CURIOUS RESULTS BEYOND THE STANDARD MODEL AND DARK MATTER

IUPAP WG9 Nuclear Science Symposium

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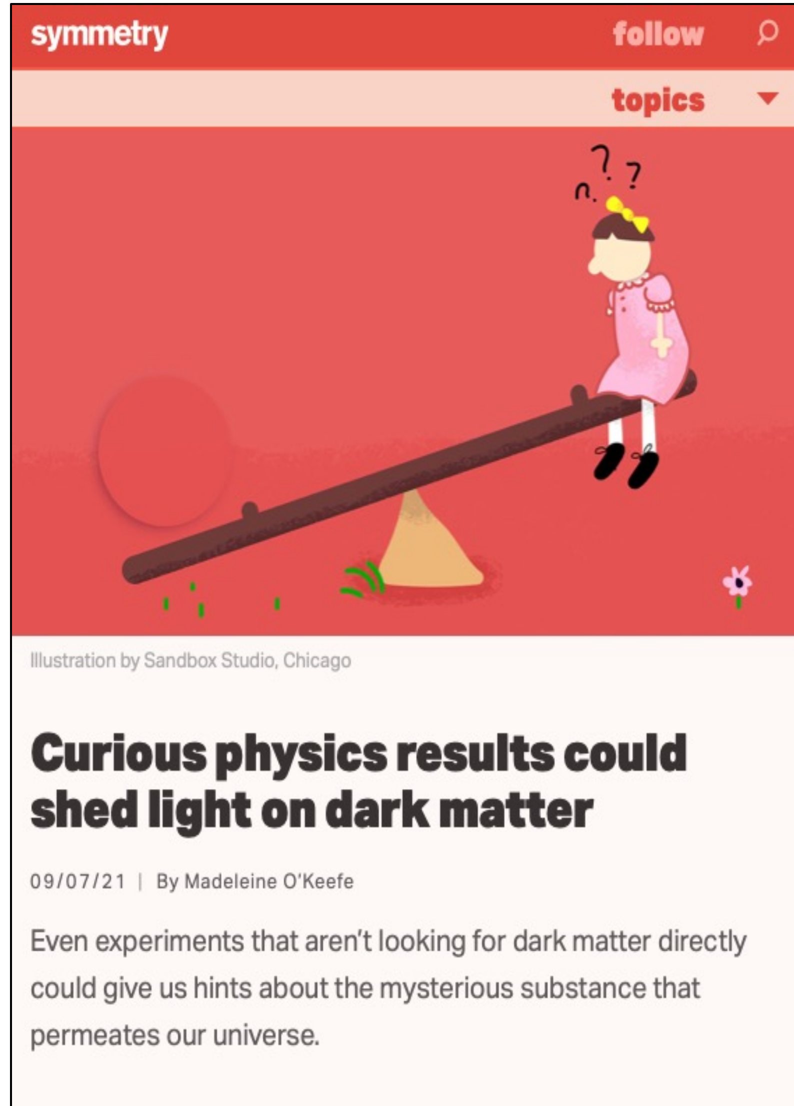
Jonathan Feng, UC Irvine

INTRODUCTION

- I am a theorist, working primarily on physics beyond the standard model and dark matter. Recently I have also become the co-spokesperson of an experiment, FASER at the LHC.
- The title of this talk is inspired (as I understand it!) by a short article in Symmetry Magazine.
- The article interviewed a number of people about current anomalies and their possible relation to dark matter.


symmetry follow

topics

Illustration by Sandbox Studio, Chicago

Curious physics results could shed light on dark matter

09/07/21 | By Madeleine O'Keefe

Even experiments that aren't looking for dark matter directly could give us hints about the mysterious substance that permeates our universe.

OUTLINE

A SNAPSHOT OF PARTICLE PHYSICS NOW

CURIOUS RESULTS

Muon g-2

^{8}Be and ^{4}He ATOMKI Anomalies

Strongly-Interacting DM

FASER AT THE LHC

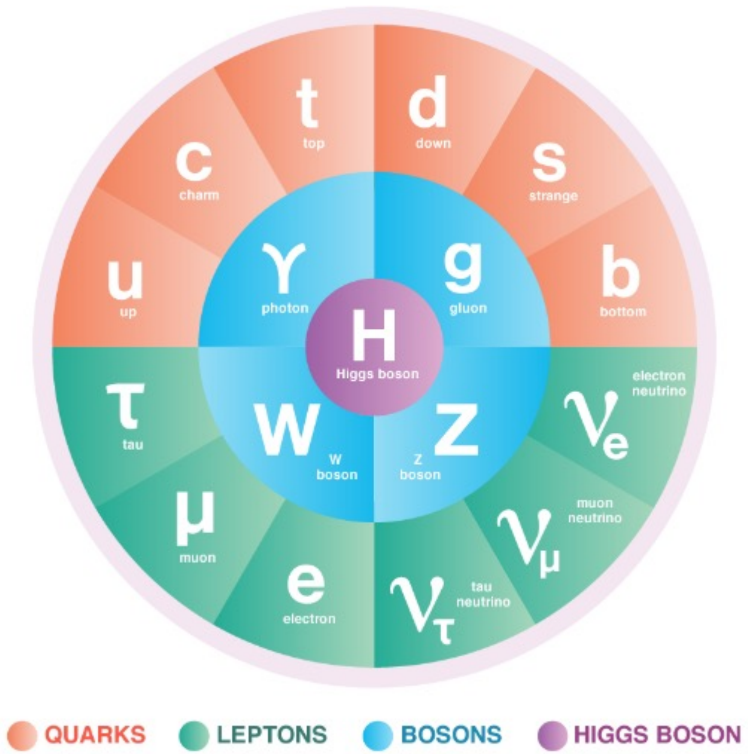
FORWARD PHYSICS FACILITY

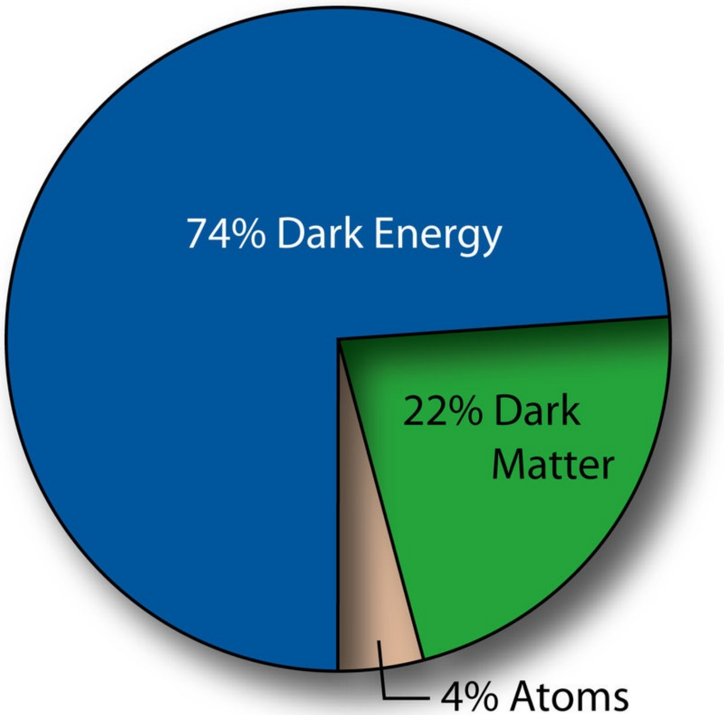
Summary: There has been a sea change in thinking about searches for new particles, with increasing focus on MeV to GeV energies, leading to new synergies between particle physics, cosmology, and nuclear physics.

A SNAPSHOT OF PARTICLE PHYSICS NOW

THE STANDARD MODEL

- This is a critical time in particle physics
  - the Higgs boson was discovered in 2012, completing the SM particle content
  - but many fascinating problems remain: dark matter, neutrino masses, dark energy, matter–anti-matter asymmetry, strong CP problem, grand unification, gauge and flavor hierarchy problems, ...





CURRENT STATUS OF THE LHC

- At the energy frontier, following the Higgs boson discovery at the LHC, we have not discovered any other evidence of new particles.

- The LHC has just emerged from Long Shutdown 2. Run 3 started in April 2022 and is ramping up to full power in July 2022.

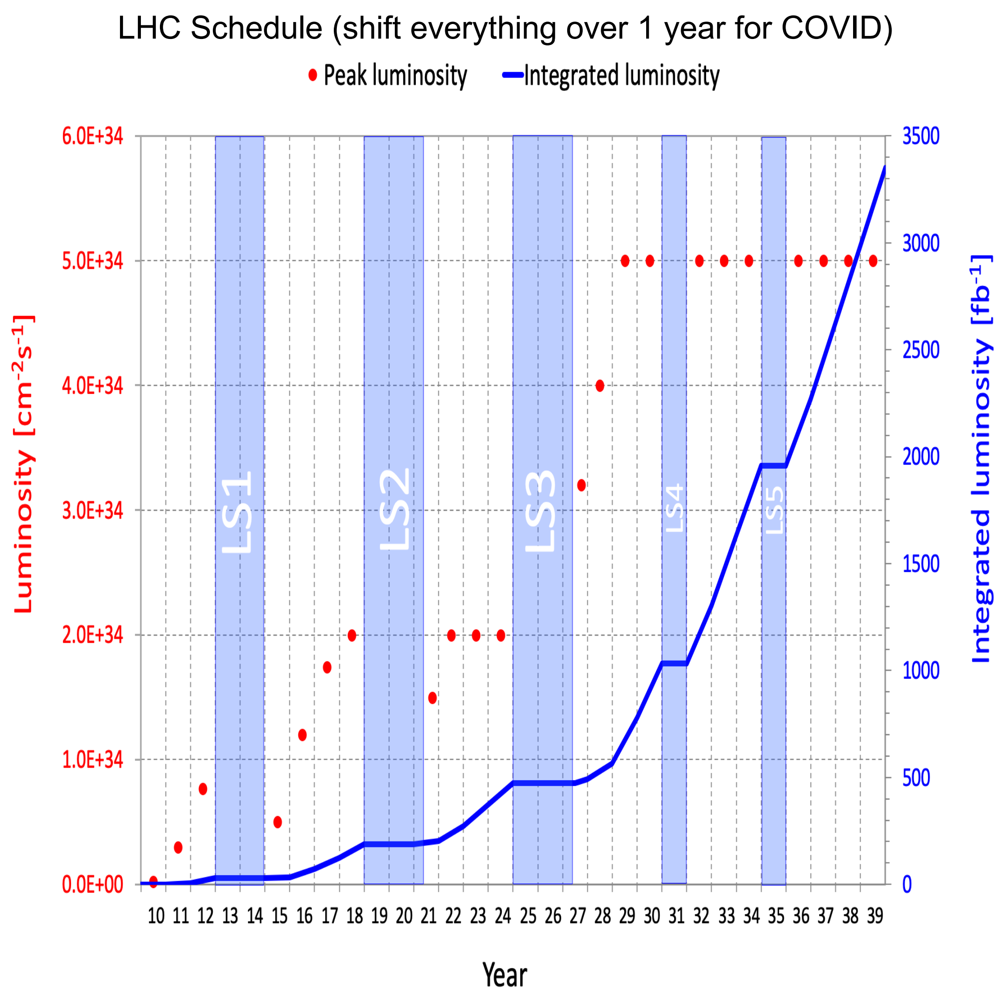
- Much more to come:

  [Run 1/2, 2010-18, 200 fb^{-1}]

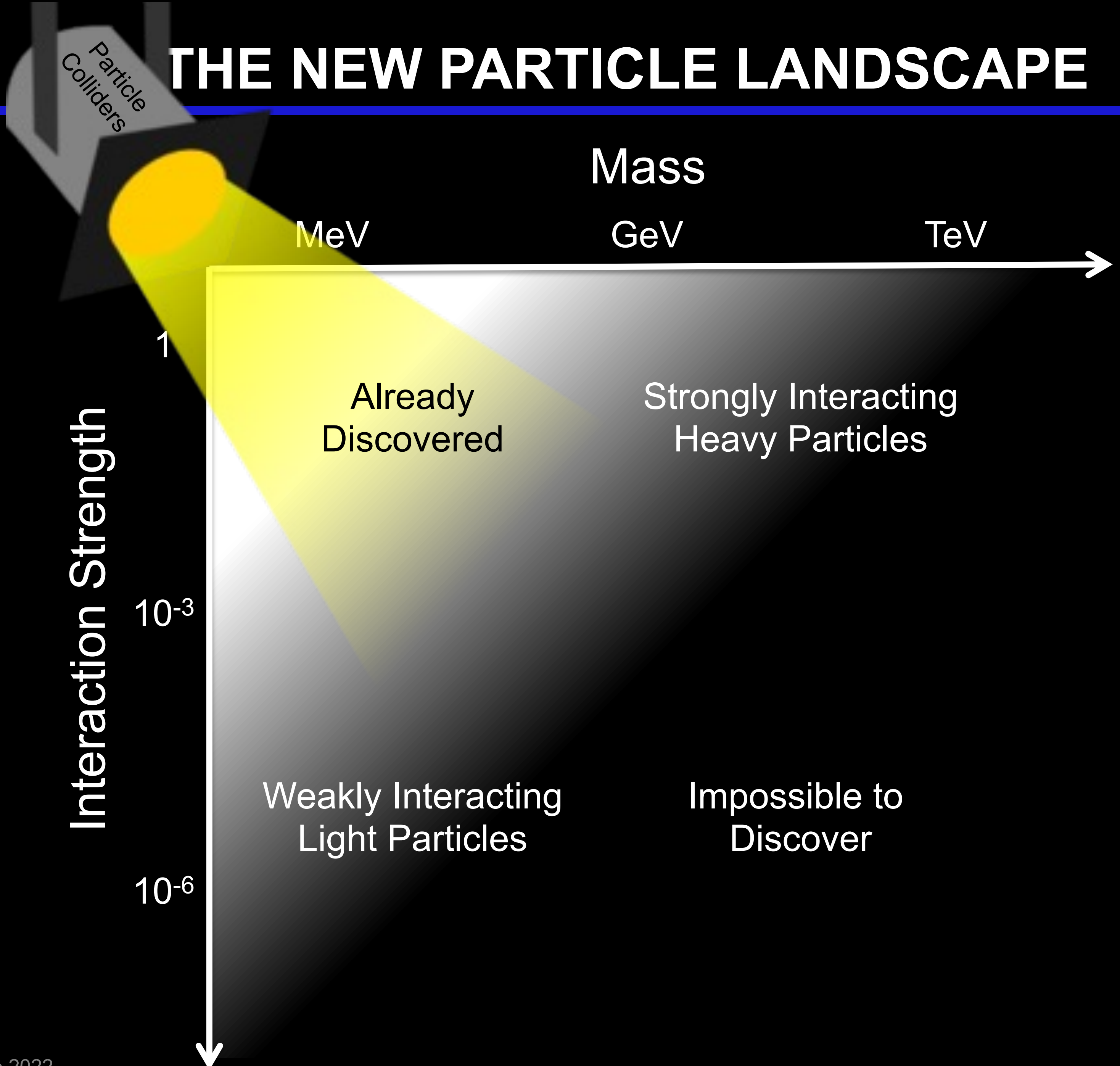
  Run 3, 2022-25, 150 fb^{-1}

  HL-LHC, 2029-40, 3000 fb^{-1}

- What can we do to enhance the prospects for discovering new physics?



THE NEW PARTICLE LANDSCAPE



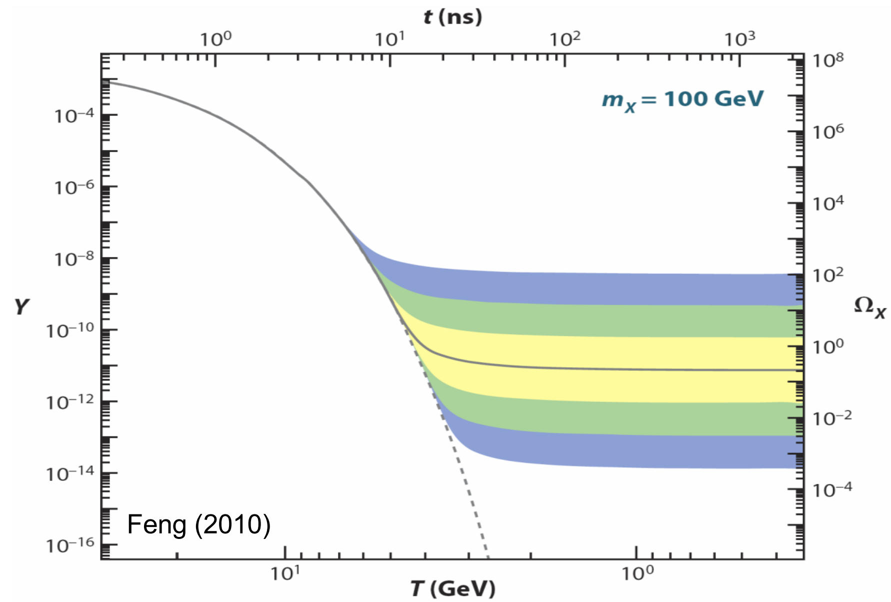
DARK MATTER

- DM is among the most obvious hints for new particles. In principle, the dark matter mass can be almost anything.

