Physics beyond the Standard Model

Dr. Matt Sullivan

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Overview

- The Universe in a nutshell
- Discussion of the SM.
    - SM particle content.
    - SM Lagrangian.
    - Open questions in the SM.
- BSM physics:
    - Direct searches.
    - Indirect searches.

About me

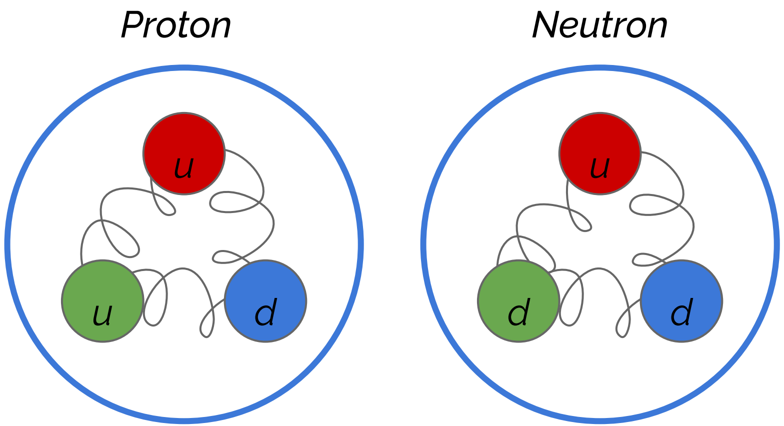
- Postdoc at Liverpool:
  - 4 years Masters at Liverpool (2012-2016)
  - 4 years PhD (2016-2020)
  - 2 years Postdoctoral researcher (2020-now)
- Research:
  - Worked on ATLAS experiment for 6 years
  - Supersymmetry and dark matter
  - Higgs measurement
  - Charged lepton flavour violation
  - Double Higgs production
  - AI for particle identification
  - Future Collider studies
- Interests:
  - Music, gaming, cycling, skiing, houseplants...

‘Matter’ in review

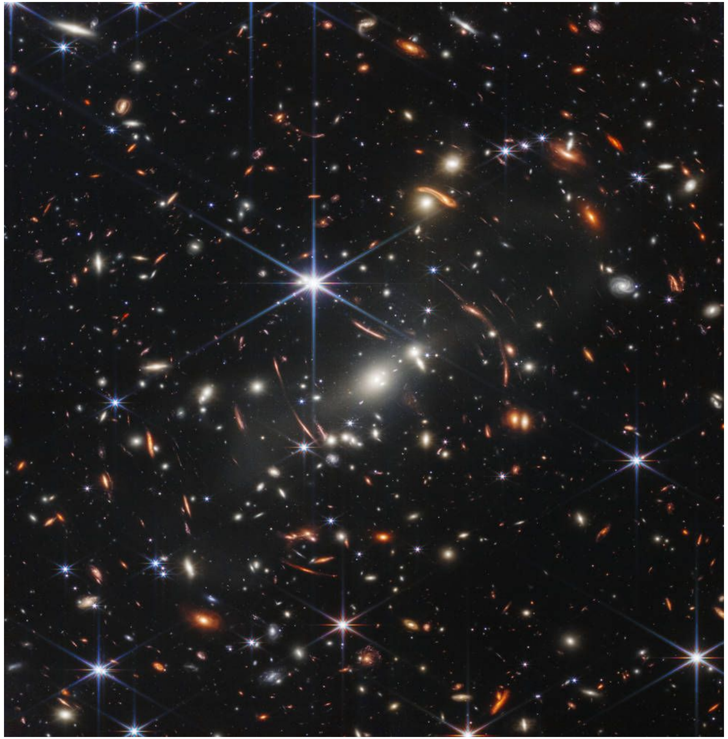
13.7 billion years of matter in 4 slides.

What is matter?

- All known matter is made up of the same building blocks: quarks, gluons & electrons:
    - Known as 'baryonic matter'
- All atoms are built up from these building blocks + Pauli exclusion principle
- From there, we get everything we *see* in the observable universe…

