Introduction to Particle Physics

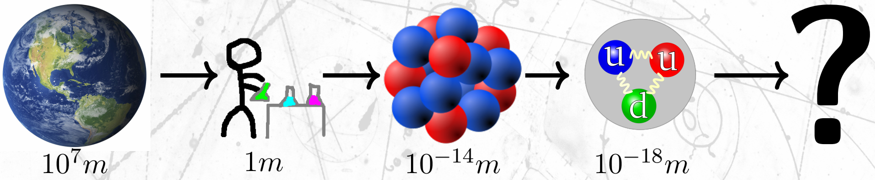
Updated by: Kyle Cormier,
with Robert Les having already done the real work

Liverpool@CERN 2024

What is Experimental High Energy Physics?

We try to understand the universe at the smallest scale

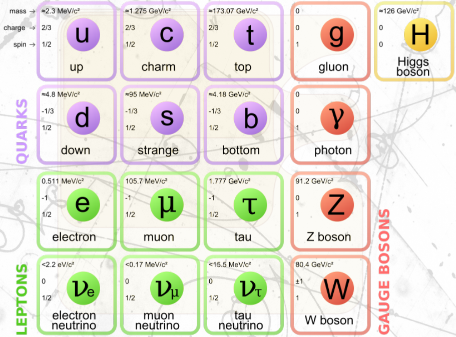
- What are fundamental constitutions of nature?
  - What are their properties?
  - How do they interact?
- Smaller scales requires higher energy (density)!
- Also describes the early universe



The Standard Model

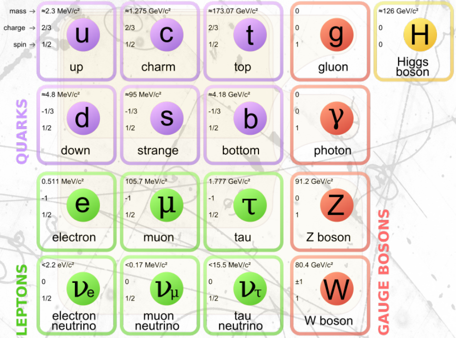
- After a culmination of over a century of great minds, hard work, brilliant insights, clever experiments ...
  - Fermi, Dirac, Feynman, Polyakov, Wu, Yang, Weinberg, ...
  - International Collaborations, research institutes ...

  we have a sort of "periodic table" of fundamental (as far as we know) particles
- These are the building blocks of almost all of physics! (minus gravitation)



The Standard Model

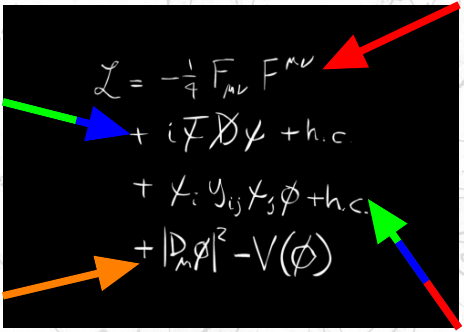
- The quarks and leptons make up pretty much all the matter content we know at a macroscopic level
  - The up+down quark and electron (and gluon) is most of the atom
- The gauge bosons described the fundamental forces between these
  - The photon mediates the electromagnetic force
  - gluons describe the forces which bind atoms together
  - Ws are responsible for nuclear decays, (and the Z tags along)
- The Higgs boson gives mass to the other particles

