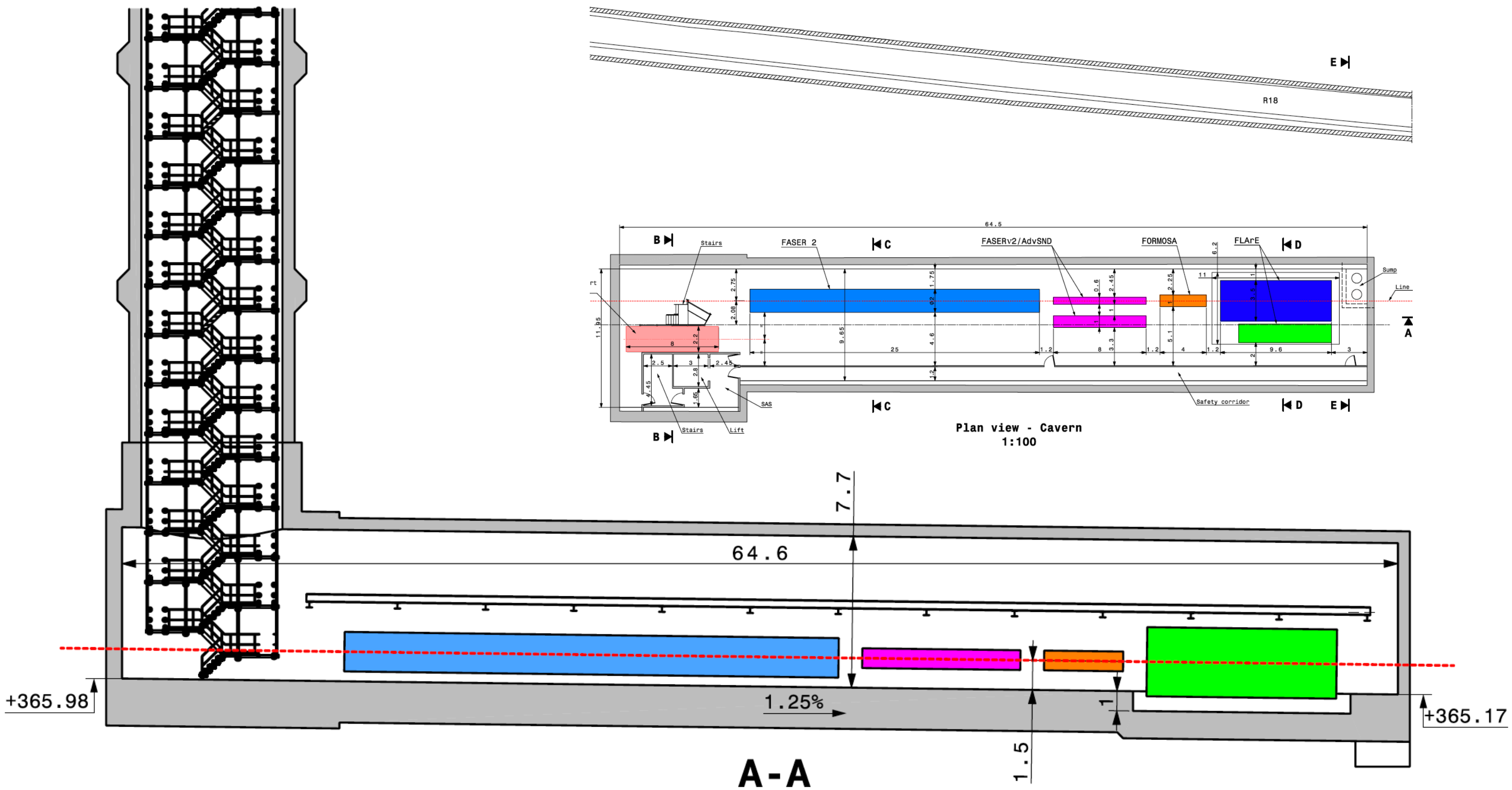
# BACKUP

# ISR AND CHARM

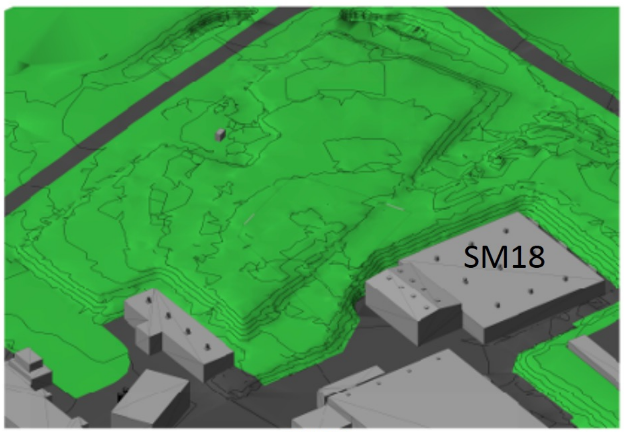
- For the 50th anniversary of the ISR, there were many fascinating articles and talks by eminent physicists looking back on the ISR's legacy.
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at 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).
- Bottom line: charm was missed in part because detectors focused on the forward region.
- Are we making the same (but opposite) mistake at the LHC?

# CAVERN AND SHAFT

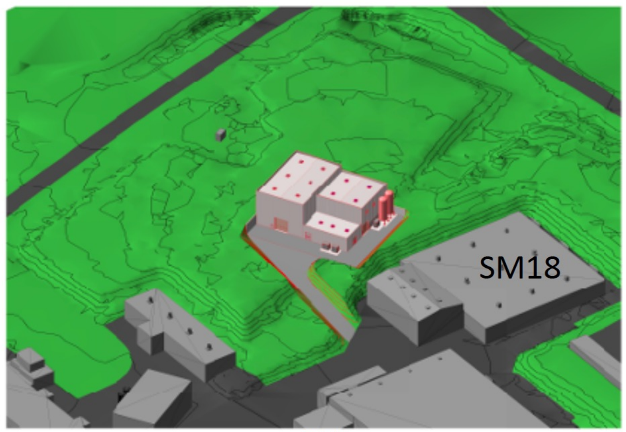
- Cavern: 65m long, 8m wide/high.  Shaft: 88m-deep, 9.1m-diameter.
- The FPF is completely decoupled from the LHC: no need for a safety corridor connecting the FPF to the LHC, preliminary RP and vibration studies indicate that FPF construction will have no significant impact on LHC operation.



