LONG-LIVED PARTICLES
AND THE
FUTURE OF PARTICLE PHYSICS

CERN Colloquium, 19 June 2023

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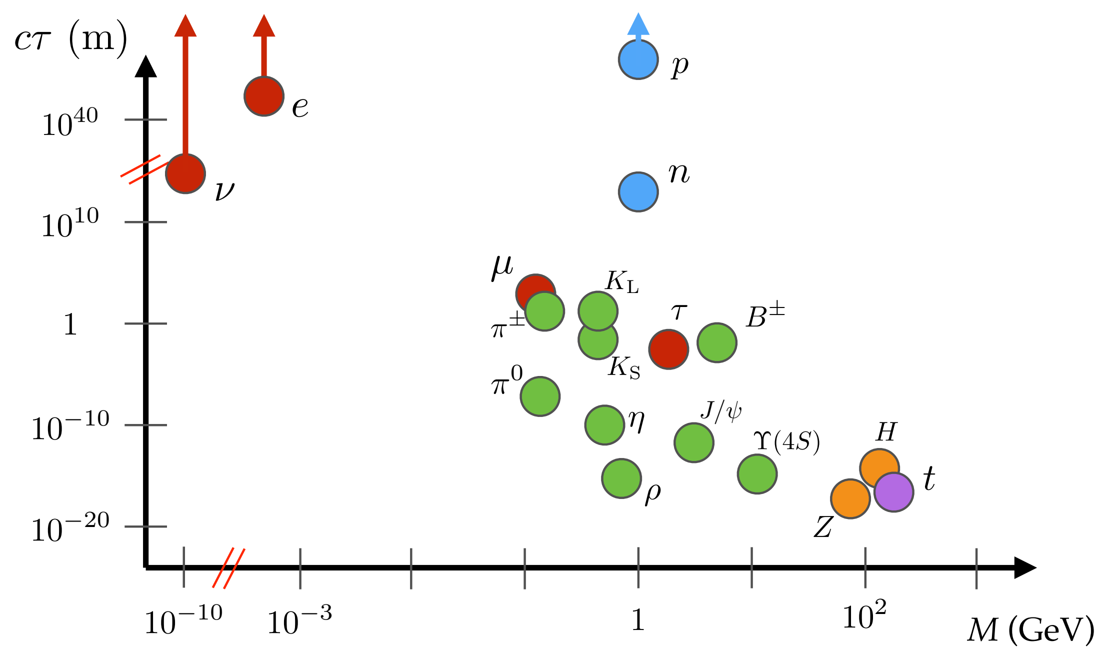
INTRODUCTION

- Long-Lived Particles (LLPs) are particles that are effectively stable or travel an observable distance before they decay.



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

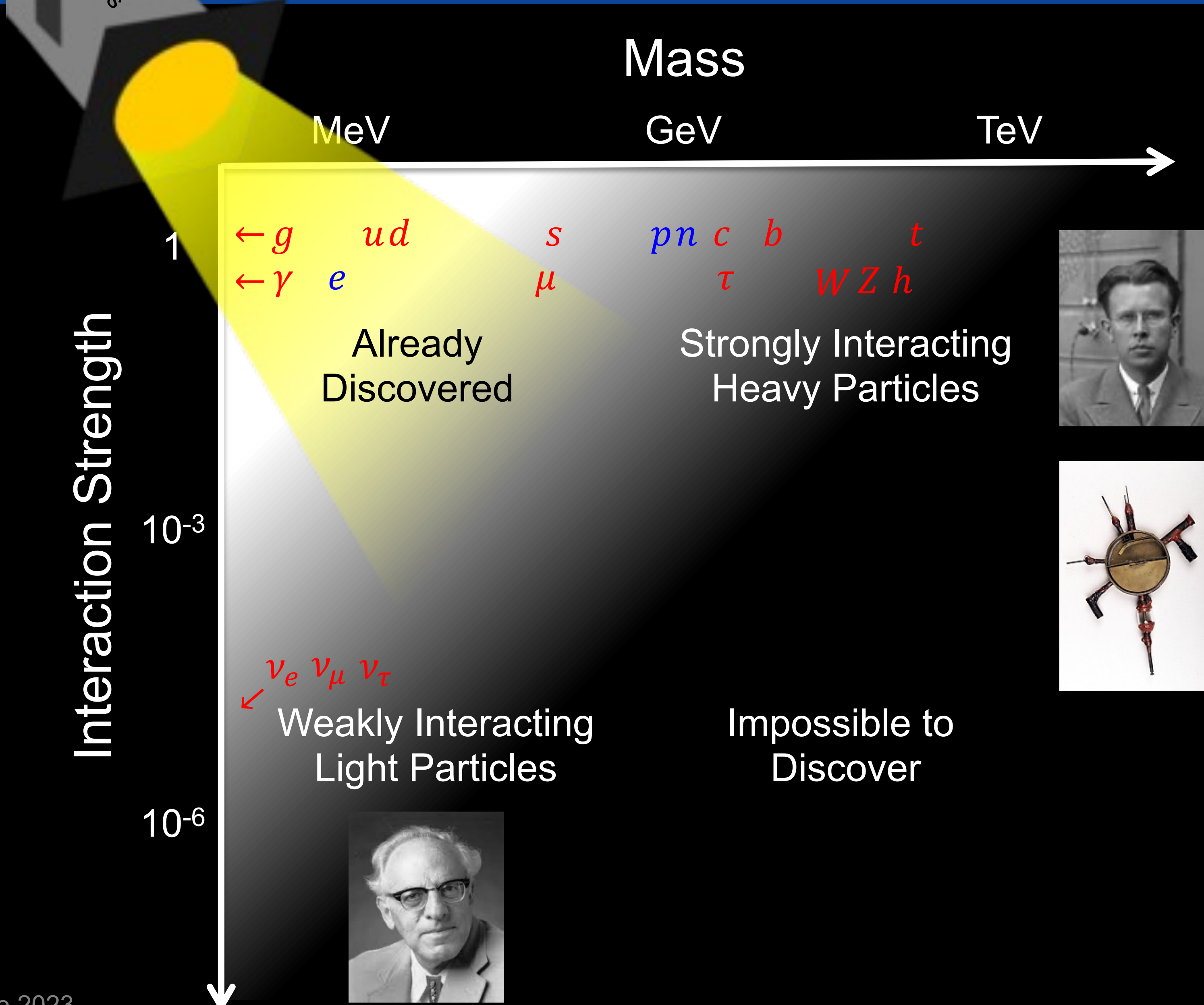
- LLPs have played an essential role in many of the conceptual breakthroughs that established the standard model: *e*, *p*, *n*, μ, *K*, ν, *B*, …

- LLPs are also likely to play an essential role in the next breakthrough that takes us beyond the standard model of particle physics.

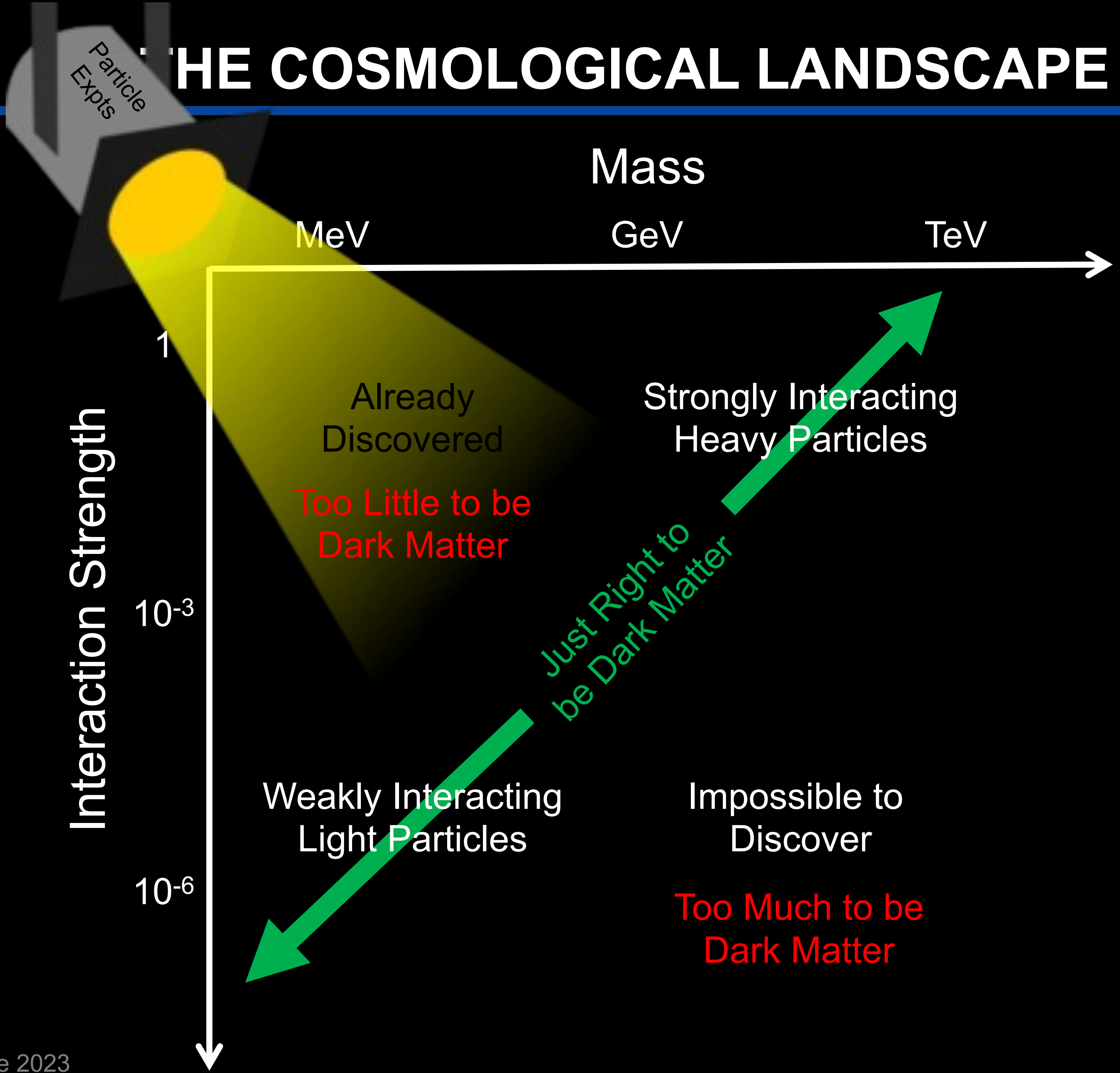
INTRODUCTION

- LLPs are also likely to play an essential role in the next breakthrough that takes us beyond the standard model. Why?
  - LLPs are ubiquitous in BSM theories, especially those with cosmological significance.
  - LLPs can be detected through a huge variety of signatures.
  - Many of these signals are truly spectacular – a few events can be a discovery.
  - For existing experiments, we have not yet reached the full LLP discovery potential.
  - LLPs present many opportunities for new experiments, some of which are already bearing fruit.
- LLPs have become a topic of great interest. Here I'll give a highly personal summary of my reasons for optimism; for more, see the LLP13 Workshop, taking place at CERN now through Friday.