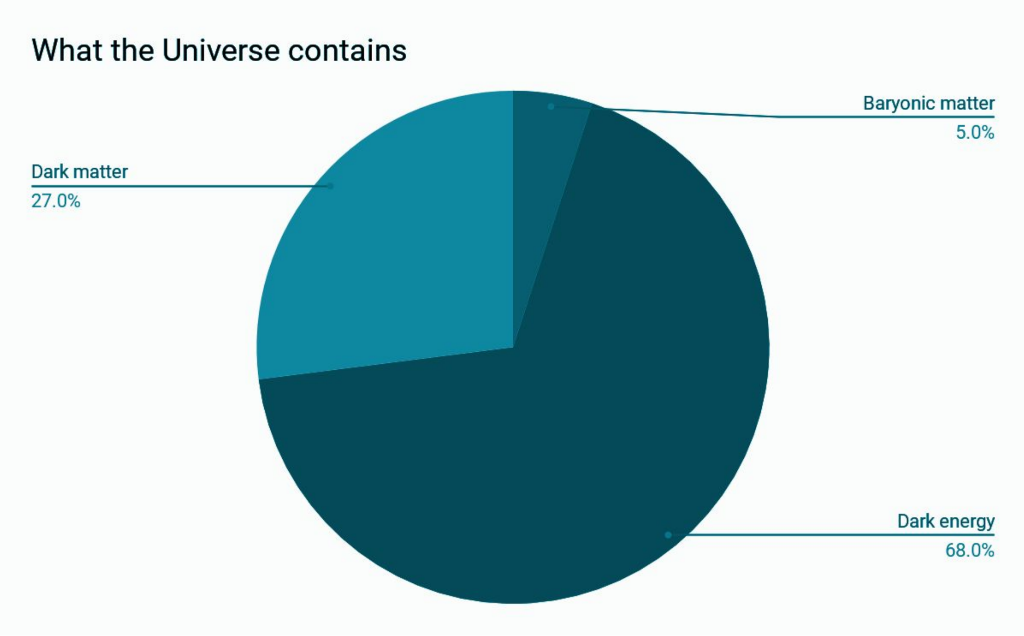


JWST



Beyond baryonic matter (1/2)

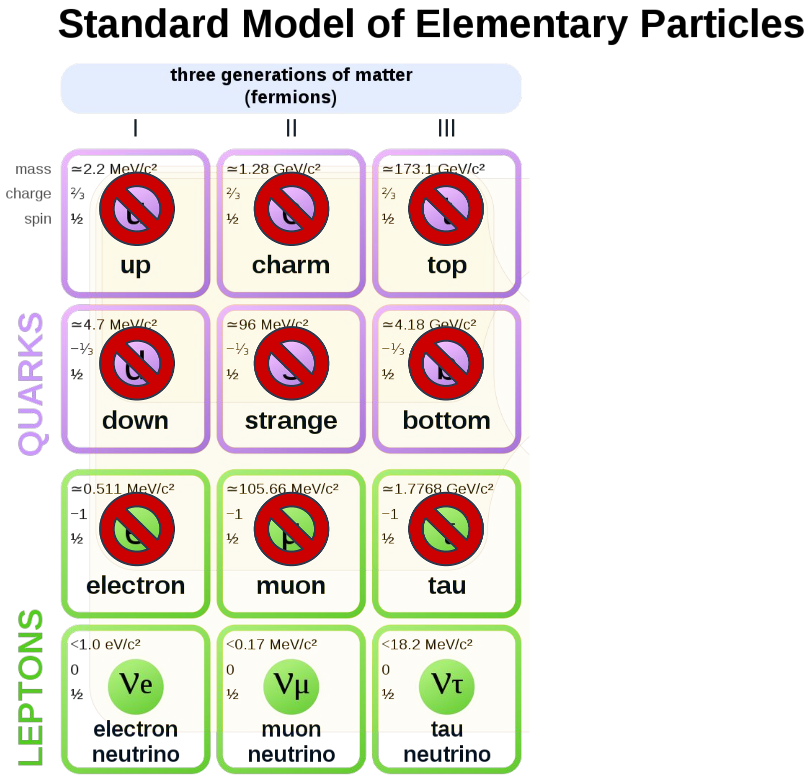
- Approximately 5% of the contents of the universe is baryonic matter.
  - Atoms, molecules → stars, galaxies.
- Around 27% is 'dark matter' (DM).
  - DM has mass, but doesn't interact with photons - "invisible"!
- Remaining 68% is known as dark energy (DE).
  - Little known about DE.
  - Thought to drive the accelerating expansion of the universe.
- **No particle candidate for DM in the SM!**



More info: Dark matter & dark energy

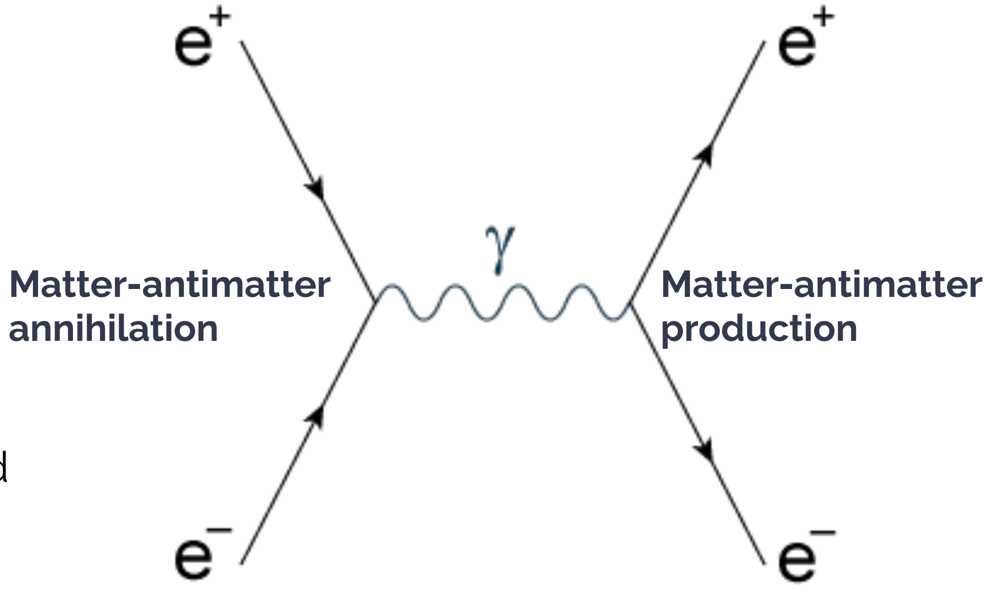
Beyond baryonic matter (2/2)

- We know that DM:
  - Electrically neutral → it does not interact with photons, hence 'dark'!
  - Has mass → we see its effect gravitationally.
  - Interacts very weakly with existing matter.
- Only neutrinos satisfy these conditions.
- They are too tiny to account for DM!
- No DM candidate in the SM.