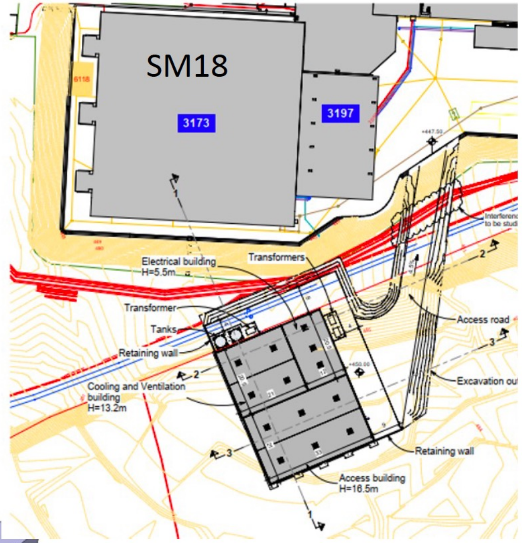
# SURFACE BUILDINGS

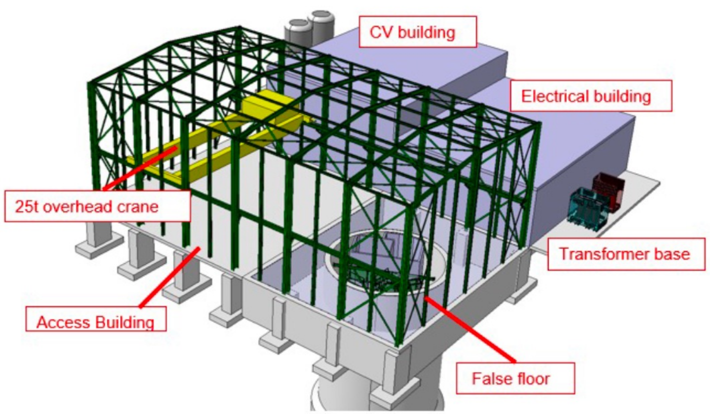


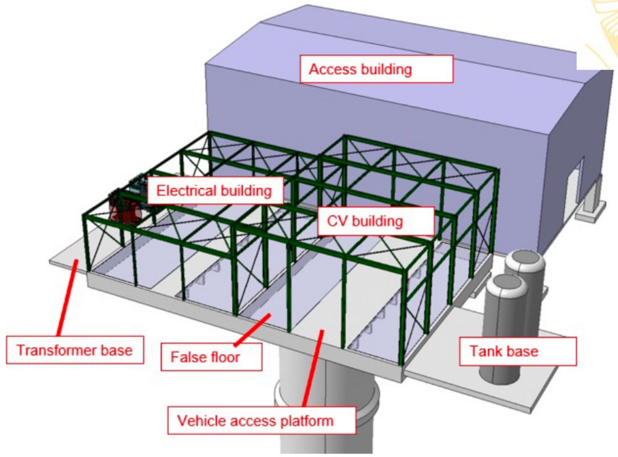

