Physics beyond the Standard Model

Dr. Matt Sullivan

Liverpool-CERN Summer School 2021

16/08/2021

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)
    - Took a job as a postdoc researcher last year!
- Research:
    - Worked on ATLAS experiment for 5 years
    - Supersymmetry and dark matter
    - Higgs measurement
    - Charged lepton flavour violation
    - Double Higgs production
- Interests:
    - Music, cycling, skiing, gaming, houseplants...

The Universe in review

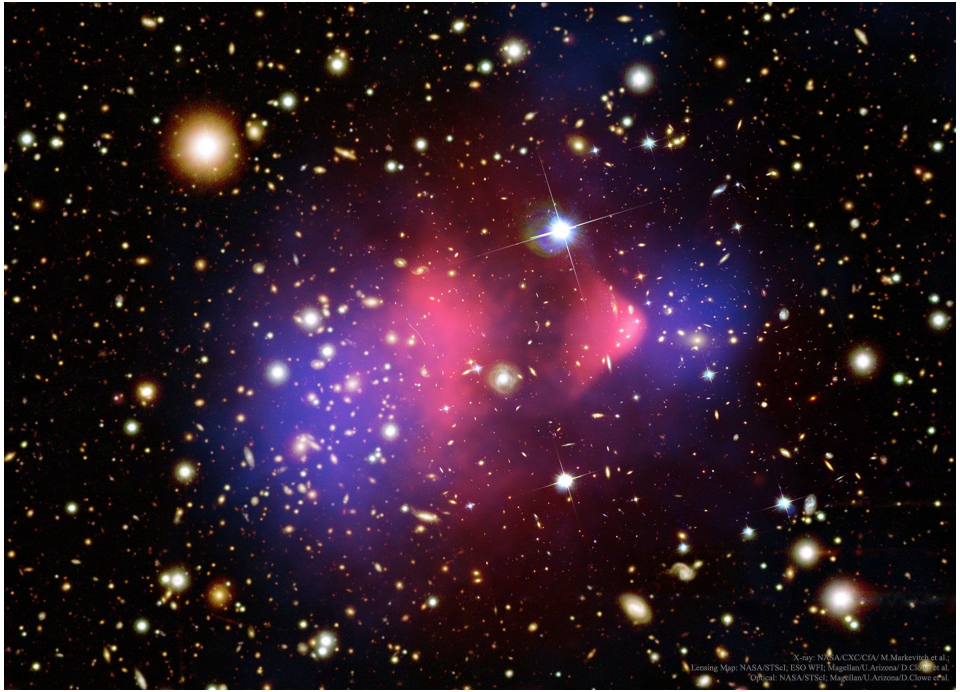
13.7 billion years in 5 slides.

Beyond baryonic matter (1/4)

- There are around 10000 galaxies in the Hubble Ultra Deep Field image shown on the right!
- Everything we see in this image is visible matter, named 'baryonic' matter.
- Cosmological observations tell us there is more to the Universe than just baryonic matter...

Beyond baryonic matter (2/4)