THE PARTICLE LANDSCAPE



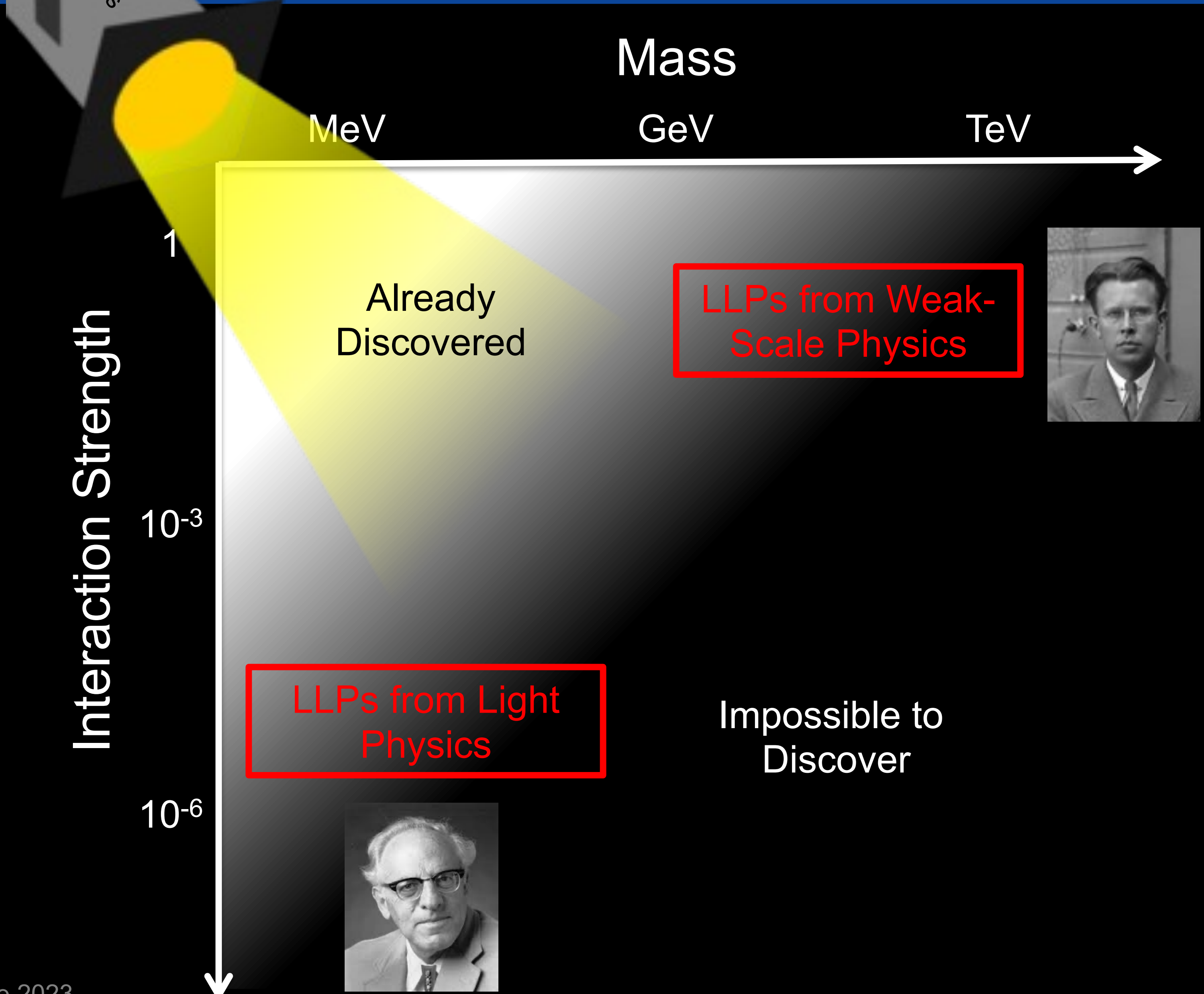
THE COSMOLOGICAL LANDSCAPE



LESSONS FROM OUR PAST

- We are not now in a golden age of particle physics.
- But particle physics is still fascinating, and the possibilities for deep connections to cosmology have never been stronger.
- The discovery of new particles is the gold standard for progress in particle physics. (Precision measurements are also very important.)
- Buoyed by past successes, we have been looking for strongly-interacting heavy particles that decay quickly, and this should continue.
- But typically, unless these are in a narrow window of masses (e.g., ~2-4 TeV for gluinos), we will not find them in the next two decades. And the most robust problems, neutrino masses and dark matter, naturally point toward very weakly-interacting particles.
- To bring us to a new golden age, we need to try new things and diversify our searches for BSM physics without breaking the bank. (As we will see, LLPs are currently a very good investment!)

THE LLP LANDSCAPE

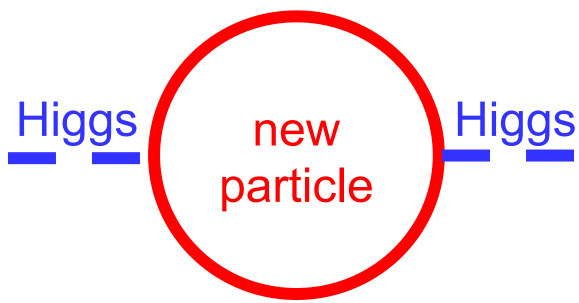


LLPS FROM WEAK- SCALE PHYSICS

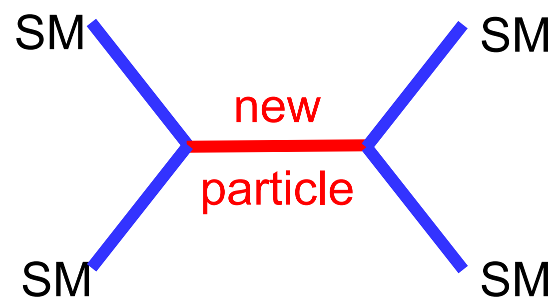
WEAK-SCALE PHYSICS AND LLPS

- Why should there be LLPs at the weak scale? After all, the natural decay length is $c\tau \sim c/m_W \sim 10^{-17}$ m!
- But the gauge hierarchy problem → new physics at 100 GeV, and precision EW (LEP) → no new physics below few TeV in 4-pt interactions

Gauge Hierarchy



Precision EW

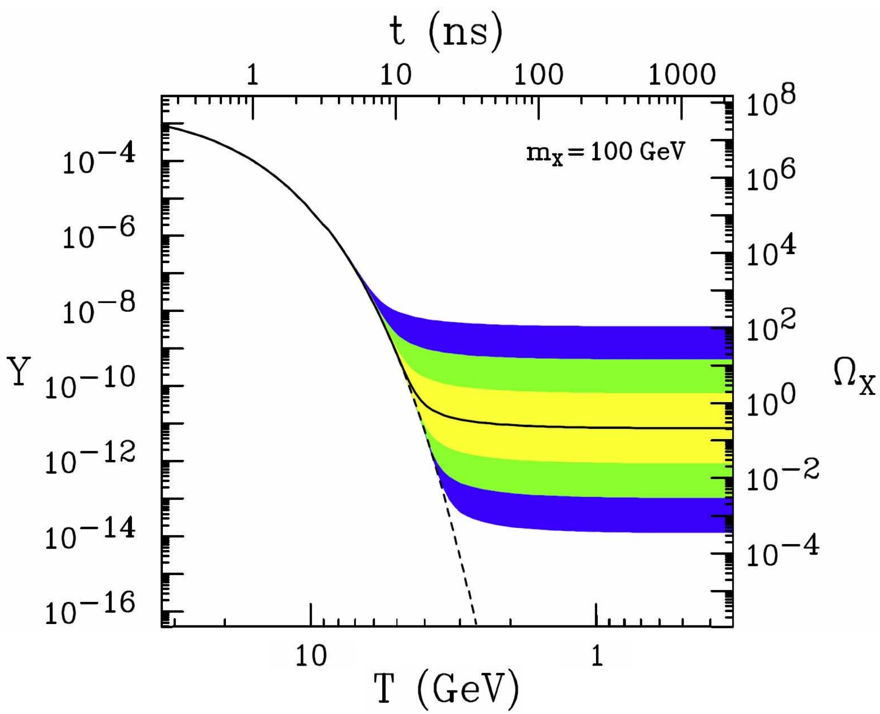


- Simple solution: impose a discrete parity, so all interactions require pairs of new particles.
- This makes the lightest new particle stable: an LLP. This is a general argument. It may be augmented in specific contexts, e.g., in SUSY, *p* decay → *R*-parity → stable LSP.

Cheng, Low (2003); Wudka (2003); Farrar, Fayet (1974)

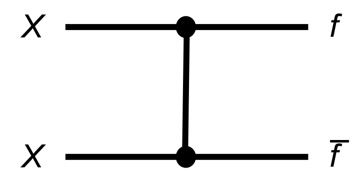
WEAK-SCALE PHYSICS AND COSMOLOGY

- What good is a stable weak-scale state? Dark matter!



- 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, $m_X \sim 100$ GeV and $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

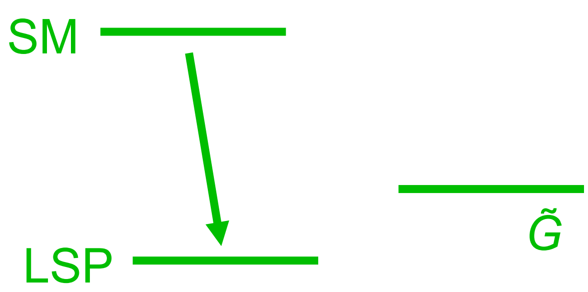
- This simple coincidence, the WIMP Miracle, ties together weak-scale physics, LLPs, and cosmology, and has led to the prominence of missing E_T searches and DM at colliders.

LLPS IN STANDARD SUSY

- But this focus on missing E_T is a vast oversimplification.

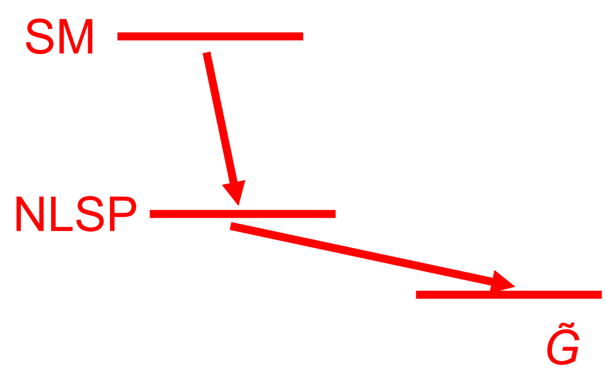
- Consider standard (gravity-mediated) supersymmetry. The gravitino has mass ~ 100 GeV, couplings ~ $M_W/M_{\rm Pl}$ ~ 10^{-16} .

