FORWARD PHYSICS FACILITY AT THE LHC

Physics Beyond Colliders Annual Workshop
1-4 March 2021

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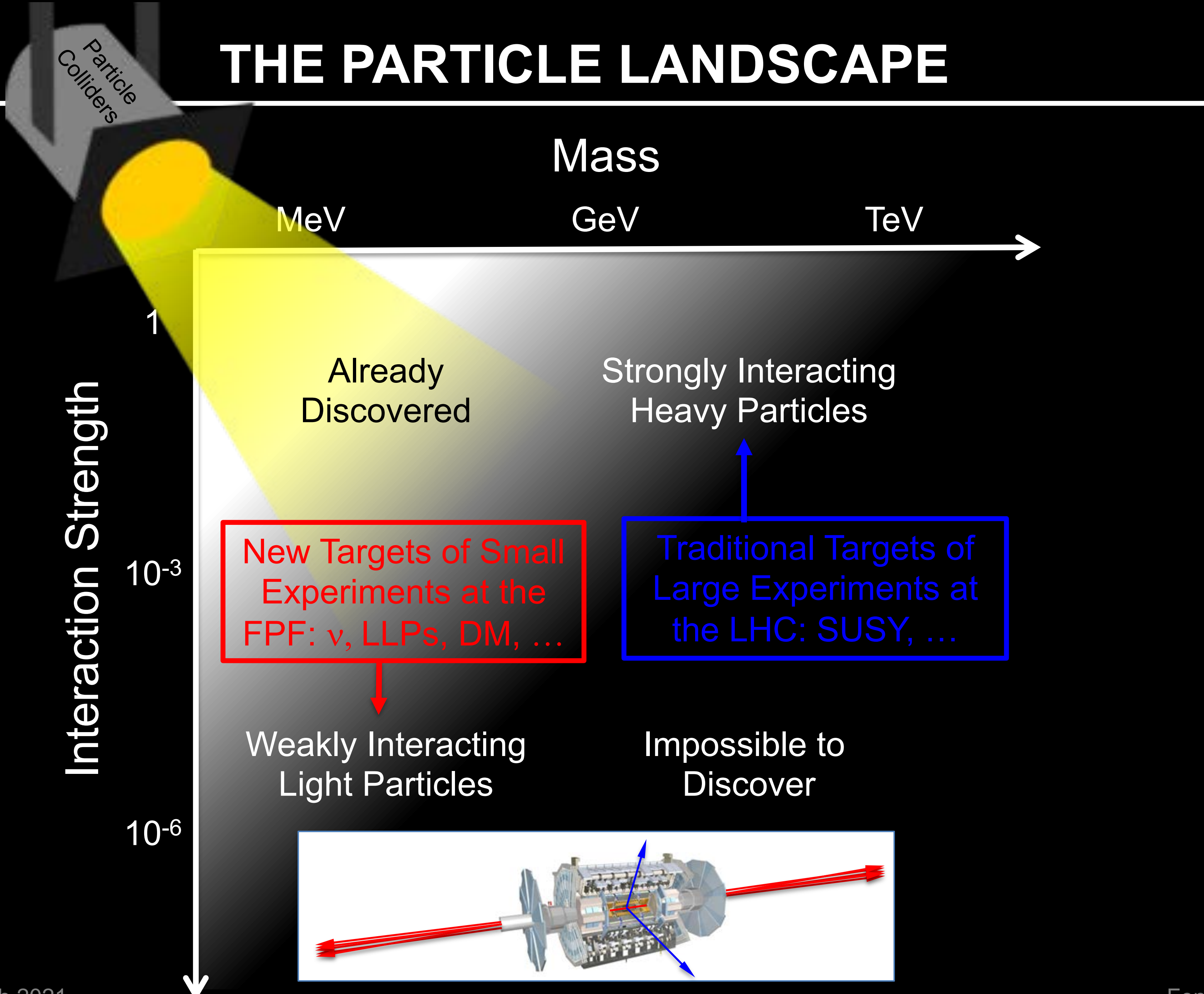
SIMONS FOUNDATION HEISING-SIMONS FOUNDATION UC IRVINE

