Beyond the Standard Model

Liverpool at CERN

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2026-08-19

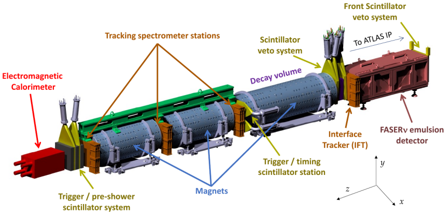
Science and Technology Facilities Council
Particle Physics

Outline

- The Standard Model and its limitations
- What is beyond the Standard Model?
- How do we look for new physics?
- Some examples

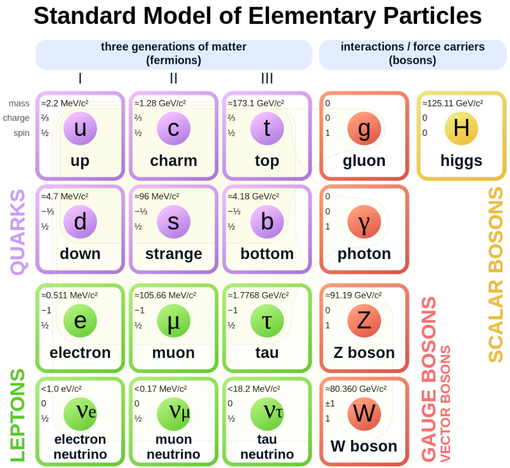
Who Am I?

- I'm Pawan.
- PhD student at University of Liverpool.
  - Previously, was doing Physics at Indian Institute of Technology, Kharagpur.
  - Was involved in some Particle Physics and Cosmology.
- Working on FASER experiment at CERN.
  - I look for Long-Lived BSM Particles
  - Among other things...
- So this talk might be a bit biased towards experimental particle physics.



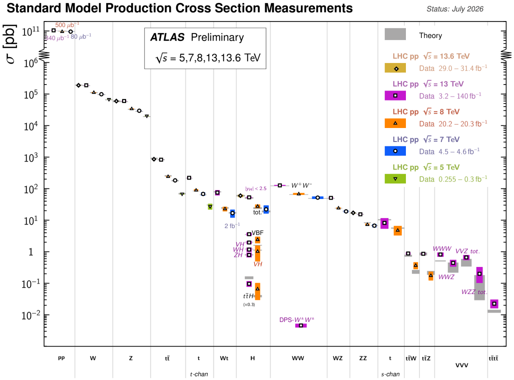
Universe in a Nutshell/Standard Model

- Everything we see is made from a small set of particles and forces
- The Standard Model (or SM) is our best theory
  - It describes the universe using
  - 12 fermions (matter particles)
  - 5 bosons (force carriers)
- It works incredibly well, often times too well.



How good is the Standard Model really?

- Some of the successes of the Standard Model is summarized in this Plot.
- It tells us how well theory and experiment agree with each other.
  - The grey band shows the theory predictions (and uncertainty)
  - The markers (+color bands) show the experimental measurements
  - Each measurement is a different analysis: different people, different methods...
- The measurements vary across 13 orders of magnitude
- The agreement is remarkable!



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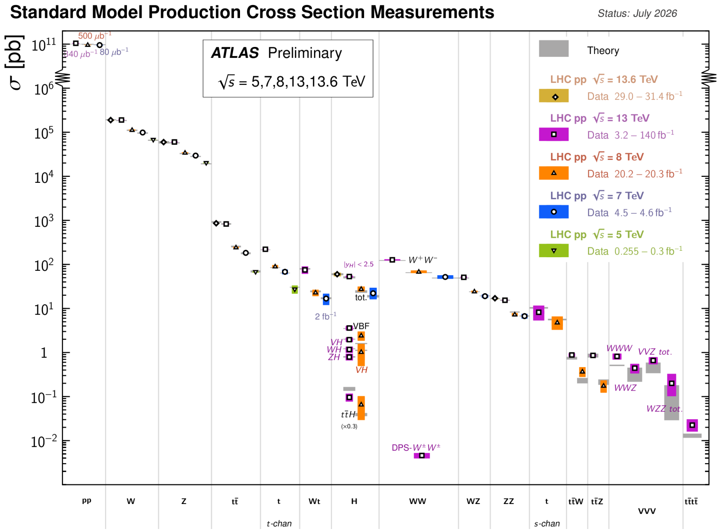
How good is the Standard Model really?



