LONG-LIVED PARTICLES

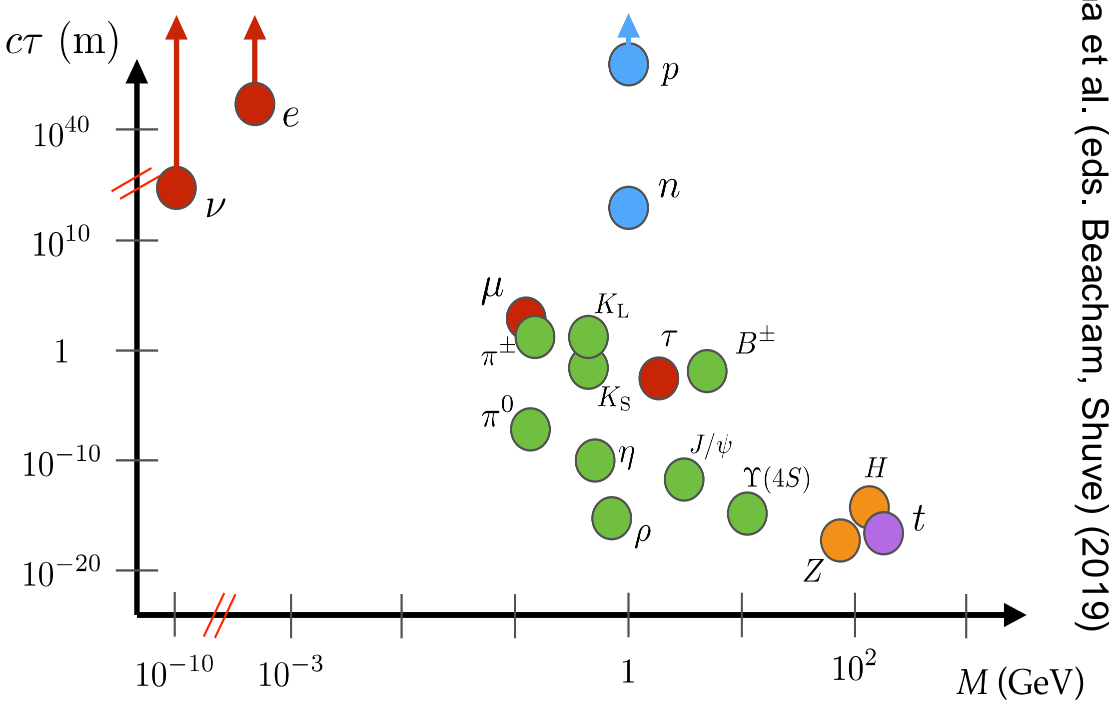
SUSY 2026, University of Oklahoma

Jonathan Feng, UC Irvine, 18 May 2026

INTRODUCTION

- Long-lived particles have played essential roles in many of the conceptual breakthroughs that established the standard model of particle physics: *e*, *p*, *n*, μ, *K*, ν, …

- There are good reasons to think that the next breakthrough in particle physics will also involve LLPs.
  - LLPs are ubiquitous in BSM theories, especially those with cosmological significance.
  - SUSY naturally motivates both heavy and light LLPs, which can be detected through a large variety of spectacular signatures.
  - Especially for light LLPs, we are in the "low-hanging fruit" era, with many opportunities for fast, small, and cheap experiments that are making (and could make) huge strides forward.



Alimena et al. (eds. Beacham, Shuve) (2019)

LONG-LIVED PARTICLES IN SUSY

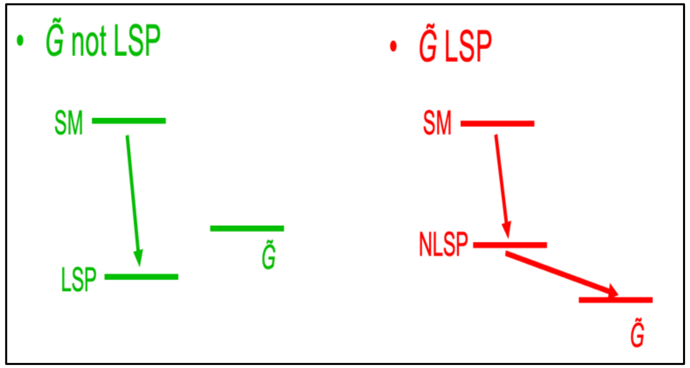
- New particles can be tuned to be long-lived in a variety of ways, but there is also a long history of LLPs emerging naturally in SUSY.

Weak coupling: Naturally arises in decays to gravitinos. Always in GMSB, but possible even for gravity-mediation when the gravitino is the LSP. Interesting colliders signals, DM phenomenology.

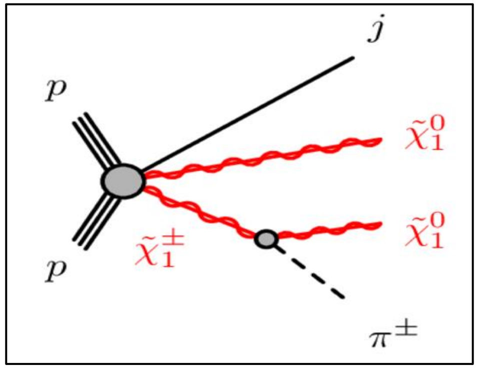
Ellis et al. (1985)

Phase-space suppressed decays: Naturally arises for Higgsino doublets, Wino triplets. Interesting colliders signals, DM phenomenology.

Drees, Tata (1990)



$$\Gamma \sim g^k \left[\frac{\Delta m}{m}\right]^n m$$



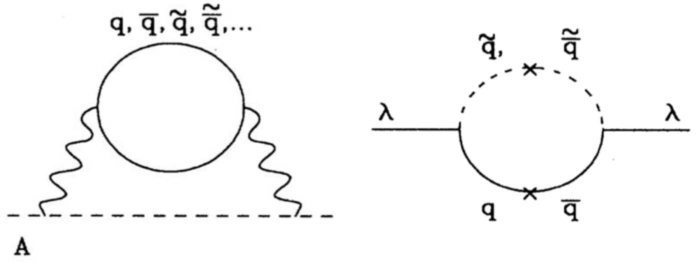
E.g., ATLAS (2603.08315); see Jeanty, Rogan talks

What about light particles? SUSY particles have masses ~ weak scale, so this can't emerge naturally, right? (Cf. light neutralinos, Dreiner et al.).