3D EXISTING




3D NEW

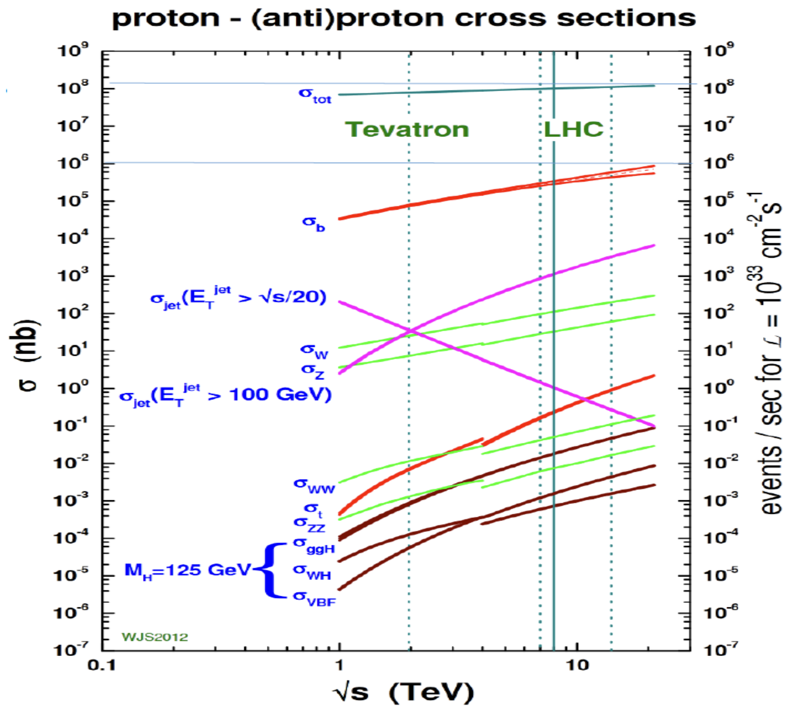


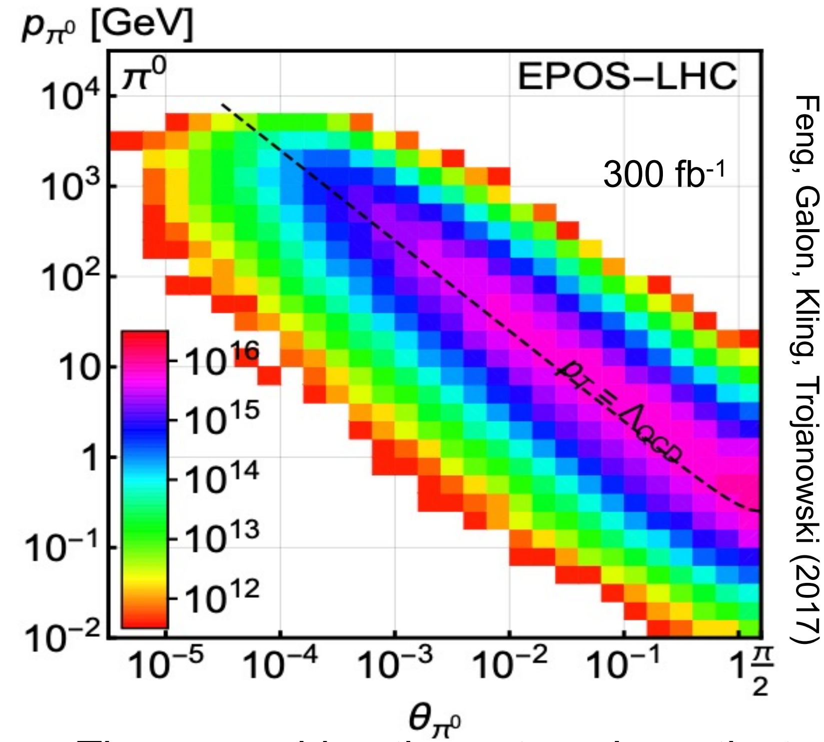




Kincso Balazs,
John Osborne,
CERN CE (2022)