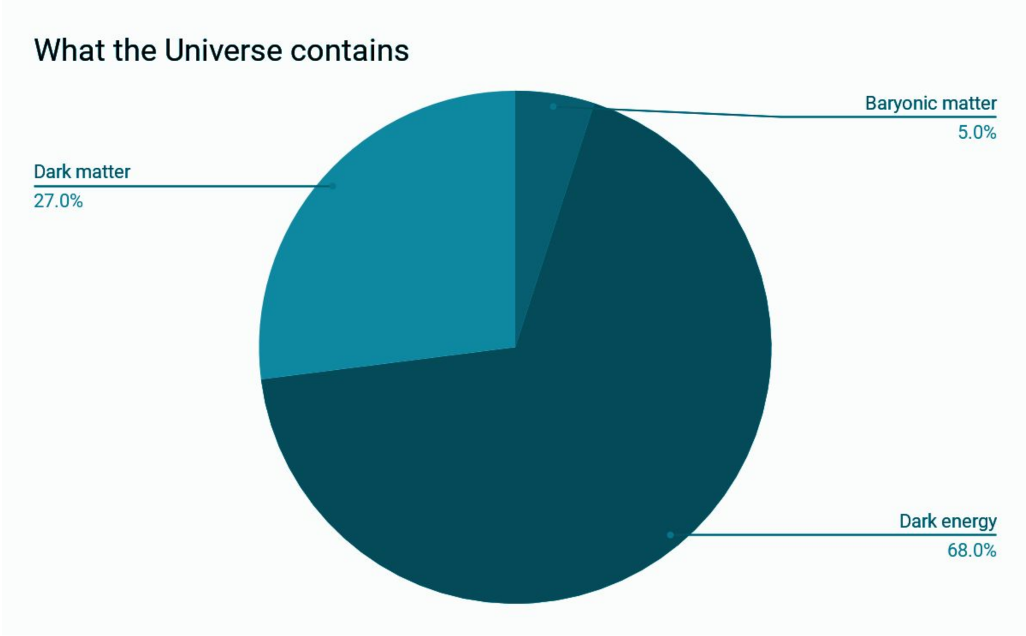
- The Bullet Cluster (right), is the result of two clusters of galaxies passing through each other.
- The gas from the two clusters interacts and heats up. This can be seen in pink.
- The mass distribution calculated (through gravitational lensing) can be seen in blue.
- **What is all of this invisible matter on the periphery?**



More info: Bullet Cluster

Beyond baryonic matter (3/4)

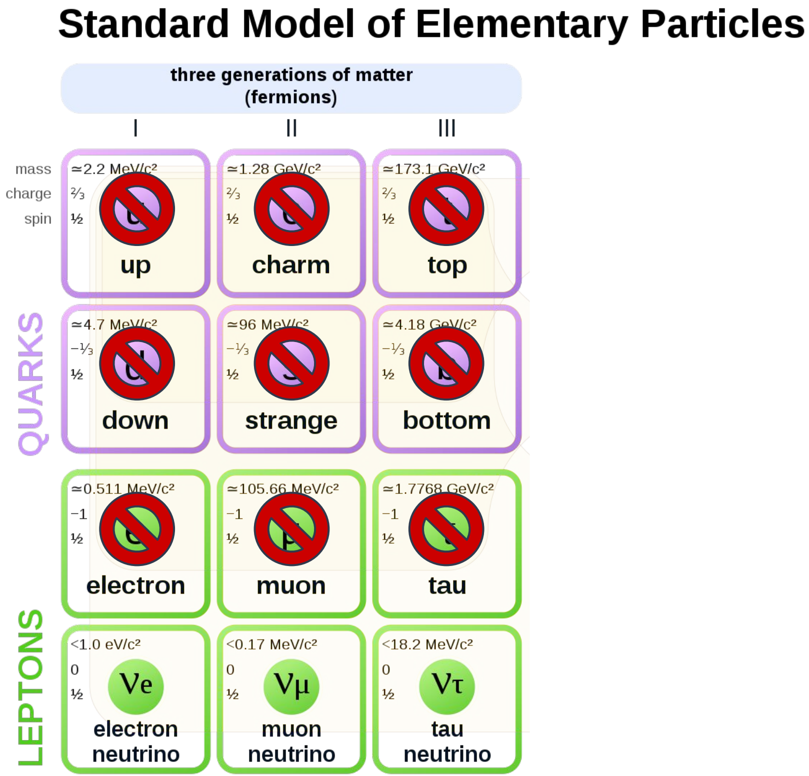
- Approximately 5% of the contents of the universe is baryonic matter.
  - Atoms, molecules → stars, galaxies.
- Around 27% is 'dark matter' (DM).
  - DM has mass, but doesn't interact with photons - "invisible"!
- Remaining 68% is known as dark energy (DE).
  - Little known about DE.
  - Thought to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



