LONG-LIVED PARTICLES AT (FUTURE) COLLIDERS

IAS Program on High Energy Physics (HEP 2022), Hong Kong

17 January 2022

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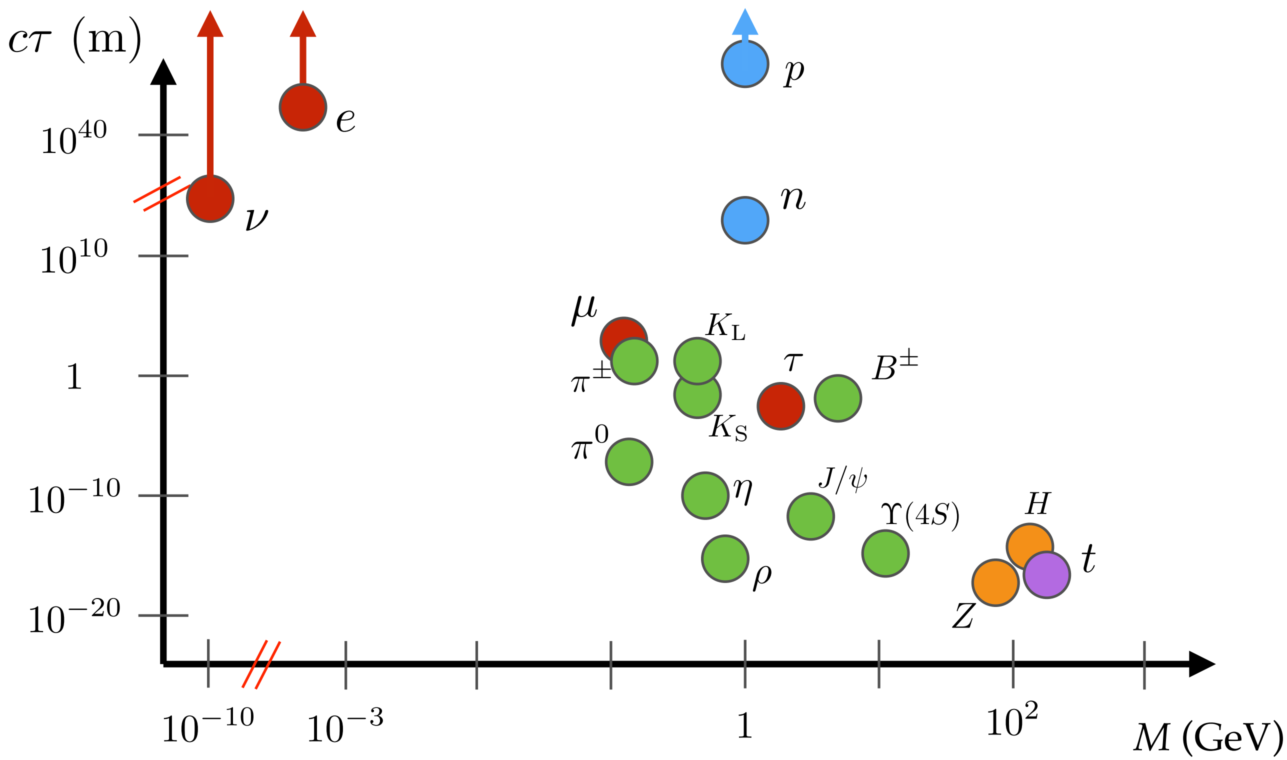
EXECUTIVE SUMMARY

- Long-Lived Particles (LLPs) are particles that travel macroscopic distances at colliders and then decay.
- LLPs have long been considered to be exotica, but they are in fact ubiquitous in new physics models.
- The LHC is currently not optimized to discover LLPs, especially light ones; new experiments and the proposed Forward Physics Facility will help.
- Future colliders can improve their discovery potential by including LLP capabilities in their plans from the beginning.

LLPS IN OUR PAST

- We have already discovered many LLPs.



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

- In fact, LLPs have played an essential role in many of the conceptual breakthroughs that established the standard model of particle physics: *n*, μ, $\pi^{\pm}$, $K_{L,S}$, *B*, …

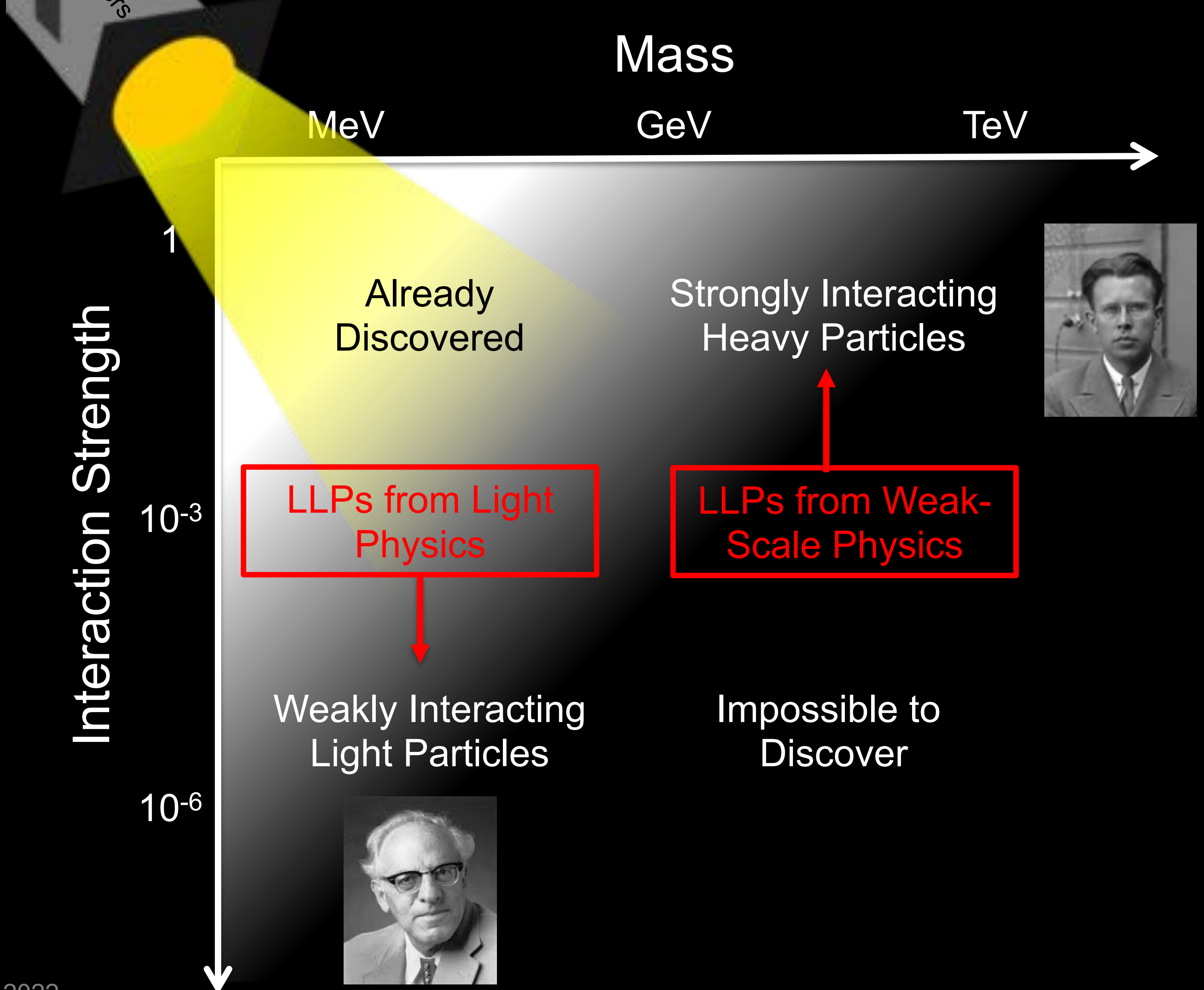
LLPS IN OUR FUTURE

- The next breakthrough in particle physics is likely to involve LLPs
  - LLPs are ubiquitous in BSM theories, especially those with cosmological significance.
  - LLPs can be detected through a huge variety of signatures, many of which are truly spectacular – a few events can be a discovery.
  - At the LHC, we have not yet reached the full LLP discovery potential, but there are many exciting initiatives now underway and proposed.

CAVEAT

- This is by now a huge field, and it is impossible to give a complete overview of either the LLP candidates or the experiments proposed to look for them.
- LLPs can emerge in many scenarios. In many BSM models, one can tune a coupling or a mass splitting to be very small to create an LLP.
- In this talk, however, I will highlight scenarios in which LLPs have some independent reason to be long-lived and particularly focus on those that have some interesting cosmological connections.

