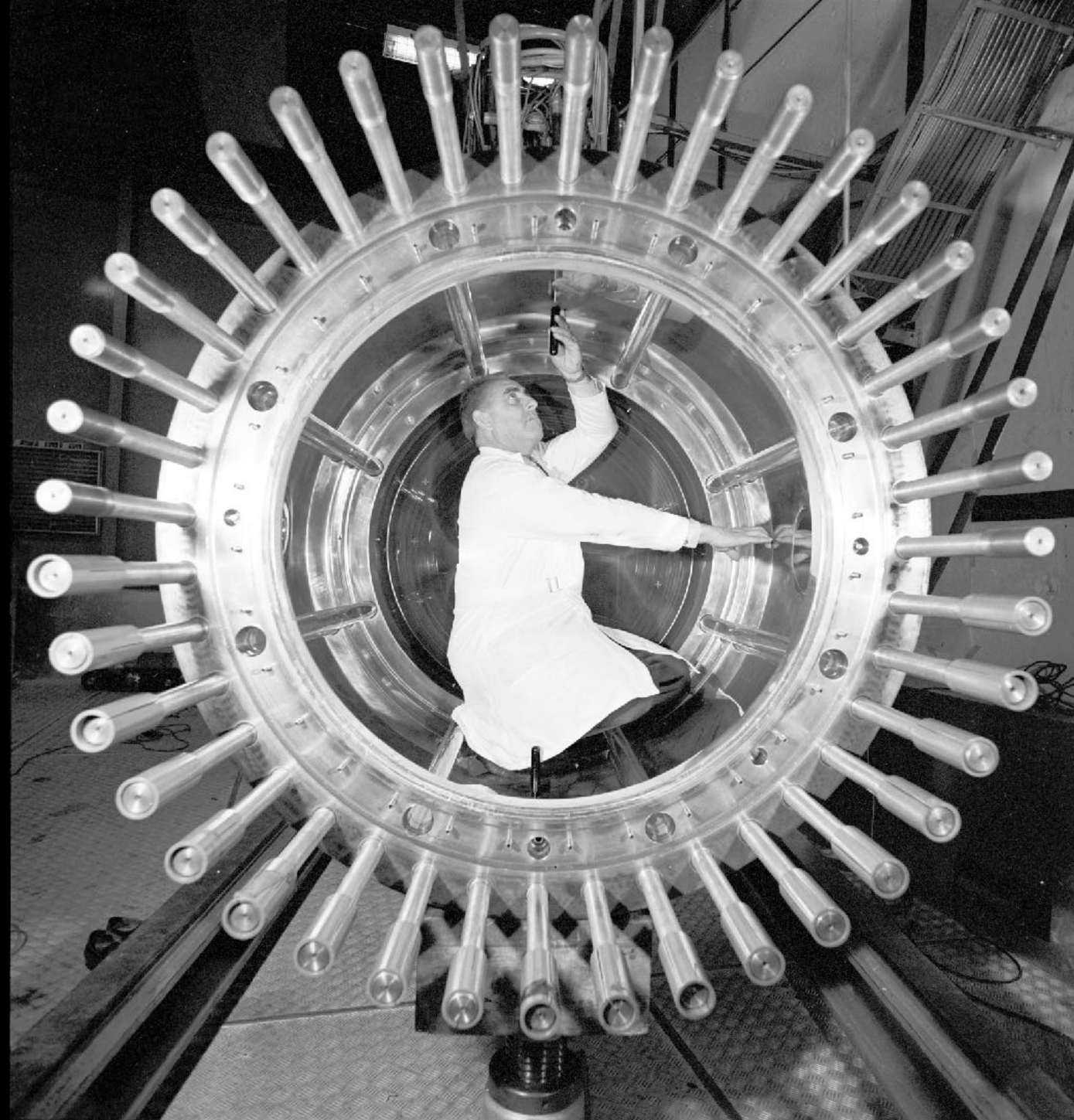
Dark sector searches

at the energy and
accelerator frontiers

Near and far future

James Beacham
Duke University

Snowmass Community
Planning Meeting
6 October 2020



Dark sectors in 2020

Still in the same epistemic dark-sector boat as we were 10 or 15 years ago

- Dark matter exists and interacts gravitationally
- We don't know what it is, nor how else it interacts, if at all

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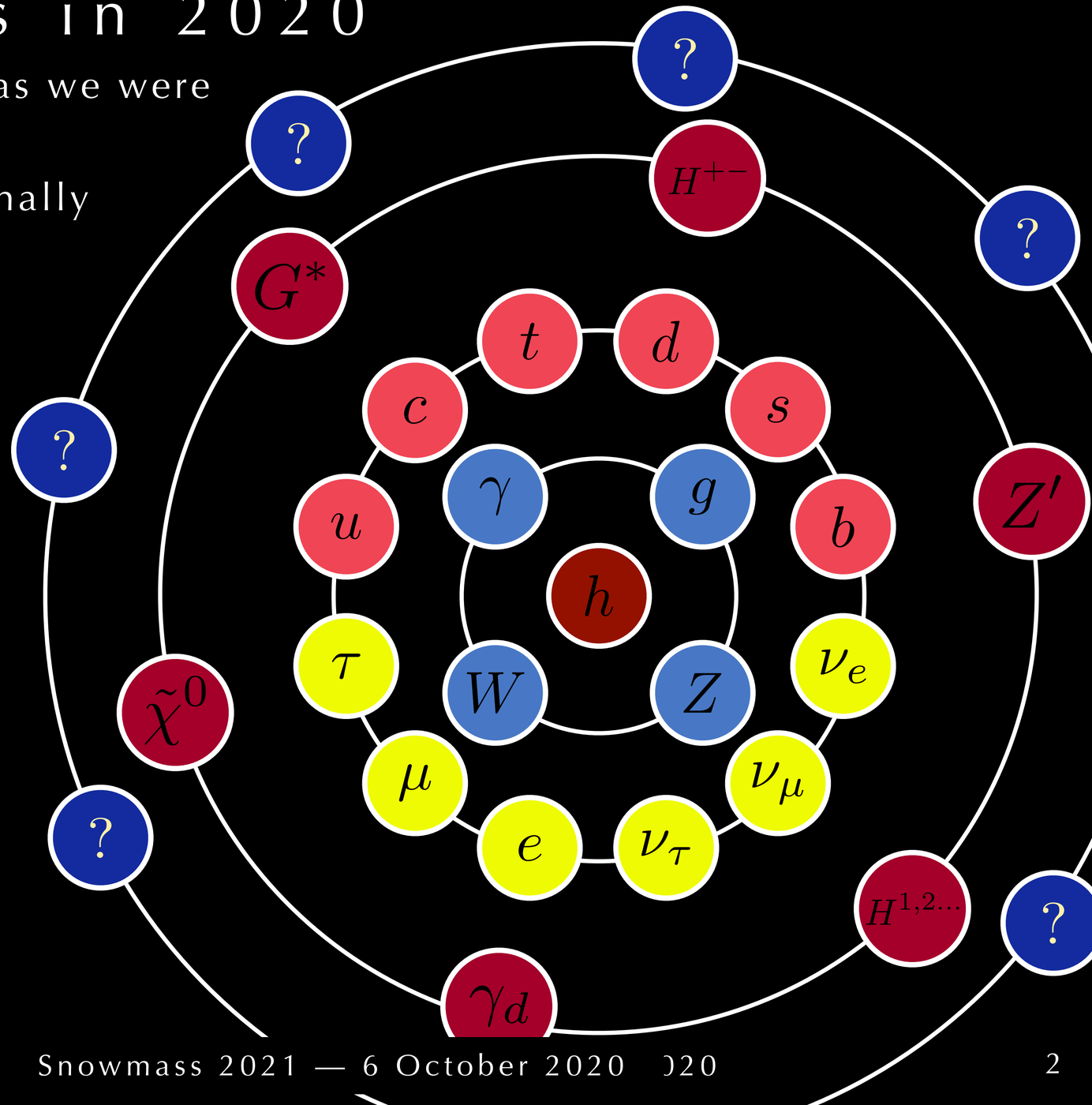
The key difference today is that we've mostly finally disabused ourselves of the notion that an answer to what dark matter is "should" or "will" show up in the "most likely" places

- Old-school WIMPs in tension
- Weak-scale SUSY a no-show so far

Even ~five years ago still had people saying that a dark sector model needed to be "elegant" or "well-motivated", two words that mean whatever you want them to mean

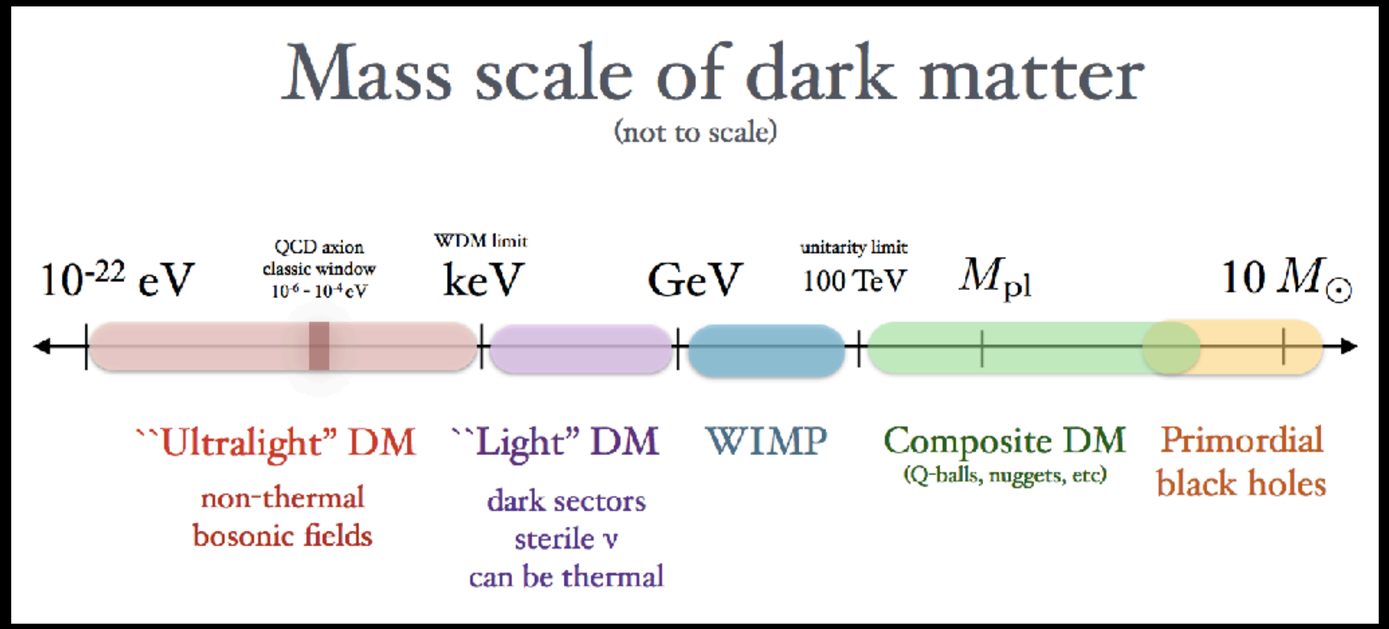
However, the universe doesn't care whether we think its laws are elegant or not



Dark sectors in 2020

The worthiness criterion for dark sector ideas in 2020 is *not*, “Is your idea well-motivated?”, but instead

- Is your idea impossible?
- Does it conflict with current observations?
- Does it horribly violate known laws of physics?
- Is it ruled out yet?