Matter-antimatter asymmetry

- At the Big Bang, it is thought that matter and antimatter were created in equal quantities.
- When matter and antimatter interact, they annihilate into photons.
- However, today the Universe is filled with matter and the antimatter is nowhere to be seen!
- To create this imbalance, about 1 in 1,000,000,000 matter particles survived annihilation.
- **From where does this asymmetry arise?**



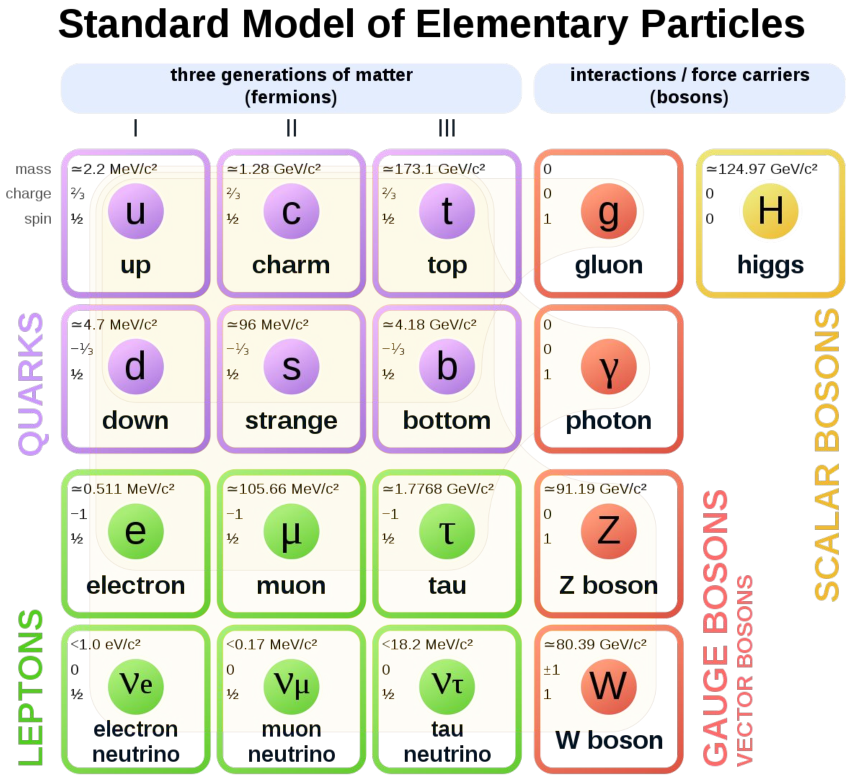
More info: Matter-antimatter asymmetry

The Standard Model

A recap and a deconstruction!

The SM: particle content

- The SM contains:
  - 12 matter particles:
    - 6 quarks
    - 6 leptons
  - 4 mediator particles:
    - Gluon: Strong/QCD
    - Photon: EM/QED
    - W/Z: Weak/EW
  - 1 Higgs boson.
- Is this *everything* the universe contains?



The SM: Lagrangian (1/5)

- The SM Lagrangian describes the entire SM!
  - Mediator particles
  - Interactions of matter particles
  - Matter particle coupling with Higgs
  - Mediator particle interaction with Higgs + Higgs self-interaction
  - Higgs field potential
- Let's discuss each piece of this...

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

The SM: Lagrangian (2/5)

- Describes photons, gluons and W/Z bosons.
  - 3 forces: Strong, weak, EM
- Where's gravity?
  - Most important interaction on large scales!
  - Matter tells space how to curve ⇔ space tells matter how to move.
  - Reconciling SM with general relativity one of the greatest open challenges in physics.
- Quantum theories of gravity:
  - E.g. string theory
  - Graviton is the proposed mediator particle of gravity

$$\mathcal{L} = \boxed{-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}}$$
$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$
$$+ \Psi_i y_{ij} \Psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

GR: $$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The SM: Lagrangian (3/5)

- Interaction of matter particles with mediators.
  - Why are the fermions organised into generations?
  - How does dark matter fit in?
  - Electroweak theory is chiral:
    - Fermions have “handedness”.
    - *RH neutrinos do not exist!*

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \Psi_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

The SM: Lagrangian (4/5)

- Coupling of Higgs with matter particles:
- Particles gain mass through interaction with the Higgs!
    - Why do the masses of the fermions span 11 orders of magnitude?
        - Top quark: ~172,500,000,000 eV
        - Neutrinos: < 1 eV
    - Neutrinos do not get their mass from the Higgs!
        - Chiral interaction means no RH neutrinos in SM.
        - How do neutrinos get their mass?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