# LIGHT, WEAKLY INTERACTING PARTICLES



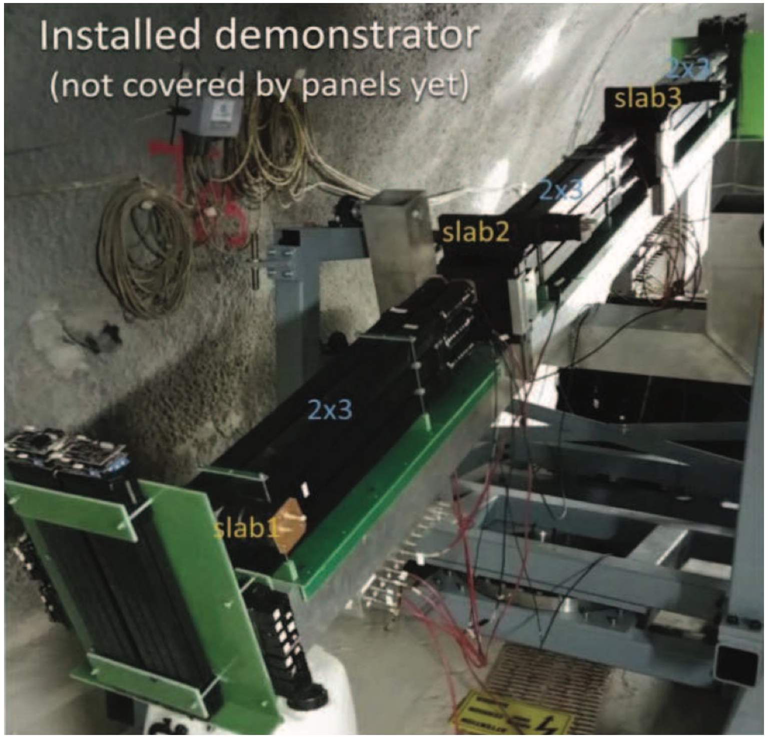

- Most BSM searches focus on σ ~ fb, pb.
- But if the new particles are
  - light → can be produced in decays of light SM particles.
  - weakly-interacting → need large numbers of SM particles to see rare processes.

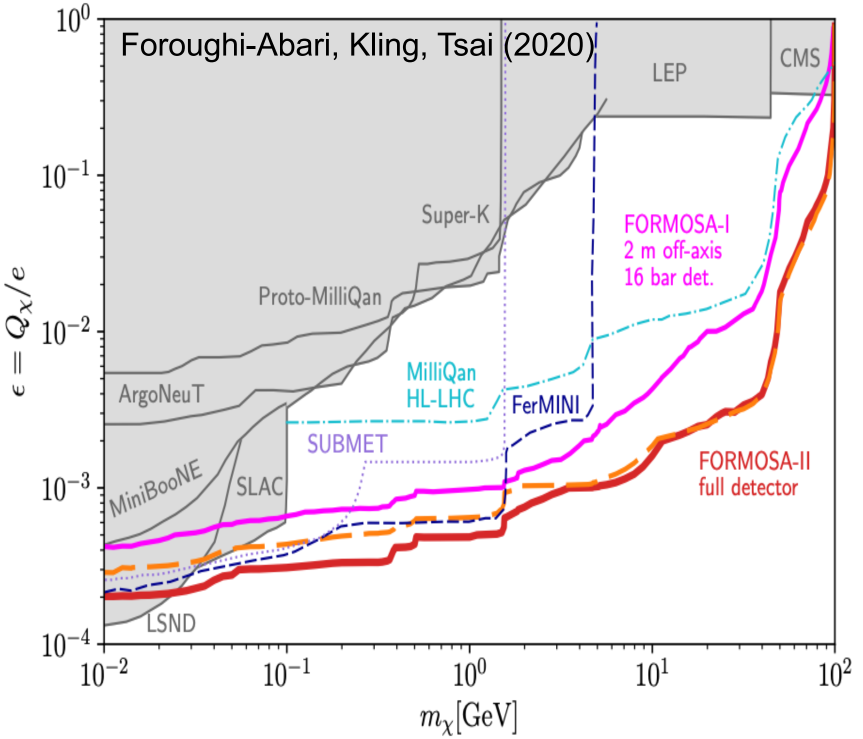
- These considerations strongly motivate considering $\sigma_{\text{tot}}$ ~100 mb, the typically "wasted" cross section for BSM searches.
- Typically low $p_T$, but possibly high $p$.
- The most energetic particles, and most easily detected, are very far forward. E.g., for pions, enormous rates with $p$ ~ TeV with $\theta \lesssim 1$ mrad (η ≳ 7.6).