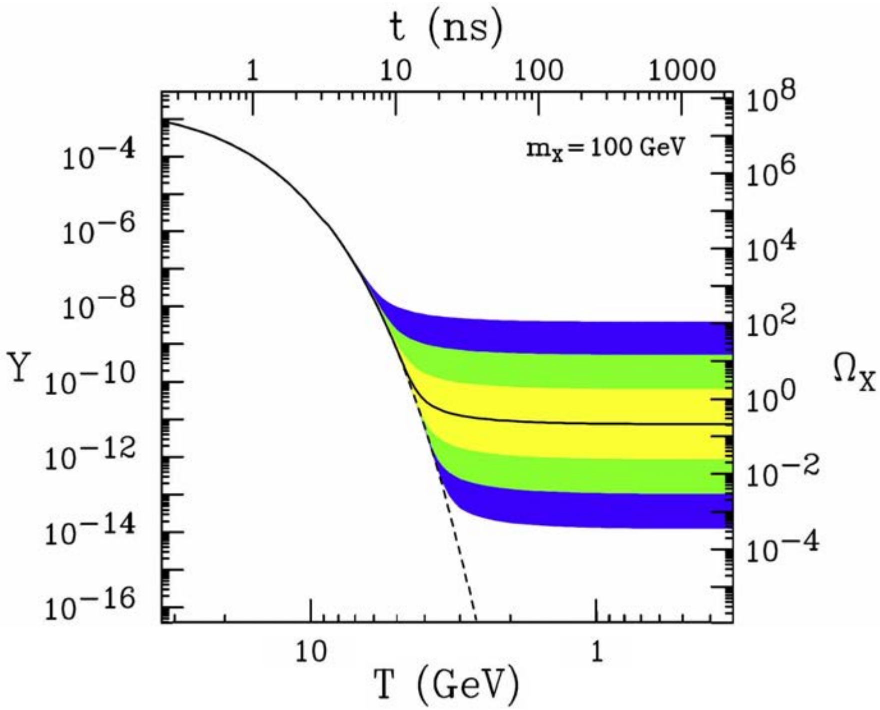
THE NEW PARTICLE LANDSCAPE



LLPS FROM
WEAK- SCALE PHYSICS

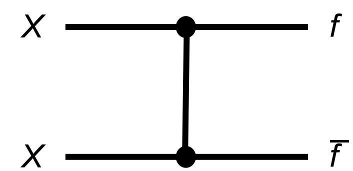
WEAK-SCALE PHYSICS AND COSMOLOGY

- Particles with g ~ O(1) and mass ~ m_W are great DM candidates.



- The resulting relic density is

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



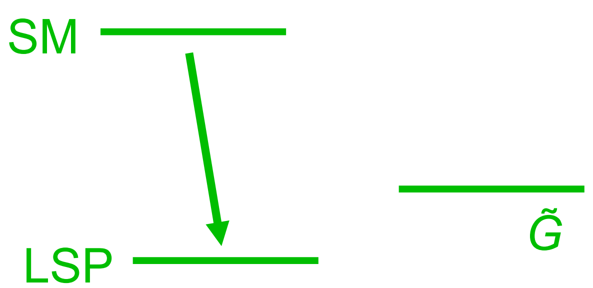
- For a WIMP, m_X ~ 100 GeV and g_X ~ 0.6 → $\Omega_X \sim 0.1$

- This simple coincidence, the WIMP Miracle, ties together weak-scale physics and cosmology, and has led to the notion that BSM searches are largely missing E_T searches at colliders.

LLPS IN STANDARD SUSY

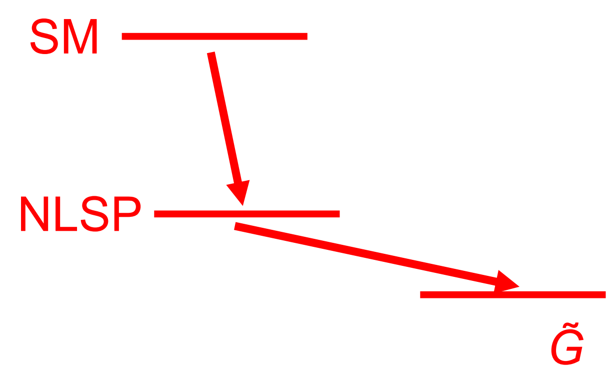
- But this focus on missing E_T is a vast oversimplification.
- Consider standard (gravity-mediated) supersymmetry. The gravitino has mass ~ 100 GeV, couplings ~ M_W/M_{Pl} ~ 10^{-16} .

- $\tilde{G}$ not LSP



- Assumption of most of literature

- $\tilde{G}$ LSP

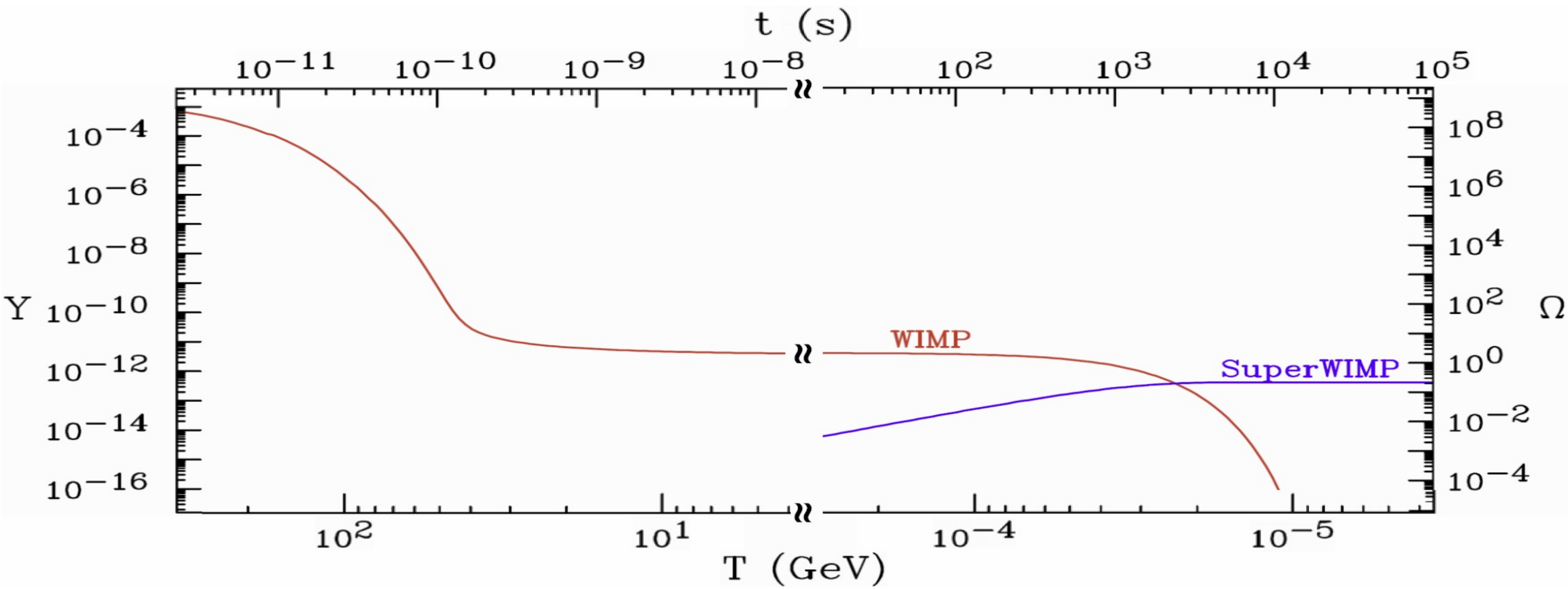


- Completely different cosmology and particle physics

LLPs IN SUPERWIMP SCENARIOS

Feng, Rajaraman, Takayama (2003)

- In the $\tilde{G}$ LSP scenario, WIMPs freeze out as usual, but then decay to $\tilde{G}$ after M_{Pl}^2/M_W^2 ~ seconds to months.



- The gravitino is superWIMP DM, naturally has the right relic density. But now the WIMP can be, e.g., a charged slepton, implying metastable charged LLPs at colliders.

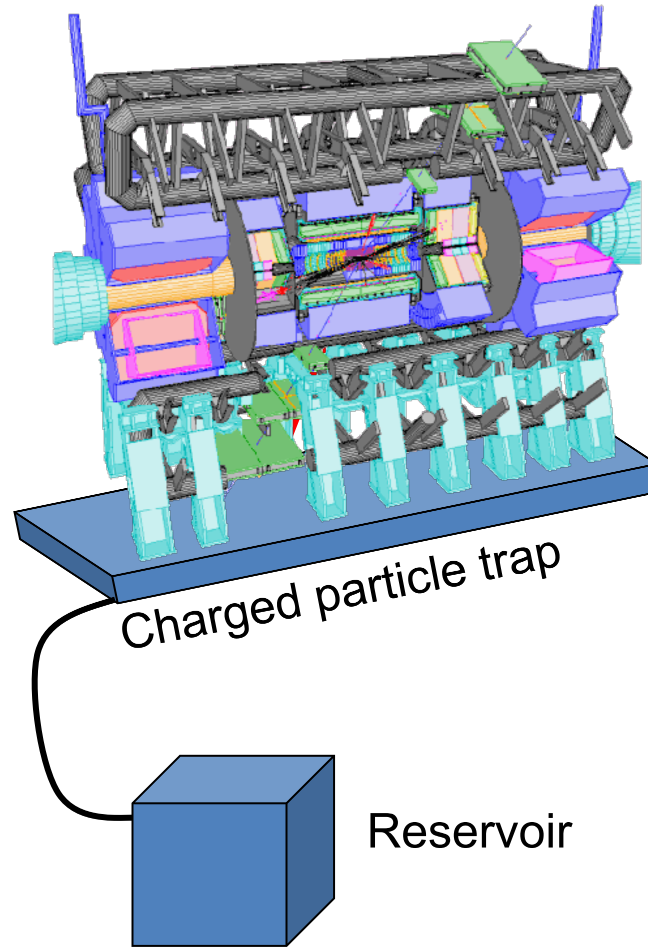
LLPs AND ADD-ON DETECTORS

- If we see metastable charged LLPs, we know they must decay.
- We can collect these particles and study their decays.
- Several ideas have been proposed
  - Catch sleptons in a 1m thick water tank (up to 1000/year) and then move them to a quiet place to observe their decays

    Feng, Smith (2004)
  - Catch sleptons in LHC detectors

    Hamaguchi, Kuno, Nakawa, Nojiri (2004)
  - Dig sleptons out of detector hall walls

    De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape (2005)



LLPs IN GAUGE-MEDIATED SUSY

- Scenarios with gauge-mediated SUSY breaking are among the most famous of those predicting LLPs.