More info: Dark matter & dark energy

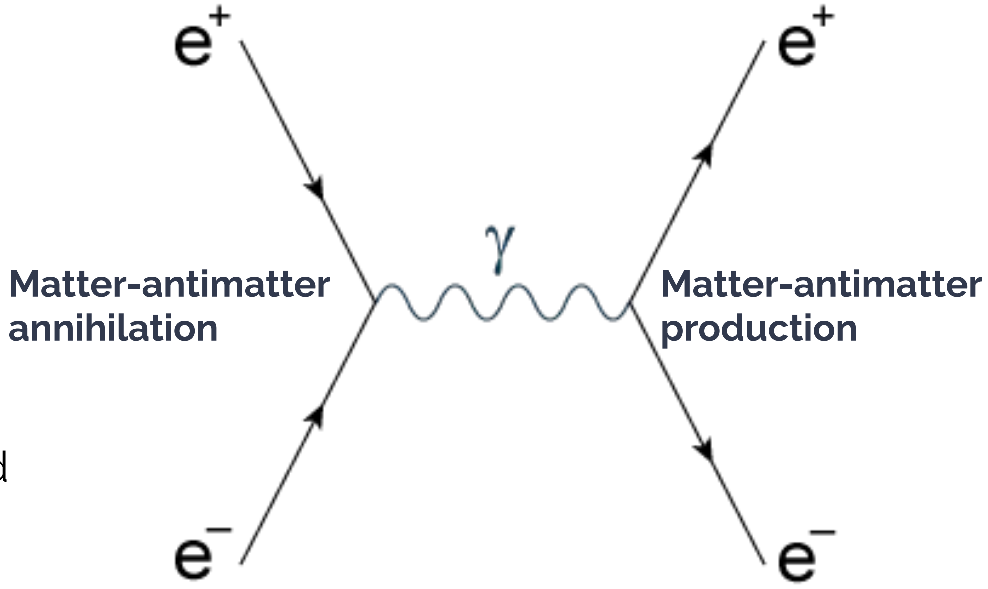
Beyond baryonic matter (4/4)

- 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?**



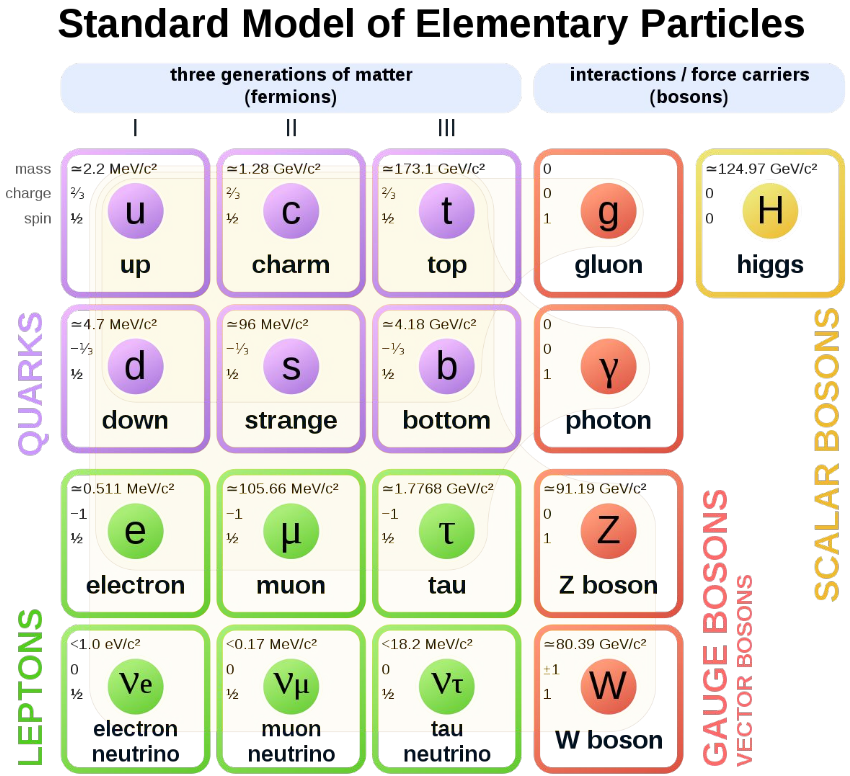
More info: Matter-antimatter asymmetry

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 <u>*everything*</u> the universe contains?



