Standard Model of Particle Physics

Allie Reinsvold Hall

Saturday Morning Physics

Fall 2019

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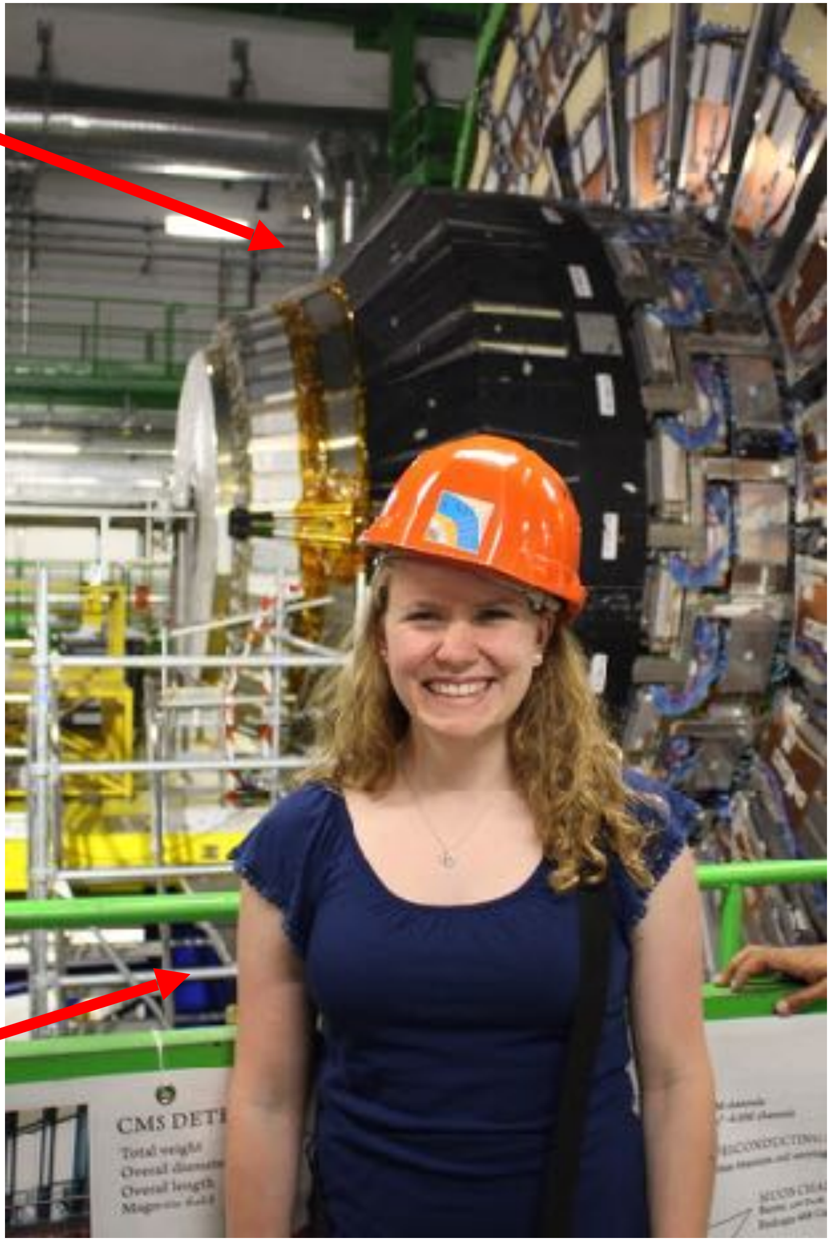
*Thanks to Javier Duarte, Cecilia Gerber, and Bo Jayatilaka!

A little about me

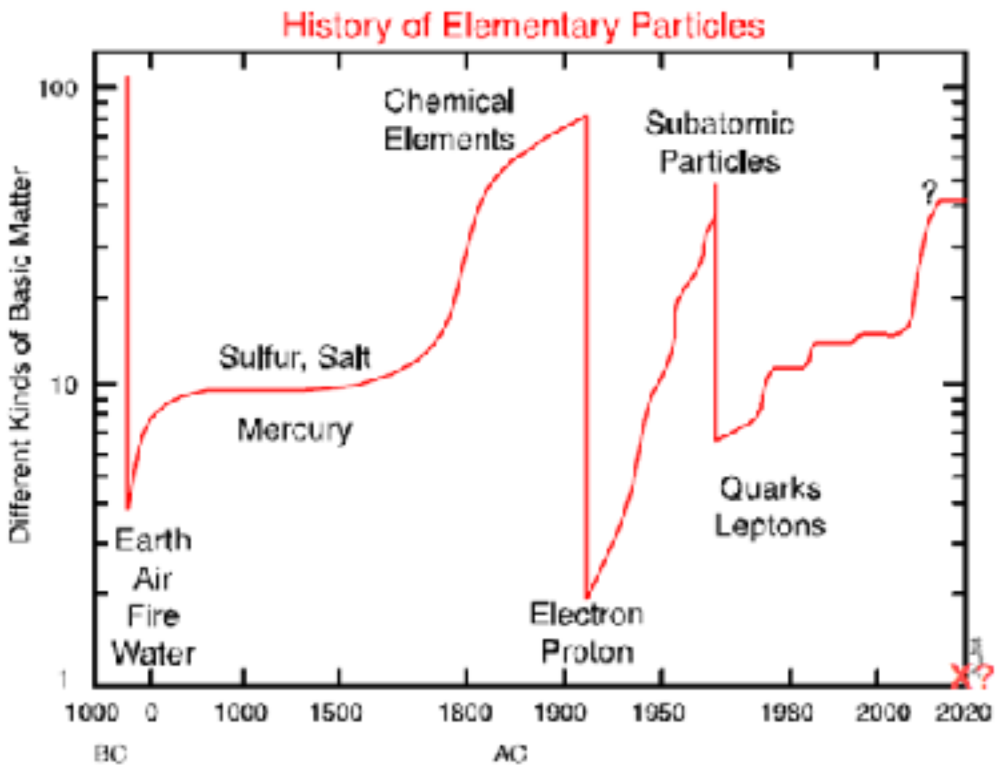
- Highschool in Des Moines, Iowa
- Majored in Physics at the College of St. Benedict in Minnesota
  - Graduated 2013
- Ph.D. in experimental particle physics from the University of Notre Dame in Indiana
  - Graduated 2018
- Now: Postdoc at Fermilab
  - Working on CMS experiment, including searches for dark matter and optimizing CMS reconstruction code

CMS Detector

CMS Physicist



Brief history of particle physics



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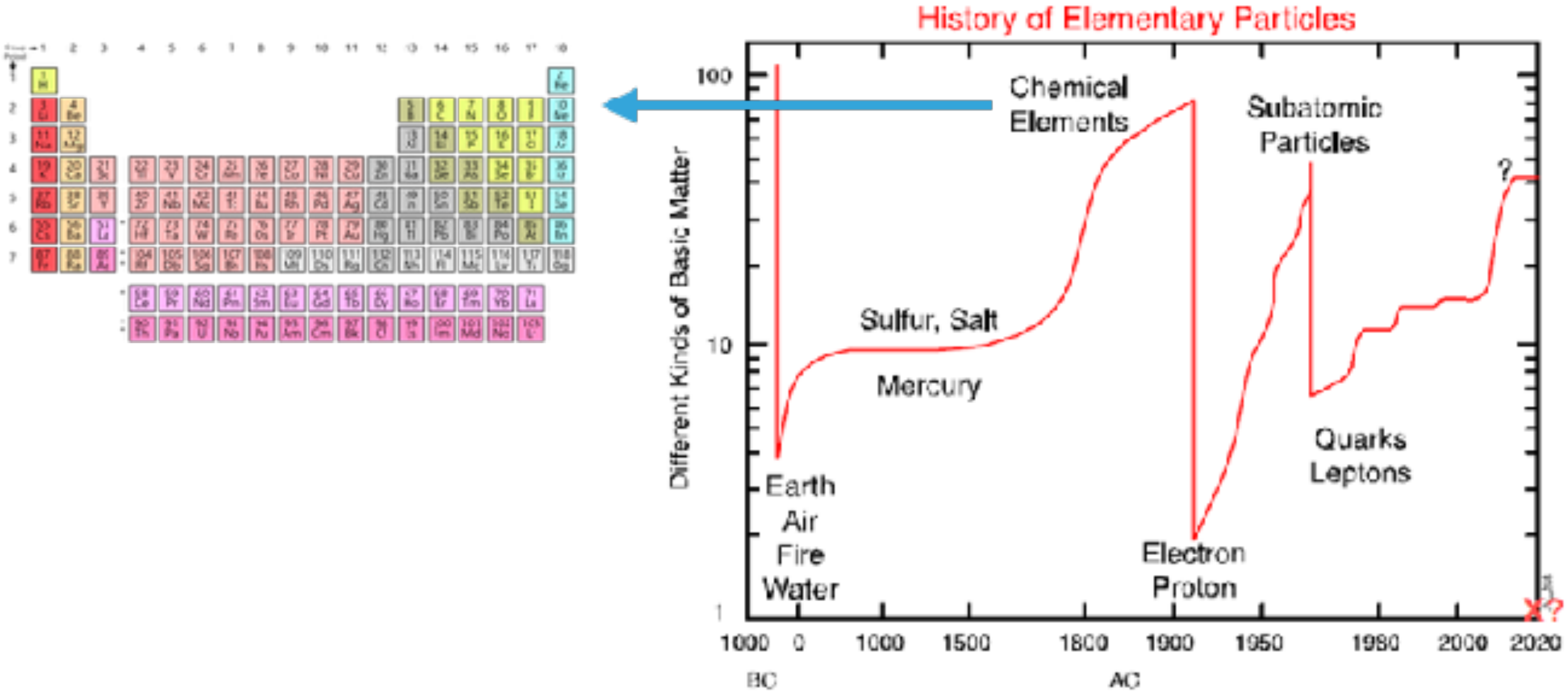

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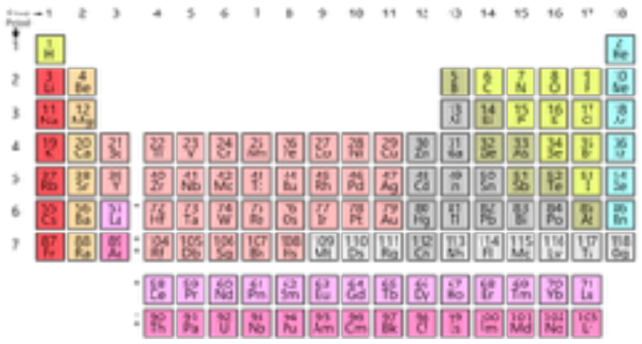

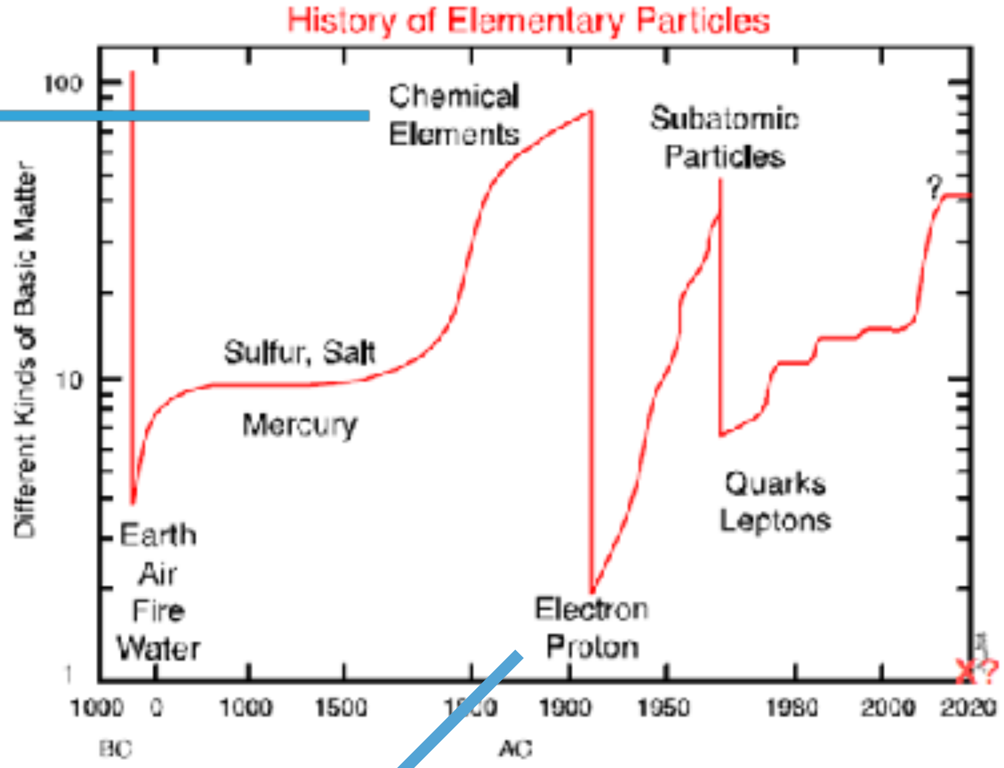

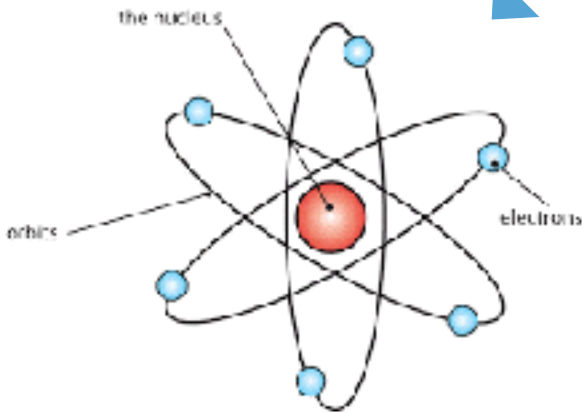

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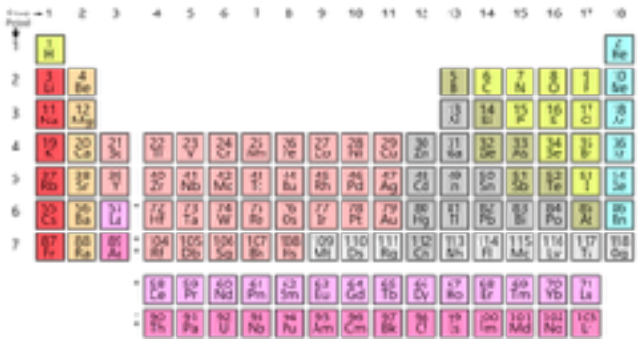
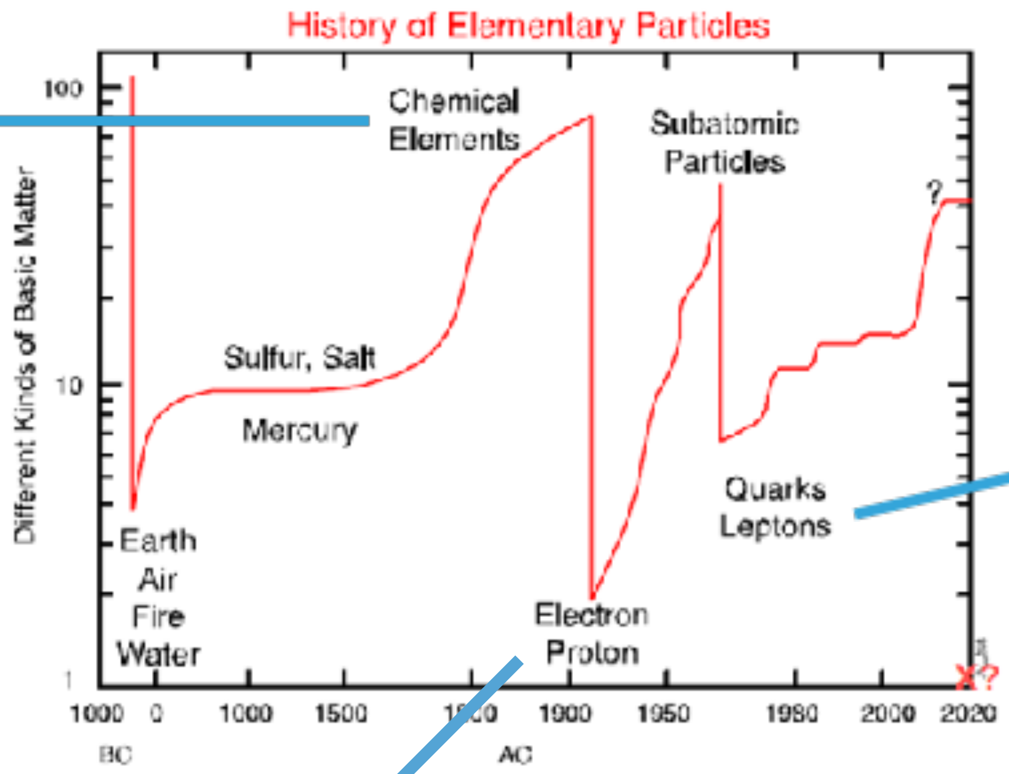
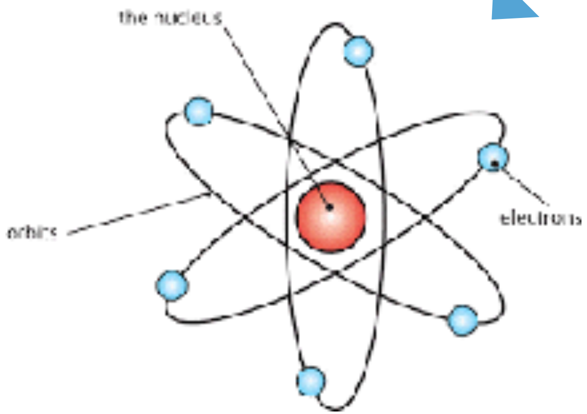
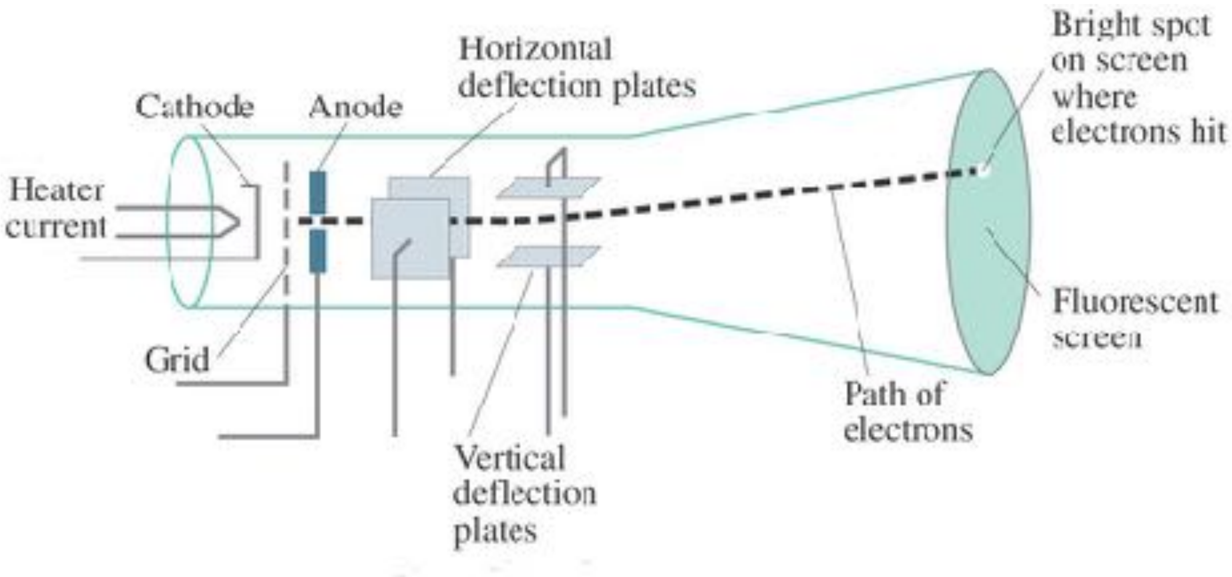






The Discovery of the Electron

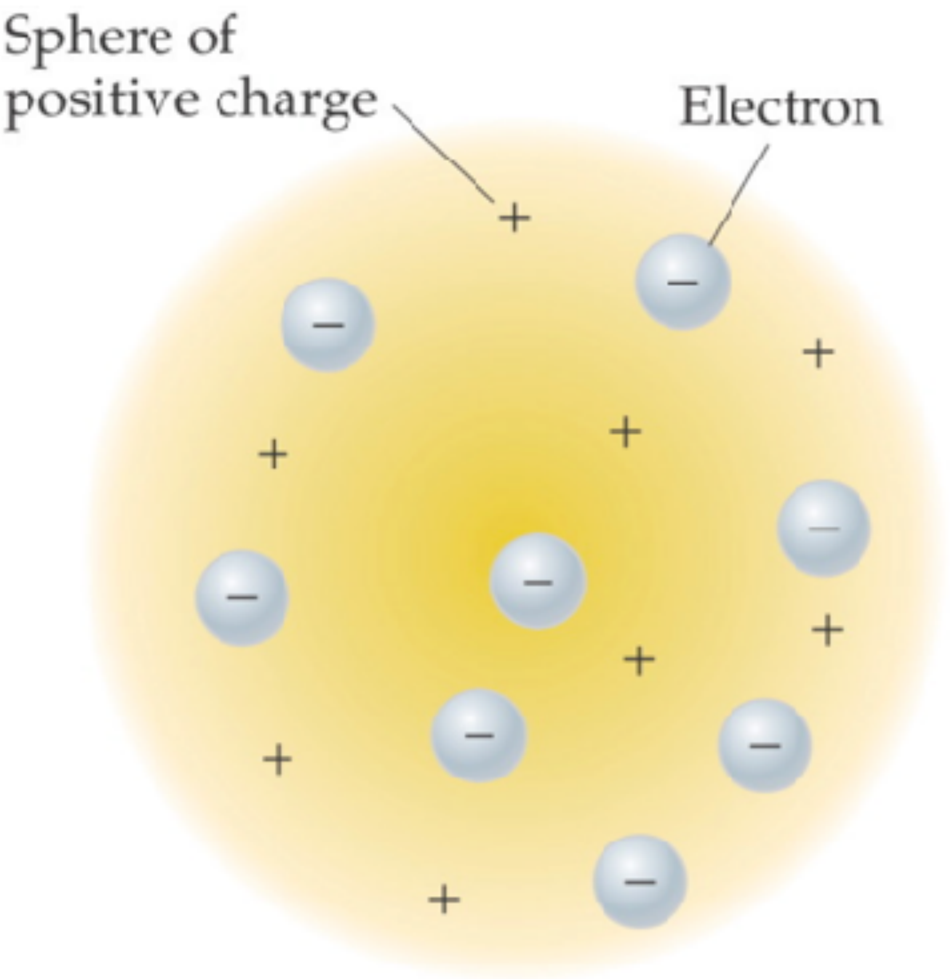
J.J.Thomson (1897)



Advanced the idea that cathode rays were a stream of small pieces of matter. 1906 Nobel Price of Physics

Plum Pudding Model of the Atom

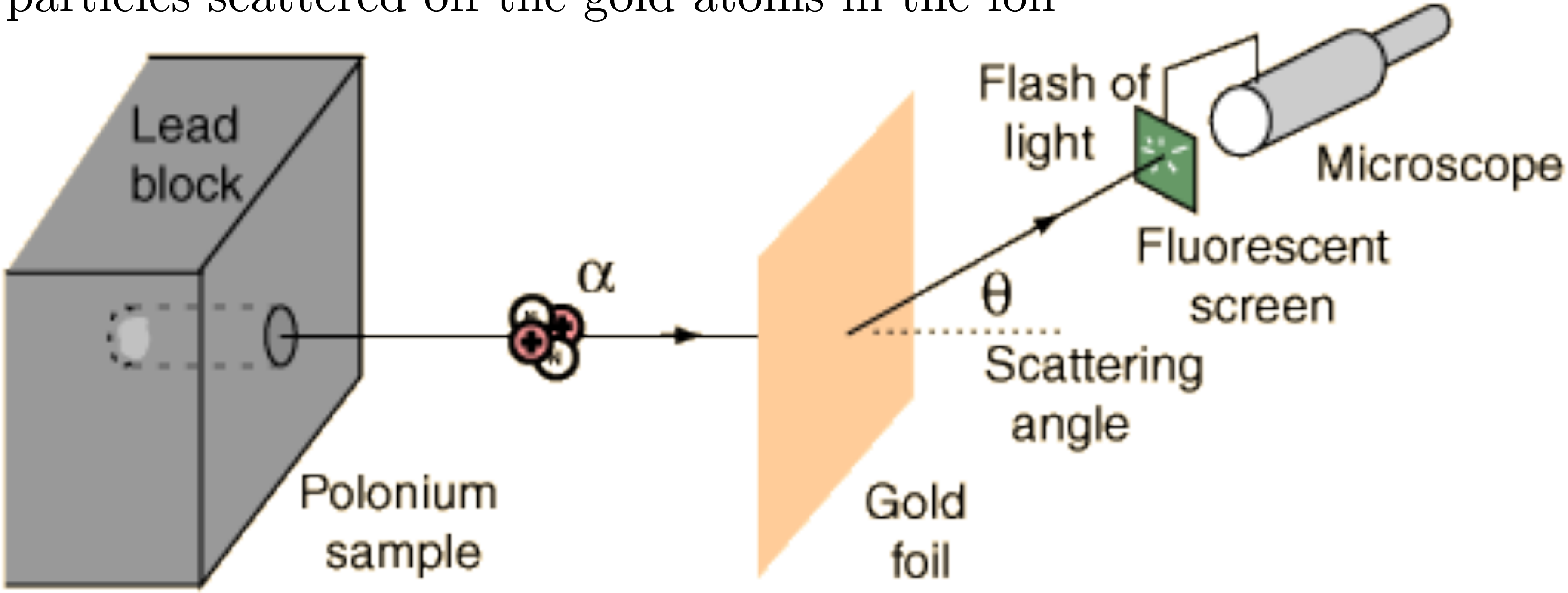
J.J. Thomson (1904)