Dine, Nelson, Nir, Shirman (1994, 1995); Dimopoulos, Dine, Raby, Thomas (1996); …

- NLSPs decay to light $\tilde{G}$ LSPs. The $\tilde{G}$ mass and the NLSP decay length are correlated. For $\tilde{G}$ masses ~ keV (motivated, with caveats, by $\tilde{G}$ DM), the decay lengths are macroscopic

$$c\tau_{\rm NLSP} \approx 50 \text{ cm} \left(\frac{200 \text{ GeV}}{m_{\rm NLSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{\text{keV}}\right)^2$$

	Neutralino NLSP	Slepton NLSP
Prompt	Prompt photons	Multi-leptons
Intermediate	Displaced photons Displaced conversion	Displaced lepton Track kinks
Long-Lived	Missing E_T	Time-of-flight High dE/dx

LLPs IN ANOMALY-MEDIATED SUSY

- Scenarios with anomaly-mediated SUSY breaking give additional interesting LLPs signals.

Randall, Sundrum (1998); Giudice, Luty, Murayama, Rattazzi (1998); …

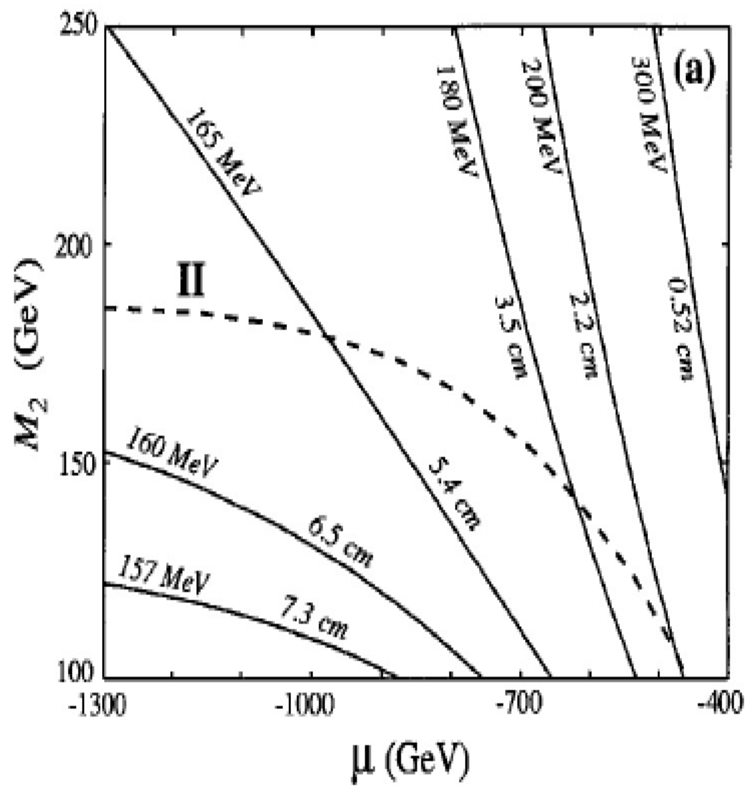
- The LSPs are a highly degenerate Wino triplet with $\Delta m_{loop} >> \Delta m_{tree}$.

- Typically, there are 2-body decays

$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$$

and disappearing tracks after ~10cm.

- This is an example of the generic possibility that a symmetry enforces small mass splittings, leading LLPs.



Feng, Moroi, Randall, Strassler, Su (1999)

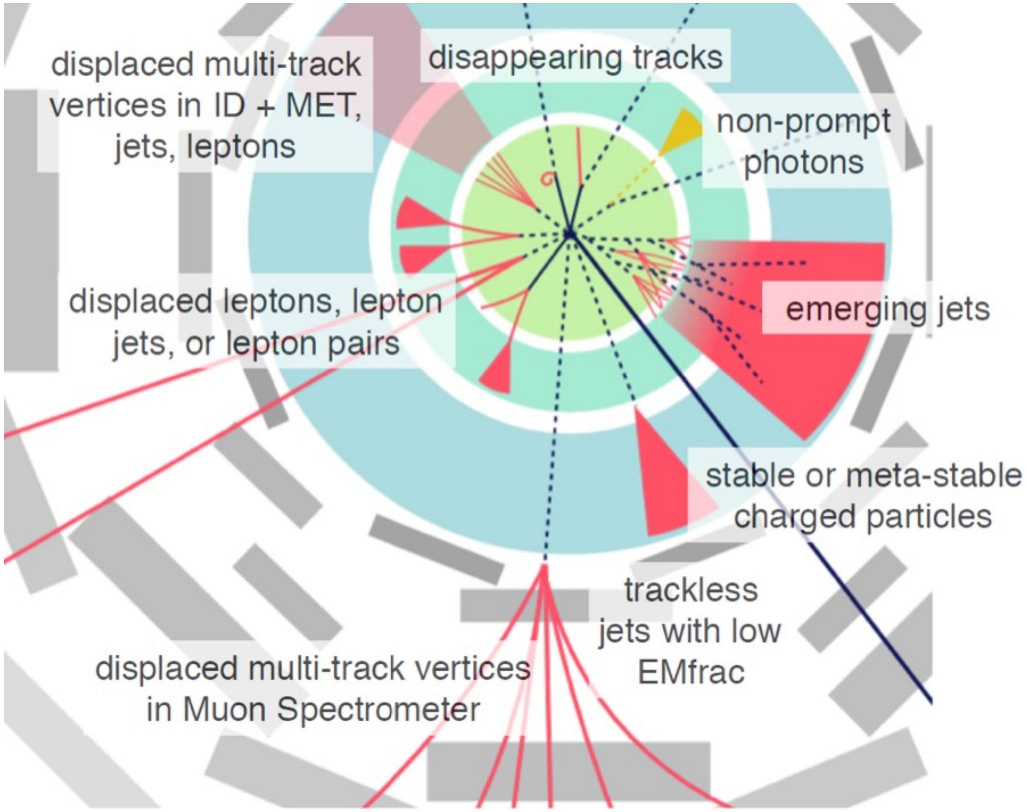
LLPs IN OTHER WEAK-SCALE MODELS

- By considering a few standard models of weak-scale physics, we have motivated a plethora of possible LLP signatures.

- Of course, there are many other motivated weak-scale models with LLPs.

- In SUSY: e.g., R-parity violating SUSY and compressed SUSY, which have become more motivated as generic, sub-TeV SUSY becomes more constrained.

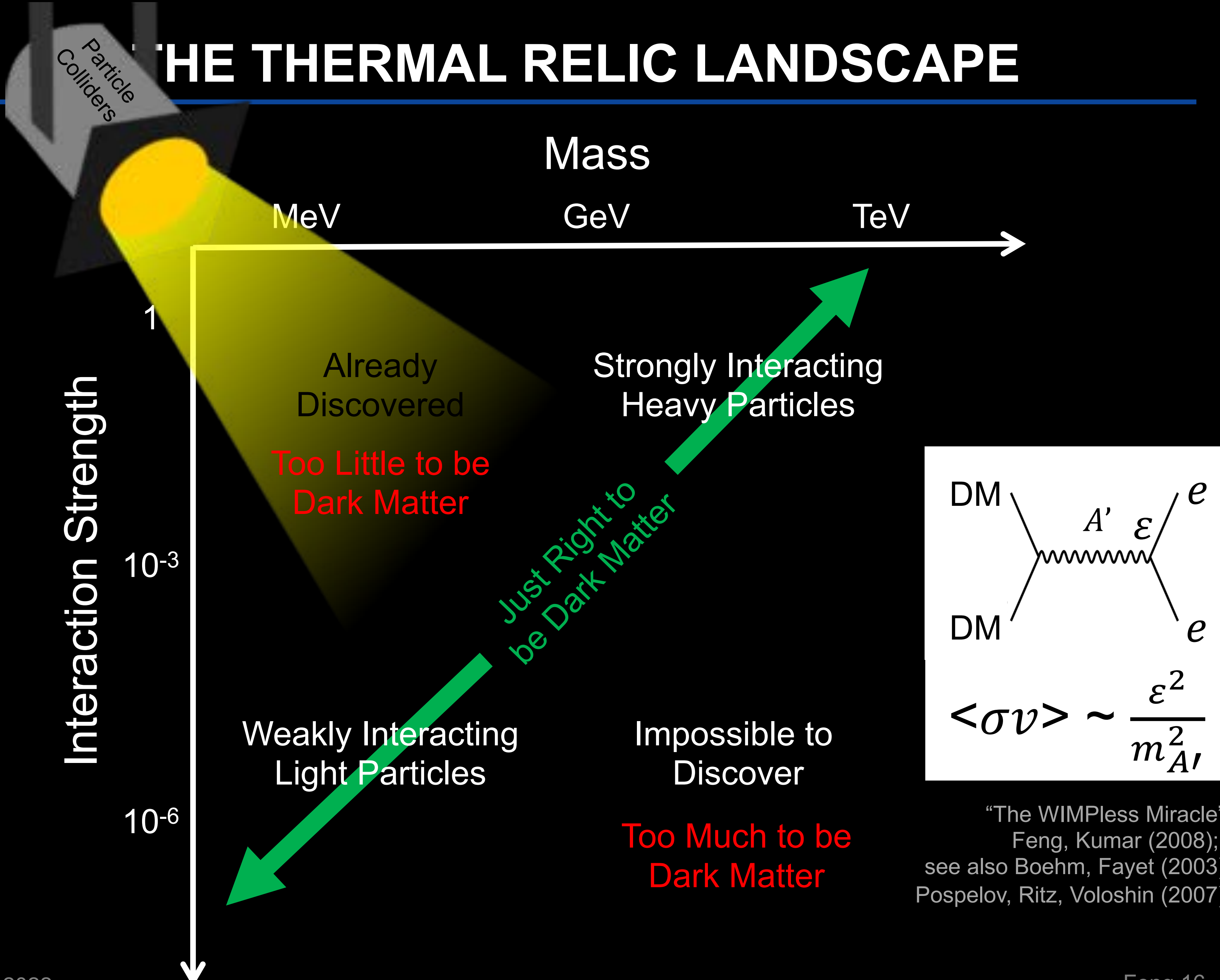
- Extra dimensional scenarios typically have similar possibilities (e.g., viewing universal extra dimensions as bosonic supersymmetry), and naturally compressed spectra.