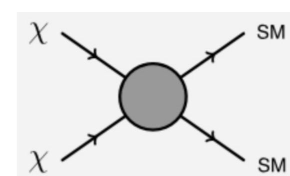
- However, there is a simple mechanism for generating dark matter: thermal relic freezeout.

- In the early universe, dark matter pair annihilates until it becomes too dilute and then "freezes out."

- The final abundance is determined by the annihilation rate: the weaker the interaction, the more DM there is now.

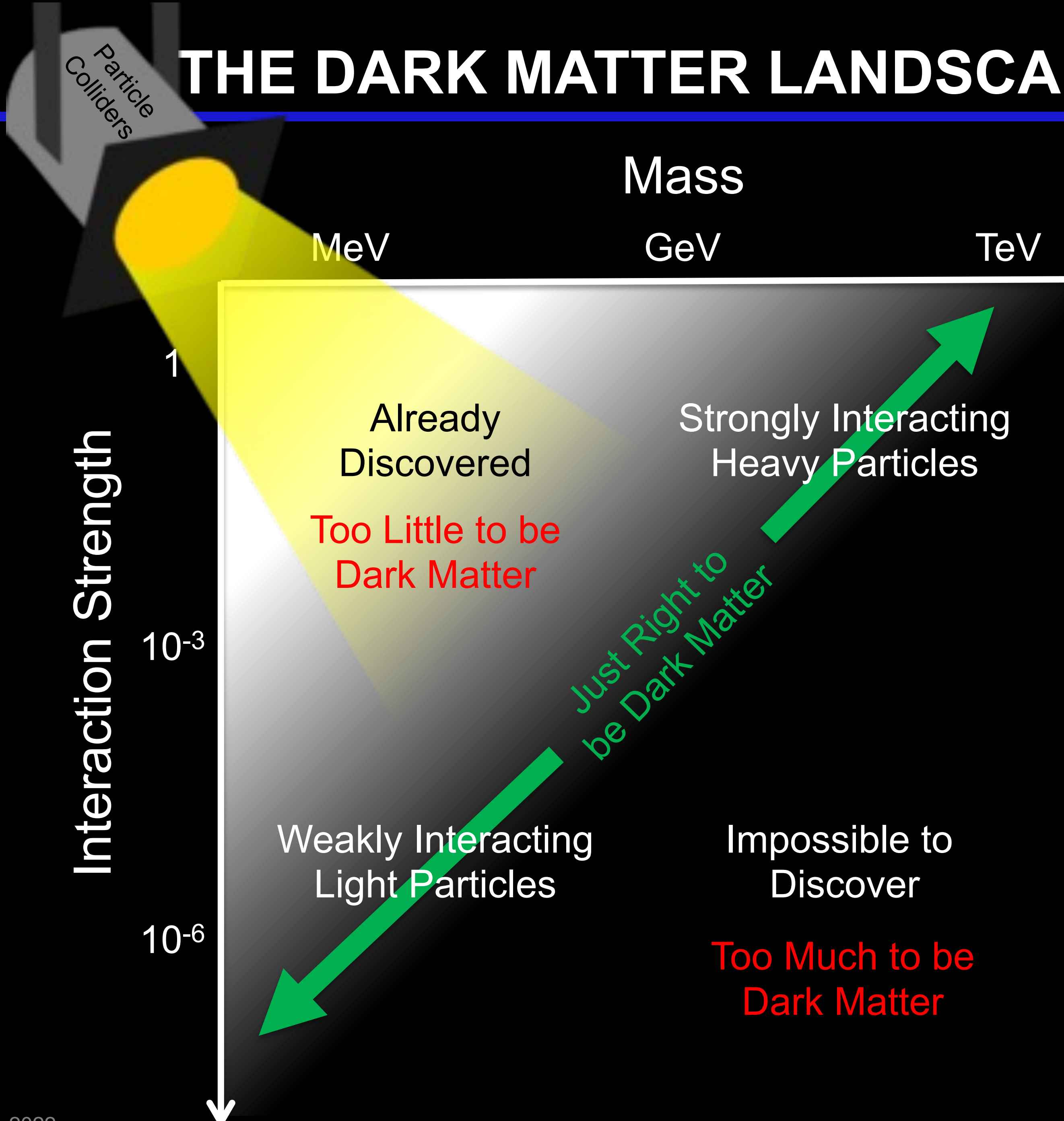


$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle}$$



- By dimensional analysis, $\langle \sigma v \rangle \sim m_X^{-2}$, so the relic density is larger for heavy particles with weak interactions.

THE DARK MATTER LANDSCAPE



The coincidence of cosmology and particle physics in the upper right corner is known as the WIMP Miracle. This has guided the field for decades.

Feng (2001)

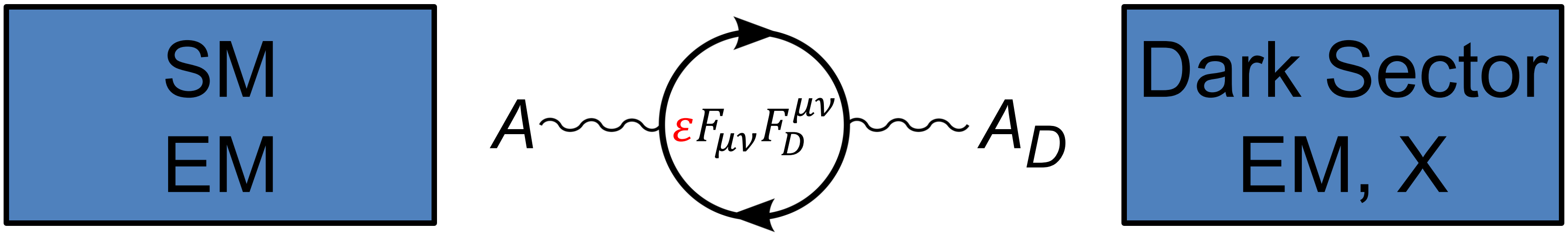
But there is an entire diagonal to explore: the WIMPless Miracle.

Feng, Kumar (2008)

AN EXAMPLE: DARK PHOTONS

- Suppose there is a dark sector that contains dark matter X and also a dark force: dark electromagnetism.

- The force carriers of our sector and the dark sector will mix
  - perhaps suppressed, but completely generic, since a renormalizable operator



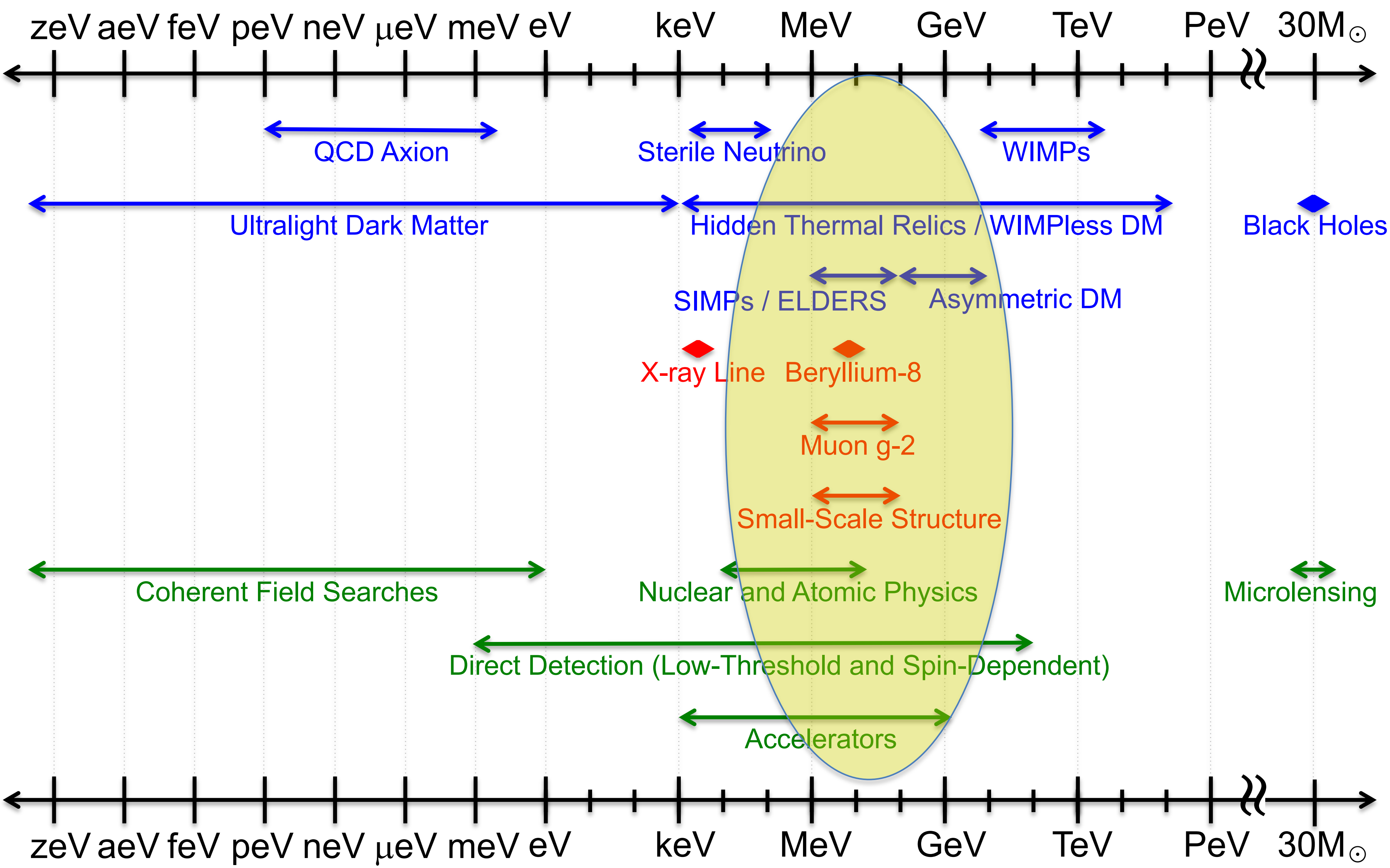
- The result? A new particle, the dark photon A': like a normal photon, but with an unknown mass $m_{A'}$ and couplings suppressed by ε. It travels through matter without interacting, but eventually decays through $A' \to e^+ e^-$, …

Holdom (1986)

- Many other possibilities: $B - L$, $L_\mu - L_\tau$ and other light gauge bosons, dark Higgs bosons $X \to K^+ K^-$, axion-like particles $a \to \gamma\gamma$, sterile neutrinos $N \to l^+ l^- \nu$, millicharged particles, …, aka long-lived particles (LLPs), feebly-interacting particles (FIPs), dark sector particles, portal particles, …

CURIOUS RESULTS

Dark Sector Candidates, Anomalies, and Search Techniques



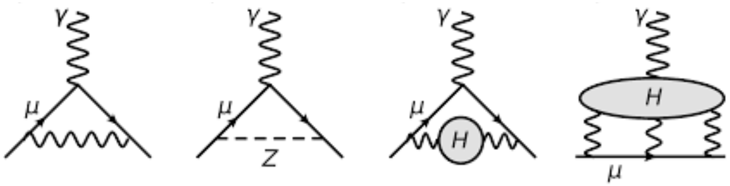
Cosmic Visions Report (2017)

THE MUON'S ANOMALOUS MAGNETIC MOMENT

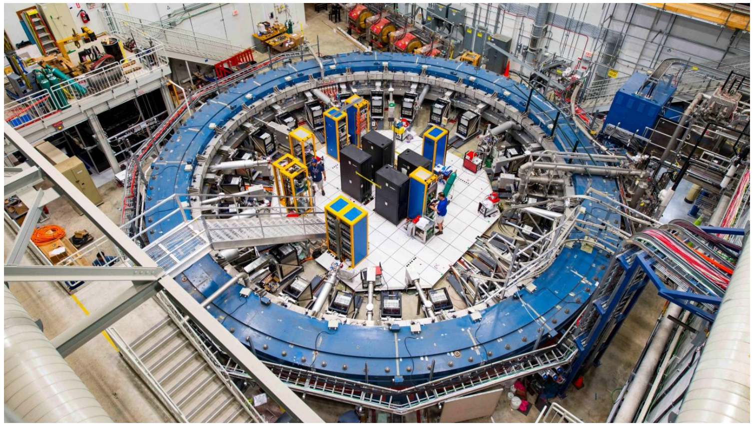
- The anomalous magnetic moment has a distinguished history. Schwinger's calculation of a_e helped establish QED.

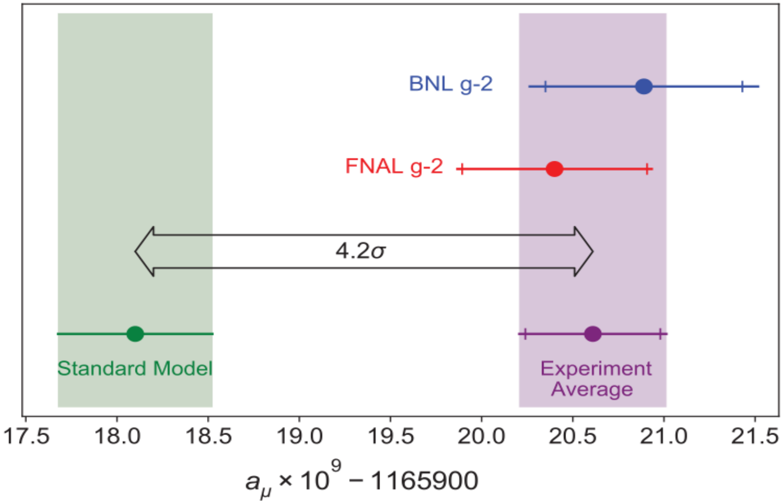
- In 2021, the Muon g-2 Collaboration announced a high precision measurement that deviates from the SM prediction by 3.3σ.

- It is sensitive to the weak interactions, but unlike other precision probes, it requires neither flavor nor CP violation, and so is a robust probe of new particles that couple to muons.



$$\vec{\mu} = g\frac{q}{2m}\vec{S} \qquad a_l = (g_l - 2)/2$$

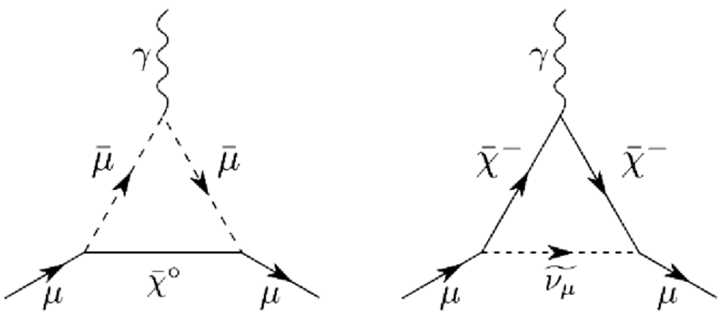


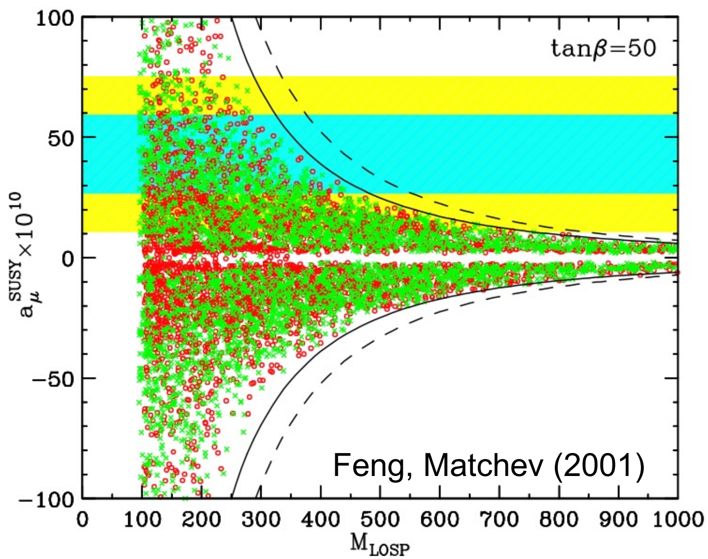


THE MUON'S ANOMALOUS MAGNETIC MOMENT

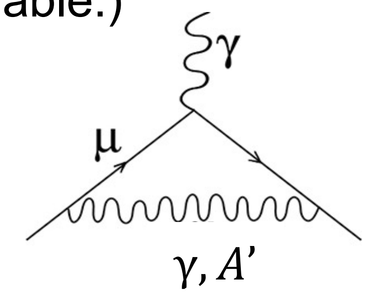
- The discrepancy can be resolved by either heavy or light new particles.