HIDDEN SECTORS AND THE BSM FLAVOR PROBLEM

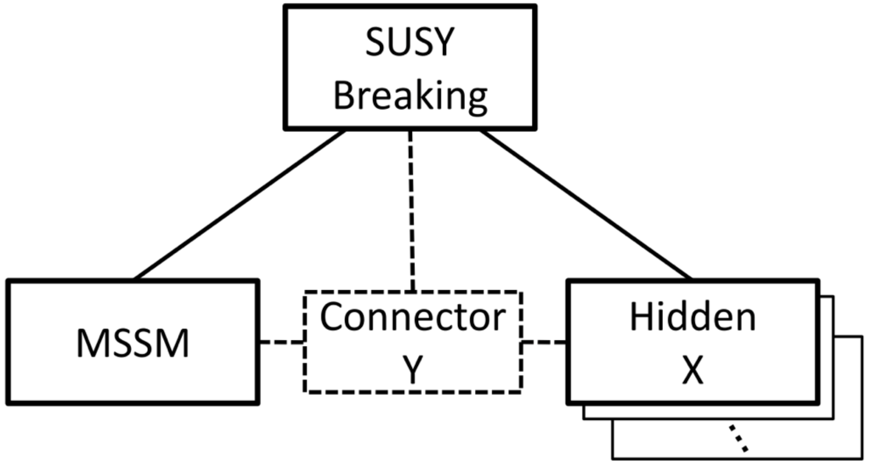
- Weak-scale SUSY's motivations include the gauge hierarchy problem, but also others: coupling constant unification, radiative EWSB, top quark quasi-fixed point, neutralino DM, …

- Key among these is the fact that there are elegant ways to solve the BSM flavor problem.



- E.g., In GMSB, SUSY particles get masses proportional to their gauge couplings squared.

Dine, Nelson, Shirman (1994)
Dine, Nelson, Nir, Shirman (1995)

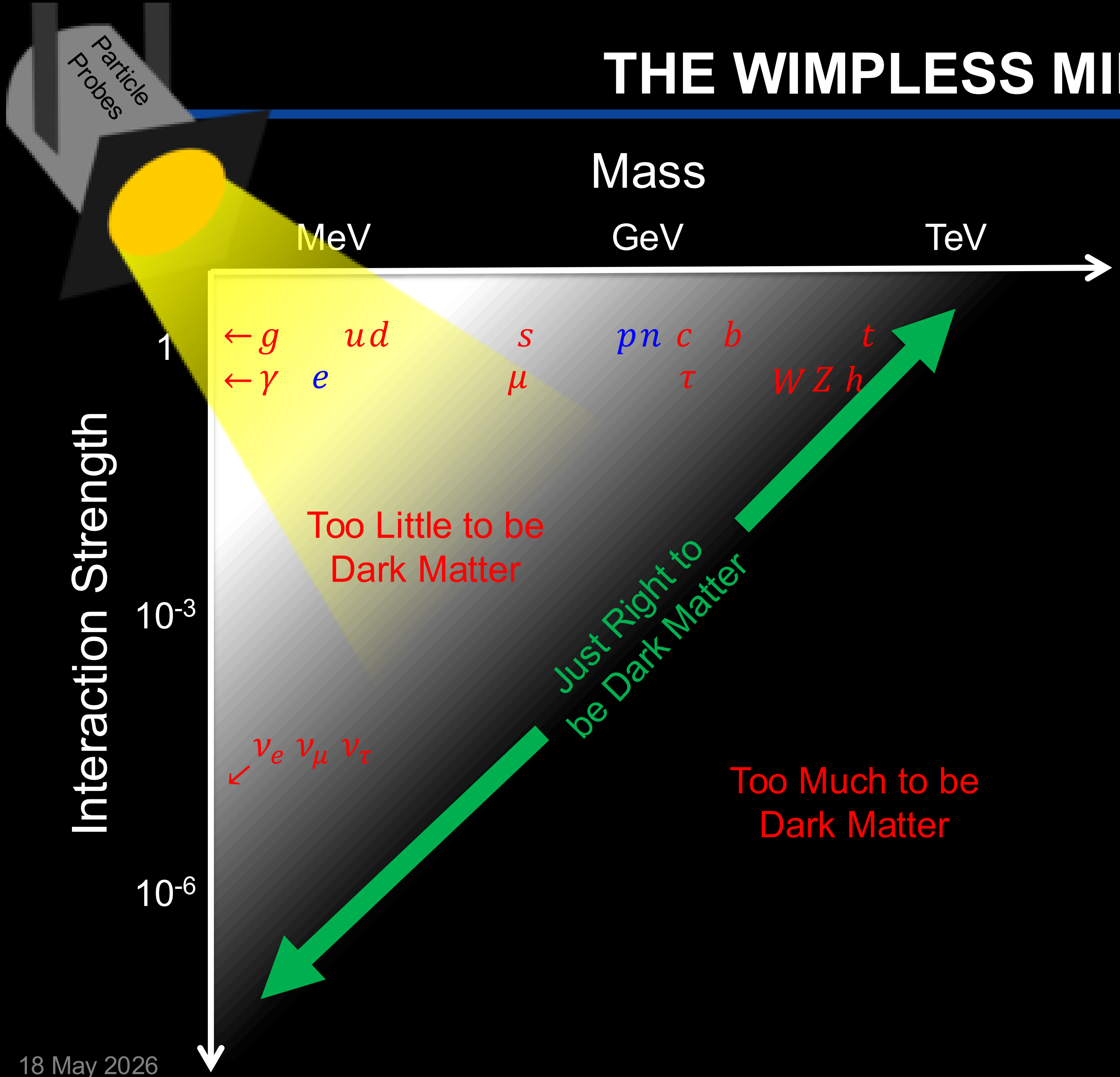


- If hidden sector particles get mass the same way, they may be heavier or lighter, but this ratio is fixed:

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

$$m \sim \frac{g^2}{16\pi^2}\frac{F_{\rm m}}{M_{\rm m}} = \frac{g^2}{16\pi^2}\frac{F}{M} \qquad m_X \sim \frac{g_X^2}{16\pi^2}\frac{F_{{\rm m}X}}{M_{{\rm m}X}} = \frac{g_X^2}{16\pi^2}\frac{F}{M}$$

THE WIMPLESS MIRACLE



- But this ratio also determines the thermal relic density:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- GMSB hidden sectors generically include particles with the right relic density to be DM. WIMP miracle → WIMPless miracle.