Credit: Heather Russell

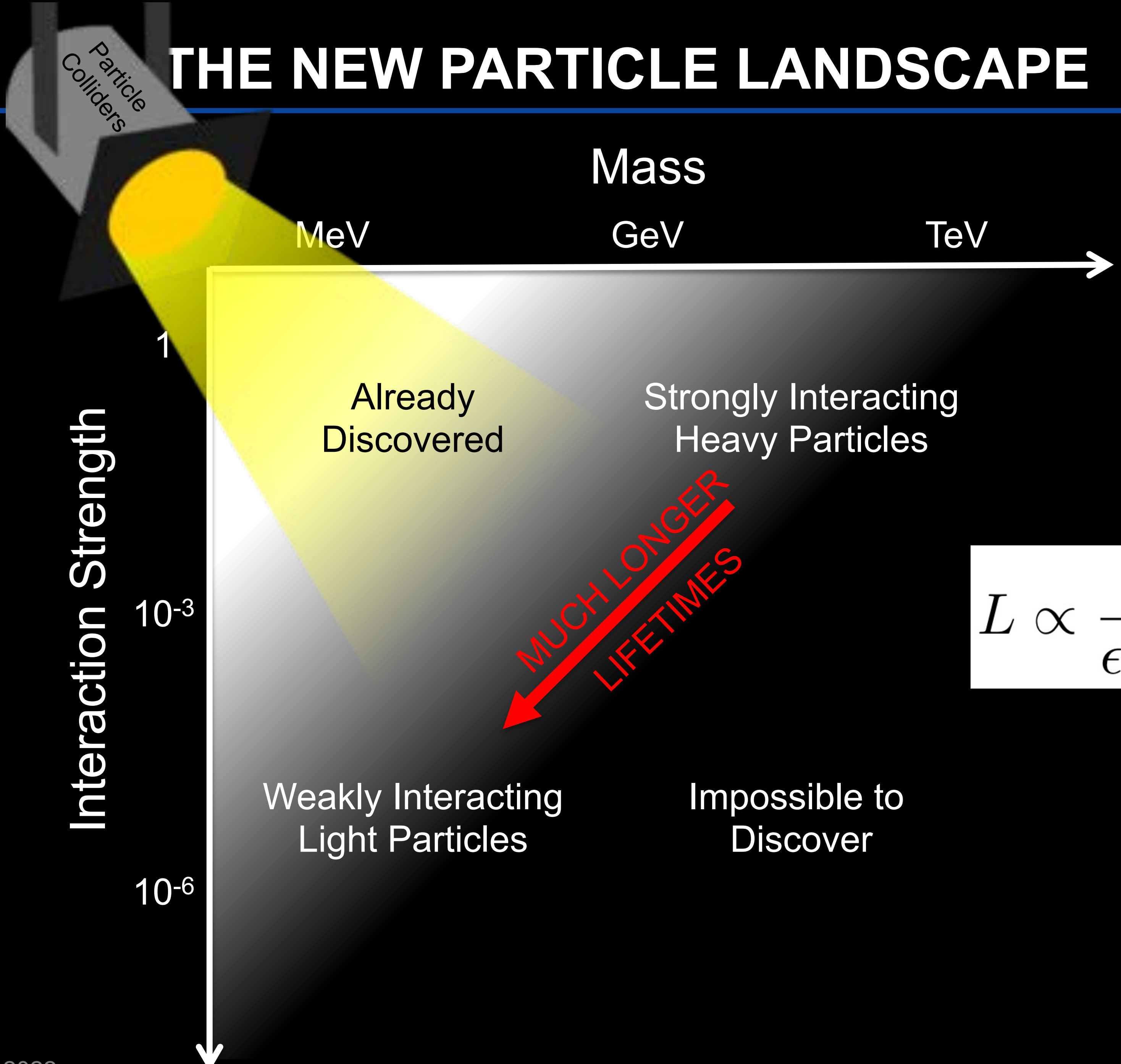
LLPS FROM
LIGHT PHYSICS

THE THERMAL RELIC LANDSCAPE



"The WIMPless Miracle"
Feng, Kumar (2008);
see also Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)

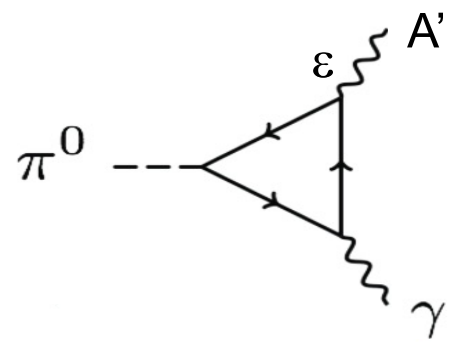
THE NEW PARTICLE LANDSCAPE



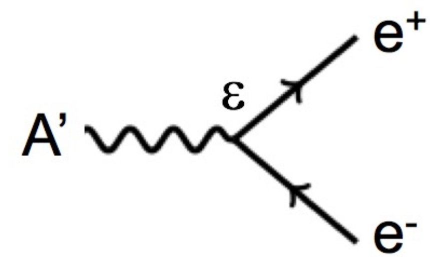
$$L \propto \frac{1}{\epsilon^2 m^2}$$

LIGHT LLP PHENOMENOLOGY

- The advent of dark sectors (along with axion-like particles, light gauge bosons, etc.) highlights a new class of LLPs.
- As an example, consider a dark photon A' with energy E ~ TeV, mass m ~ 100 MeV, coupling $\varepsilon \sim 10^{-5}$.
- It can be produced in large numbers through the decays of light particles, like pions.



- It passes through matter essentially without interacting: radiation length is (10 cm) $\varepsilon^{-2} \sim 10^9$ m, the distance to the moon!
- It decays to visible particles, but only after traveling a long distance.

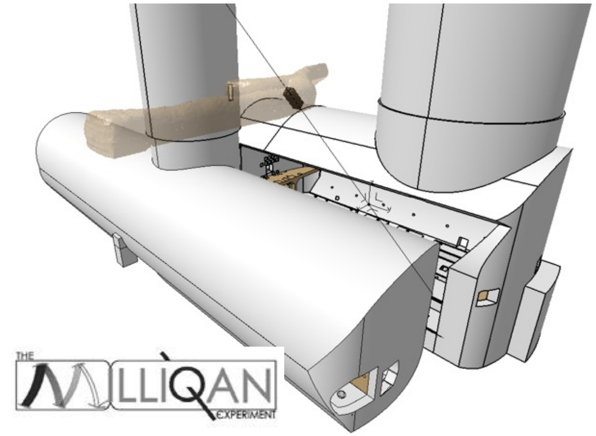


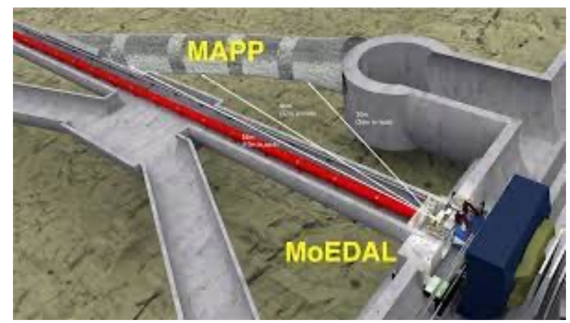
$$L = v\tau\gamma \sim (100\text{ m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{100\text{ MeV}}{m}\right]^2 \left[\frac{E}{\text{TeV}}\right]$$

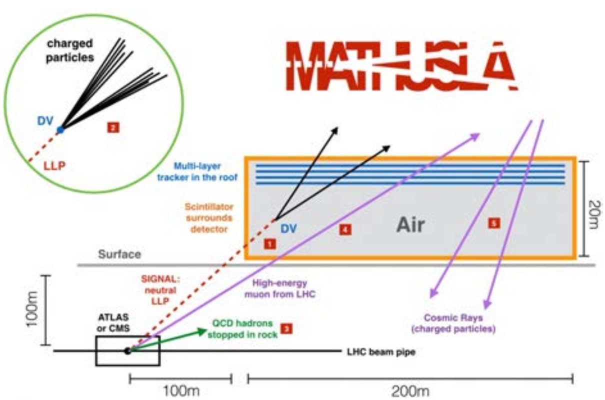
LIGHT LLPS AT THE LHC

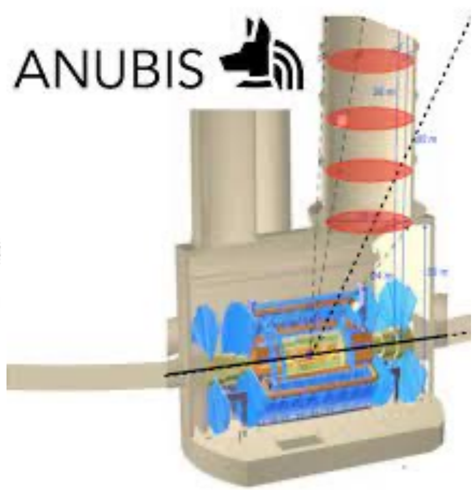
- How can we find light LLPs at colliders?