# 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.

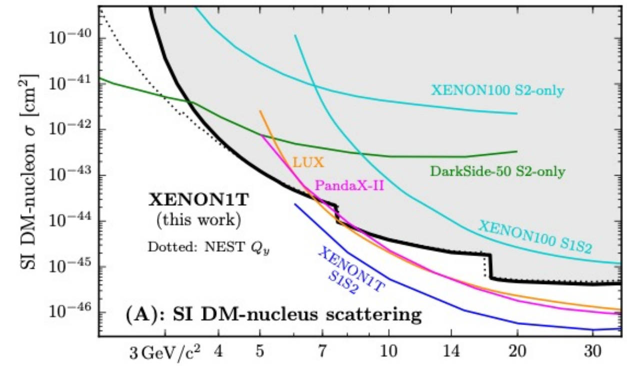
- The MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan can also run in this location in the HL-LHC era, but the sensitivity may be improved significantly by moving it to the FPF (FORMOSA).



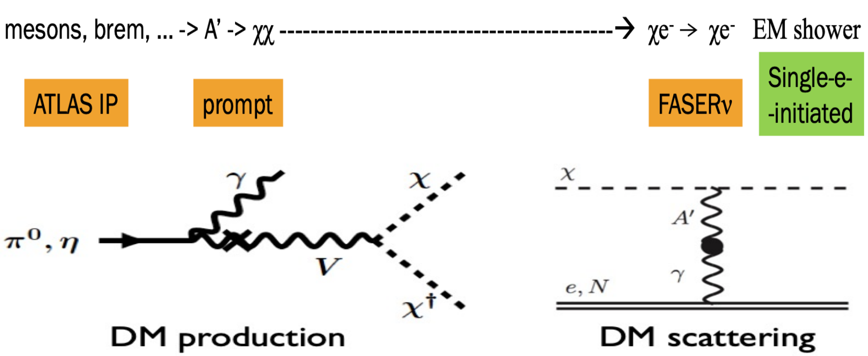



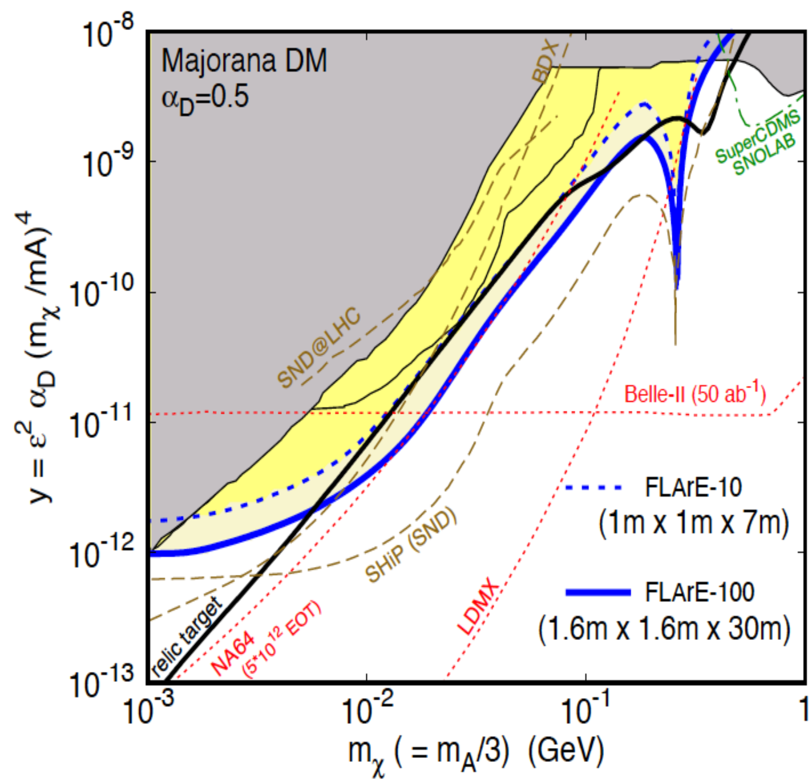
# DARK MATTER DIRECT DETECTION

- 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.