Feng, Kumar (2008)

[Same thing works in AMSB.]

Feng, Shadmi (2011)

- Bottom line: Light, weakly-interacting LLPs emerge naturally in SUSY and they are as cosmologically motivated as WIMPs.

PORTAL PARTICLES

- The interactions with the SM are determined by the “connectors” or portal particles. The interactions they induce that are most likely to be big are the renormalizable ones. There are just a few options:

- Spin 1

SM $F_{\mu\nu} F_D^{\mu\nu}$ Dark Force

→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: εq_f.

Holdom (1986)

- Spin 0

SM $h^\dagger h \phi_D^\dagger \phi_D$ Dark Scalar

→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin\theta\, m_f$.

Patt, Wilczek (2006)

- Spin 1/2

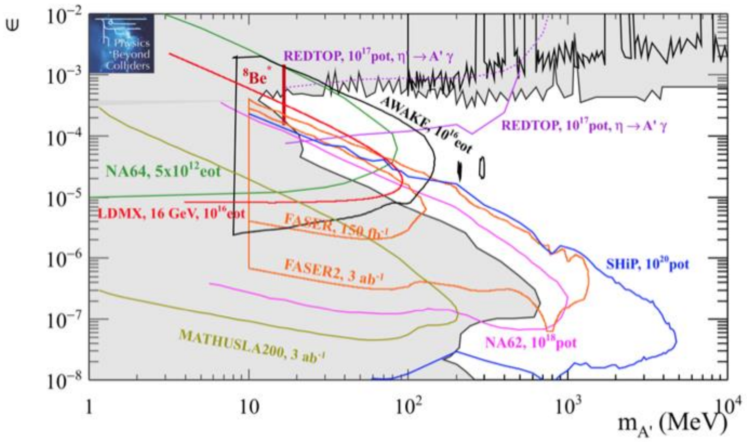
SM $hL\psi_D$ Dark Fermion

→ heavy neutral lepton, couples to SM fermions with suppressed coupling proportional to $\sin\theta$.

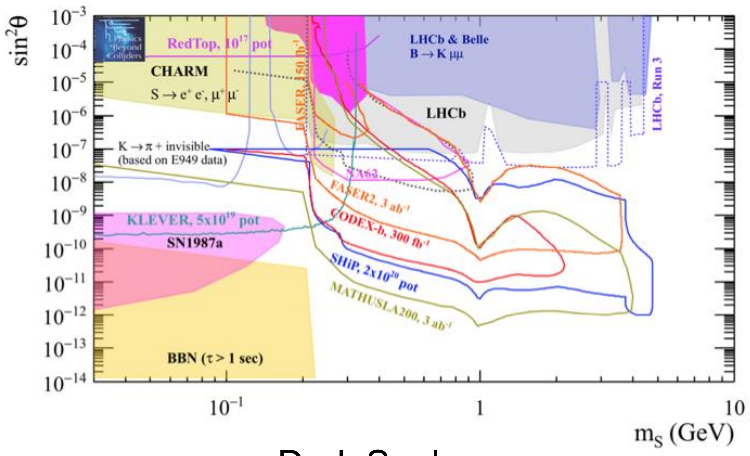
EXPERIMENTAL LANDSCAPE

- Light LLPs can be discovered at both the high energy and high intensity frontiers with fast, small, and cheap experiments.

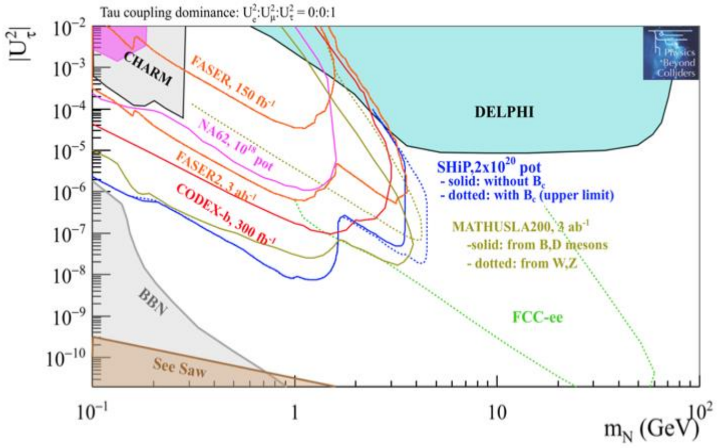
- In the 2017-2021 period, many community studies were done to understand the search reaches of the various existing and proposed experiments LLPs, resulting in plots like these:



Dark Photon



Dark Scalar



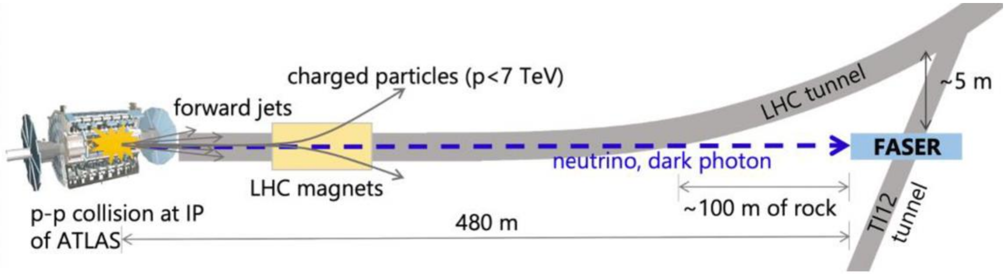
Dark Fermion

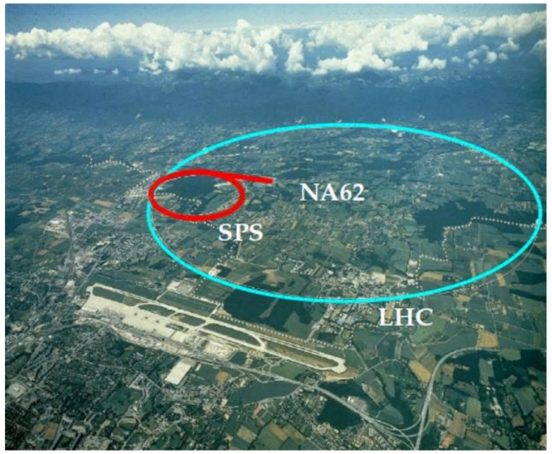
- Unfortunately, progress on many worthy projects has been slowed by a variety of factors (COVID, P5, EPPSU, global funding crises, …), but let me highlight some new results and some tantalizing prospects.