The SM: Lagrangian (1/4)

- 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 (2/4)

- 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

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

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 (3/4)

- 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!*

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

The SM: Lagrangian (4/4)

- 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?

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

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 <u>*not*</u> 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: Direct searches

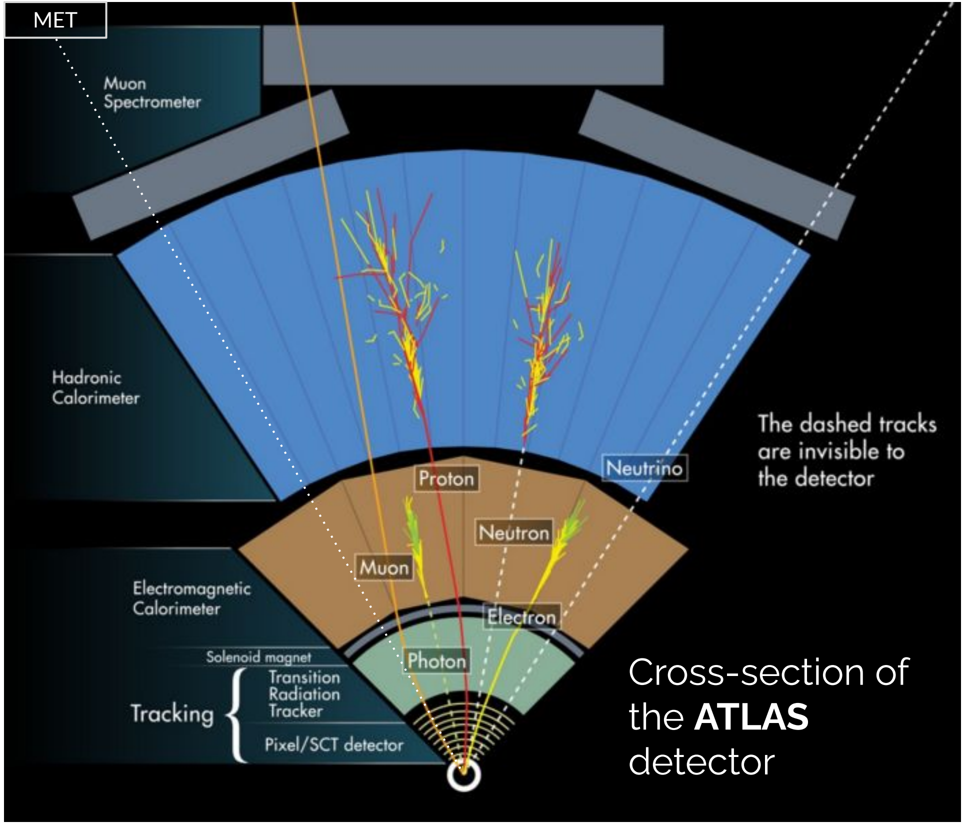
- BSM theories predict the existence of new particles and interactions.
  - E.g. provides a DM candidate.
  - Most are unstable and decay quickly. Many are very massive!
- Examples of BSM theories:
  - Supersymmetry (SUSY)
  - Heavy gauge bosons (HGB)
  - Microscopic black holes (QBH)
  - Leptoquarks (LQ)
  - Extended Higgs sectors (2HDM)

BSM physics: Analysis overview

1. Make a prediction based on the SM:
    a. If a given BSM theory exists, how many times do we expect to see particles with momentum above X.
    b. If we collide X protons, what percentage of the time do we expect to see a Higgs boson decay invisibly?
2. We design an analysis to measure the prediction:
    a. We can design selection criteria, e.g. require all particles have momentum above X.
    b. We can use AI to do this for us, e.g. neural networks.
3. We compare the predictions with the data we collect in our experiment.
    a. If the data is compatible with the SM prediction, we have found nothing new!
    b. If there is a discrepancy, we may have found BSM physics!