T. Lin, 1904.07915

If you can answer *No* to all of these, then we should and will look for evidence of your idea

In this sense, the portal framework and ideas like new generic or SM-like vector gauge bosons are good, because they focus on what’s possible and not ruled out

But more complicated, non-minimal dark sectors are just as “motivated” as anything and should be front-and-center for searches, as well

Yes, we must look everywhere; if we don’t, we’ll simply never know

The guiding principle for dark sector searches in the future is, “Explore everywhere”

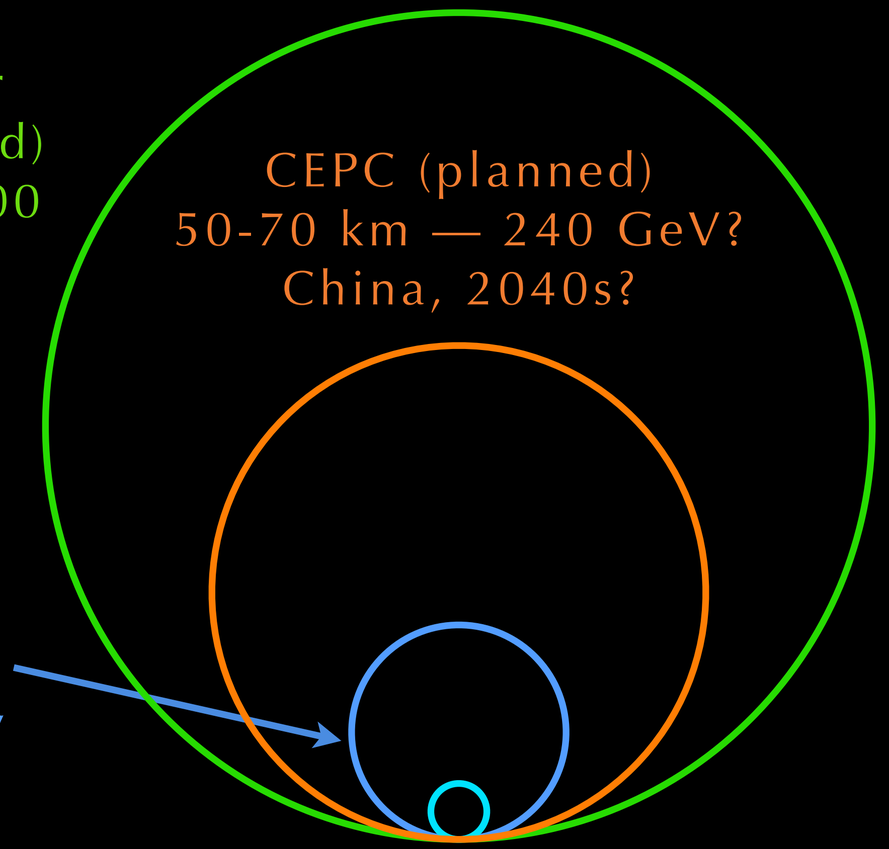
As evidenced by the number, scope, and breadth of the dark-sector-related Snowmass LoIs received, this luckily seems to be the dominant mindset!

Obviously, the energy and accelerator frontiers play a central exploratory role

Colliders at the energy and accelerator frontiers

Circular

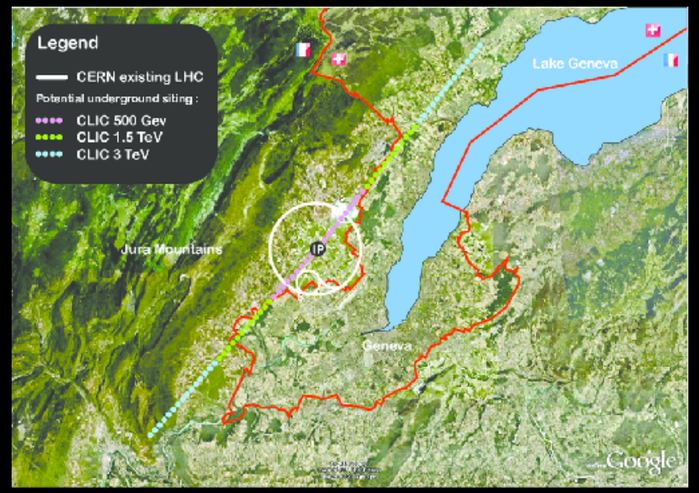
Future Circular Collider (planned)
80-100 km — 100 TeV?
CERN, 2040s?

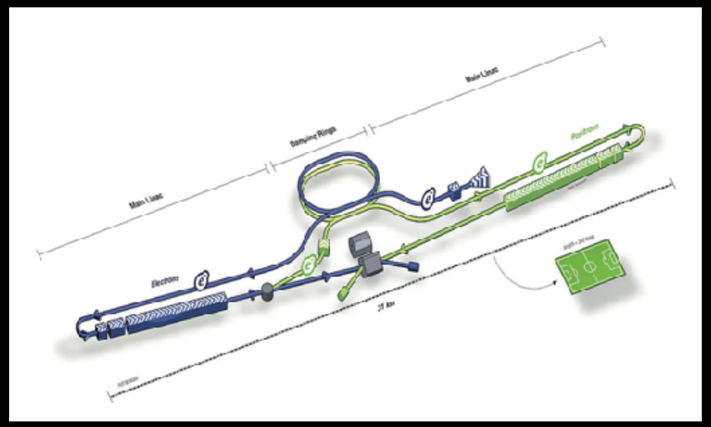


LHC
27 km — 13 TeV
CERN, 2010

Also discussed: LHeC and HE-LHC
CEPC —> SppC

Linear



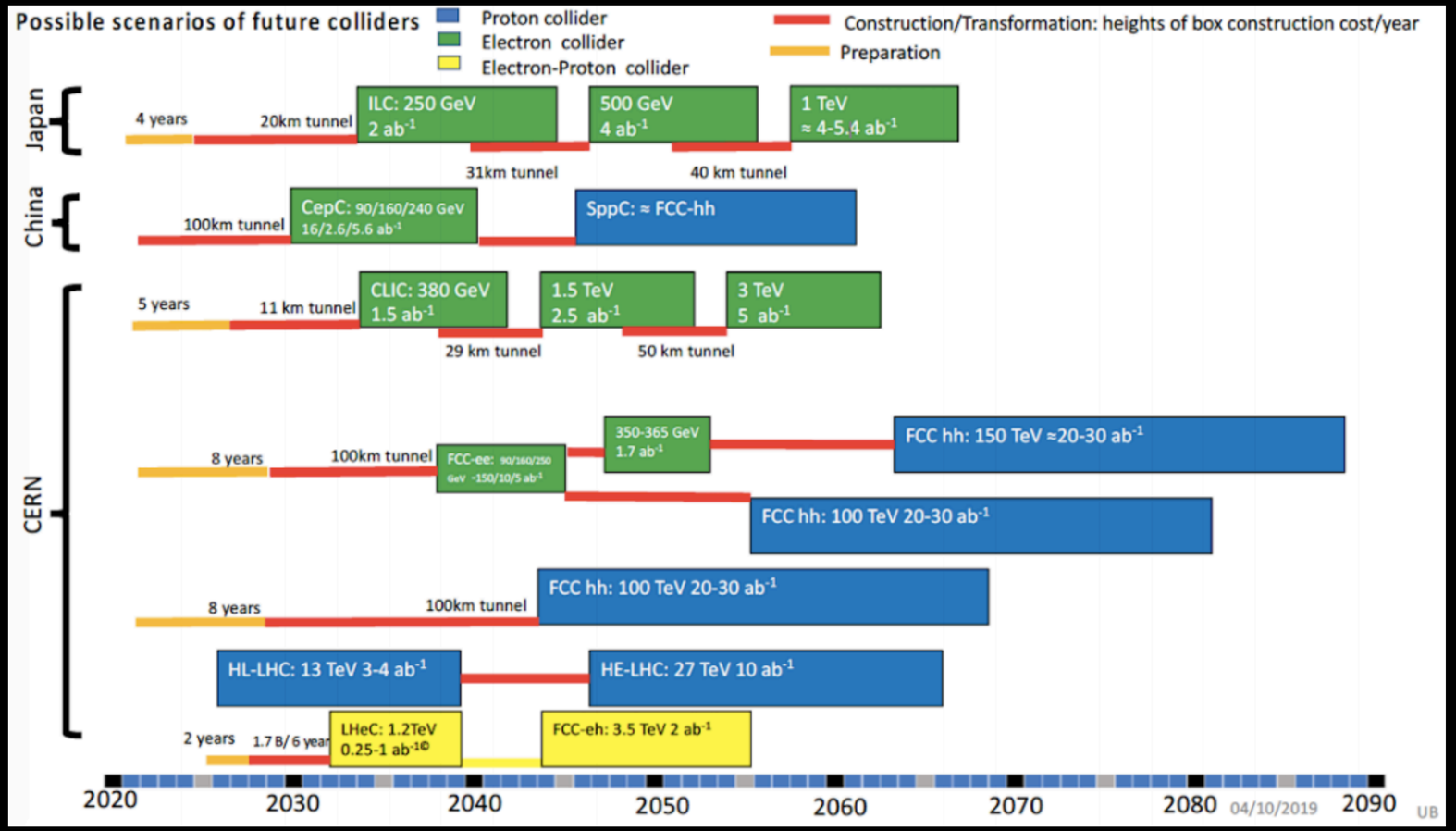


CLIC and ILC

Colliders at the energy and accelerator frontiers

Several proposed projects at the energy / accelerator frontiers

- Higgs/Z factories colliding e+e- at fixed, ~100s of GeV to few TeV energies (ILC, CLIC, FCC-ee, CEPC, muon collider)
- High-energy pp discovery machines (FCC-hh and SppC at 100/150 TeV, 500 TeV Collider in the Sea)



U. Bassler via G. Taylor)

But the present and near future are packed with ideas and experiments, too

- HL-LHC encompasses a wide range of projects and sub-projects
- Fixed target / beam dump accelerator projects not shown here that either use existing facilities to search for dark sectors or will be entirely new projects
  - SeaQuest, SHiP, NA62, NA64, LDMX, AWAKE, KLEVER, X@JLab, Mainz, Frascati, many others — this talk is a sampling

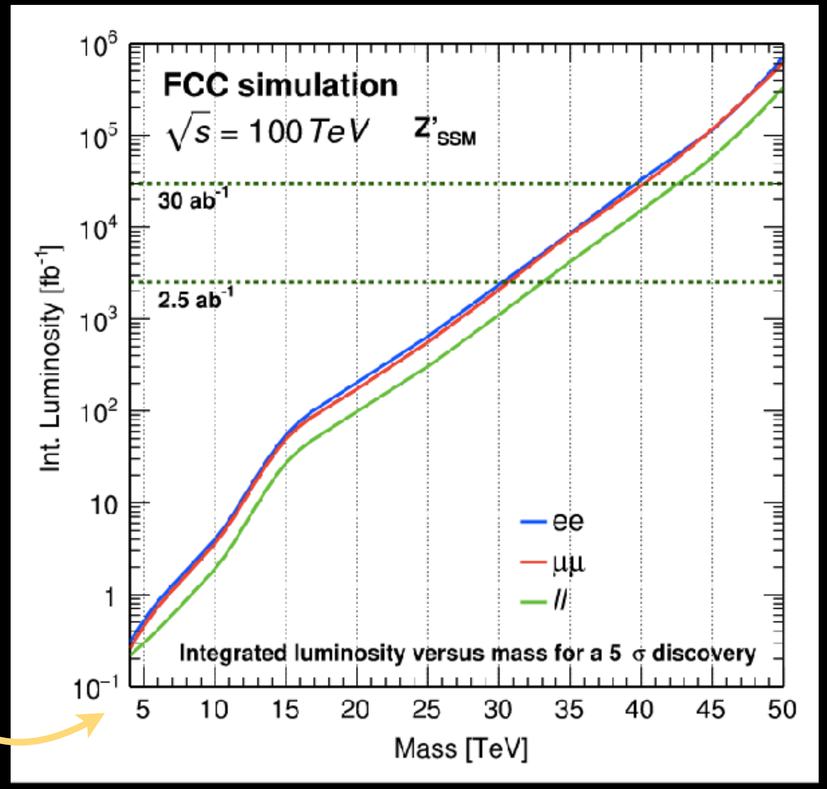
Dark sectors at the energy and accelerator frontiers

How do EF and AF projects probe dark sectors?