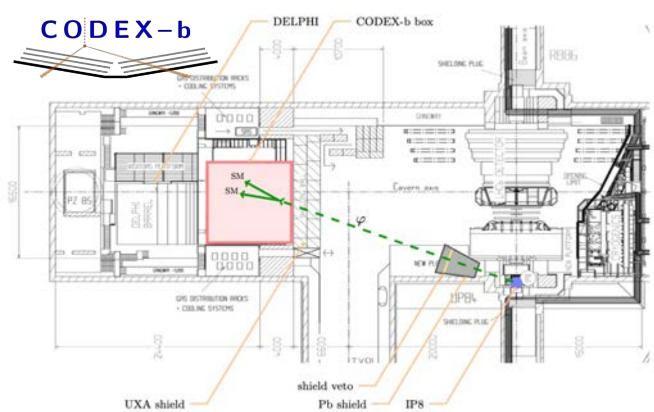
- Many ideas for new detectors at the LHC
  - Transverse detectors: MoeDAL/MAPP, MilliQan, MATHUSLA, Codex-b, ANUBIS, …
  - Far-forward detectors: FASER, FASERν, SND@LHC









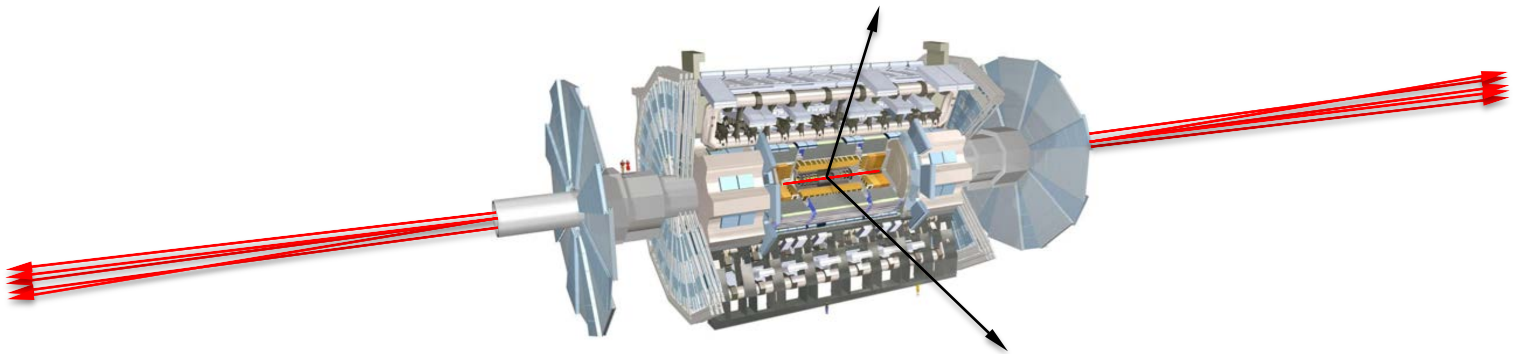


FASER

SEARCHES FOR NEW LIGHT PARTICLES

- If new particles are light and weakly interacting, the existing big LHC detectors are perfectly designed NOT to see them.

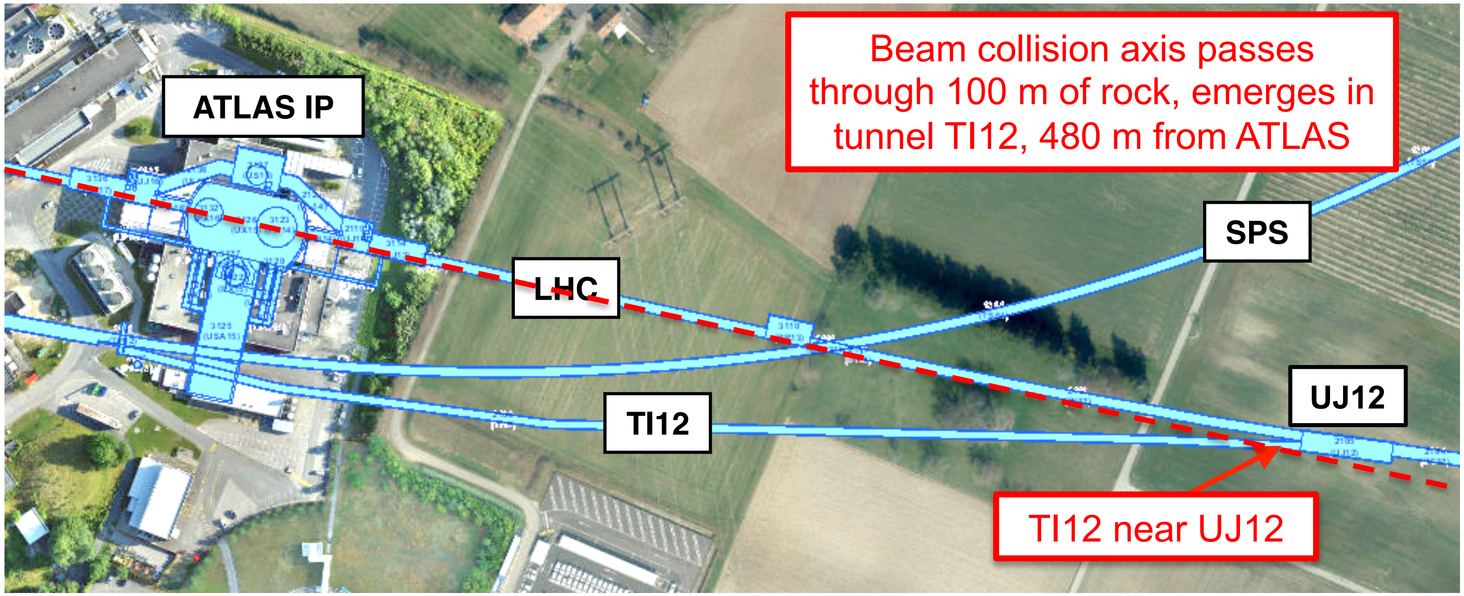
- Existing detectors are designed to find new heavy particles. These particles are produced almost at rest and decay isotropically.

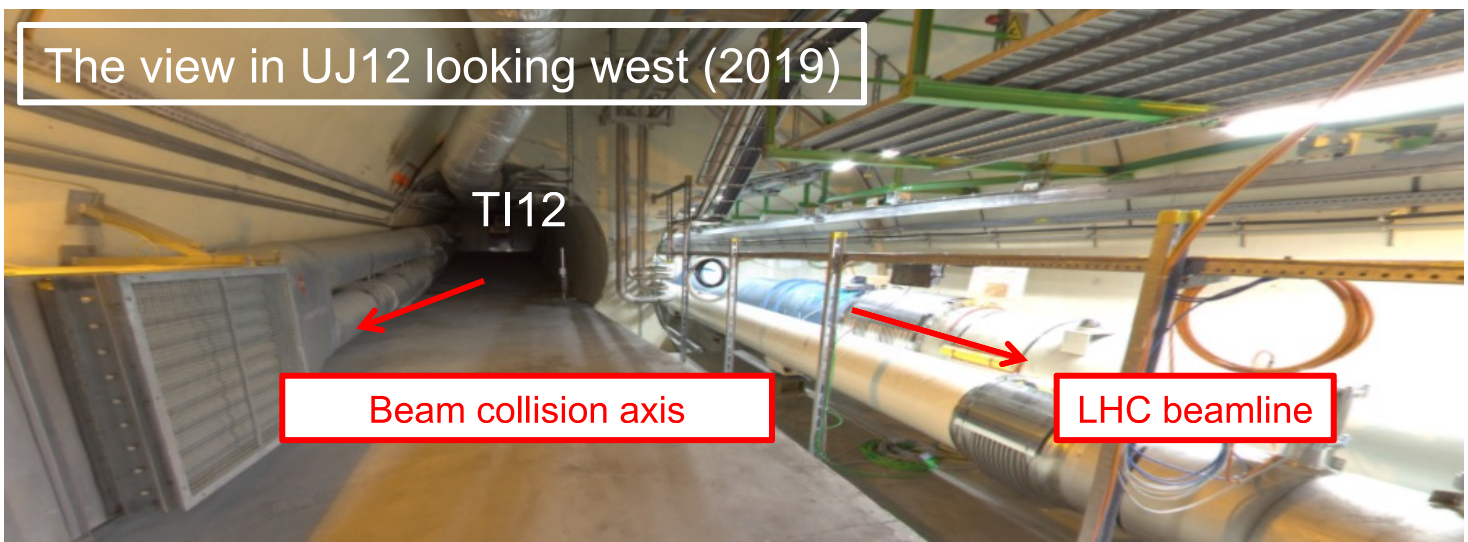


- But new light particles are mainly produced in the decays of light particles: π, η, K, D and B mesons. These are mainly produced along the beamline, and so the new particles disappear through the holes that let the beams in.

- Clearly we need a detector to exploit the "wasted" $\sigma_{inel} \sim 100$ mb and cover these "blind spots" in the forward region. If we go far enough away, the proton beams are bent by magnets (it's a circular collider!), whereas the new light particles will go straight.

THE FAR-FORWARD REGION

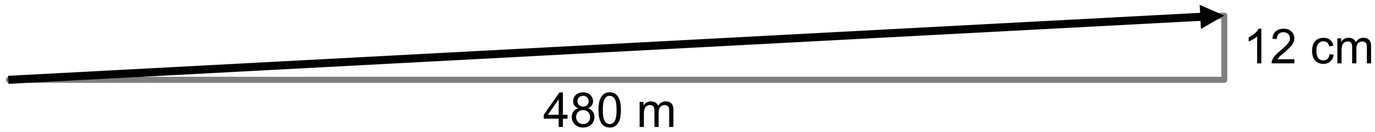




HOW BIG DOES THE DETECTOR HAVE TO BE?