VISIBLE DARK PHOTON SEARCH

- There is a vast parameter space that remains unprobed. In the “cosmologically favored” region, masses in the 10 MeV – GeV mass range, and couplings from 10^{-6} to 10^{-3} are allowed.

- In the last 3 years, new results have been announced by two experiments:
  - FASER at the LHC: a dedicated LLP search and TeV neutrino experiment. Dark photons produced in forward pion/eta decays, travel 480 m (through 100 m of rock), decay to e^+e^-.
  - NA62 at the SPS: a kaon experiment that can search for LLPs in beam dump mode. Dark photons produced in meson decays/dark bremsstrahlung that then decay to e^+e^-, $\mu^+\mu^-$.





VISIBLE DARK PHOTON SEARCH RESULTS

- In 2023, using 2022 Run 3 data, FASER set the first new limits on parameter space from low coupling since the 1990's. Started probing new parameter space on Day 1, ended up ~100 times more sensitive than previous experiments

  FASER Collaboration (2308.05587, PLB)

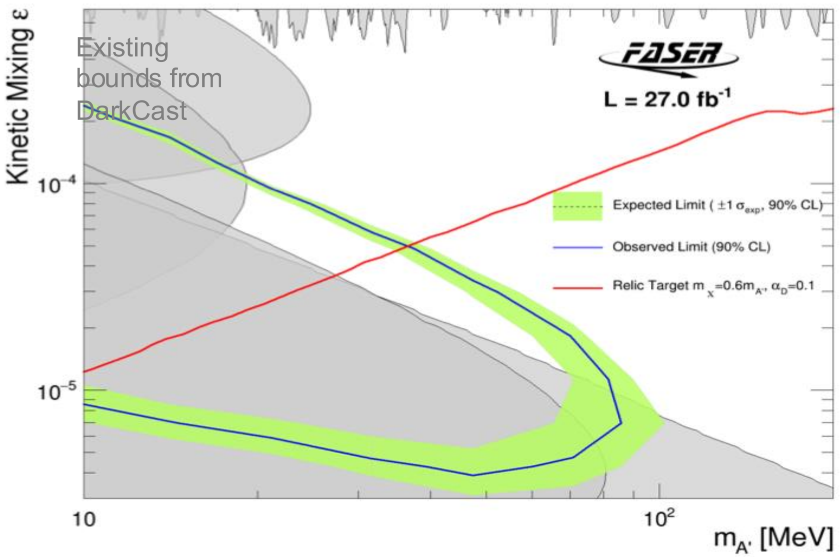
- Later in 2023, NA62 provided complementary limits, overlapping at low masses and extending to higher masses.

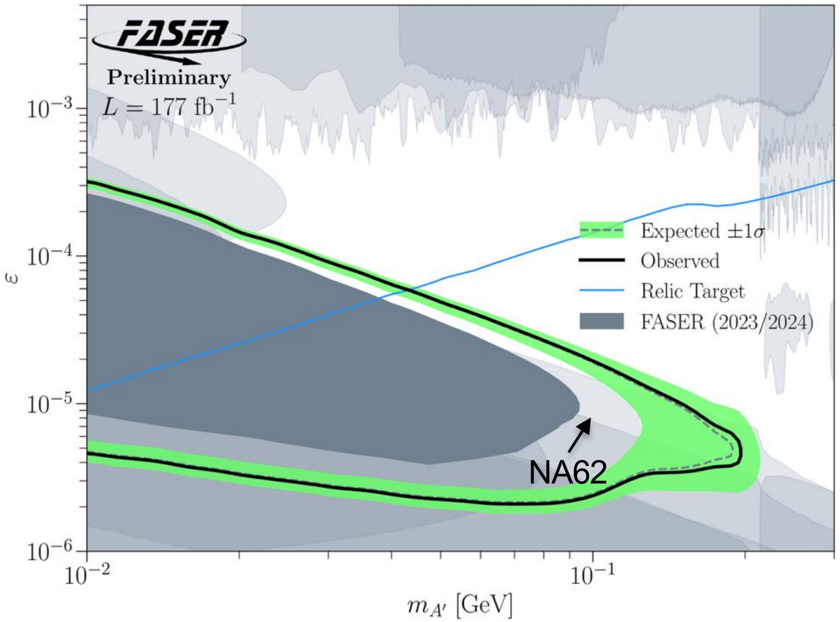
  NA62 Collaboration (2312,12055, PRL)

- In March 2026, using 2022-24 data, FASER set new limits: ~6x more data, ~3x more powerful analysis (more gen. signatures).

  FASER Collaboration (CERN-FASER-CONF-2026-001)

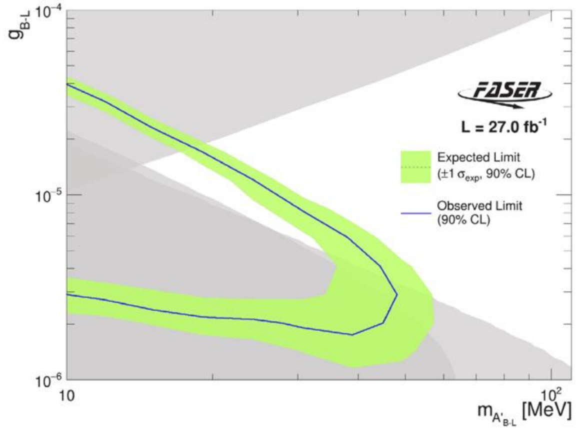
- Prospects for the future
  - From high coupling: Belle2 and LHCb may push into the unprobed from the top another factor of ~3 in coupling.
  - From low coupling: FASER is approved for HL-LHC (10x more luminosity), and SHiP at the SPS is projected to be able to extend the reach much further.