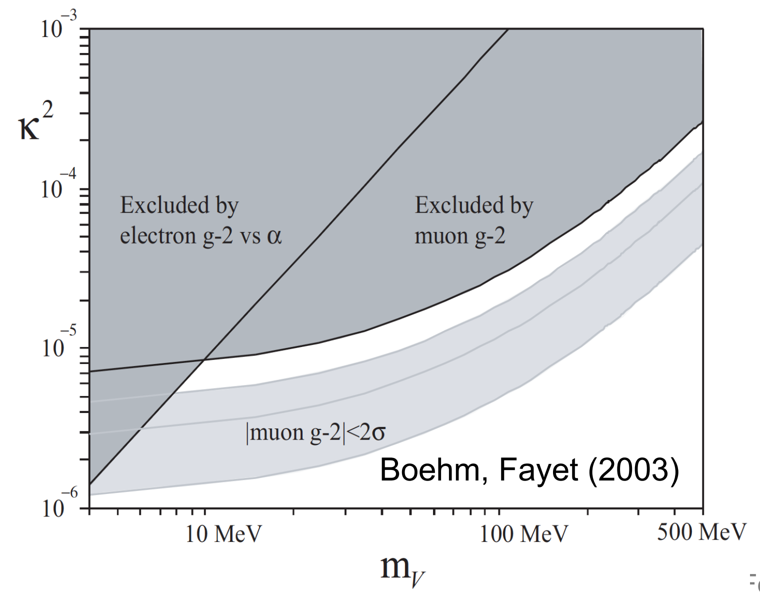
- Supersymmetry with superpartners below the TeV scale.





- Particles with MeV-GeV masses and couplings ~ 10^{-3}. (Dark photon now excluded, but other similar particles remain viable.)





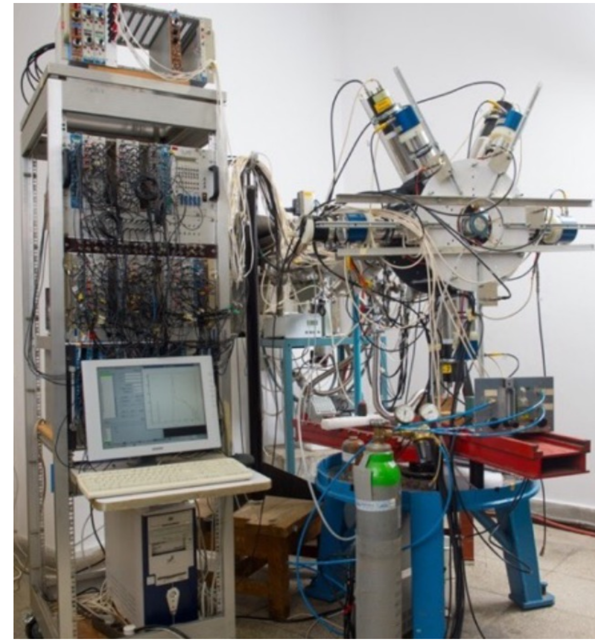
THE ^{8}Be and ^{4}He ATOMKI ANOMALIES

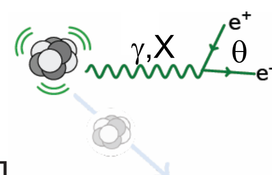
- New particles at the ~ 10 MeV scale and below can be produced in the decays of excited nuclei.

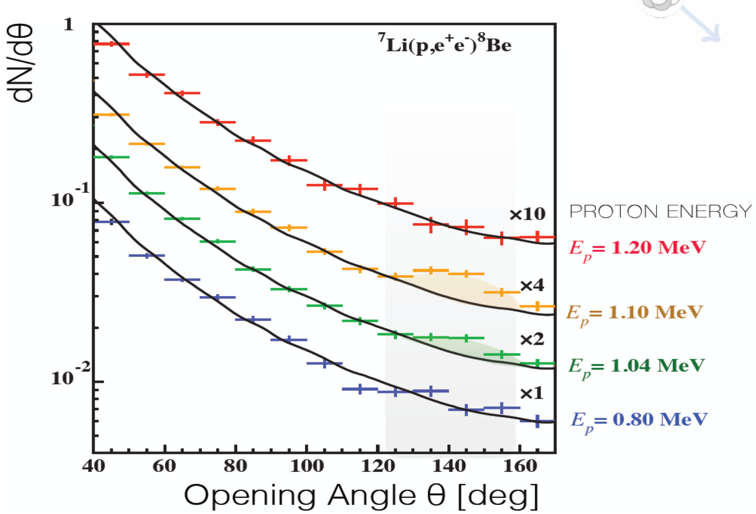
Treiman, Wilczek (1978); Donnelly, Freedman, Lytel, Peccei, Schwartz (1978); Savage, McKeown, Filippone, Mitchell (1986)

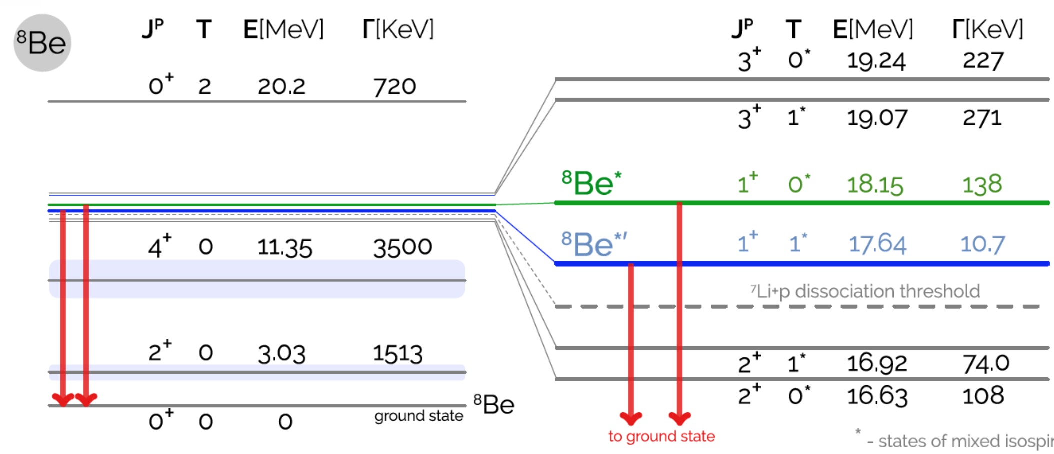
- In 2015, an ATOMKI group reported a 7σ excess in ^{8}Be (18.15) → ^{8}Be e^+e^- decays at $\theta_{e^+e^-} \approx 140°$.

Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]









THE ^{8}Be and ^{4}He ATOMKI ANOMALIES

- The anomaly in the decays of excited ^{8}Be nuclei can be explained by a new protophobic gauge boson X with mass 17 MeV and couplings ~ 10^{-4} to 10^{-3}: ^{8}Be (18.15) → ^{8}Be X, followed by X → $e^+ e^-$.

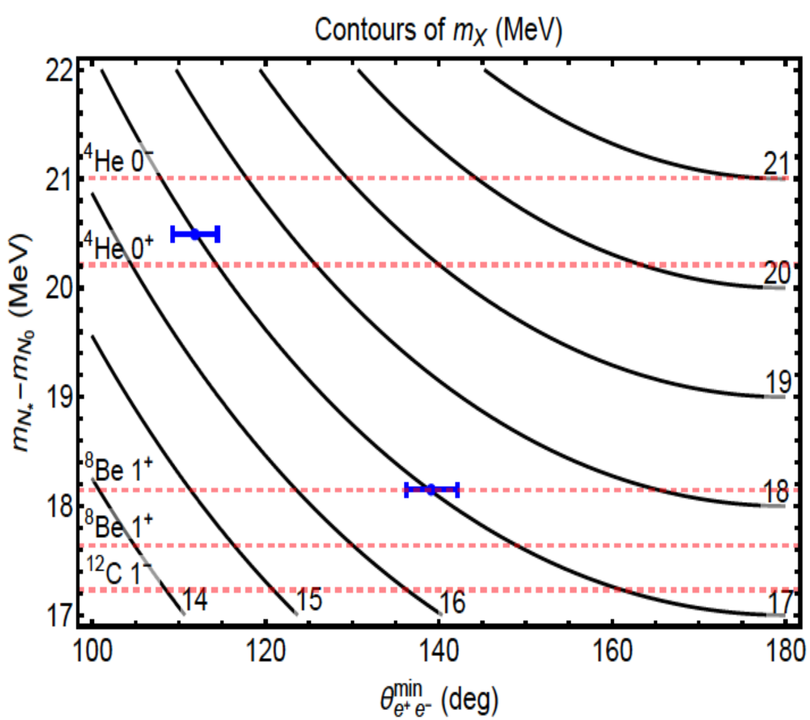
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)

- In 2019 the ATOMKI group reported a new 7σ excess in the decays of excited ^{4}He (20.49) nuclei at $\theta_{e^+e^-} \approx 115°$.

Krasznahorkay et al. (2019)

- Remarkably, this anomaly can be explained by the same new particle, which can also reduce the muon g-2 discrepancy to 2σ.

Feng, Tait, Verhaaren (2020)
See also Zhang, Miller (2020)



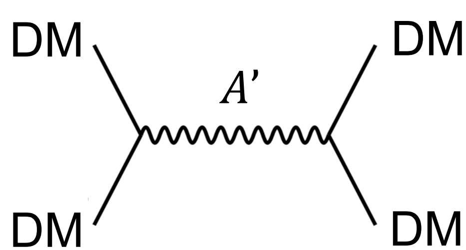
SELF-INTERACTING DARK MATTER

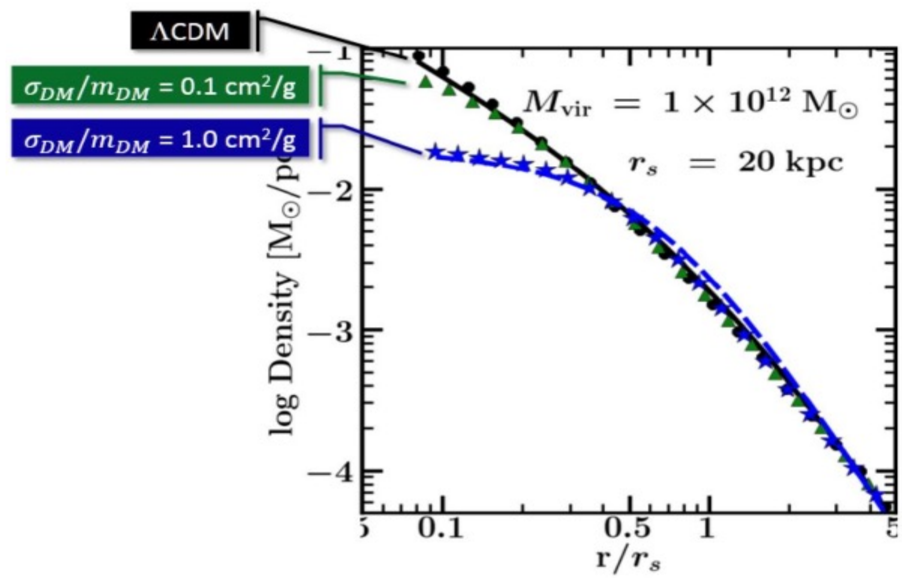
- There are indications from small-scale structure that dark matter may be strongly self-interacting.

- For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted for standard collisionless cold dark matter (WIMPs, axions, sterile neutrinos, …).

- To smooth out the cusps, need a self-interaction cross section

$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\ \text{MeV})^{-3}$$





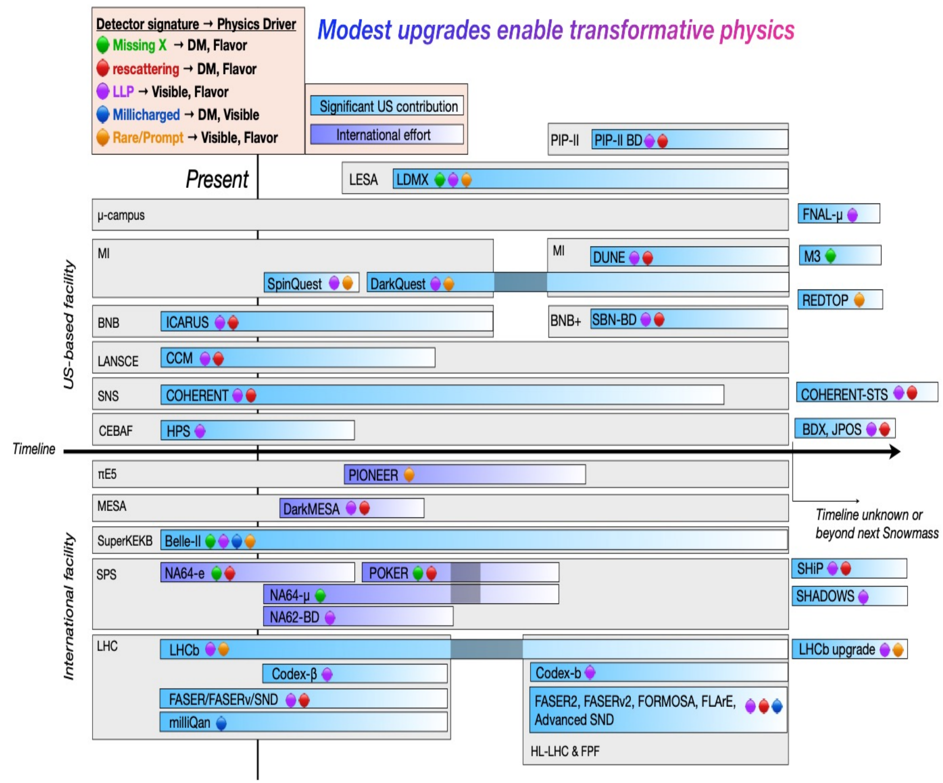
Tulin, Yu (2017)
Rocha et al. (2012); Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)

- This can be explained by a dark sector mass scale of ~ 10-100 MeV ("dark neutrons interacting through dark pions").