- $\tilde{G}$ not LSP



- Assumption of most of literature

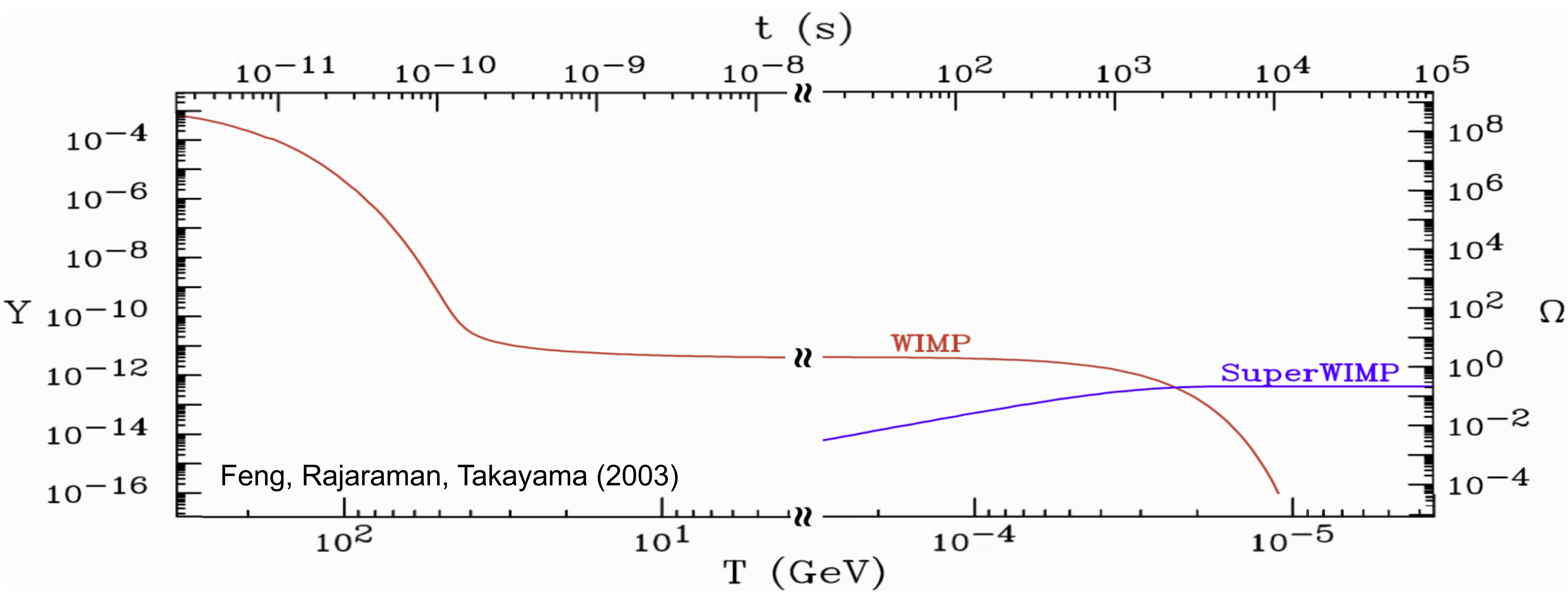
- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

LLPs IN SUPERWIMP SCENARIOS

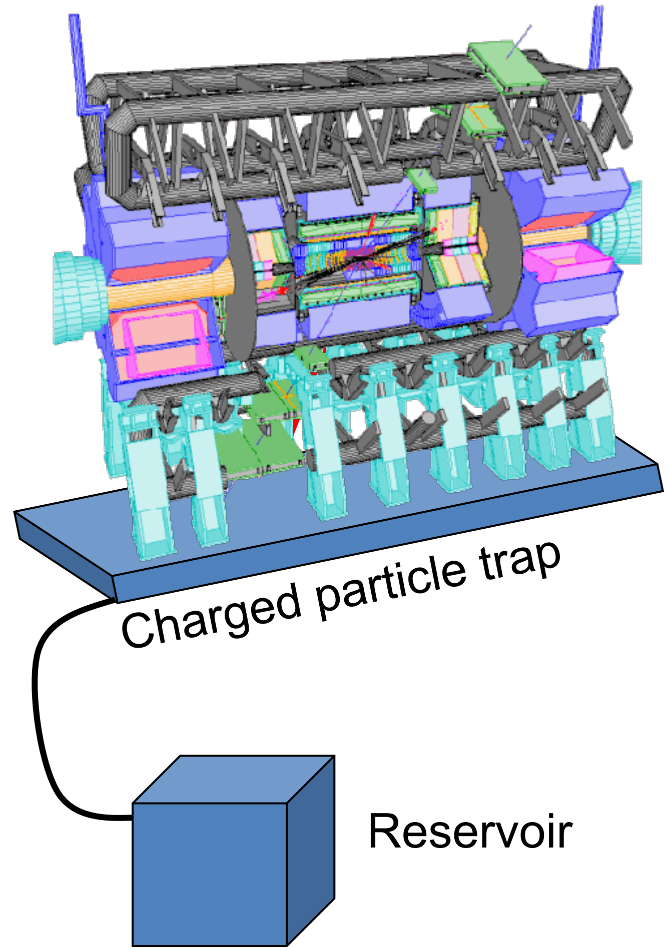
- In the $\tilde{G}$ LSP scenario, WIMPs freeze out as usual, but then decay to $\tilde{G}$ after M_{Pl}^2/M_W^3 ~ seconds to months.



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

LLPS AND AUXILIARY 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 OTHER SUSY MODELS

- SuperWIMPs lead to very long lifetimes, but there is a continuum of possibilities in SUSY models (GMSB), with the lifetime controlled by the gravitino mass.

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

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

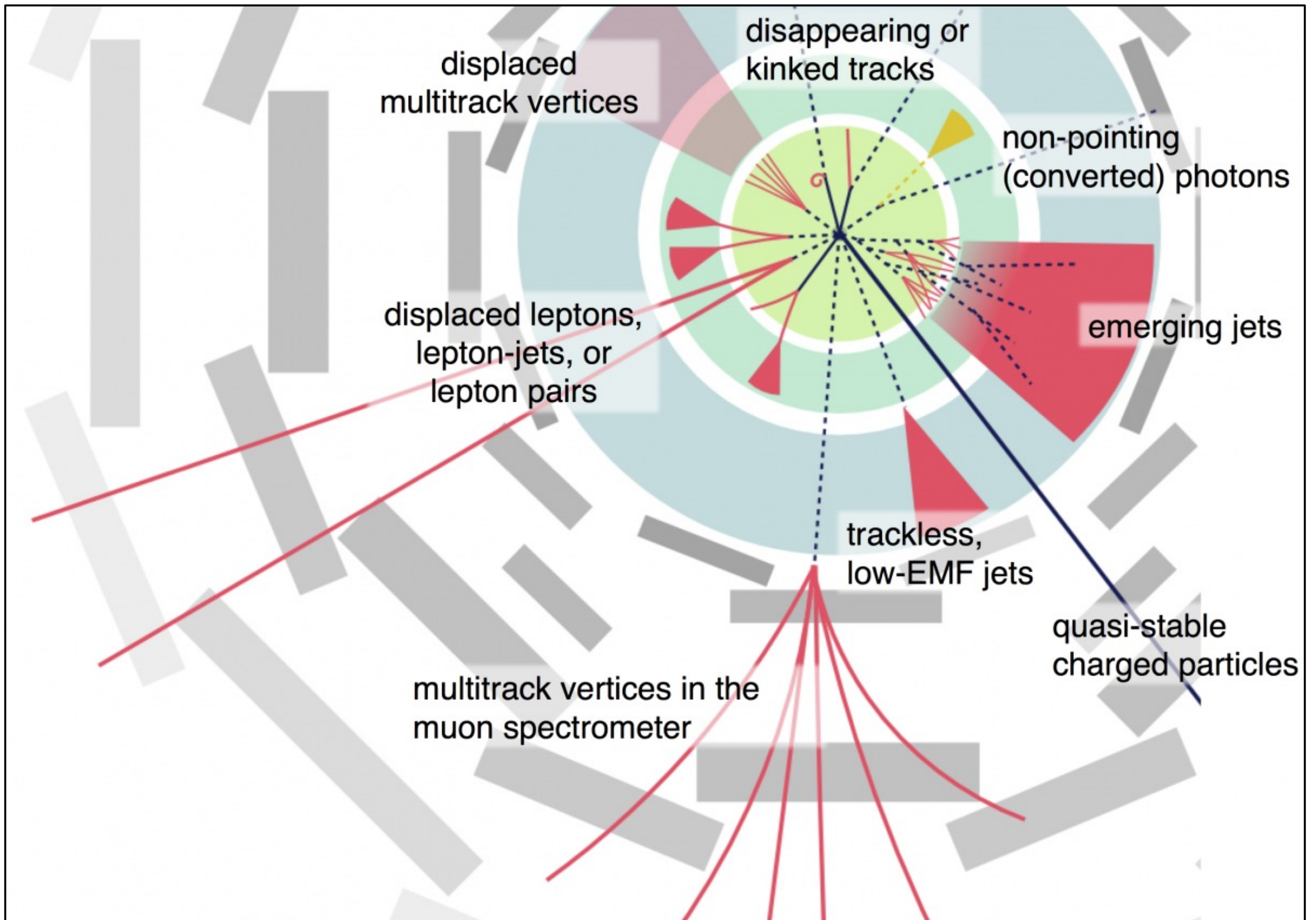
	Neutralino NLSP	Slepton NLSP
Prompt	Prompt photons	Multi-leptons
Intermediate	Displaced photons Displaced conversion	Displaced lepton Track kinks
Long-Lived	Missing E_T	Time-of-flight High dE/dx

- In other SUSY models (AMSB), naturally small degeneracies lead to other remarkable signals, e.g., disappearing tracks from $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$.

Randall, Sundrum (1998); Giudice, Luty, Murayama, Rattazzi (1998); Feng, Moroi, Randall, Strassler, Su (1999)

LLP SIGNATURES AT ATLAS AND CMS

- These models lead to many possible signatures, which are spectacular, if one is looking for them. Requires excellent knowledge of detectors, dedicated triggers, special reconstruction methods, …



Russell (see, e.g., LLP White Paper 2019)

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 excluded.
- Extra dimensional scenarios typically have similar possibilities (e.g., viewing universal extra dimensions as bosonic supersymmetry), and naturally compressed spectra.
- Many other motivations and cosmological connections: leptogenesis, neutrino masses, etc.

LLPS FROM LIGHT PHYSICS

DARK SECTORS

- Dark matter may be part of a dark sector, with its own set of forces. What do we know about its properties?

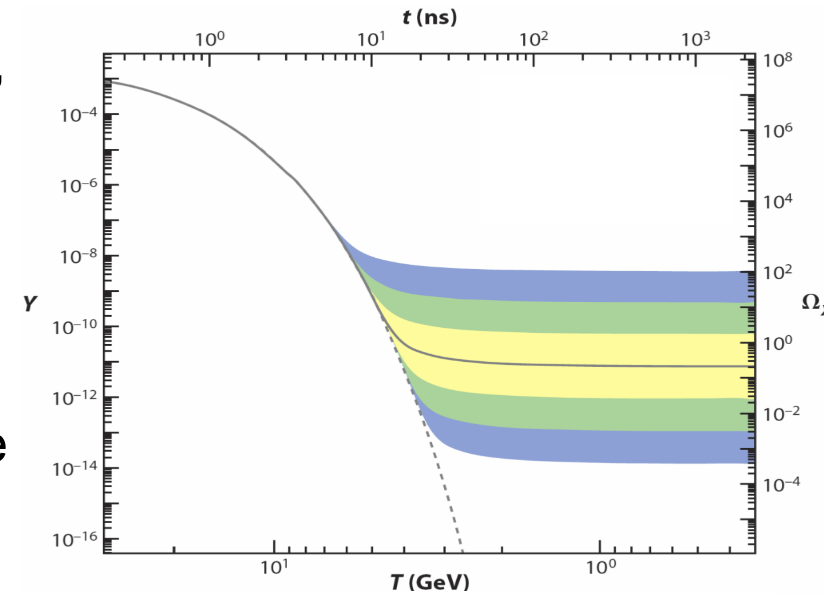
- In general, nothing. But suppose DM is produced in the dark sector just as we discussed above for WIMPs in the visible sector:

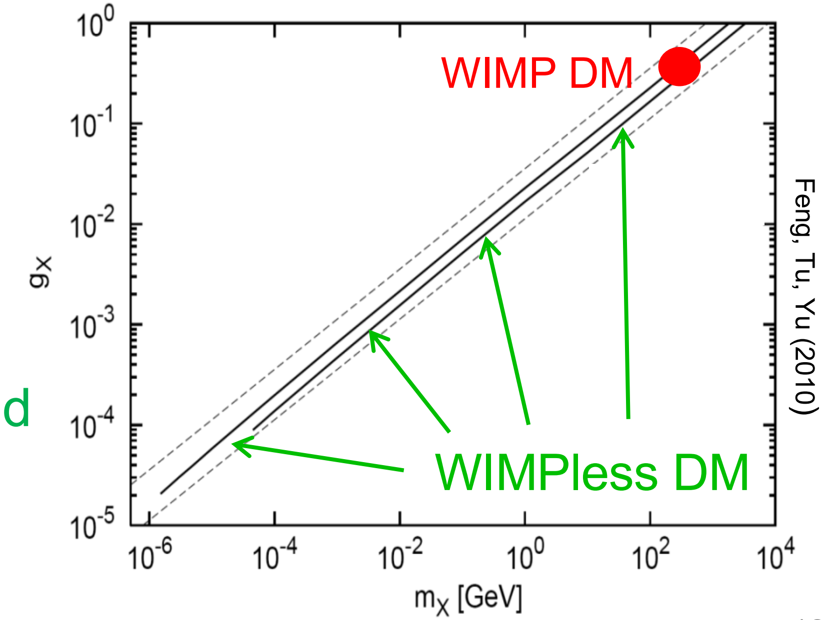
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- WIMP Miracle: $g_X \sim 1$, $m_X \sim 100$ GeV → right abundance.