FORWARD PHYSICS FACILITY

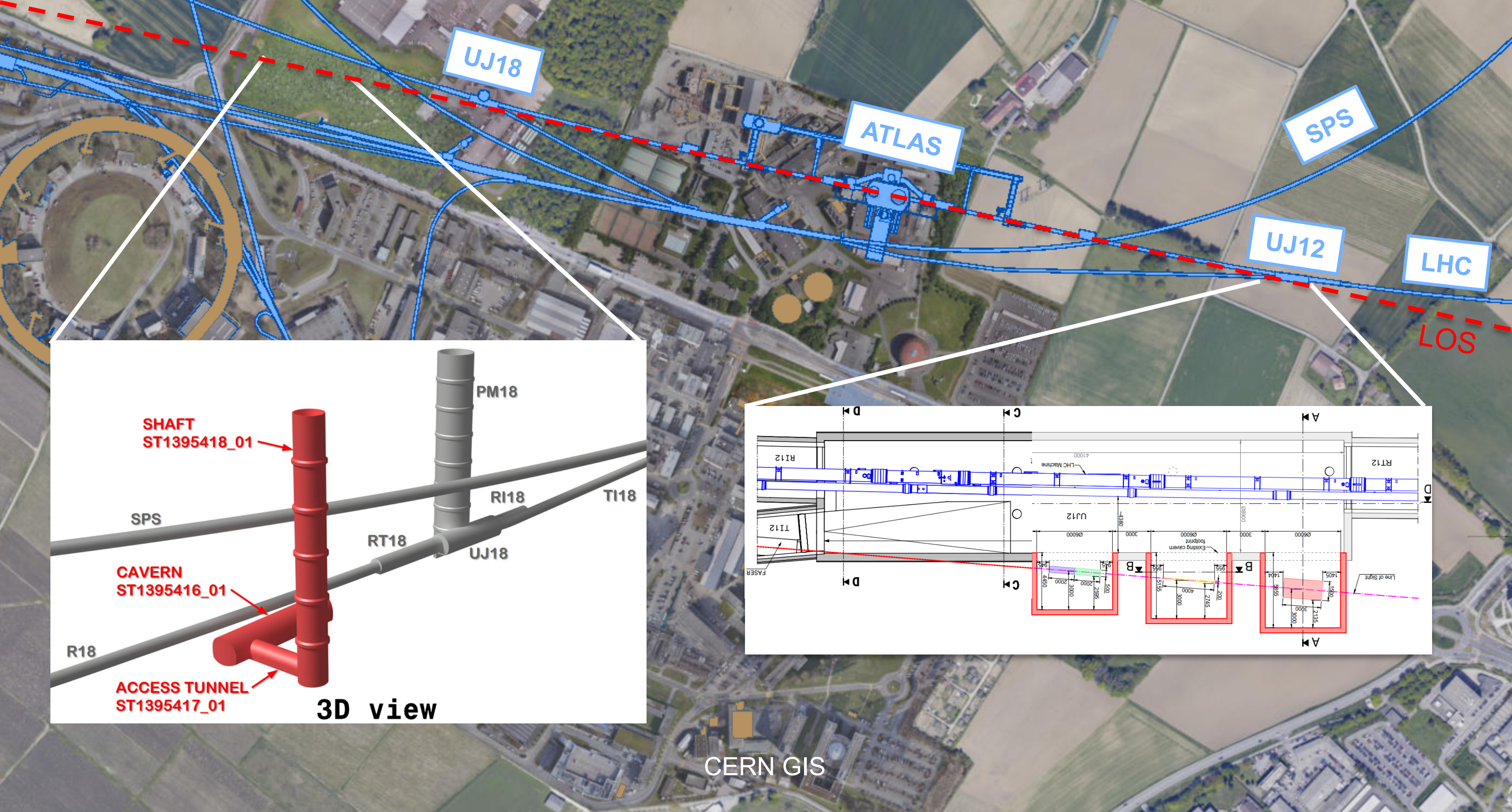
- As the LHC runs at much higher luminosities in the next 15+ years, how can its potential be maximally exploited?
- Upgrades for the HL-LHC era have focused on high p_T / low cross section physics (~fb, pb, nb).
- But the total cross section is ~100 mb, and most of these events (and most of the highest energy particles) are in the far forward region / low p_T.
- In recent years, it has become clear that there is a rich physics program that remains to be explored in the far forward region, and this can be done with relatively little additional investment.
- The proposal: create a Forward Physics Facility for the HL-LHC to house a suite of experiments that will greatly enhance the LHC's potential for both BSM physics (LLPs, FIPs, milli-charged particles, dark matter, dark sectors) and SM physics (neutrinos, QCD, cosmic ray physics).


THE PARTICLE LANDSCAPE
Particle Colliders
Mass
MeV
GeV
TeV
Interaction Strength
1
10-3
10-6
Already Discovered
Strongly Interacting Heavy Particles
New Targets of Small Experiments at the FPF: ν, LLPs, DM, …
Traditional Targets of Large Experiments at the LHC: SUSY, …
Weakly Interacting Light Particles
Impossible to Discover

FPF LOCATION

See John Osborne's talk

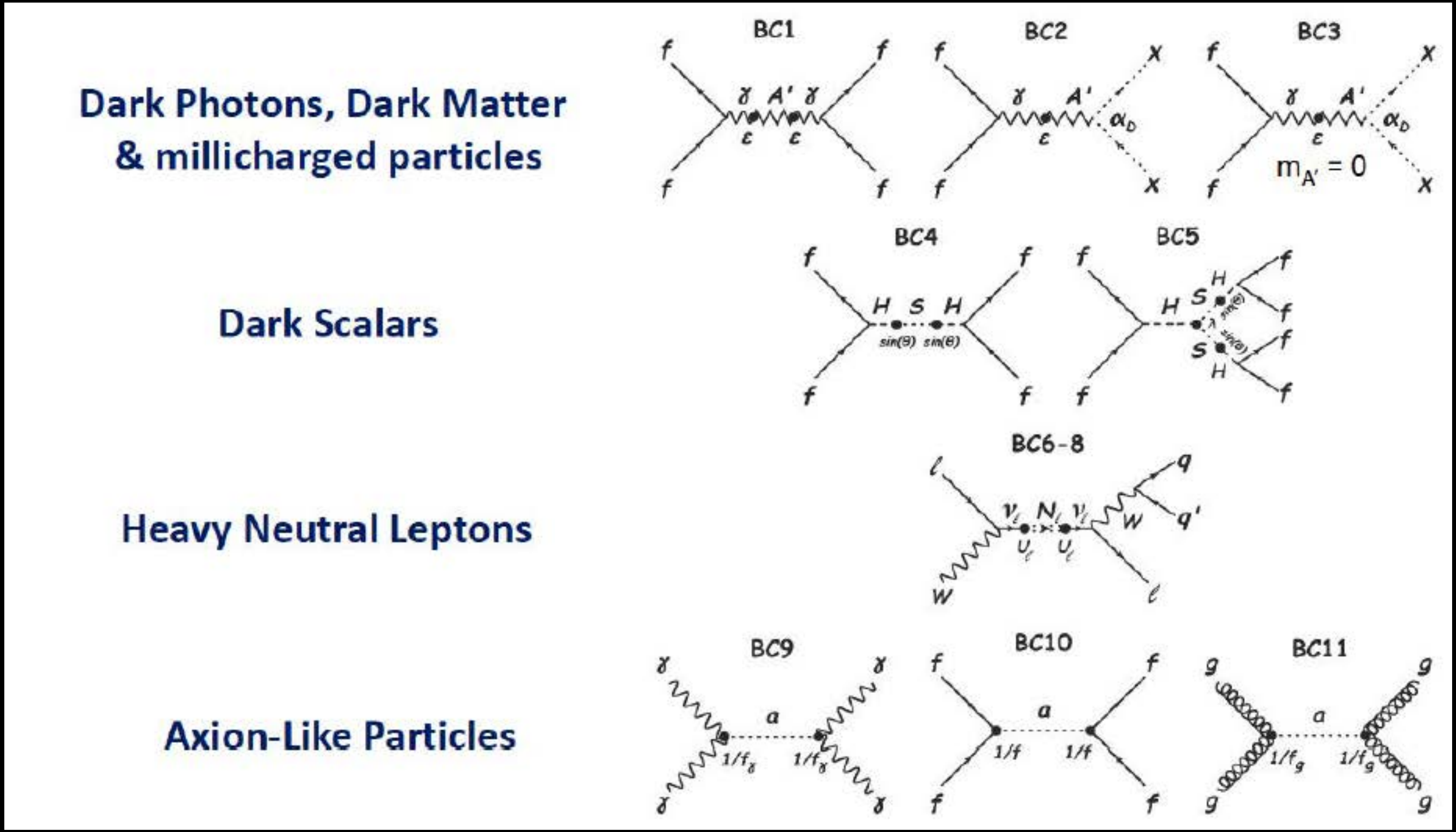
Possibilities under active investigation: enlarge existing cavern UJ12, 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock; or create a new shaft and cavern ~612 m from ATLAS past UJ18.