- High-mass mediators / force-carriers inaccessible at prior facilities
- Low-mass, feebly-coupled mediators that only show up with high luminosity / larger datasets
- Missing mass / energy / momentum searches
- Long-lived particle signatures (ubiquitous in dark sectors)
- Precision measurements, of, e.g., Higgs width
- Atypical detector objects / phenomenology that could correspond to dark QCD / dark showers / rich dark sectors in general
- Something unexpected / deviation from background expectation

New high-mass mediators / force-carriers at colliders

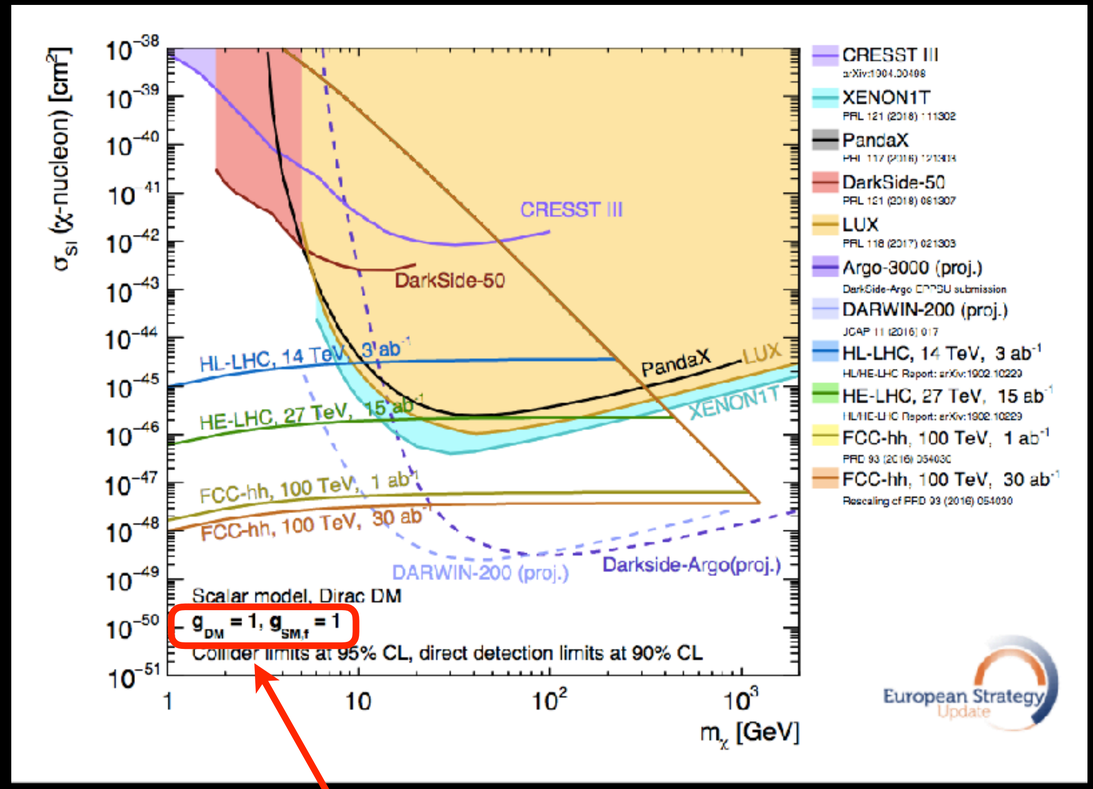
Z′ decaying to leptons at an FCC-hh



Maximum mass sensitivity for HL-LHC

Eur. Phys. J. Spec. Top. 228, 755–1107 (2019)
BSM HL-LHC Yellow Report

Translating jet final states into exclusions on DM mass



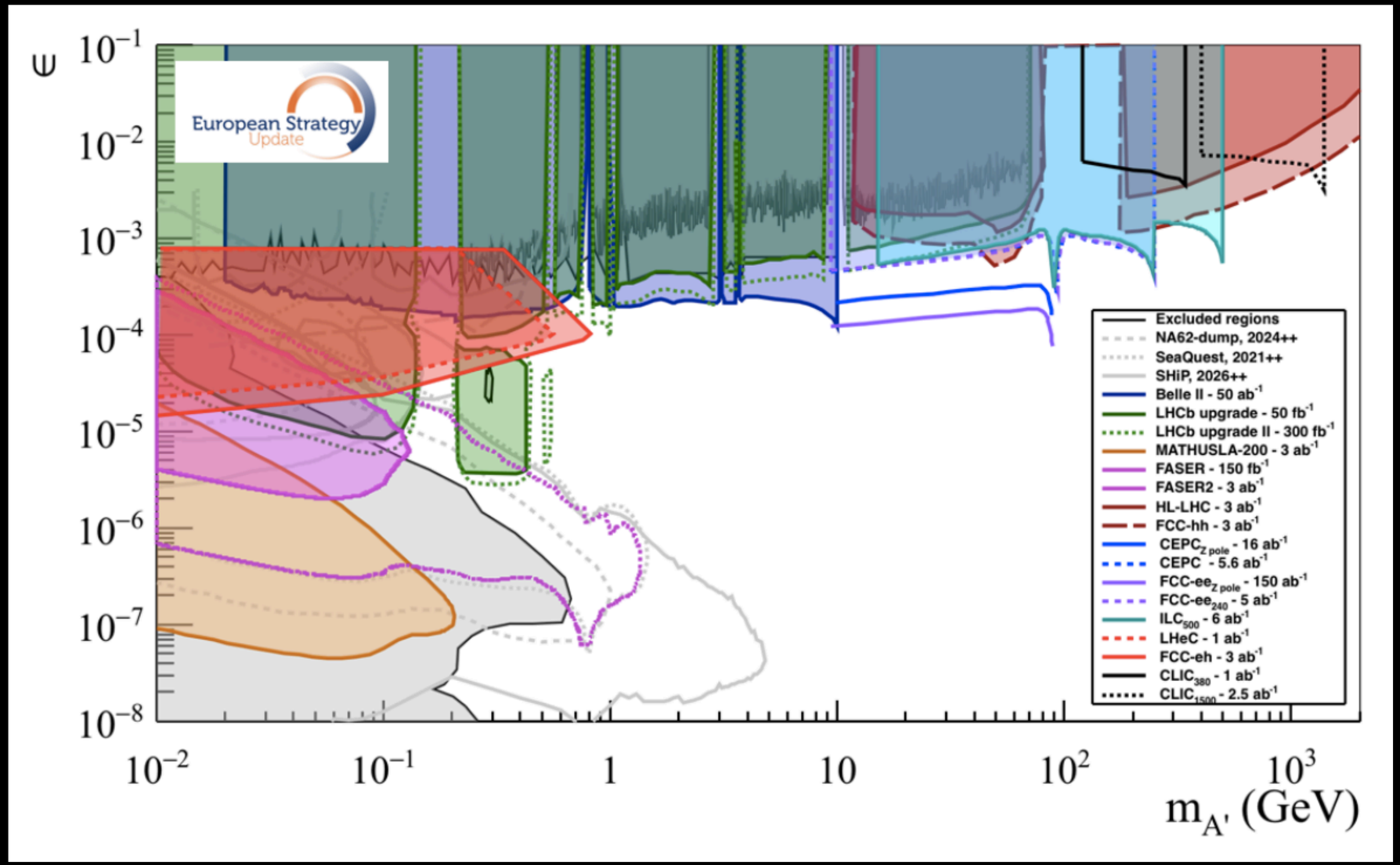
1910.11775

Good to see Snowmass LoIs hopefully about better understanding and developing comparisions like these

High-energy machines are good at making new, high-mass SM-to-dark-sector mediators, if they exist (not shown here: mono-X searches)

Low(ish)—mass, feebly-coupled mediators

Dark photon (A′) / dark Z



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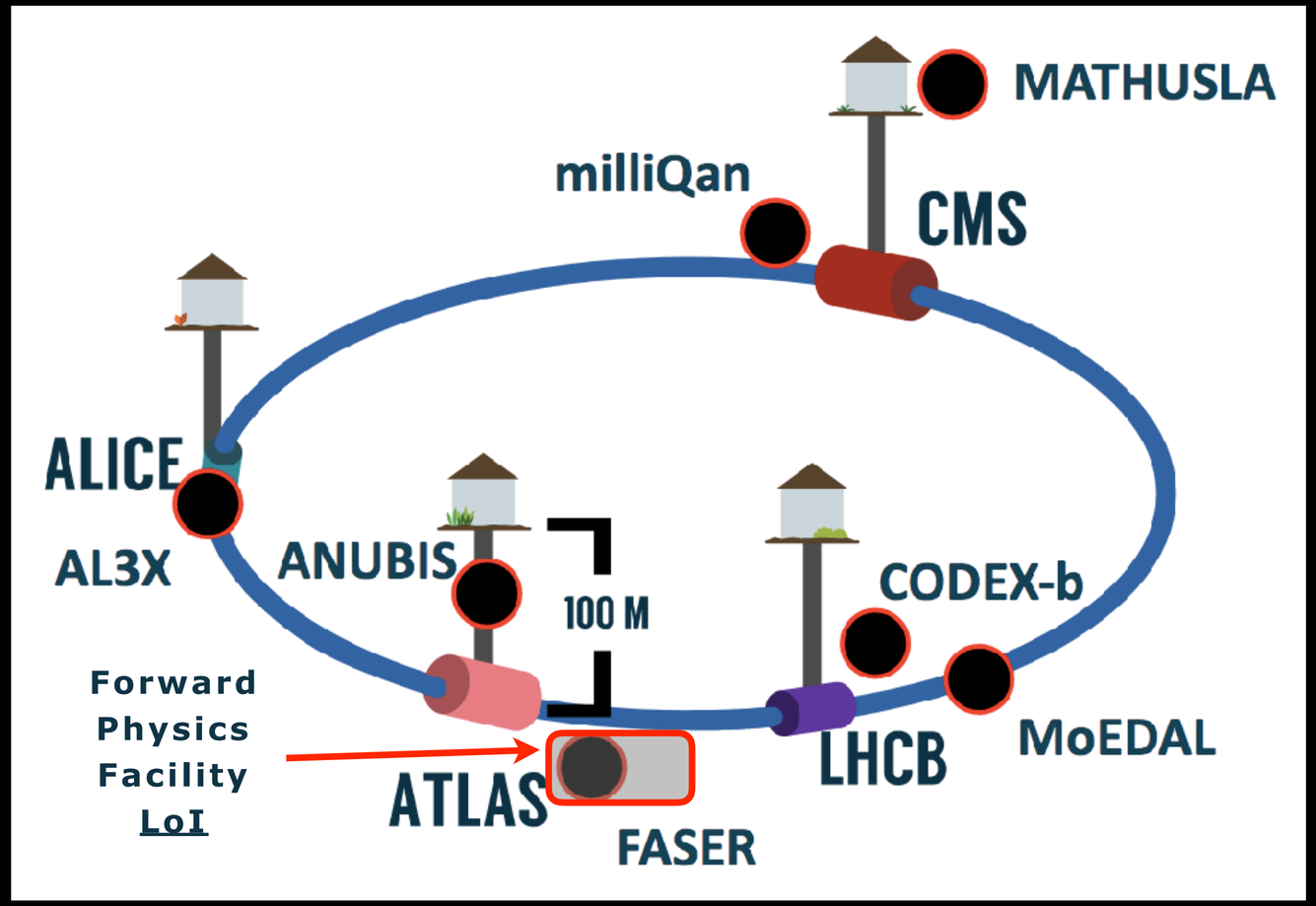
Complementarity is key