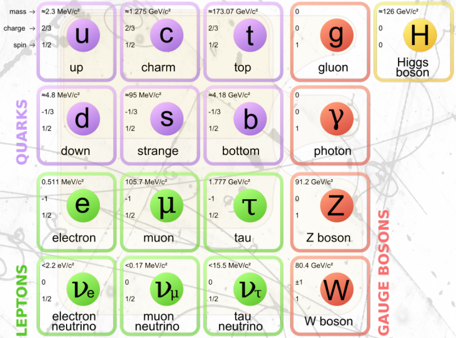


It's is as simple as

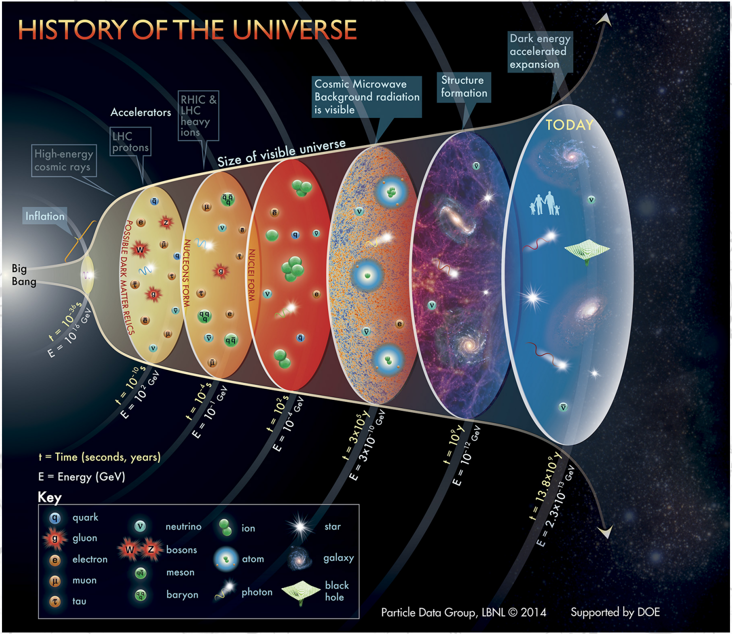
$$
\begin{gathered}
\mathcal{L}_{\mathrm{StandardModel}} = \\
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \\
\bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - \\
1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
(\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \\
\tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + \\
m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
\tfrac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0].
\end{gathered}
$$

It’s is as simple as

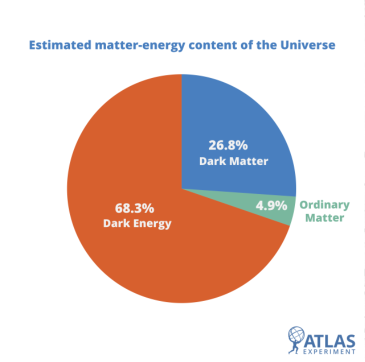


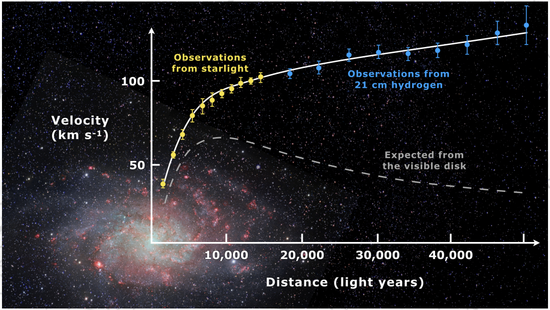


Cosmology


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

Beyond the Standard Model





Evidence from cosmology shows there is more matter/energy than what the Standard Model predicts:

- Less than 5% of the 'energy budget' of the universe is in 'ordinary' matter that we understand pretty well
- From rotation of galaxies see more "matter" than what is visible

It's not enough!

- Neutrino Masses
  - Not included in the Standard Model
- Hierarchy of Particle Masses
  - Why are some particles $> 10^9$ times heavier than others?
- Matter/anti-matter asymmetry
  - Why is there more matter than anti-matter?
- Dark Matter
  - Are there more particles than those in the Standard Model?

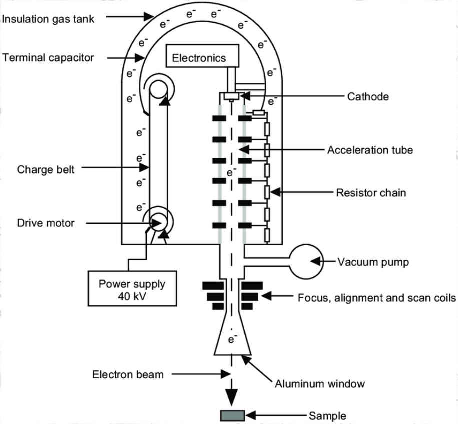
Is there anything beyond the Standard Model?