FASER AT THE LHC

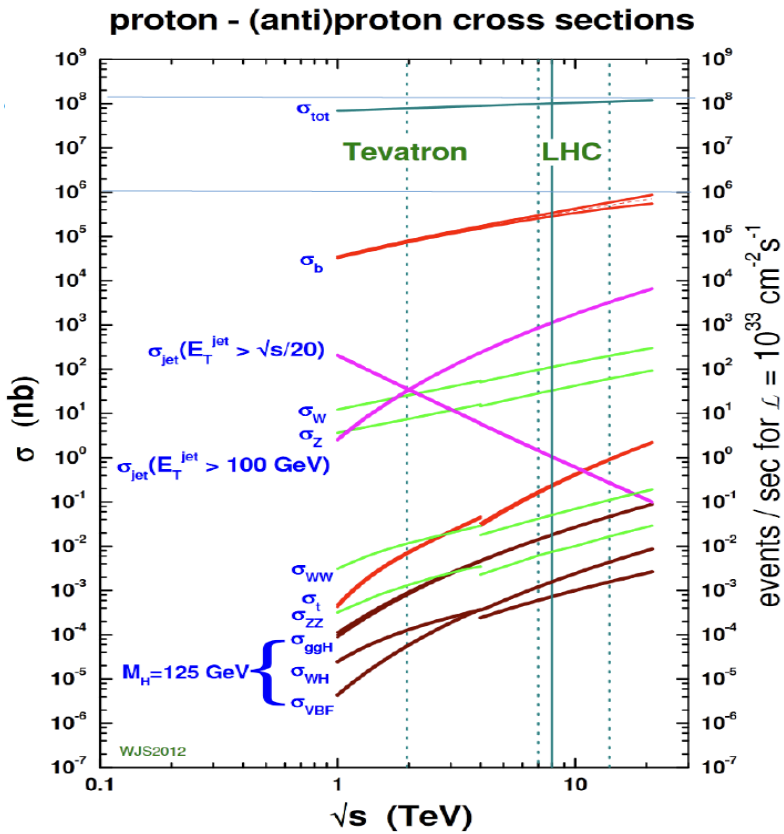
NEW SEARCHES FOR LIGHT PARTICLES

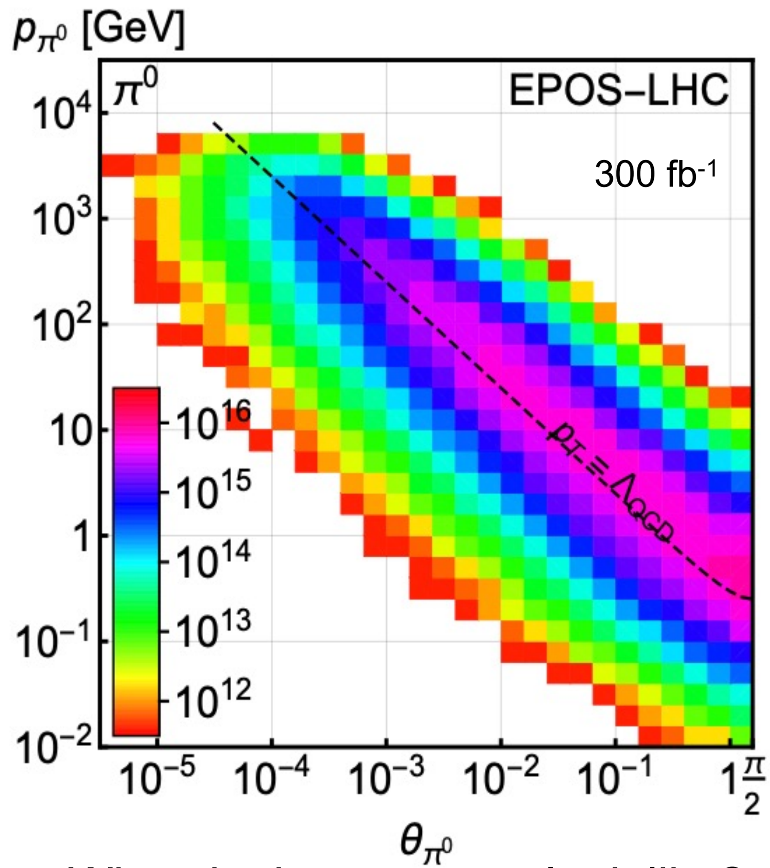
- BSM physics has been re-invigorated by new ideas to search for Long-Lived Particles (LLPs), Feebly-Interacting Particles (FIPs), portal particles, dark sectors, …



Ilten, Tran et al. (2206.04220)

LIGHT PARTICLES AT THE LHC



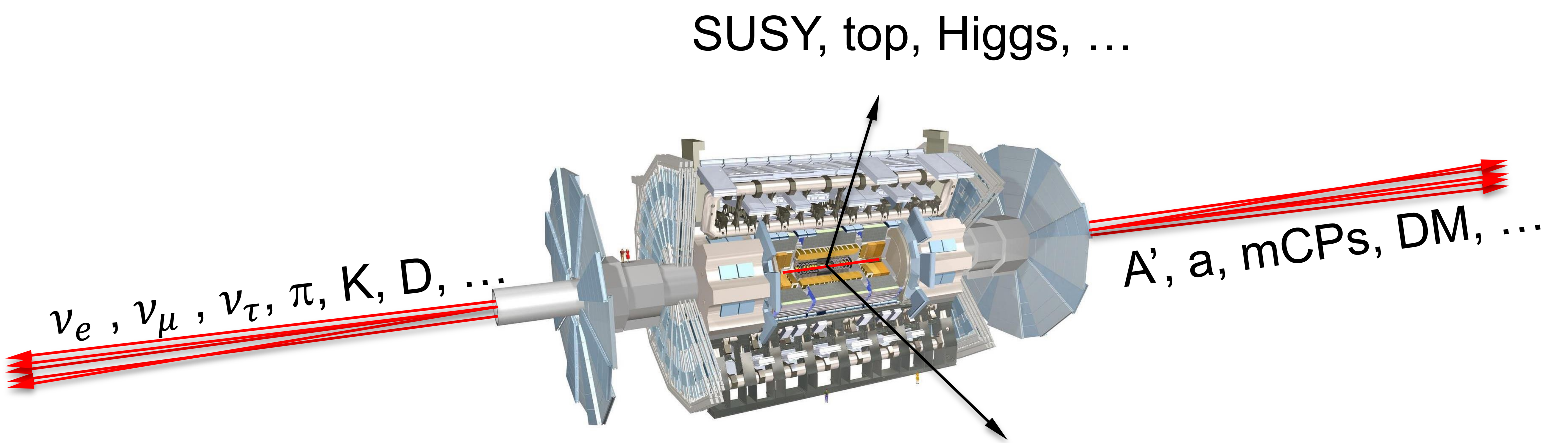


Feng, Galon, Kling, Trojanowski (2017)

- Most searches have focused on processes with σ ~ fb, pb.
- But σ_{tot} ~100 mb, currently wasted in new physics searches.
- What do these events look like? Consider pions.
- Enormous event rates. Typical p_T ~ 250 MeV, but many with p ~ TeV within 1 mrad (η > 7.6) of the beamline.

SEARCHES FOR NEW LIGHT PARTICLES

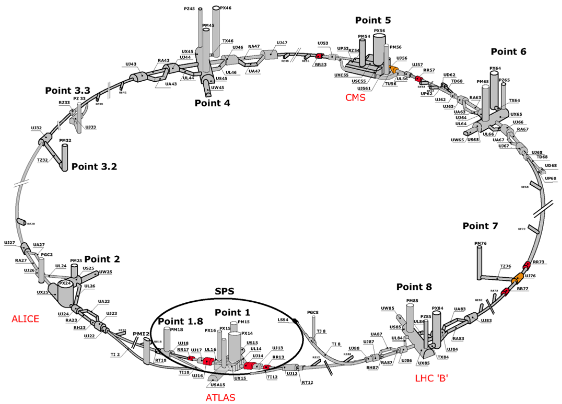
- At the LHC, the existing large detectors were designed to find strongly-interacting heavy particles.



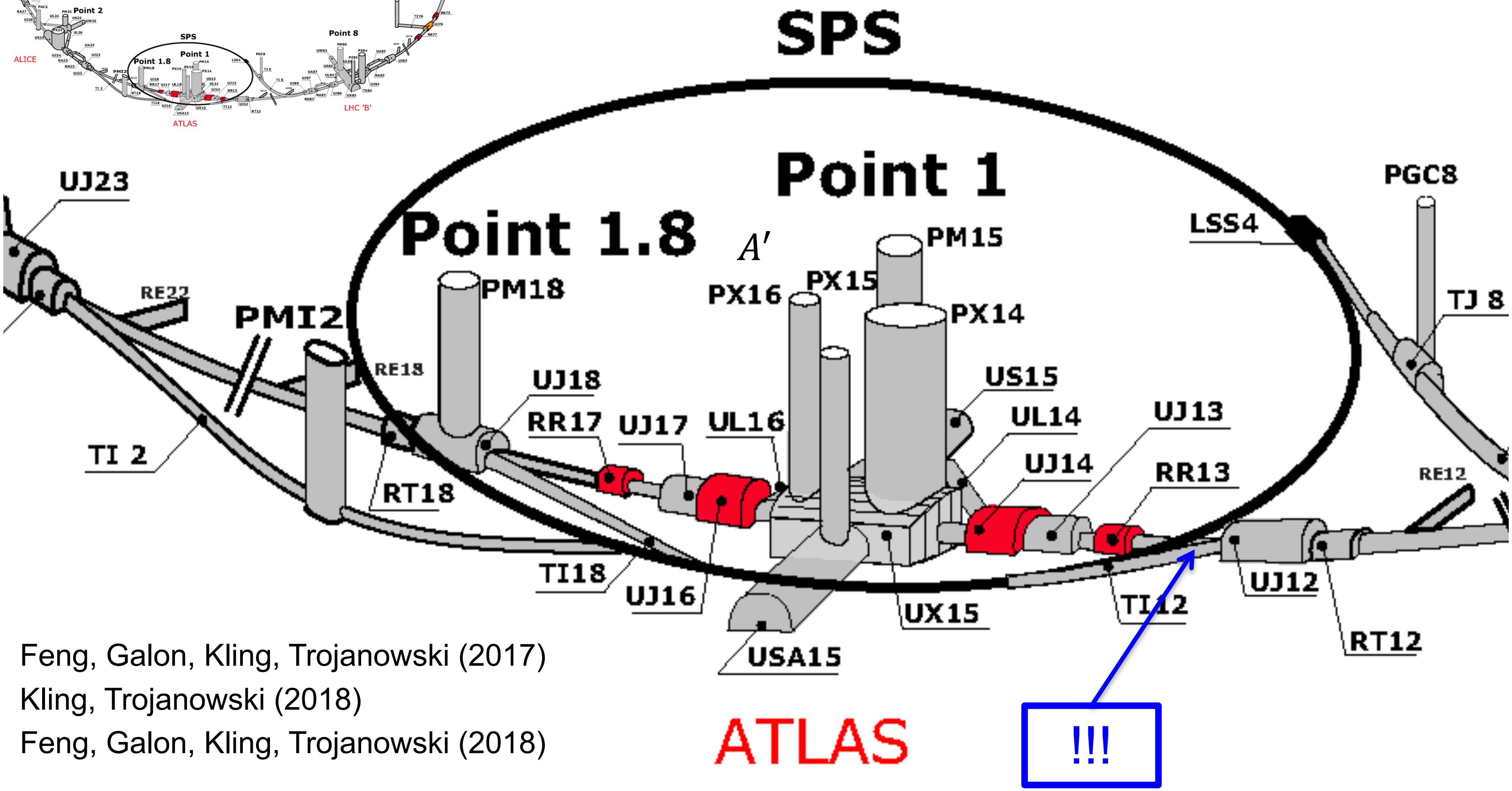
- Unfortunately, they are also almost perfectly designed to not find weakly-interacting light particles. These are dominantly produced in the rare decays of light particles (π, η, K, D, B, …) along the forward direction, and so the new particles escape through the blind spots down the beamline.

- There are both SM and BSM motivations to explore the "wasted" σ_{tot} ~ 100 mb and cover these blind spots in the far forward region.

THE BASIC IDEA

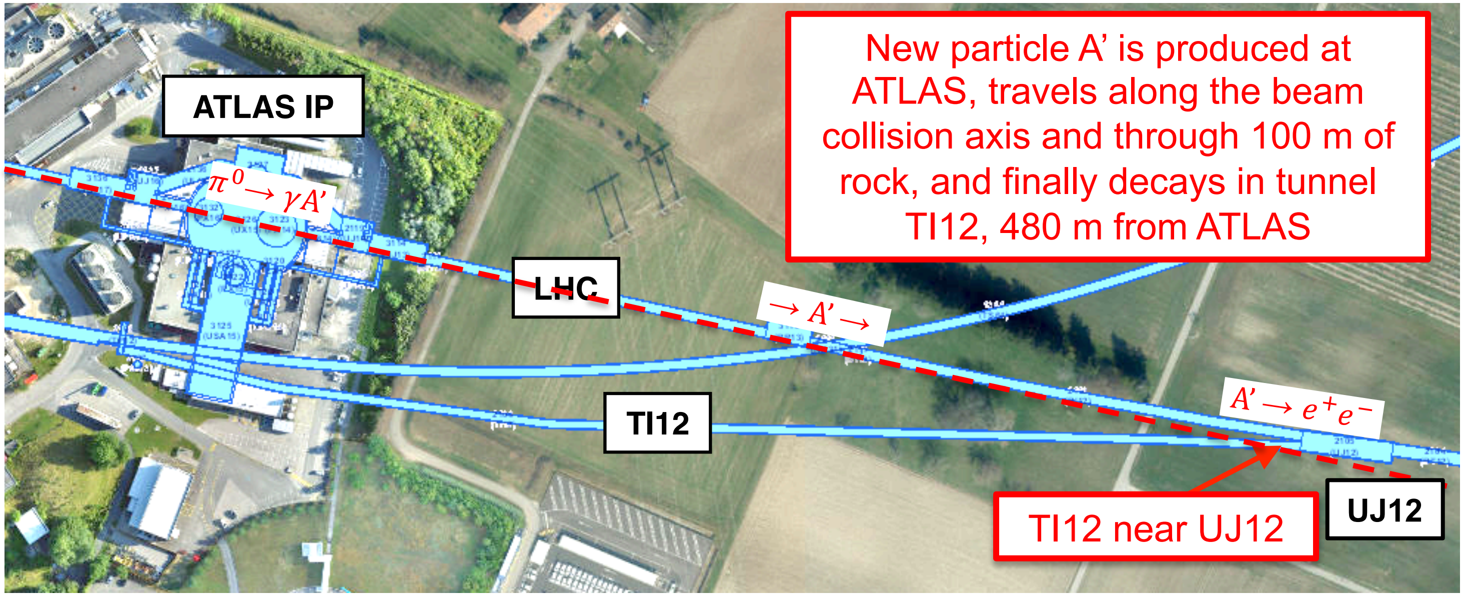


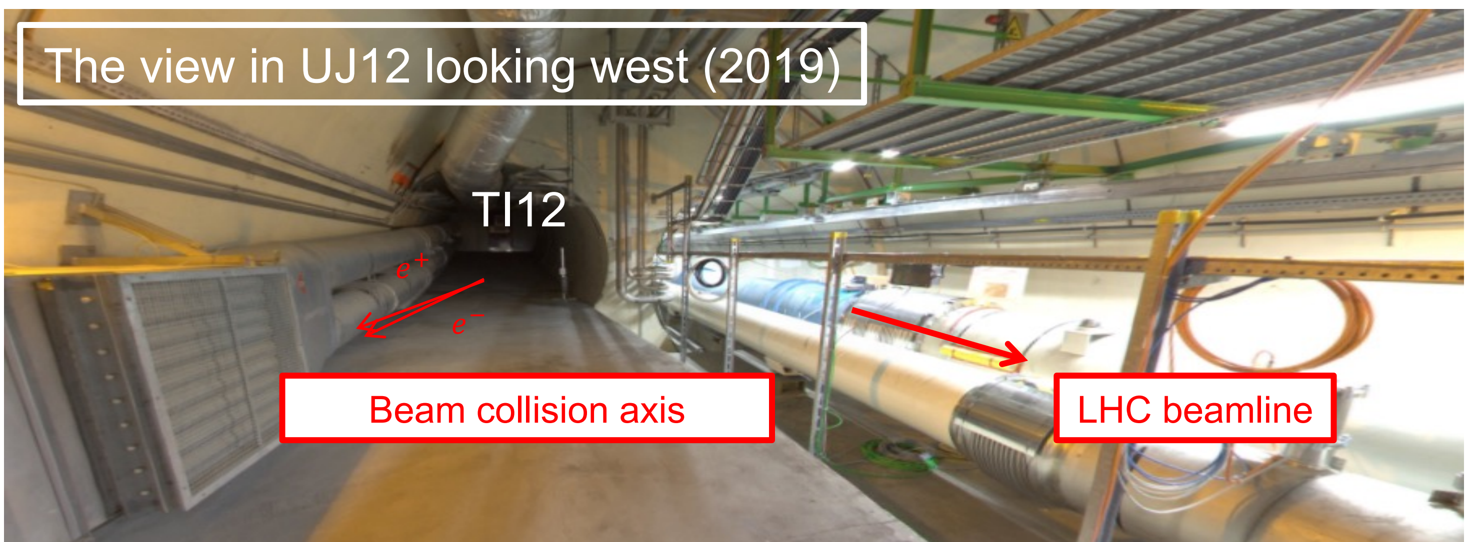
We cannot block the beams, but if we go far away, the proton beams are bent by magnets, whereas light, weakly-interacting particles go straight.



Feng, Galon, Kling, Trojanowski (2017)
Kling, Trojanowski (2018)
Feng, Galon, Kling, Trojanowski (2018)

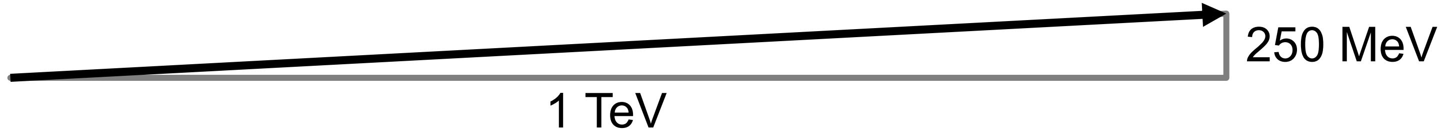
THE FAR-FORWARD REGION



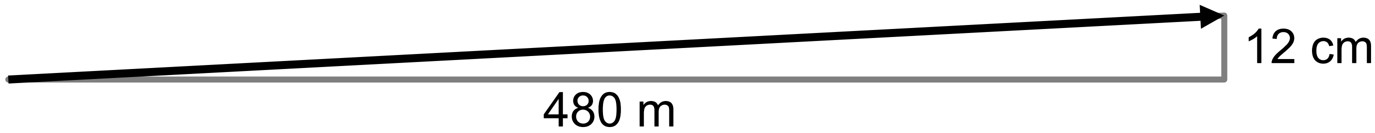


HOW BIG DOES THE DETECTOR HAVE TO BE?