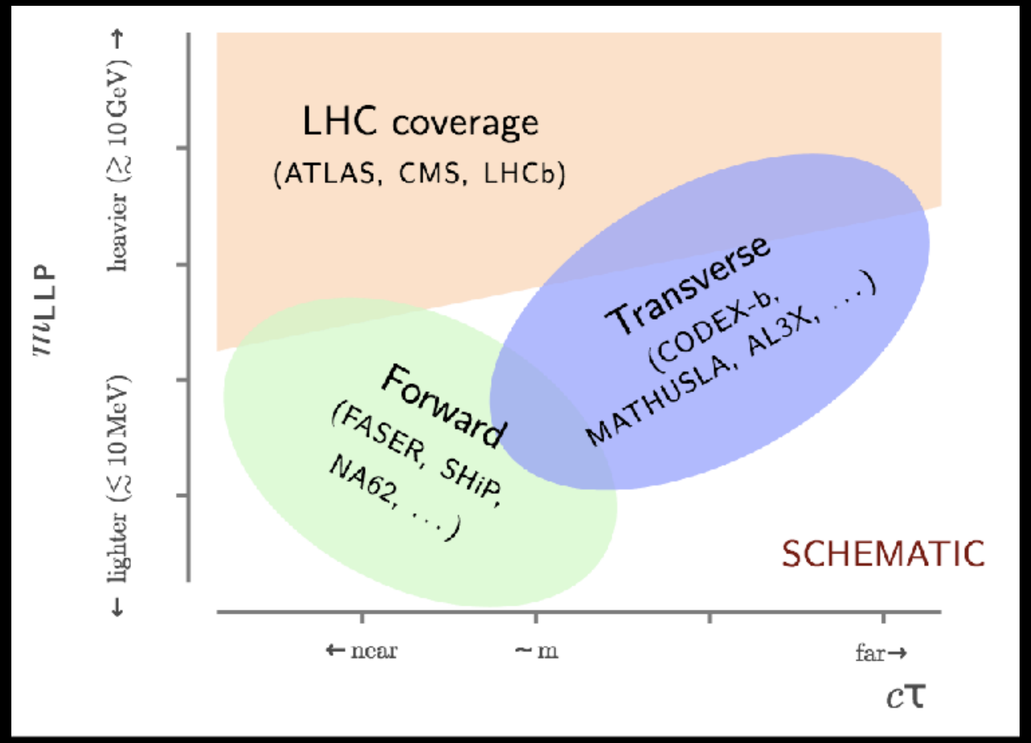
Only way to ensure adequate and corroborable coverage is with multiple experiments

Not shown here: A′ —> invisible

Dedicated detectors at the LHC



Modified from H. Russell at FIPs 2020



P. Ilten

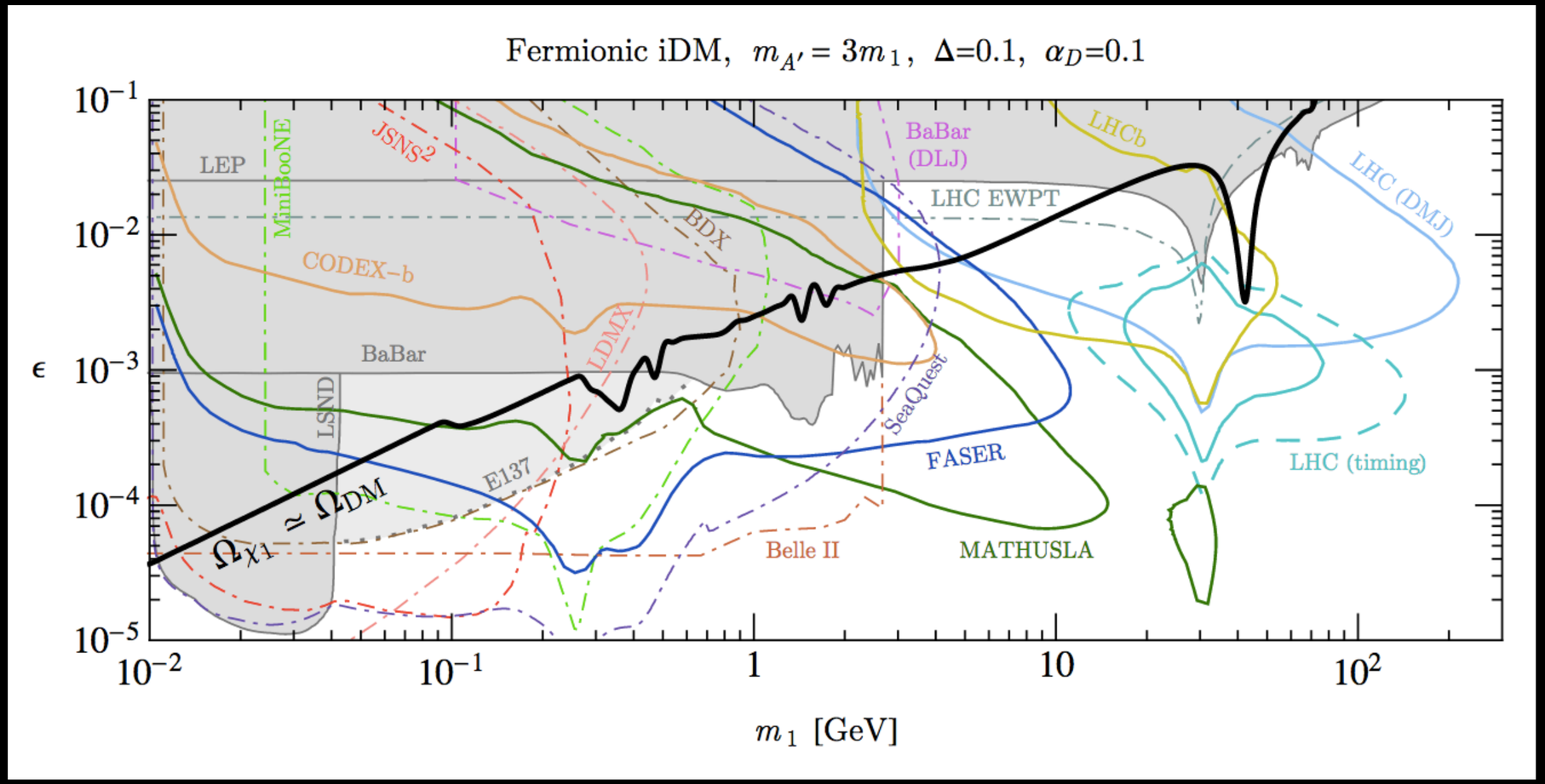
If the dark sector particle (dark photon, dark pion, heavy neutral lepton, millicharged particle, etc.) has such a long lifetime that it escapes the detector volume of the central LHC detectors, can build dedicated LLP detectors near the pp interaction point

experiments like CODEX-b [104] (see section 5.3.5), FASER [105] (see section 5.3.6), or MATHUSLA [103] (see section 5.3.4). Each of these dedicated experiments is sensitive to different LLP lifetimes, masses, and production modes based on their position and orientation and thus each can be considered a necessary component of a comprehensive, coordinated search program for very long-lived particles at the LHC.

LLP Community white paper

Dark photons and dark matter

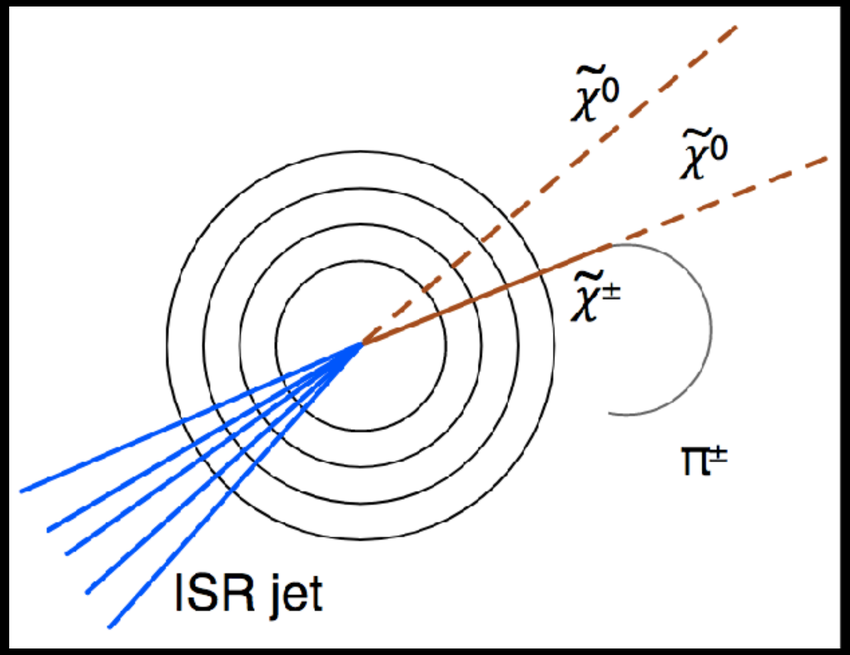
For a fixed dark photon mass, can see the vital need for multiple experiments for, e.g., this inelastic dark matter model