- Dark Energy
  - We have nothing direct to say about it
- Quantum Gravity
  - No unified theory of Gravity+SM

Particle Accelerator History: Electrostatic Accelerators

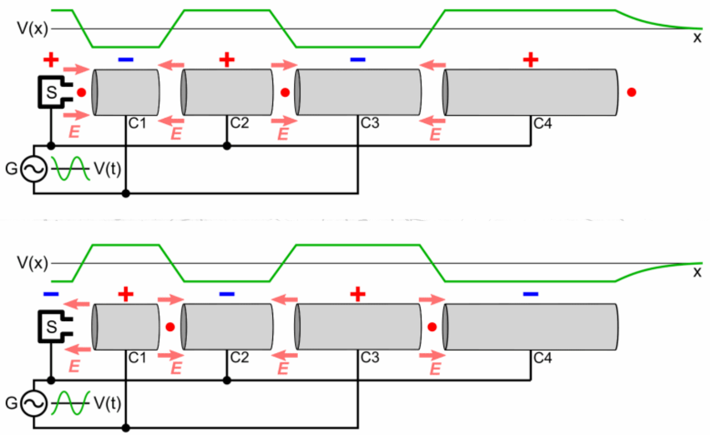
Simplest particle accelerator was the Van Der Graff generator (1929):

- Accumulates charge on a metallic surface with a moving belt
- 20-100 keV in energy



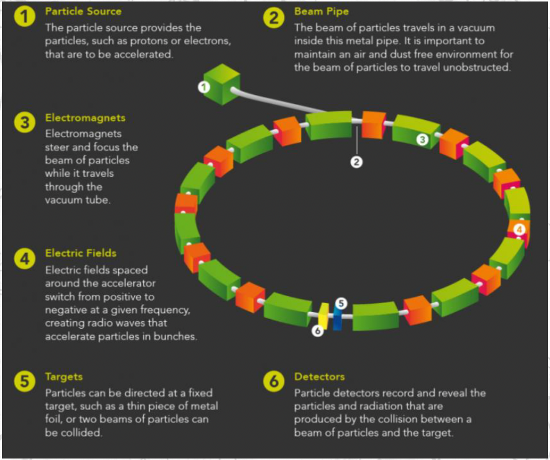
Next step up was the development of the linear accelerator (linac)

- Quickly switch the charge of electric field to cause acceleration between cavities



Particle Accelerator History: Circular Accelerators

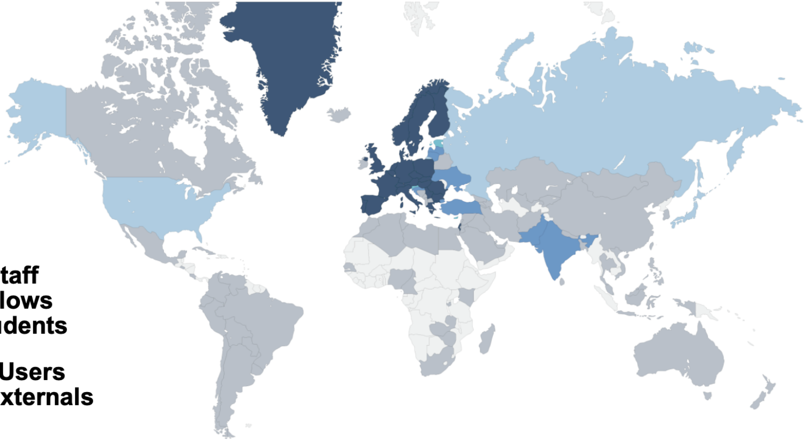
While linacs are still used today, they get very long very quickly



Synchrotron:

- Bend particles with a magnetic field in a circular path, moving through several accelerator cavities
- Can circulate the particles many times to reach higher energies

