Beyond the Standard Model*

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THE UNIVERSITY *of* EDINBURGH

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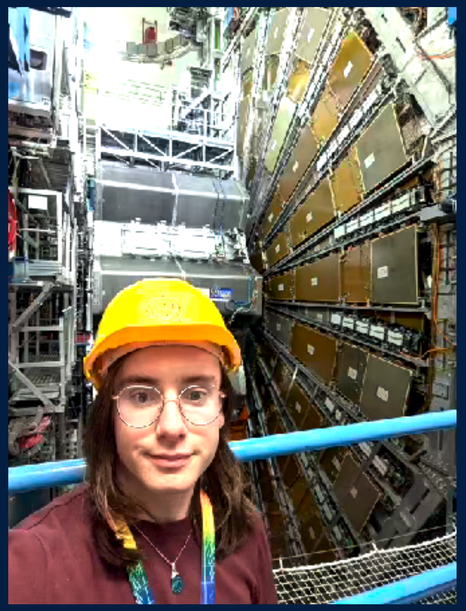
* From an experimental particle physics point of view

So who am I

- South African/British Physicist
- PhD student at the University of Edinburgh
- I work on the ATLAS experiment searching for exotic new particles with long lifetimes*
  - Part of what is known as **beyond standard model physics**



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& Astronomy

* Long lived on the scale of the ATLAS detector (EXTRA CONTEXT MARKER)

Standard Model of Particle Physics

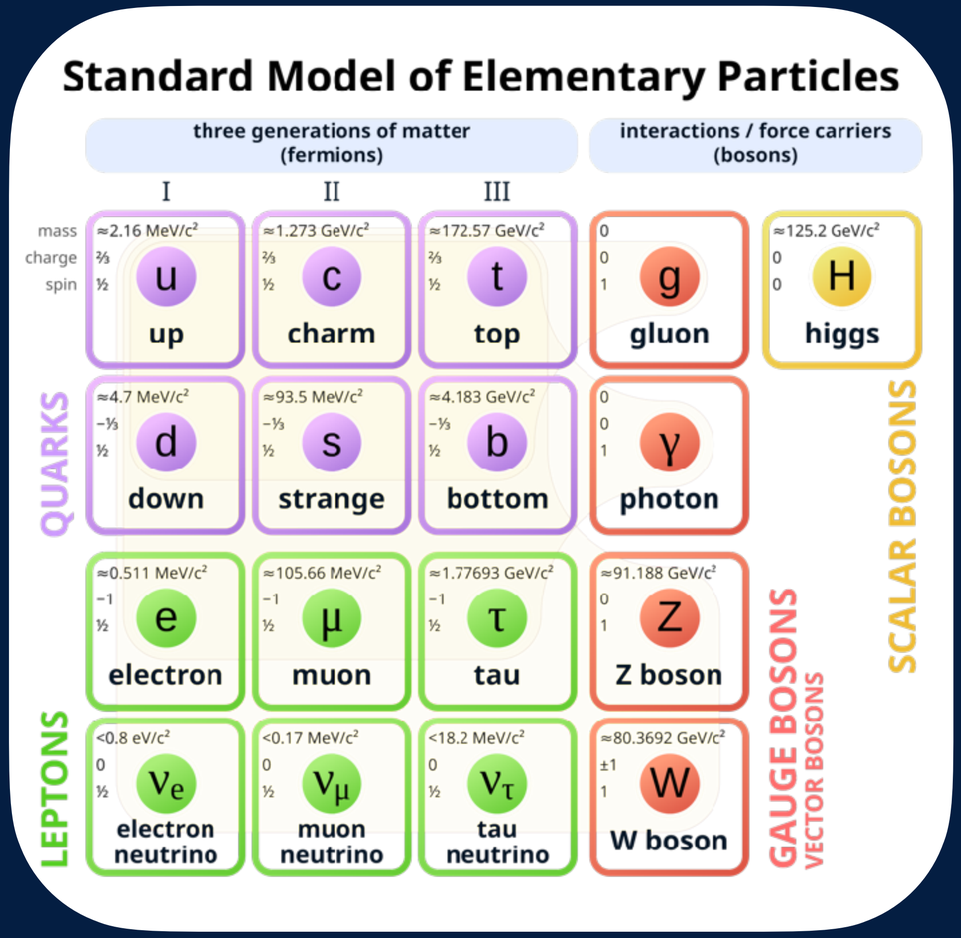
- Set of particles for matter (fermions)
  - Quarks and Leptons
- Set of mathematical symmetries that provide particles describing how matter interacts
  - Interaction mediated by new particles (bosons)

$$U(1)_\gamma \times SU(2)_L \times SU(3)$$

Electro-weak

Strong

- Plus the Higgs boson that provides mass to everything



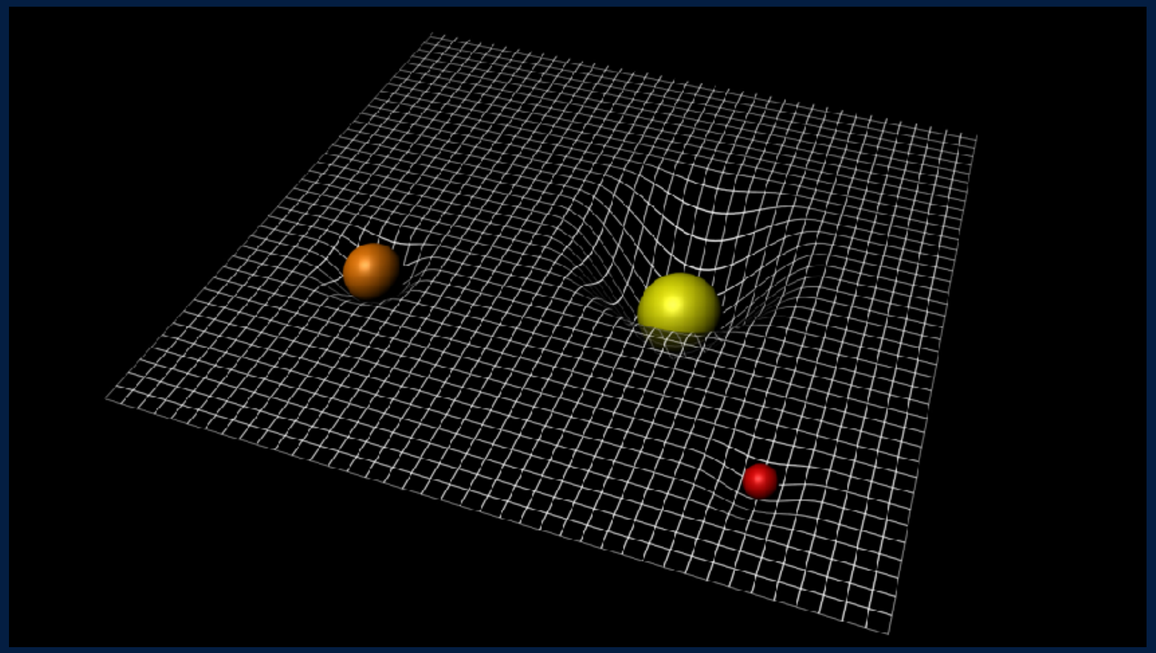
The Standard Model is unbelievably successful