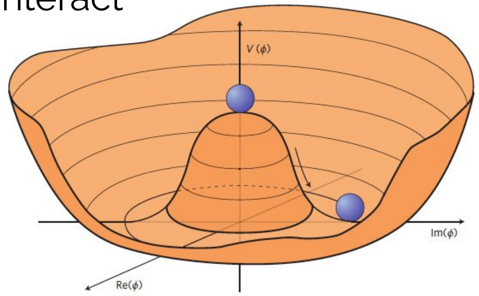
$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

$$+ \boxed{\psi_i y_{ij} \psi_j \phi} + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

The SM: Lagrangian (5/5)

- Higgs field & potential.
- Is there only one Higgs boson? If not, there would be multiple Higgs fields.
  - Different SM particles could get their mass from different Higgs fields.
- Shape of Higgs potential (below) is weird!
  - Minimum is not at zero…
  - Implies that pairs of Higgs bosons can interact



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \Psi_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

The SM: open questions

- So far, we have identified a number of open questions in the SM:
    - Where's gravity?
    - Where does dark matter fit in?
    - Where do neutrino masses come from?
    - Where does the matter-antimatter asymmetry come from?
- This is *not* an exhaustive list!

Physics beyond the SM

BSM: what could it look like, and how do we find it?

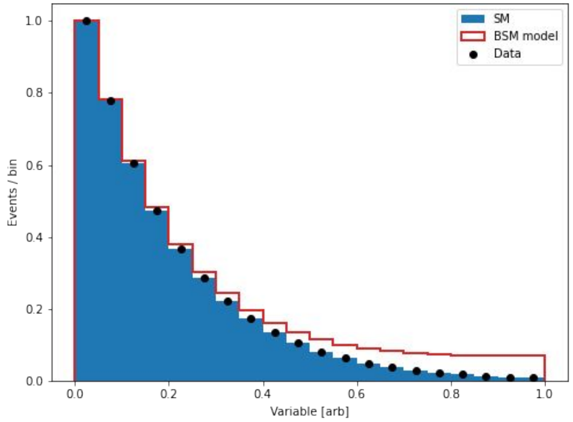
BSM physics: Overview

- We know the SM works very, very well!
  - SM successes span ~60 years!
  - New physics theories aim to extend the SM to answer open question(s).
- BSM searches come in many flavours!
  - Direct searches:
    - Make prediction of BSM physics, test hypothesis, accept or reject BSM prediction.
  - Indirect searches:
    - Measure SM predictions and look for discrepancy. If SM fails to describe measurement (within statistical and systematic constraints), could be new physics?

BSM physics: How to find it?

Direct searches

1. Design a model which can explain the SM and some BSM phenomena, e.g. dark matter
2. Design a data analysis which can study the predictions of the model
3. Decide if the model is a good description of nature or not…



Indirect searches

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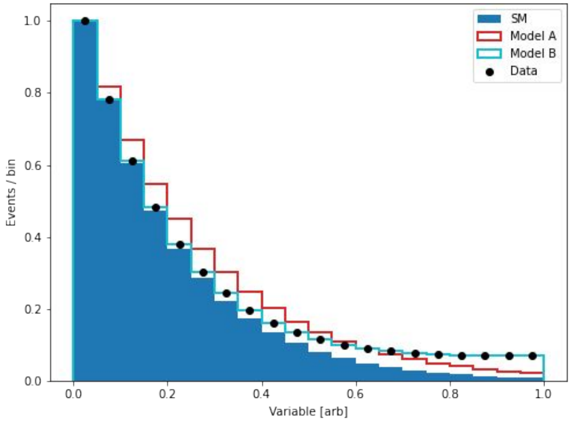
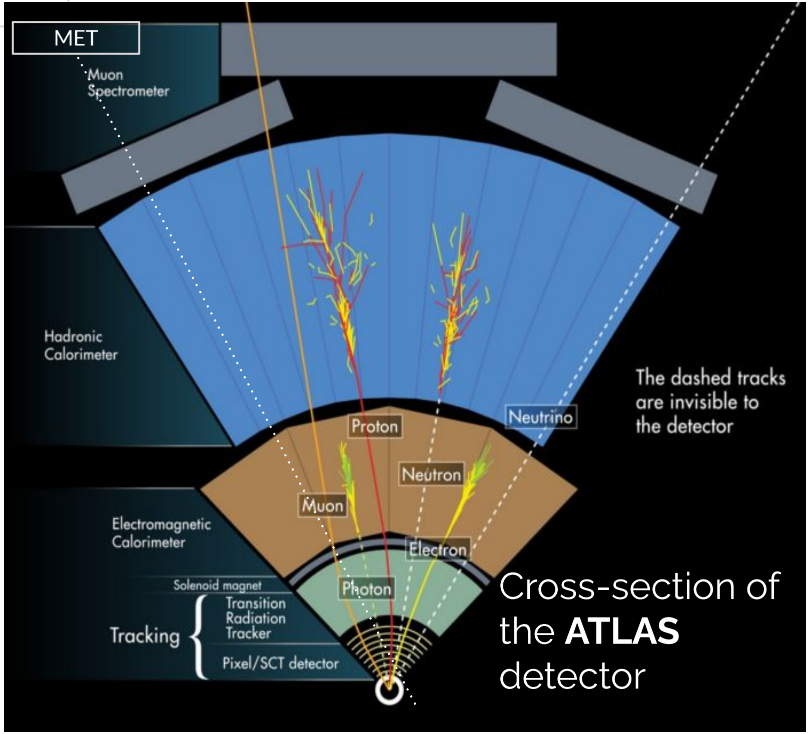