CERN



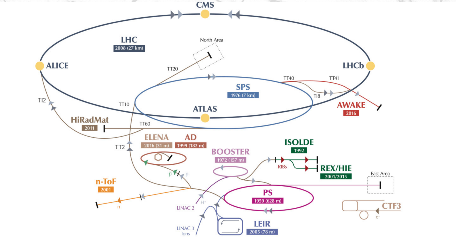
2,600 Staff
800 Fellows
550 Students

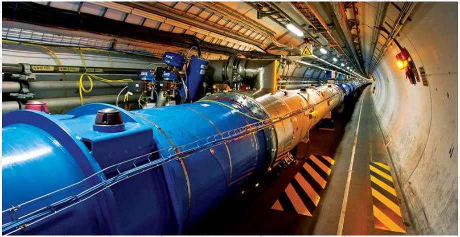
15,000 Users
2,000 Externals

The Large Hadron Collider

The most powerful accelerator ever built

- Accelerates two beams of protons (or lead ions) to almost the speed of light
- 27km ring, 100m underground with 9000+ magnets
- Beams collide at 4 locations about 32 million times a second





View from the sky

Detectors at the LHC

ATLAS

- "General purpose detector":
- For scale: 46m long, 25m diameter, and 7000 tones
- For scale: 5000+ contributors across 40+ countries

CMS

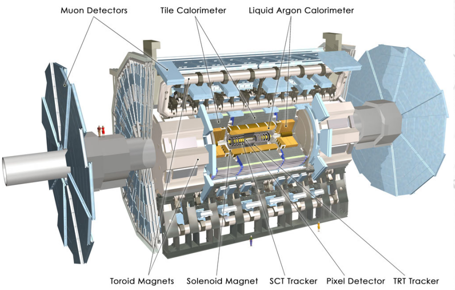
- General purpose detector

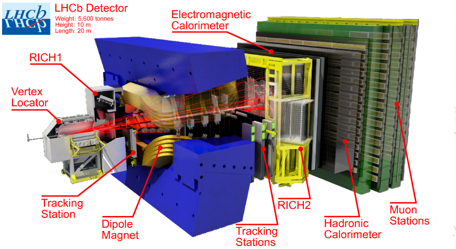
LHCb

- Forward-designed detector
- Physics goals to study "flavour sector" and relation to matter-antimatter asymmetry

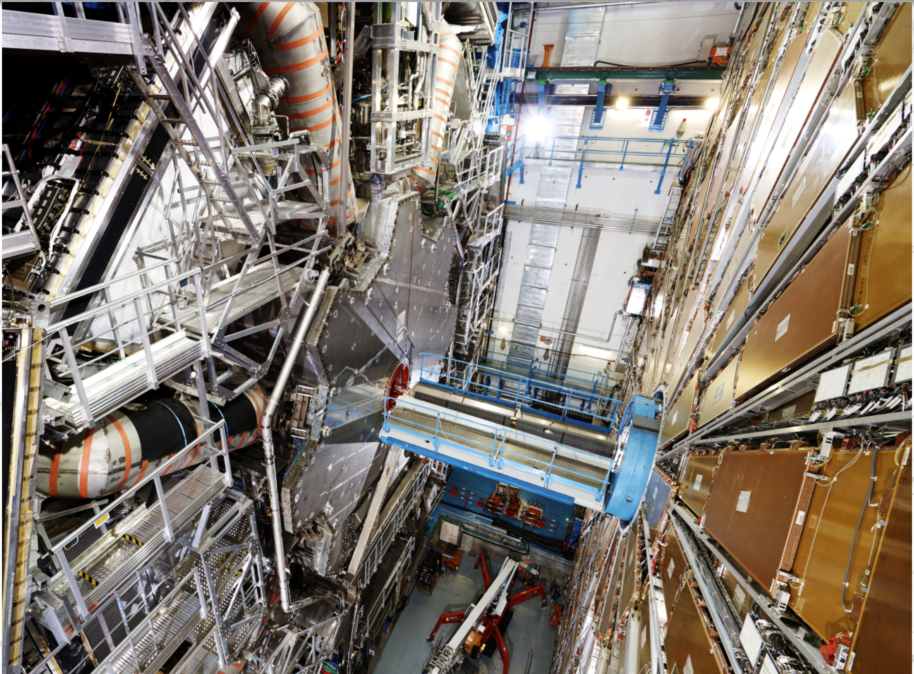
ALICE

- Primarily heavy-ion focused detector
- Designed to study very hot, extreme density matter: quark-gluon plasma