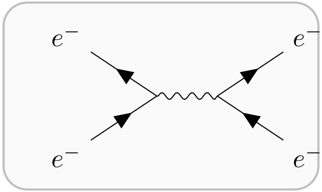
But...The Standard Model is Incomplete

- But the Standard Model is incomplete.
- It doesn't explain everything we see in the universe.
- For example, it doesn't explain:
  - Gravity
  - Dark Matter
  - Baryon Asymmetry
  - Neutrino Masses
  - ...
- I'll try to describe some of these problems in the next few slides.

Gravity

- The SM describes three of the four fundamental forces in nature:
  - Electromagnetism, Weak and Strong forces.
- But it doesn't describe Gravity.
- Gravity is described by Einstein's General Relativity.
- In the SM, the forces are carried by particles called bosons.
- For example:

The force between charged particles is electromagnetism.



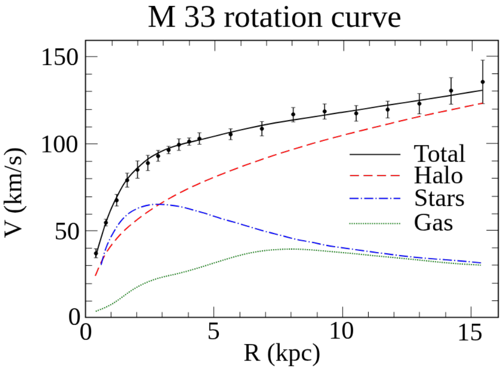
The photon mediates electromagnetism.

- Similarly, Gravity should then be carried by a particle?
  - Unfortunately, we haven't observed this particle yet. We call it the Graviton.
- Good thing is, Gravity is very weak.

Dark Matter

- Look at galaxies with our fancy telescopes.
  - how fast are the stars are moving
  - how are the stars/gases distributed

- It seems to be moving faster than expected.

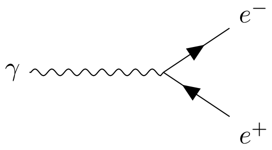


arXiv:astro-ph/9909252

- Almost 85% of the matter in the universe is Dark Matter.
- What is it made of? We don't know yet.

Baryon Asymmetry

- Also known as matter-antimatter asymmetry
- The SM predicts that matter and antimatter should have been created in equal amounts in the early universe.
- But we see a universe dominated by matter. Where did all the antimatter go?

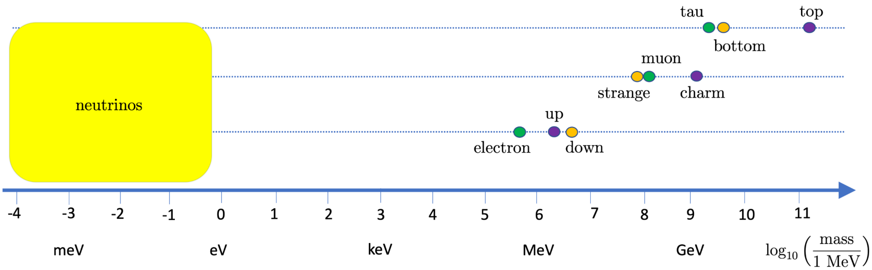


Photon converts to an electron-positron pair.

Neutrino Masses

- Neutrinos are extremely weird.
- They have very low masses?
  - Actually suspiciously low mass – 10^{-3} eV
  - Electron mass is about 10^{6} eV

  How did they get the mass?
- Similar to the the other particles from the Higgs?
  - In which case where is the right-handed neutrino?



So, Where are we?