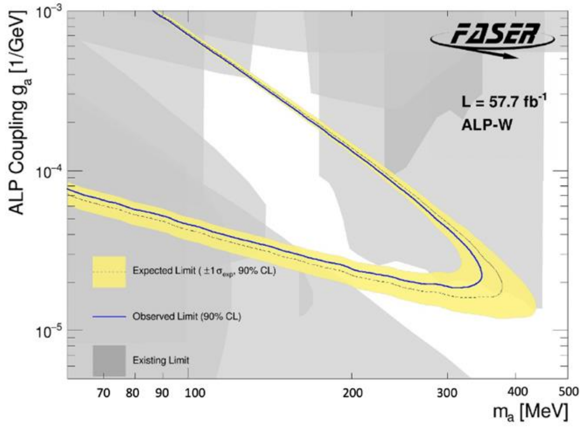


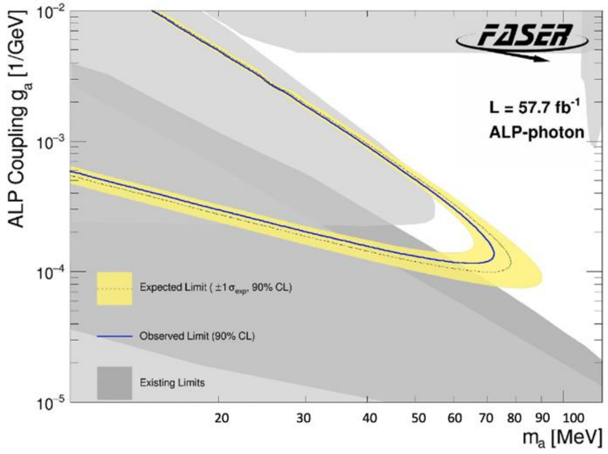


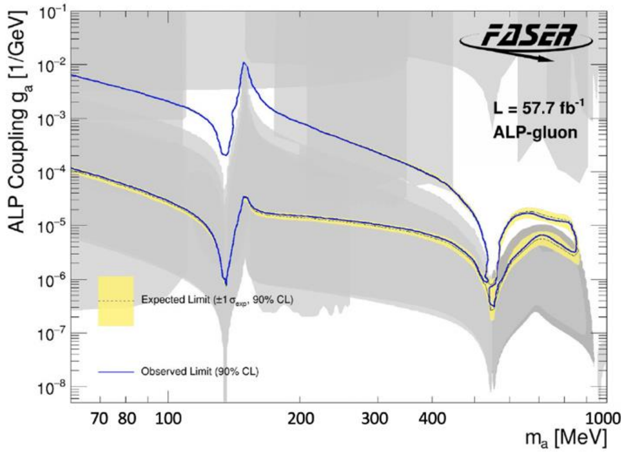
MORE NEW PARTICLE SEARCHES

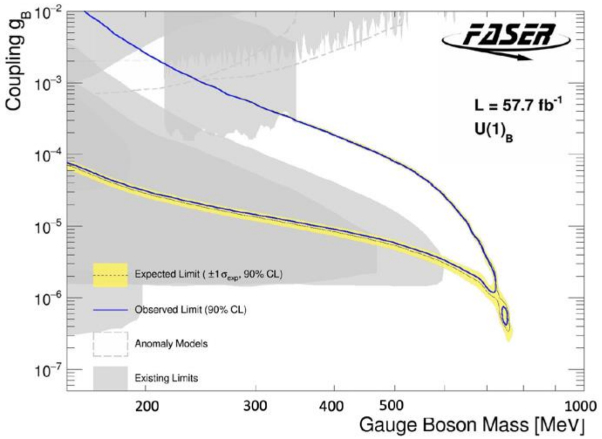
FASER has also looked for many other new particles: other new force carriers ($U(1)_{B-L}$, $U(1)_B$), axion-like particles with photon, W, gluon couplings, up-philic scalars, two Higgs doublet models, etc., all with world-leading sensitivities in interesting parts of parameter space.