Why the SM isn't everything

Why the SM isn't everything

Gravity

- The SM does not provide a quantum description of gravity
- All other forces have their particles
  - Do we have a Graviton?

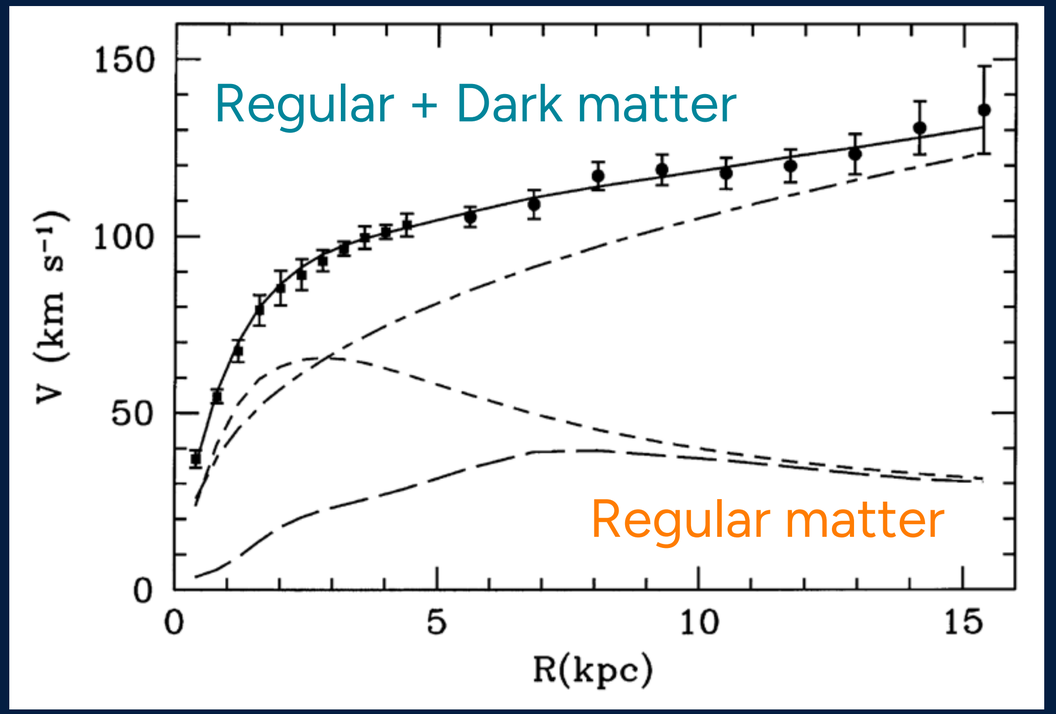


[©ESA–C.Carreau]

Why the SM isn't everything

Dark Matter exists

- From cosmological observation, far more matter in the universe
- But how does this matter come into the SM?

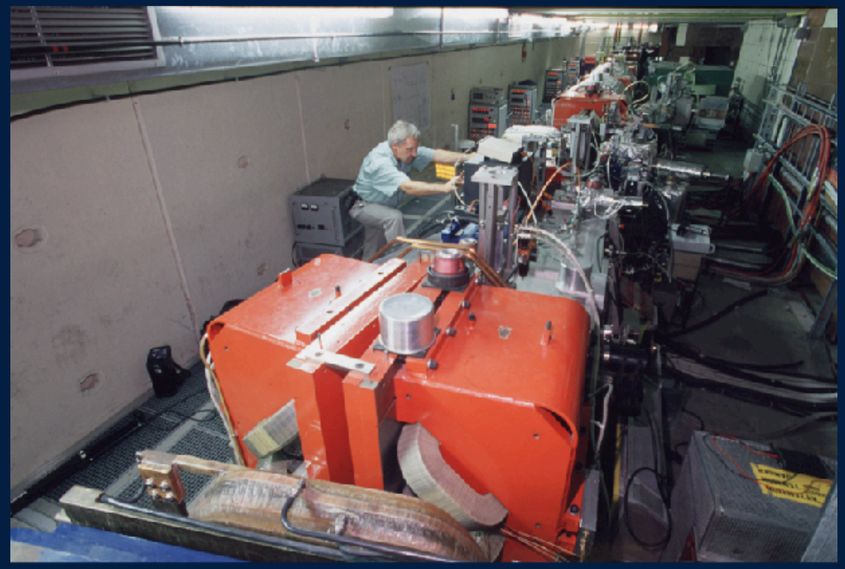


Galaxy rotation curve of Messier 33 [arXiv:astro-ph/9909252]

Why the SM isn't everything

Matter-Antimatter asymmetry

- In the universe, we see more matter than antimatter
- The SM does not provide an answer for this disparity
  - Matter and antimatter are treated equally*
  - Something else is required...