Electrons were embedded in a positively charged atom like plums in a pudding

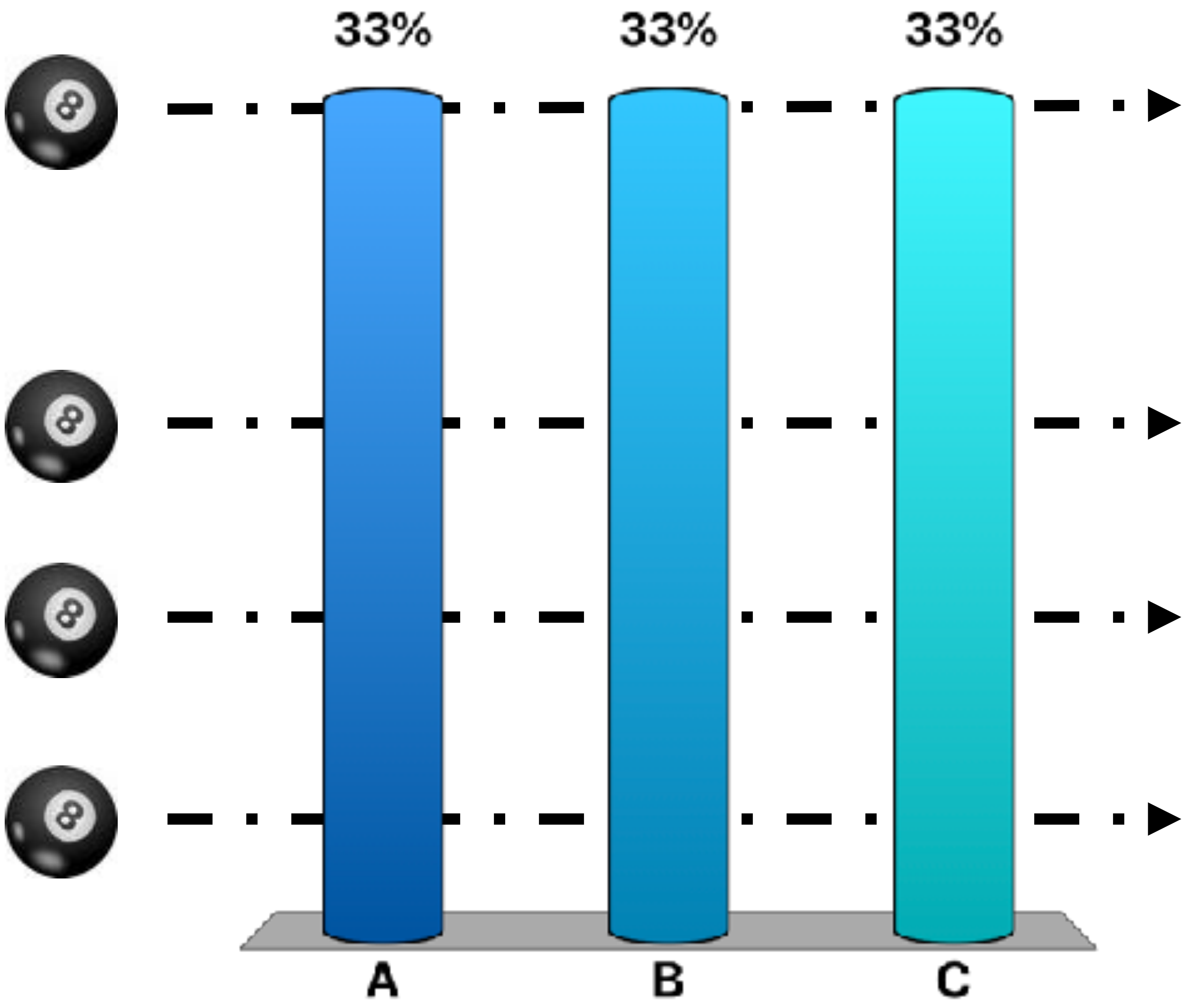
Rutherford Scattering

- Beam of alpha (α) particles were directed at a thin gold foil
- A fluorescent screen was used to detect the angle θ at which the particles scattered off the gold atoms in the foil



E. Rutherford (1909)

Rutherford Scattering



What do you expect to happen to the pool balls?

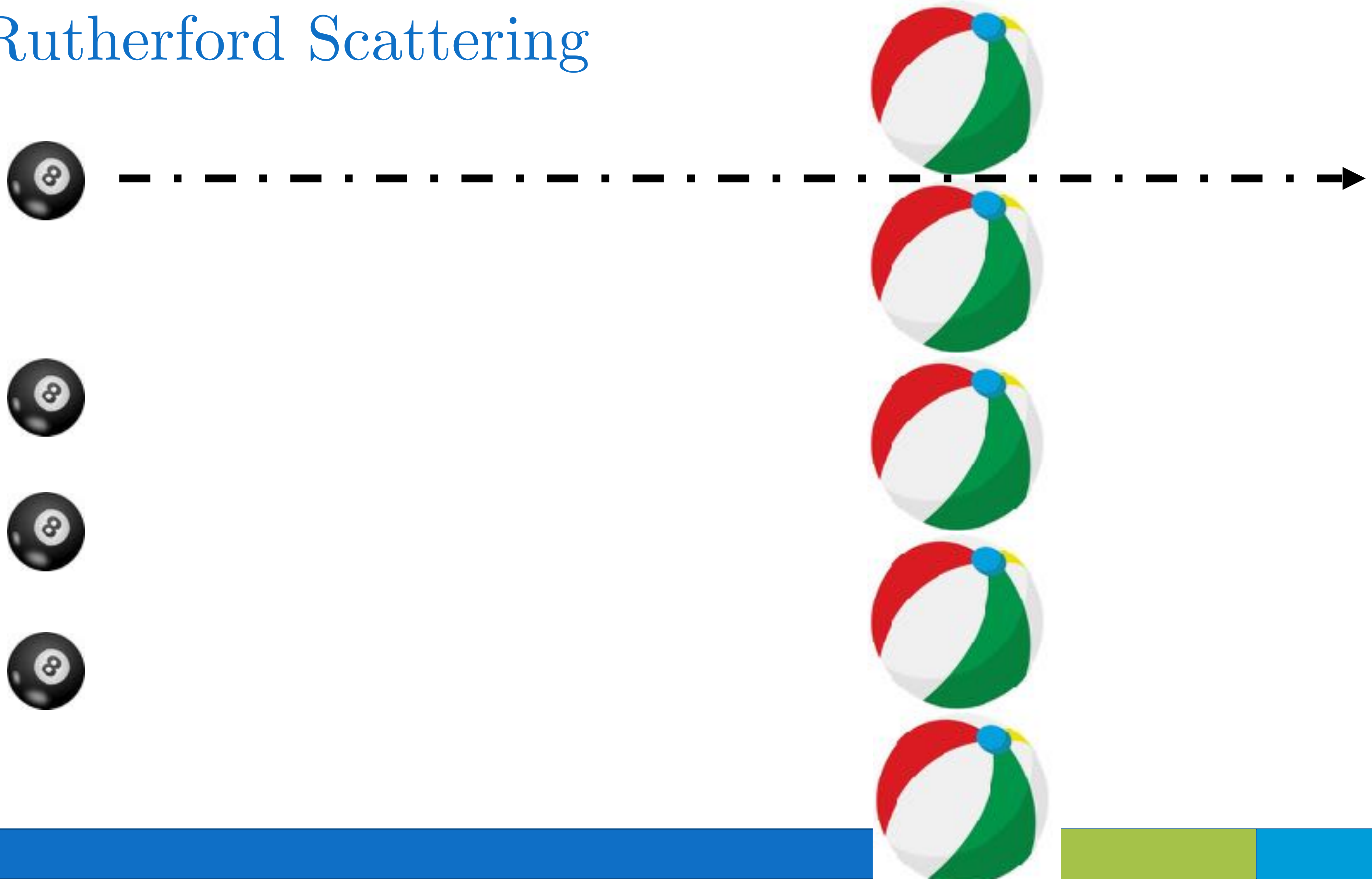
A. Pass through the beach balls without getting deflected

B. Scatter back towards the left

C. Most particles will pass through, some will scatter back towards the left

Rutherford Scattering

Rutherford Scattering



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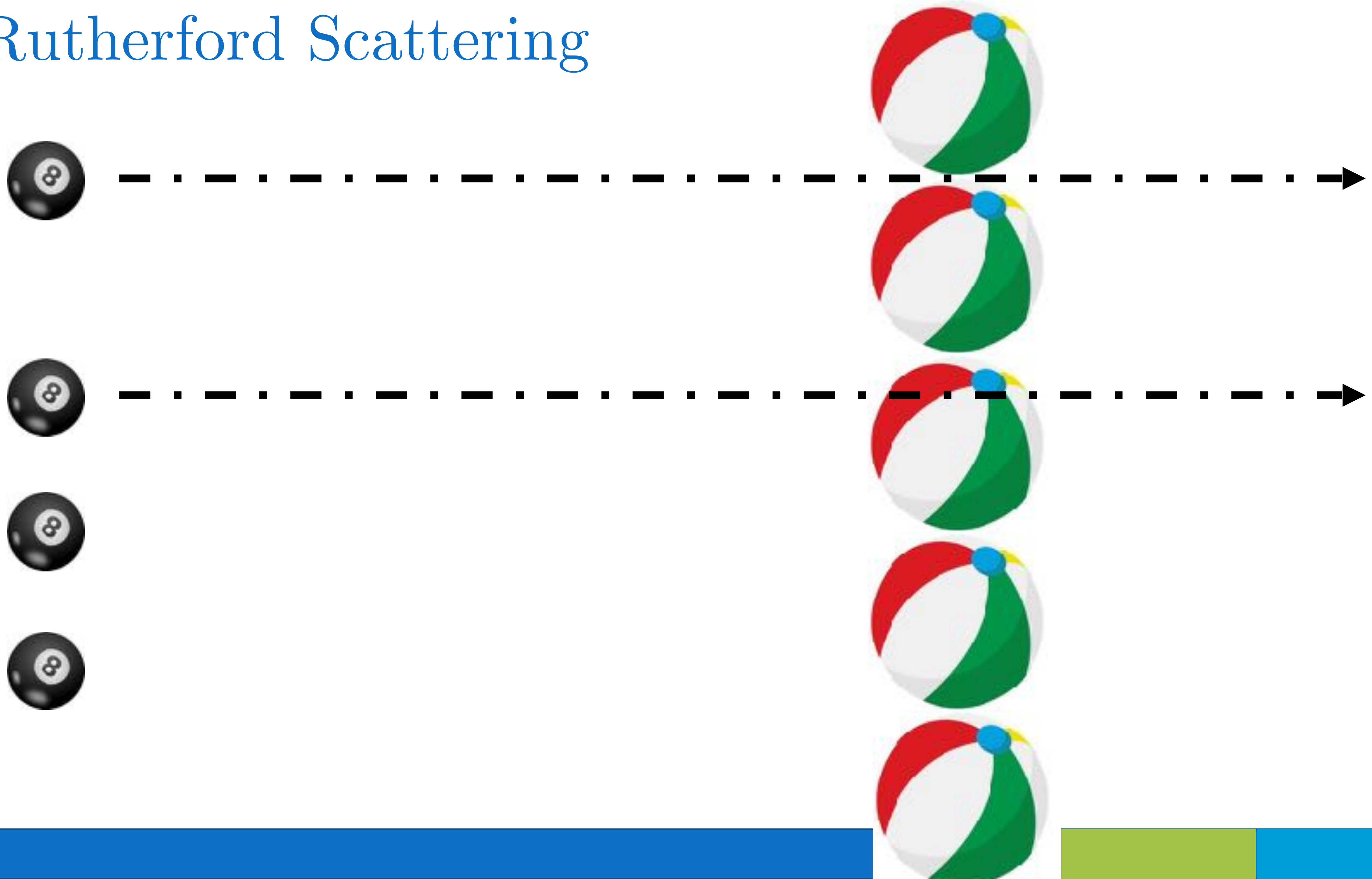

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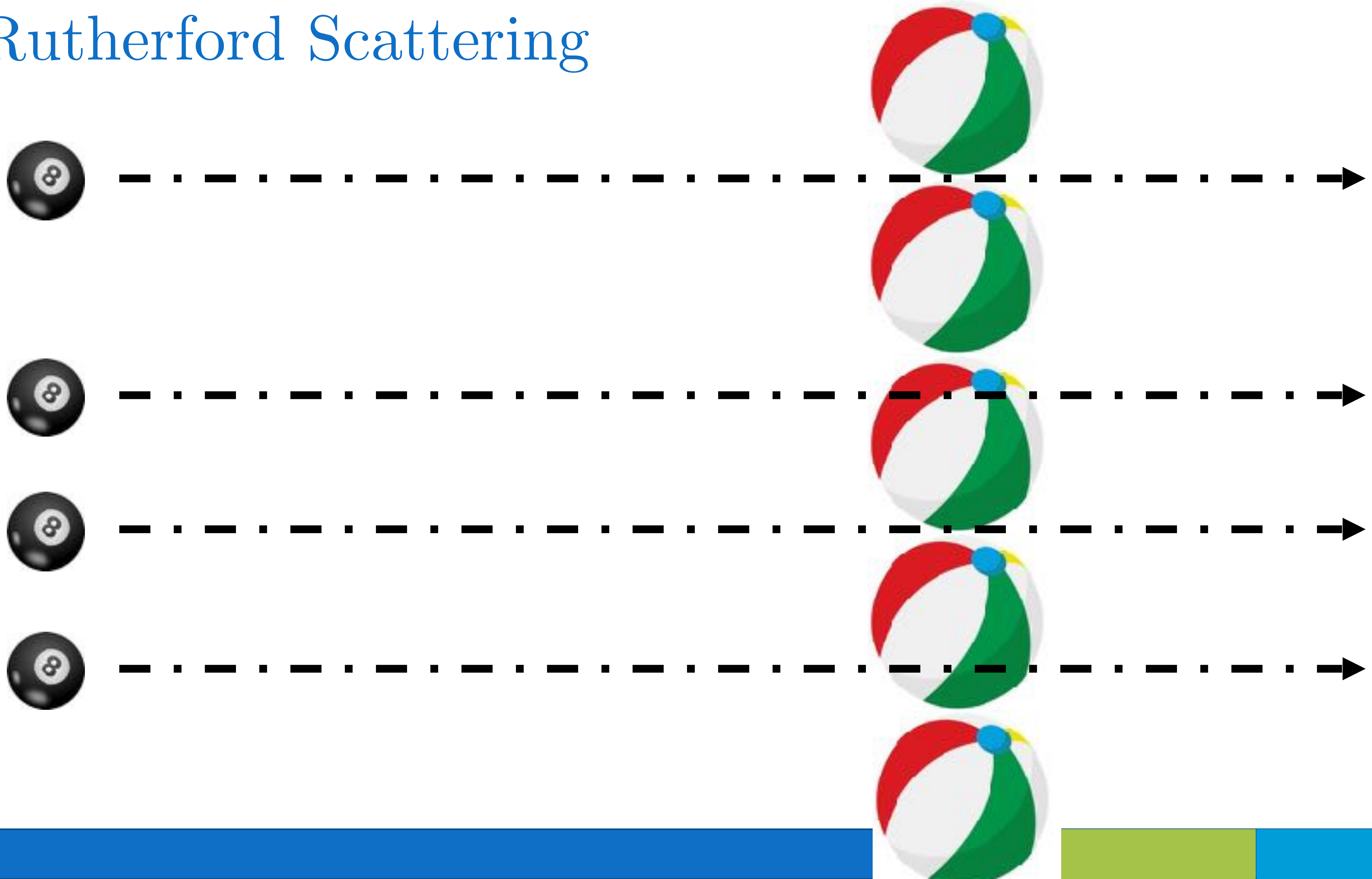

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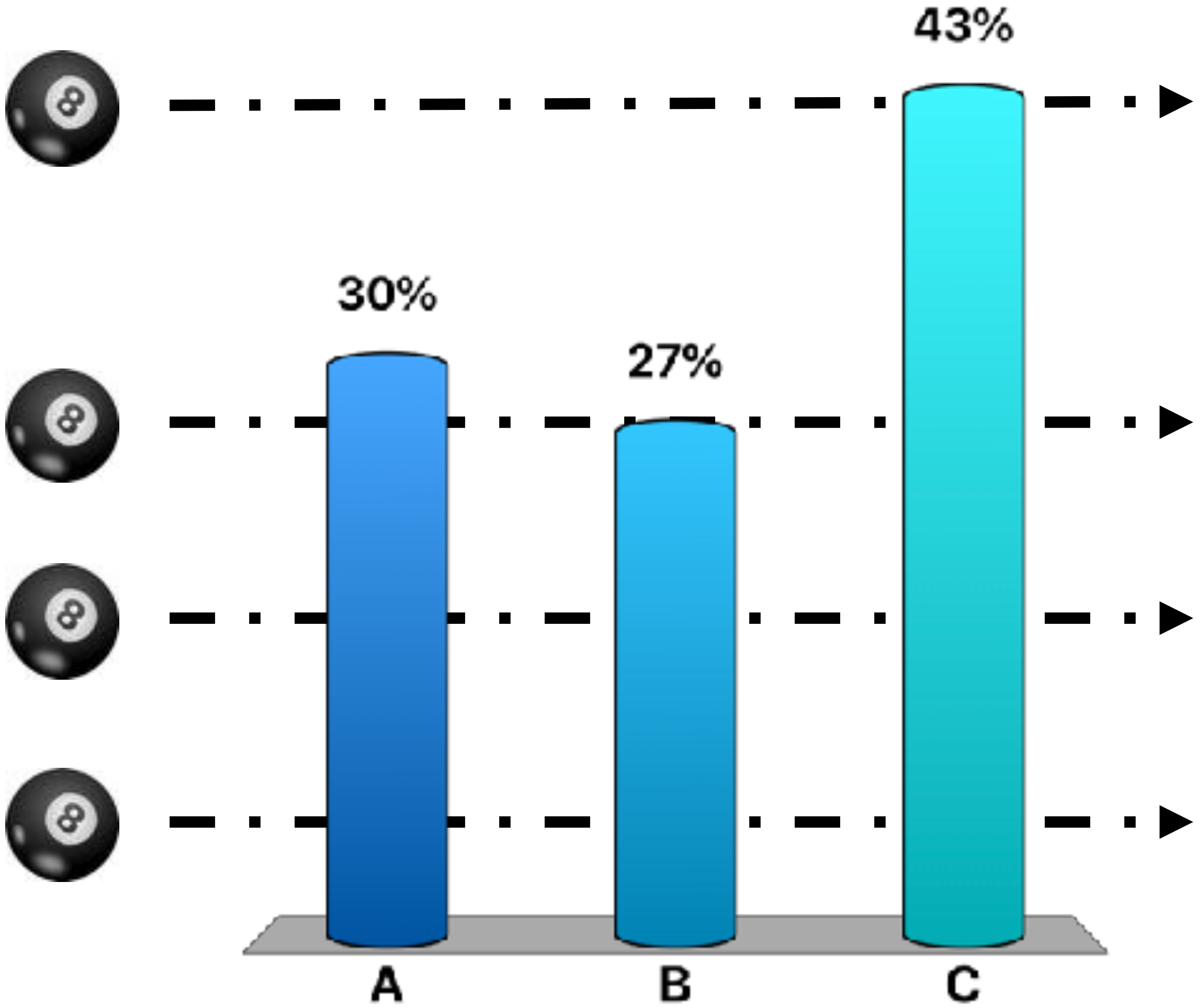

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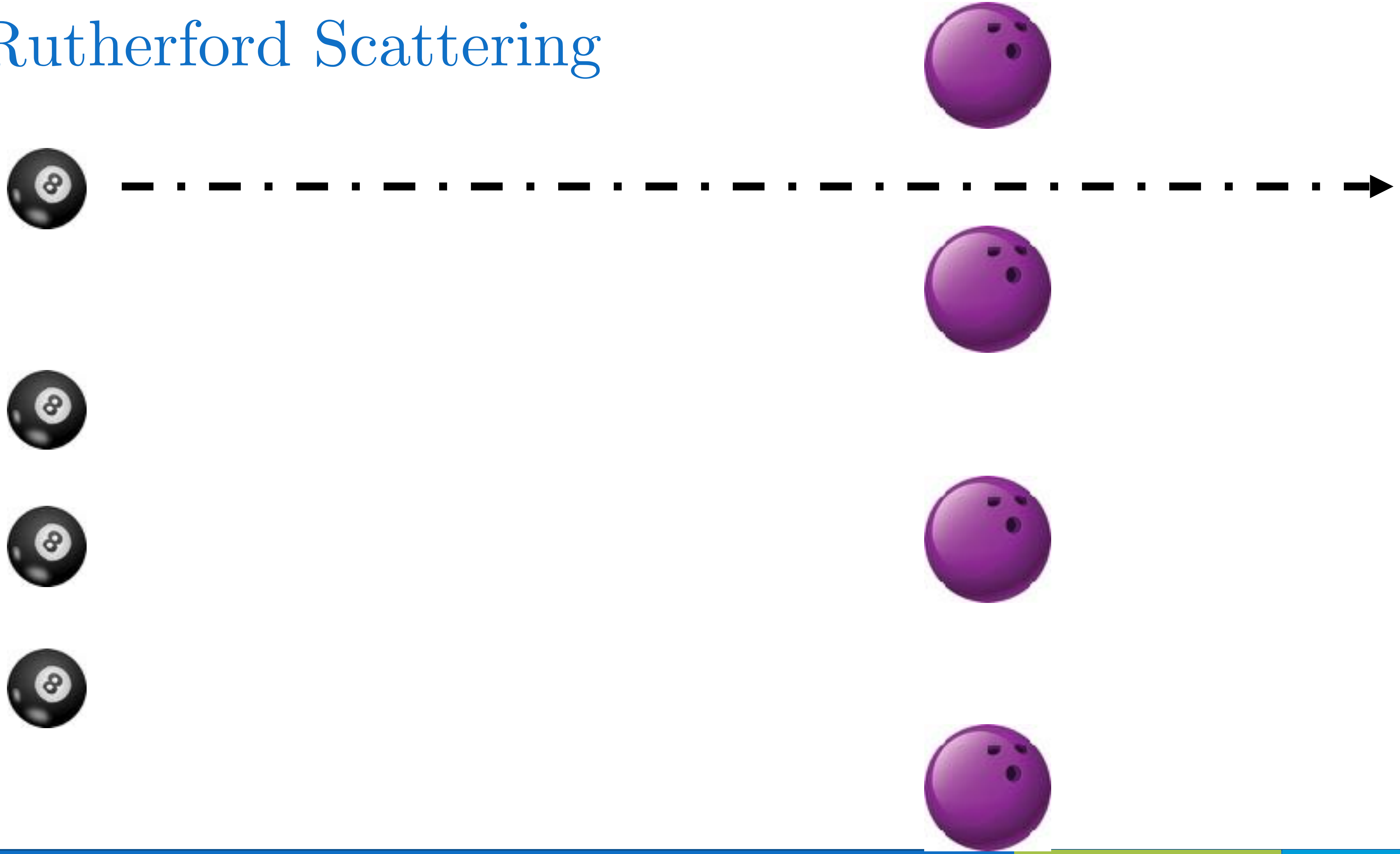