BSM physics: Experimental overview

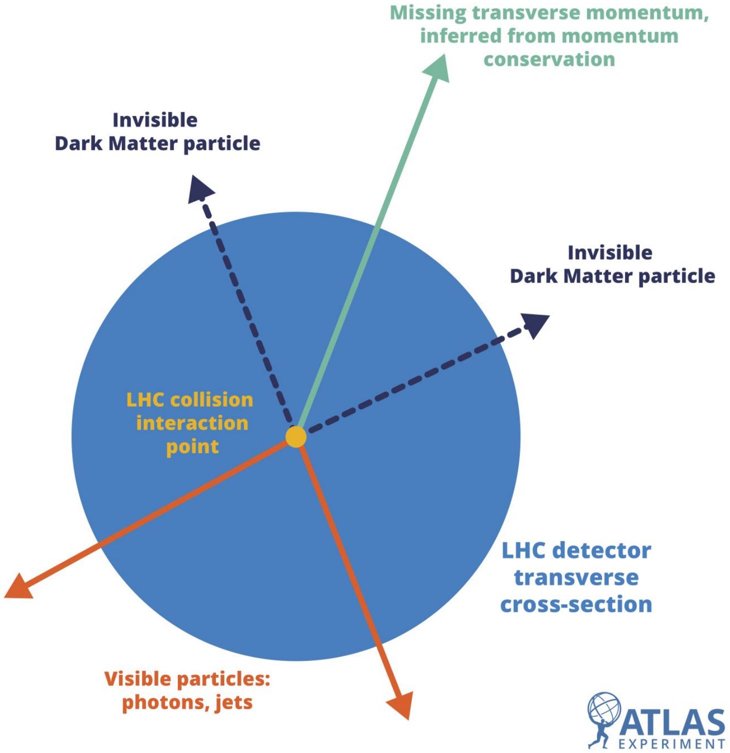
- With the exception of neutrinos, all SM particles leave some ‘trace’ in our detectors.
    - Tracks = spatial information
    - Calorimetry = energy information
- Many particles predicted by BSM theories escape our detector without leaving track hits or calorimeter deposits.
- We can infer their existence through missing transverse energy (MET).



Cross-section of the **ATLAS** detector

BSM physics: What is MET?

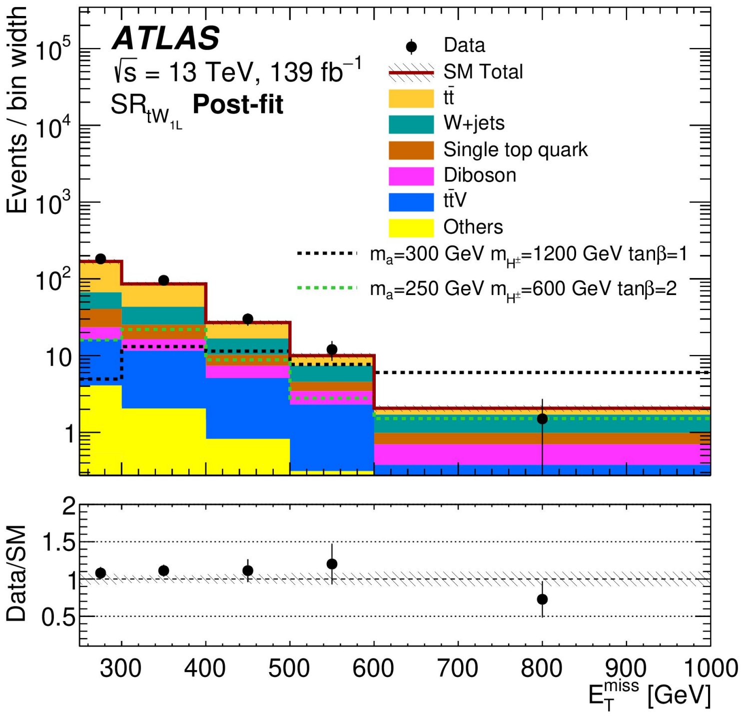
- <u>Conservation of momentum</u>!
- An example:
  - Imagine an ice skater throwing a heavy ball away from them.
  - They will recoil against the ball, sliding backwards.
- In BSM physics, the ball is invisible.
  - We see the recoil, but not the object that caused the recoil!