BSM physics: Examples

- BSM theories predict the existence of new particles and interactions.
  - E.g. provides a DM candidate.
  - Most are unstable and decay quickly. Many are very massive!
- Examples of BSM models we can study:
  - Supersymmetry (SUSY), Heavy gauge bosons (HGB), Microscopic black holes (QBH), Leptoquarks (LQ), Extended Higgs sectors (2HDM)
- Examples of indirect searches:
  - Measure rates of SM particle production e.g. proportion of Higgs bosons which decay ‘invisibly’, measure anomalous muon magnetic moment (g-2)

BSM physics: Detection

- With the exception of neutrinos, all SM particles leave some 'trace' in our detectors.
  - Tracks = spatial information
  - Calorimetry = energy information
- Many particles predicted by BSM theories leave distinct 'signatures' in our detectors!
- We can infer their existence through signatures such as missing transverse energy (MET) or a displaced decay vertex.



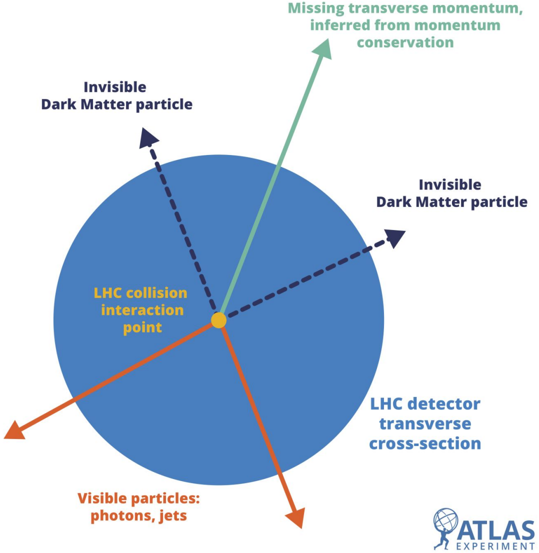
Cross-section of the **ATLAS** detector

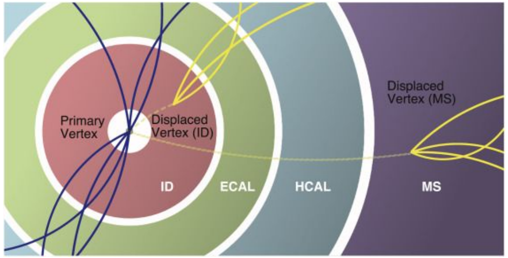
BSM physics: Example detector signatures

- MET is just conservation of momentum:
  - Imagine an ice skater throwing a heavy ball away from them.
  - They will recoil against the ball, sliding backwards.

  - In BSM physics, the ball is invisible - We see the recoil, but not the object that caused the recoil!
- Some BSM particles ‘live’ a relatively long time before decaying into particles we can see (long-lived particles).
  - When we reconstruct where the particles decayed, we see that they have a *displaced decay vertex*.