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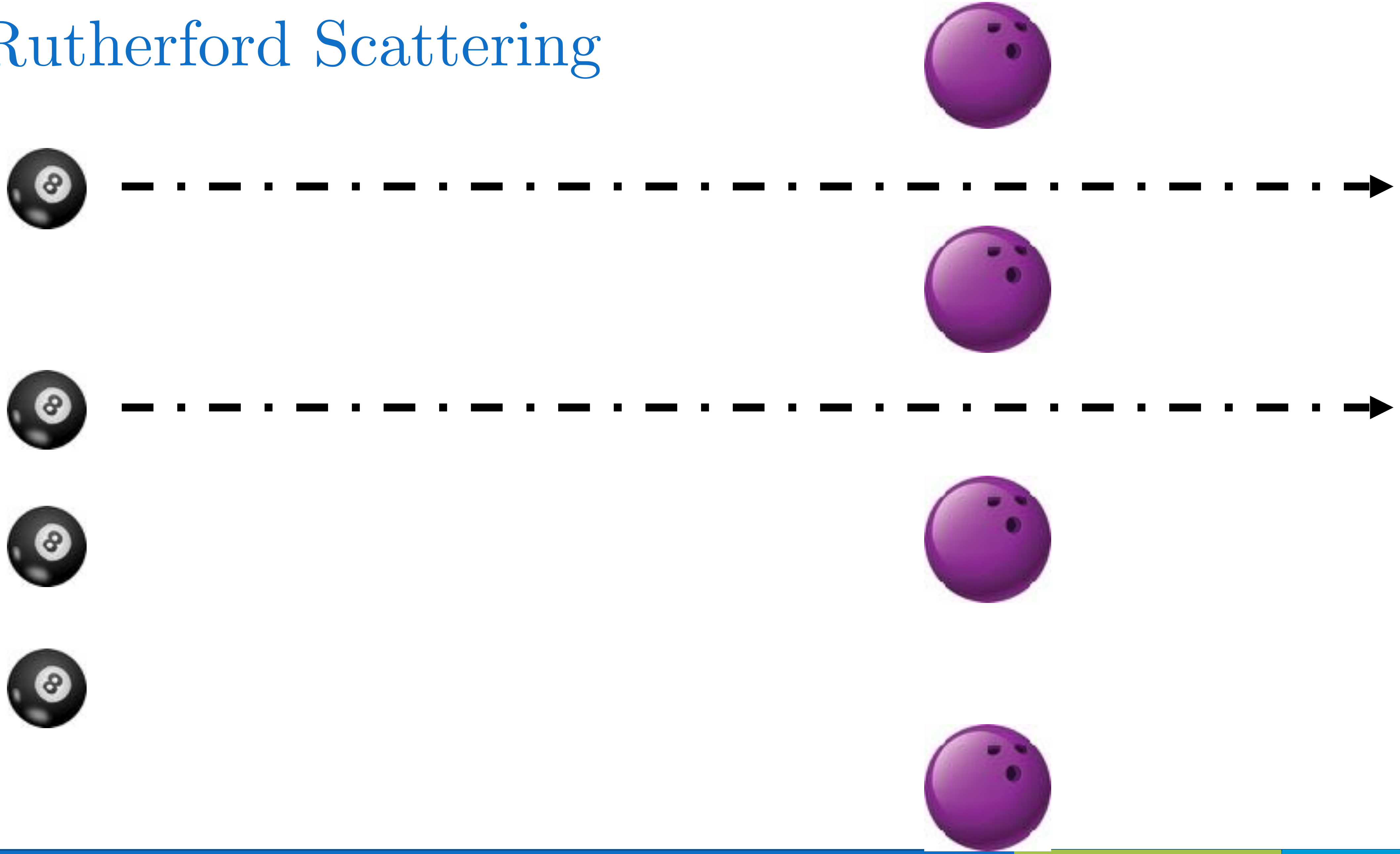

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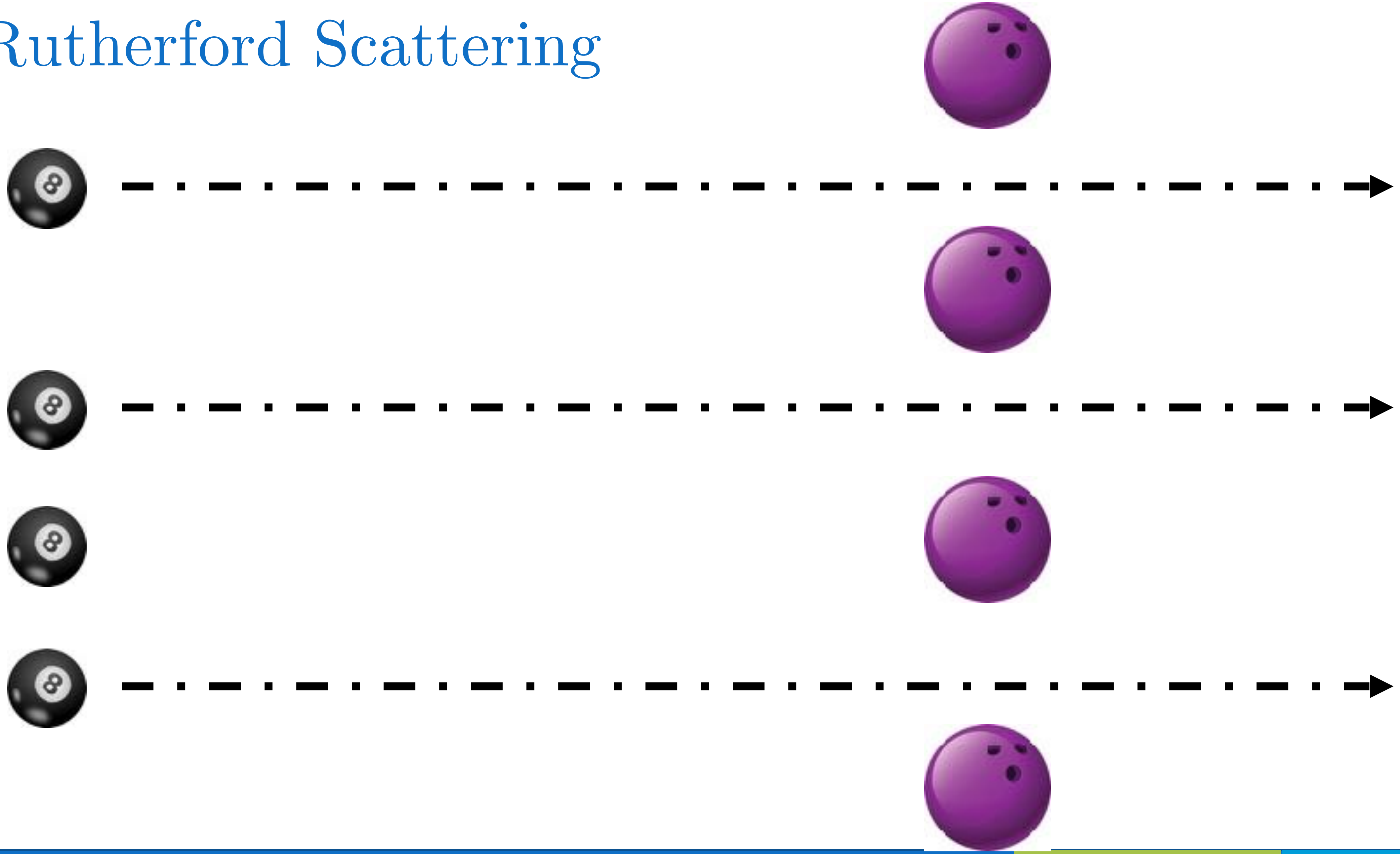

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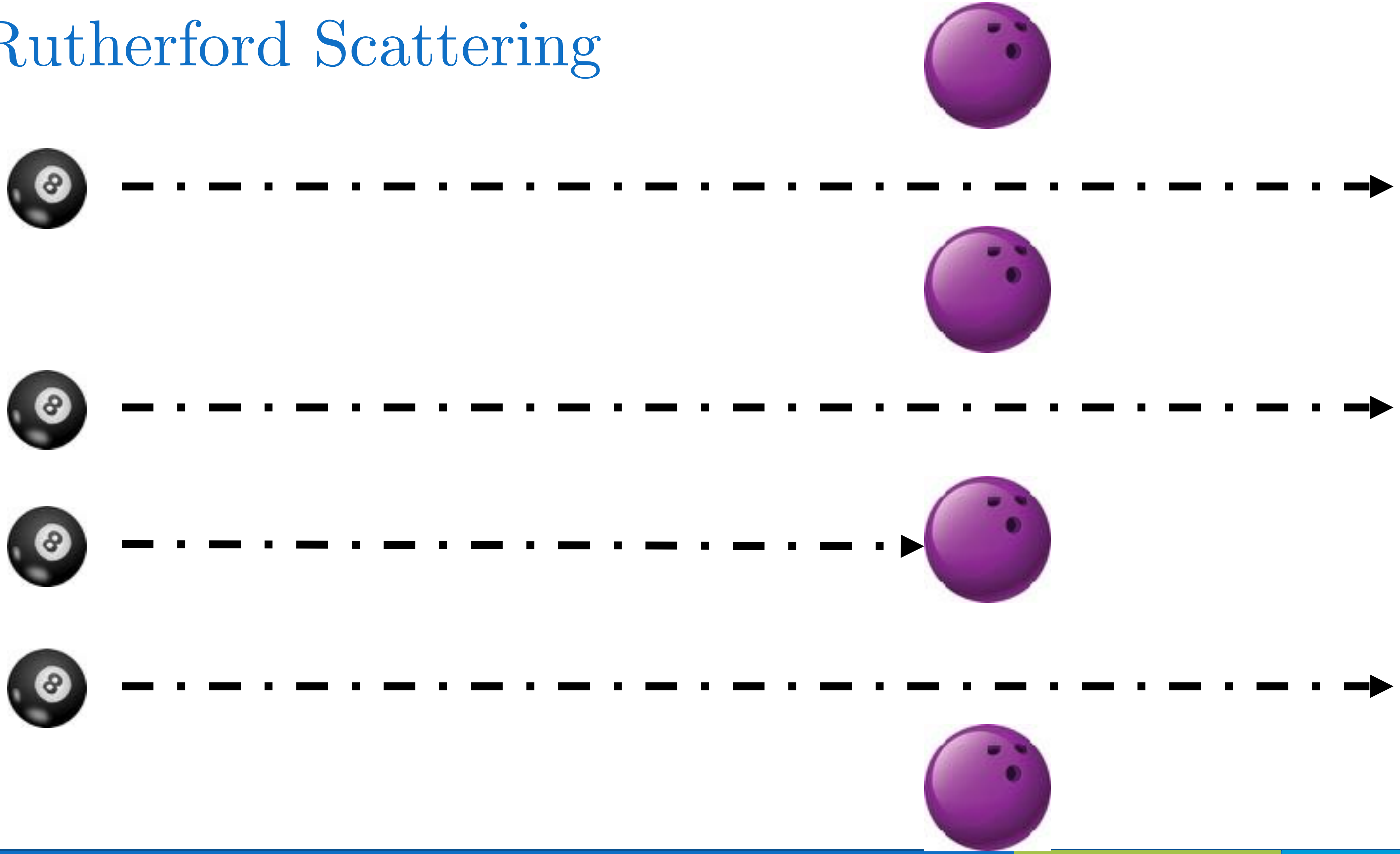

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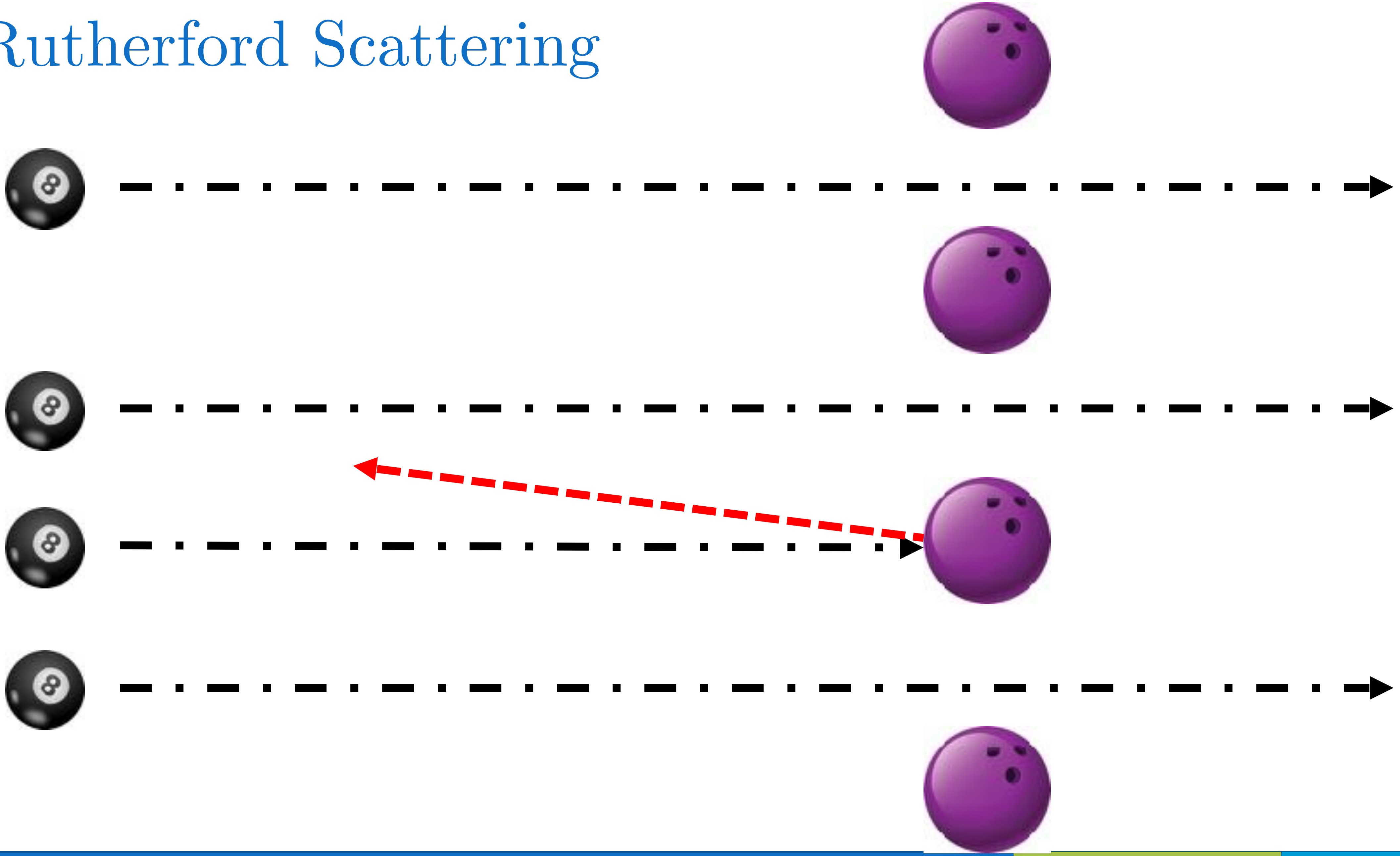
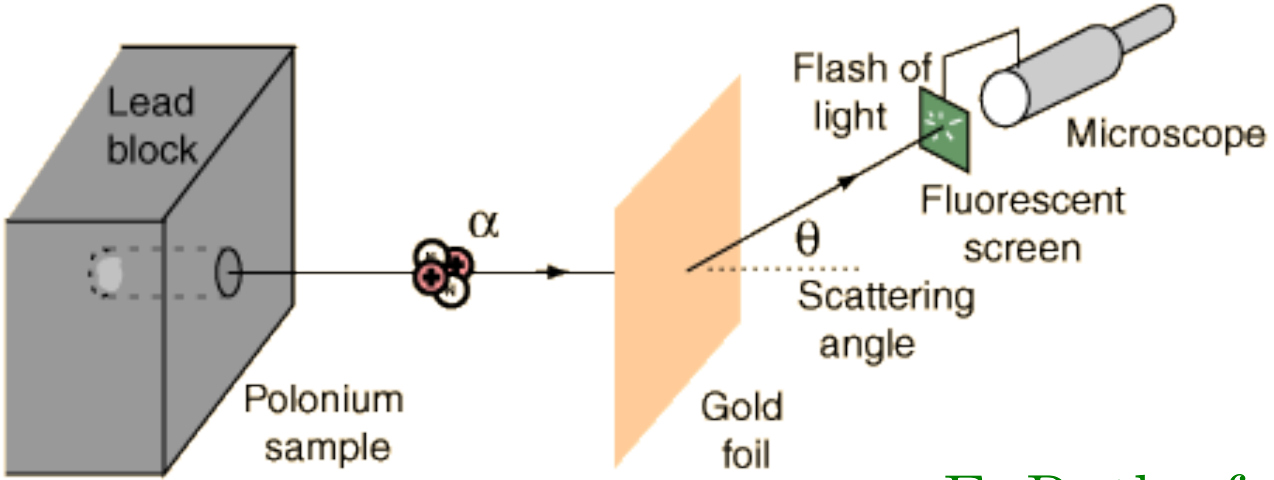


Rutherford Scattering

- One in 8000 α particles were deflected back towards the source
- This showed that the positive matter in atoms was concentrated in an incredibly small volume (10^{-13}cm)
- Gave birth to the idea of the nuclear atom



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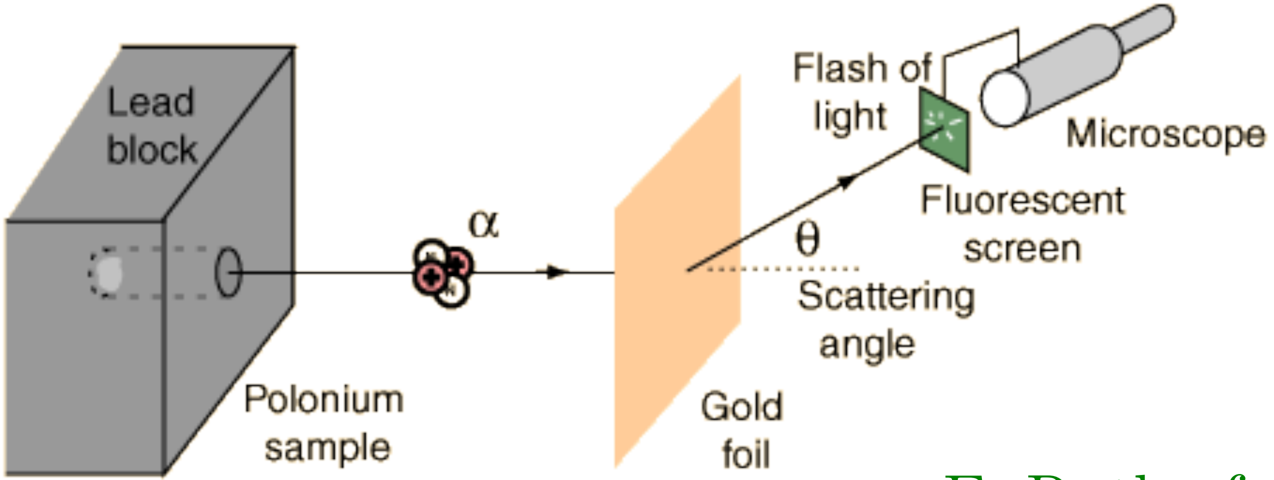
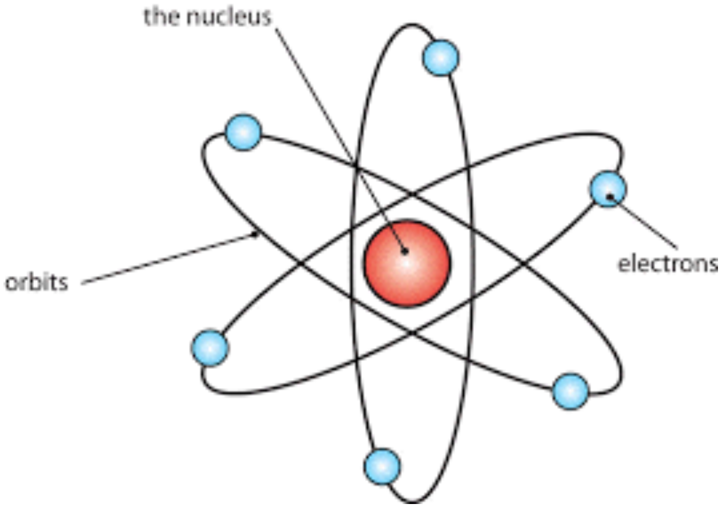


"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

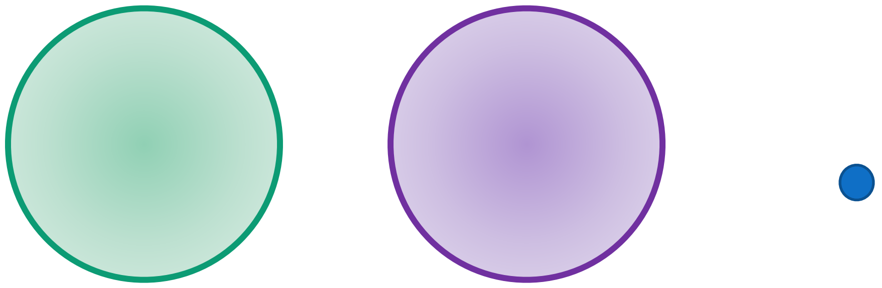
E. Rutherford (1909)

Planetary Model of the Atom

Ernest Rutherford (1911)



- Atoms are made up of a central positive charge surrounded by a cloud of orbiting electrons
- All atoms are made up of protons, neutrons, and electrons



Proton (+) Neutron (0) Electron (-)

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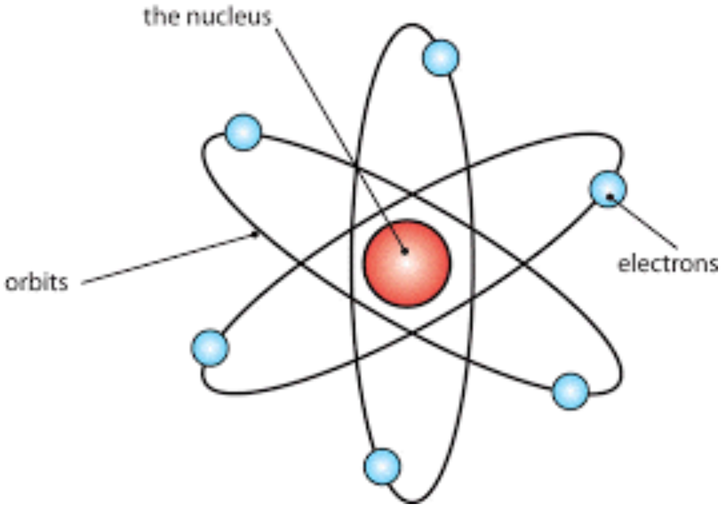

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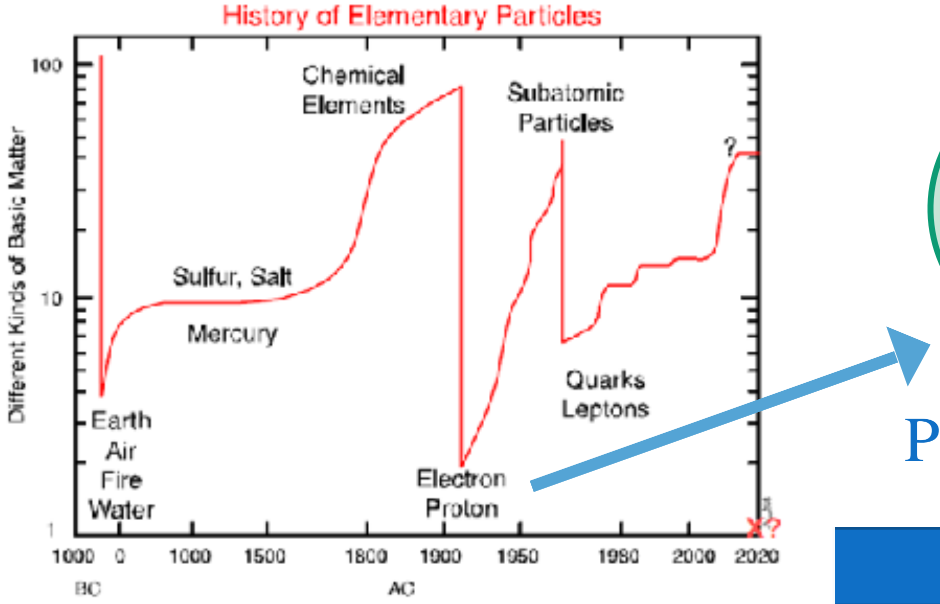
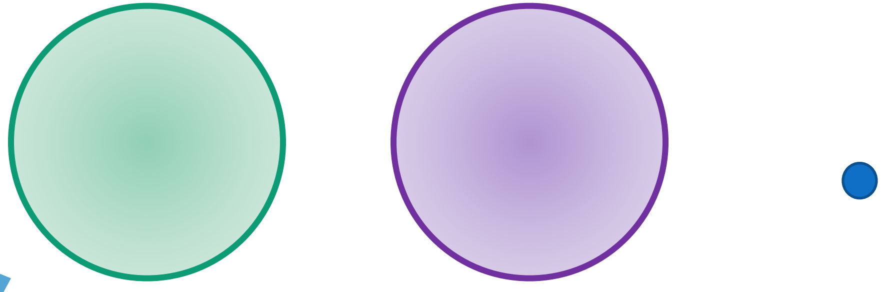
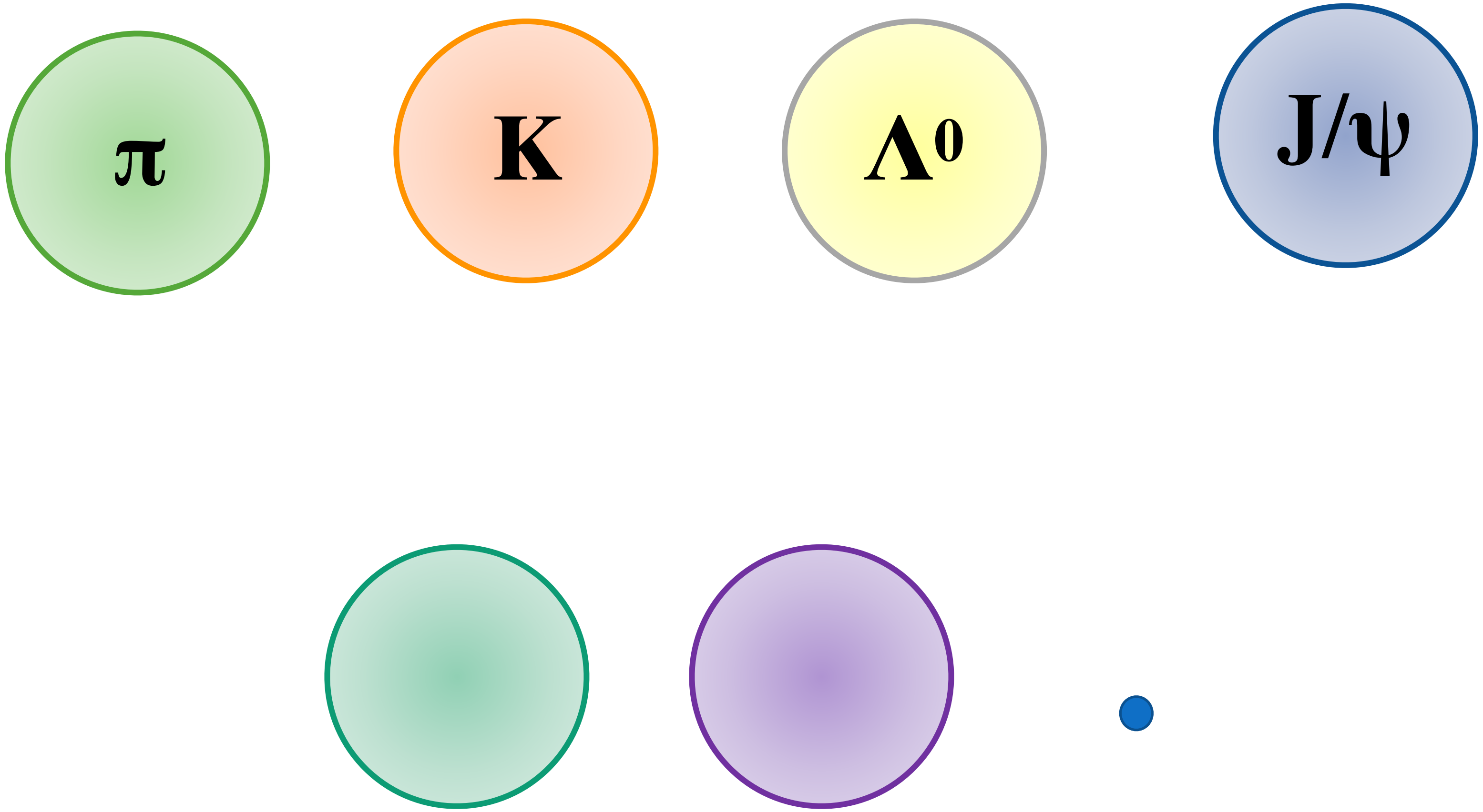