- WIMPless Miracle: But with a dark sector, we don't need to fix $g_X \sim 1$. The dark sector can have lighter particles and weaker interactions and still have the right abundance.

Boehm, Fayet (2003); Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

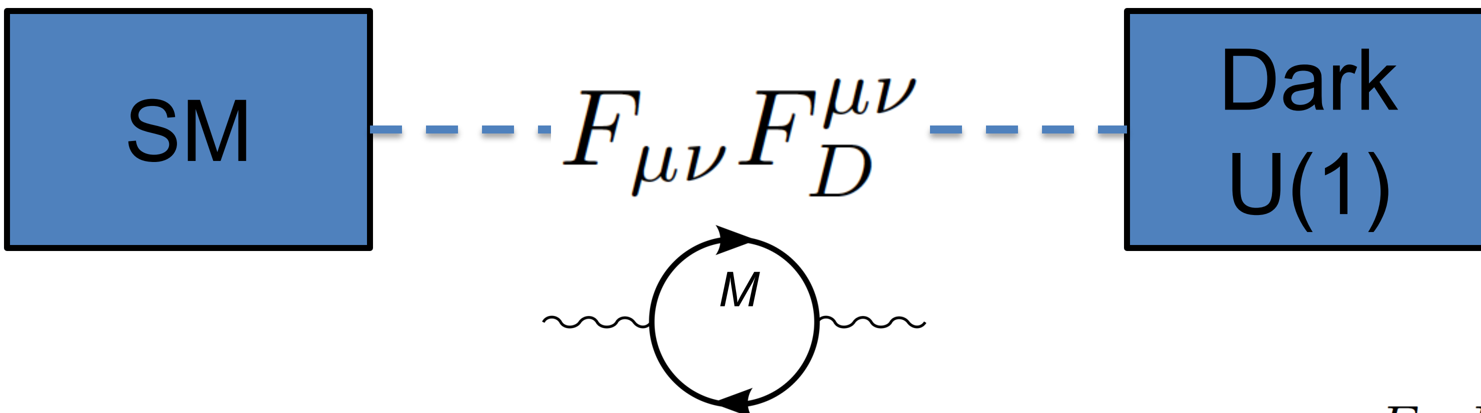




PORTALS

- Dark sectors need not talk with us. But if they do, what are the most likely non-gravitational interactions?

- Suppose the dark sector has U(1) electromagnetism. There are infinitely many possible SM-dark sector interactions, but one is induced by arbitrarily heavy mediators:



- It is "most likely" because it is non-decoupling. Cf. $\dfrac{F_{\mu\nu}F_D^{\nu\alpha}F_\alpha^\mu}{M^2}$

- It is also naturally small, since it is induced by a loop.

Holdom (1986)

DARK PHOTON, DARK HIGGS, HNLS

- This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. 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

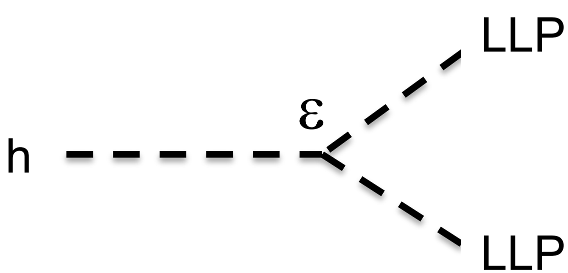
SM $h L \psi_D$ Dark Fermion

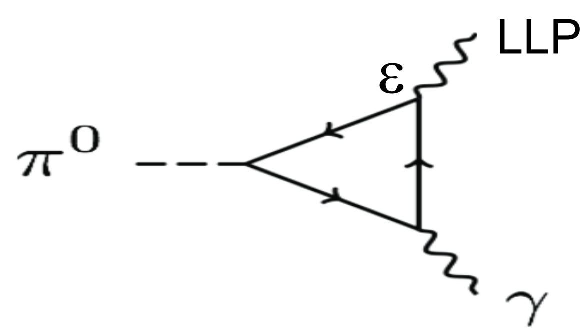
→ Heavy neutral leptons, mixes with SM νs with suppressed mixing $\sin\theta$.

LIGHT LLP PHENOMENOLOGY

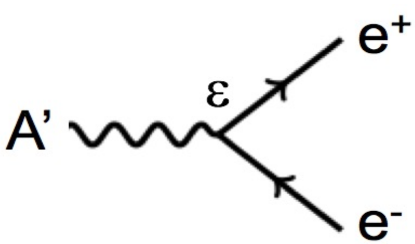
- Dark sectors, along with axion-like particles, light gauge bosons, etc., have highlighted a new class of LLPs: light, neutral particles, with extremely weak interactions and fascinating phenomenology.

- Because they are light, they may be produced in the decay of both heavy and light SM particles (and also in other ways).



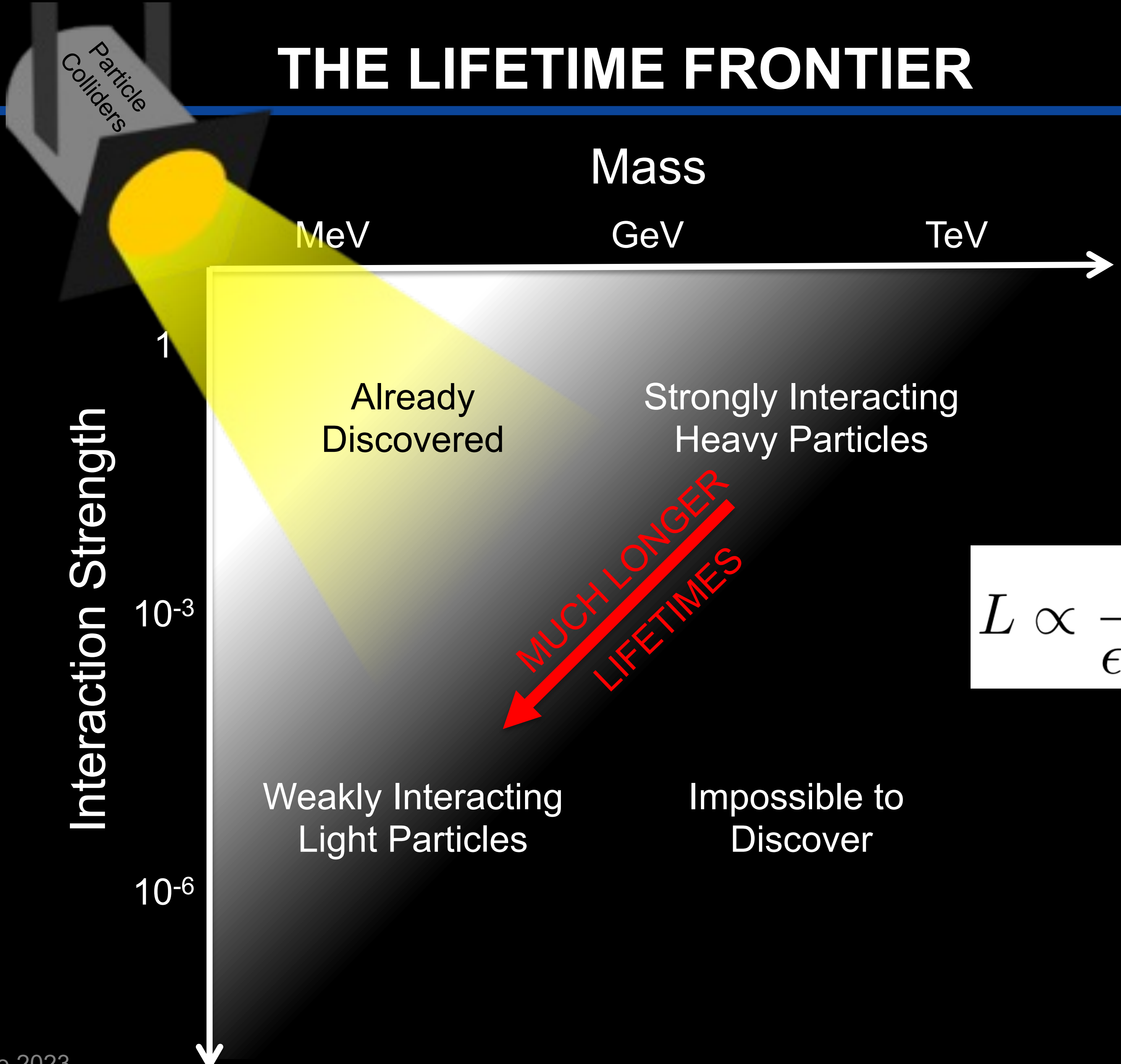


- Because they are very weakly-interacting, they pass through matter without interacting, but then may visibly decay after a long distance.