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

BSM physics: Example analysis

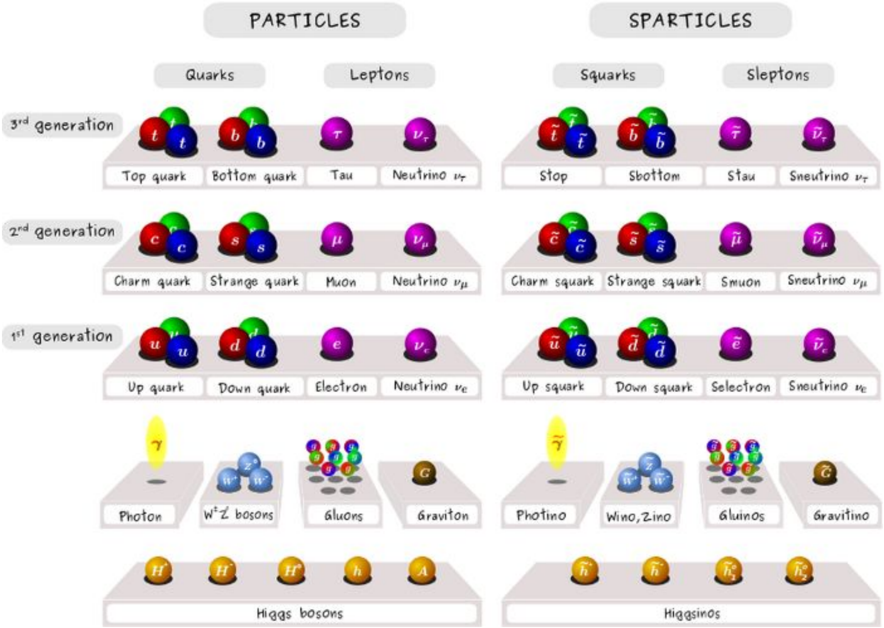
- The colourful histograms are the SM predictions after our analysis.
  - Different SM processes contribute differently depending upon the BSM search.
- The dashed line shows what the simulated BSM physics process should look like.
- The black points show the data we measured!
  - Does this look compatible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



ArXiv: 2011.09308

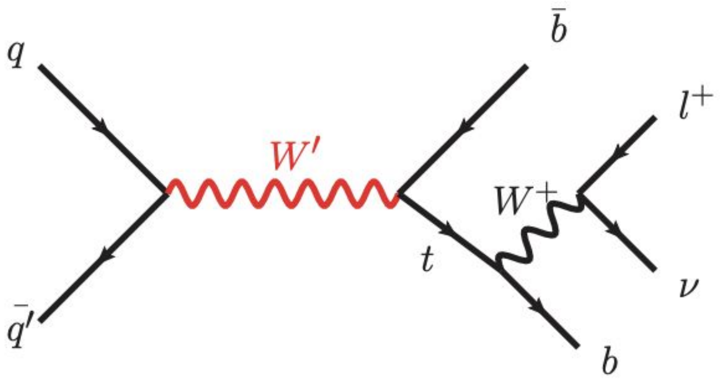
BSM physics: SUSY

- 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!