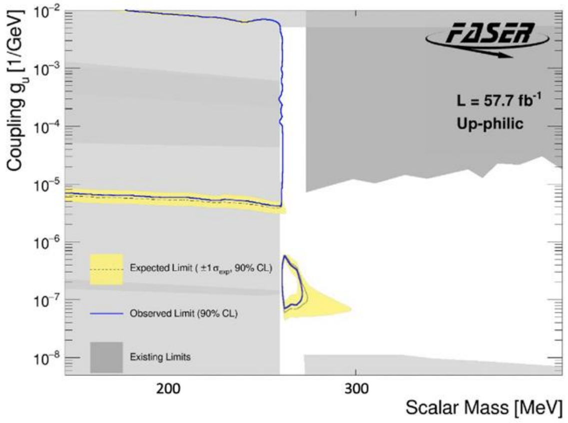


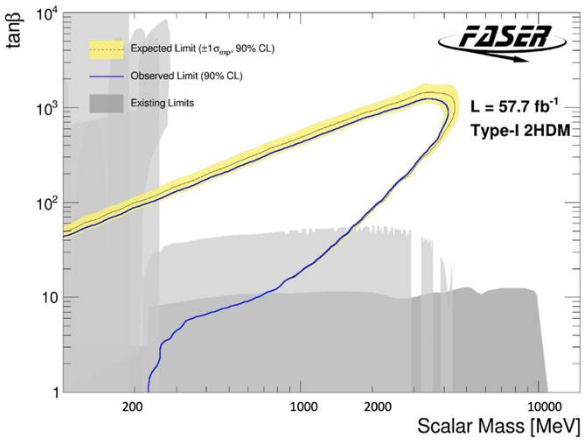


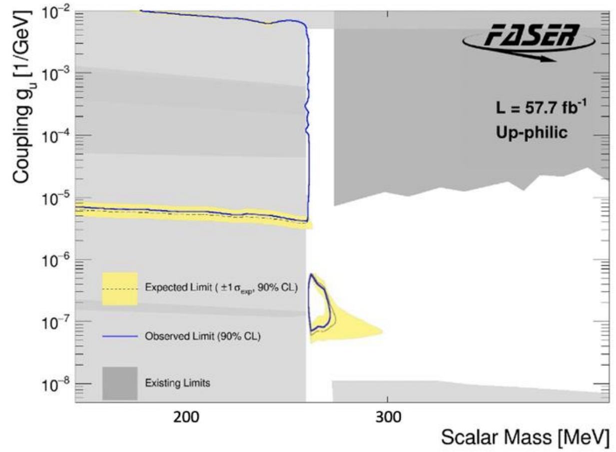








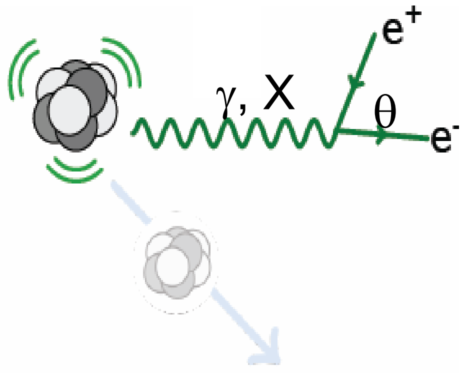


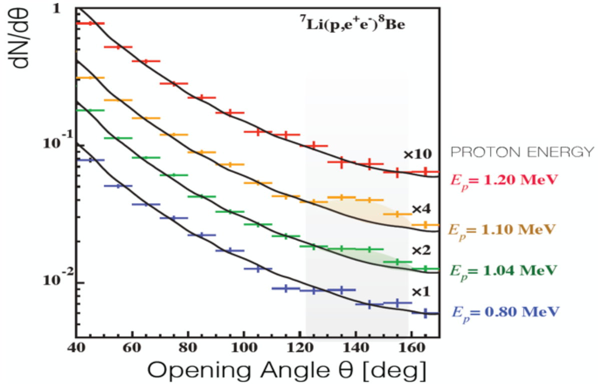


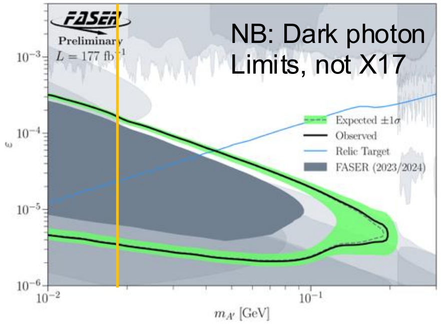
FASER Collaboration ([2308.05587](2308.05587), PLB; [2410.10363](2410.10363))

X17 AND THE ATOMKI ANOMALIES

- New particles at the ~ 10 MeV scale and below can be produced in the decays of excited nuclei.
- In 2015, the ATOMKI group reported a 7σ excess in ^{8}Be (18.15) → ^{8}Be e^+e^- decays at $\theta_{e^+e^-} \approx 140°$. Krasznahorkay et al., 1504.01527 [nucl-ex], PRL
- This was explained by a 17 MeV protophobic gauge boson. Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)
- In 2019, the same group reported a new 7σ excess in the decays of excited ^{4}He (20.49) nuclei at $\theta_{e^+e^-} \approx 115°$. Remarkably, this can also be explained by the same 17 MeV protophobic gauge boson. Krasznahorkay et al., 1910.10459 [nucl-ex], PRC; Feng, Tait, Verhaaren (2020)
- There has since been a ~2σ exclusion of the X17 by MEG2, but also a ~2σ excess seen at 17 MeV reported by PADME. MEG II Collaboration, 2411.07994 [nucl-ex], EPJC; PADME Collaboration, 2505.24797 [hep-ex]
- Can this all be explained by a new particle? See Toni Makela's parallel talk tomorrow. Fieg, Makela, Tait, Toman, 2602.11263





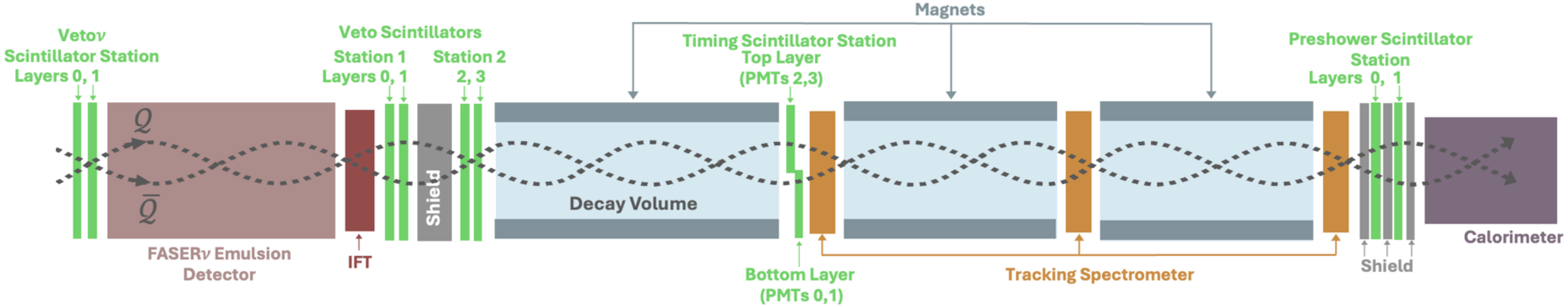


QUIRKS

- What if the dark sector does not have electromagnetism, but instead has particles bound together by a strong force, similar to QCD? Can get bizarre new particles: quirks.

Kang, Luty (2008)

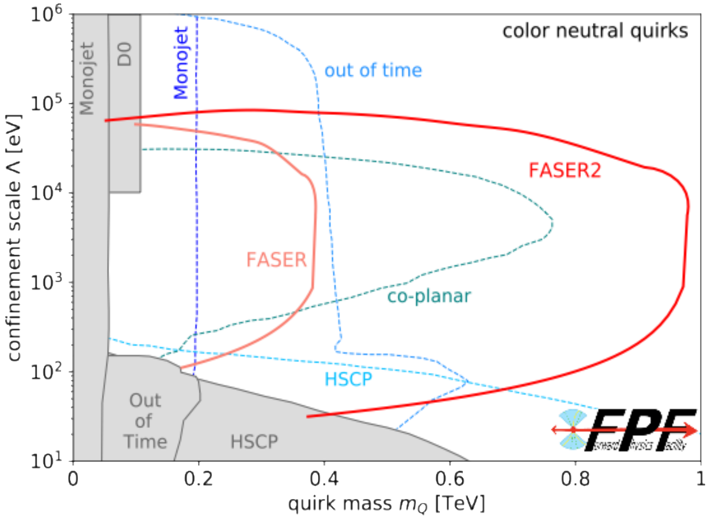
- Quirks are particles with dark QCD interactions and
  - Mass $m \sim$ O(100) GeV.
  - Confining scale $\Lambda_{\mathrm{QCD}}^{\mathrm{dark}} \ll m$.



- If quirks have SM electric charge, they are produced at colliders, but cannot dark hadronize by popping pairs of particles out of the vacuum. Instead, they oscillate around their center of mass and propagate slowly in the forward direction.