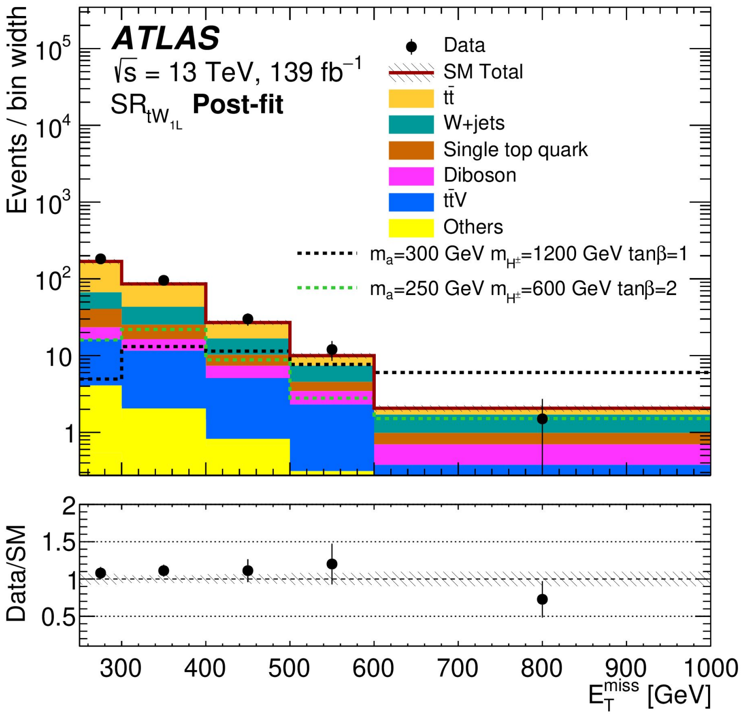
http://cds.cern.ch/record/2665178





BSM physics: Example analysis

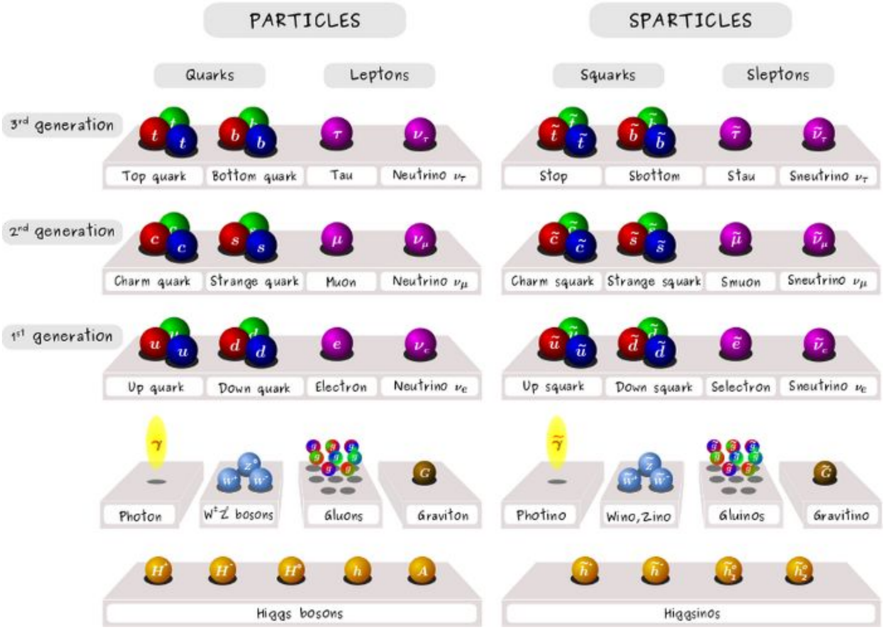
- The colourful histograms are the SM predictions after our analysis.
  - Different SM processes contribute differently depending upon the BSM search.
- The dashed line shows what the simulated BSM physics process should look like.
- The black points show the data we measured!
  - Does this look compatible with the SM or the BSM physics?



[ArXiv: 2011.09308](https://arxiv.org/abs/2011.09308)

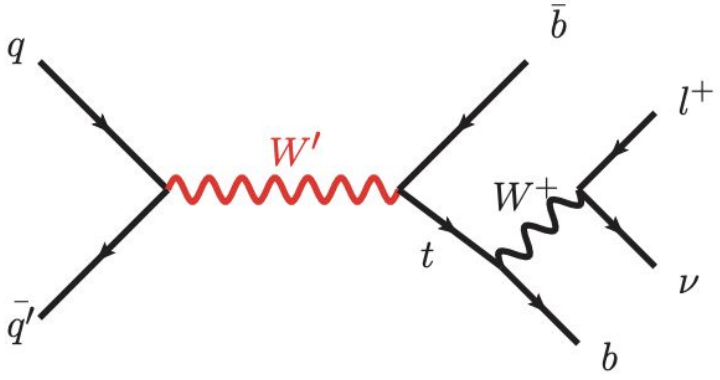
BSM physics: SUSY

- Supersymmetry (SUSY) is an excellent example of a BSM extension to the SM.
- It predicts partner particles for all of the SM particles, named ‘sparticles’.
- SUSY is studied as:
    - It provides a DM candidate
    - Explains the Higgs boson mass
    - Can explain the muon g-2 anomaly
    - Gauge coupling for GUT



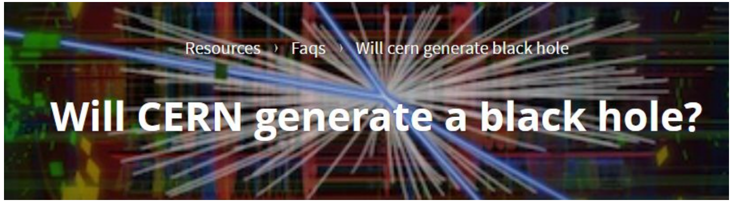
BSM physics: Heavy gauge bosons

- Many BSM models predict the existence of heavy W' and Z' bosons.
    - Partners to the SM W and Z.
- LHC could discover such particles upto 50x heavier than the SM particles.
- Can explain why neutrino masses are so small!
- The existence of such a particle can imply the existence of extra dimensions!