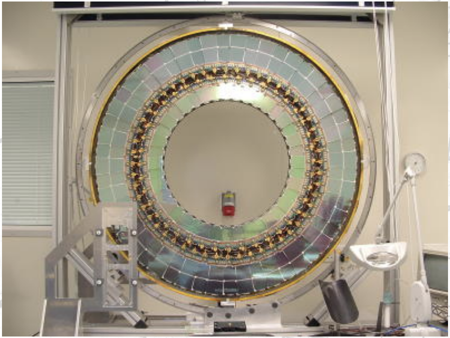


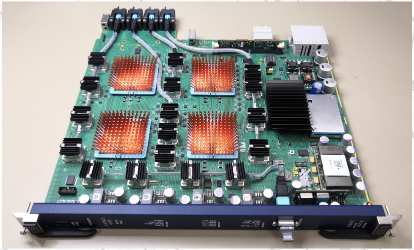


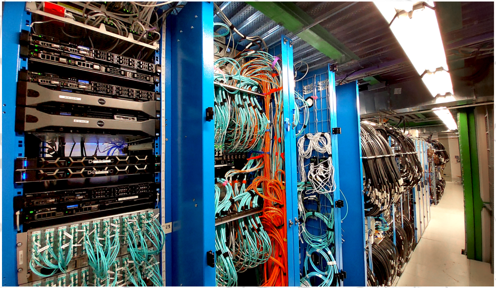
ATLAS detector



ATLAS Hardware

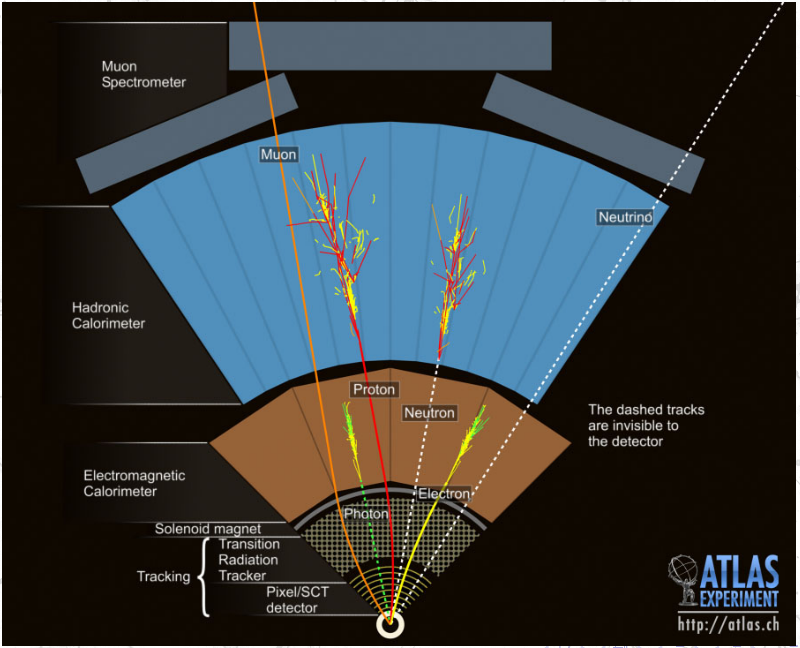






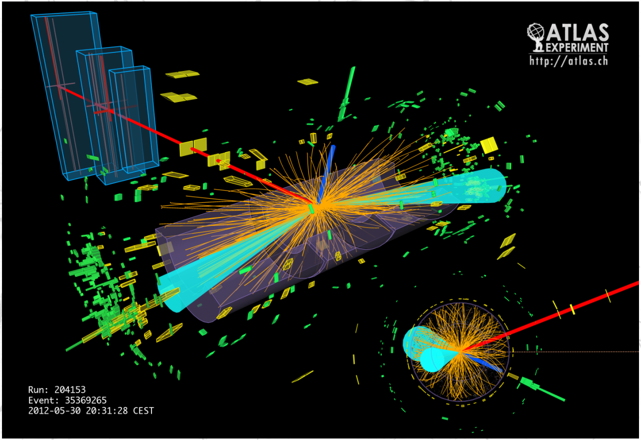
Operating ATLAS

Identifying particles in modern detectors



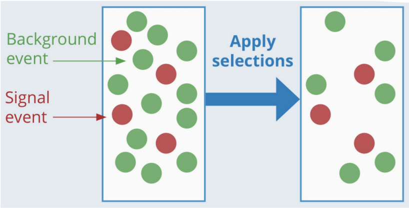
What the physics actually looks like

From the collision results, we search through the mess and look for new physics (or study in detail the ones we already know)



Problem is that we sometimes what we think looks like one particle is actually a poorly reconstructed other particle!

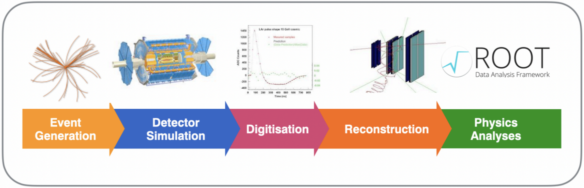
What the physics actually looks like



So this is a data science problem

Have to separate our wanted signals from possible background

- Very detailed study of underlying physics to separate these two
- Often rely on very good simulations