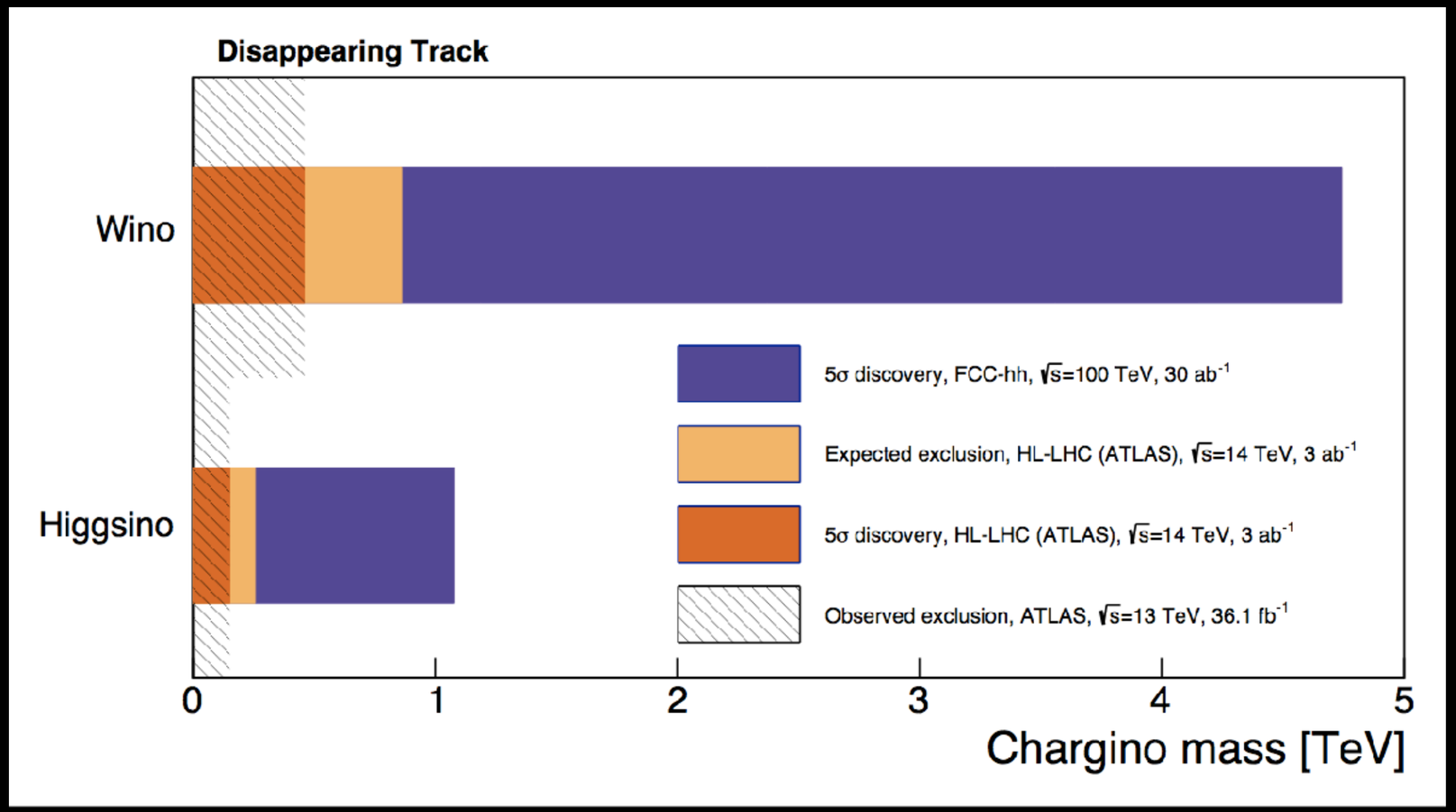


1810.01879

Good to see Snowmass LoIs dedicated to exploring and expanding these proposals — they all need to be funded and approved as soon as possible

Disappearing tracks for Wino / Higgsino DM





These studies underscore the necessity of including LLP signatures within the standard set of benchmarks when designing future detectors

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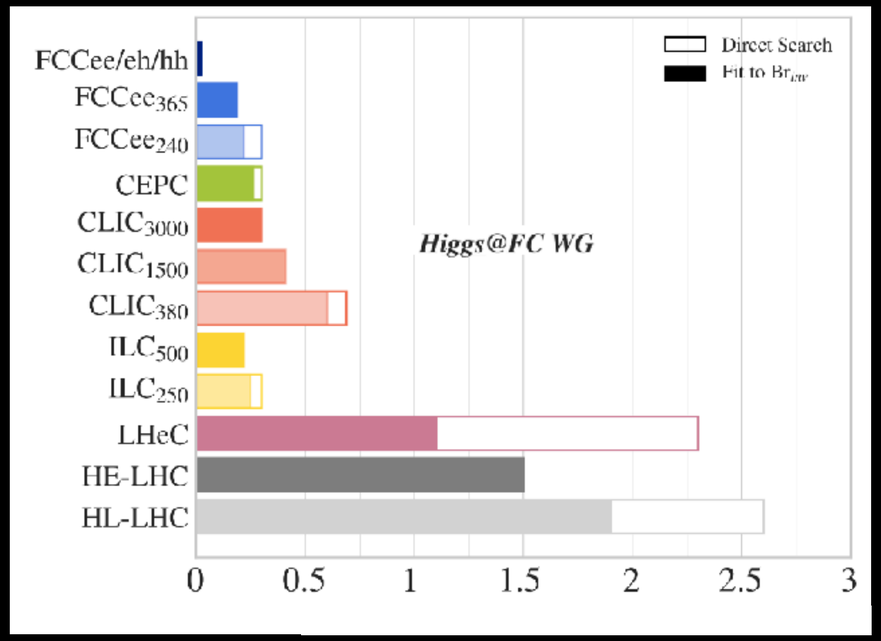
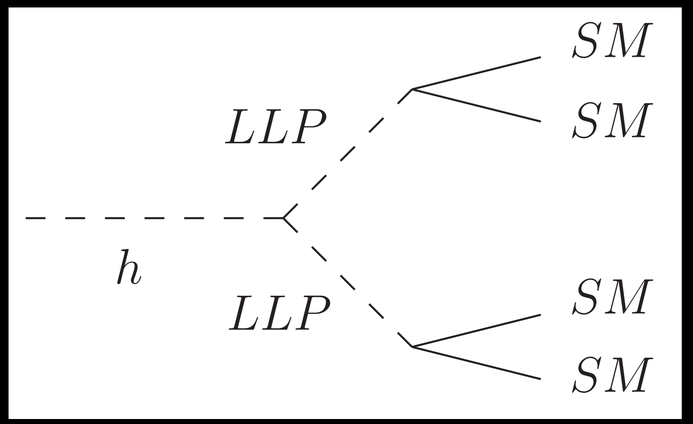
Some other studies have been done for, e.g., CLIC, FCC-ee/CEPC, and very good to see a Snowmass LoI about LLPs at FCC-ee