Antimatter decelerator [https://cds.cern.ch/record/39751/]

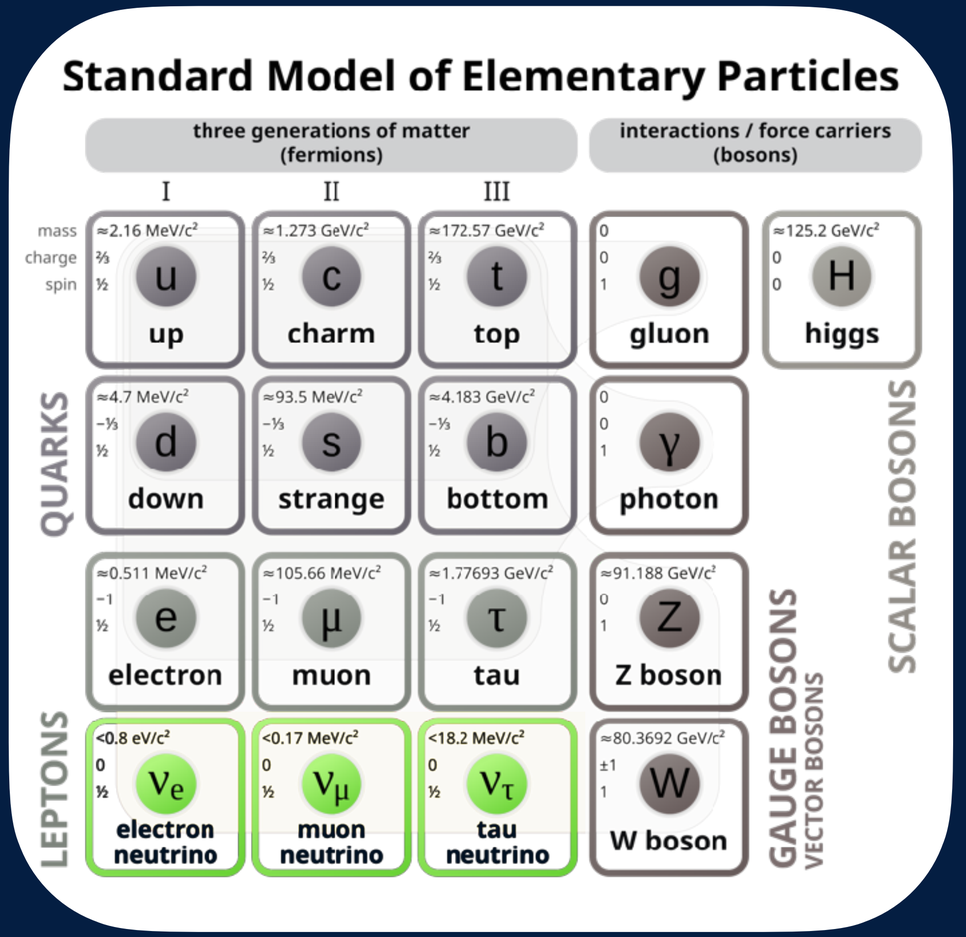
* Some deviations exist between matter and antimatter in minor cases (known as CP violation)

Why the SM isn't everything

Weirdness with Neutrinos

- Extremely light compared to all other particles
  - No explanation for this scale difference
- We're not sure if it gets mass like the other fermions
  - Does it get mass from the Higgs like the other?*

- They also change themselves???
  - Known as neutrino oscillation
  - One type of neutrino can later be measured as another type of neutrino



* Would require a right-handed neutrino, which has not been observed

How do find BSM physics

Models of new physics

Technicolor Models

Seesaw Mechanism

Super Symmetry

Grand Unified Theories

SBND LHCb CMS

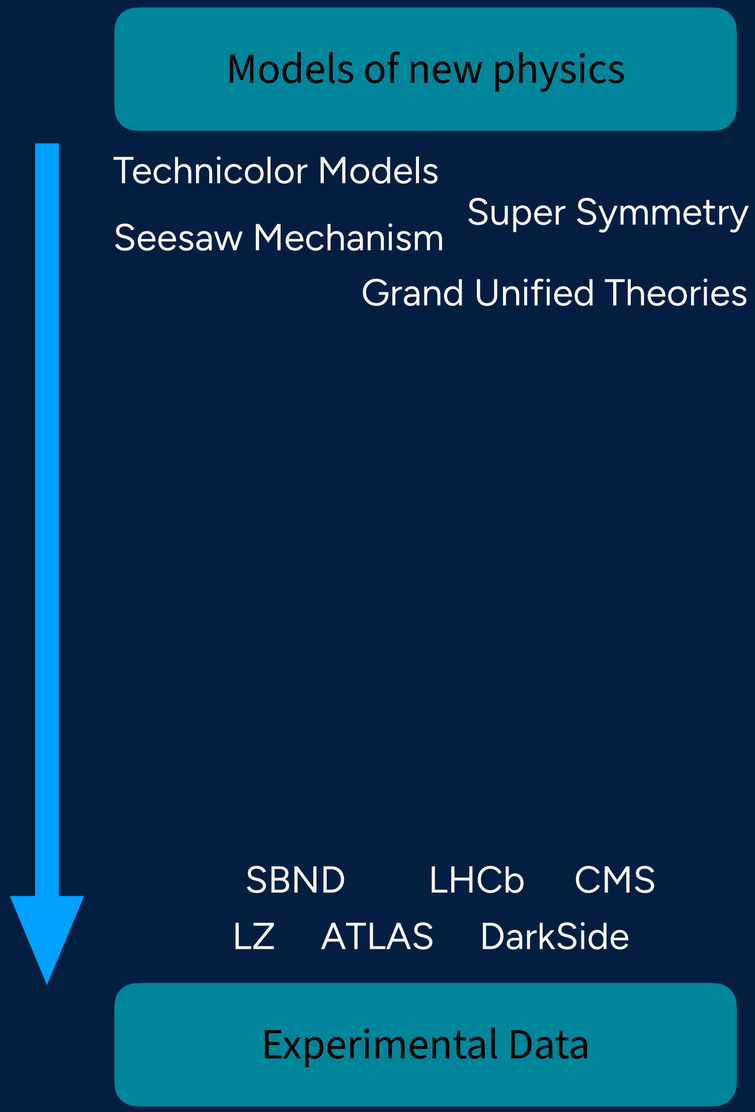
LZ ATLAS DarkSide

Experimental Data

How do find BSM physics

Top down

- Theorist propose theories and derive predictions
- Design experiment to observe these predictions
- Examples
  - Proton Decay
  - Magnetic monopoles