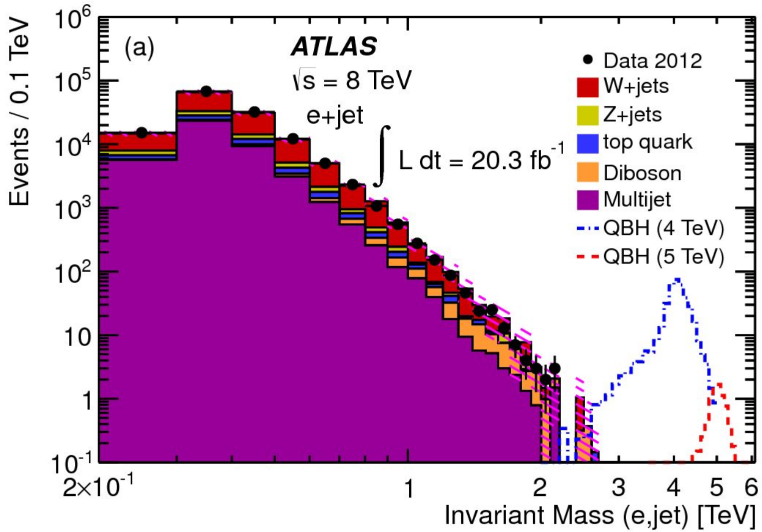


BSM physics: Microscopic black holes

(NO!)



- Numerous BSM theories predict we could produce microscopic black holes at the LHC.
- QBHs distinct from cosmological black holes → CERN is not going to end the world!



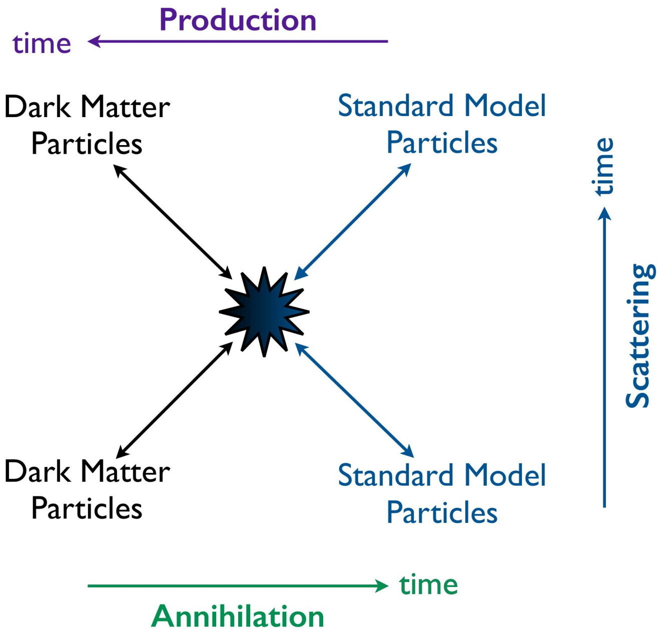
BSM physics: Indirect searches

- By measuring SM predictions precisely, we could find hints of BSM physics!
  - By measuring many SM predictions, we can get hints on where New Physics exists.
- Examples:
  - DM detection experiments
  - Higgs portal
  - Muon g-2
  - Higgs self-coupling

BSM physics: DM detection (1/2)

There are three ways we can detect DM!

1. Annihilation
2. Scattering
3. Production

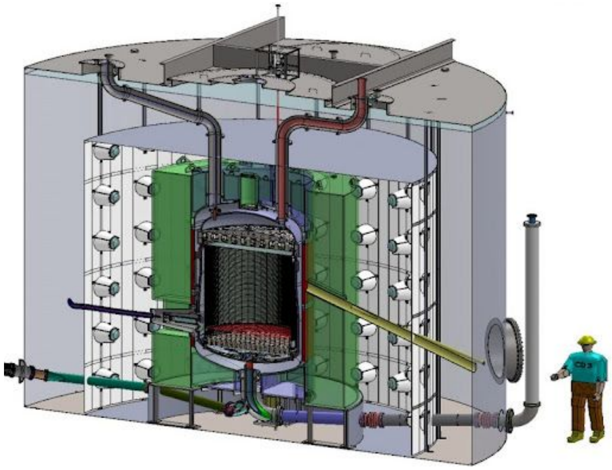


BSM physics: DM detection (2/2)

Scattering: DM comes in and we see a nucleus recoil against it. Nucleus emits photon.

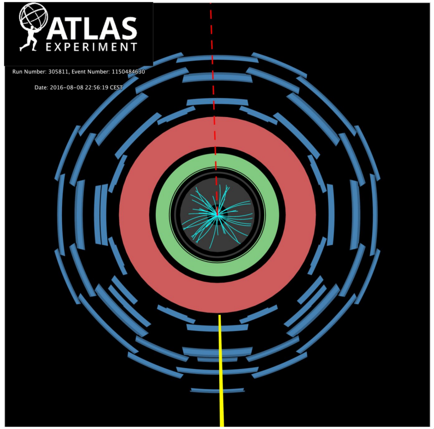
Annihilation: DM particles annihilate to photons in space. Measure ultra high-energy photons arriving at detector.

Production: DM is produced through proton-proton collisions. Measure excess in MET distribution.