Proton (+) Neutron (0) Electron (-)

An abundance of particles



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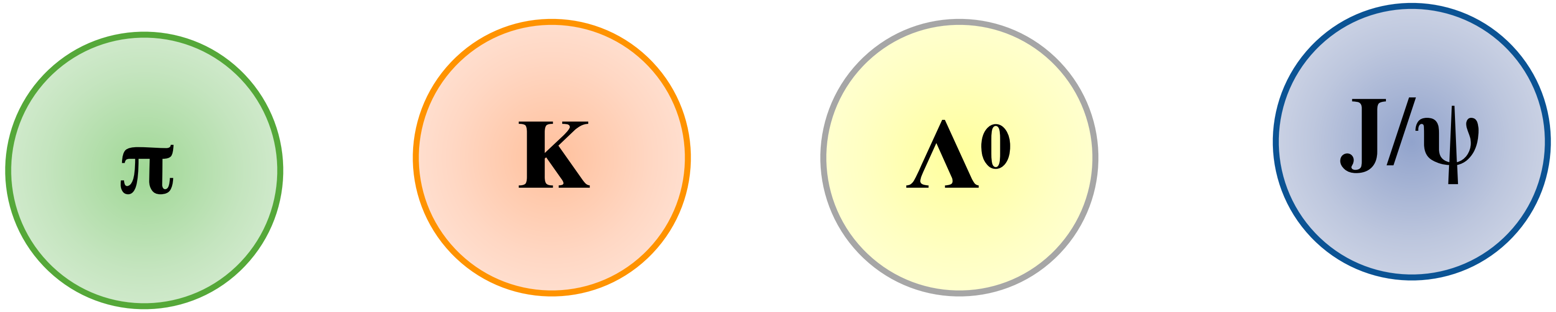
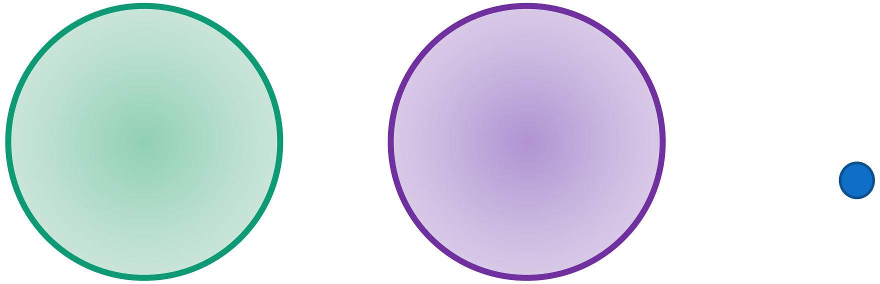
An abundance of particles

- 1947 to 1964: More and more "elementary" particles discovered



- Solution: all of these *hadrons* are different combinations of even smaller particles, called quarks



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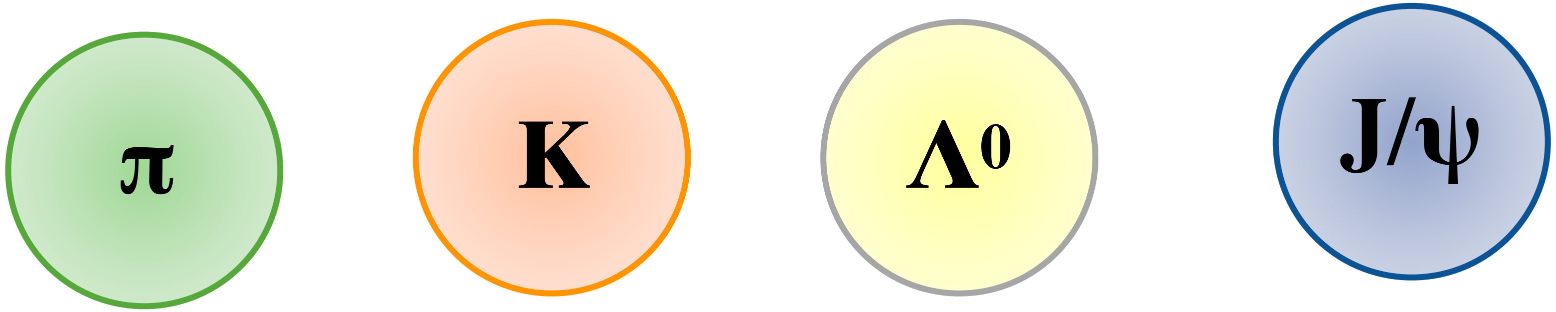

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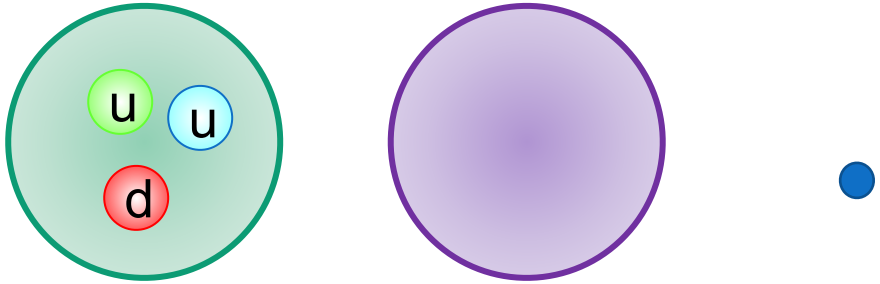

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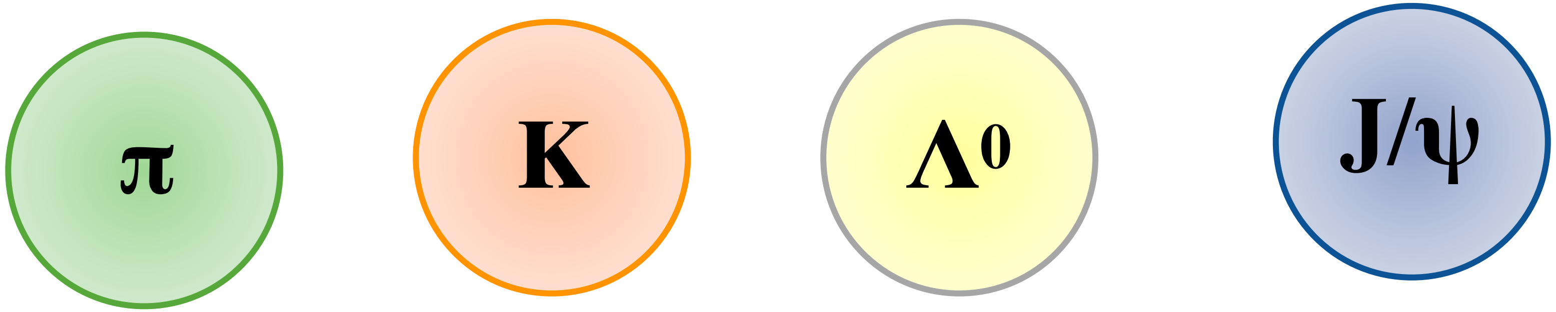

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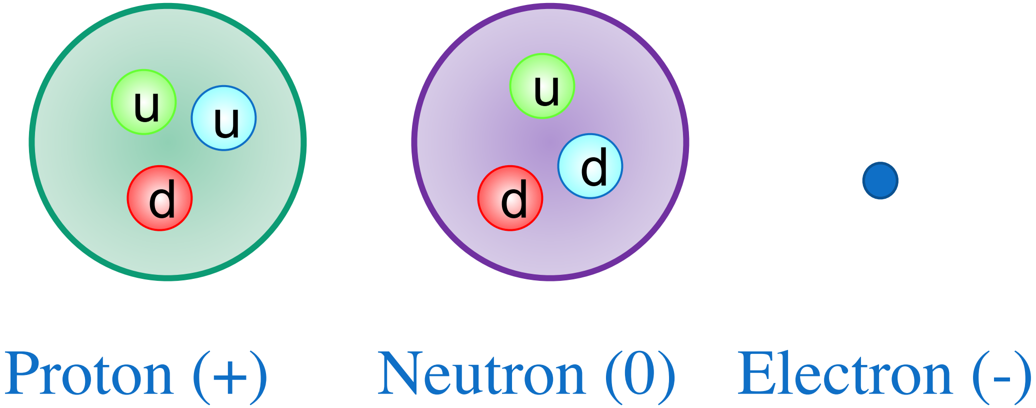
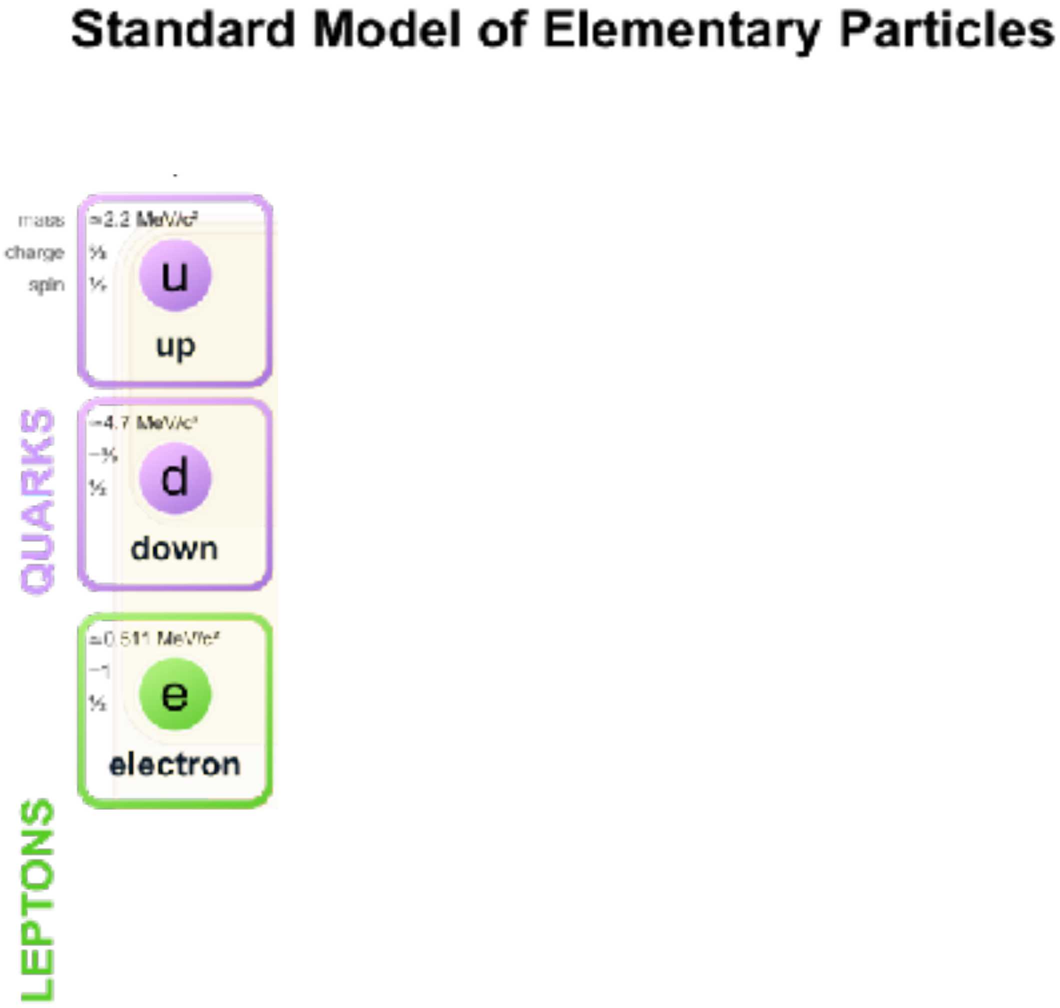
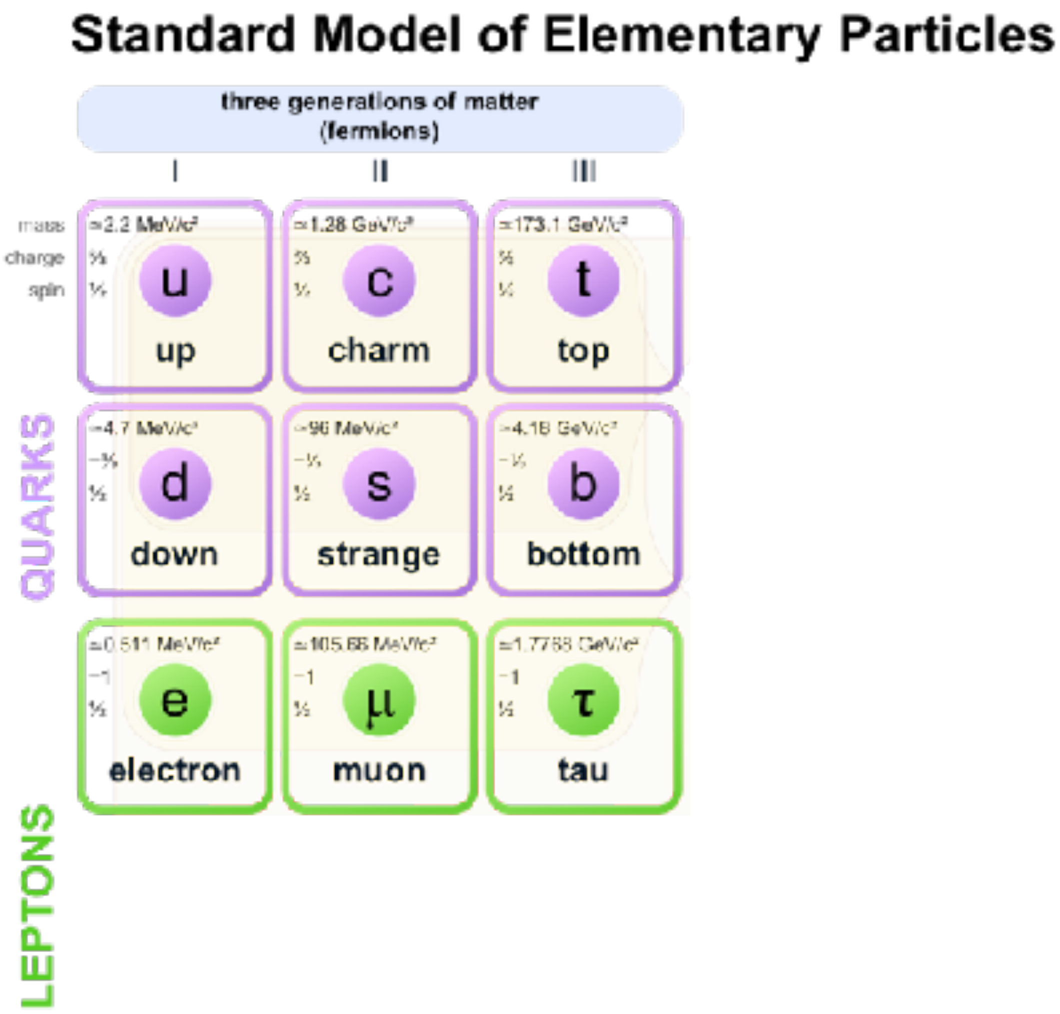


Earth’s building blocks



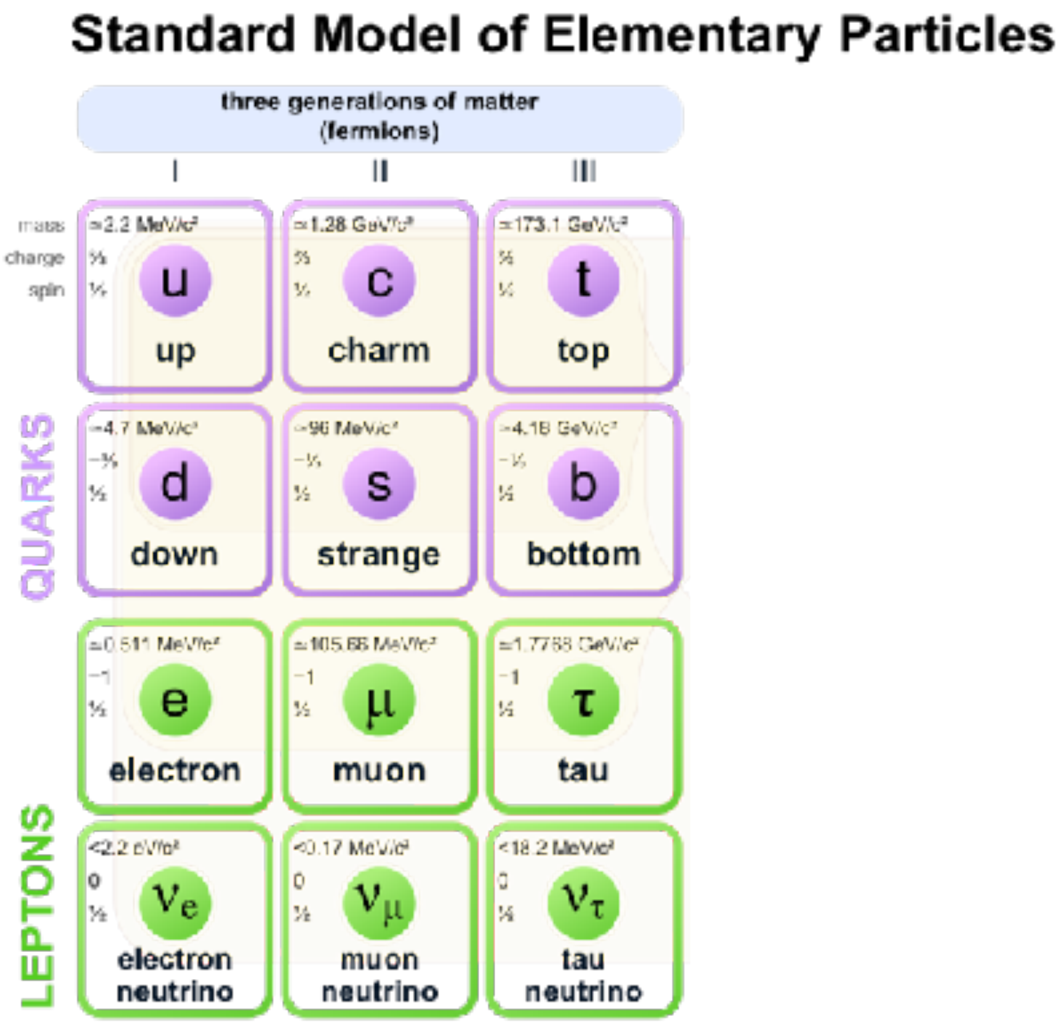
- All ordinary matter is made from up quarks, down quarks, and electrons

Three generations

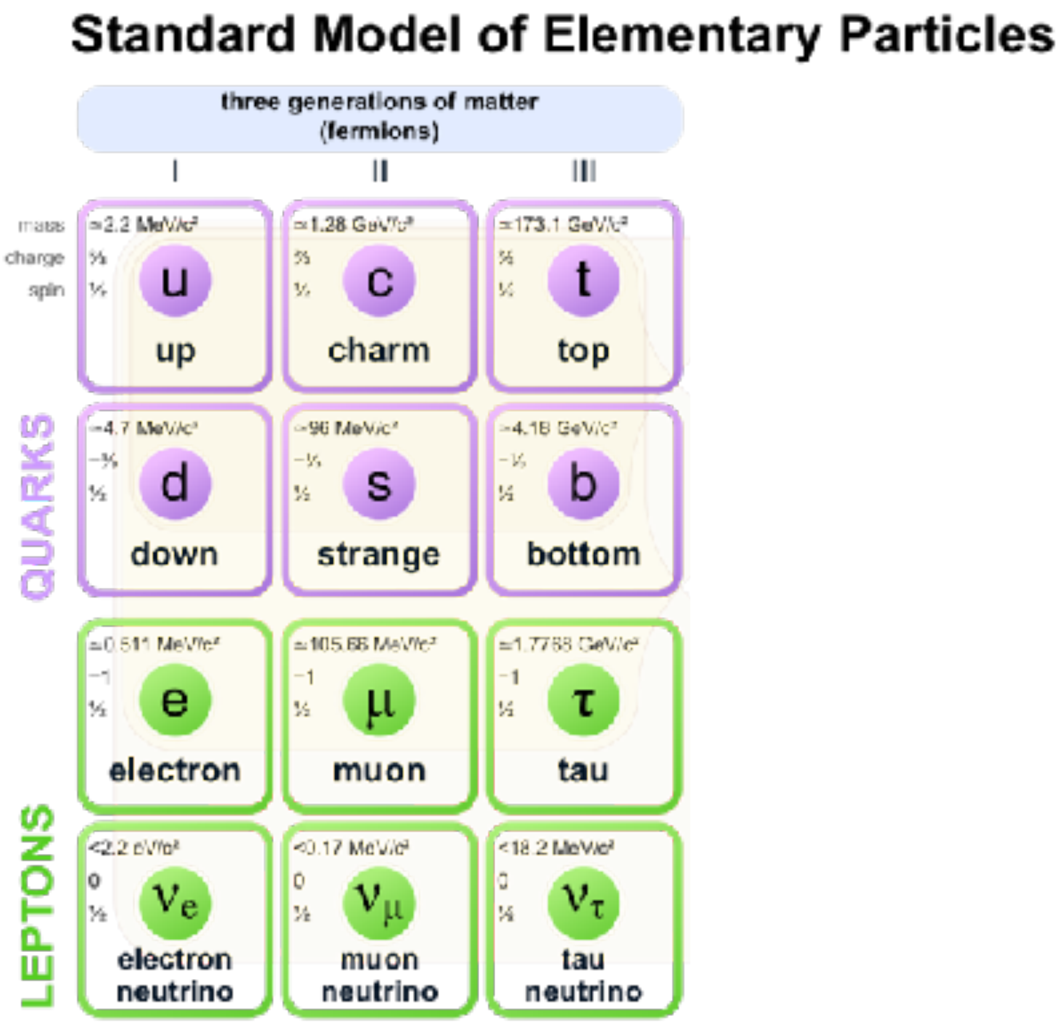


- All ordinary matter is made from up quarks, down quarks, and electrons
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier

Neutrinos


Standard Model of Elementary Particles
three generations of matter
(fermions)
I
II
III
mass
charge
spin
u
up
c
charm
t
top
d
down
s
strange
b
bottom
e
electron
μ
muon
τ
tau
νe
electron
neutrino
νμ
muon
neutrino
ντ
tau
neutrino
QUARKS
LEPTONS

Neutrinos



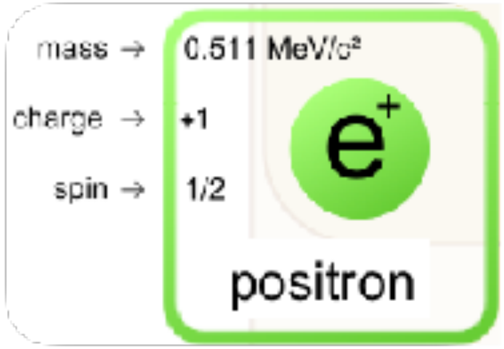
- All ordinary matter is made from up quarks, down quarks, and electrons
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier
- Leptons also include neutrinos, one for each generation