- The Universe is largely explained by the Standard Model.
- The Standard Model is the best theory we have.
- But some open questions remain:
  - Gravity, Dark Matter, Baryon Asymmetry, Neutrino Masses, ...
- Safe to say, the Standard Model is incomplete.
- More importantly, What do we do about it?

How to *do* Physics Beyond the Standard Model?

Top-Down

- Make a completely new theory
- Check that it is *consistent* with the SM
- Make new predictions.

Bottom-Up

- Start with your known theory (SM)
- Assume it is an effective approximation
- How far can we push the approximation

Direct Search

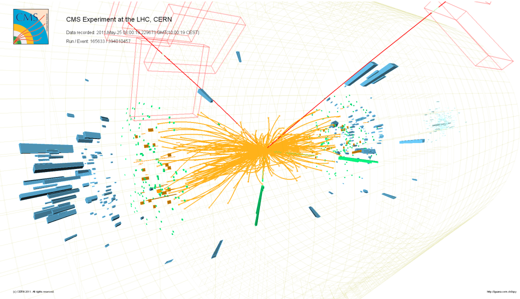
- Look for new particles in experiments

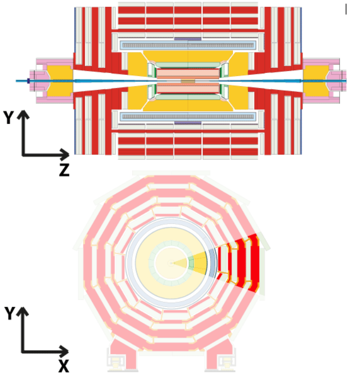
Indirect Search

- Look for deviations from SM

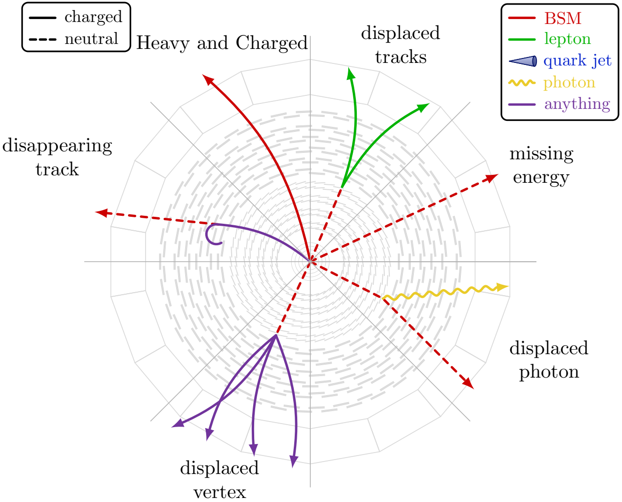
Quick Reminder on Detectors

- Protons come in though the z-direction
- Creating particles in the $x - y$ plane



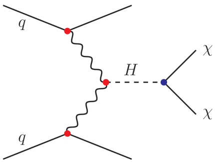


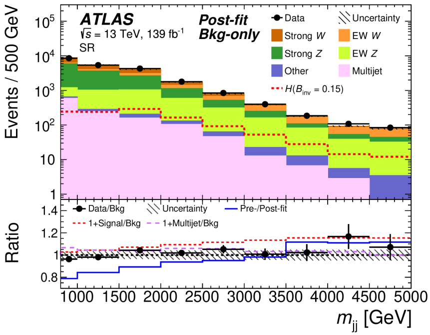
How to look for new Particles?



Dark Matter and the Higgs

- We know Dark Matter exits, and seems to interact gravitationally.
  - In which case it should have mass?
  - Did it get its mass from the Higgs?
- If so, then the Higgs should decay to Dark Matter particles.
- Alert: Scary Plot ahead!
- Actually, its simpler than it looks.