- Momentum:

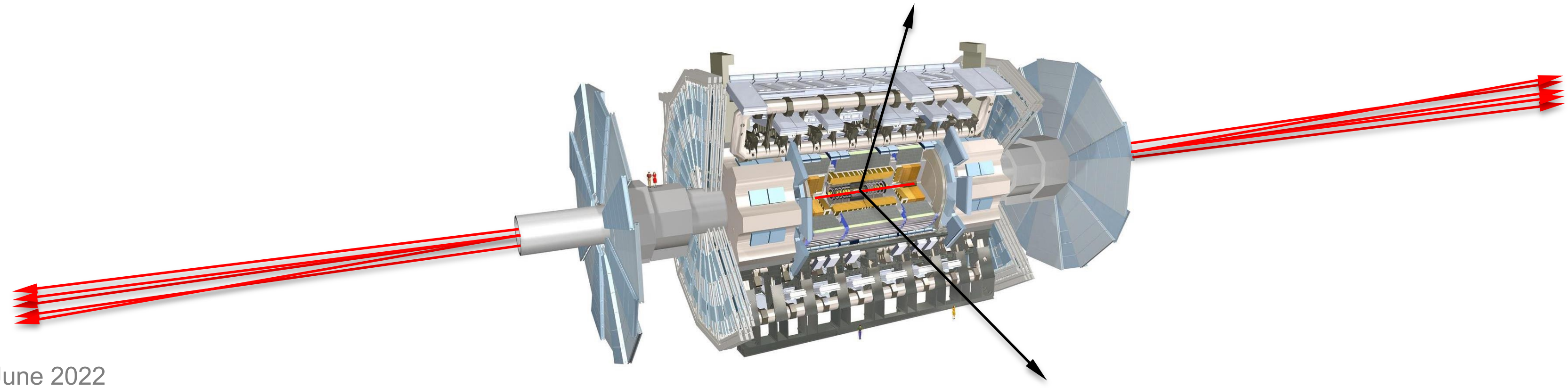


- Space:



- Particles produced in pion decays have θ ~ 0.2 mrad (η ~ 9); cf. the moon (7 mrad).

- Particles produced in π, η, K, D, B decay are therefore far more collimated than shown below, motivating new, small, fast, and cheap experiments at the LHC.

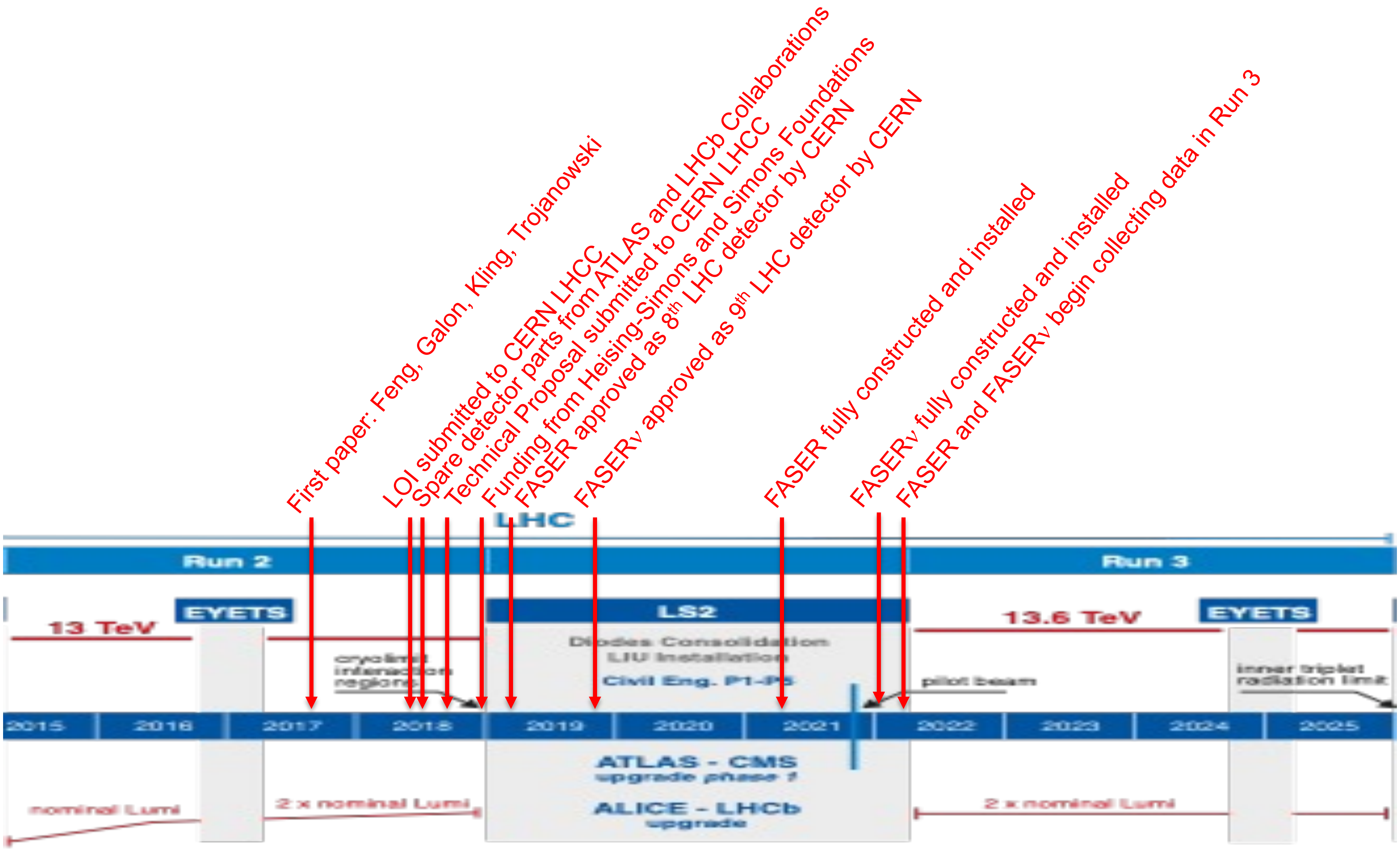


CURRENT FAR FORWARD DETECTORS

3 far forward detectors have been constructed and installed and are currently taking data in LHC Run 3: FASER, FASERν, and SND@LHC.

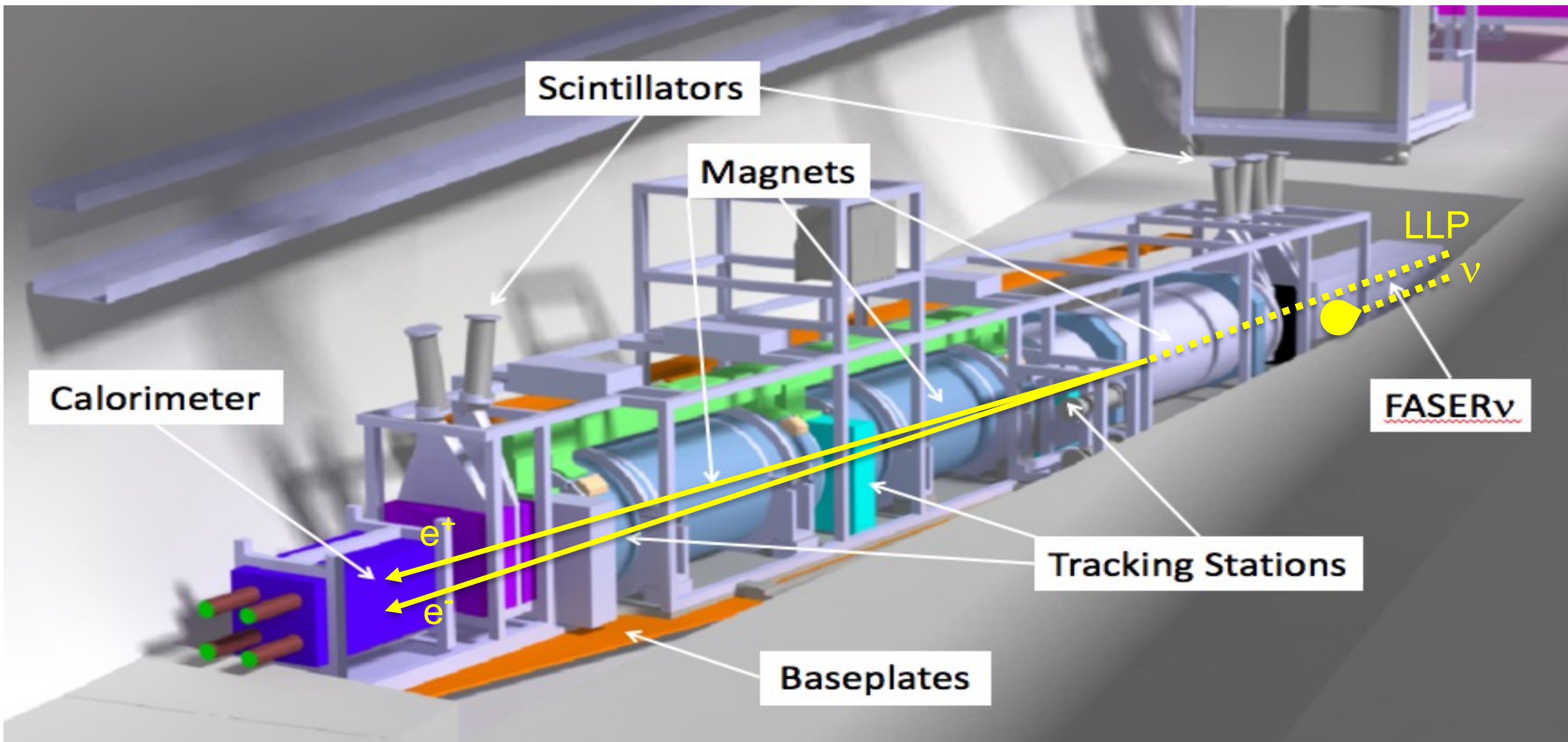
CERN GIS

FASER AND FASERν TIMELINE

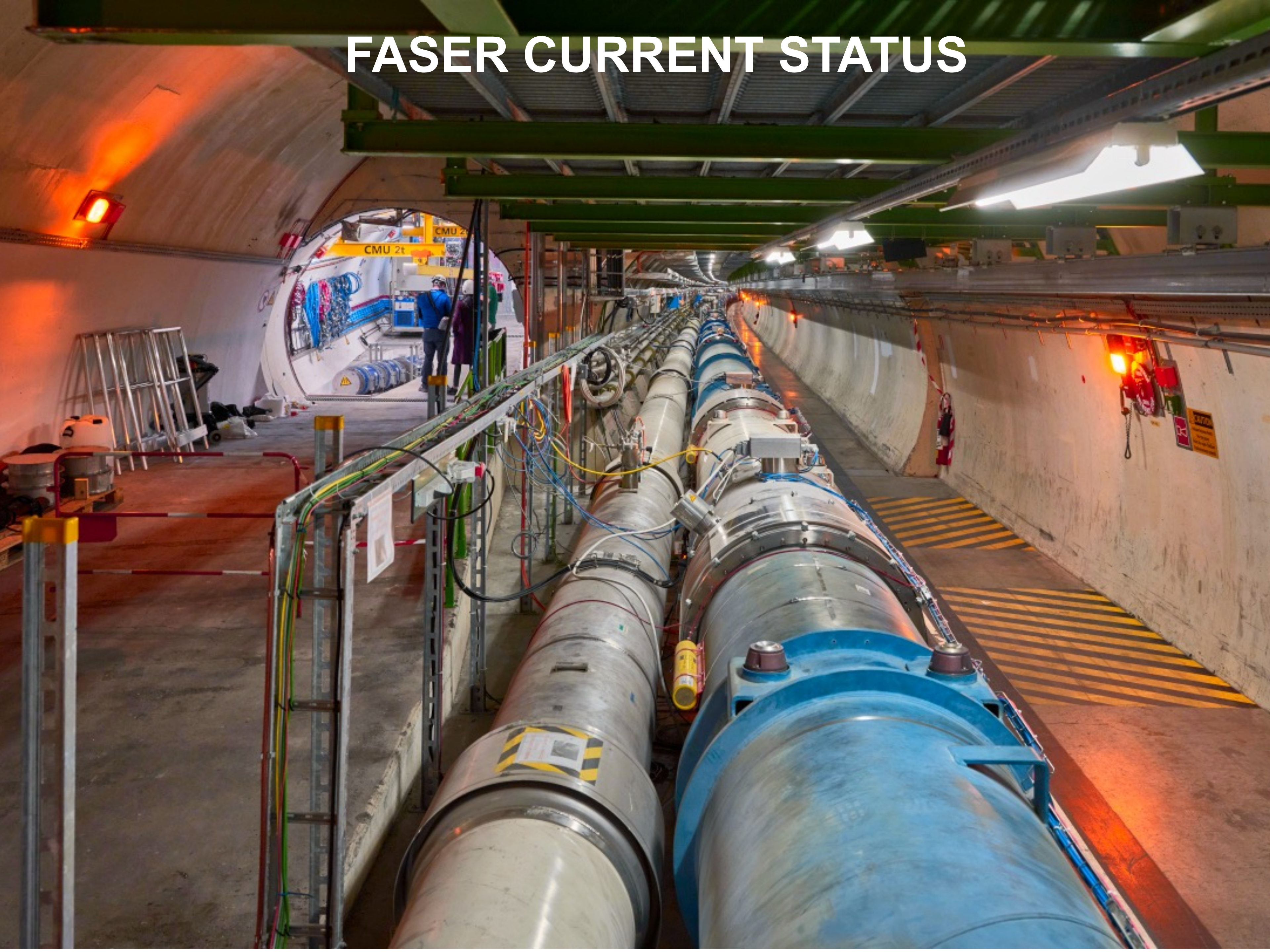


THE FASER DETECTOR

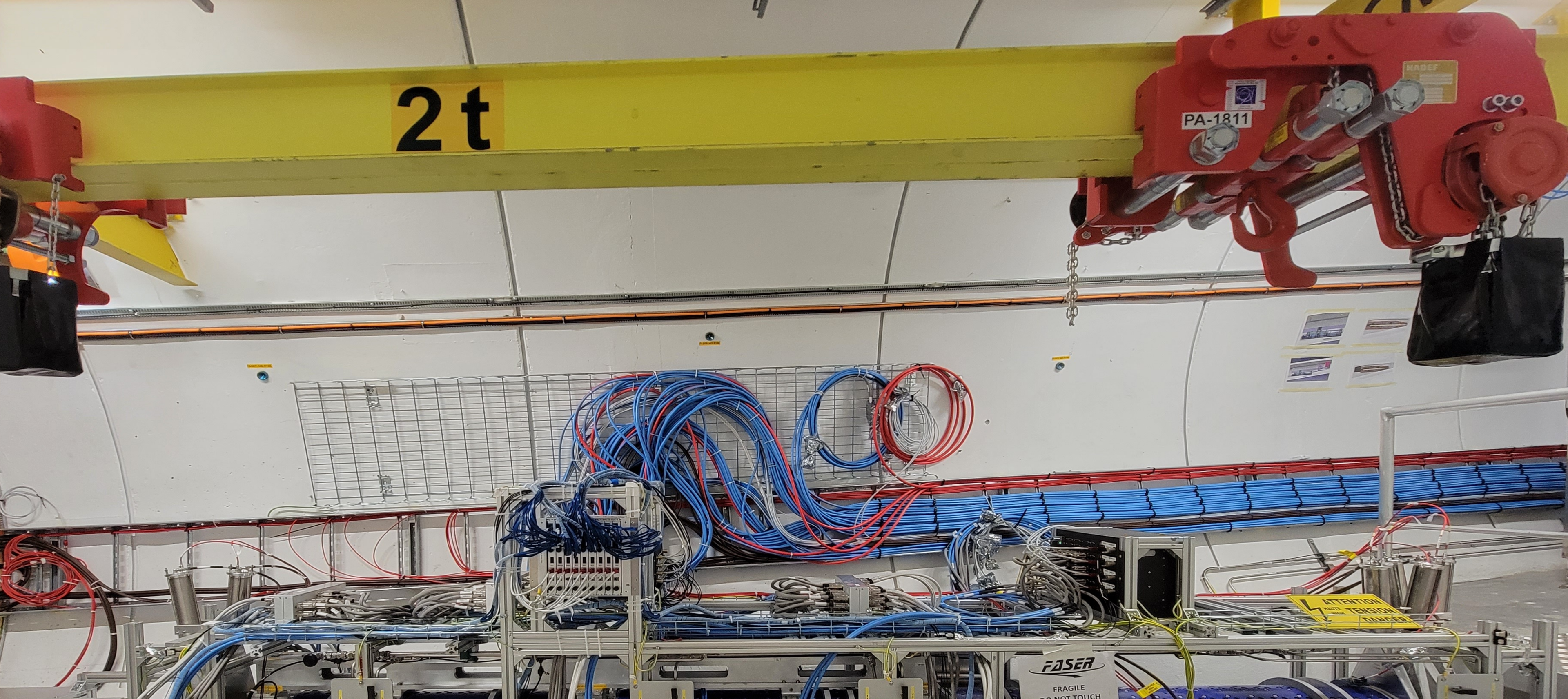
- Nothing incoming and 2 ~TeV, opposite-sign charged tracks pointing back to the ATLAS IP: a "light shining through (100 m-thick) wall" experiment.
- Scintillators veto incoming charged tracks (muons), magnets split the charged tracks, which are detected by tracking stations and a calorimeter.