- By looking for 2 charged tracks that are slow and delayed (out of time with bunch crossings), can discover quirks with masses well beyond the embarrassingly weak current bounds (50 GeV!). FASER results coming soon. [See also Batell and Verhaaren talks.]

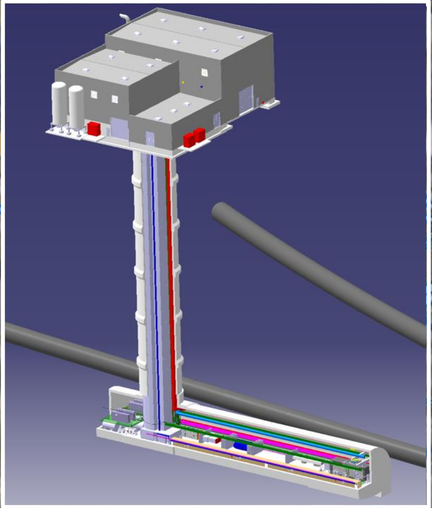
FASER Collaboration (Eli Welch thesis)



Feng, Li, Liao, Ni, Pei (2024)

FORWARD PHYSICS FACILITY

CERN is also considering the possibility of excavating a new underground detector hall to house diverse forward experiments for the rest of the LHC's lifetime until the 2040s.



https://cds.cern.ch/record/2851822

FPF site selection and core studies have identified an ideal site in France just outside the CERN main gate