All of these are *matter* particles, or fermions

Antimatter

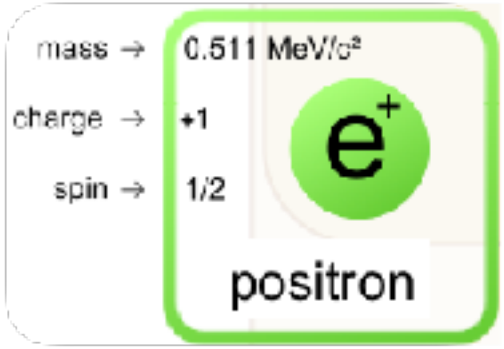
Antimatter


mass →
charge →
spin →
0.511 MeV/c²
-1
1/2
e-
electron


mass →
charge →
spin →
0.511 MeV/c²
+1
1/2
e+
positron

Antimatter

- Antimatter is exactly the same as matter except one attribute is flipped: the *charge*



- A particle and its antiparticle can annihilate into a pair of light particles (*photons*)

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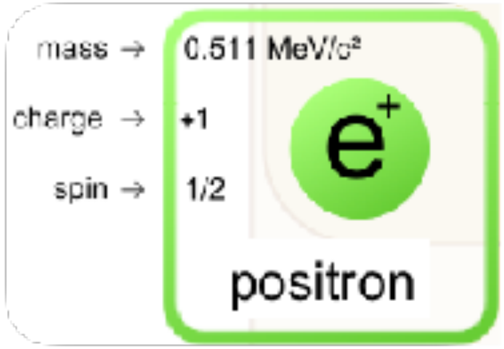

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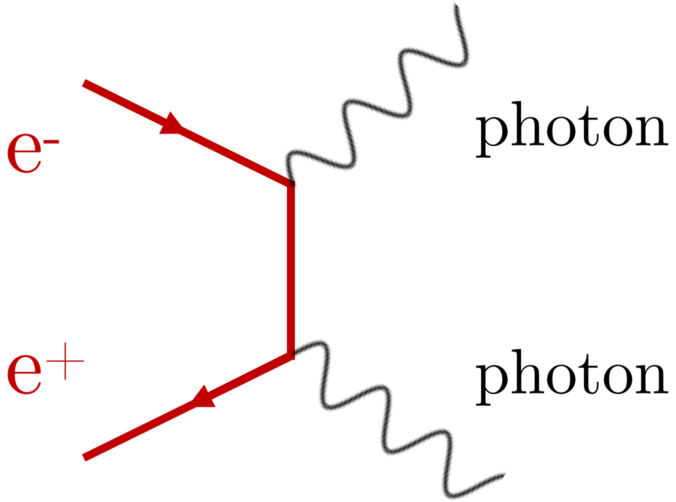
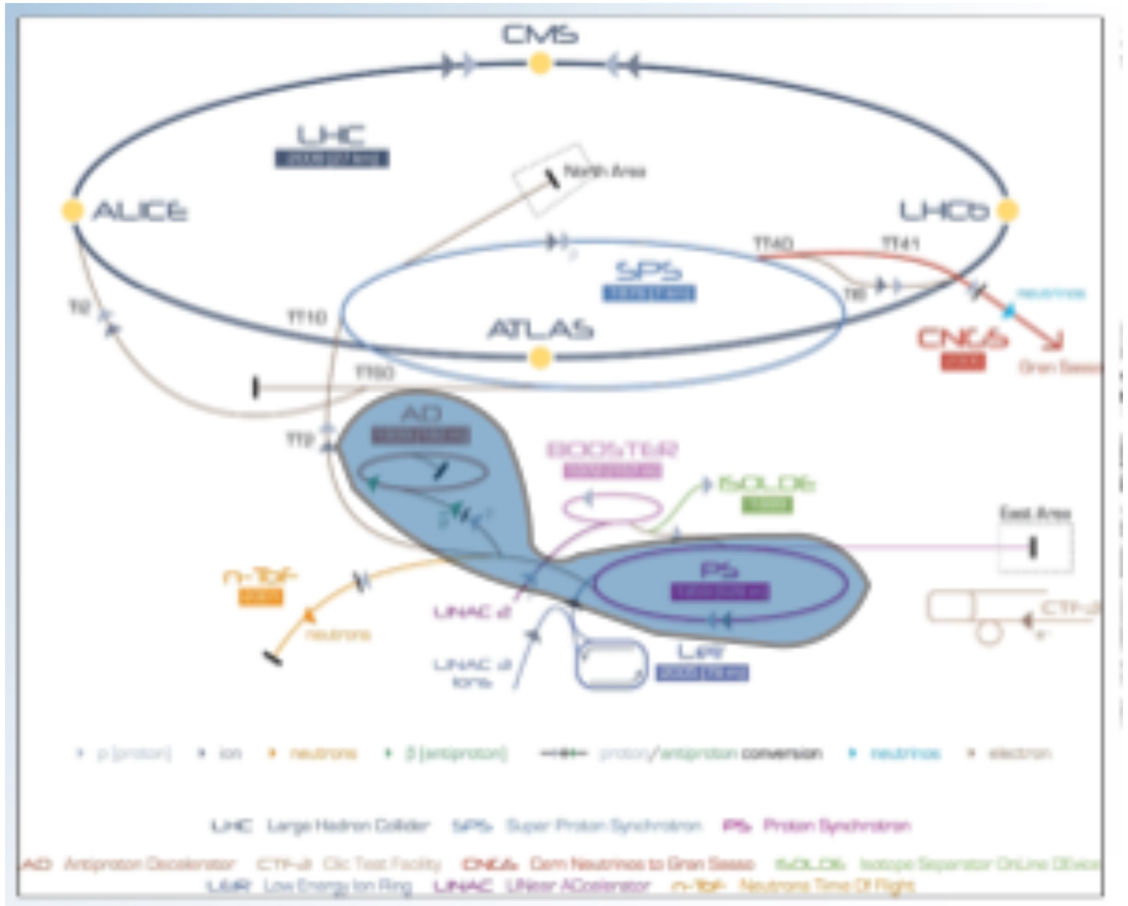


How do we make antimatter?

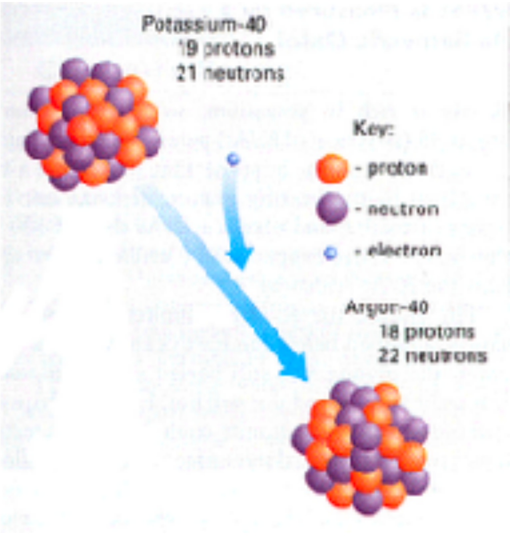
At the antimatter factory of course!



How do we make antimatter?

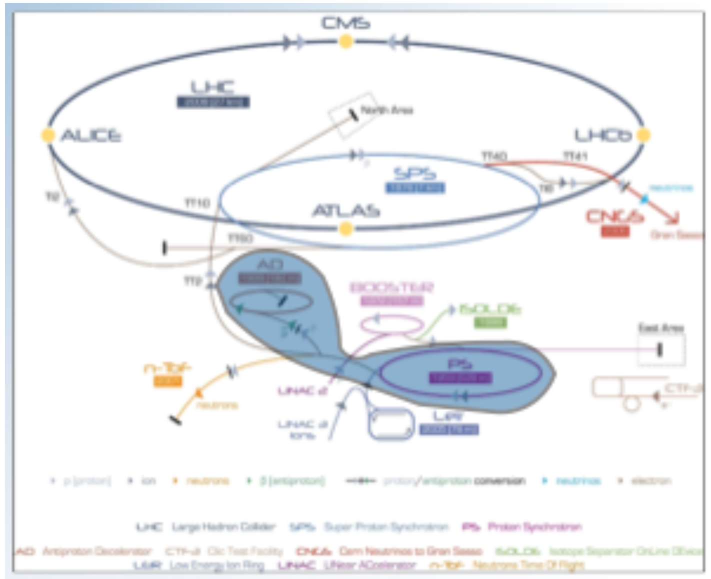
Positrons from Potassium-40: your body produces about 180 positrons per hour!

$$^{40}_{19}\mathrm{K} \rightarrow ^{40}_{18}\mathrm{Ar} + e^{+} + \nu_e$$

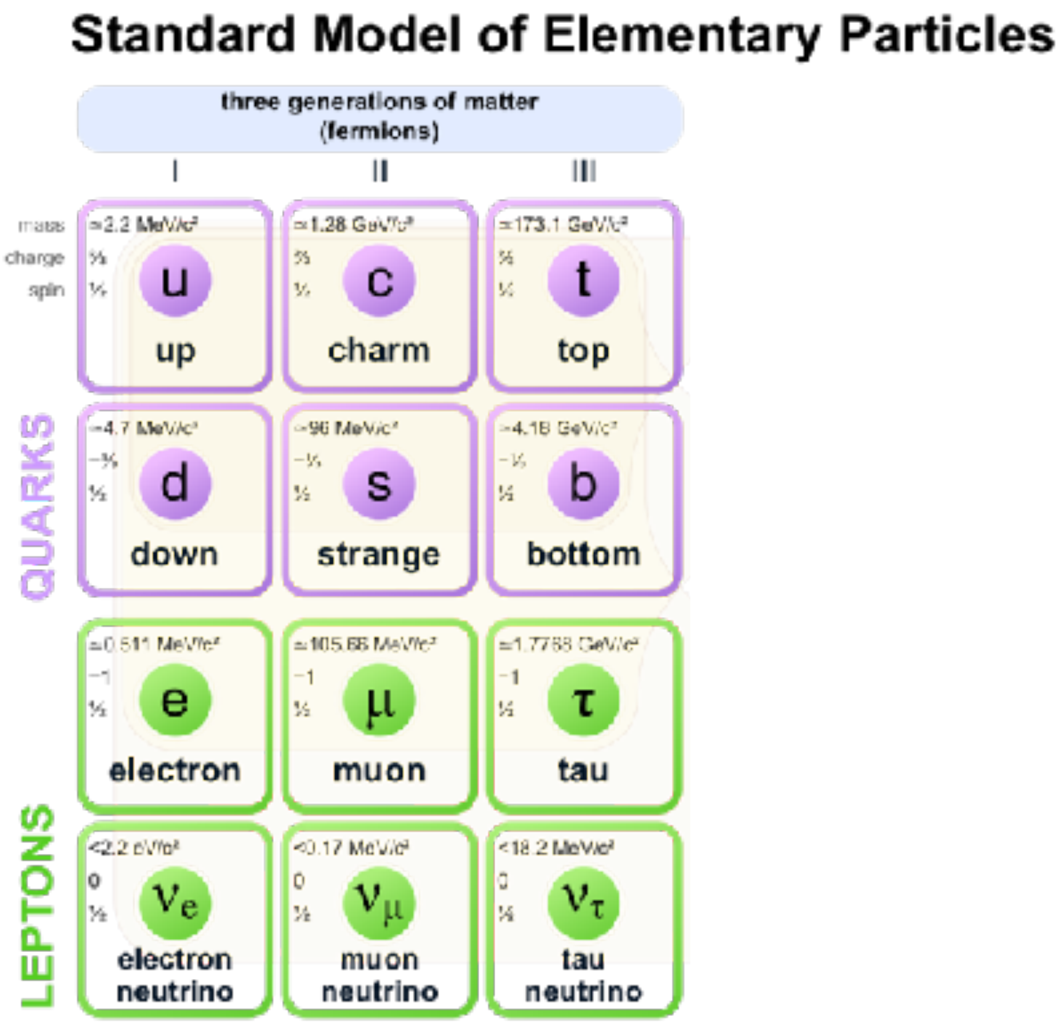


Antiprotons from high energy collisions of a proton beam on a fixed target of metal

$$p + p \rightarrow \overline{p} + p + p + p$$



Force carriers



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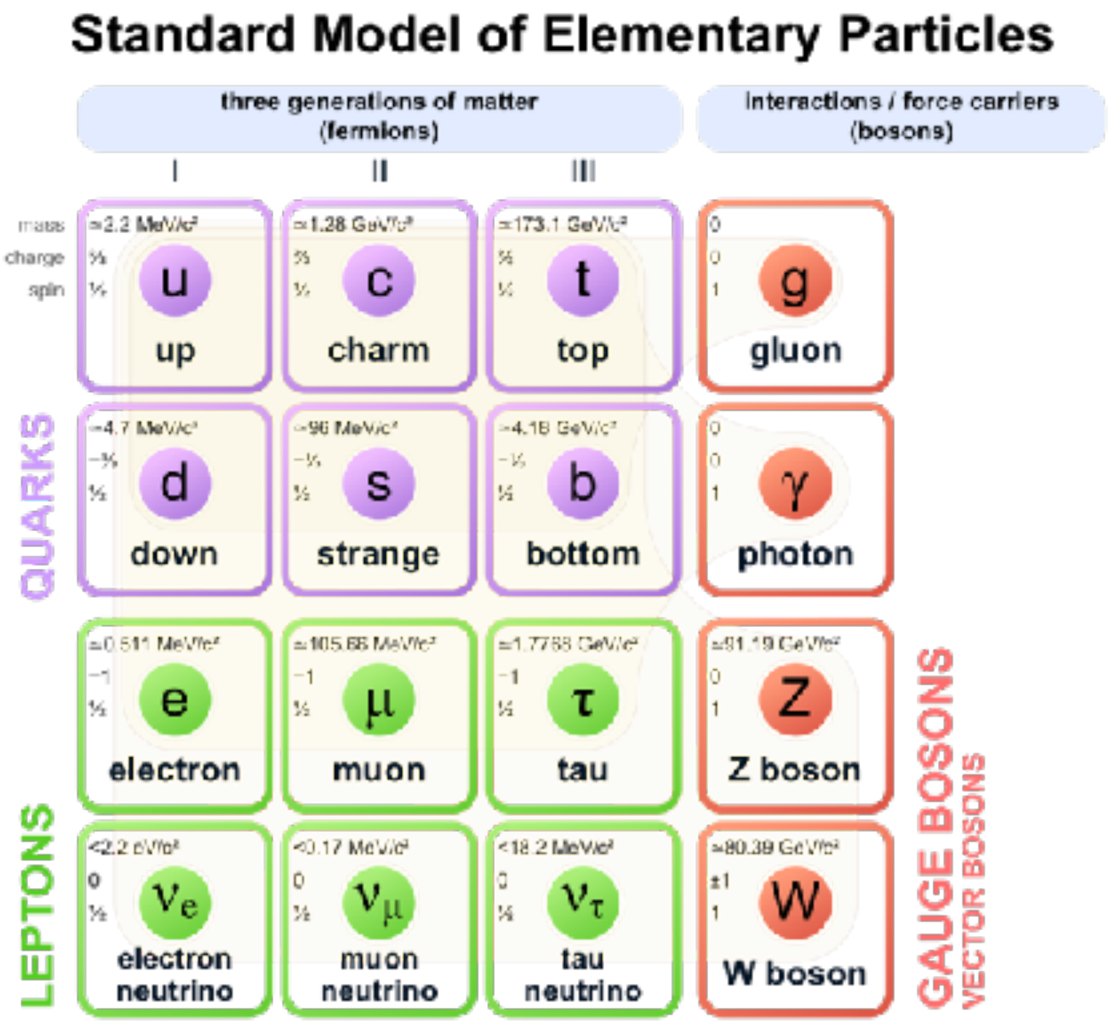

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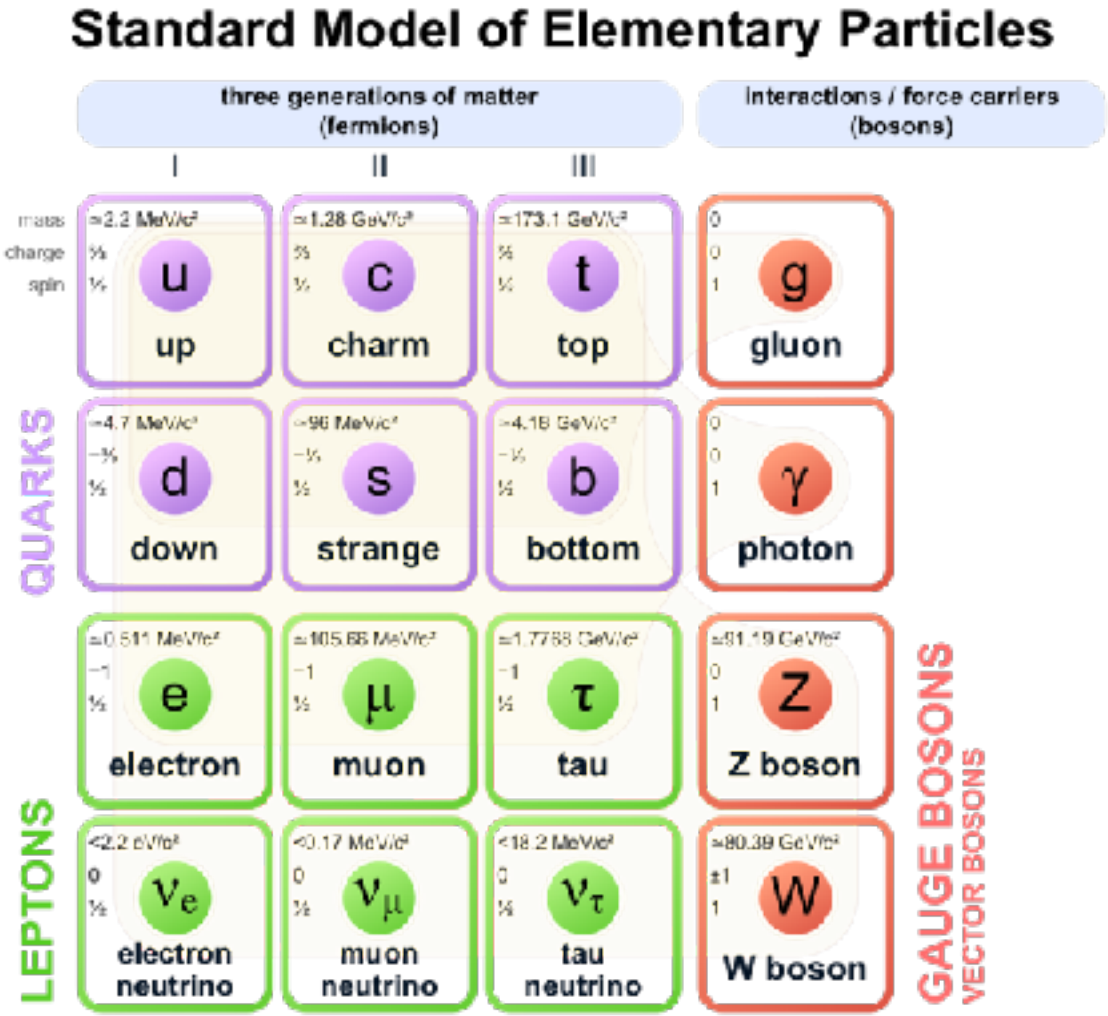
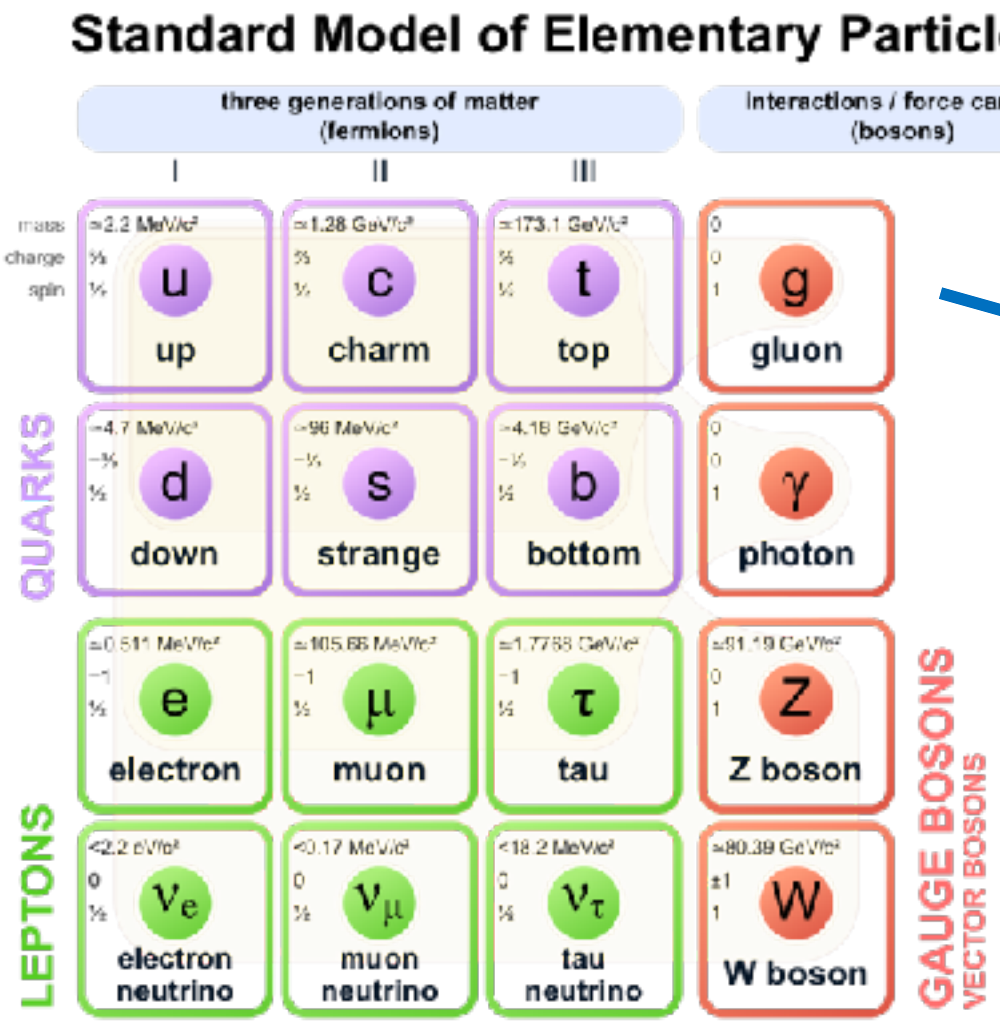


- The other group of particles in the Standard Model are bosons

Force carriers



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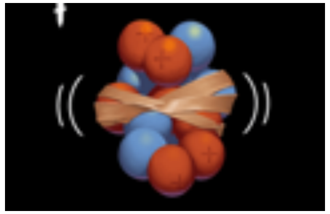
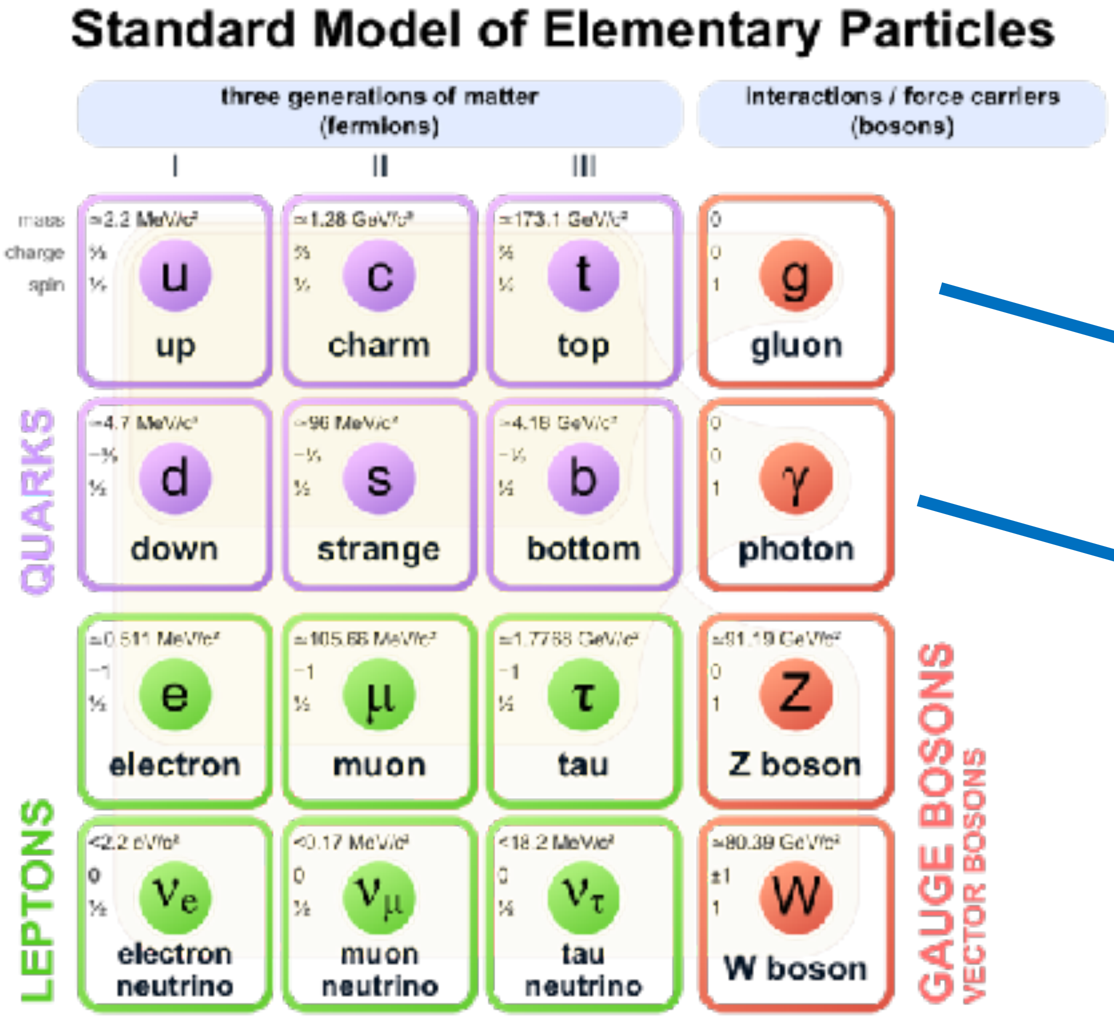