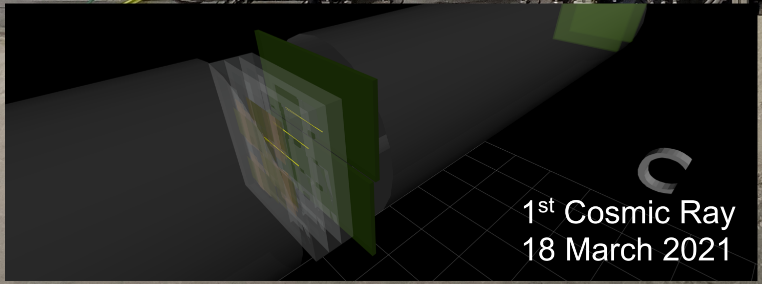


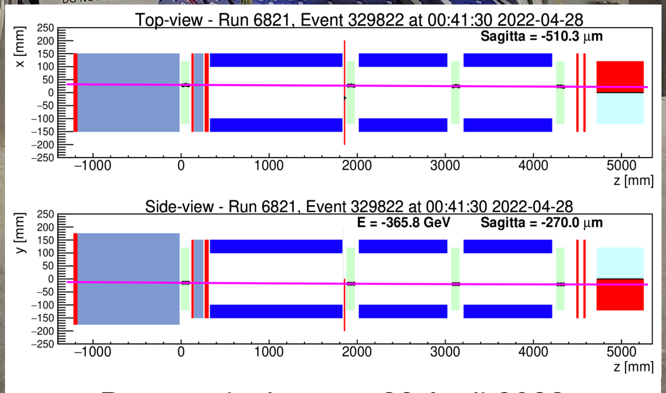
FASER CURRENT STATUS



FASER CURRENT STATUS

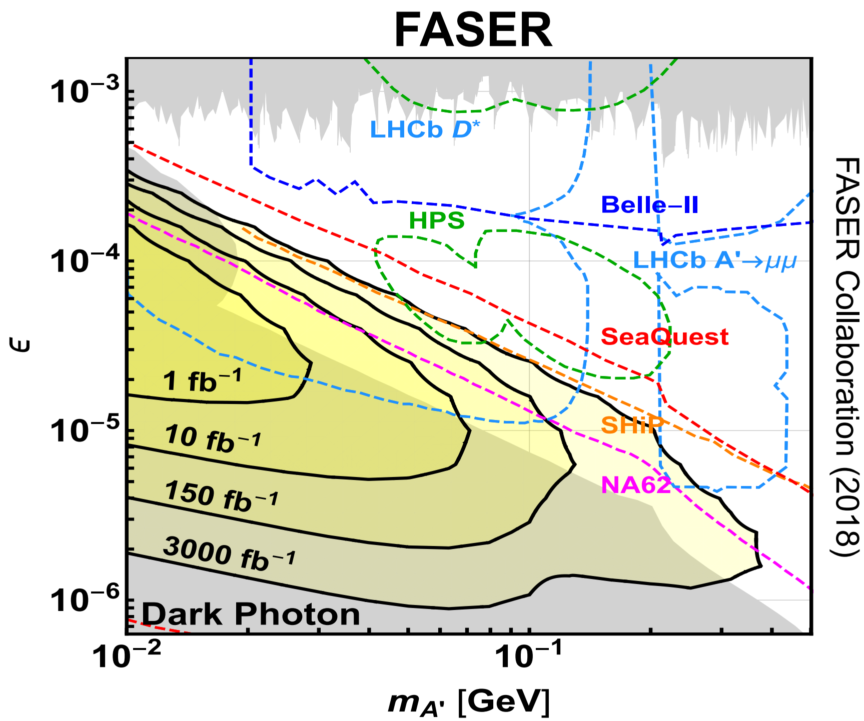


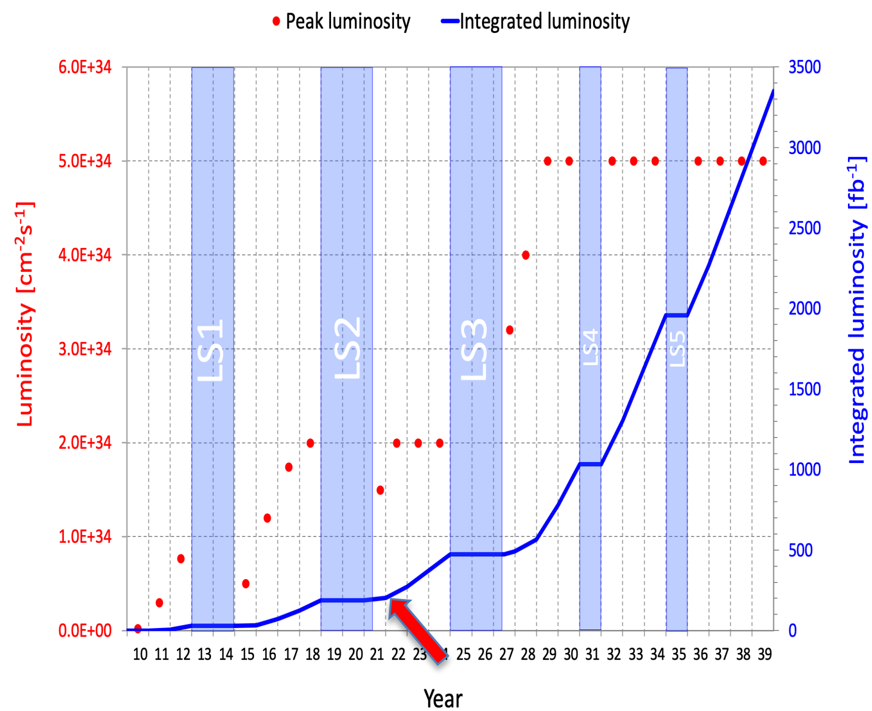




Beam splash event 28 April 2022

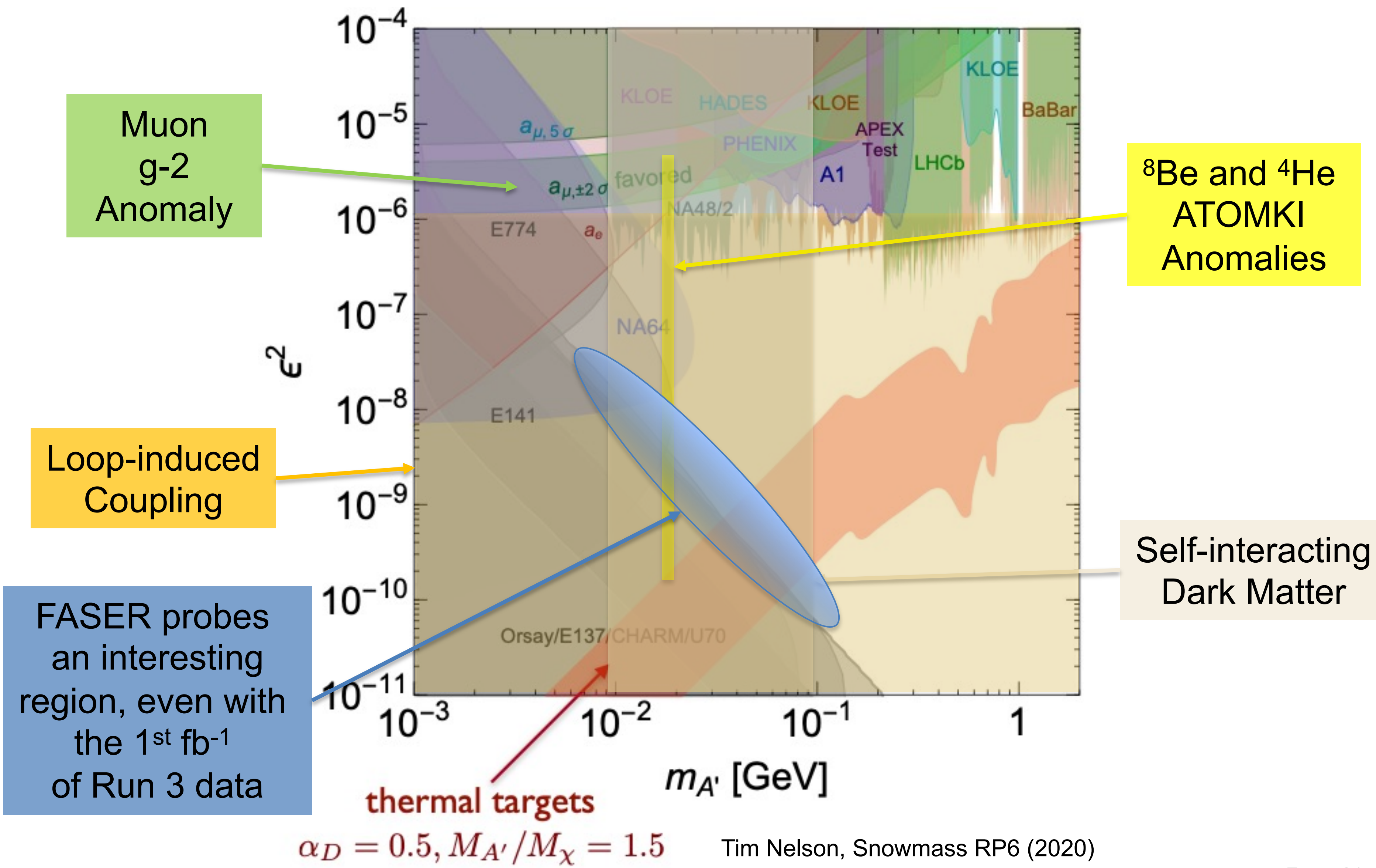
DARK PHOTON SENSITIVITY REACH





- FASER probes new parameter space with just 1 fb^{-1} starting in July 2022.
- In Run 3, will probe the MeV-GeV region favored by thermal relic considerations, muon g-2 explanations, SIDM, ATOMKI anomalies, …
- Even without a detector upgrade, the HL-LHC extends (Luminosity*Vol) by factor of 3000 – could detect as many as 10,000 dark photons.

TARGETS IN DARK PHOTON PARAMETER SPACE

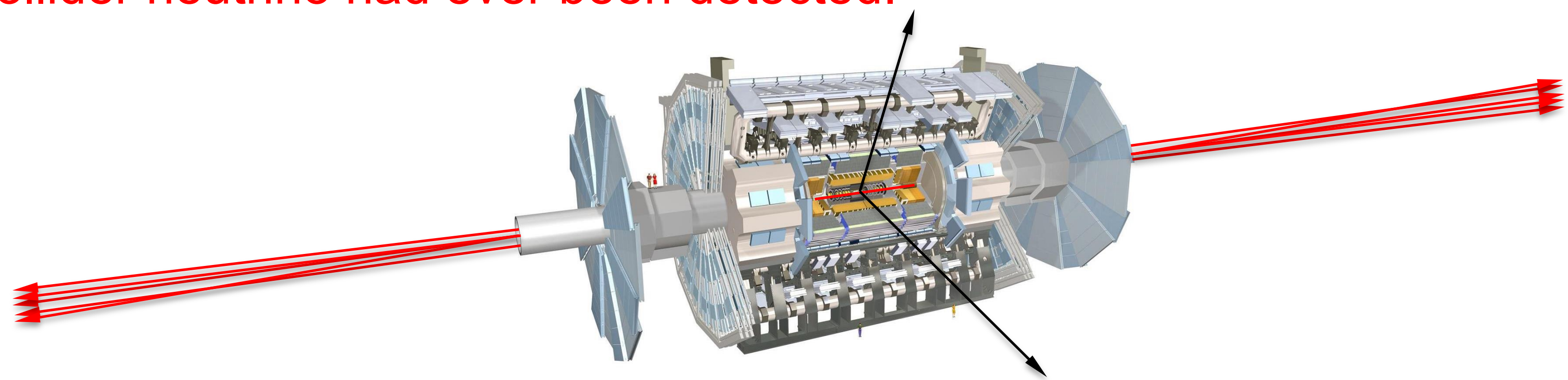


Tim Nelson, Snowmass RP6 (2020)

FASERν

- In addition to the possibility of hypothetical new light, weakly-interacting particles, there are also known light, weakly-interacting particles: neutrinos.

- The high-energy ones, which interact most strongly, are overwhelmingly produced in the far forward direction. Before May 2021, no candidate collider neutrino had ever been detected.



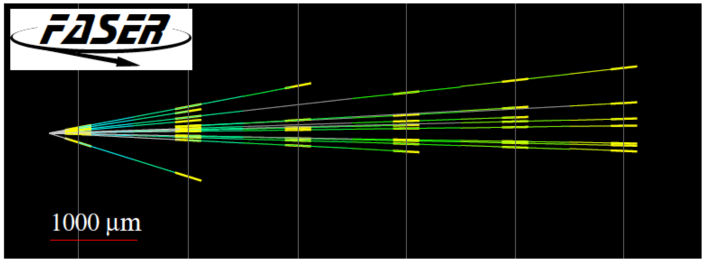
- If they can be detected, there is a fascinating new world of LHC neutrinos that can be explored.
  - The neutrino energies are ~TeV, highest human-made energies ever.
  - All flavors are produced ($\pi \to \nu_\mu$, $K \to \nu_e$, $D \to \nu_\tau$) and both neutrinos and anti-neutrinos.

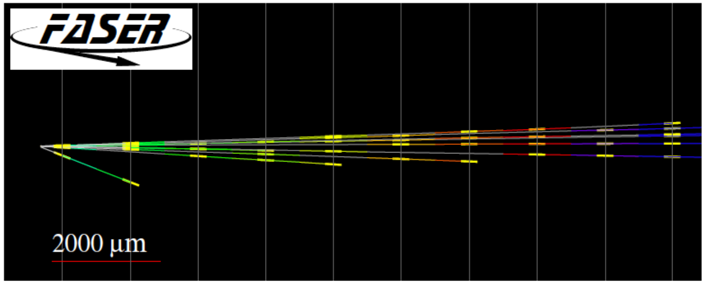
De Rujula, Ruckl (1984); Winter (1990); Vannucci (1993)

FIRST COLLIDER NEUTRINO CANDIDATES

- 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).



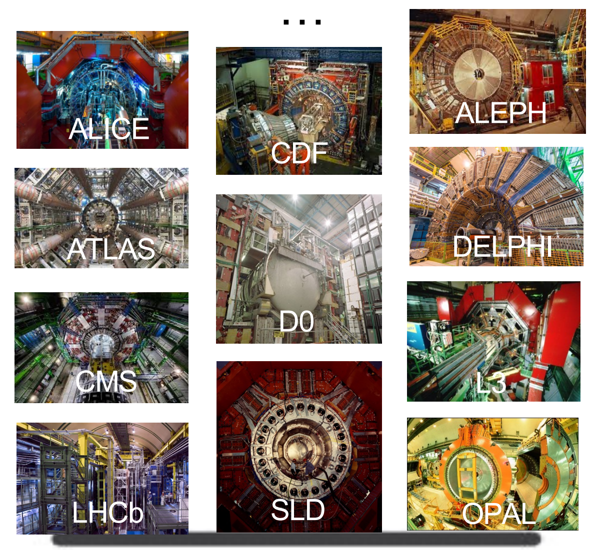


LOCATION, LOCATION, LOCATION

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

This opens up a new field:
neutrino physics at colliders

FPF

Forward Physics Facility

FORWARD PHYSICS FACILITY

- FASER, FASERν, and SND@LHC are currently highly constrained by 1980's (LEP!) infrastructure that was never intended to support experiments.