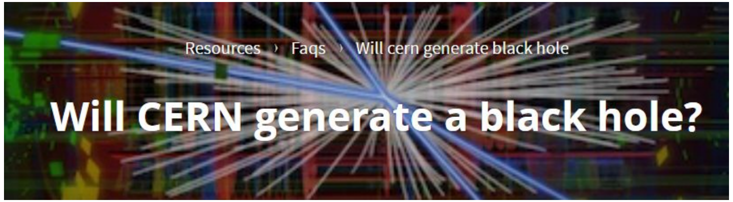
BSM physics: Microscopic black holes

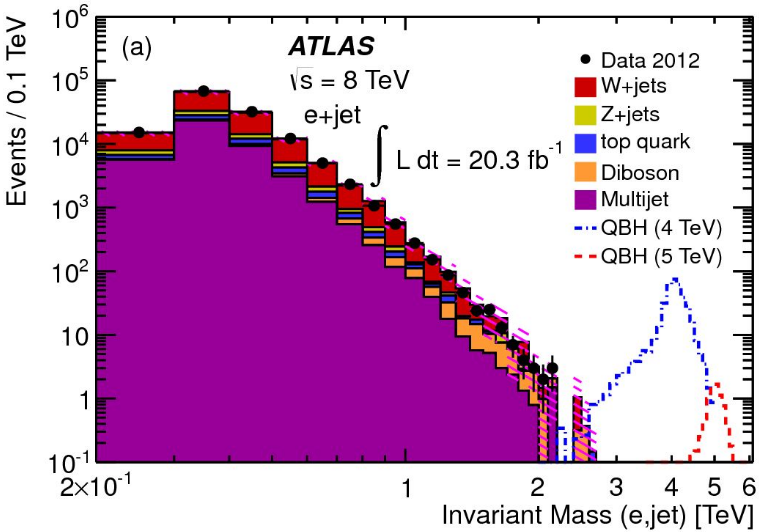

Could The Large Hadron Collider Make An Earth-Killing Black Hole?

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

This article is more than 5 years old.

(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!

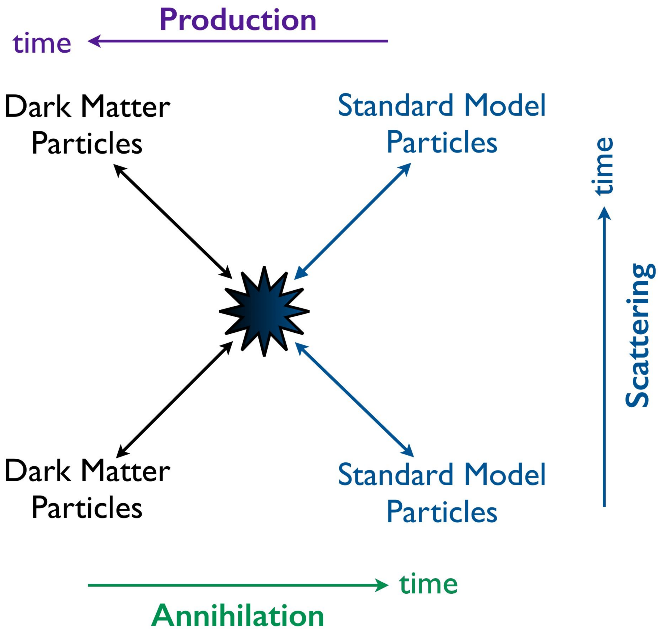
BSM physics: Indirect searches

- 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

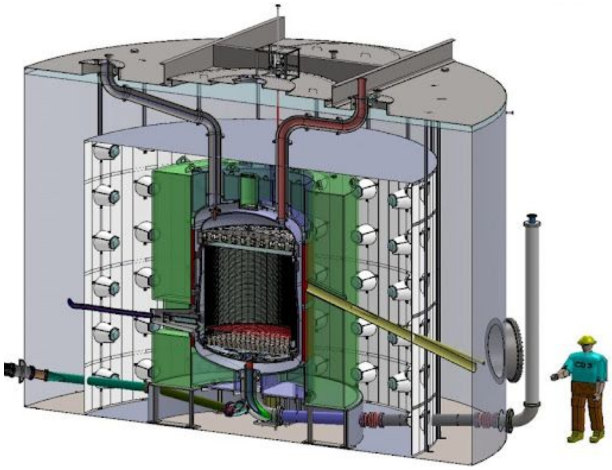


BSM physics: DM detection (2/2)