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

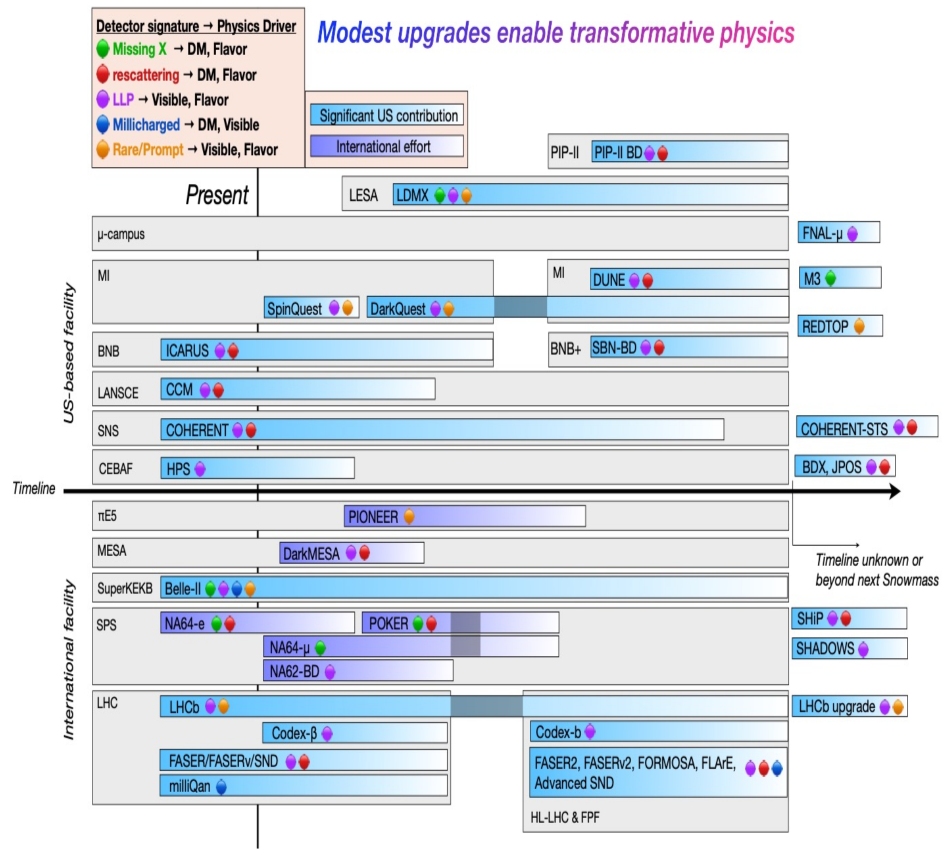
THE LIFETIME FRONTIER



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

SEARCHES FOR LIGHT LLPS

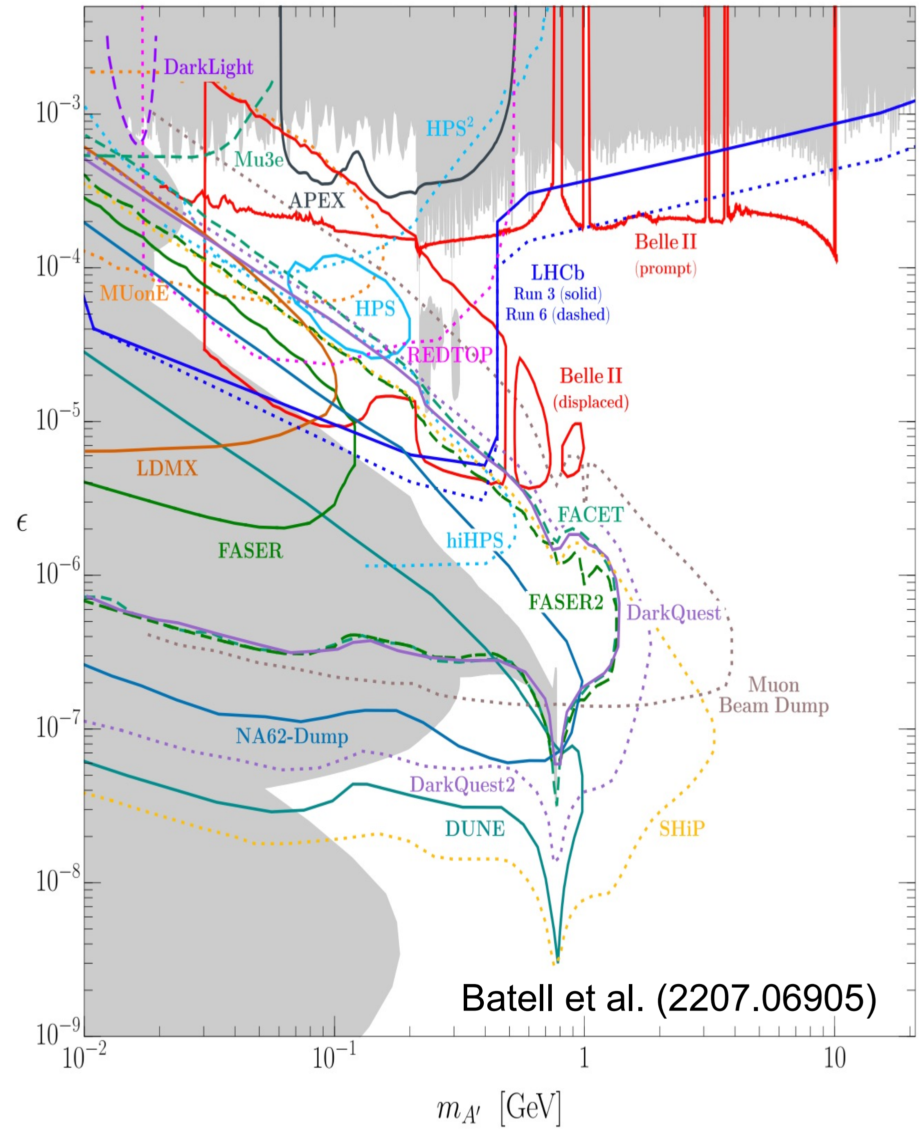
- BSM physics has been re-invigorated by new ideas for LLP searches.
- Many large community studies (LLP Community, PBC at CERN, Snowmass in the US, …), and many new experiments have been proposed for labs around the world.



Ilten, Tran et al. (2206.04220)

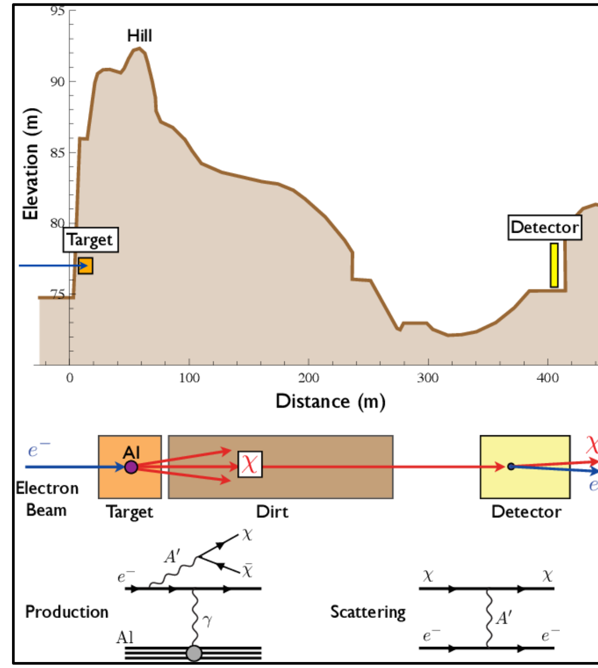
CURRENT EXPERIMENTAL SEARCHES

- The sensitivities of ongoing and proposed experiments have been evaluated by these large community efforts.
- For example, for dark photons, in the next few years, the thermal relic region will be probed by currently running experiments (LHCb, Belle2, NA62, NA64, FASER, …) and also potentially by proposed experiments.
- This is the low-hanging fruit of dark sectors – similar to *Z*-mediated WIMP cross sections for DM direct detection. In a few years, this parameter space will look completely different.



FIXED TARGET EXPERIMENTS

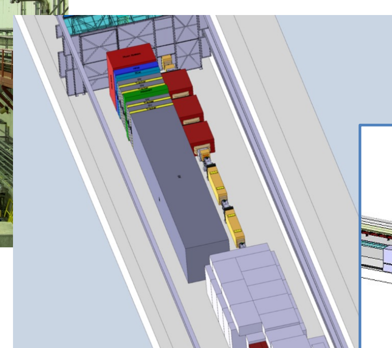
- Old fixed target experiments (suitably re-interpreted) set constraints on light LLPs.
- At CERN, ongoing experiments at the SPS (NA62, NA64) have set world-leading limits, and proposed experiments (SHiP, SHADOWS) have sensitivity far into new parameter space in many models.



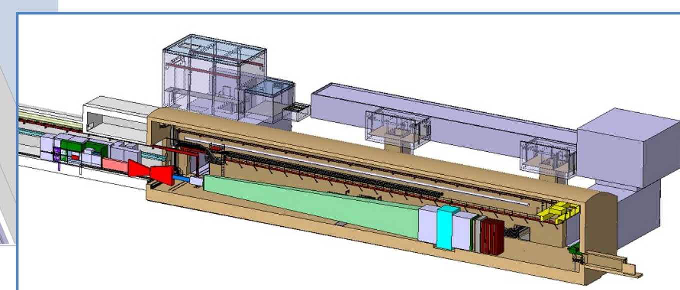
SLAC E137 (1988)
Batell, Essig, Surujon (2014)

NA64

NA62



SHADOWS

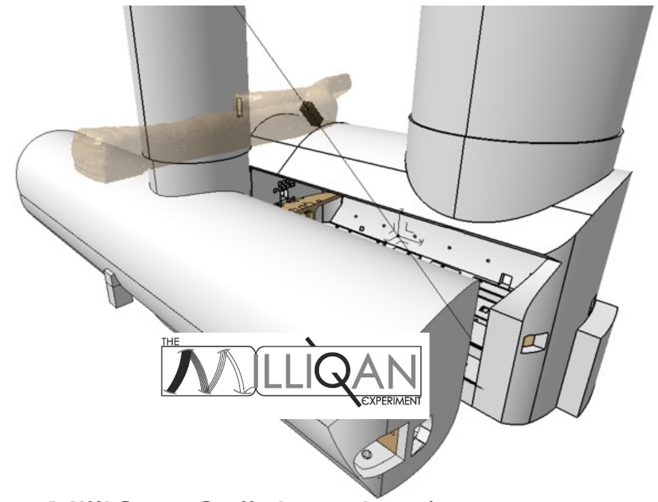


SHiP@ECN3

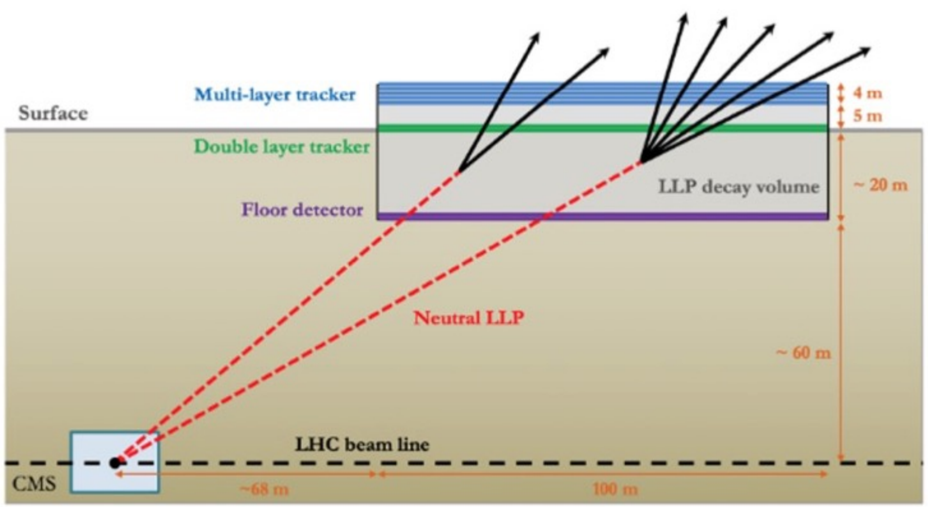
DEDICATED TRANSVERSE LHC EXPERIMENTS

- The LHC provides unique opportunities at the energy frontier. Several ongoing and proposed detectors are dedicated to searching for LLPs and milli-charged particles at large angles to the beamline.