Strong force

Force carriers



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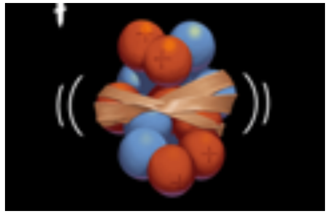
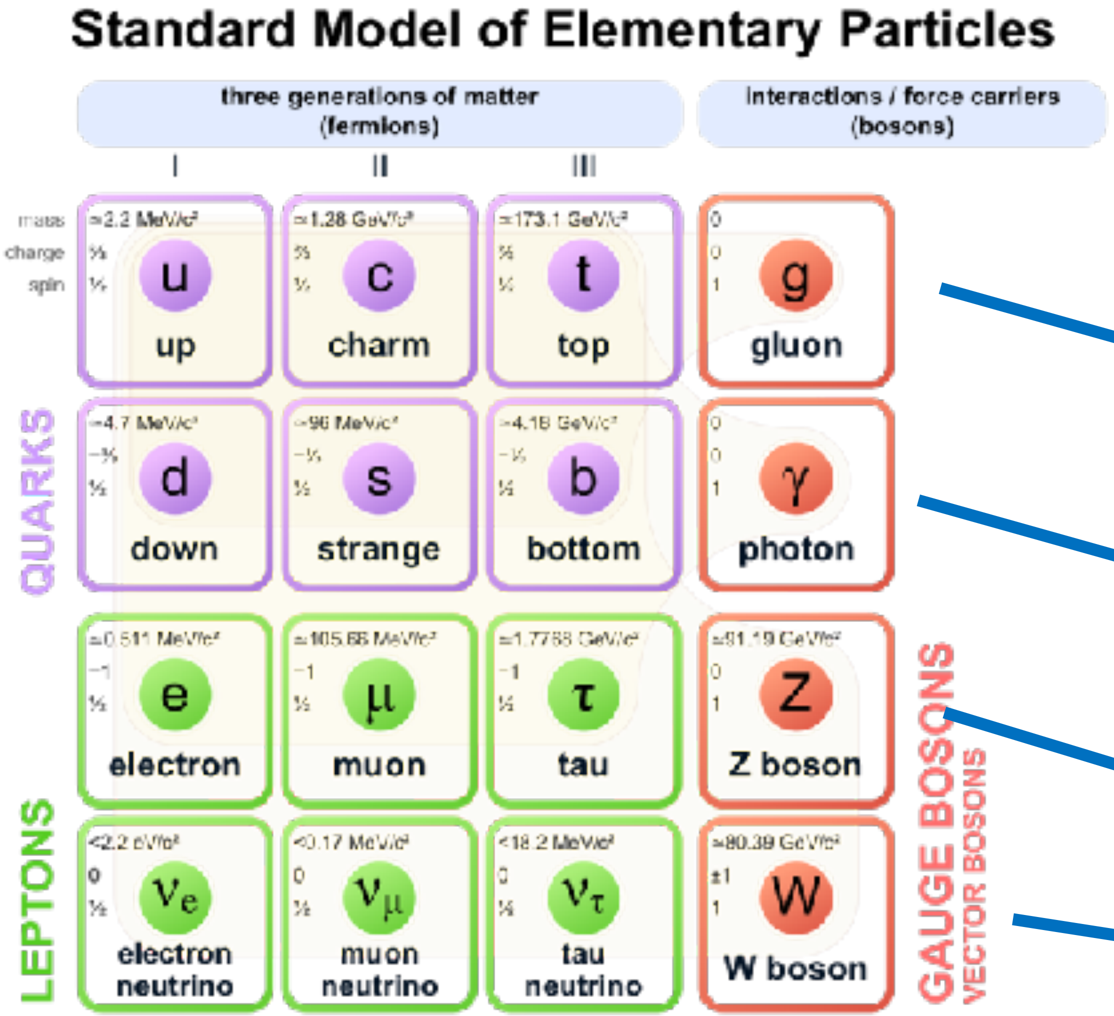


Strong force

Electromagnetic force

Force carriers



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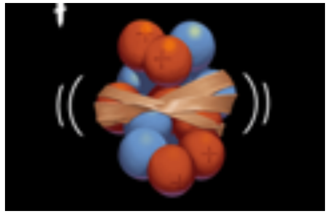
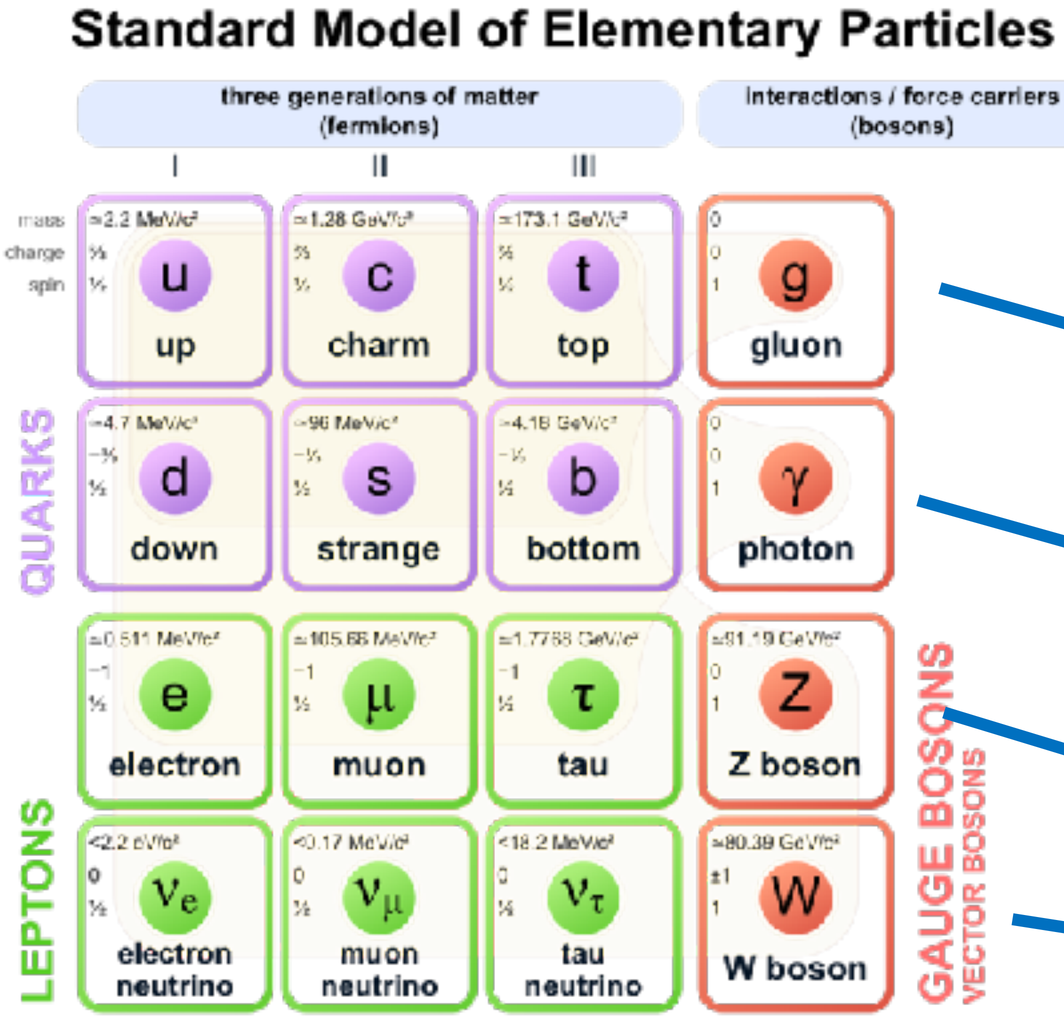


Strong force

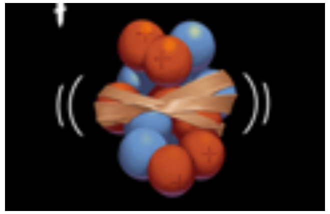
Electromagnetic force

Weak force

Force carriers



- The other group of particles in the Standard Model are bosons
- These are the force carriers



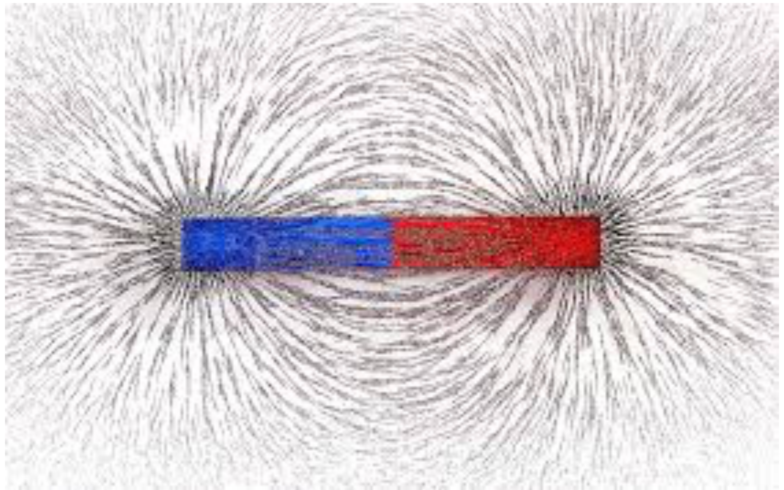
Strong force

Electromagnetic force

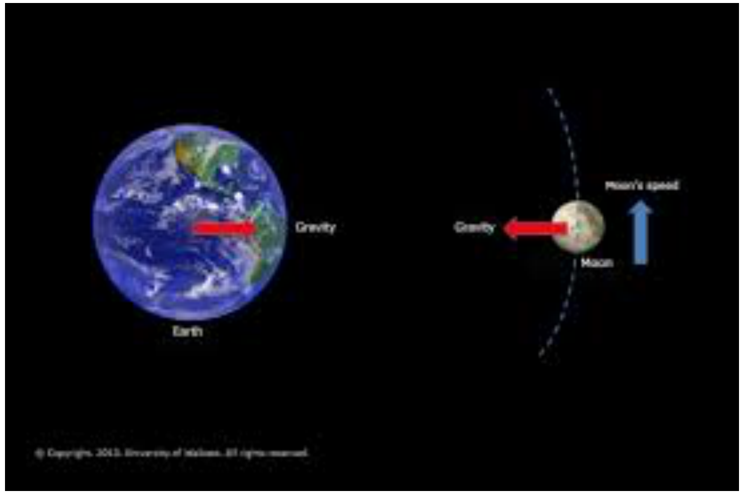
Weak force

How do Matter Particles Interact?

- Particles interact without touching!

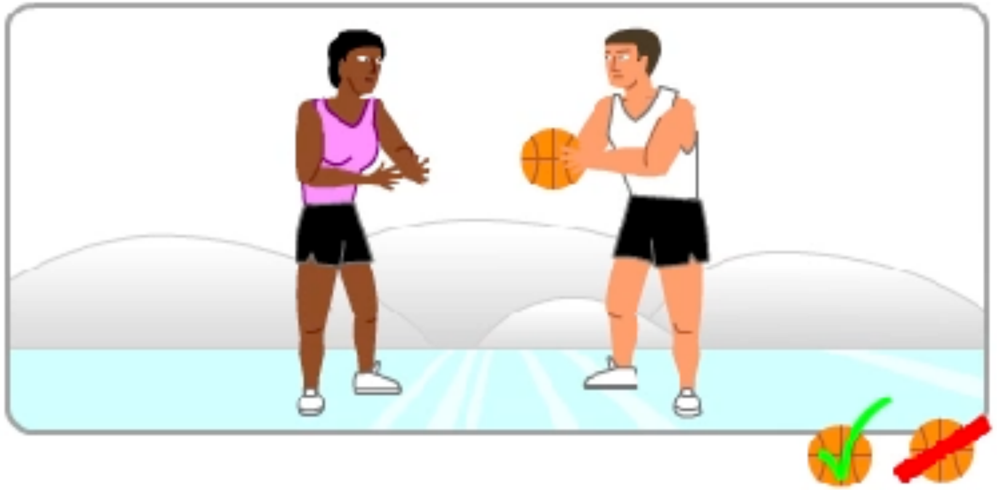


Iron filings “feel” the presence of a magnet



Earth attracts the Moon.

The Unseen Effect

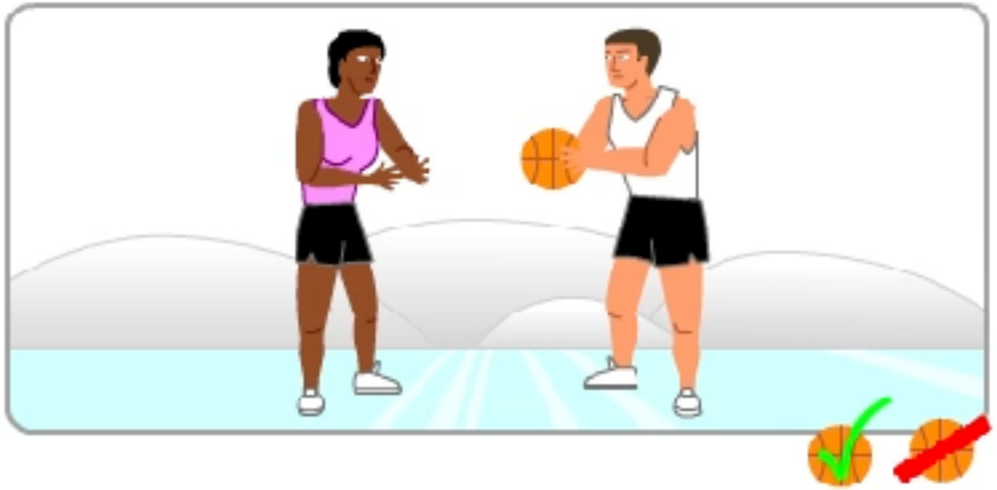


- Even though we cannot see the basketball, we see the effect throwing it has on the two people.

- All interactions which affect matter particles are due to the exchange of force carrier particles

- What we think of as forces, are the effects of the force carrier particles on matter particles

The Unseen Effect



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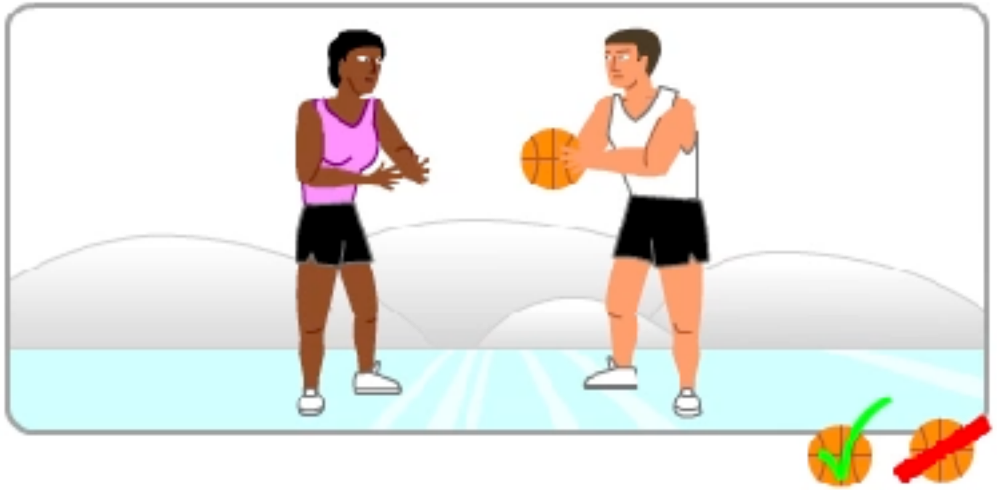

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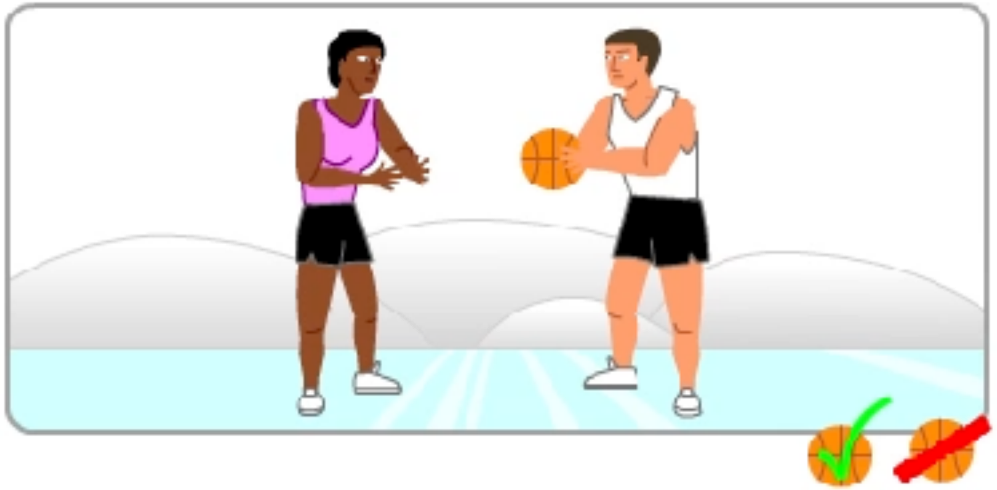

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Color Charge

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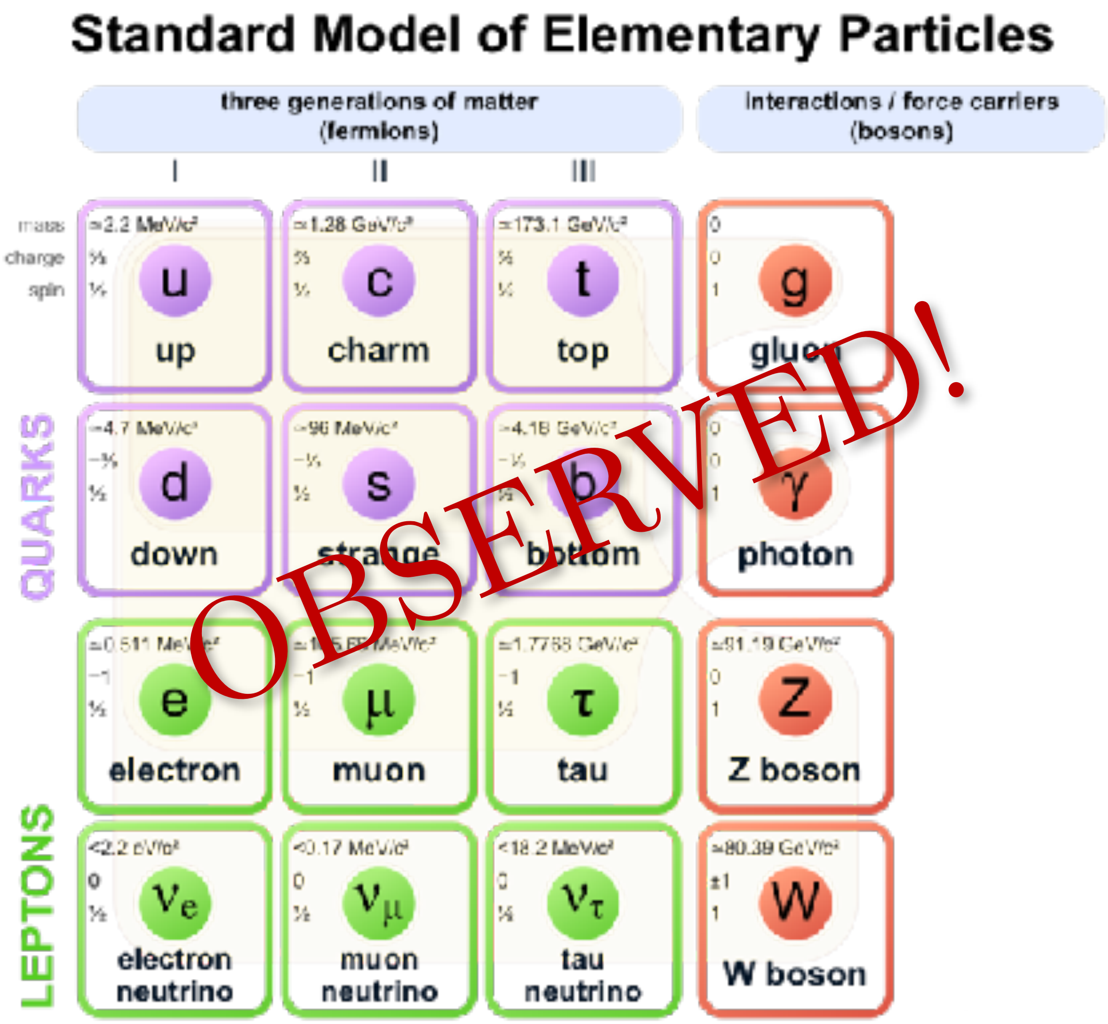
Color Charge

- Quarks and gluons are color-charged particles*
- Quarks constantly change their color charges as they exchange gluons with other quarks.
- This exchange creates a very strong color force field that binds the quarks together.
- Color-charged particles cannot be found individually. The color-charged quarks are confined in groups with other quarks. These composites are color neutr

* "Color charge" has nothing to do with the visible colors, it is just a convenient naming convention for a mathematical system

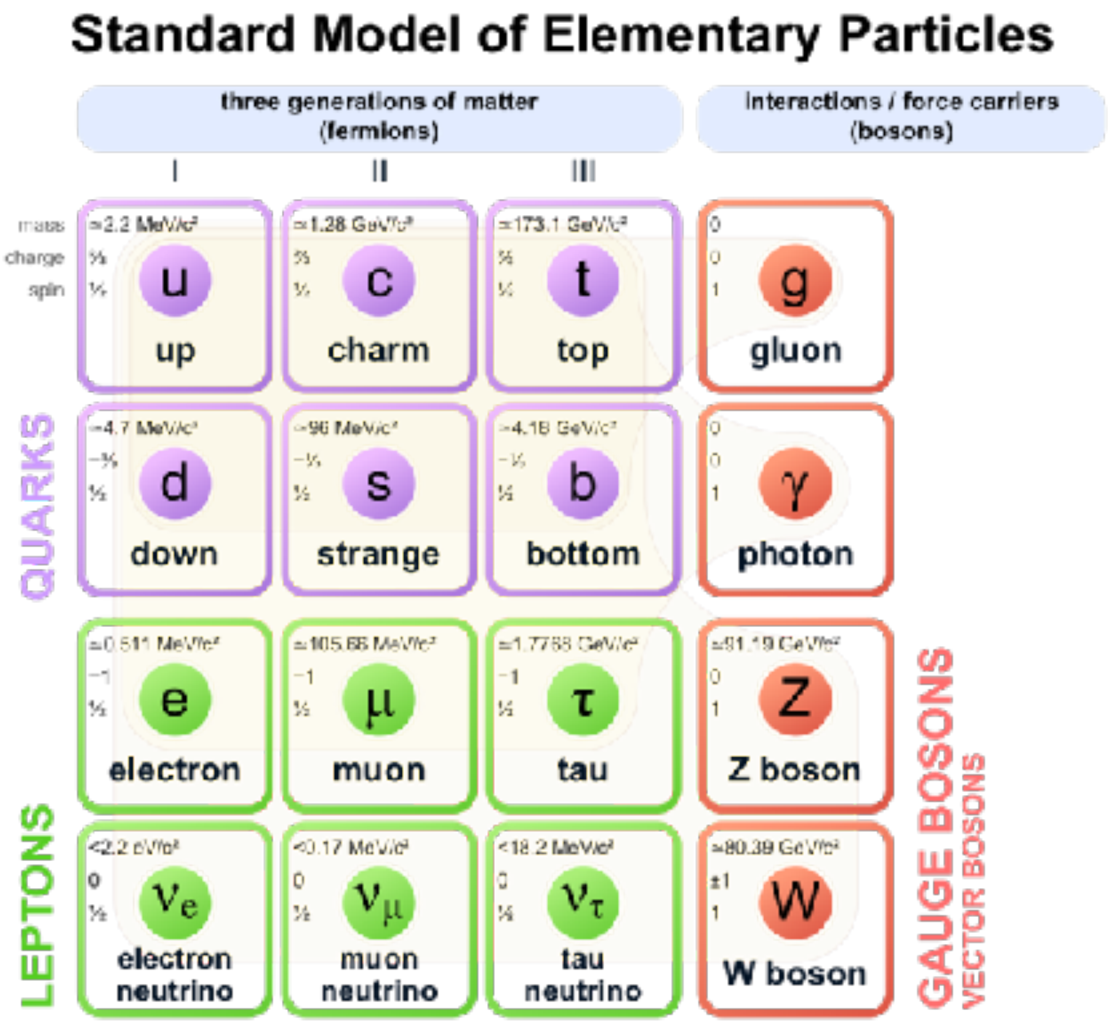
Experimental confirmation



Status in 2000: all gauge bosons, quarks, and leptons particles have been discovered!