BSM PHYSICS

PBC BSM BENCHMARK CASES

- 11 models of light, weakly-interacting particles (LLPs, FIPs)

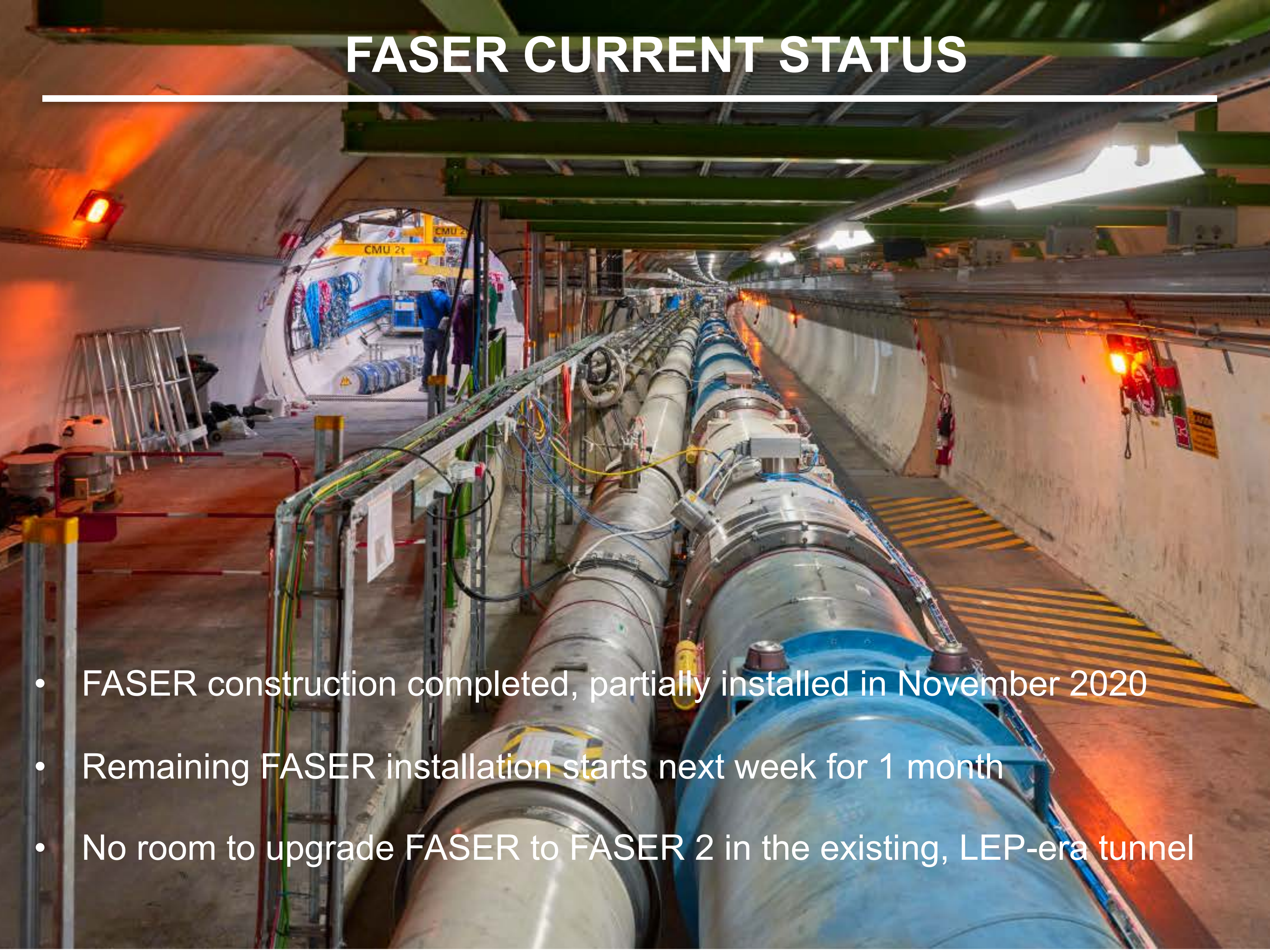


FPF DISCOVERY PROSPECTS

- The discovery prospects for FASER and FASER 2 are well-studied by the PBC
- Recent studies show the promise of the FPF for exploring all the BCs