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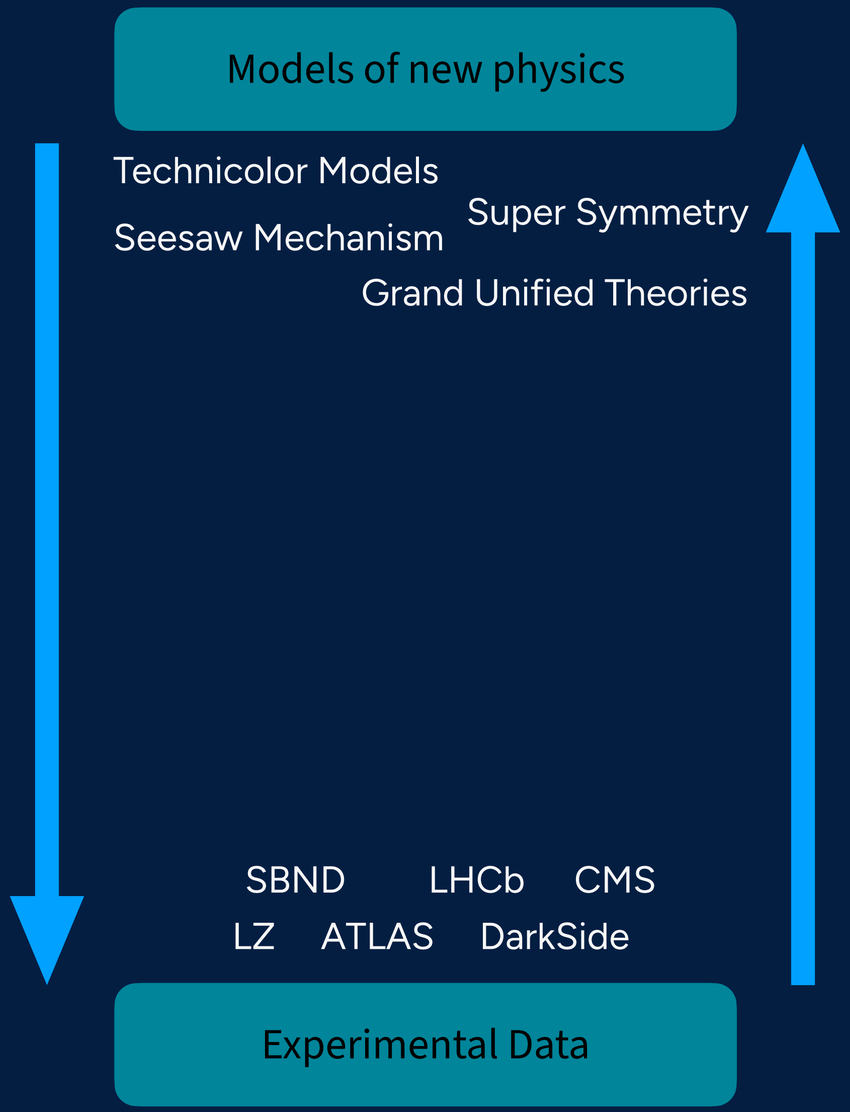

Bottom up

- Measure data very very very well
- Use statistical methods to limit where new physics could be
- Rule out new physics models or find anomalies

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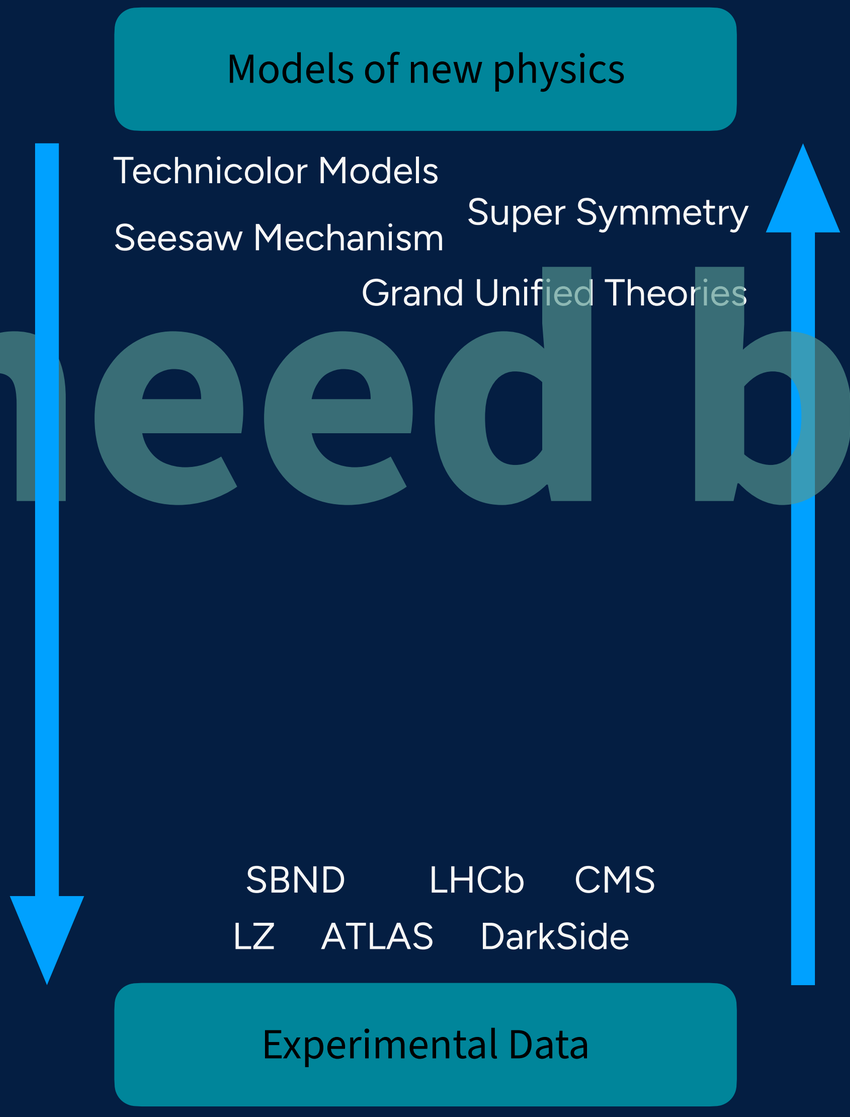

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We need both!

Examples of the systems working

Top down

Higgs Boson was proposed as a consequence of the Brout–Englert–Higgs mechanism in 1964 but only discovered by ATLAS and CMS experiments in 2013

Bottom up

Tau lepton was discovered in 1975 by Martin Perl et al. at the Stanford Linear Accelerator Centre. A new lepton was expected but not needed in SM.