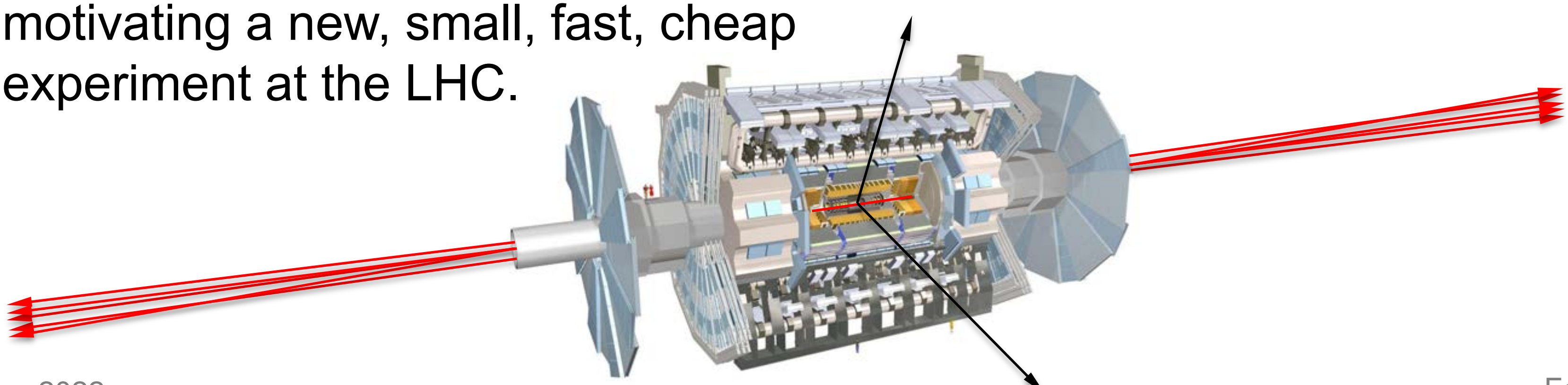
- Momentum:

- Space:



- The opening angle is 0.2 mrad (η ~ 9); cf. the moon (7 mrad). Most of the signal passes through 1 sheet of paper at 480 m.

- TeV dark photons (or any other new particles produced in π, η, K, D, B decay) are far more collimated than shown below, motivating a new, small, fast, cheap experiment at the LHC.

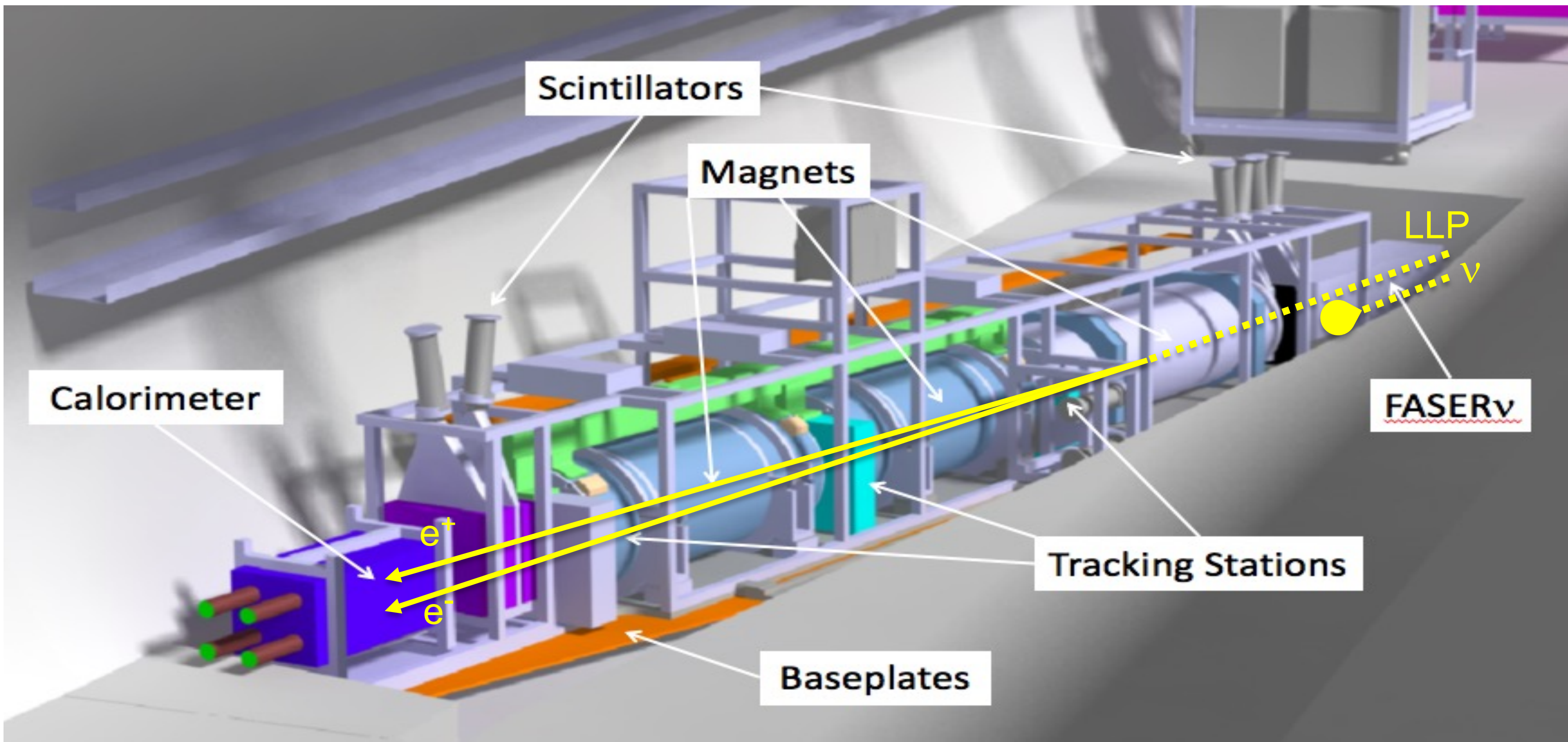


FASER TIMELINE

- September 2017: Initial proposal (Feng, Galon, Kling, Trojanowski)
- July 2018: Submitted LOI to CERN LHCC
- October 2018: Approval from ATLAS SCT and LHCb Collaborations for use of spare detector modules
- November 2018: Submitted Technical Proposal to LHCC
- November 2018 – January 2019: Experiment funded by the Heising-Simons and Simons Foundations
- March 2019: FASER approved as 8^{th} LHC detector by CERN
- March 2021: FASER fully installed, commissioning of the detector begins
- Mid-2022: FASER to begin collecting data in Run 3

THE FASER DETECTOR

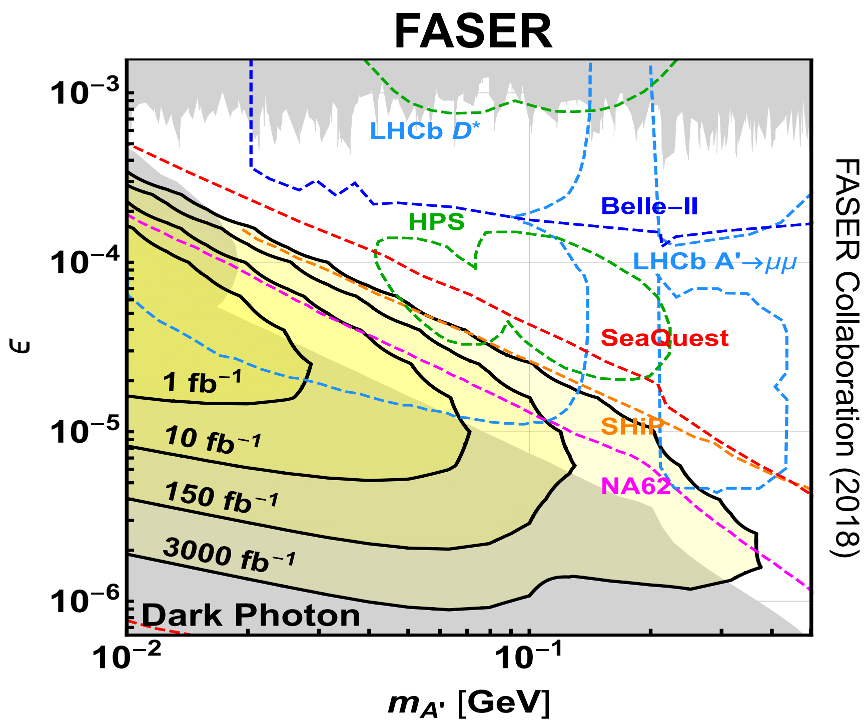
- The signal: nothing incoming and 2 ~TeV, opposite-sign charged tracks pointing back to ATLAS: a "light shining through (100 m) wall" experiment.
- Scintillators veto incoming charged tracks (muons), magnets split the charged tracks, which are detected by tracking stations and a calorimeter.