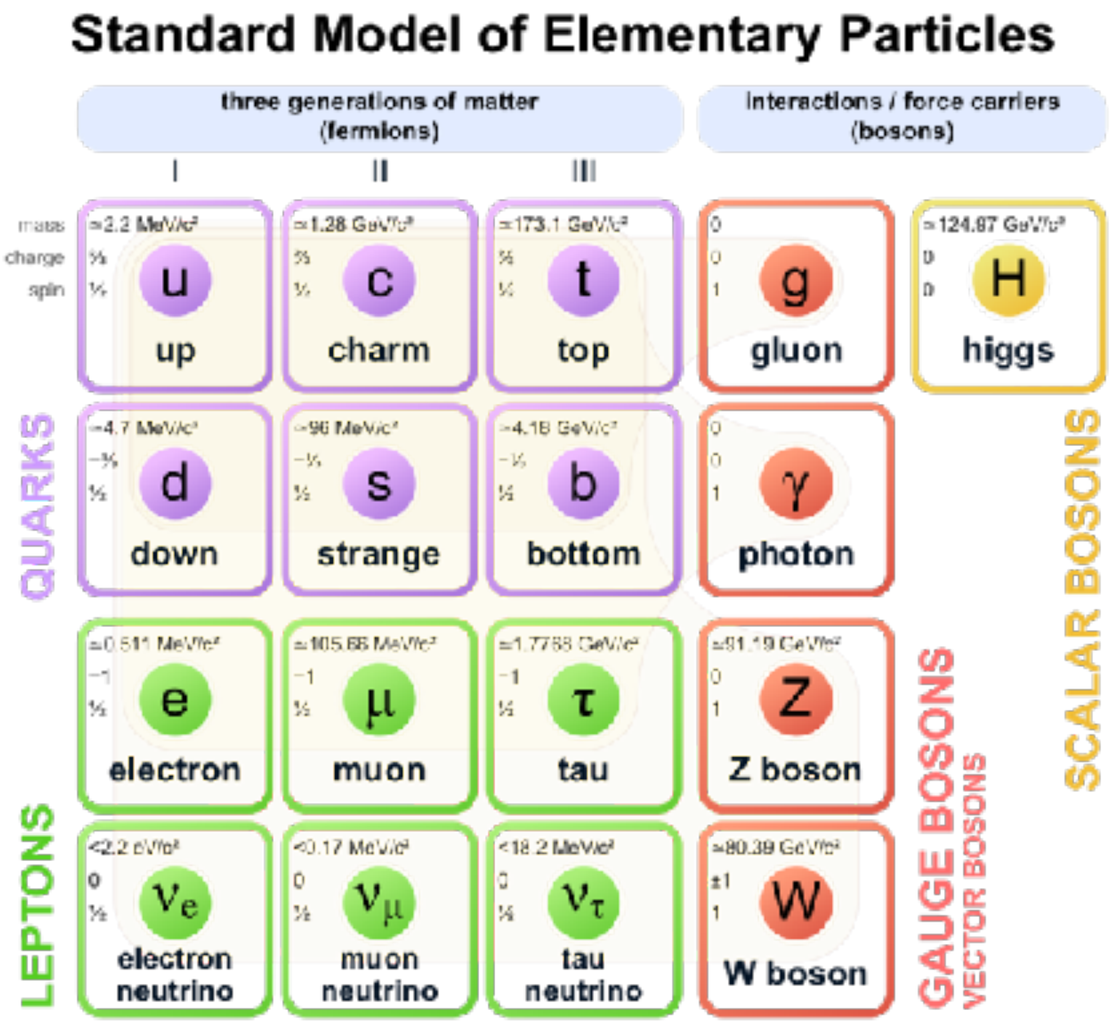
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1978@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL

Last piece of the puzzle



- Last missing piece = Higgs boson

Last piece of the puzzle



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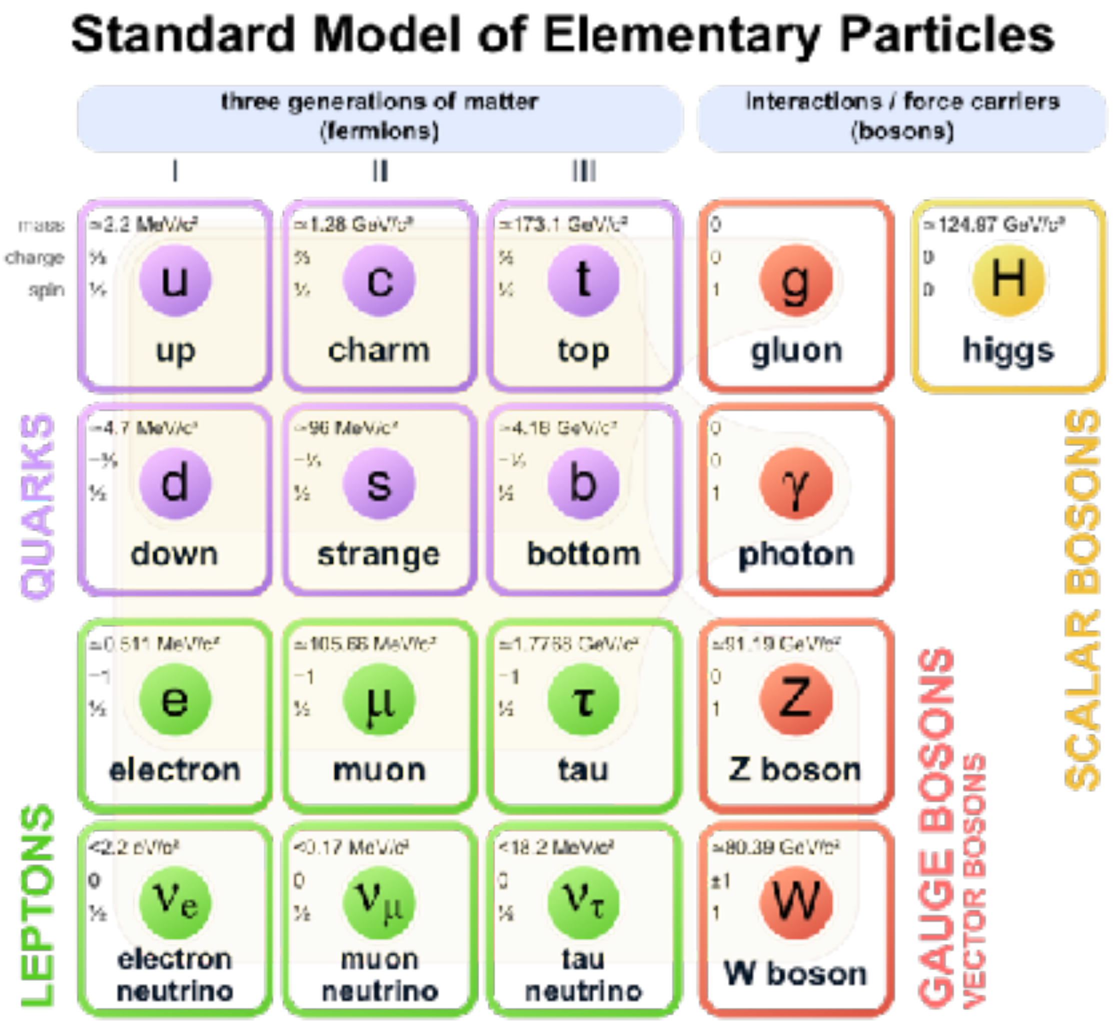


- Last missing piece = Higgs boson

- Higgs mechanism was proposed in the 1960's by Peter Higgs and François Englert to explain how particles get their mass
  - Higgs field permeates the universe
  - New particle predicted, the Higgs boson

Recipe for Higgs boson discovery

Ingredients

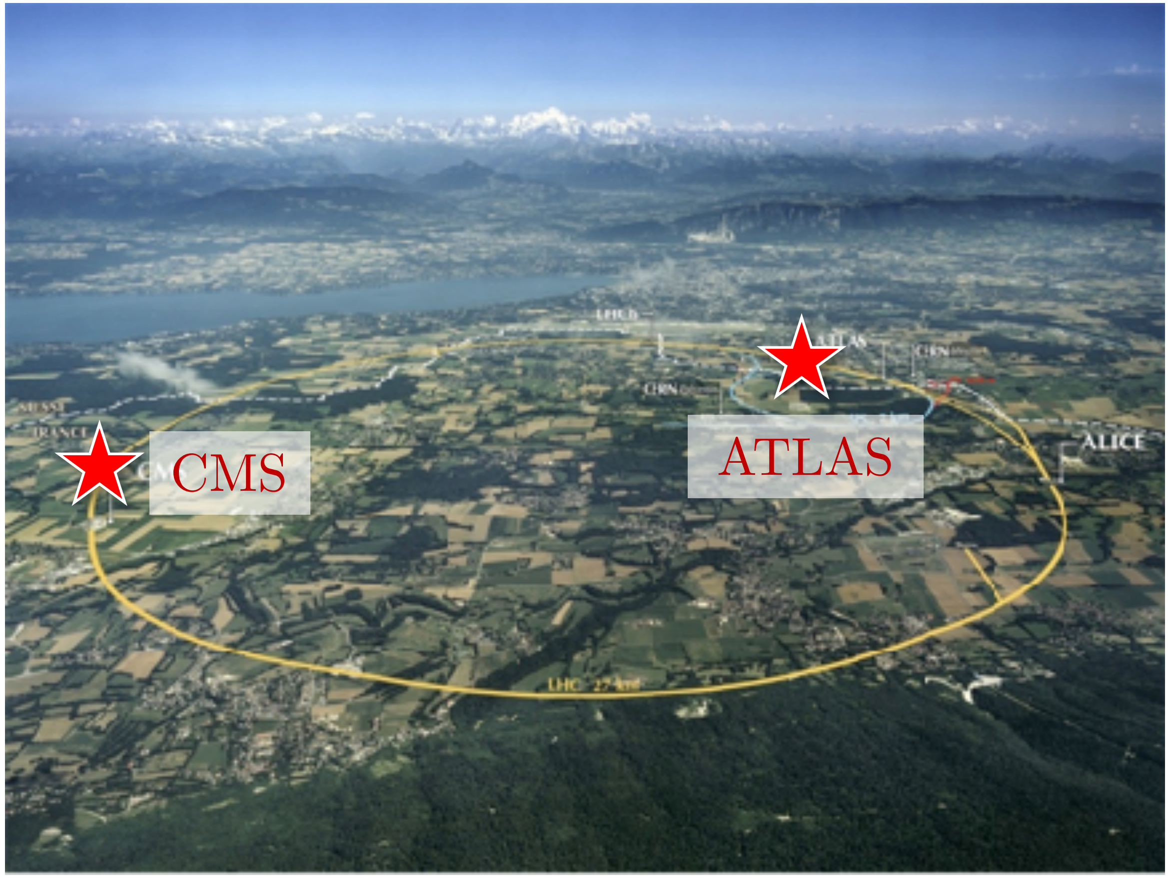
- One theoretical prediction
- One high energy particle accelerator
- Two all-purpose particle detectors
- 7,000 scientists, engineers, and students from over 40 countries and nearly 400 institutes

Baking Time

Approximately 5 decades

Serving Size:

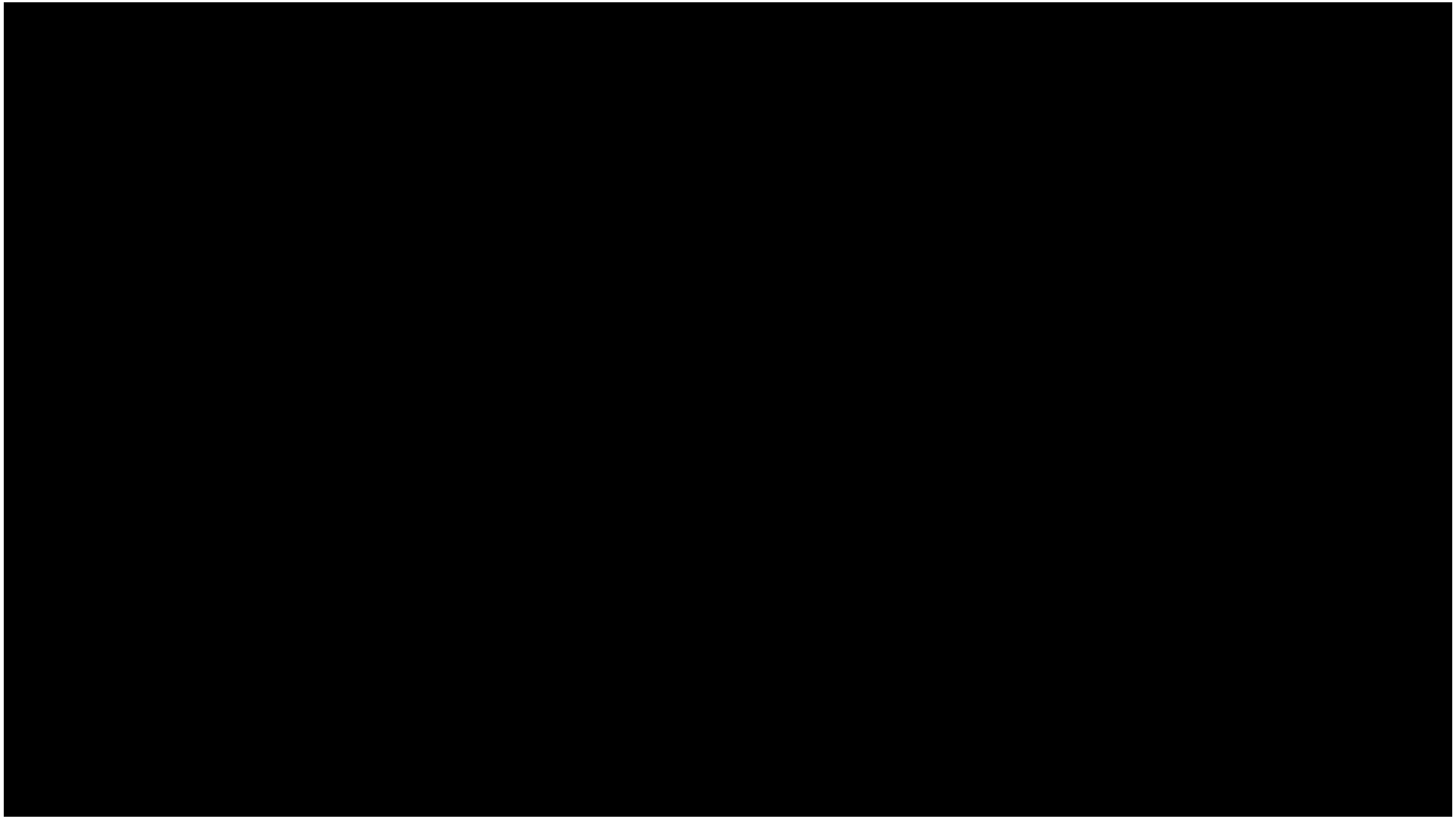
One Higgs boson



July 4, 2012: Higgs Boson discovery!

Englert and Higgs receive the 2013 Nobel Prize in Physics

The Higgs Boson - Explained



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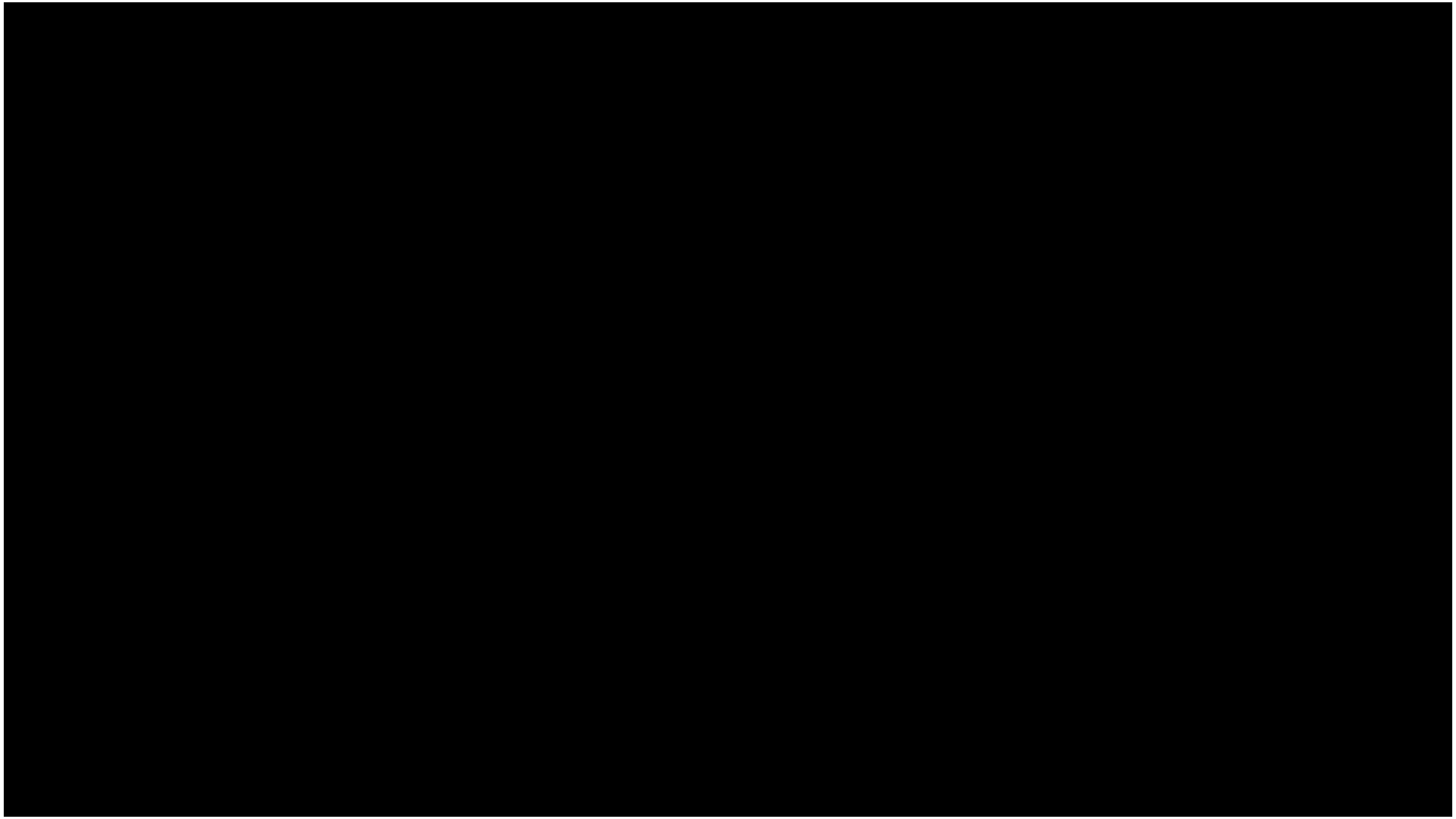

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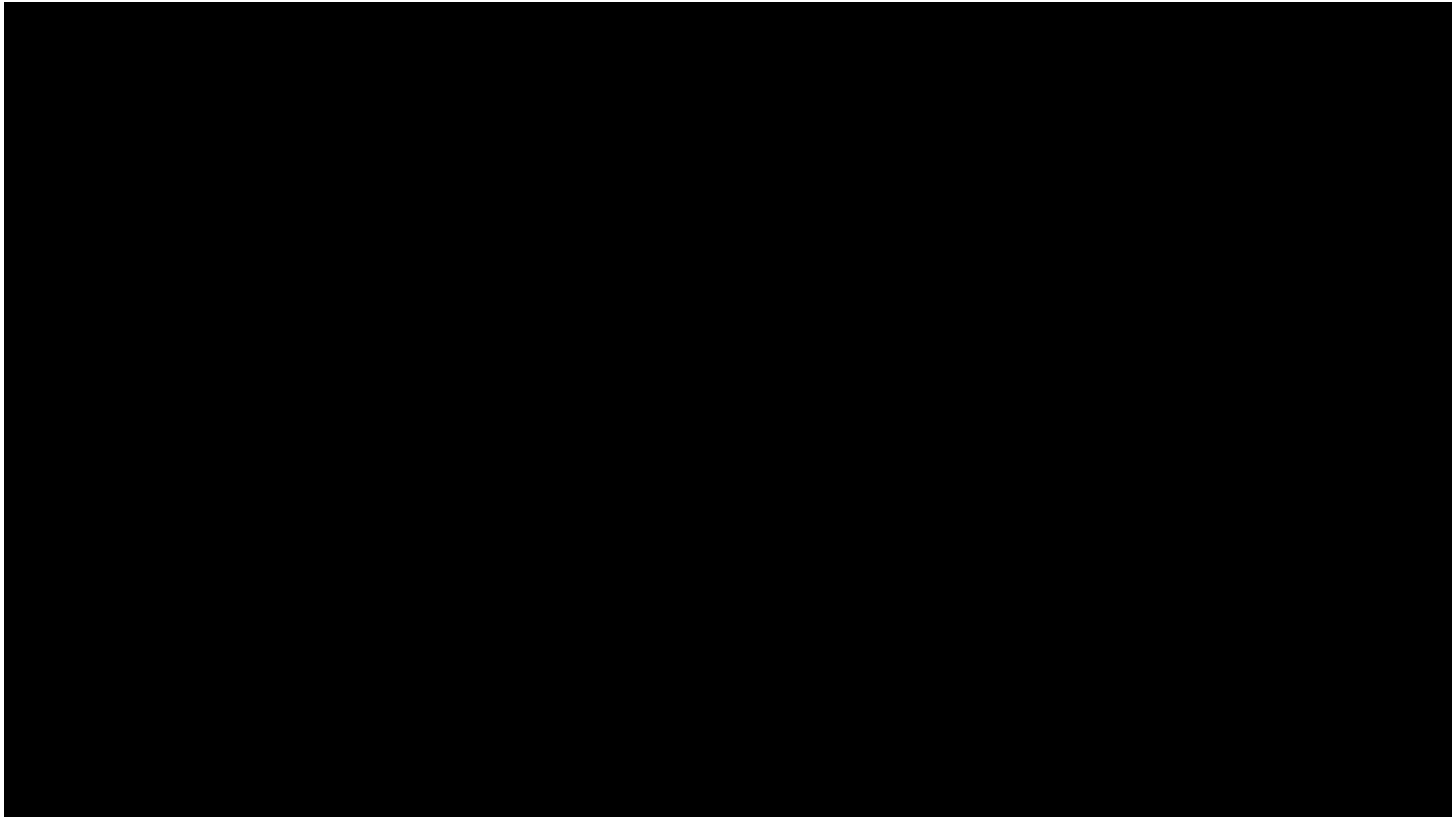
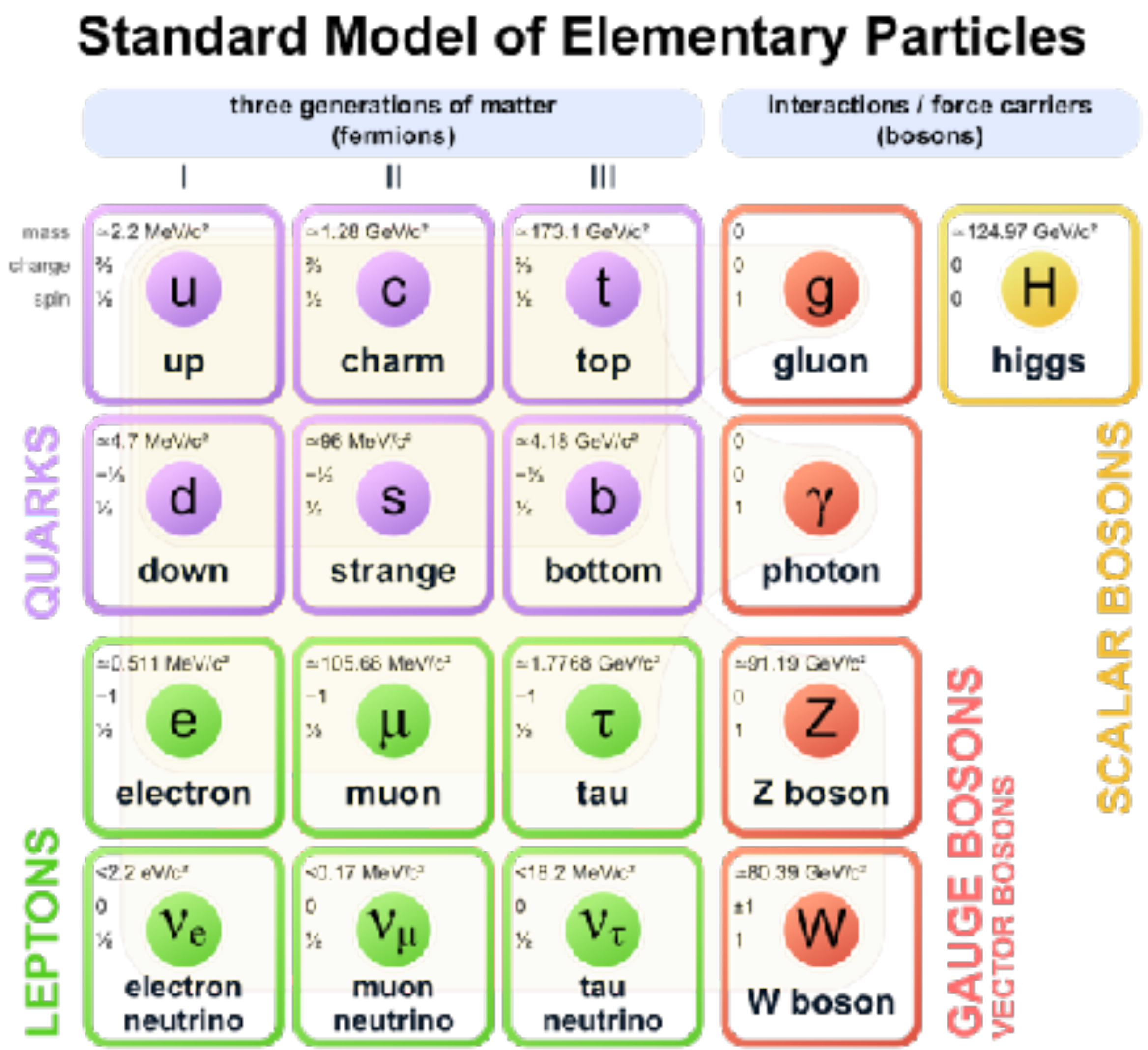




Standard Model

Everything we have learned in the last several decades about fundamental particles and their interactions

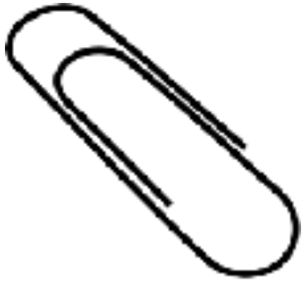
Experimental Methods

Quantum Play-Doh

How do we detect sub-atomic particles that are far too small for us to see?