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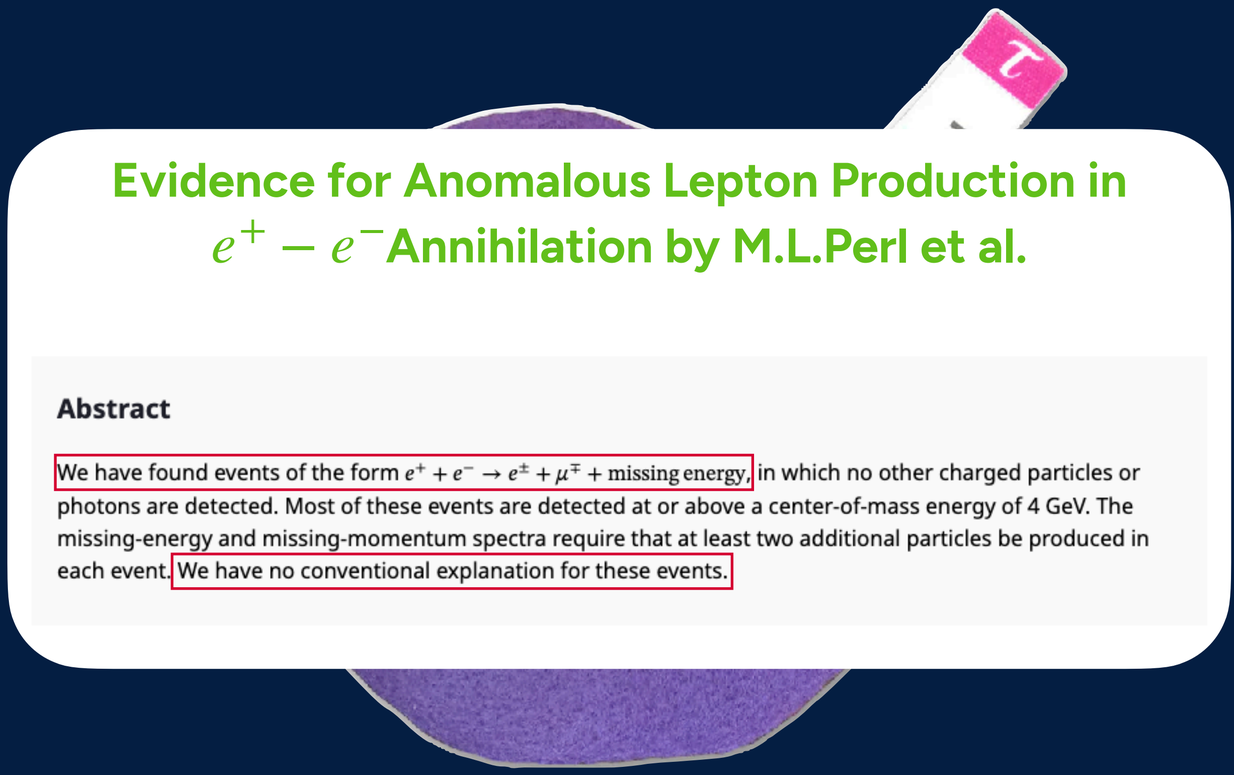

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The joint effort

Better Theorists

- Paradigm shift to provide a new path

$$\mathscr{L}_{Higgs} = D_\mu \phi^\dagger D^\mu \phi + V_{Higgs}(\phi)$$

Equation describing the particle nature of Higgs boson

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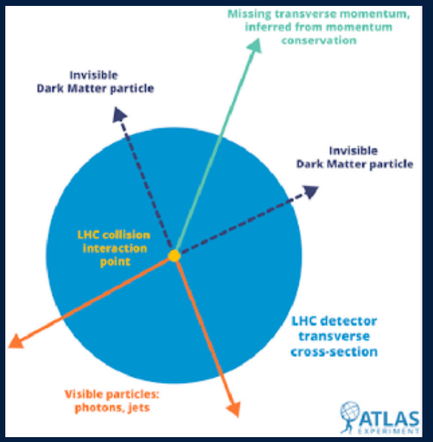
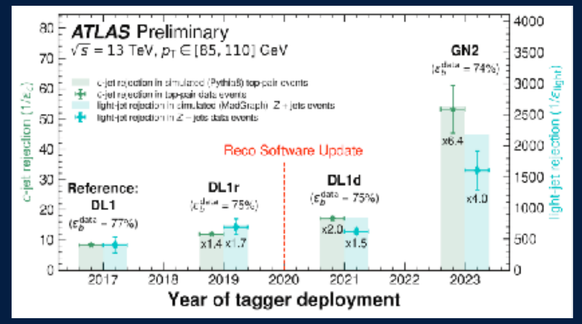
Better Experimentalists

- Better techniques and insights into the data



Better missing energy calculation



ML developments in object tagging

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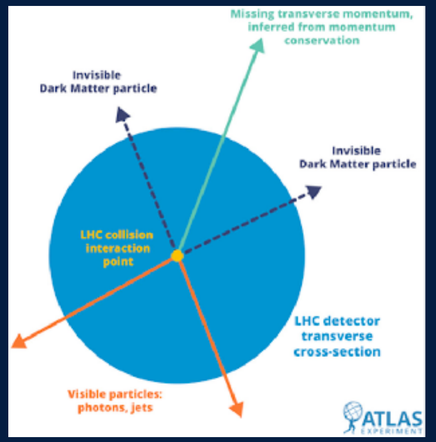

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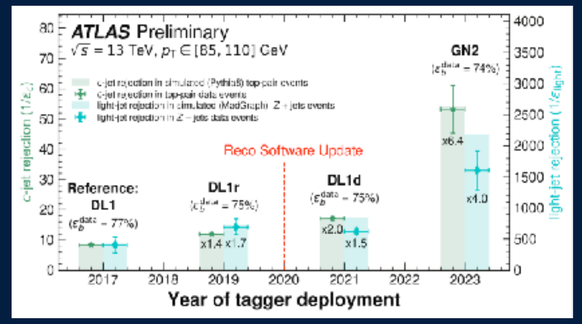
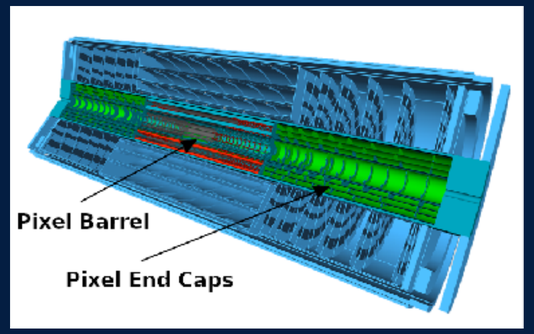


ML developments in object tagging

Better Technology

- Unlocks inaccessible places to look for new physics



ATLAS ITK [hep.physik.uni-siegen.de]