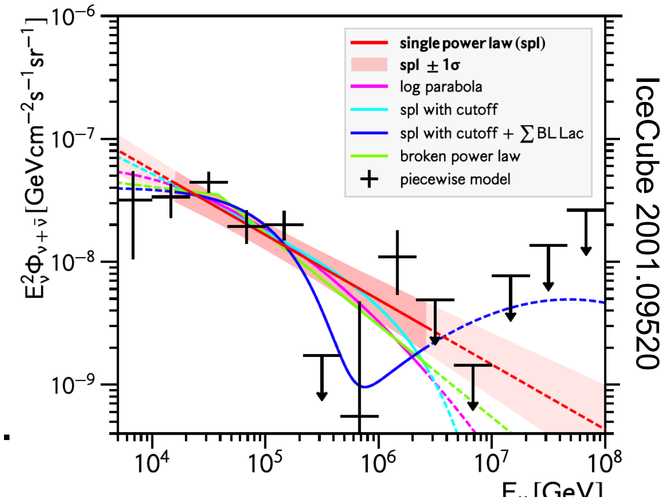

Batell, Feng, Trojanowski (2021)

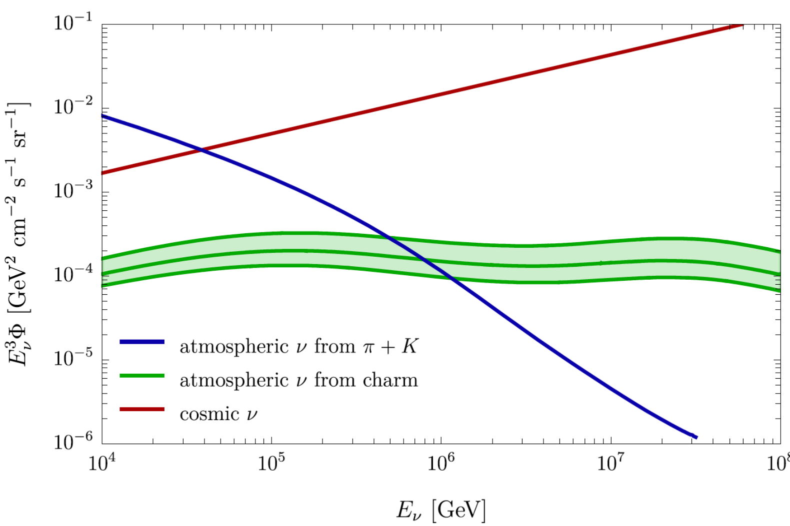
- FLArE is powerful in the region favored/allowed by thermal freezeout.

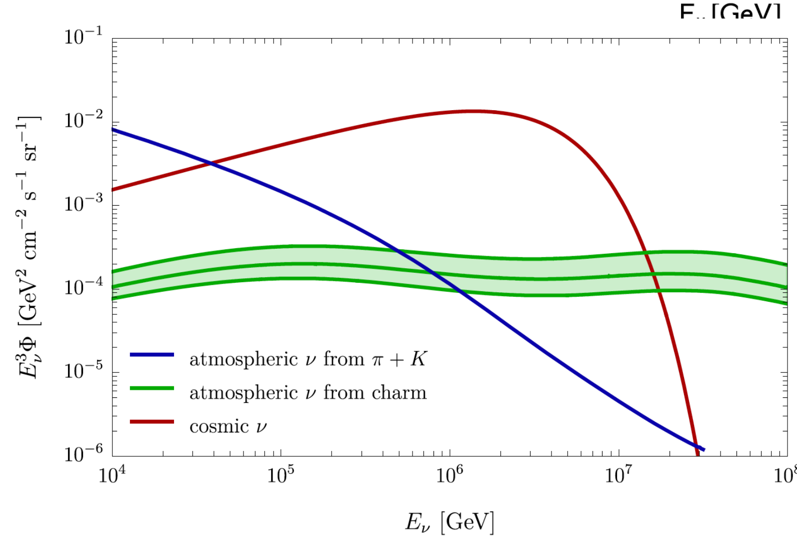
# ASTROPARTICLE IMPLICATIONS

- The current IceCube cosmic neutrino flux can be fit by a power law, a power law with cutoff, etc.

- More data may be able to distinguish these, but only if the atmospheric neutrino background from charm is better determined.




- The neutrino energies of ~$10^7$ GeV are well matched by LHC pp energies ~ 10 TeV. What is required is FPF observations at $\eta$ ~ 6 to 8.