Invisible and exotic Higgs decays

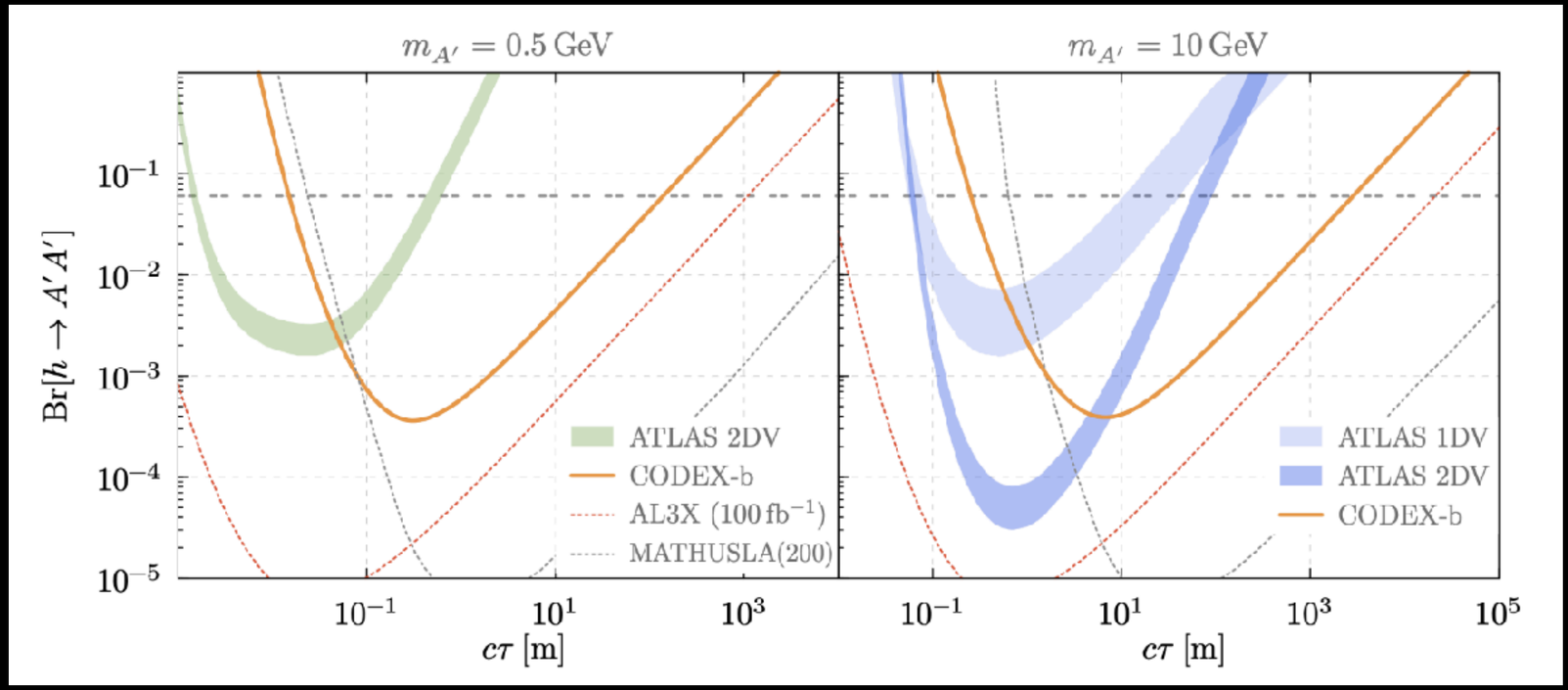


M. Cepeda at FIPs 2020
1905.03764

Future colliders will reduce limits on invisible Higgs width to tiny

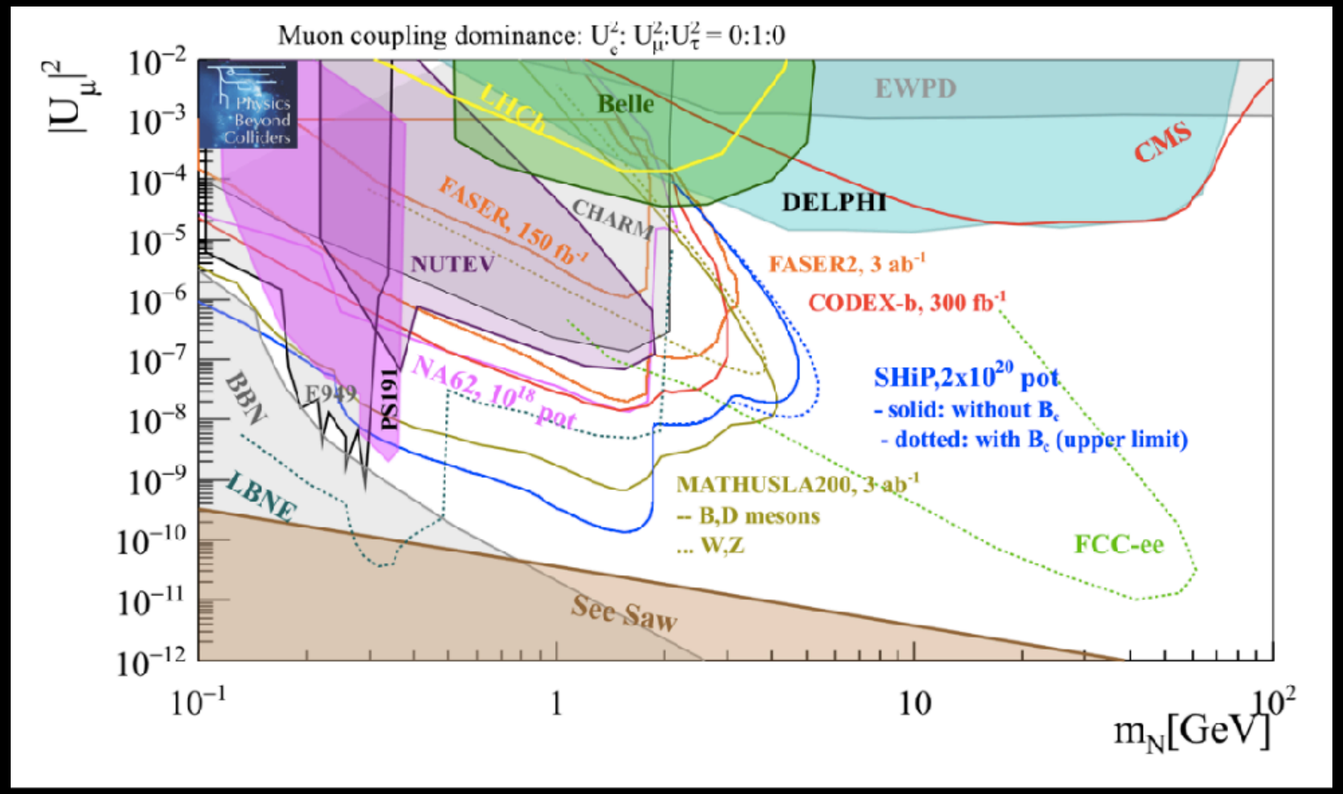


But searches for Higgs decays to, e.g., BSM LLPs at the LHC can be powerful direct dark sector probes



D. Curtin at FIPs 2020 (and refs)

Heavy neutral leptons / sterile neutrinos



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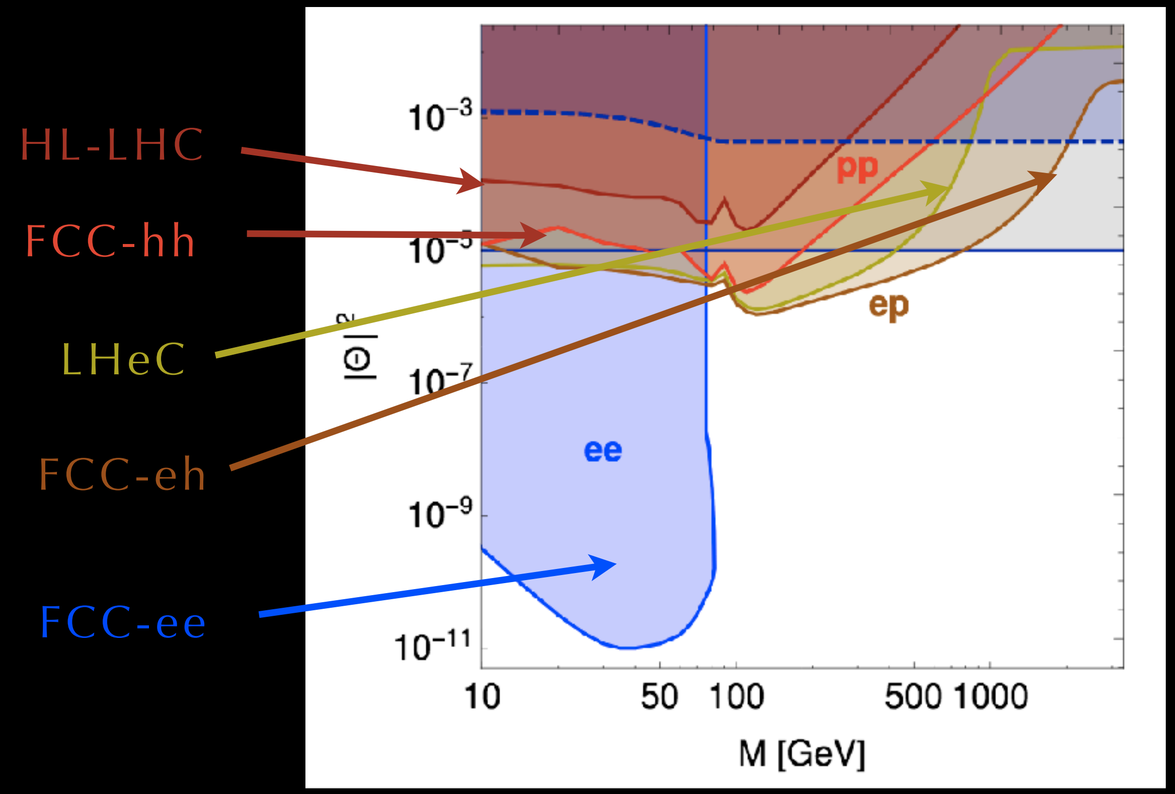


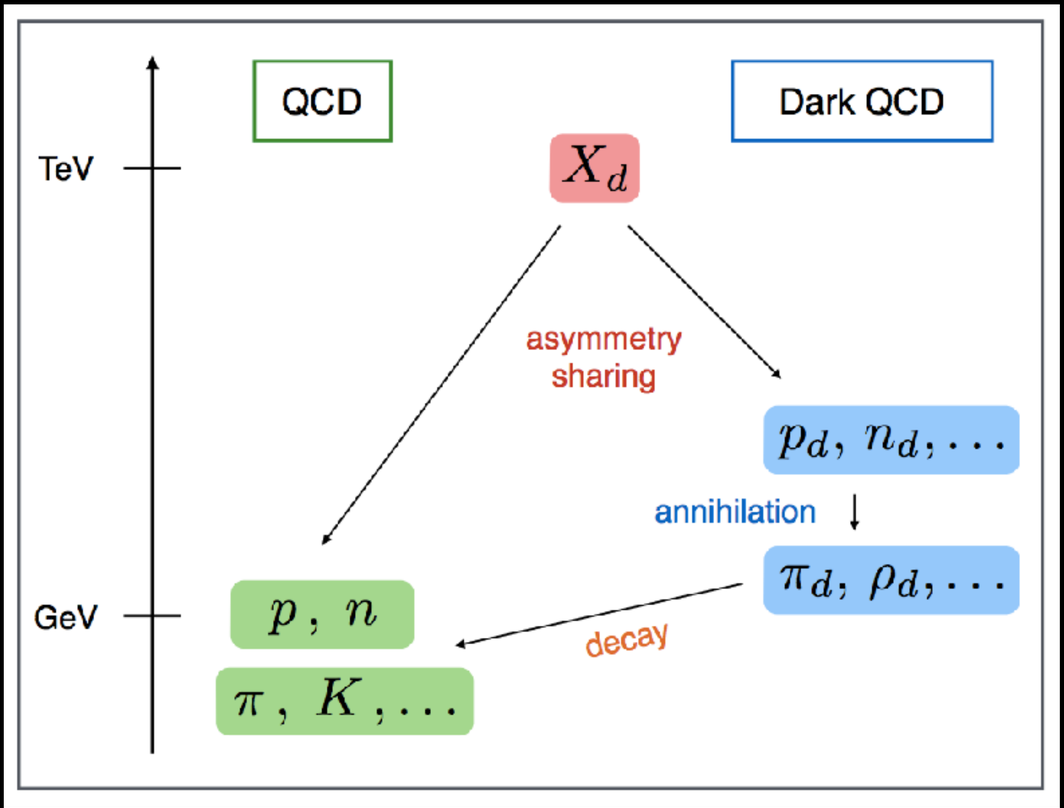
1612.02728

Heavy BSM neutrinos could explain many things, like why SM neutrinos have such tiny masses — and in some cases one of the HNLs could be a DM candidate

Current dominant HNL benchmark models can be limiting — need to include non-minimal models — see HNL session at FIPs 2020

Dark QCD and rich dark sectors

JHEP (2015) 2015: 59



The SM is a bit complicated

Why would we expect the dark sector, 5x the universal energy budget of the SM, to be *less* complicated?

Dark / hidden sectors with confining dynamics could yield a zoo of dark particles

Can also yield very different collider phenomenology than we might original expect

QCD-like or -unlike dark sectors underscore how much we don't know about what we don't know

Wide range of collider phenomenology, from jet-like objects to soft radiation patterns and in between

To ensure we're not missing anything, need good benchmarks (like the LoI about jet-like objects at the LHC), but also better understanding of the phenomenology both at the LHC and beyond

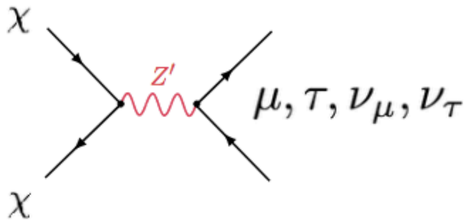
Emerging jets —PRD 89, 063522 (2014); JHEP (2015) 2015: 59; JHEP 02 (2019) 179
Semi-visible jets / dark jets — PRL 115 (2015) 17, 171804
Soft, unclustered energy patterns (SUEPs) — JHEP (2017) 2017: 76
Classic hidden valley literature — PLB 651:374-379, 2007; JHEP 07 (2008) 008, others
Dark showers, Chapter 7 of the LLP white paper — J. Phys. G 47 090501 (2020)
Recent work — 2004.06125; 2009.08981

Dark sectors at a muon collider

Muon Philic DM

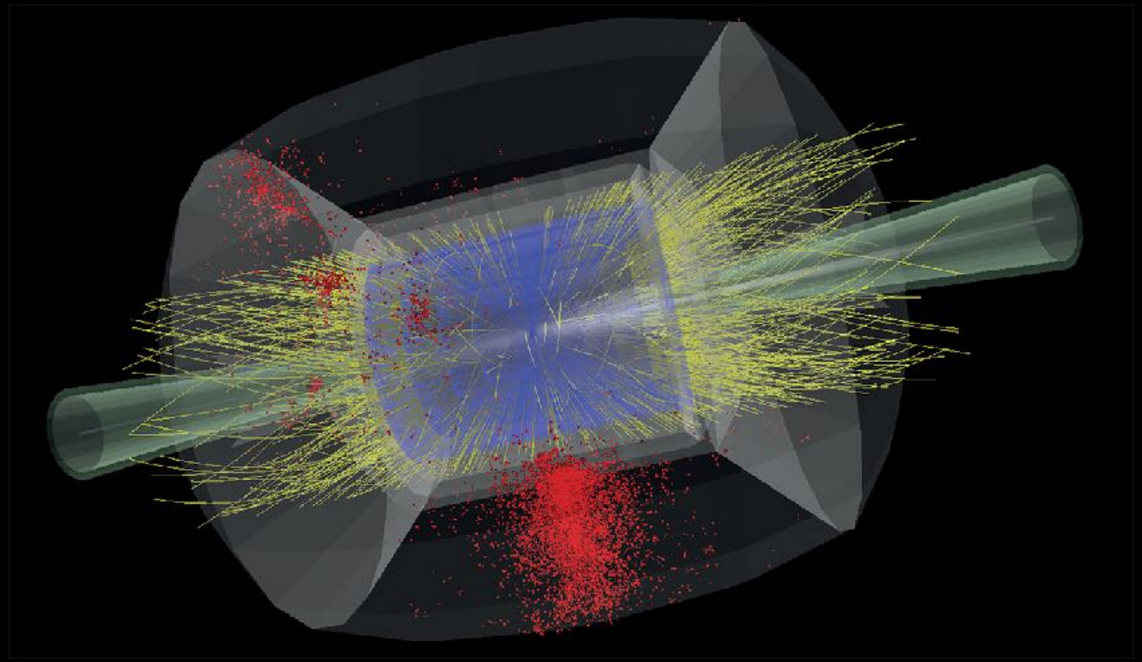
Q: Why haven't we discovered DM thus far?