LHC magnets [irfu.cea.fr]

UK Computing research on worldwide grid [gridpp.ac.uk]

What is a search for BSM physics

- Most statements about new physics are statistical
  - Assume a null hypothesis
  - Show that it is unlikely that the null hypothesis is true

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Hypothesis: There are more people living in Glasgow than Edinburgh

Glasgow: 632 350
Edinburgh: 506 520

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Alternative Hypothesis: There are more people living in Glasgow than Edinburgh

Hypothesis: New physics exists beyond the Standard Model

Null Hypothesis: The standard model is correct

Alternative Hypothesis: The standard model is incorrect

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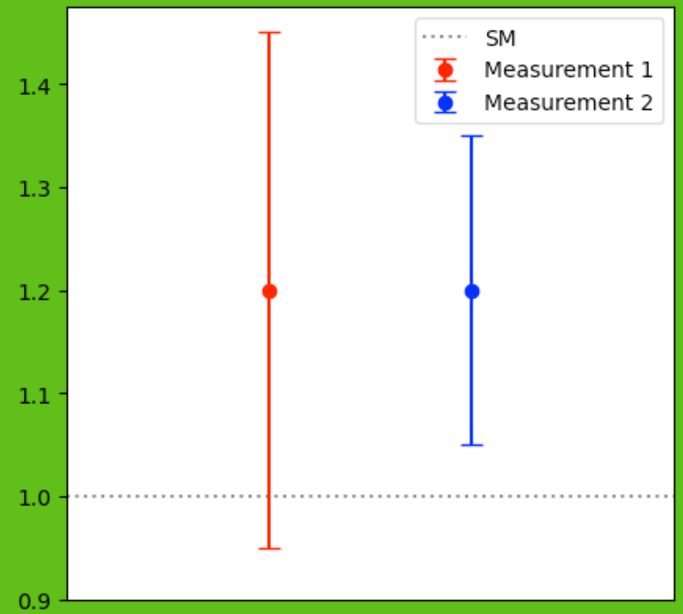
- We first make some measurements and compare to SM
- The error/uncertainty* on the measurements matters
- Does our data *disagree* with the SM and by how much?



*Measurements are commonly shown with errors/uncertainties that represents a 68% confidence interval of a normal distribution

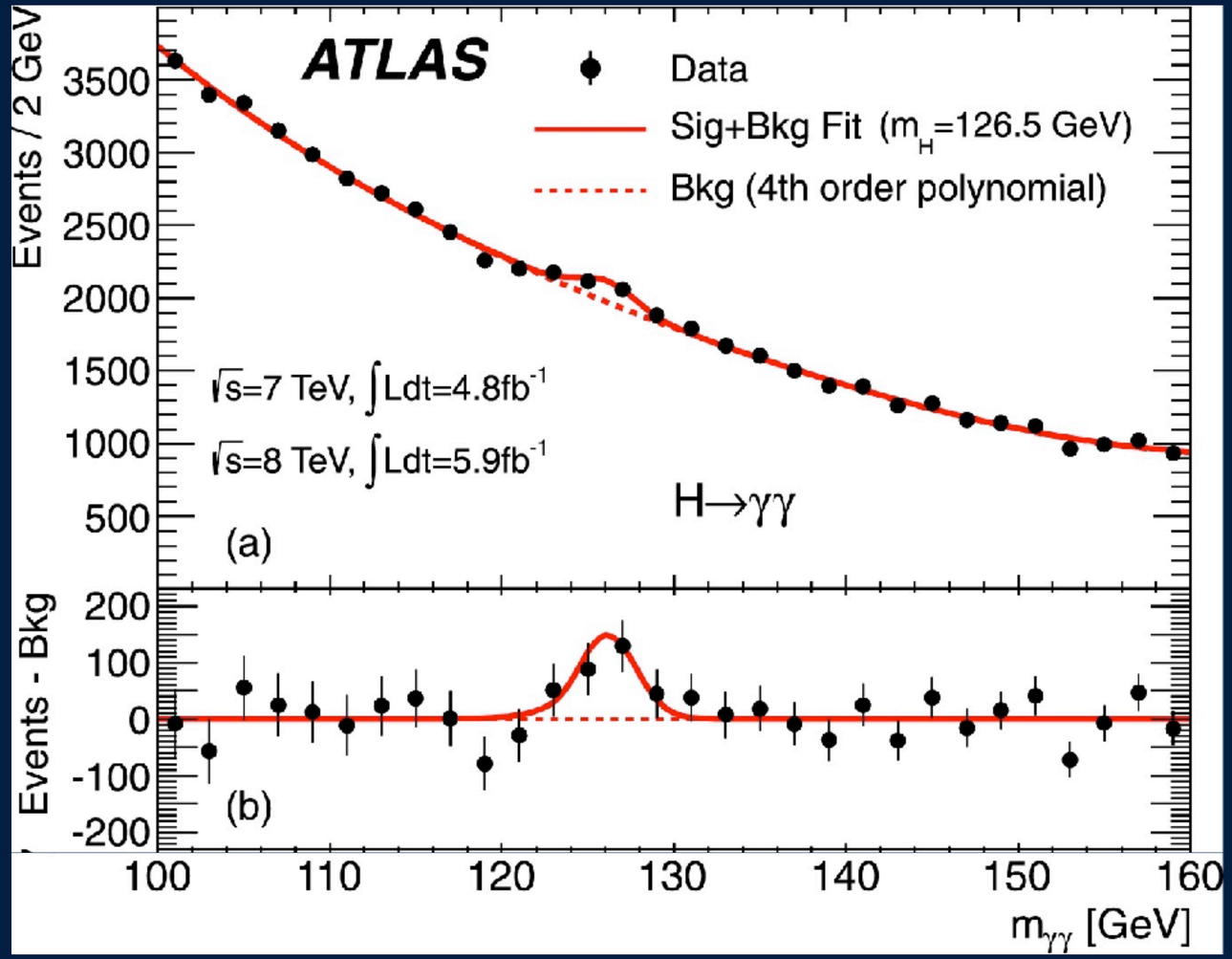
Searching for new physics isn’t about finding new physics, it’s about proving the current physics wrong

What is a search for BSM physics: Example

- Discovery of Higgs boson
  - Produce a model of physics without the Higgs boson (dotted line)
  - Produce to a model with the Higgs boson (solid line)
  - Look at the data and show that the model without Higgs is *improbable*