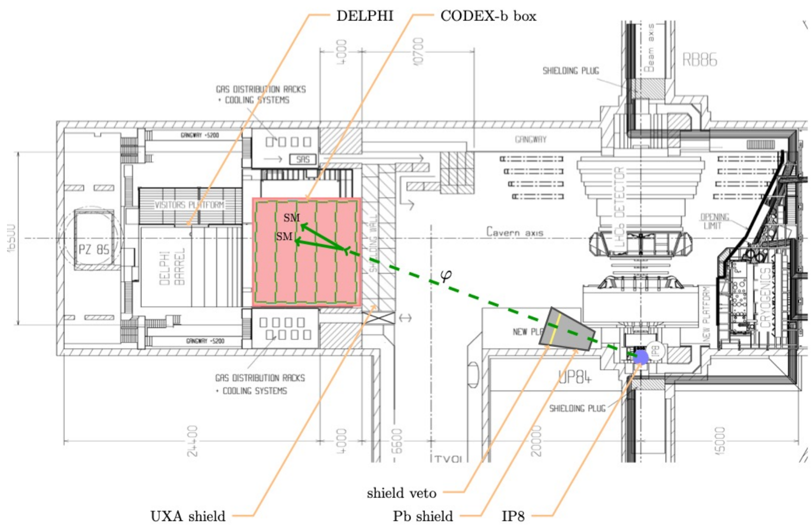
- MoeDAL/MAPP, MilliQan, MATHUSLA, Codex-b, ANUBIS, …



MilliQan Collaboration (2104.07151)



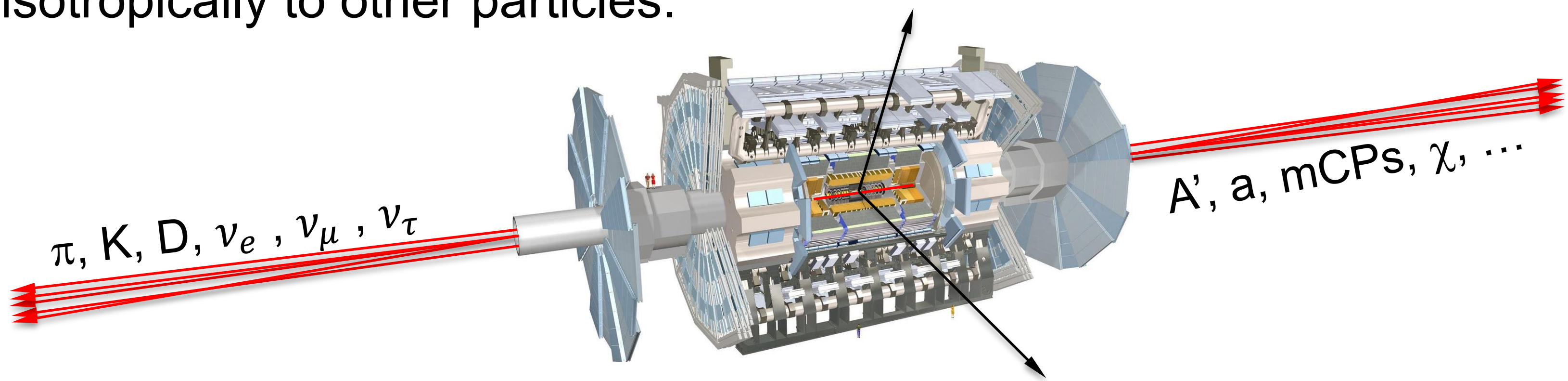
MATHUSLA White Paper (2203.08126)



CODEX-b White Paper (2203.07316)

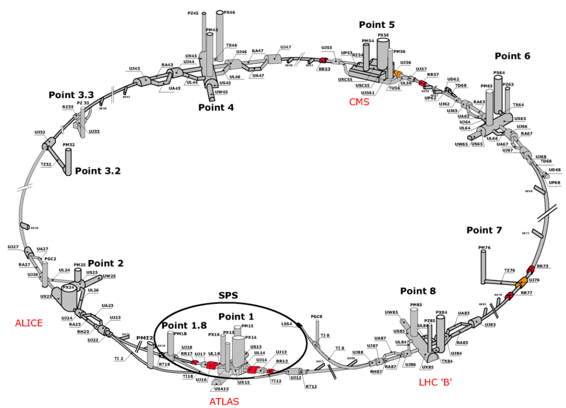
DEDICATED FORWARD LHC EXPERIMENTS

- In the last few years, we've increasingly realized that the large LHC detectors are beautifully optimized to discover new heavy particles, but also beautifully optimized to miss new light particles. De Rujula, Ruckl (1984)
- Heavy particles are produced at low velocity and then decay roughly isotropically to other particles.

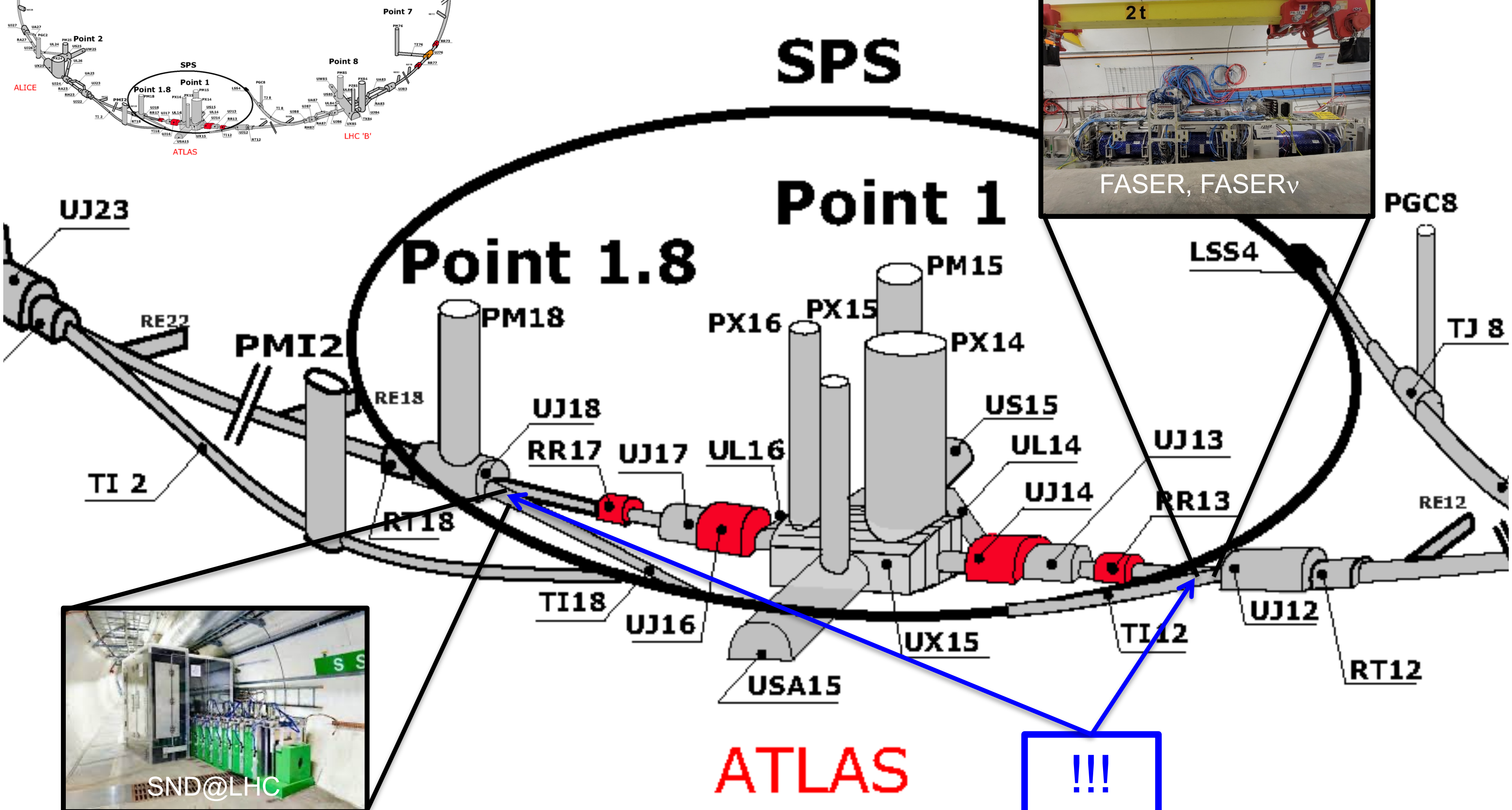


- But high-energy light particles are dominantly produced in the forward direction and escape through the blind spots of existing detectors.
  - This is true for all known light particles: pions, kaons, D mesons, neutrinos.
  - It is also true in many models for many hypothetical new particles: dark photons, dark Higgs bosons, HNLs, ALPs, light gauge bosons, …
- These blind spots are the Achilles heels of the large LHC detectors.

PRE-EXISTING TUNNELS FOR FORWARD EXPTS



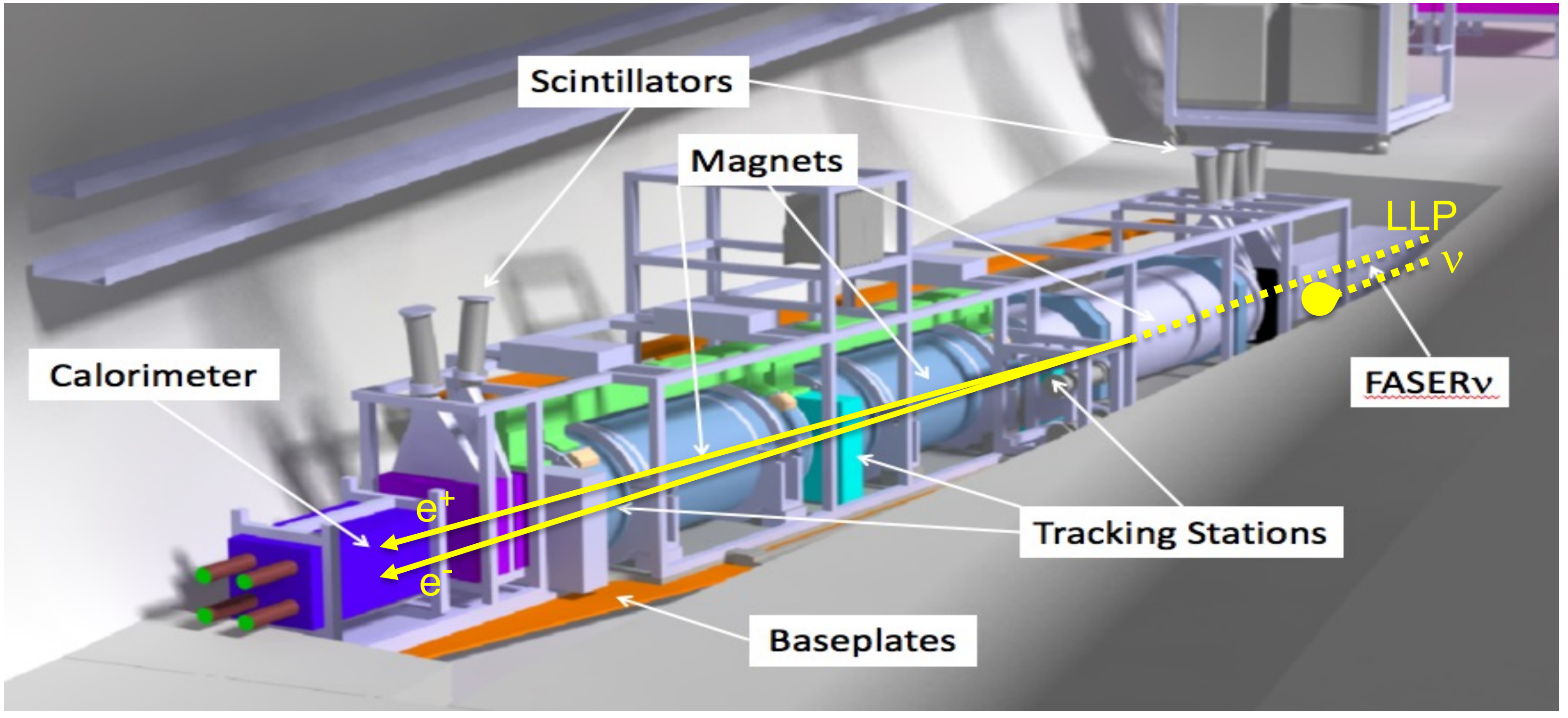
Feng, Galon, Kling, Trojanowski (2017)



FASER AND THE LHC

SIGALS AT FASER

- LLPs: Nothing incoming and 2 ~TeV, opposite-sign charged tracks pointing back to the ATLAS IP: a "light shining through (100 m-thick) wall" experiment.
- Collider neutrinos: Nothing incoming and a high energy muon passing through the rest of the detector from $\nu_\mu N \to \mu X$.
- Scintillators veto incoming charged tracks (muons), magnets split the charged tracks, which are detected by tracking stations and a calorimeter.