A: Maybe because it couples more to higher generations



Example: gauged $L_\mu - L_\tau$ Interaction

Talk at EF10 meeting



CERN Courier, May 2020

A few to 10s of TeV muon collider could potentially do fantastic physics (including dark sector searches) without the need to build a new, big tunnel

Currently understudied

The good news: Several LoIs about a muon collider with dark sector implications

What I'd like to see emerge from Snowmass 2021

Ensure that LLP signatures are positioned within the central set of considerations for future detector design

- IDEA: Innovative Detector for an Electron-positron Accelerator — LoI
- LLPs at the FCC-ee — LoI

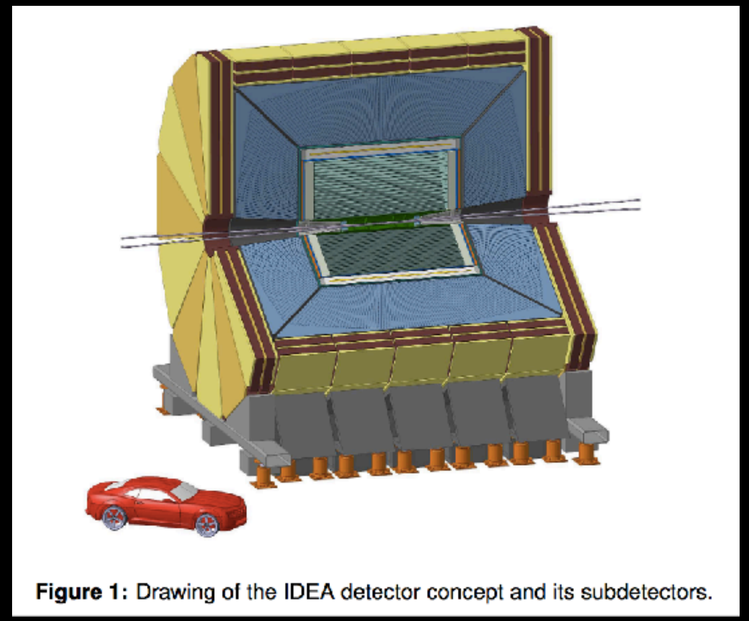
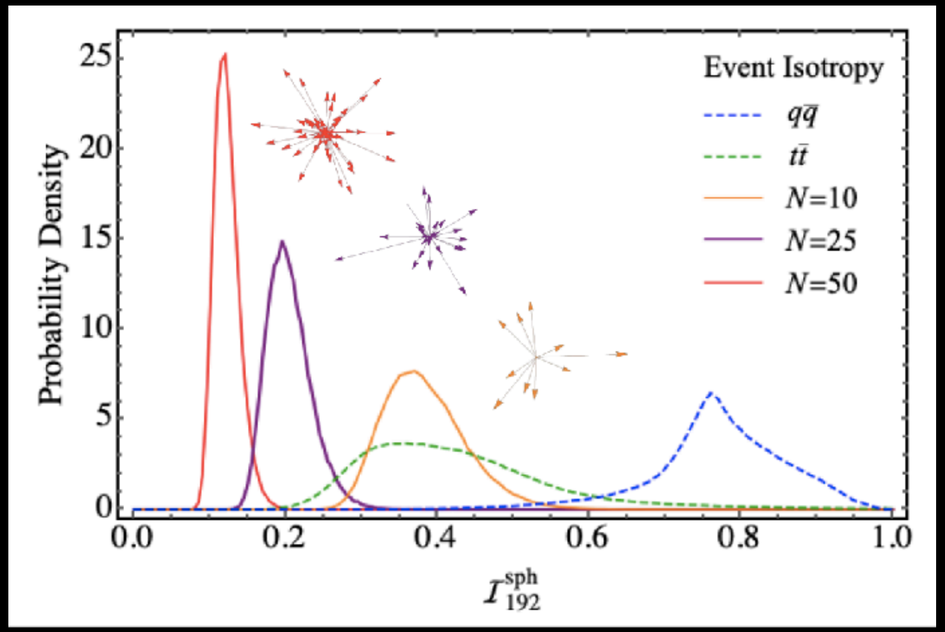


Figure 1: Drawing of the IDEA detector concept and its subdetectors.

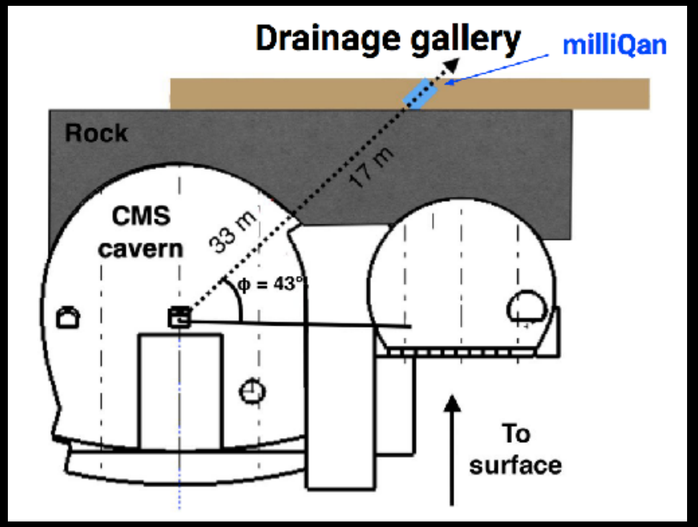


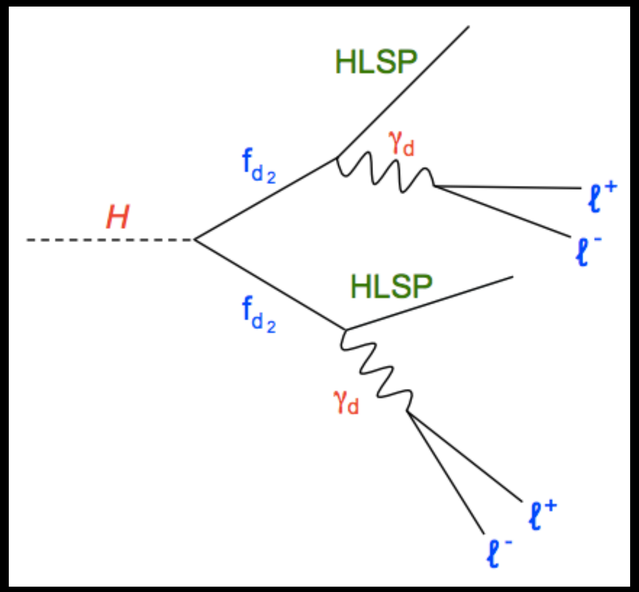
Better understanding of dark-QCD-like signatures at current and especially future EF and AF projects

What I'd like to see emerge from Snowmass 2021

Clear message that the entire slate of dedicated LLP detectors at the LHC receive full funding and approval, to adequately explore dark sectors at the HL-LHC

- They all cover complementary dark sector parameter space and are all needed



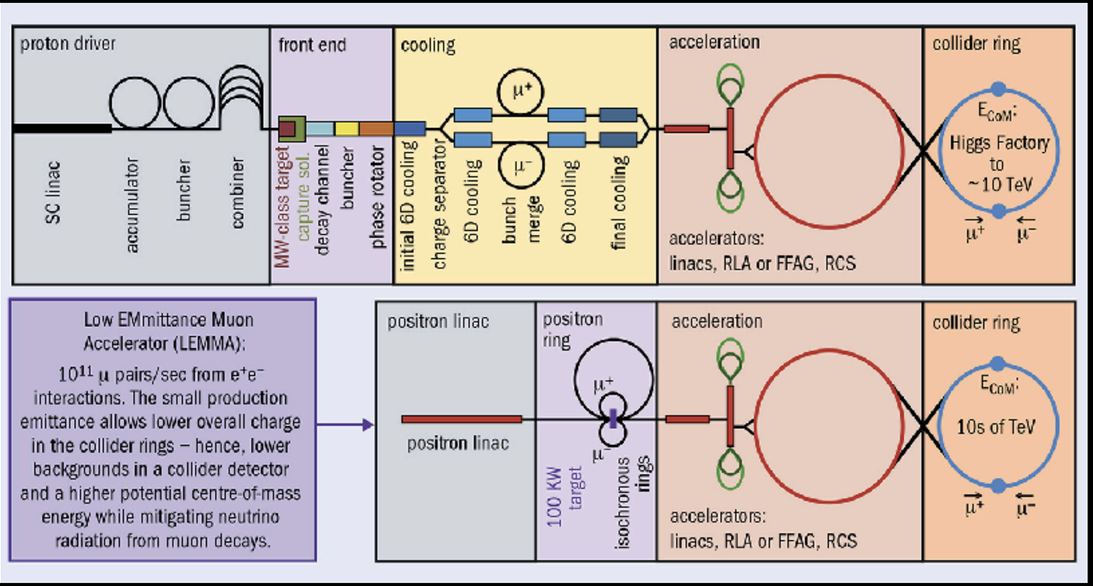


Clear message that, while benchmarks are fine, focus should be the physics inspiration of the benchmark; non-minimal benchmarks can be developed and centered, as well

- Dark photon with Higgs coupling
- Non-minimal HNL scenarios
- Dark QCD, et al

Many pheno papers and experimental results and projections do this already, but sometimes different approach taken by community efforts

What I'd like to see emerge from Snowmass 2021



More comprehensive understanding of the physics potential of a muon collider

- Several LoIs about this, which is great

More comprehensive consideration of very forward-thinking ideas like a <u>500 TeV Collider in the Sea</u> — or my long-standing idea of building a PeV-scale collider on the moon in collaboration with NASA ("NASA is going back to the moon. How could physicists collaborate?" — Jim Siegrist, DoE, yesterday)

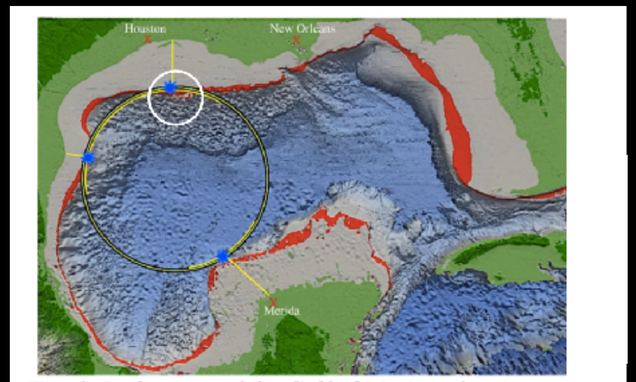
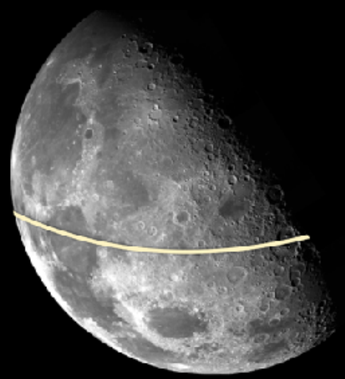


Fig. 1. Bathymetry of the Gulf of Mexico, showing one potential alignment of a 1,900 km circumference hadron collider. Red=100→200 m isobaths; Gray=0–100 m isobaths; blue=detectors. White = 300 km ring for FCC-ee, then 100 TeV FCC-hh, and later as injector for 500 TeV collider.