Benchmark Model	Underway	FPF	References
BC1: Dark Photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Dark Matter	–	FLArE	Batell, Feng, Trojanowski, 2101.10338
BC3: Milli-Charged Particle	–	FORMOSA	Foroughi-Bari, Kling, Tsai, 2010.07941
BC4: Dark Higgs Boson	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
BC5: Dark Higgs with hSS	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387
BC6: HNL with e	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC7: HNL with μ	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC8: HNL with τ	FASER	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC9: ALP with photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1806.02348
BC10: ALP with fermion	FASER	FASER 2	FASER Collaboration, 1811.12522
BC11: ALP with gluon	FASER	FASER 2	FASER Collaboration, 1811.12522

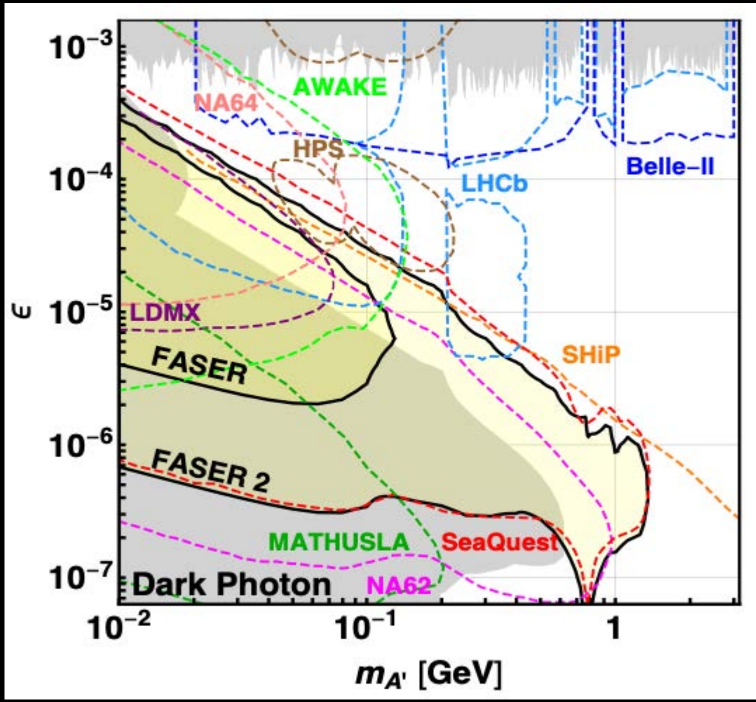
FASER CURRENT STATUS

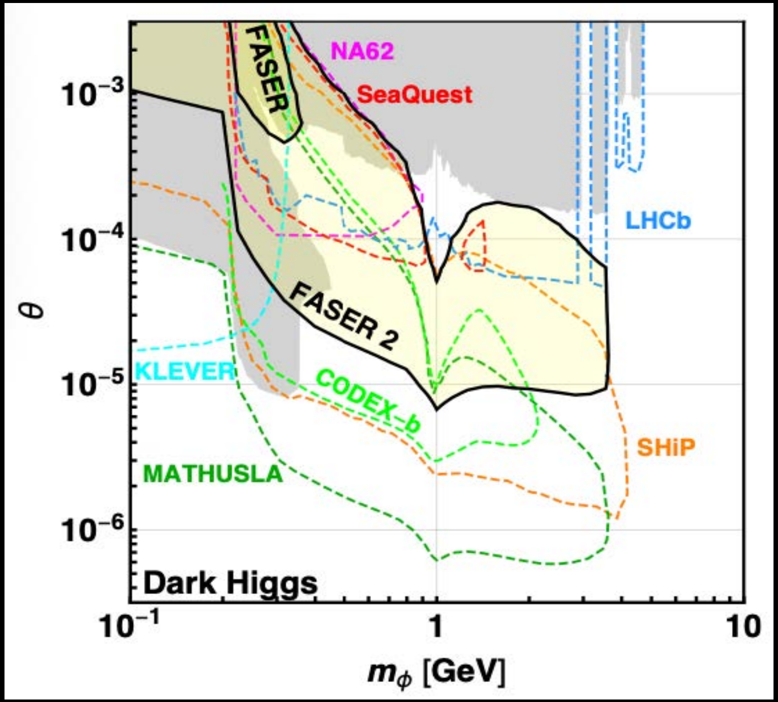


- FASER construction completed, partially installed in November 2020
- Remaining FASER installation starts next week for 1 month
- No room to upgrade FASER to FASER 2 in the existing, LEP-era tunnel

BC1, 4-11: LLPS AT FASER AND FASER 2

- FASER probes new parameter space in some models with just 1 fb^{-1}.
- The Forward Physics Facility will provide space to upgrade FASER (R=10cm, L=1.5m, Run 3) → FASER 2 (R=1m, L=5m, HL-LHC), either extending sensitivity greatly (e.g., dark photon), or providing new discovery prospects (e.g., dark Higgs) complementary to other expts.