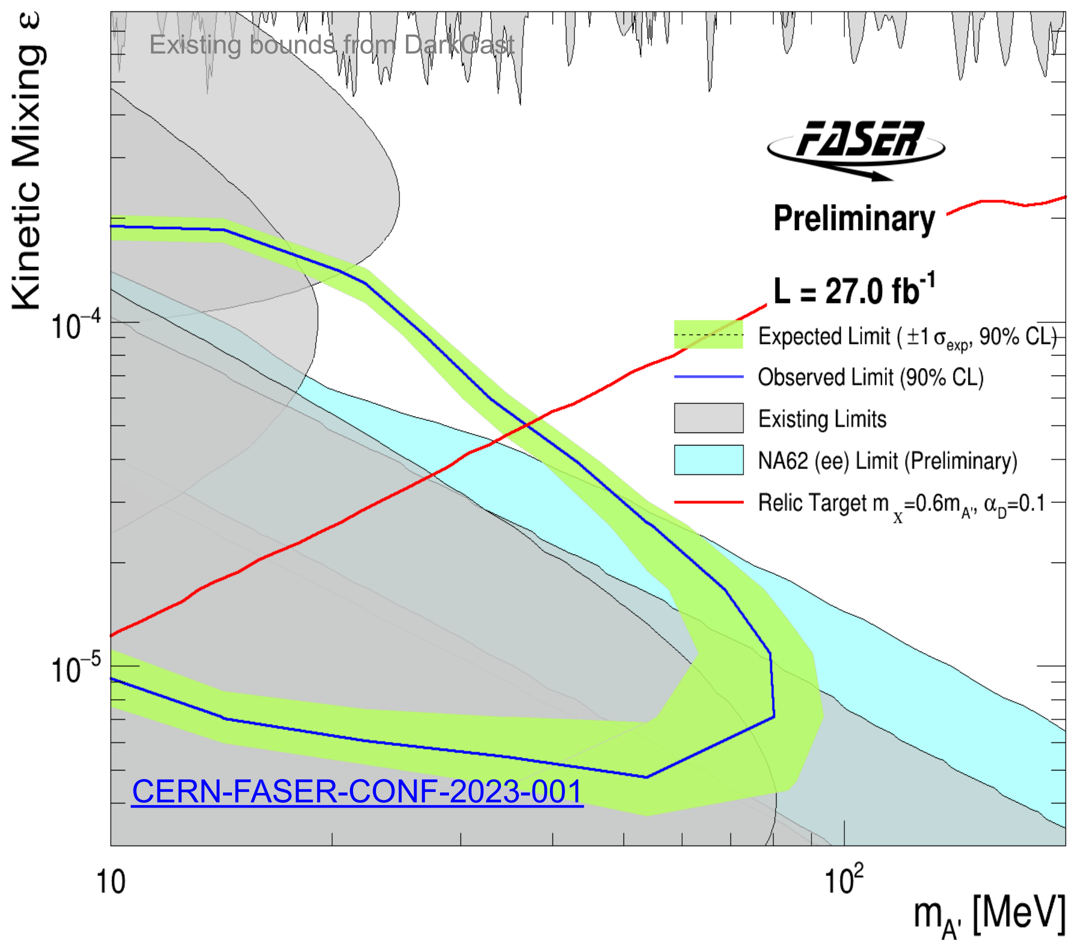


DARK PHOTON RESULTS

- After unblinding, no events seen in signal region, FASER sets limits on previously unexplored parameter space.

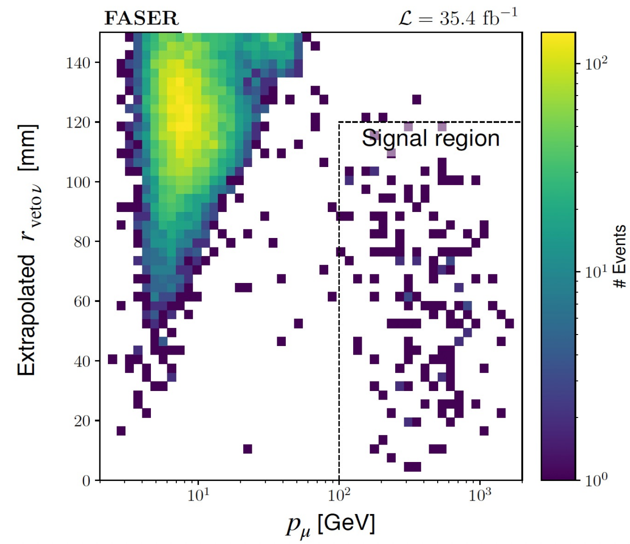
- Along with new results from NA62, these are the first new probes of the thermal relic region from low coupling since the 1990's.

- Background-free analysis bodes well for future sensitivity. Expect factor of ~10 more luminosity in Run 3 from 2022-25.



COLLIDER NEUTRINO RESULTS

- With 2022 Run 3 data alone (~30 fb^{-1}), first direct observation of collider neutrinos: 153 events (FASER) + 8 events (SND@LHC), ~0 background.
  - Signal significance of ~16σ
  - Muon charge → both ν and $\bar{\nu}$
  - Almost certainly these include the highest energy ν and $\bar{\nu}$ from a human source



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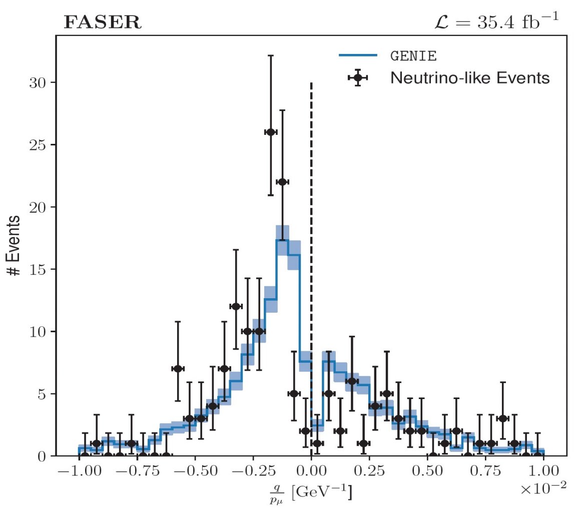
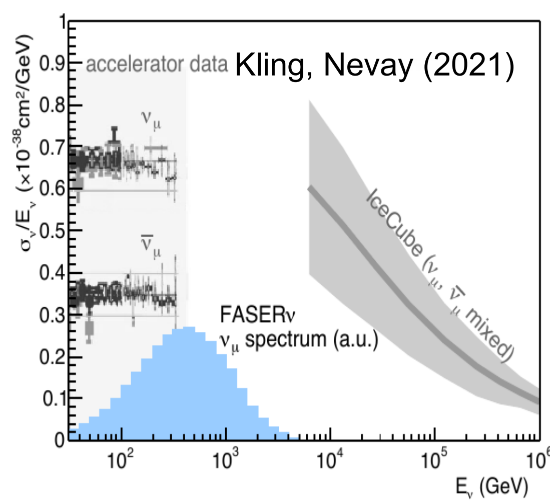
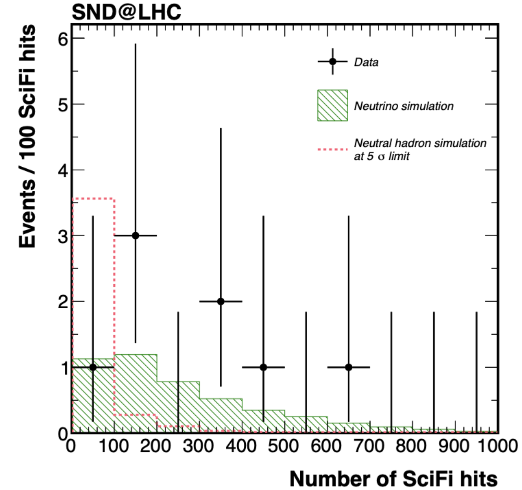


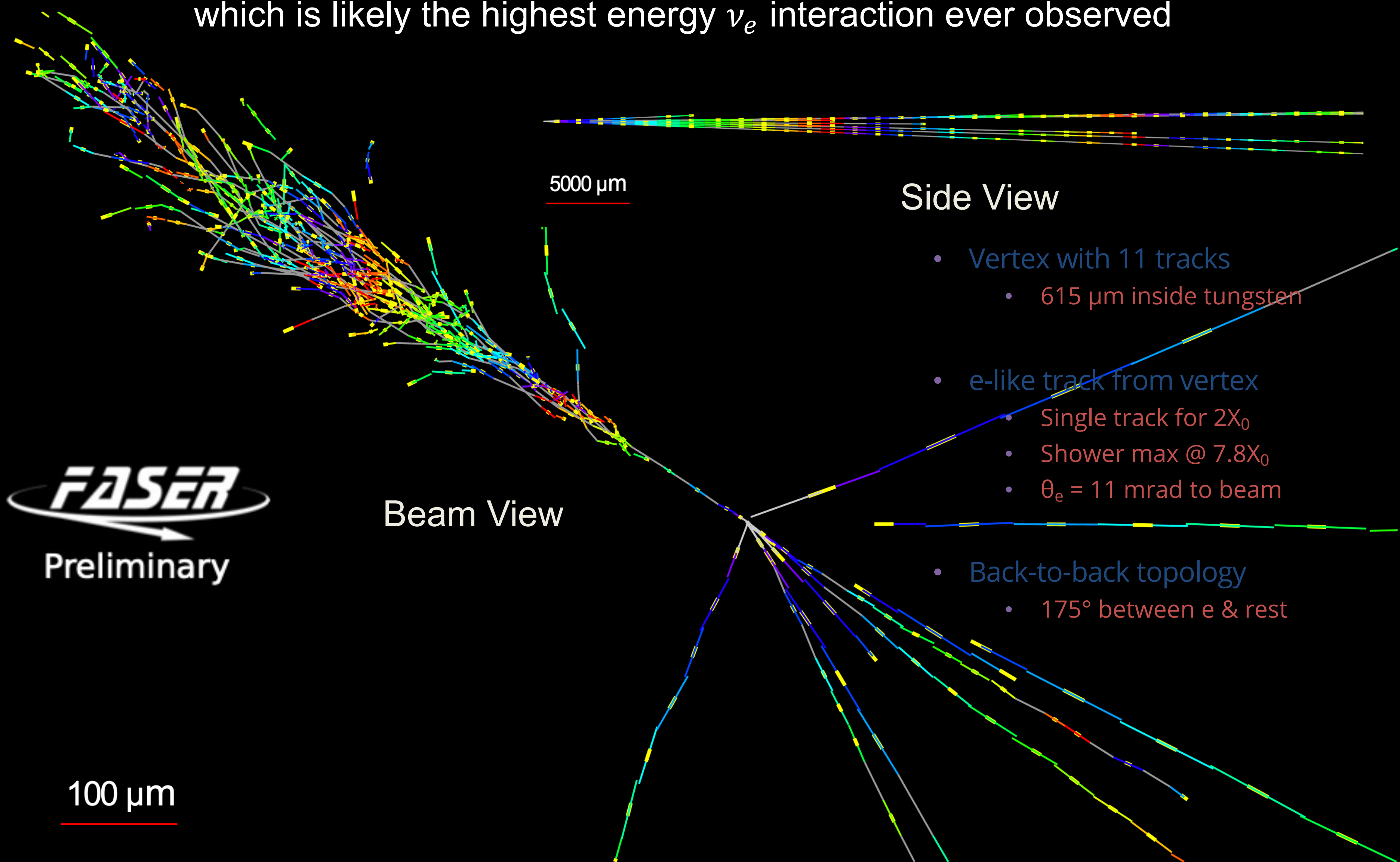




2305.09383

NEUTRINOS FROM EMULSION IN FASERν

Much more to come: this analysis does not even use the emulsion data!
Analysis underway, but already many neutrino candidates, including this event, which is likely the highest energy ν_e interaction ever observed