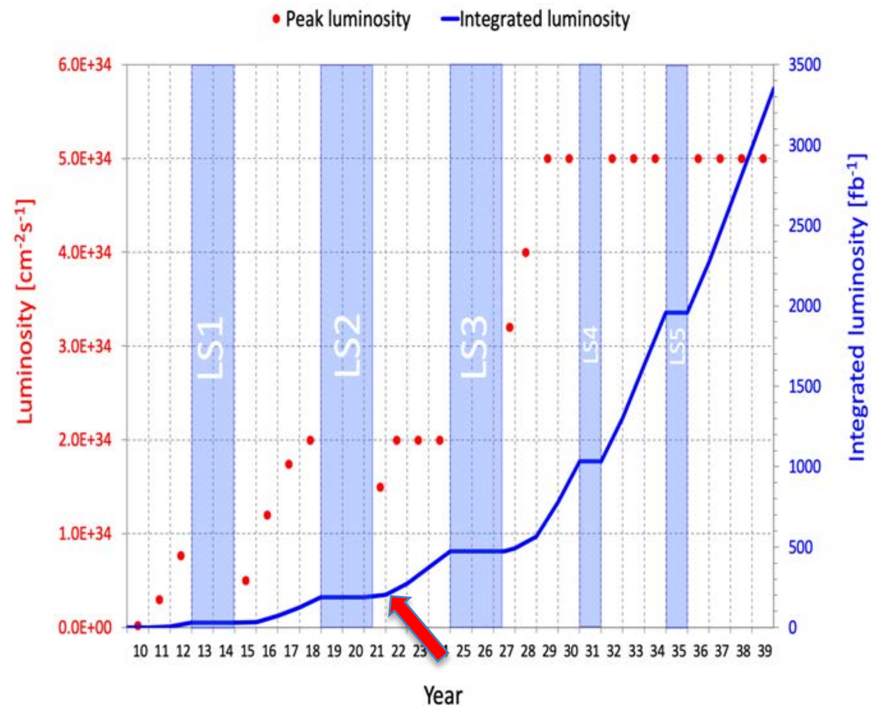


FASER INSTALLED IN TI12

FASER INSTALLED IN TI12

DARK PHOTON SENSITIVITY REACH

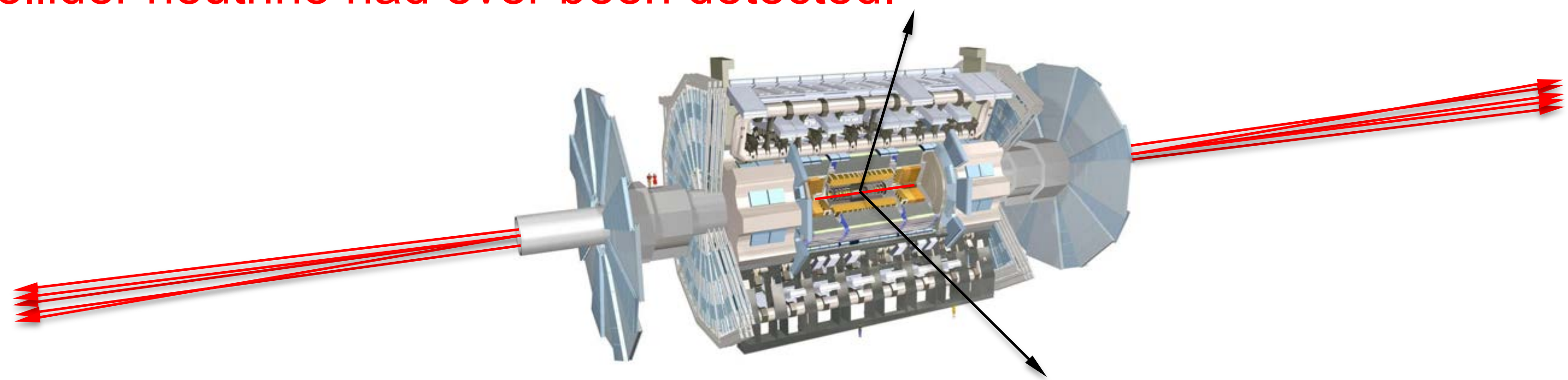




- FASER probes new parameter space with just 1 fb^{-1} starting in 2022.
- Without upgrade, HL-LHC extends (Luminosity*Vol) by factor of 3000 – could detect as many as 10,000 dark photons.
- Possible upgrade to FASER 2 (R=1m, L=20m) extends (Luminosity*Vol) by factor of ~10^6 – could detect as many as 3,000,000 dark photons.

COLLIDER NEUTRINOS

- 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)

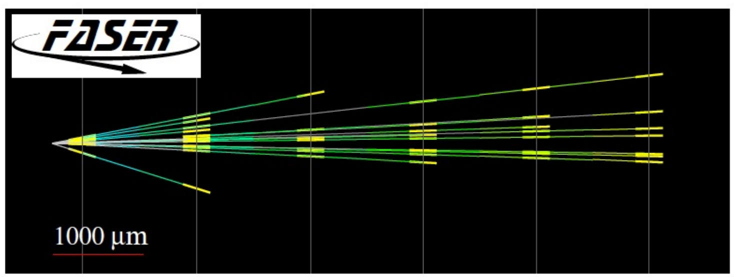
FASERν AND SND@LHC

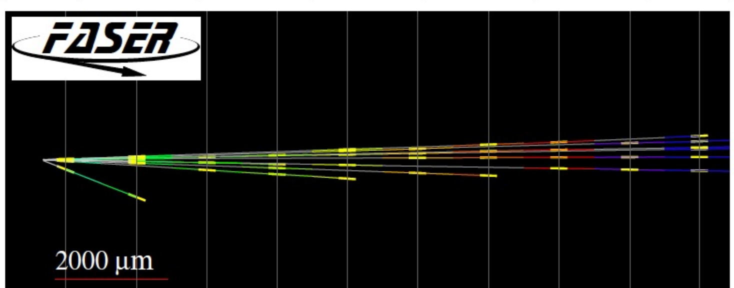
FIRST COLLIDER NEUTRINOS

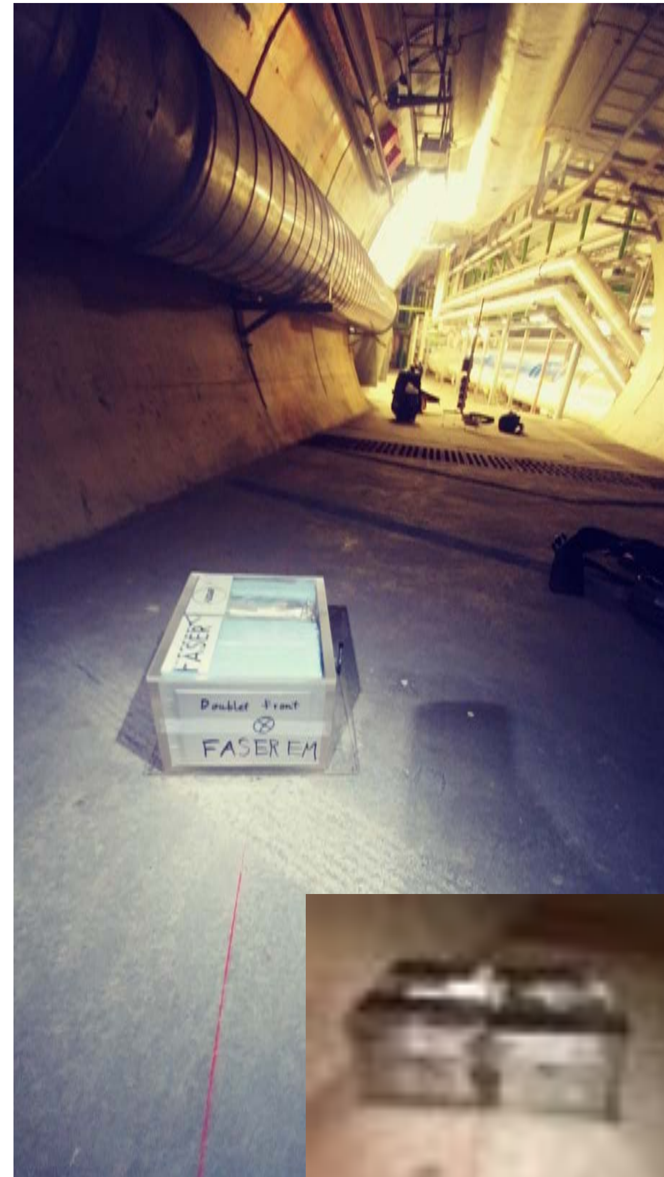
- In 2018 a FASER pilot emulsion detector with 11 kg fiducial mass collected 12.2 fb^{-1} on the beam collision axis (installed and removed during Technical Stops).

- In May 2021, the FASER Collaboration announced the direct detection of 6 candidate neutrinos above 12 expected neutral hadron background events (2.7σ).

- Not the discovery of collider neutrinos, but a sign of things to come.





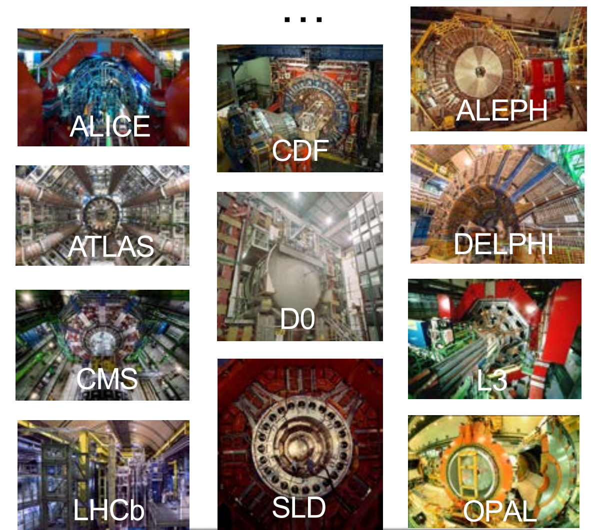


LOCATION, LOCATION, LOCATION

FASER Pilot Detector

Suitcase-size, 4 weeks
$0 (recycled parts)

6 candidate neutrinos



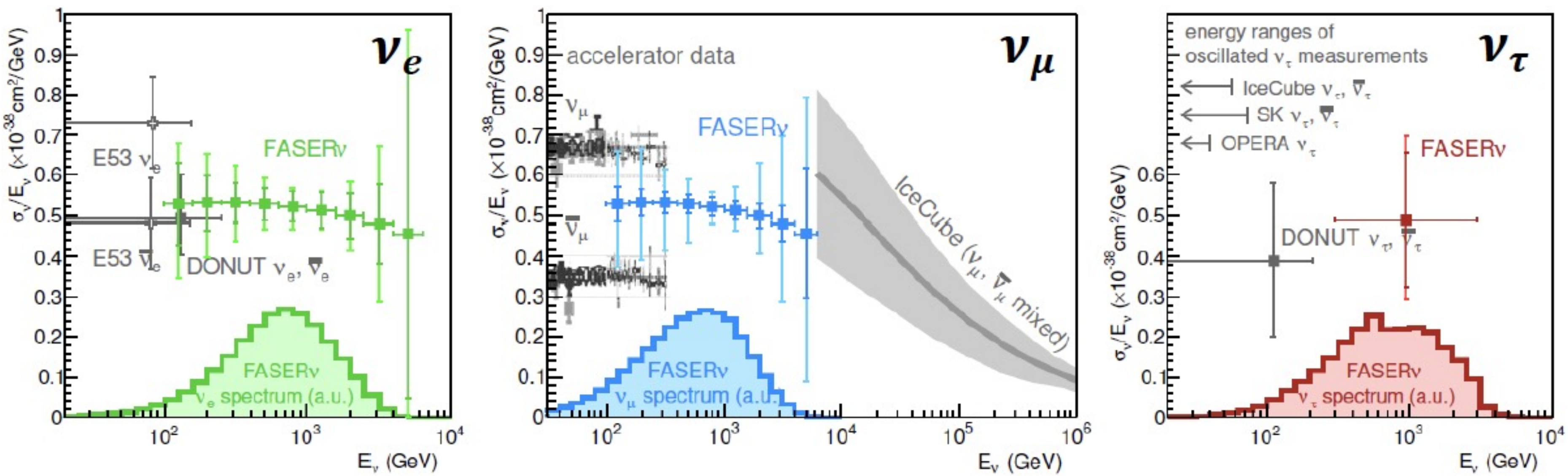
All previous
collider detectors

Building-size, decades
~$$10^9$

0 candidate neutrinos

NEUTRINO PHYSICS

- In Run 3 (2022-24), the goals of FASERν are to
  - Detect the first collider neutrino.
  - 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.
  - Distinguish muon neutrinos from anti-neutrinos by combining FASER and FASERν data, and so measure their cross sections independently.
  - Add significantly to the number of ν_τ and detect the first anti-ν_τ .