- The rich physics program in the far-forward region therefore strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2029-2040.

- FPF Meetings
  - FPF Kickoff Meeting, 9-10 Nov 2020, https://indico.cern.ch/event/955956
  - FPF2 Meeting, 27-28 May 2021, https://indico.cern.ch/event/1022352
  - FPF3 Meeting, 25-26 Oct 2021, https://indico.cern.ch/event/1076733
  - FPF4 Meeting, 31 Jan-1 Feb 2022, https://indico.cern.ch/event/1110746

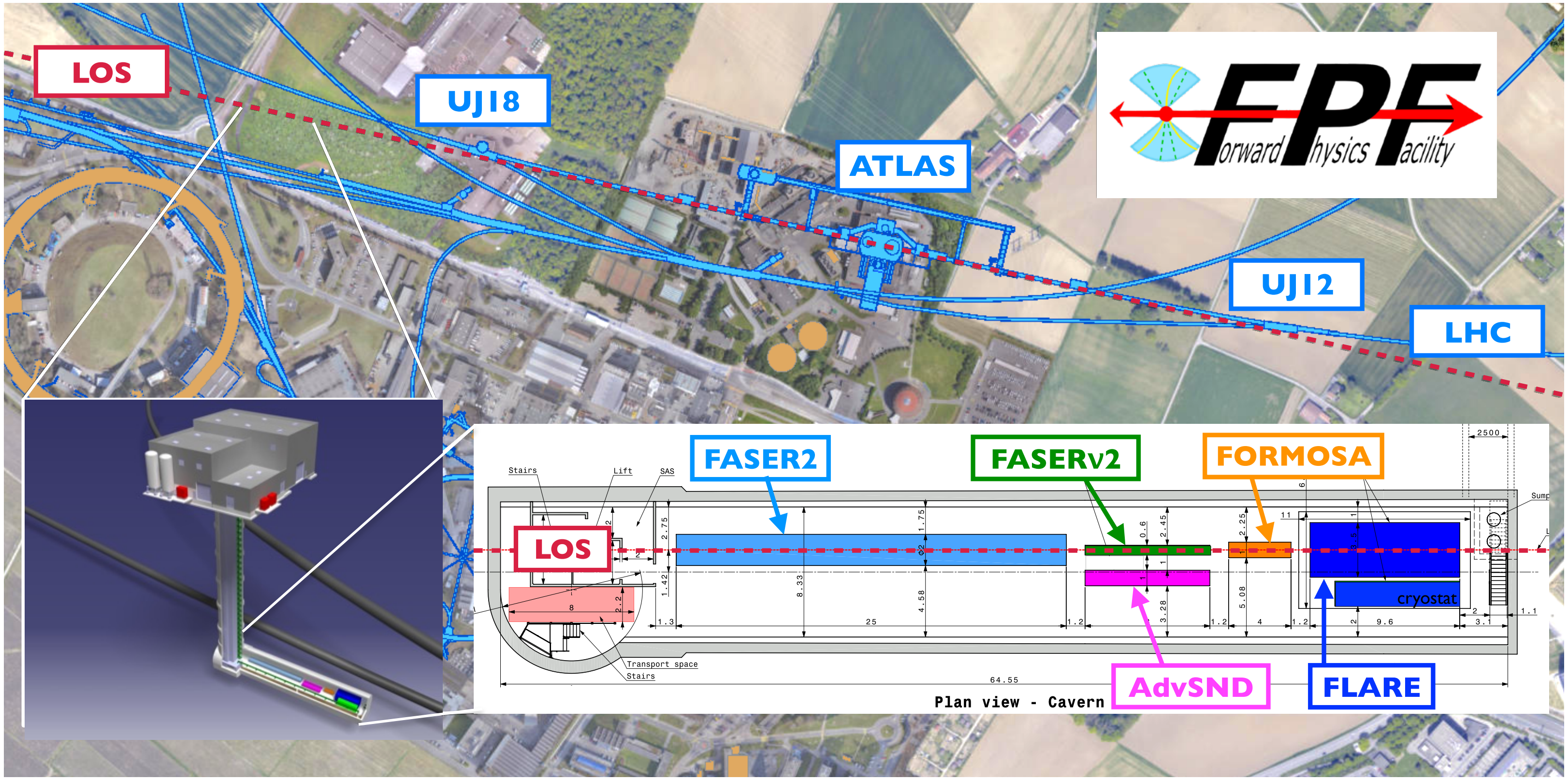
- FPF Short Paper: 75 pages, 80 authors completed in Sep 2021 (2109.10905, Physics Reports 968, 1 (2022)).

- FPF Snowmass White Paper: Feng, Kling, Reno, Rojo, Soldin et al. A comprehensive, 429-page, 392-author+endorser summary (2203.05090).

THE LOCATION

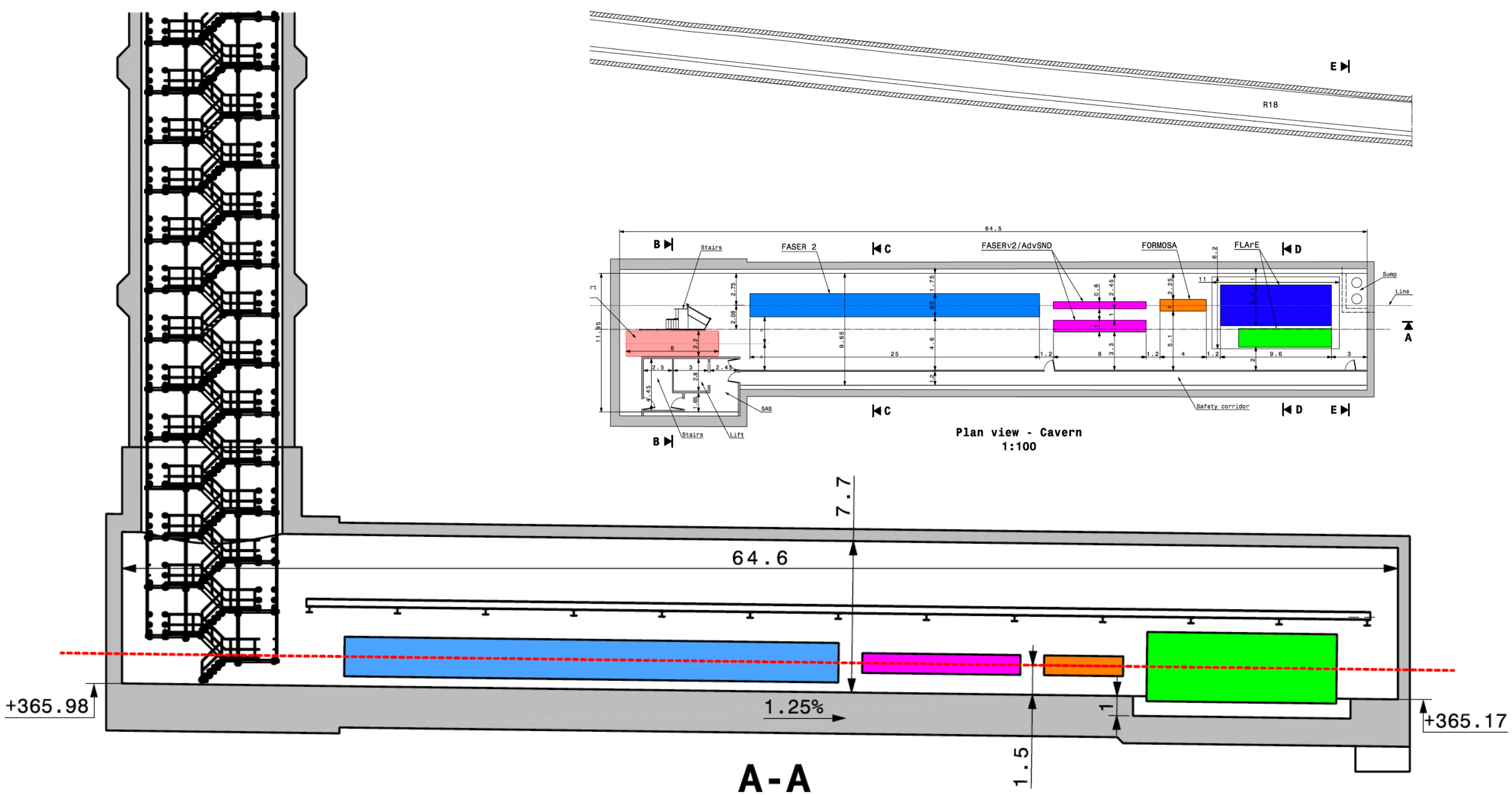
- The CERN civil engineering team has considered many sites around the LHC ring that are on the beam collision axis of an IP.

- A preferred location has been identified ~620-680 m west of the ATLAS IP, shielded by ~200 m of rock. The site is on CERN land in France.

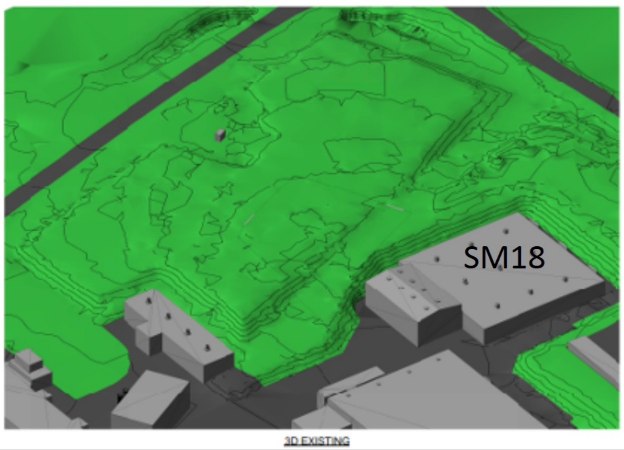


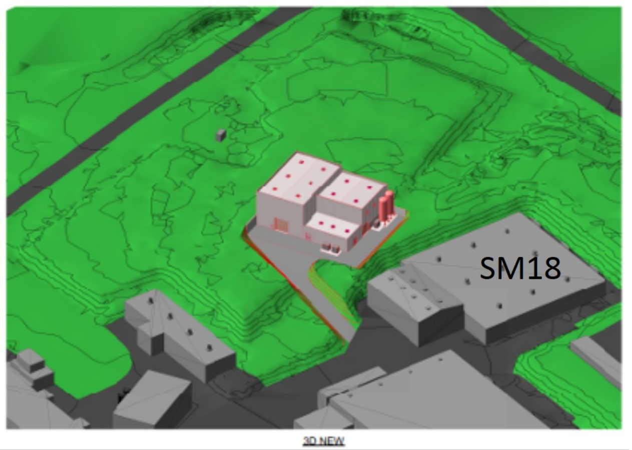
CAVERN AND SHAFT

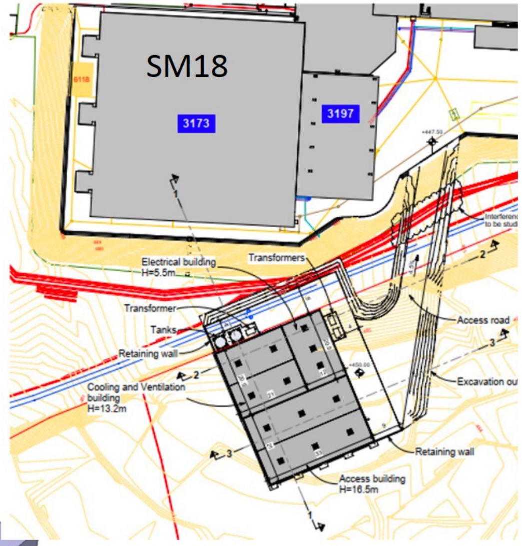
- Cavern: 65m long, 8m wide/high. Shaft: 88m-deep, 9.1m-diameter.
- The FPF is completely decoupled from the LHC: no need for a safety corridor connecting the FPF to the LHC, preliminary RP and vibration studies indicate that FPF construction will have no significant impact on LHC operation.

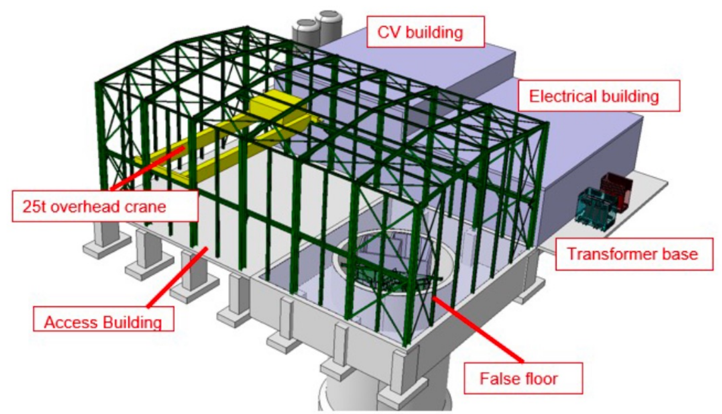


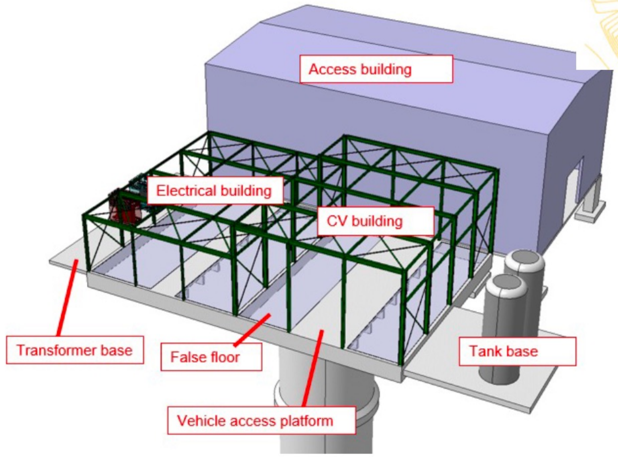
SURFACE BUILDINGS







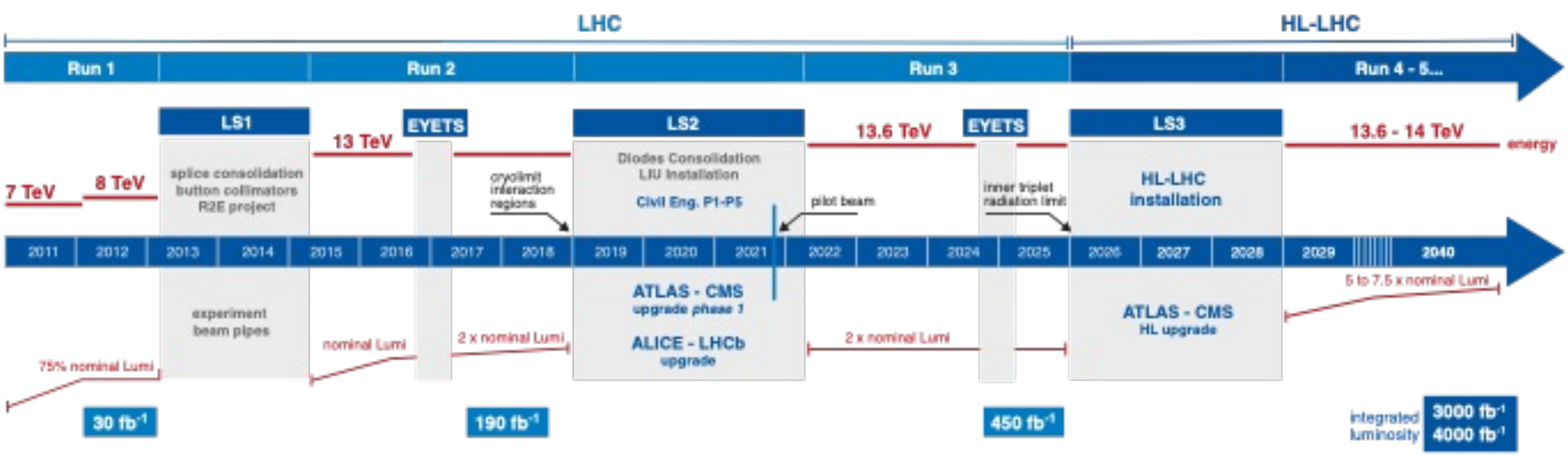




Kincso Balazs,
John Osborne,
CERN CE (2022)