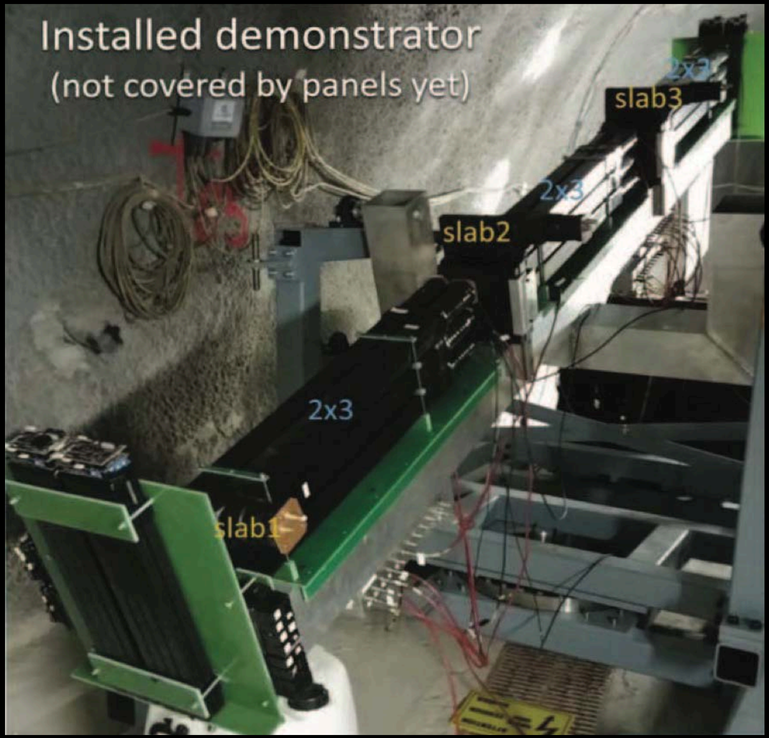


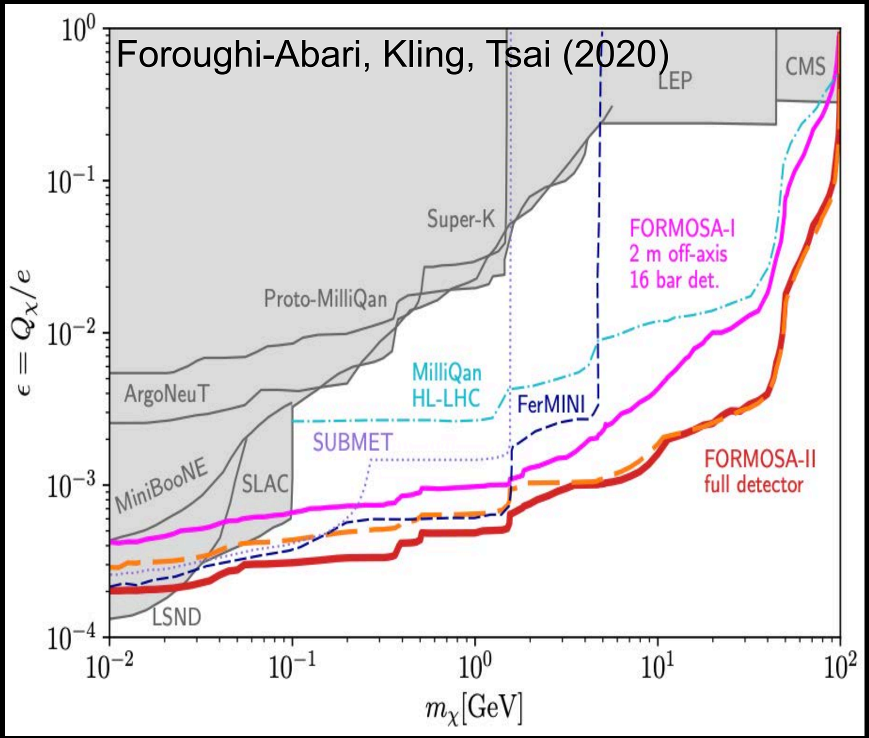


FASER Collaboration, 1811.12522 (2018)

BC2: MILLI-CHARGED PARTICLES AT FORMOSA

- Currently the target of the MilliQan experiment near the CMS IP.
- MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan planned to run in this location at HL-LHC, but the sensitivity can be improved significantly by moving it to the FPF (FORMOSA).