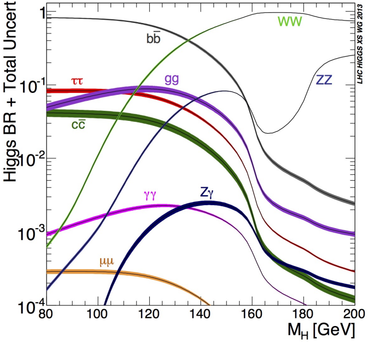


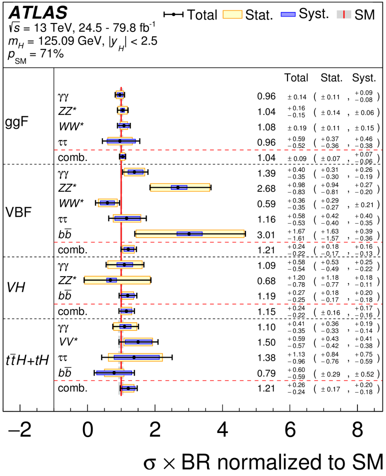


arXiv:2202.07953

Precision Higgs Physics

- The SM predicts how often the Higgs should decay to different particles.
- If we see a deviation from the SM prediction, it could be a sign of new physics.

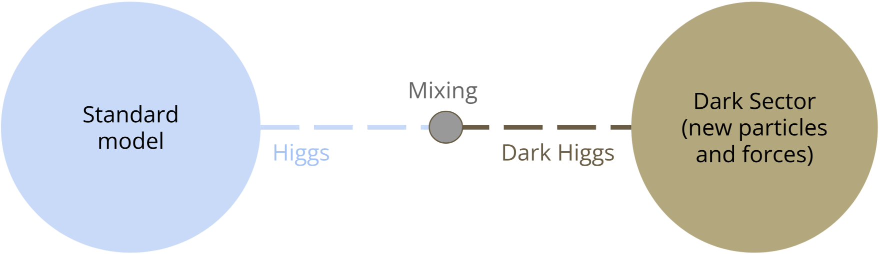




arXiv:1909.02845

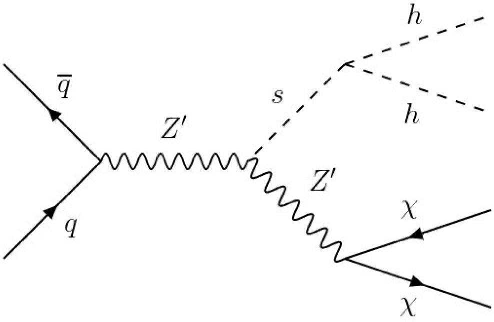
Alternatively – Dark Higgs

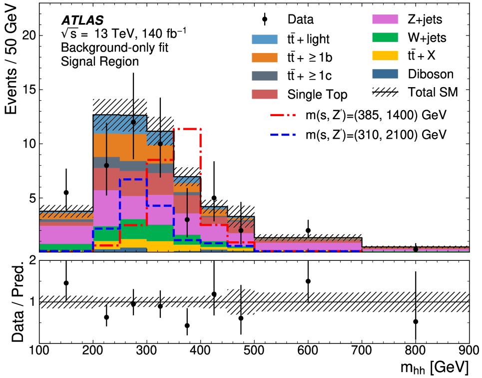
- We know Dark Matter exists
- Assume it is its own collection of particles and forces, call this Dark Sector
- How did it get this mass? Maybe it has its own Higgs Field (Dark Higgs)
- In which case.. The Dark Higgs could be produced in pp collisions.



Dark Higgs

- So, we have a new particle (Dark Higgs) that can be produced in pp collisions.
- It then decays into our favourite SM Higgs