LZ experiment

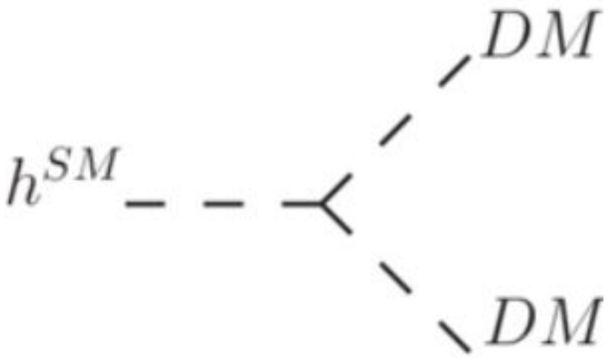
AMS experiment



ATLAS experiment

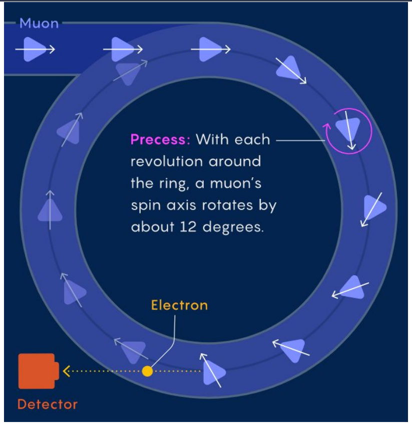
BSM physics: Higgs portal

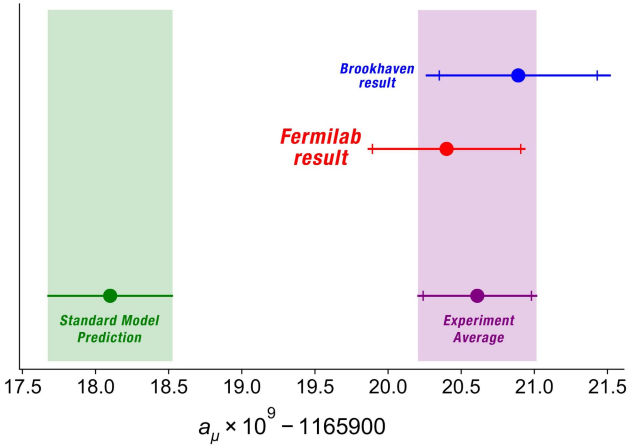
- SM predicts that the Higgs boson decays “invisibly” around 1/1000 times.
- We have measured this property and found it to be < ~1/10 times.
    - Still lots of room for possible discovery!
- Some new physics coupling to the Higgs boson might exist and we just haven’t yet discovered it!



BSM physics: Muon g-2

- Muons are like a tiny dipole magnet.
    - When in a strong magnetic field, they precess like a spinning top.
- The muons decay in-flight, from which we can measure the muon magnetic moment.
    - a = (g-2) / 2
- Most precisely-predicted value in science.
    - Experiment and prediction differ at the 11th decimal place!
    - <u>Any BSM physics which couples to muons will alter a.</u>
- First results published in April 2021 show tension with the SM!

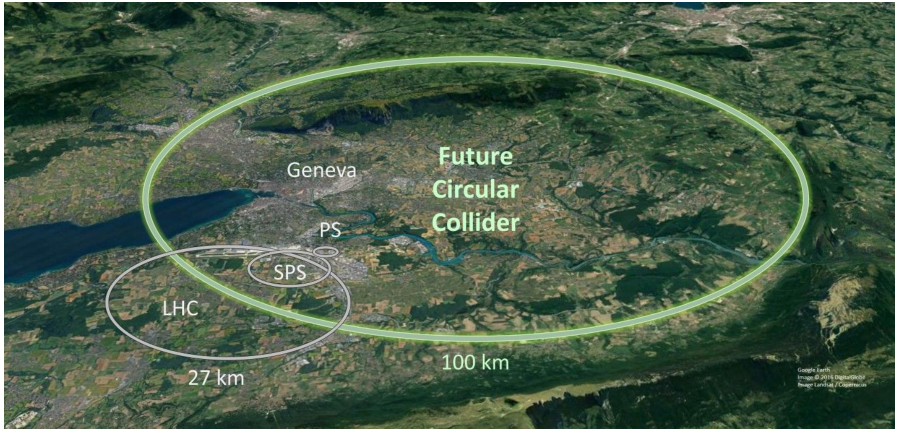




The future of BSM physics

BSM physics: the next 50-100 years

- The timescales of HEP experiments are very, very long!
- LHC has another ~5 years of running.
- HL-LHC will have ~15 years of running.
- FCC has two phases (ee & hh), extending long into this century!



- ~Now — 2020-2025 — **FCC feasibility Study**
- HL-LHC starts, you finish your BSc — 2027- 2028 — **Update of the European Strategy for Particle Physics**
- 2030-2031 — **End of detailed studies. Presentation to CERN Council for decision**
- You finish your PhD — 2032- 2040 — **Civil engineering works**
- We find new physics? — 2041 – 2043 — **Start operation of FCC-ee collider**
- I retire happy — 2060 — **Start operation of FCC-hh collider**

Conclusion

Summary

- SM excellently predicts physics measurements for the past 60 years:
  - However, it is incomplete: gravity, DM, neutrino masses…
- Can use direct and indirect searches to find hints of new physics!
  - Direct searches: SUSY, HGB, microscopic black holes…
  - Indirect searches: DM detection, Higgs portal, muon g-2…
- LHC & its successors are key to understanding new physics:
  - HL-LHC & FCC will provide access to highest energies.

Any questions?

Thanks for listening!

Gauge coupling unification