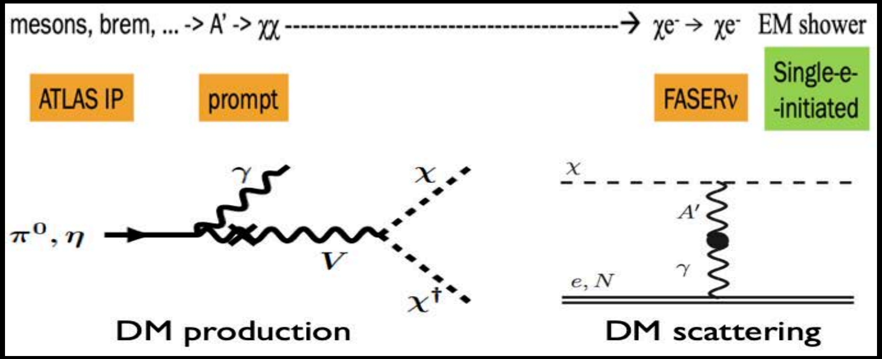




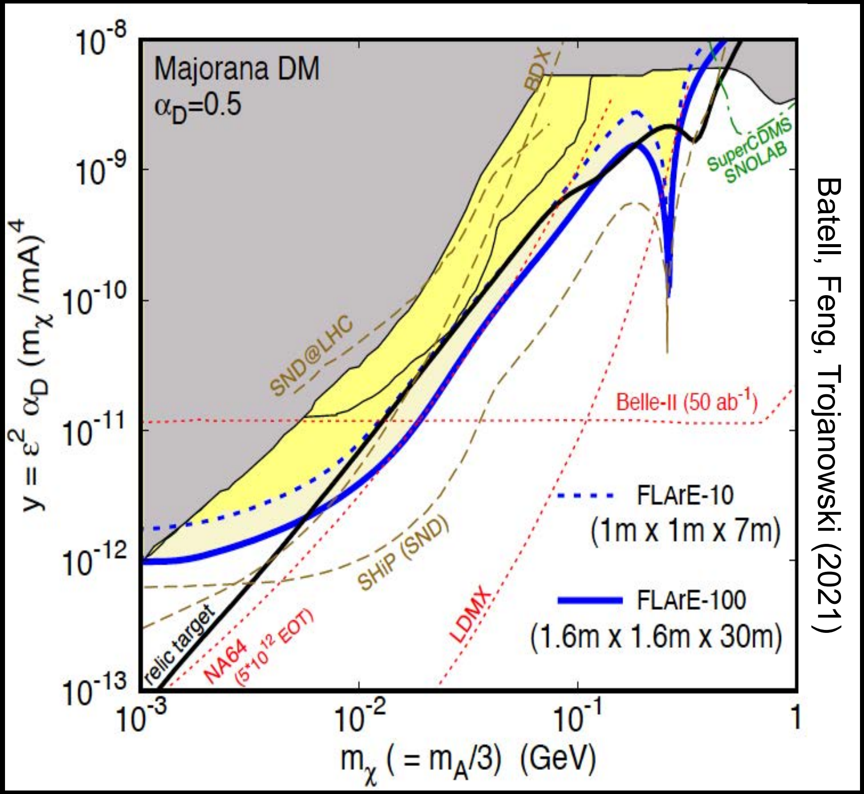
BC3: DARK MATTER DETECTION AT FLARE

- If $m_{LLP} > 2m_{DM}$, the LLP will typically decay to dark matter, leading to a highly collimated beam of dark matter particles.

- Can look for the resulting DM to scatter off electrons at FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.



- FLArE probes most of the favored/ allowed relic target region. Complementary to missing energy experiments that probe more of the "too large $\Omega_\chi h^2$" region, but don't detect DM scattering.



Batell, Feng, Trojanowski (2021)

BSM SUMMARY

- The FPF will house a number of experiments.
- These will have the potential to discover new physics in all of the PBC benchmark cases.
- There are many other models worth consideration, and much further work required to realize these FPF detectors.

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BC8: HNL with τ	FASER	FASER 2
BC9: ALP with photon	FASER	FASER 2
BC10: ALP with fermion	FASER	FASER 2
BC11: ALP with gluon	FASER	FASER 2

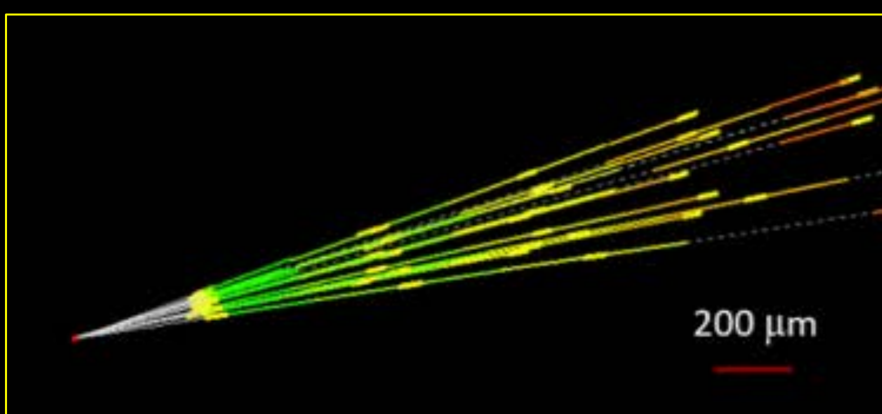
SM PHYSICS

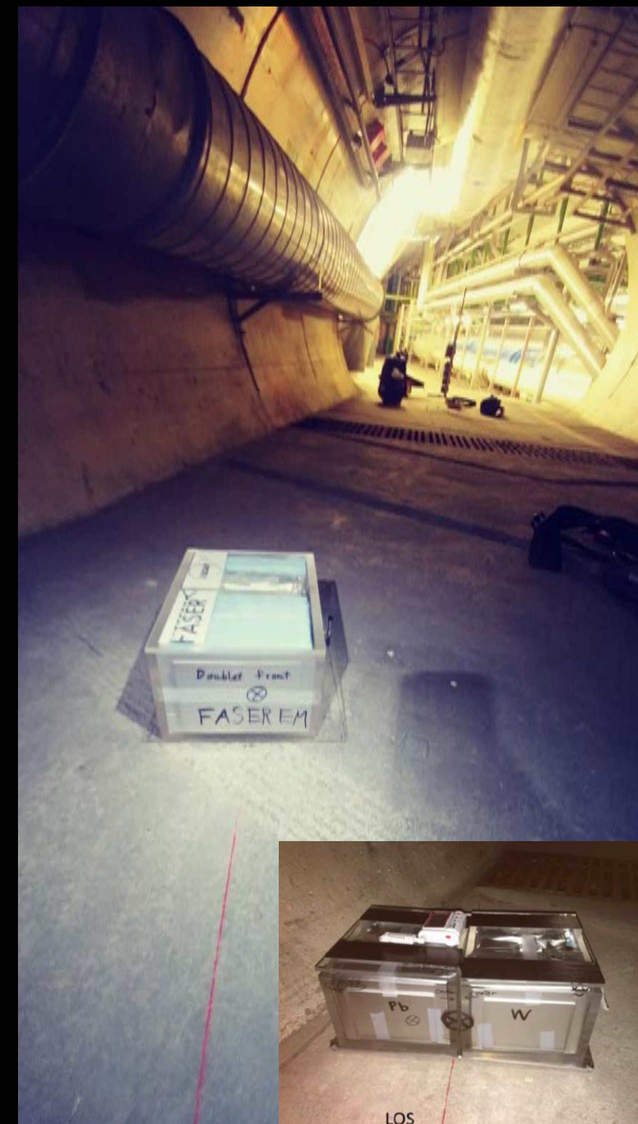
FIRST COLLIDER NEUTRINOS

- No collider neutrino has ever been detected.
- But there is a huge flux of TeV neutrinos in the far forward direction.