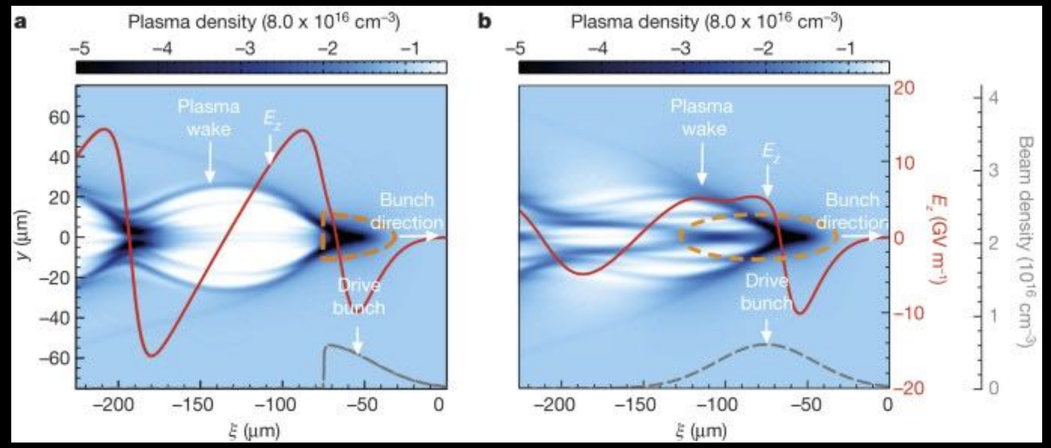
Tens of thousands of TeV

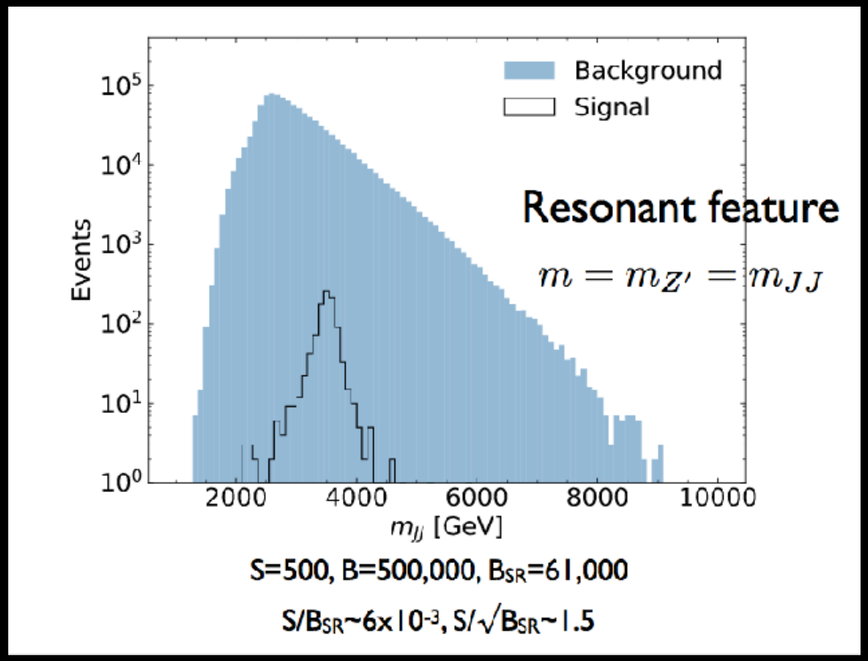


What I'd like to see emerge from Snowmass 2021

Clear message that full utilization of plasma wakefield technology is of the utmost importance

- Robust research and plenty of LoIs in this direction





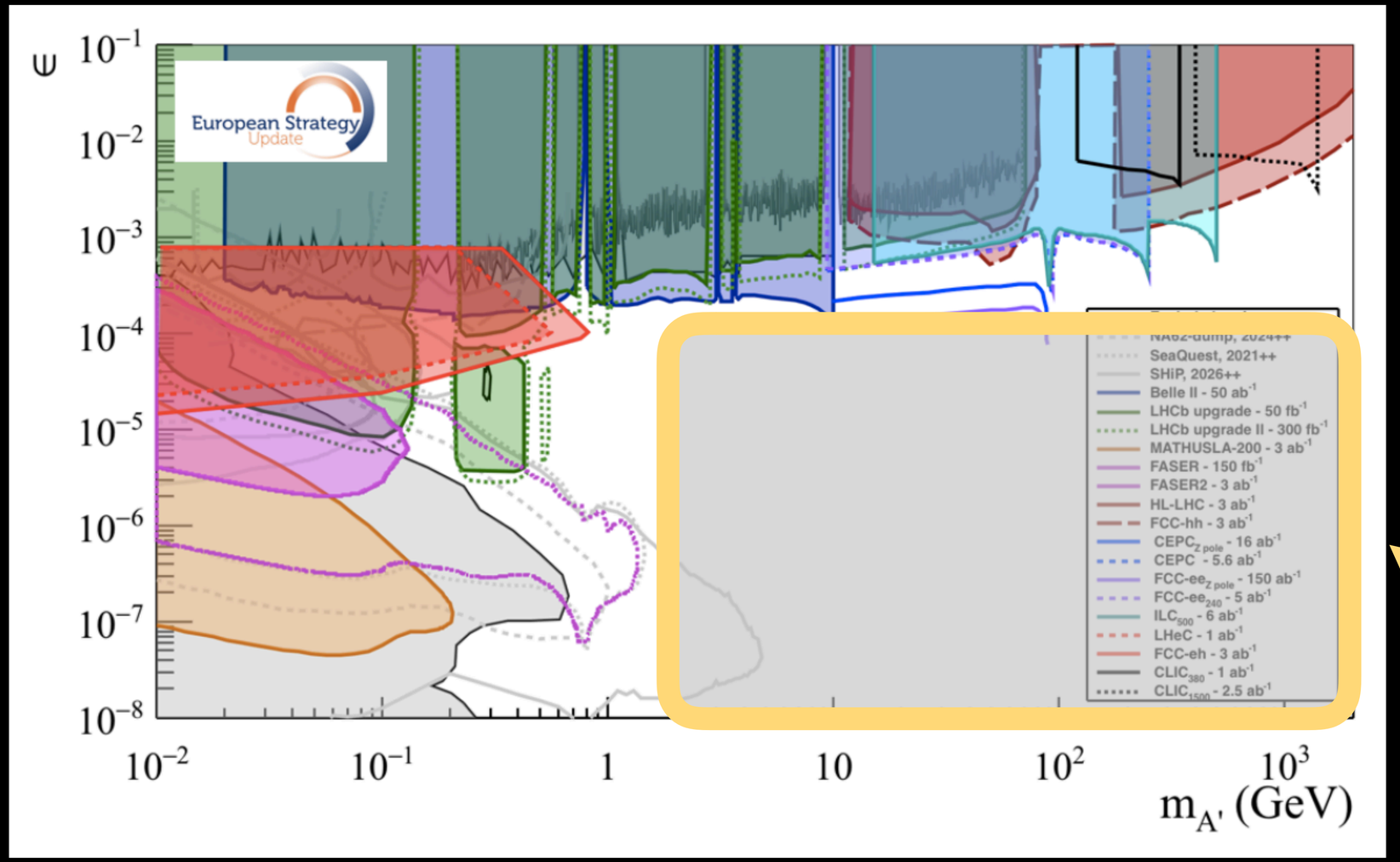
Automated anomaly detection

- Modern data analysis / deep learning techniques could greatly assist ability to spot deviations from SM expectations
- Modest efforts to investigate this at the LHC so far, but because the future of particle physics is experimental our searches can benefit from being guided by very model-independent methods like ML / AI
- Good to see one LoI about this in the context of the LHC Olympics

Reserve slides

Low(ish)—mass, feebly-coupled mediators

Dark photon / dark Z



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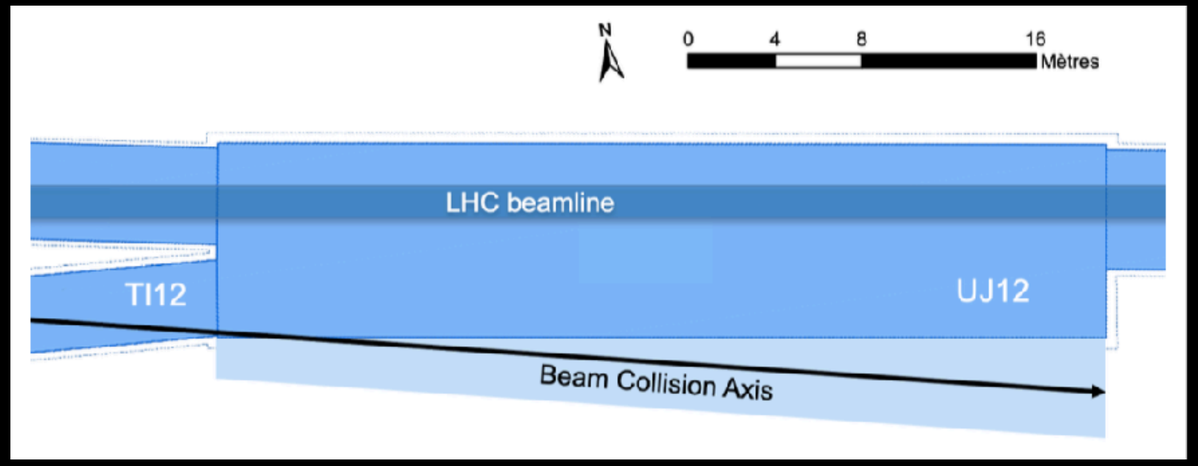
What about here? Is this really only for future civilizations with centuries to take data?

Dedicated detectors for long-lived particles at the LHC

Forward Physics Facility

The proposers of FASER have also proposed that one of the existing caverns, about 500 m from ATLAS, be enlarged to house an entire facility dedicated to LLP searches in the forward region

Similar to FASER, new particles are perhaps being created by pp collisions that are being lost due to their being too close to the LHC beam axis



Proposed for the High-Luminosity LHC (HL-LHC), 2026 or later

Snowmass Letter of Interest