ATLAS

SPS

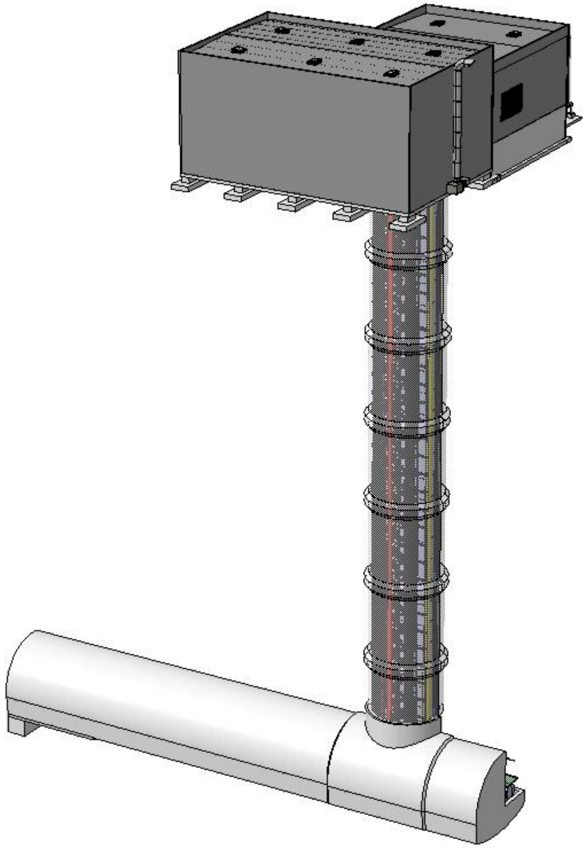
LHC

FASER

LOS

CERN GIS

FORWARD PHYSICS FACILITY

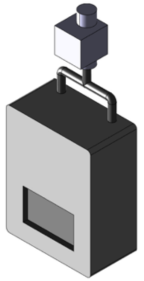


Anastasiya Magazinik, Julien Prosic, talk at FPF9, 5 March 2026

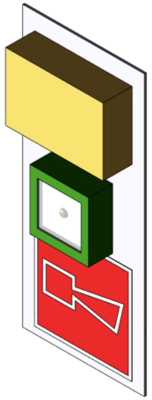
FORWARD PHYSICS FACILITY: SAFETY DESIGN

CERN Engineering Department

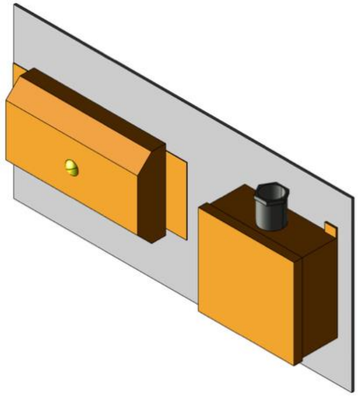
ACTEMIUM



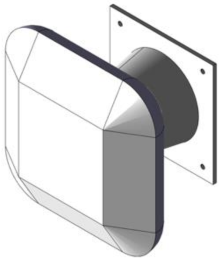
Fire detector



Evacuation panel

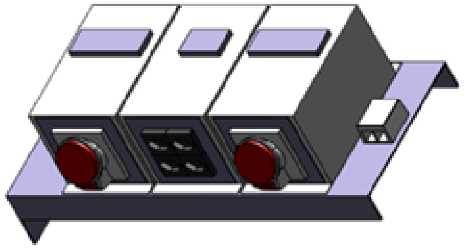


Anti Panic light

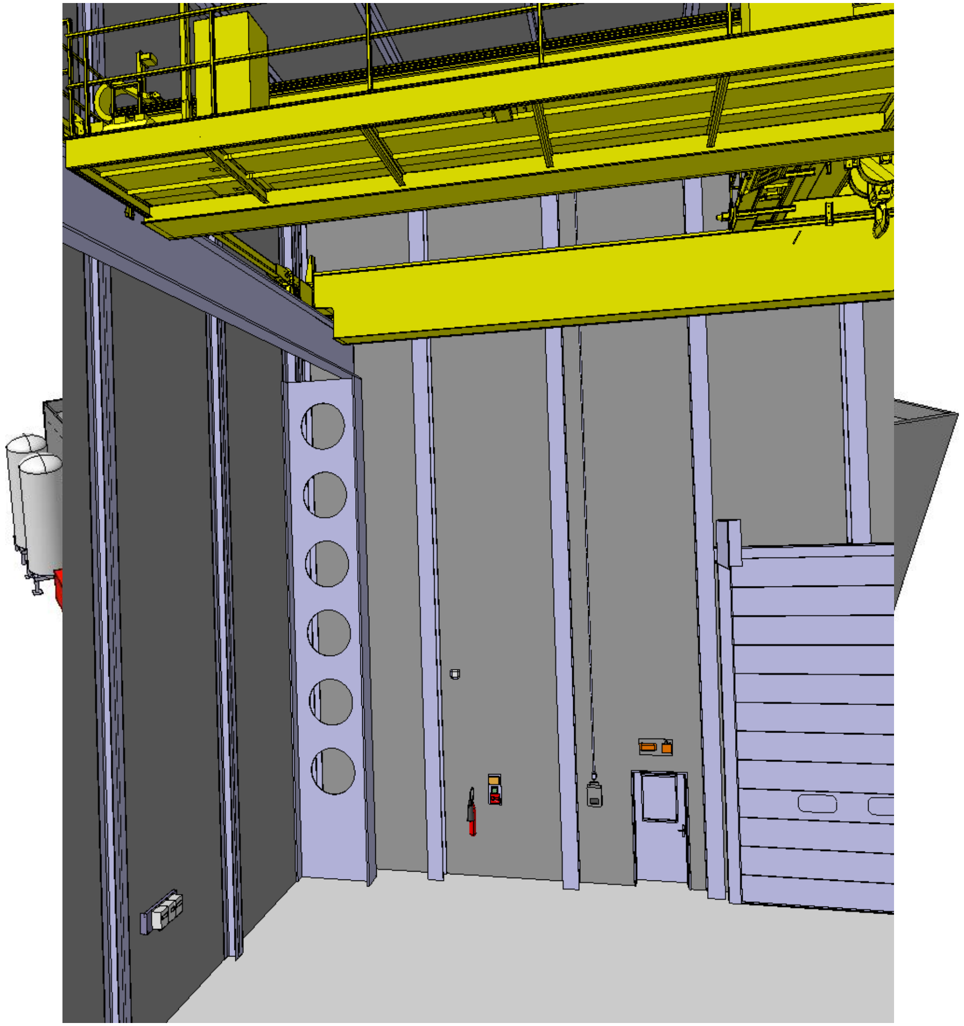


WIFI

Fire extinguisher



Electrical boxes

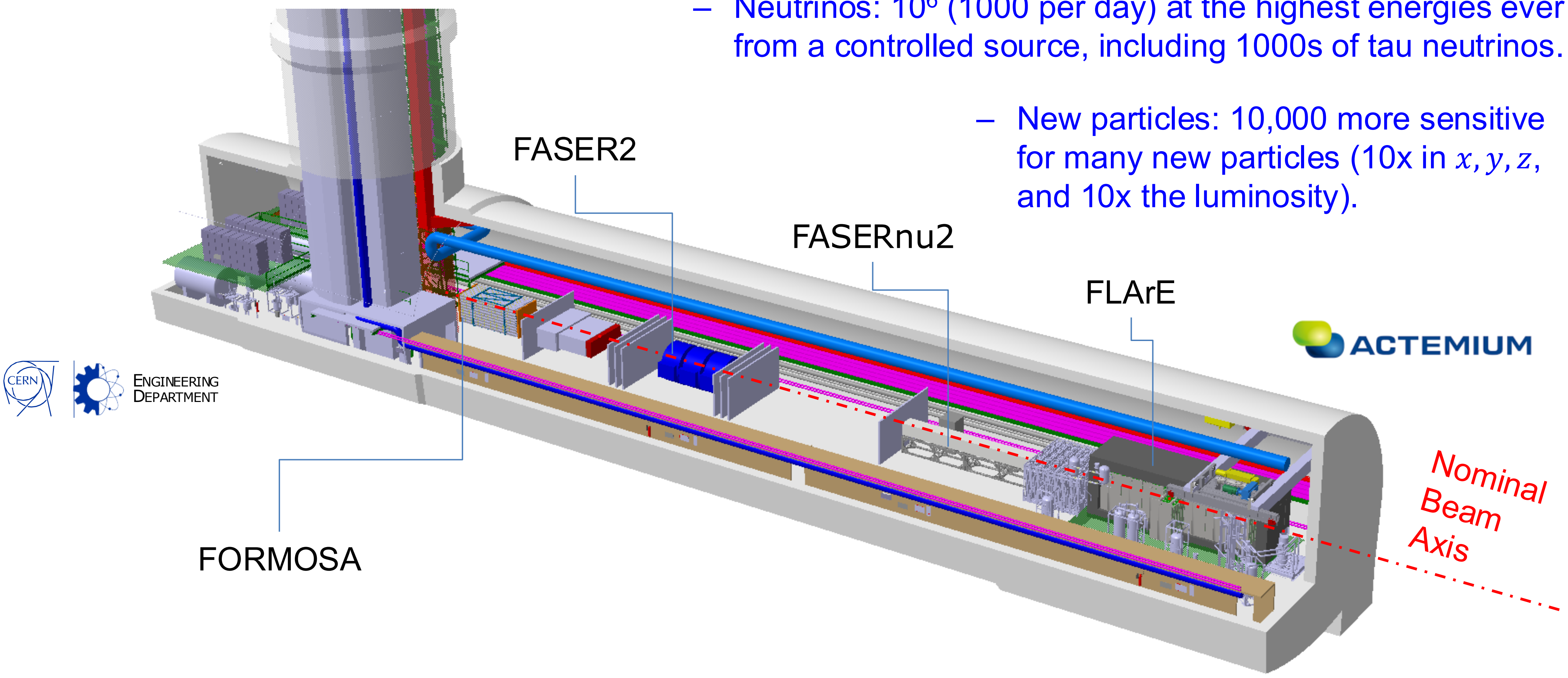


Anastasiya Magazinik, Julien Prosic, talk at FPF9, 5 March 2026

FORWARD PHYSICS FACILITY

4 experiments, all on the LOS to maximize the discovery potential of the LHC.

- Neutrinos: 10^6 (1000 per day) at the highest energies ever from a controlled source, including 1000s of tau neutrinos.
- New particles: 10,000 more sensitive for many new particles (10x in x, y, z, and 10x the luminosity).



Anastasiya Magazinik, Julien Prosic, talk at FPF9, 5 March 2026

CONCLUSIONS

There are good reasons to think that the next breakthrough in particle physics will involve LLPs.

- LLPs are ubiquitous in BSM theories, especially those with cosmological significance.
- SUSY (with GMSB, AMSB) naturally motivates both heavy and light LLPs.
- Especially for light LLPs, we are in the "low-hanging fruit" era, with many opportunities for fast, small, and cheap experiments that are making (and could make) huge strides forward. We are beginning to see results, with much more to come!