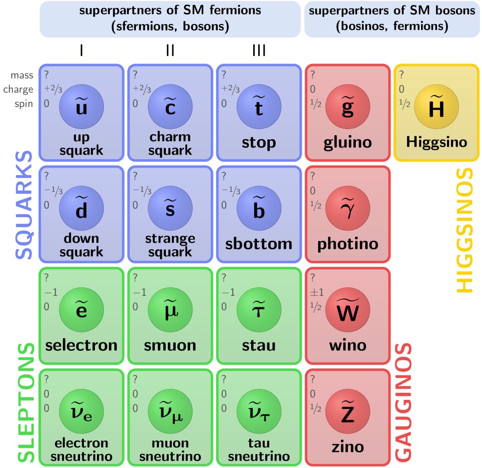




arXiv:2507.02175

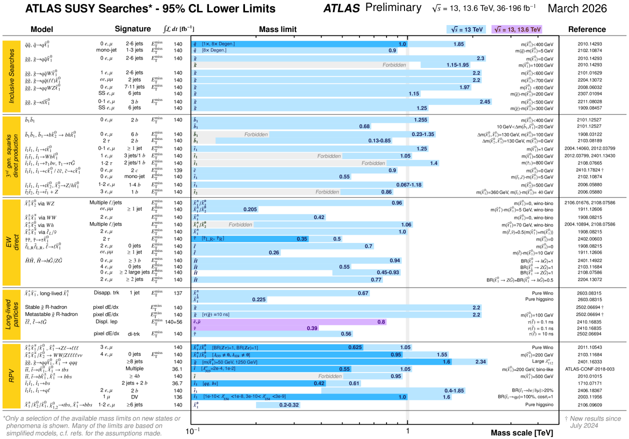
Supersymmetry

- Example of a Top-Down approach is Supersymmetry (or SUSY)
- SUSY fixes a lot of problems in the SM
  - Posits a new symmetry between fermions and bosons
  - Predicts a super-partner for every SM particle
  - Can explain Dark Matter
  - Introduces new symmetries
  - Unifies the forces
- Prediction: New **particles** should be produced in pp collisions



SUSY Searches Summarized

- We were hoping to see at least some of these new particles.
- Have we seen any? Not yet.

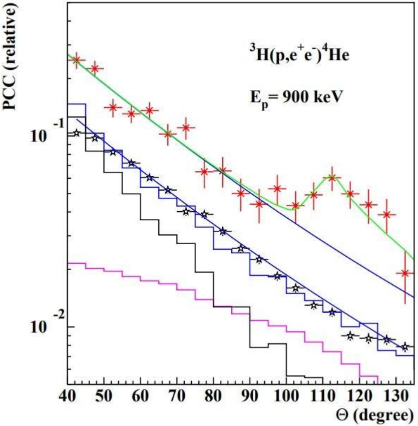


So where are we again?

- The LHC hasn't seen any sign of new physics yet.
- But we have only looked at a small fraction of the data.
- But in Physics, we never know where the next breakthrough will come from.
- But..Maybe we have something already?

Atomki Anomaly or X17 Particle

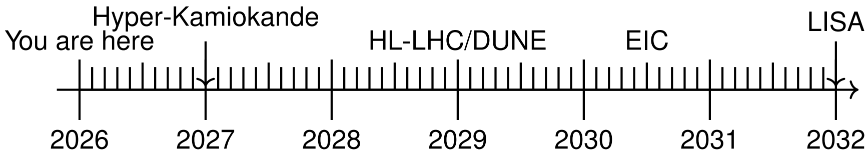
- Recently, 2015 (2019) a Hungarian group (Atomki) reported an anomaly in the decay of Beryllium (Helium) nuclei.
- They saw an excess of e^+e^- pairs at a particular angle.
- This could be explained by a new particle with mass of 17 MeV
- They called it X17.



- We are now trying to look for this particle in the LHC data.

Next five years in HEP

- LHC now heading into Long Shutdown.
  - Will come back with upgrades in 2029: HL-LHC
- We have JUNO with first data
  - promising results with neutrino mass ordering
- Hyper-Kamiokande is coming online in 2027
  - Might give us clues on CP violation in neutrinos
- DUNE is coming online in 2029
- Very exciting times for young people like you
  - Very likely that some of you will be working on these.



Summary and Outlook

- The Standard Model is the best theory we have
  - but it is incomplete.
  - open questions remain: Gravity, Dark Matter...
- We saw some example of physics beyond the SM
  - and how we can look for it in our experiments.
- Thank you for your attention. Any questions?