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

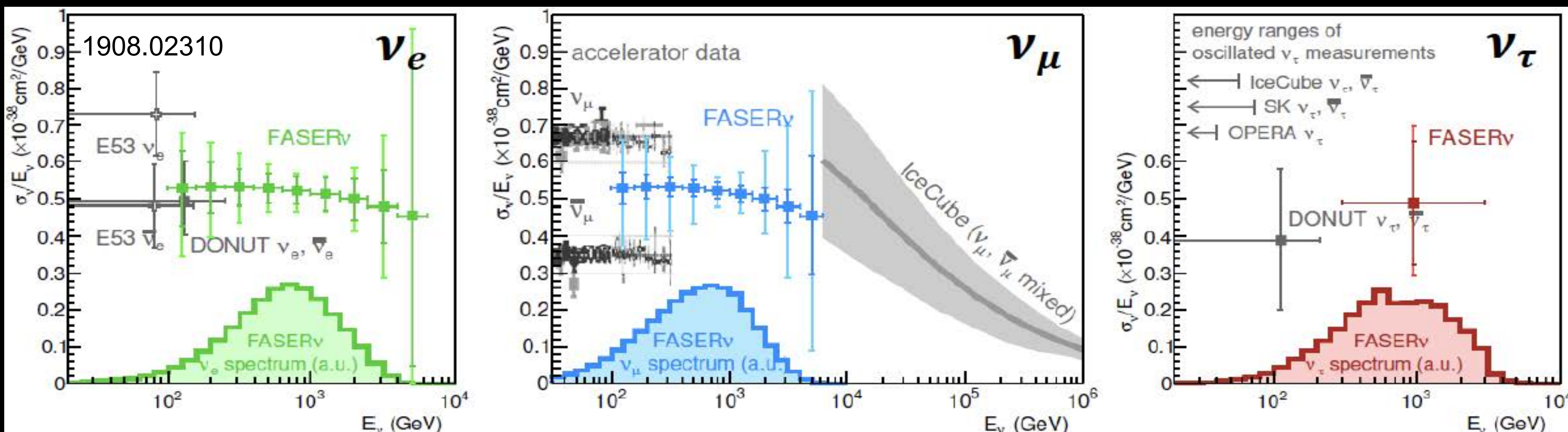
- In 2018, the FASER Collaboration placed ~30 kg emulsion detectors in the far forward region for 6 weeks (inserted and removed in TSs).
- Expect ~few neutrino interactions. Several neutral vertices have been identified, likely to be neutrinos. Analysis ongoing.





NEUTRINO PHYSICS

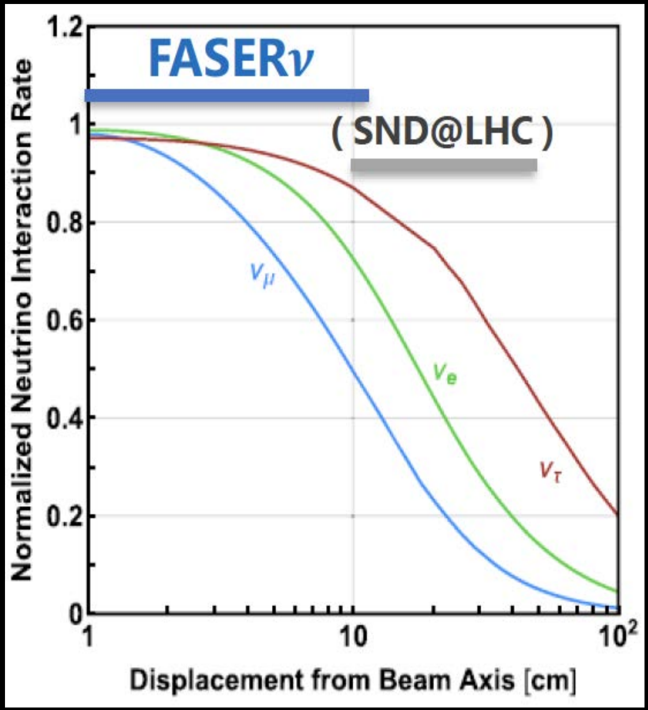
- Run 3: FASERν (on-axis) and SND (off-axis), ~1-tonne emulsion/tungsten detectors, will open a new field of neutrino physics at the LHC
  - Will record ~1000 ν_e, ~10,000 ν_μ, and ~10 ν_τ interactions at TeV energies, the first direct exploration of this energy range for all 3 flavors.