- Whole process takes usually 2(+) years/paper



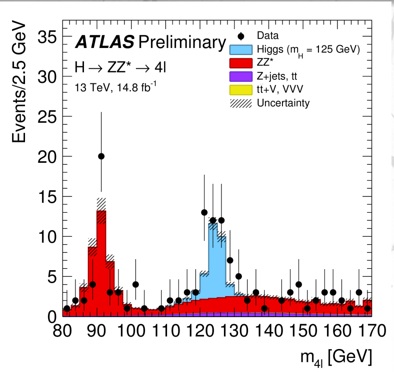
Collaborative C++/python inside ATLAS Athena framework

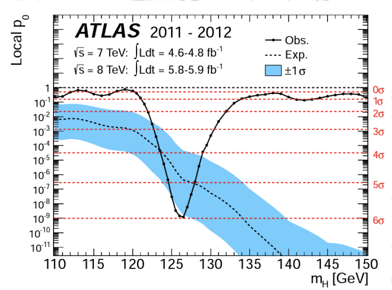
What the physics actually looks like

Once all the optimization is done we do a statistical analysis to quantify how confident we are the result is not just by accident

Often hear the term "sigma" to quantify this

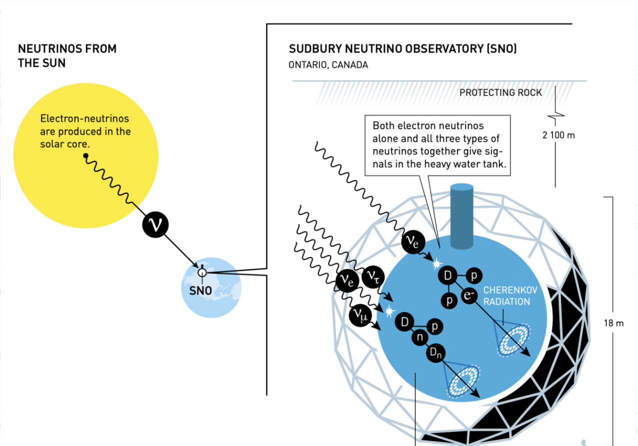
- 1,2,3 sigma means 1 in 3, 22, 370 chance of getting a result like this if the 'background' model is true, but we have a fluctuation
- High energy physics standard is 5σ=1 in 3.5million





Non-Collider Physics: Neutrinos

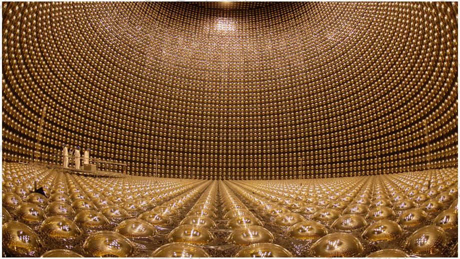
- Neutrinos (ν) are allusive particles which only barely interact with matter
- 2015 Nobel prize was related to "neutrino oscillations" (changing between neutrino types)
  - This means neutrinos have a mass
  - But the SM predicts no mass!!!