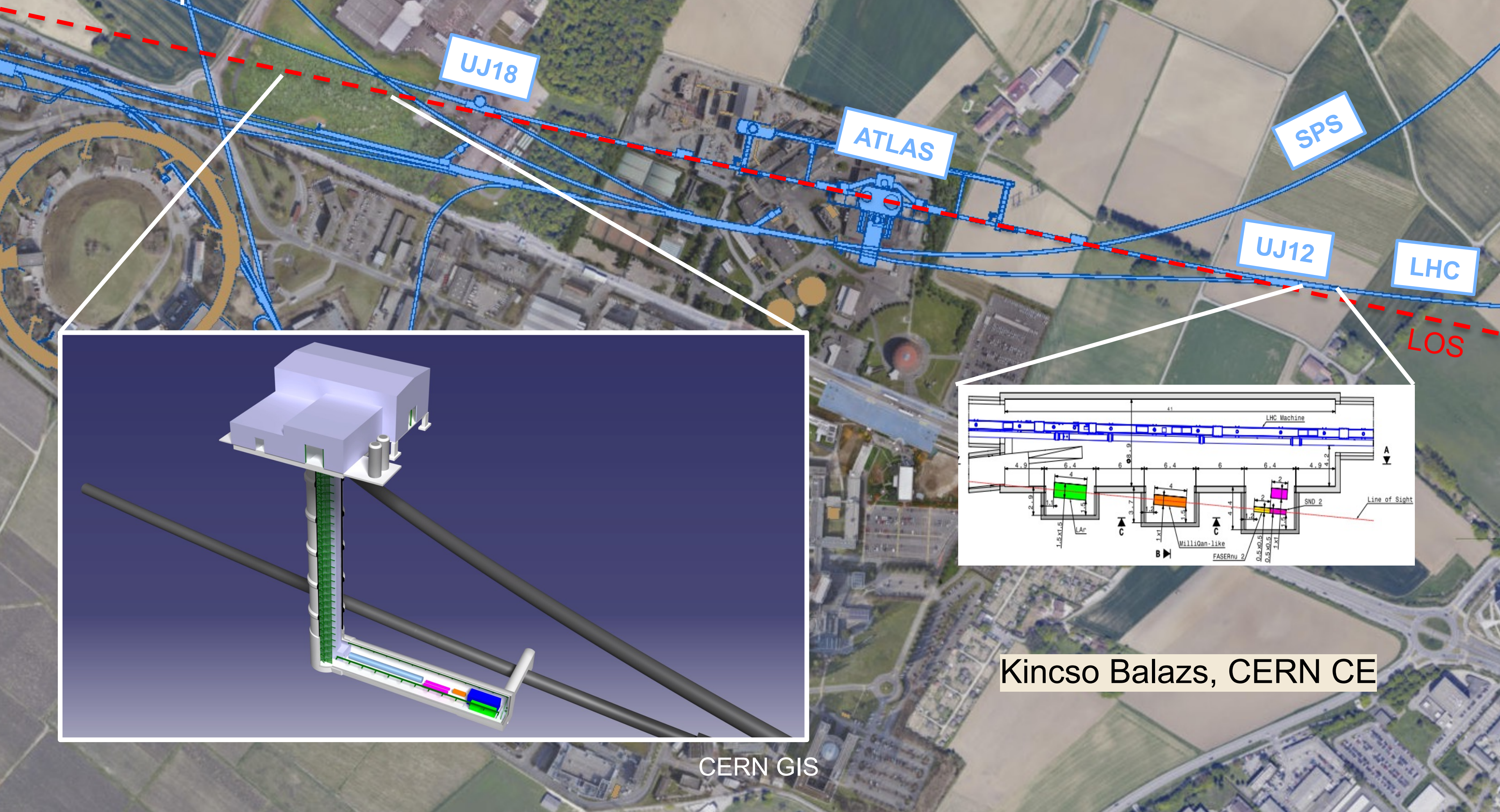


FASER Collaboration 1908.02310 (2019)

FPF Forward Physics Facility

FORWARD PHYSICS FACILITY

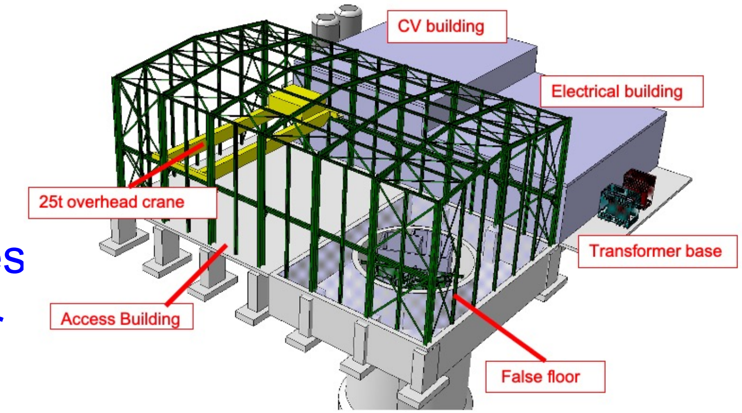
- The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2027-37.

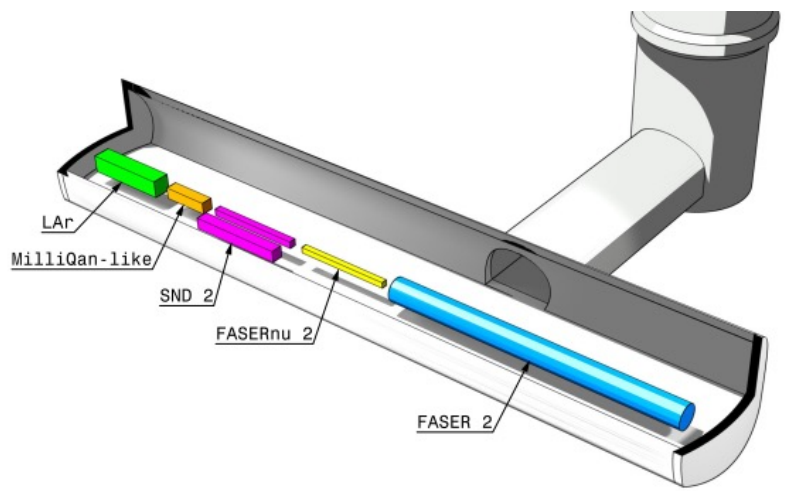


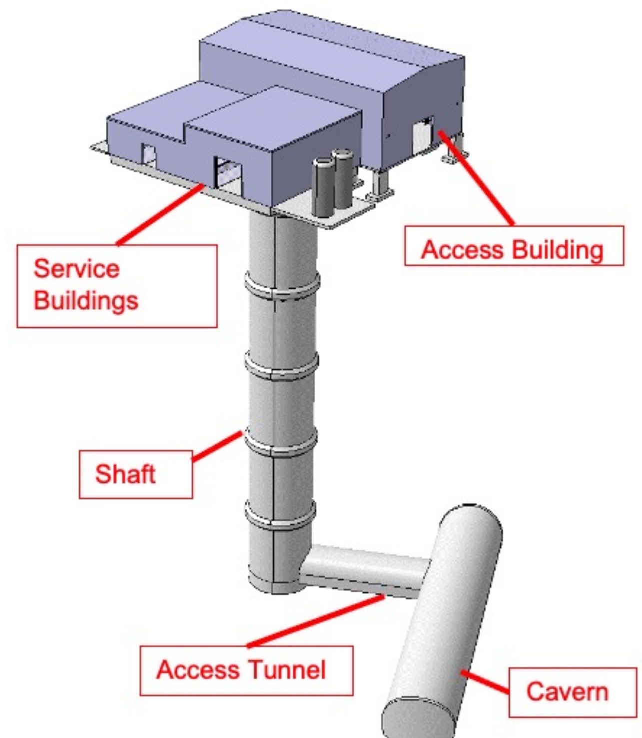
FORWARD PHYSICS FACILITY

- Currently envisioned to house 5 experiments, including upgrades of FASER, FASERnu, and SND, as well as
  - FORMOSA, targeting milli-charged particles
  - FLArE, targeting neutrinos and dark matter

- Very preliminary (class 4) cost estimate for cavern and services: 40M CHF.







Design by Liam Dougherty (EN-ACE-INT)

FPF PLANS

- The FPF is being studied in both the Physics Beyond Colliders framework at CERN and as part of the Snowmass community exercise in the US.

- 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 Sept 2021 (2109.10905).

- The FPF White Paper (~200-300 pages) is being prepared to be submitted to Snowmass in February-March 2022.

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- Future colliders can improve their discovery potential by including LLP capabilities in their plans from the beginning.