- HL-LHC: FPF could accommodate FASERν2 and SND2 (~10-tonne emulsion detectors), FLArE (10+ tonne LArTPC), FORMOSA, …
  - Will record ~10^5 ν_e, ~10^6 ν_μ, and ~10^3 ν_τ interactions at TeV energies.
  - Detect 1st anti-ν_τ, probe neutrino properties (NSIs, ν_τ MDM), …

QCD PHYSICS

- The forward production of hadrons is currently subject to large uncertainties. FPF experiments would provide useful insights.
  - By accommodating both on-axis and off-axis neutrino detectors, could provide complementary information ($\pi \rightarrow \nu_\mu$, $K \rightarrow \nu_e$, $D \rightarrow \nu_\tau$).
  - Different target nuclei (lead, tungsten) to probe different nuclear pdfs
  - Strange quark pdf through $\nu s \rightarrow lc$
  - Forward charm production, intrinsic charm
  - Refine simulations that currently vary greatly (EPOS-LHC, QGSJET, DPMJET, SIBYLL, PYTHIA…)
  - Provide essential input to astroparticle experiments; e.g., distinguish galactic neutrino signal from atmospheric neutrino background at IceCube



SUMMARY AND PLANS

- The FPF is well-aligned with
  - the European Strategy Update's recommendations for a diverse experimental program, connections to astroparticle experiments, etc.
  - CERN's updated Physics Beyond Colliders mandate
  - the American Snowmass community study and P5 prioritization exercise

- There are already many experiments that would be excellent fits for the FPF. These build on current experiments, such as FASER, FASERν, SND@LHC, and MilliQan, but also new ideas, such as FLArE.

- The physics topics addressed by these experiments are already astoundingly diverse: measurements of TeV neutrino properties, proton pdfs, nuclear pdfs, forward hadron production, implications for IceCube and other cosmic ray experiments, searches for dark portal particles, light gauge bosons, axion-like particles, other LLPs, dark matter scattering, milli-charged particles, …

SUMMARY AND PLANS

- Clearly, now is the time to establish the FPF's physics case and feasibility if it is to benefit from running in the HL-LHC era.

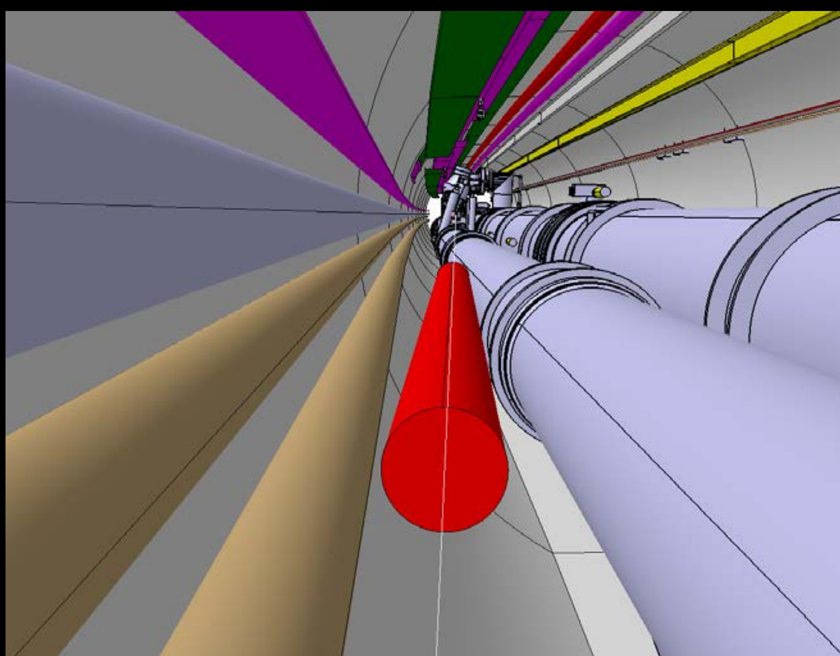
- We would like to determine the optimal suite of experiments that will maximize the physics potential within the constraints of cost, schedule, safety, …. An interesting and multi-faceted optimization problem!

- The FPF Kickoff Workshop was held 9-10 November 2020
  - 40 talks, lots of fascinating discussions across the broad range of relevant topics
  - For talk slides and recordings, see https://indico.cern.ch/event/955956
  - Next meeting will be announced soon

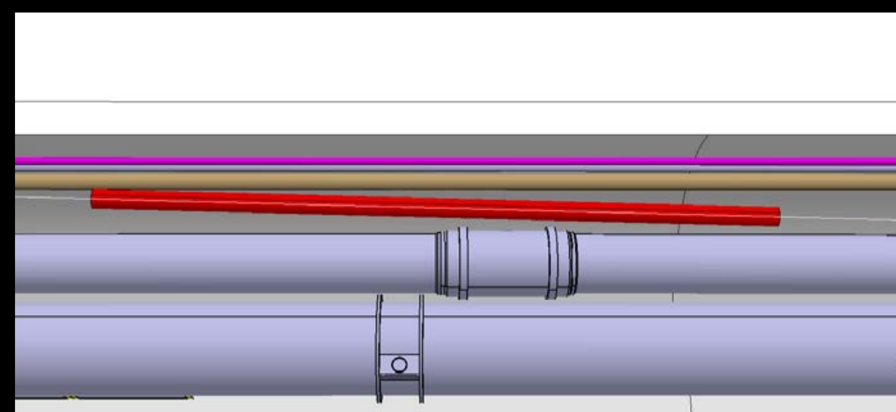
BACKUP

SWEEPER MAGNET

- For the FPF, a magnet can sweep away muons, greatly reducing backgrounds.
- A 7-m-long, 20-cm-diameter magnet along the LOS can fit in the LHC tunnel after muons leave the LHC beampipe.



$$h_B \approx \frac{ecd}{E_\mu} B\ell = 60\ \text{cm} \left[\frac{100\ \text{GeV}}{E_\mu}\right] \left[\frac{d}{200\ \text{m}}\right] \left[\frac{B \cdot \ell}{\text{T} \cdot \text{m}}\right]$$



Liam Dougherty (2021)