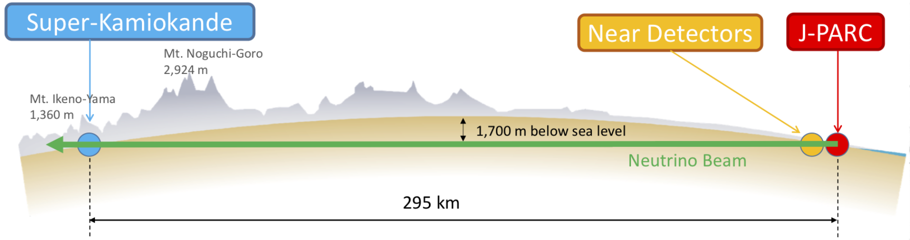


Non-Collider Physics: Neutrinos

Several experiments designed to study neutrinos specifically from:

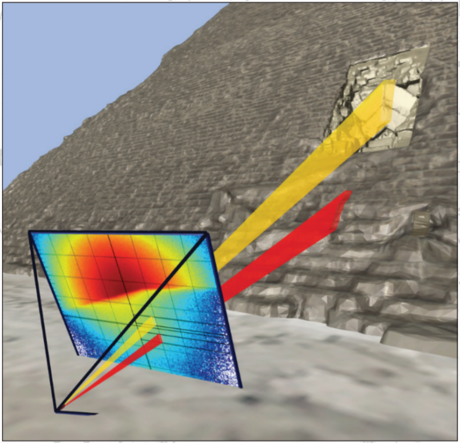
- Cosmic sources like the sun
- Nuclear reactors
- Specially designed neutrino beams

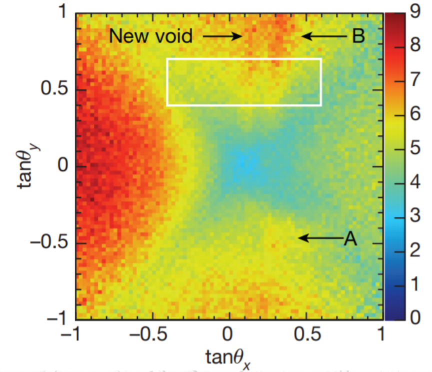




Application of particle physics: Muon tomography

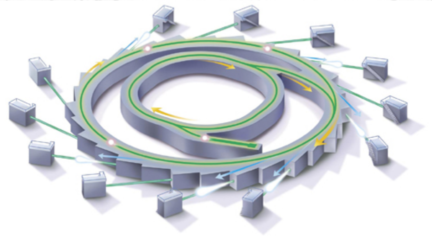
One of biggest archaeology discoveries in 2015 was a new cavern in the pyramids; it was found by mapping the pyramid via subatomic particles (muons) from the sky





Application of particle physics: Medical Sciences

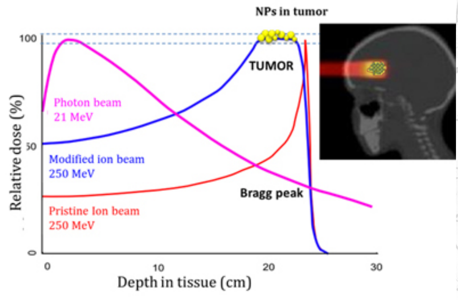
Historically a lot of nuclear/particle physics technology used for medicine: x-ray, MRI, CT-scan



Also "synchrotron" radiation from particle accelerators can be used as "cameras" for studying structure of biological samples or advanced materials