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

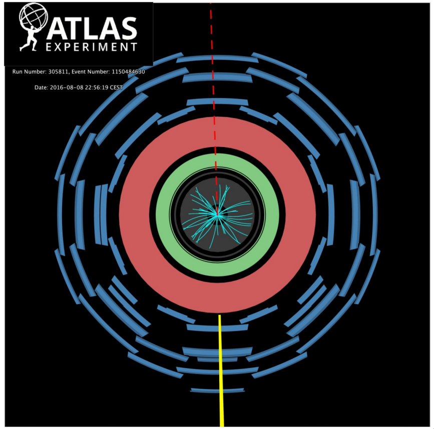
Annihilation: DM particles annihilate to photons in space. Measure ultra high-energy photons arriving at detector.

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



LZ experiment

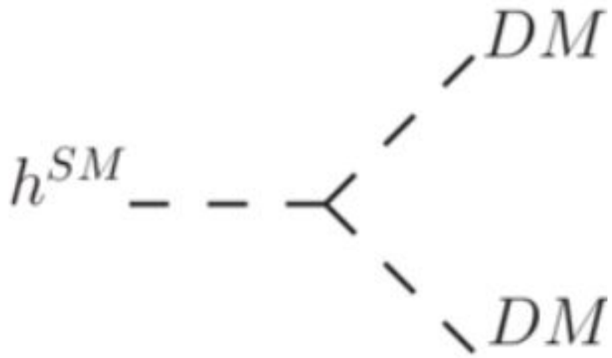
AMS experiment



ATLAS experiment

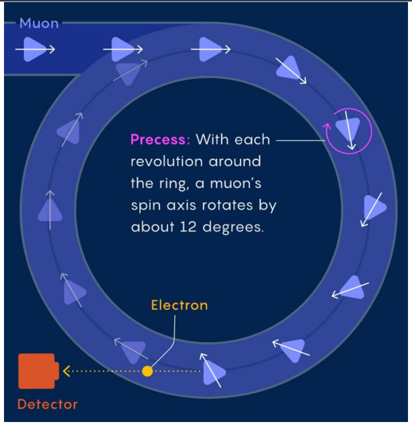
BSM physics: Higgs portal

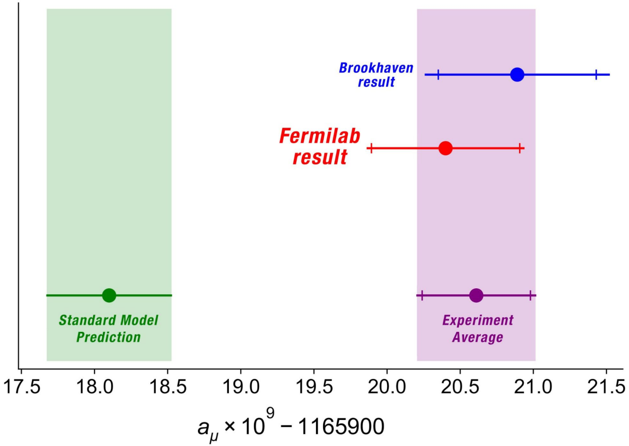
- SM predicts that the Higgs boson decays “invisibly” around 1/1000 times.
- We have measured this property and found it to be < 1/5.
- Some new physics coupling to the Higgs boson might exist and we just haven’t yet discovered it!



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!





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.
  - ILC & CLIC will provide extremely high precision measurements of SM quantities.

Any questions?

Thanks for listening!

Gauge coupling unification