- Vertex with 11 tracks
  - 615 µm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

LOCATION, LOCATION, LOCATION

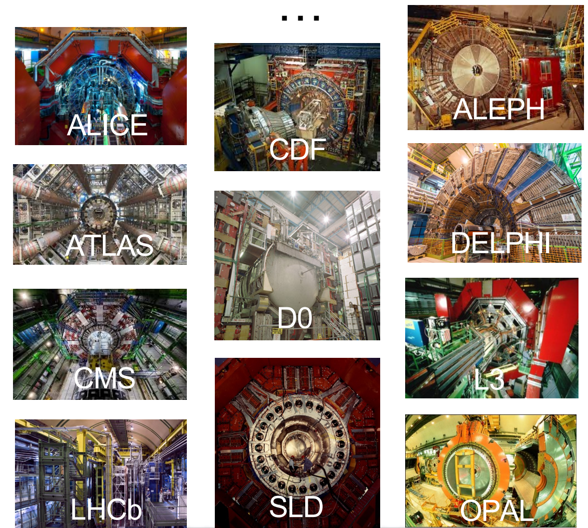
FASER and SND@LHC

“Tabletop,” ~ 2 years*, ~$1M

161 neutrinos

*with essential help from ATLAS, LHCb!

…



All previous collider detectors

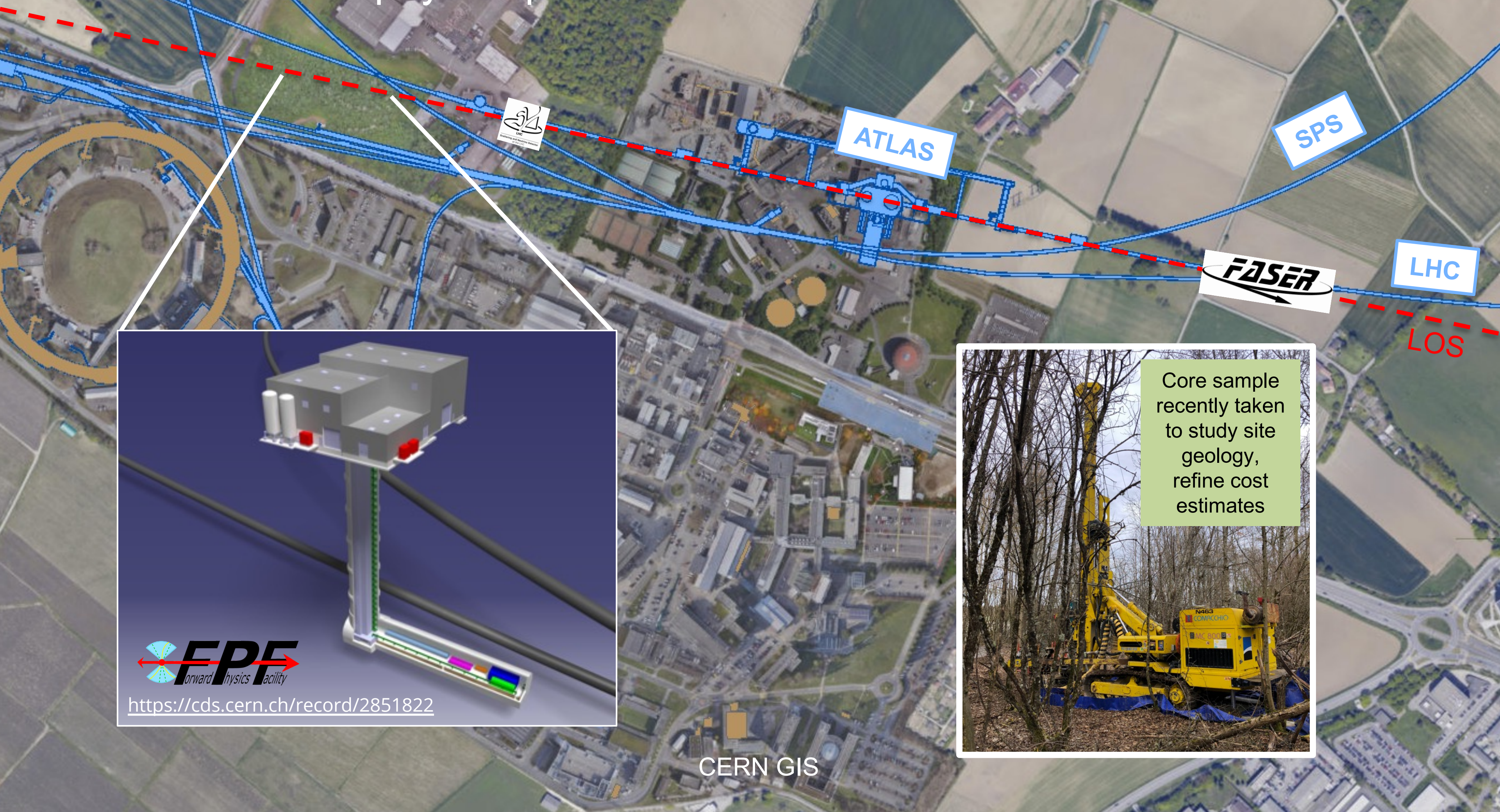
Building-size, decades, ~$1B

0 neutrinos

Unambiguous discovery, opening up the new field of neutrino physics at colliders

FORWARD PHYSICS FACILITY

- The rich BSM and SM physics cases motivate work on a dedicated Forward Physics Facility to house experiments that will greatly enhance the physics potential of the HL-LHC.



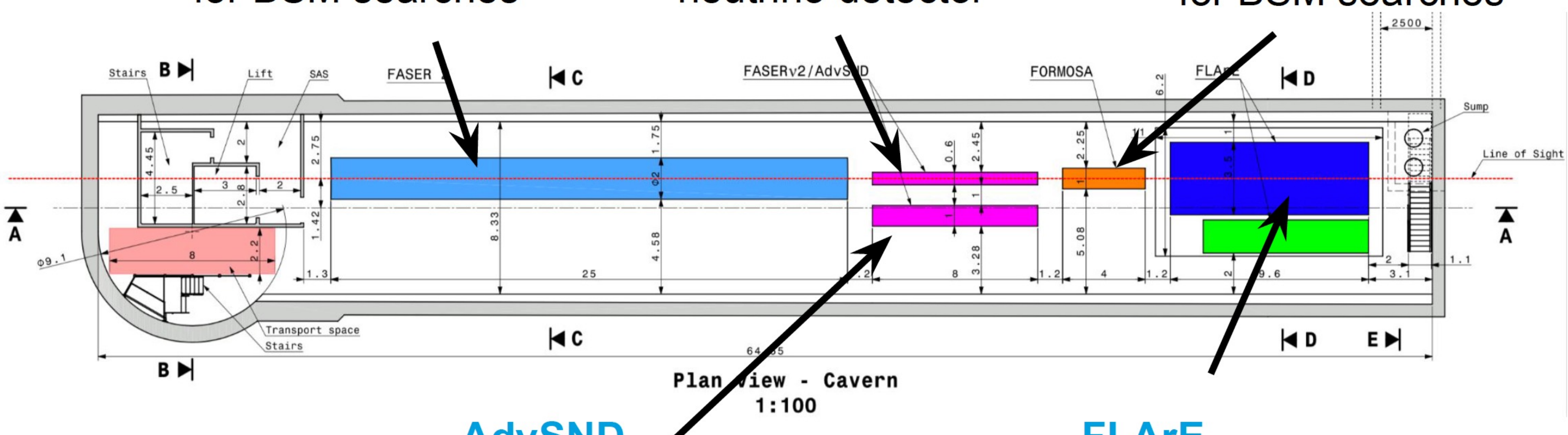
FPF EXPERIMENTS

- At present there are 5 experiments being designed to explore the breadth of physics topics.
  - Millions of TeV-energy neutrinos will provide new probes of neutrino properties, QCD, and astroparticle physics.
  - $O(10^4)$ times greater sensitivity for new particle searches.

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches

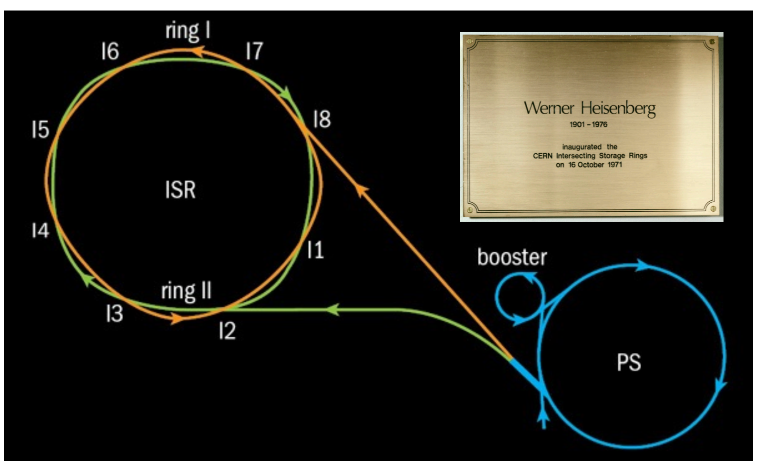


AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

A CAUTIONARY TALE

- Sometimes to look forward, it pays to first look back.
- 2021 was the 50th anniversary of the birth of hadron colliders.
- In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.



ISR'S LEGACY

- During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists looking back on the ISR's legacy.
  - "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.
  - "There was initially a broad belief that physics action would be in the forward directions at a hadron collider…. It is easy to say after the fact, still with regrets, that with an earlier availability of more complete… experiments at the ISR, CERN would not have been left as a spectator during the famous November revolution of 1974 with the J/ψ discoveries at Brookhaven and SLAC ." – Lyn Evans and Peter Jenni, "Discovery Machines," CERN Courier (2021).
- Bottom line: The collider was creating new forms of matter (charm), but the detectors focused on the forward region (along the beamline) and so missed them. Let's not follow this precedent!

SUMMARY

- LLPs are likely to play an essential role in the next breakthrough that takes us beyond the standard model.

  – LLPs are ubiquitous in BSM theories, especially those with cosmological significance.

  – LLPs can be detected through a huge variety of signatures.

  – Many of these signals are truly spectacular – a few events can be a discovery.

  – For existing experiments, we have not yet reached the full LLP discovery potential.

  – LLPs also present many opportunities for new experiments, some of which are already bearing fruit.