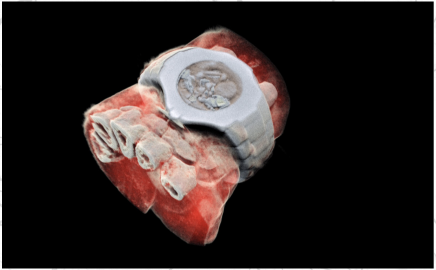
Application of particle physics: Medical Sciences

Can use high-energy physics to do "hadron therapy" for cancer



→ Can reduce radiation dosage by targeting the cancer cells in 3D space

Use high-energy physics detector technology for spectral CT scan



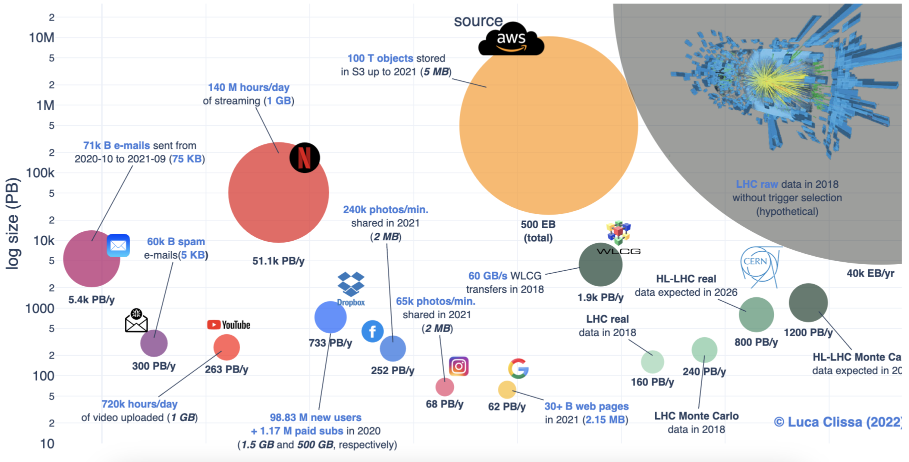
→ First 3D colour x-ray

Application of particle physics: General technology

World-wide web was invented at CERN

→ Originally designed for sharing information/papers between scientists around the globe

Application of particle physics: Data Science



The LHC is **THE BIG DATA** set!

- Active investigating in the experiments on the usage of machine-learning and AI tools

Future detectors

LHC will undergo some upgrades rebrand as the High-luminosity LHC

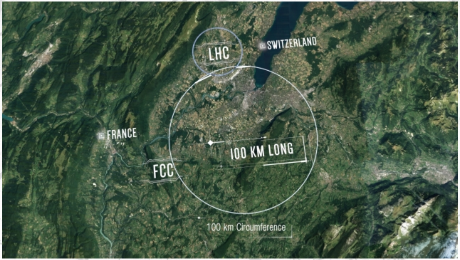
- Operate from 2028 $\sim$ 2040
- Will run at 5-7x the luminosity and collect 10x more data than currently

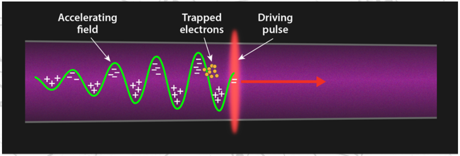
One of the leading ideas for next collider is the FCC

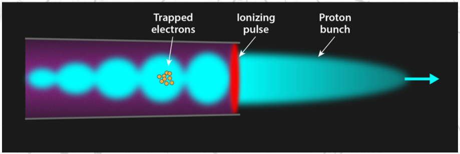
- Will be 100km long! 10x the energy! 20 Billion USD to build!
- Could be ready by 2050, but need to start soon

New accelerator technologies being studied like "plasma-wakefields"

- Can possibly make accelerators 1000x smaller







Future

High-energy physics is the study of nature at the smallest scale

- Has needed some of the largest scale engineering projects to study

The field involves a lot of inter-disciplinary action

- Interplay of physics theory, engineering, data science
- Science and technology developed here also being used in other fields

Many big questions still un-answered!

- Even bigger experiments are being discussed and new technologies always being developed
- Excited for the next generation of scientists, engineers, (you?) to continue on