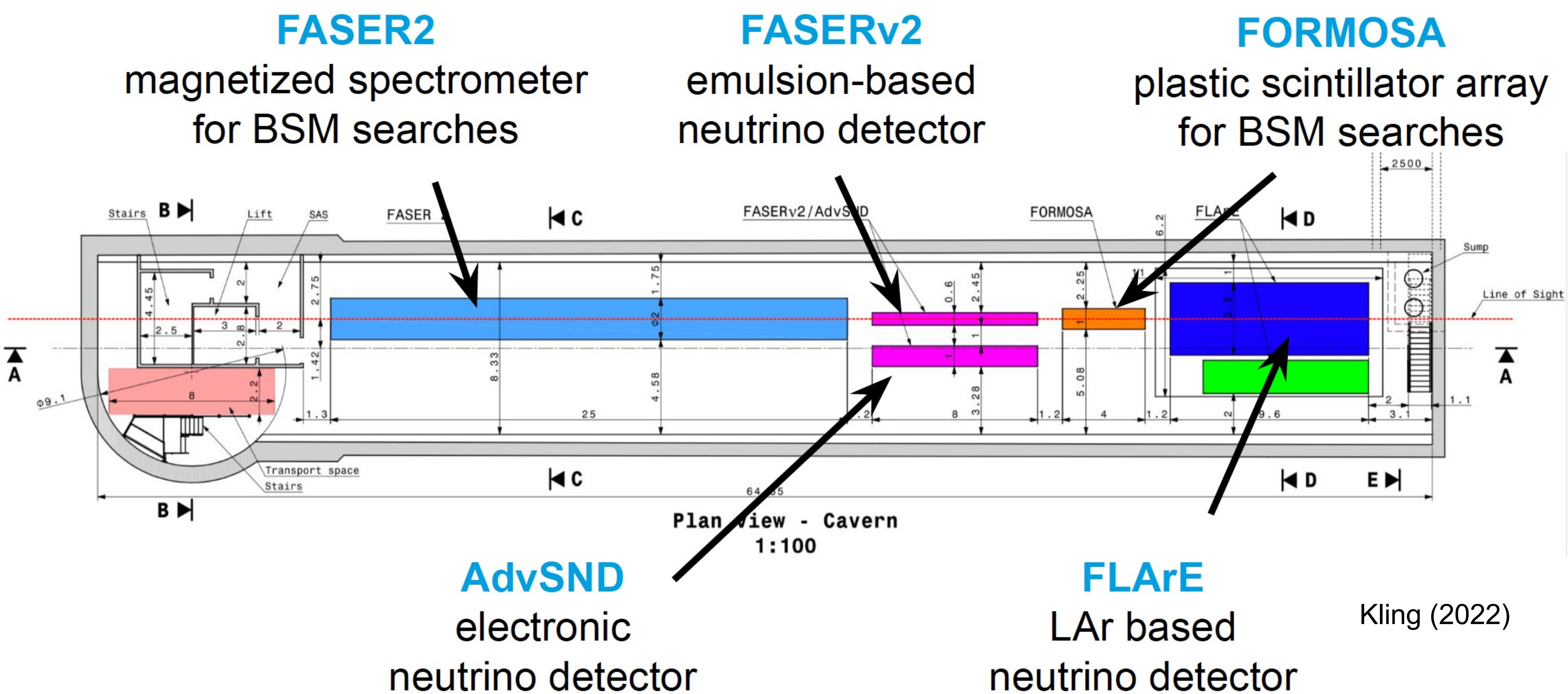
COST AND TIMELINE

- Very preliminary (class 4) cost estimate: 23 MCHF (CE) + 15 MCHF (services) ≈ 40 MCHF (+50%/-30%), not including experiments.
- Timeline presented at Chamonix workshop (Jamie Boyd, Feb 2022).
- Expect CDRs for FPF and its experiments in the coming 6-12 months.
- Begin CE works, installation of services in LS3, followed by installation and commissioning of experiments in early Run 4. Physics begins in Run 4 and continues to the end of the HL-LHC era.



FPF EXPERIMENTS

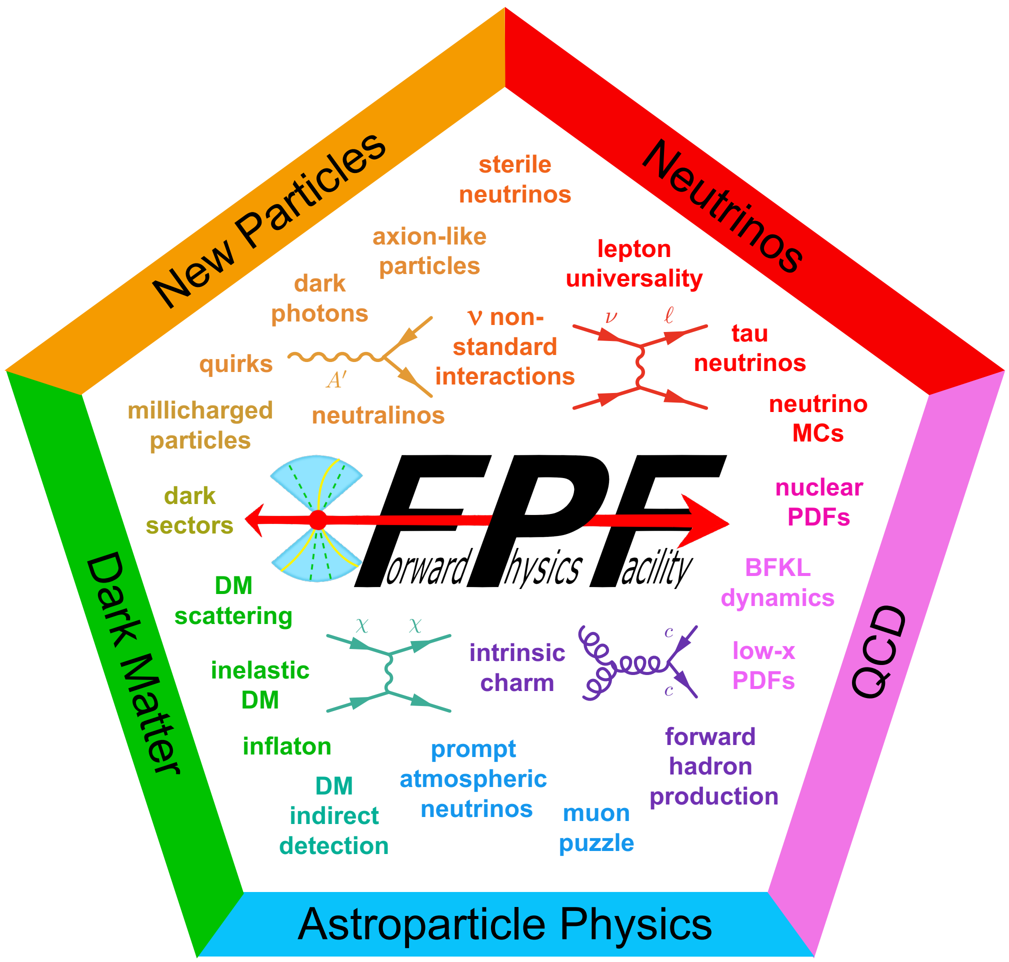
- At present there are 5 experiments being developed for the FPF.
- Pseudo-rapidity coverage in the FPF is η > 5.5, with most experiments on the LOS covering η > 7.



Kling (2022)

FPF PHYSICS

- The FPF is a general purpose facility with a broad SM and BSM physics program that expands on the physics of FASER and FASERν. Here I will just give a few examples. For more, see the FPF White Paper.

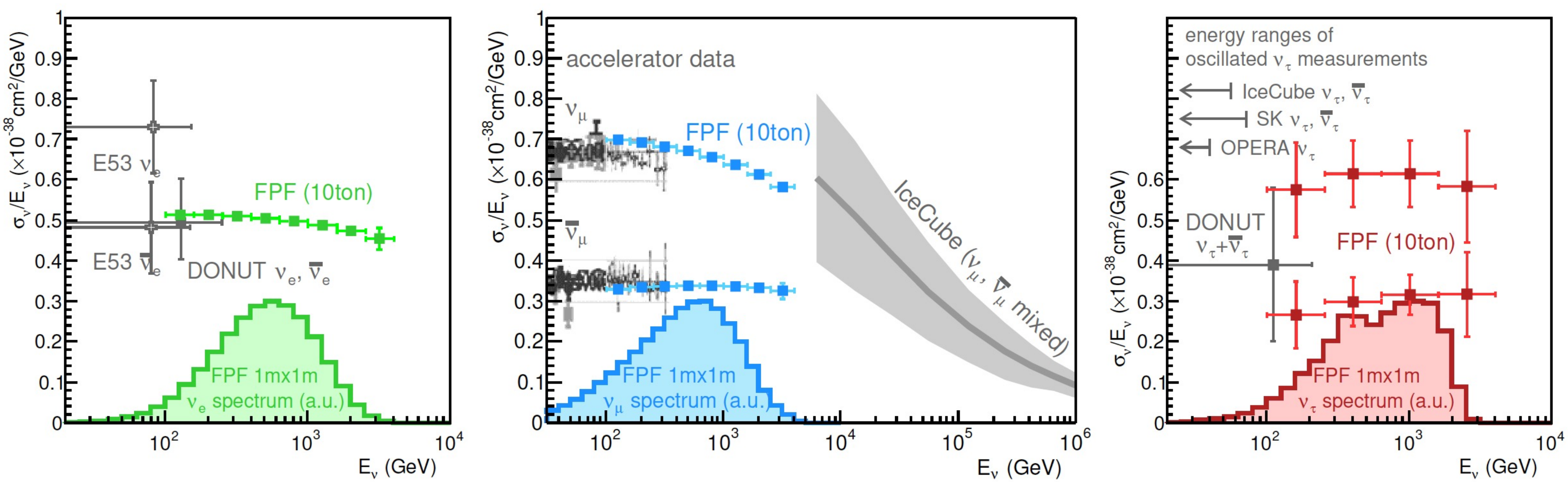


NEUTRINOS

- At the FPF, three proposed ~10-ton detectors FASERν2, AdvSND, 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.

- Will enable precision studies of the tau neutrino.

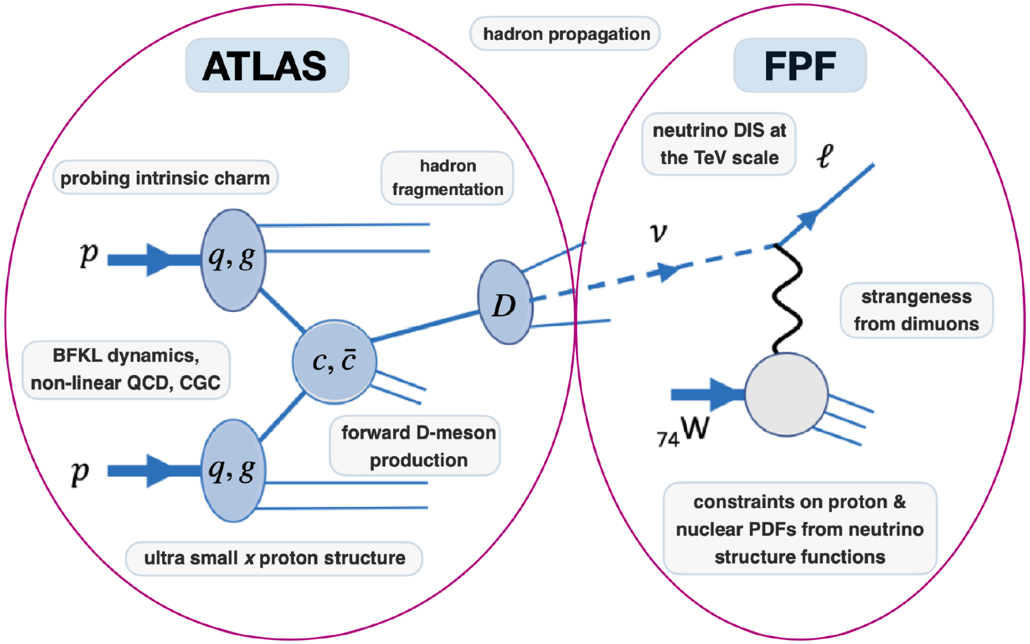
- Can also distinguish neutrinos and anti-neutrinos for muon and tau.



FASER White Paper (2022)

QCD

- The FPF will also support a rich program of QCD and hadron structure studies.
- Forward neutrino production is a a probe of forward hadron production, BFKL dynamics, intrinsic charm, ultra small x proton structure, with important implications for UHE cosmic ray experiments.
- Neutrino interactions will probe DIS at the TeV-scale, constrain proton and nuclear structure, pdfs. Many synergies with the EIC.

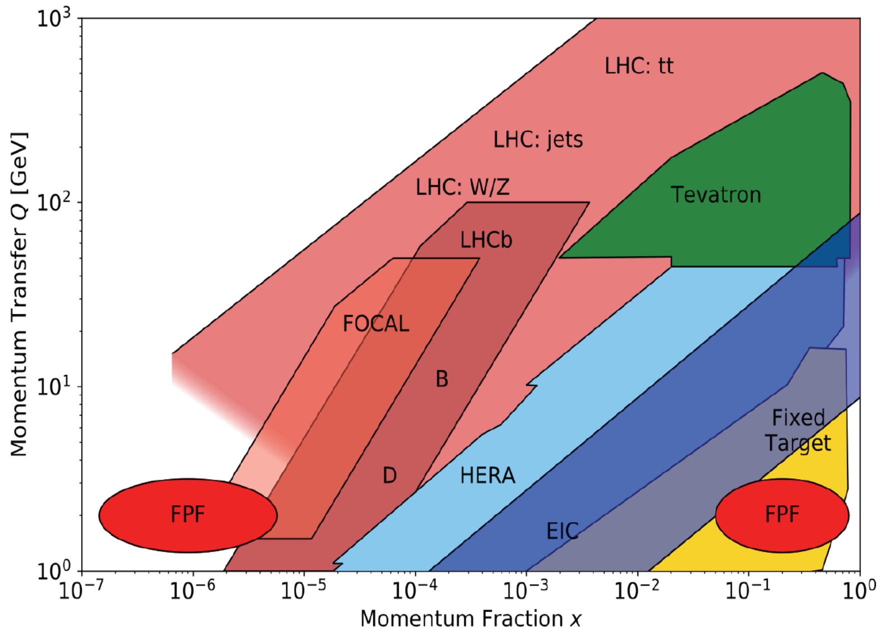


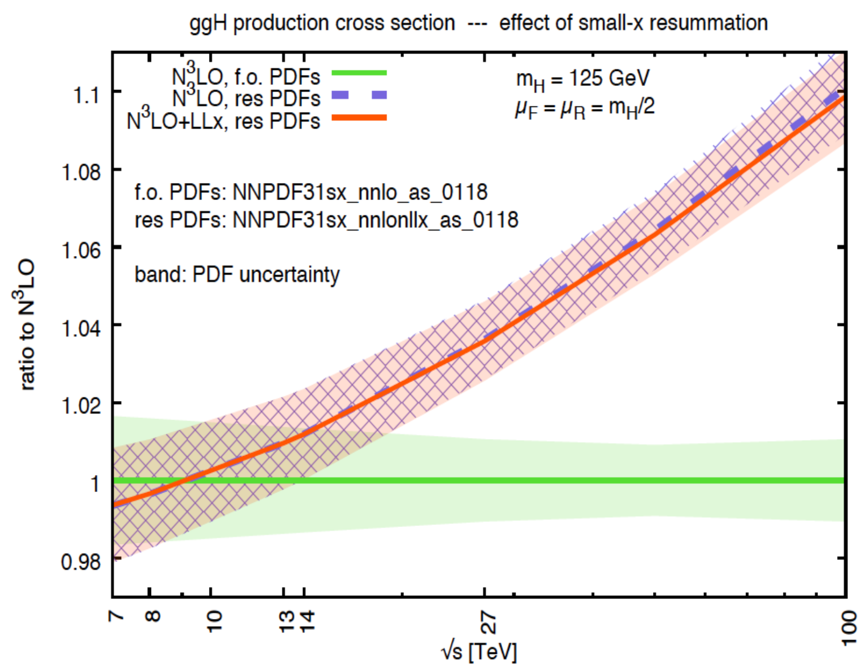
FASER White Paper (2022)

QCD

- The FPF will probe proton structure at ultra small $x \sim 10^{-7}$ (and also high $x \sim 1$).

- In addition to the intrinsic interest in QCD, ultra small-x physics will become more and more important at higher energies, for example, in making precise predictions for $\sigma(gg \to h)$ at a 100 TeV pp collider.





FPF White Paper (2022)

SUMMARY

- The possibility that new particles may be light and very weakly-interacting opens up new connections between particle physics, cosmology, and nuclear physics.

- At the LHC, this has led to new interest in building experiments in the far forward region to catch particles produced along the beamline.

- The Forward Physics Facility, proposed for the HL-LHC, will enhance the LHC's potential for new physics searches, neutrinos physics, and QCD.