5 sigma rule (or 5σ)

In particle physics, we define *improbable* as saying that only 3/10 000 000 times would the old model produce the data we saw*



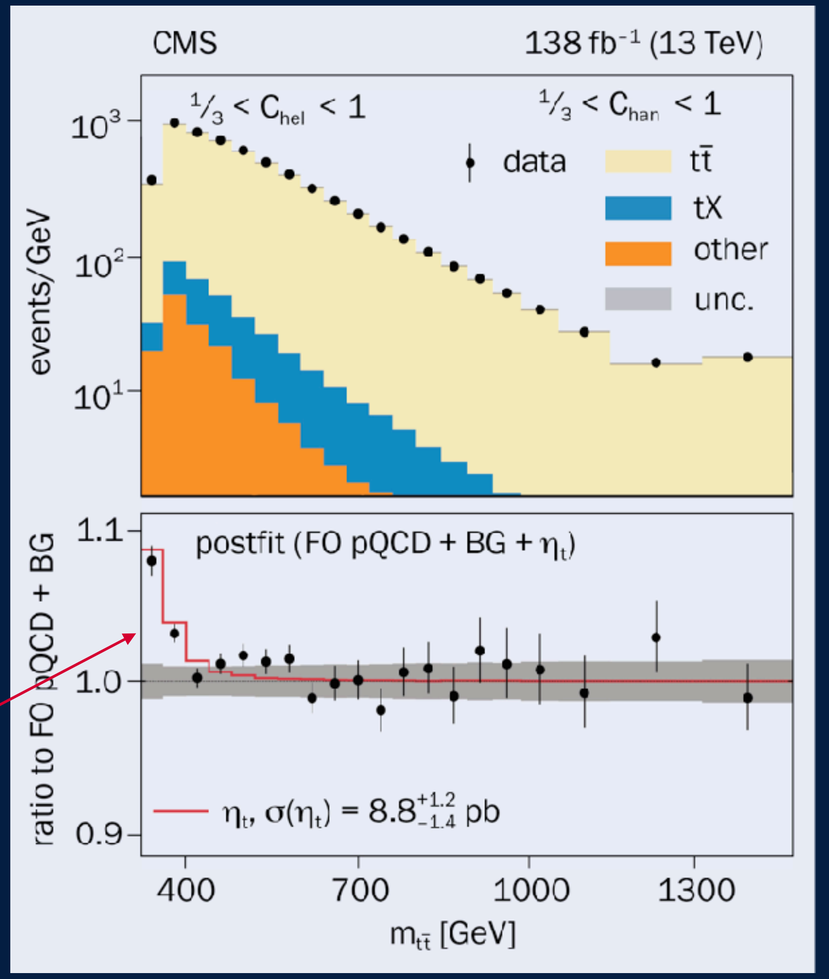
[arXiv:1207.7214]

* If you know hypothesis testing in statistics, a p-value > 3×10^{-7} from one tail of a normal distribution

What is a search for ~~B~~SM physics: Example

- Observation of Toponium
  - Short-lived bound state of a top quark and an antitop quark allowed by SM
- Observed by the CMS collaboration this year!
- Same statistical interpretation as the Higgs discovery

This is where the toponium lives

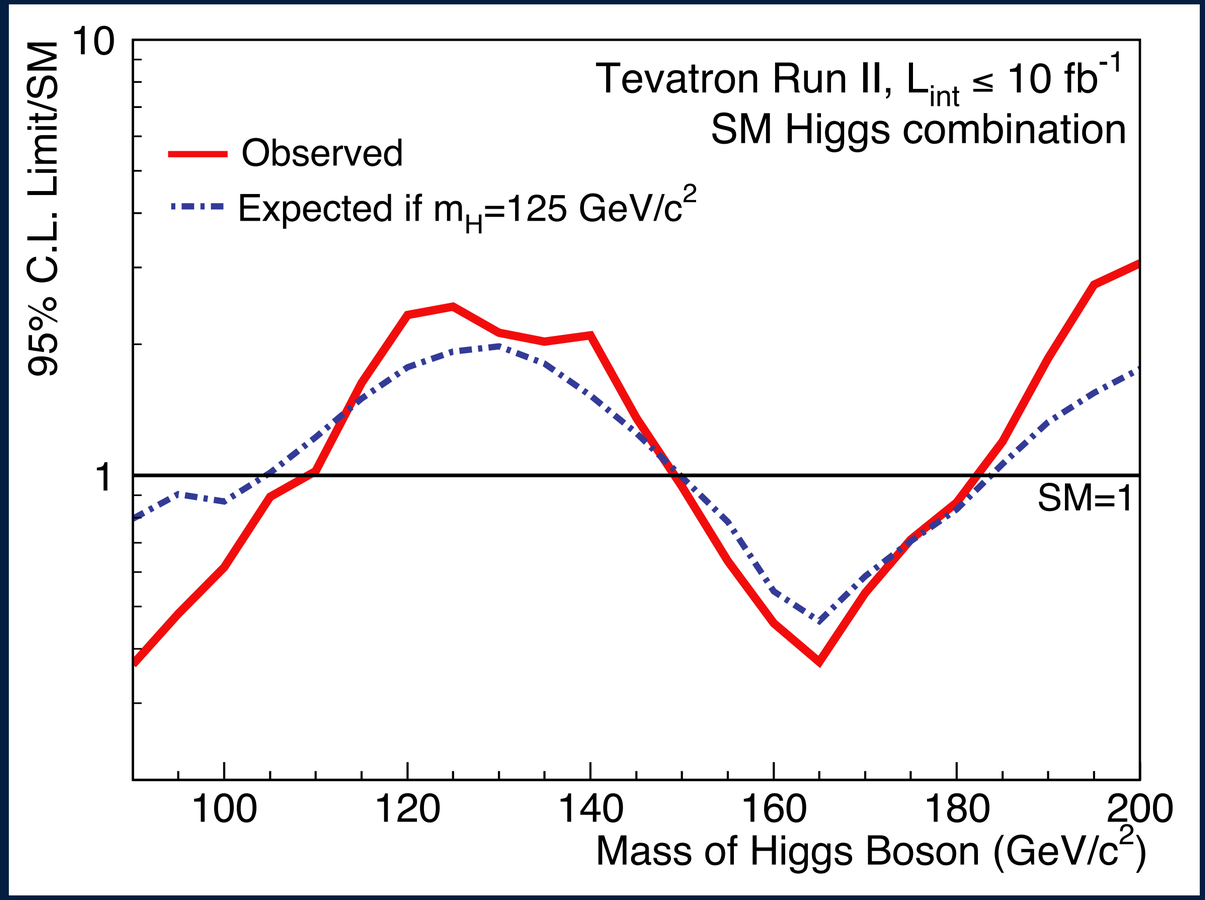


Mass spectrum of di-top system[arXiv:2503.22382]

Well what if we don’t see anything?

Excluding BSM physics

- Invert the statistical question
  - Try to reject the new physics to get a better idea of where to look
- The Higgs could not be found at the Tevatron (1983-2011) but results helped the LHC experiments



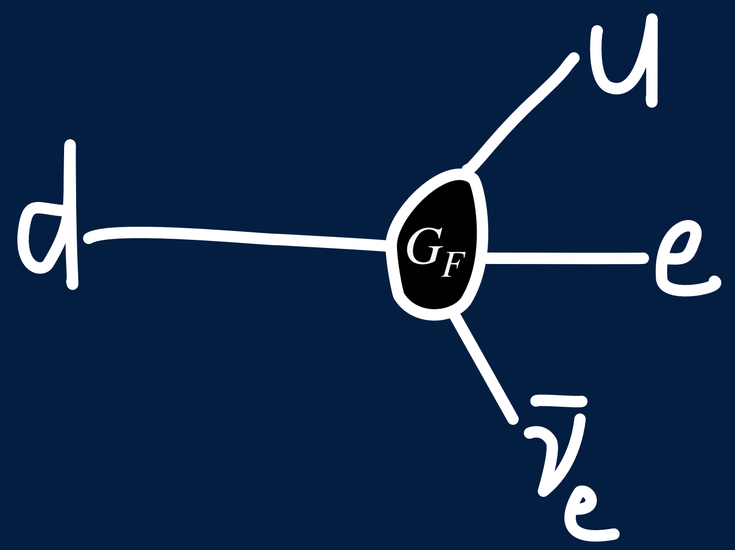
Exclusion of Higgs boson mass* [arXiv:1303.6346]

* Technically this is a more modern plot released in 2013 but the Higgs was still unseen at the Tevatron.

Probing new physics: Effective theories

- Beta decay: $n \to p + e + \bar{\nu}_e$
- At quark level: $d \to u + e + \bar{\nu}_e$
- Fermi theory described by Enrico Fermi in 1934

Effective theories are simplified models that may hide new physics



Fermi Theory

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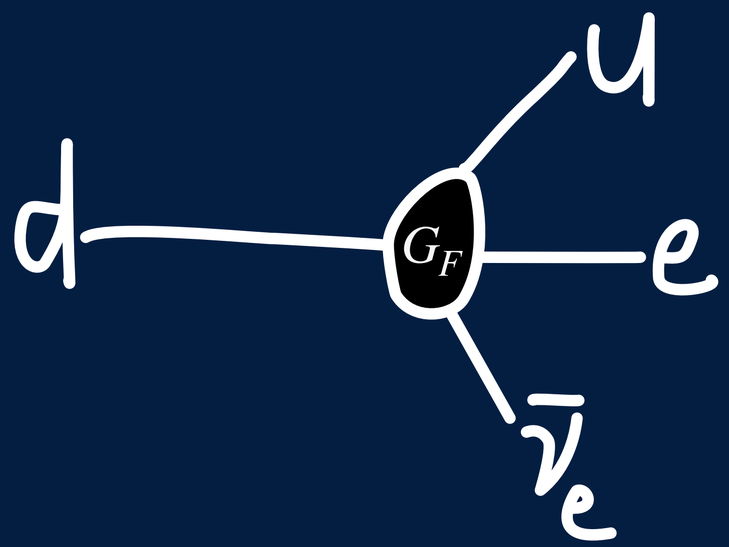


Fermi Theory

$$G_F \propto \frac{g_W^2}{m_W^2}$$

Electro weak theory (1967)

What toy's are we looking forward to

Luminosity upgrade to the LHC (2028)

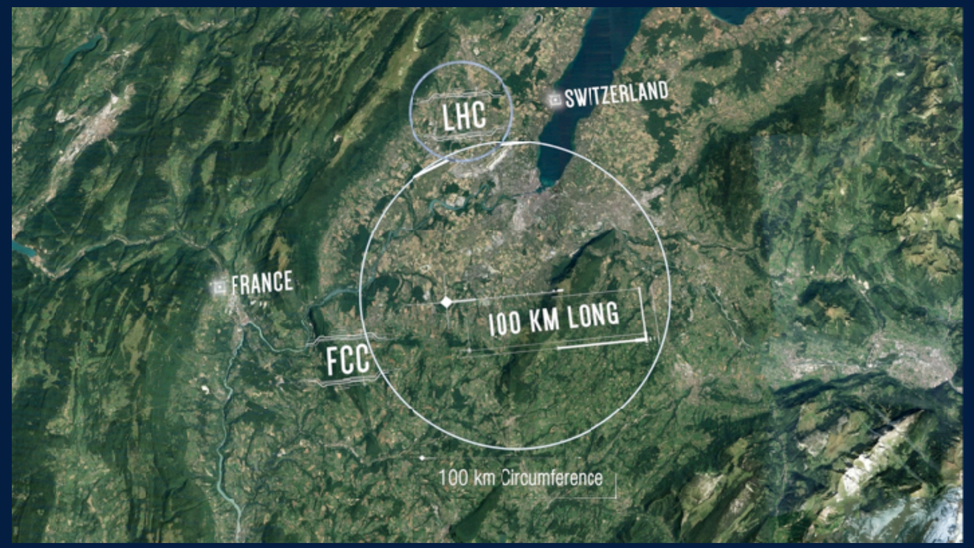
Japanese-based Neutrino Experiment (~2027)

CERN-based linear e^-e^+ (~2035)

Any muon collider (?)

USA-based Neutrino experiment (2027?)

China-based Circular Electron Positron Collider (~2035)



Future Circular Collider (>2050)

Conclusions

- New unexplained physics exists
- Two options
  - Option 1: We haven't looked hard enough
  - Option 2: We are missing something…
- To find new physics we need more from everyone
  - Theorists, experiments, engineers, accelerator physicists, material scientists, computer scientists, universities, research councils, science communicators, …
- Ask me anything!
  - BSM physics
  - Working at CERN
  - Doing a PhD in the UK

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