-> Particle physics is all about indirect detection.

Particle Collison



Detector

Particles to discover

- Using your paper clip, try to figure out what is in your Play-Doh
- No peeking!!

Quantum Play-doh

- Using your paper clip, try to figure out what is in your Play-Doh
- No peeking– only indirect detection is allowed!

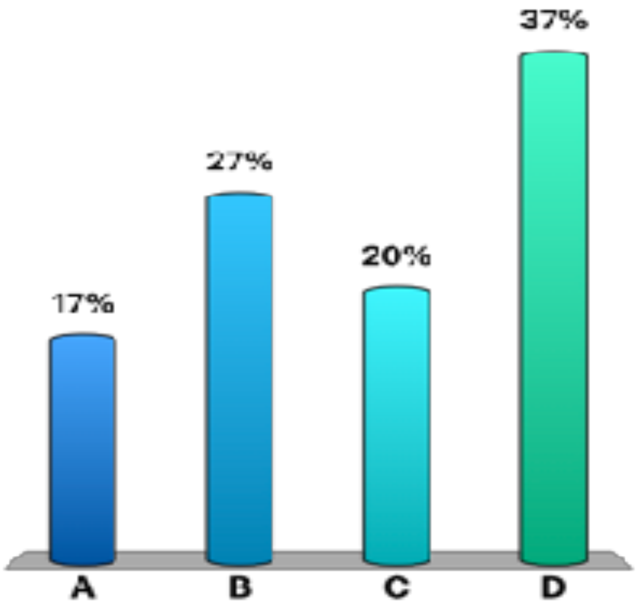
What particle is hiding in your quantum play-doh?

A. Rod

B. Screw

C. Nut

D. Other?



Quantum Play-doh

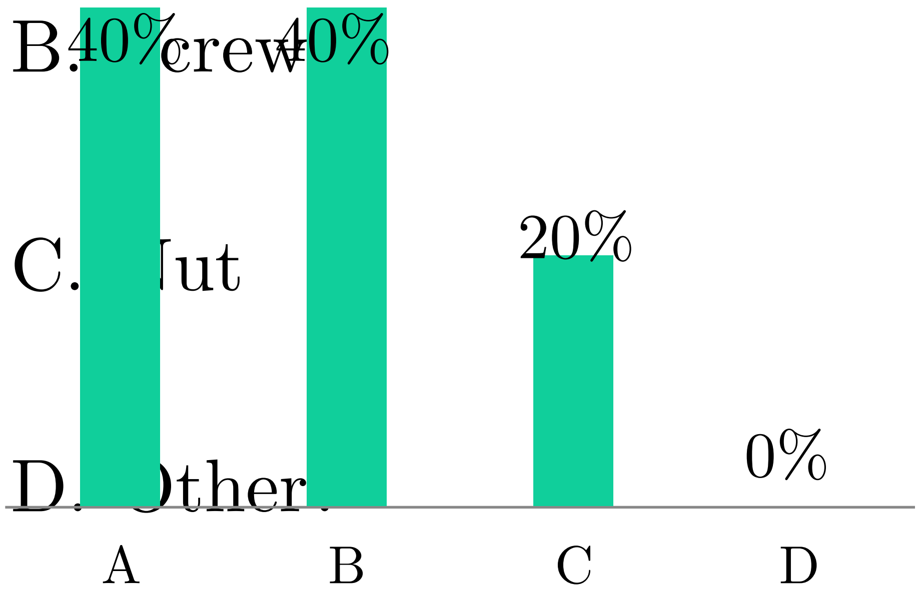
- After collecting the data, the big question is

Does the data agree with what we expected?

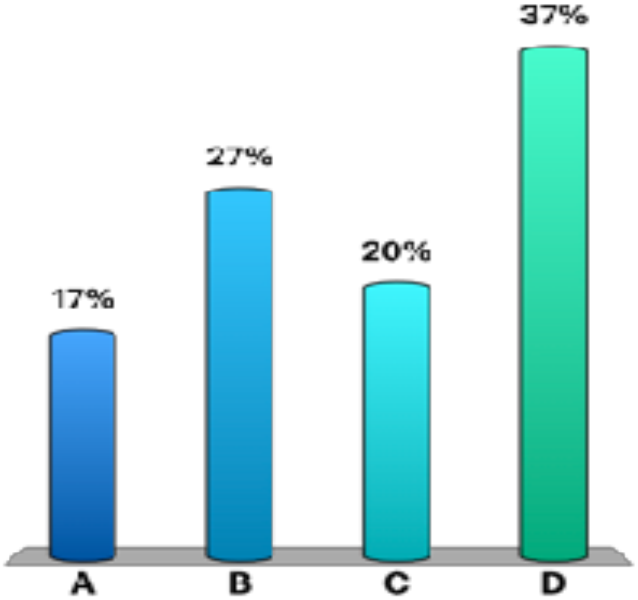
If YES: Hurray! The Standard Model works!

If NO: Hurray! We found evidence for new physics!

PREDICTION



OBSERVATION



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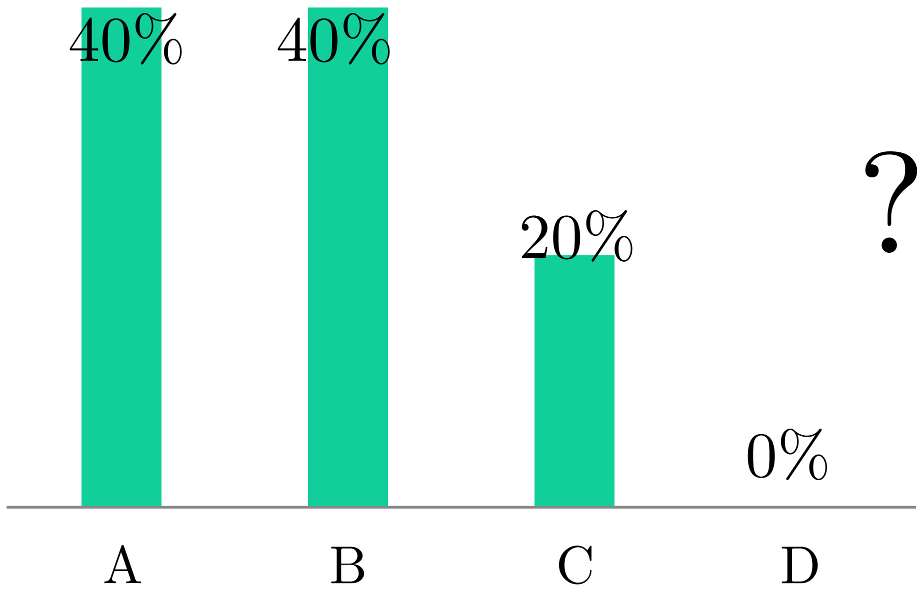

$\stackrel{?}{=}$

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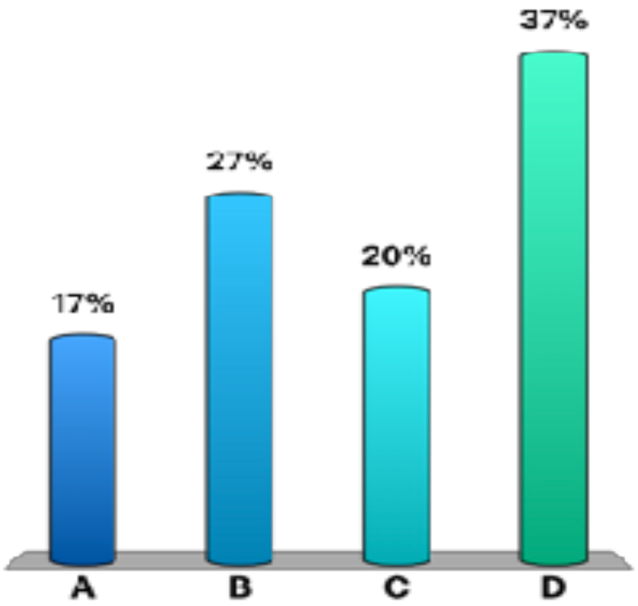
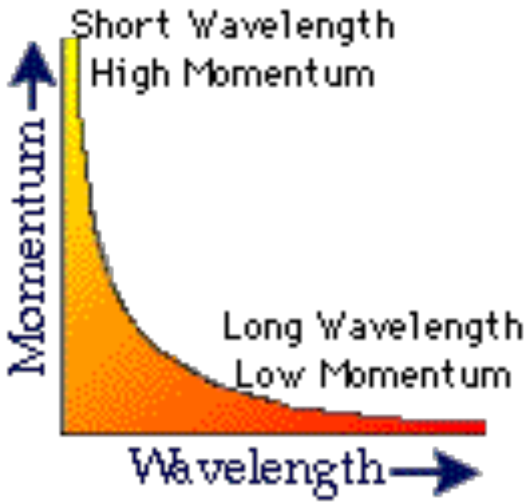
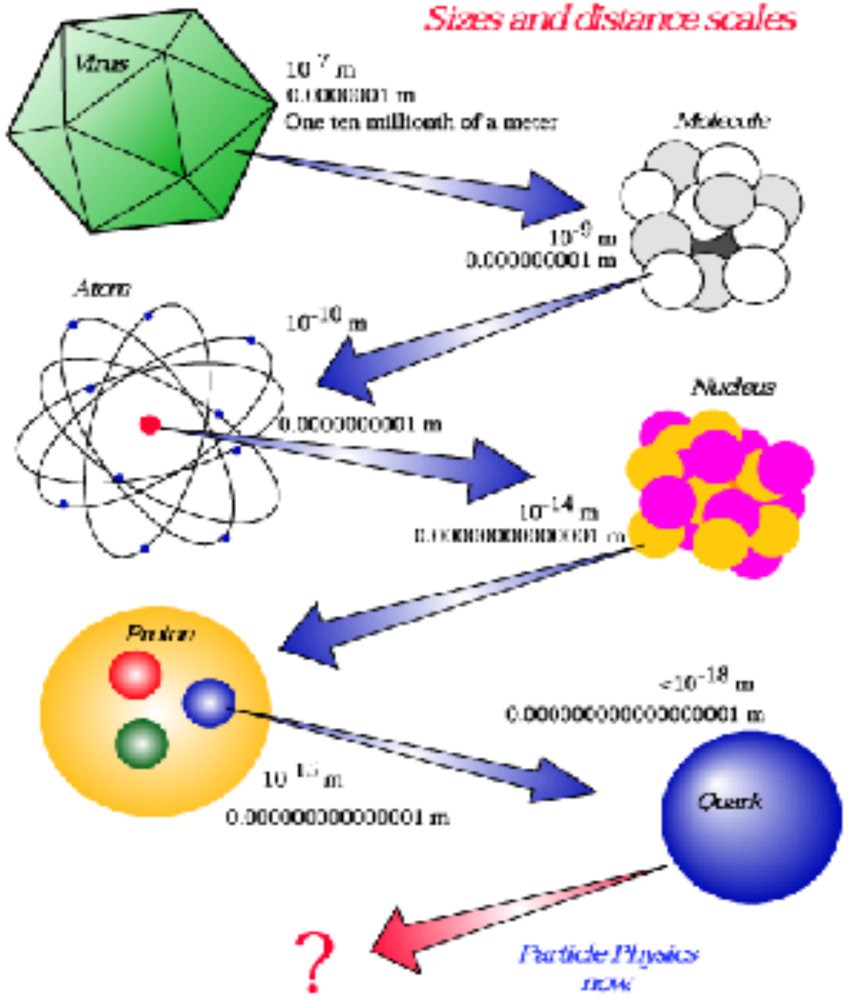


Accelerators

- All particles have wave properties
- We need to use particles with short wavelengths to get detailed information about small things
- A particle's wavelength is inversely proportional to its momentum
- Higher momentum means we can probe smaller scales!





Large Hadron Collider

- 17 miles in circumference
- World's largest and highest energy hadron collider
  - Collides protons at 99.999 999 99% the speed of light!
  - 13 TeV center of mass energy
  - Beats the previous record held by the Tevatron at Fermilab

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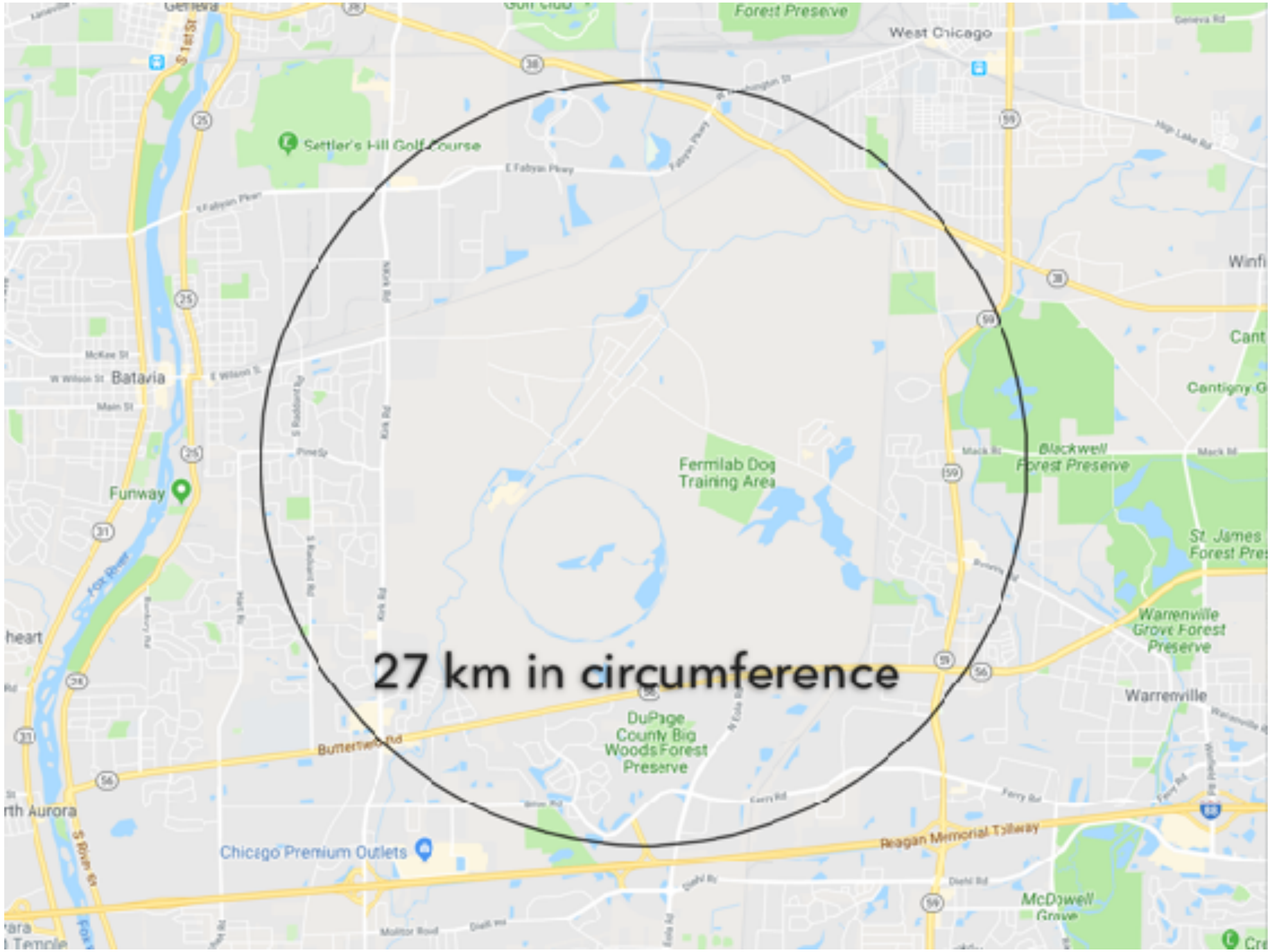
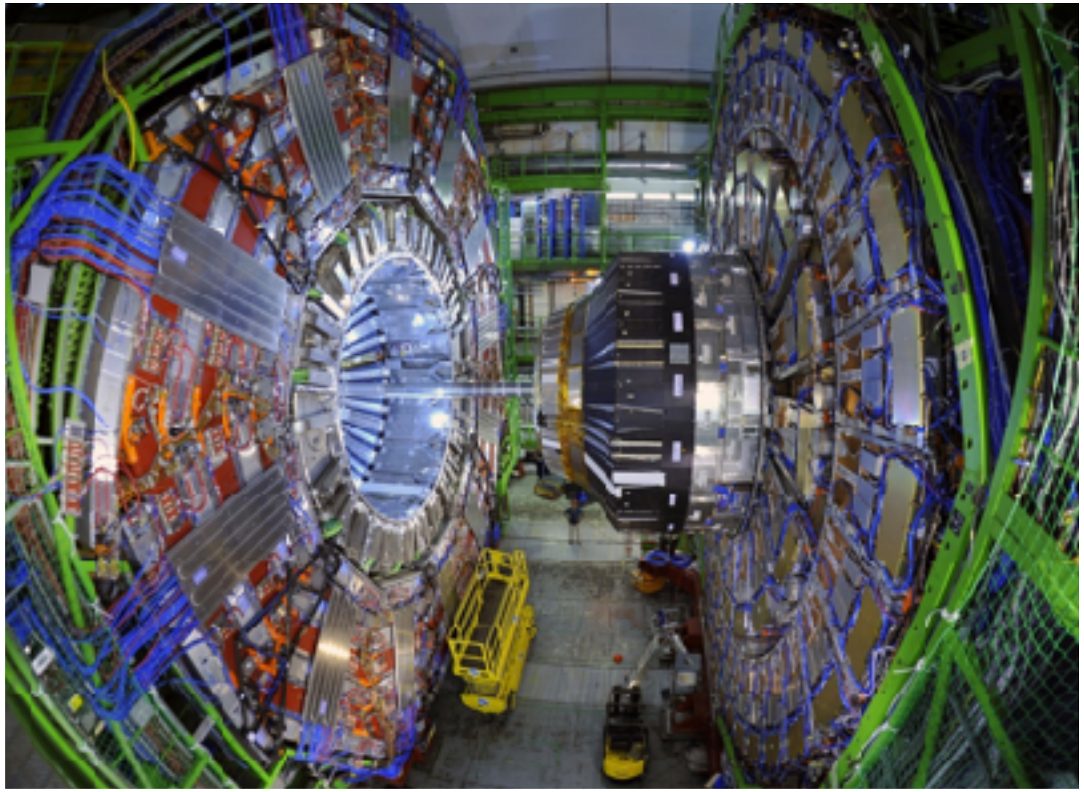
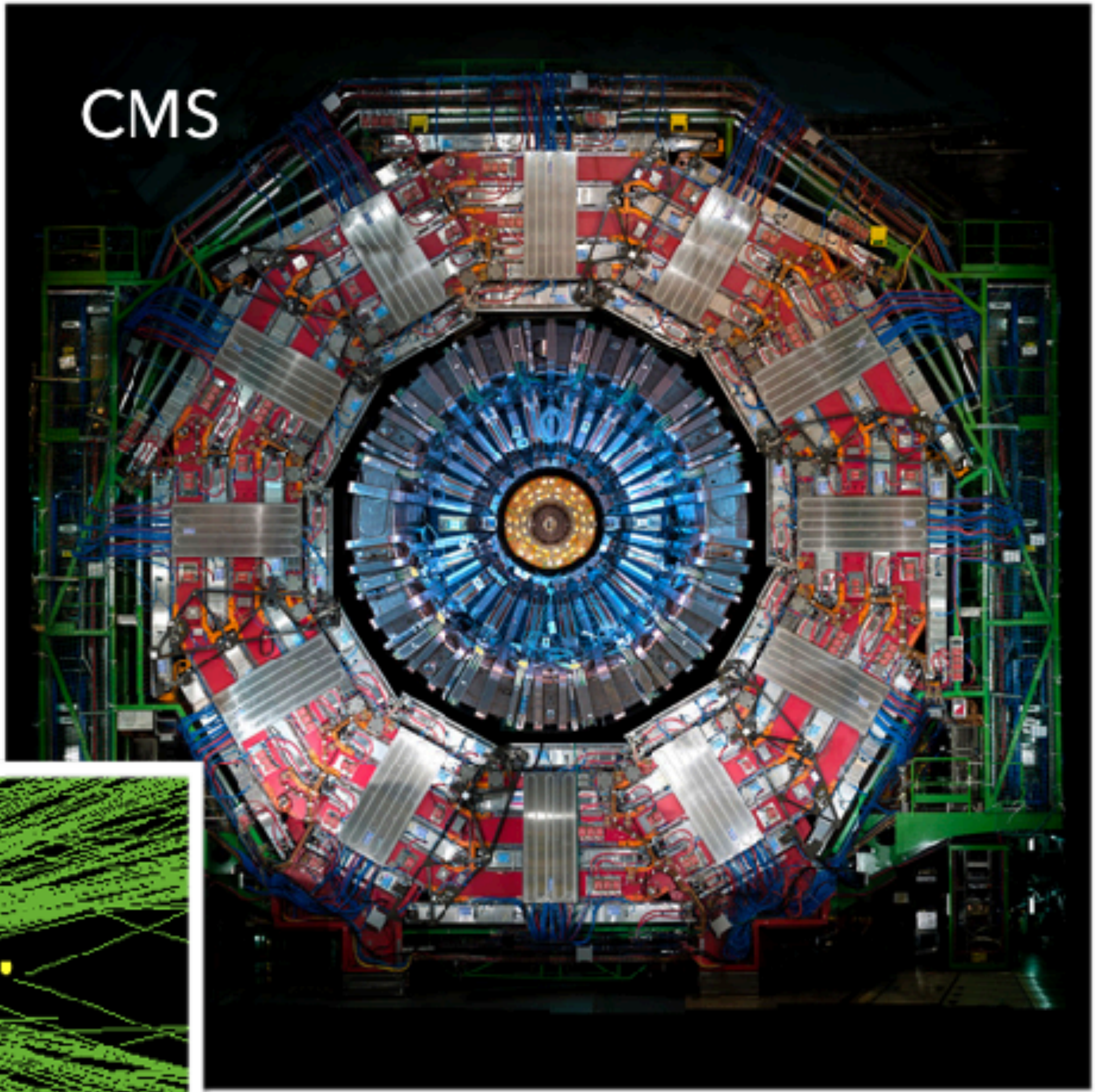
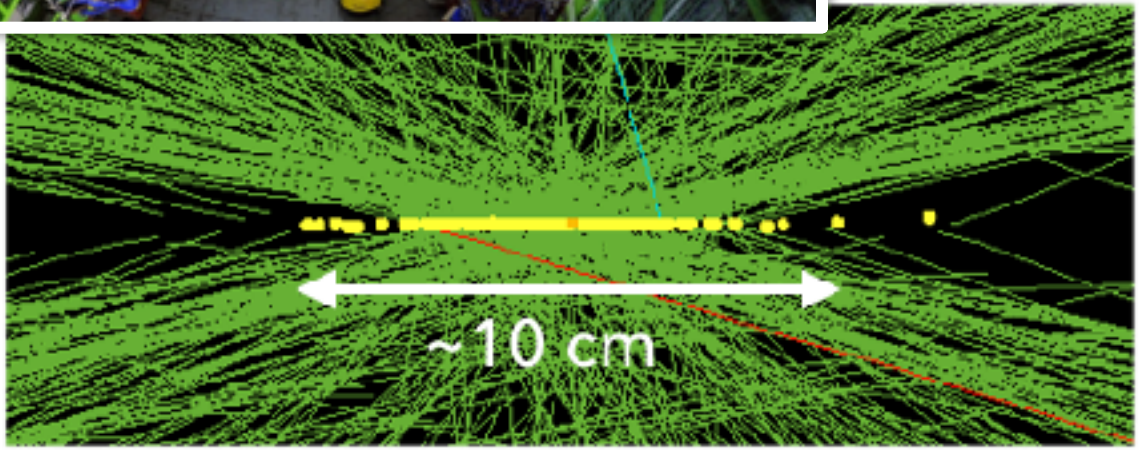


Compact Muon Solenoid





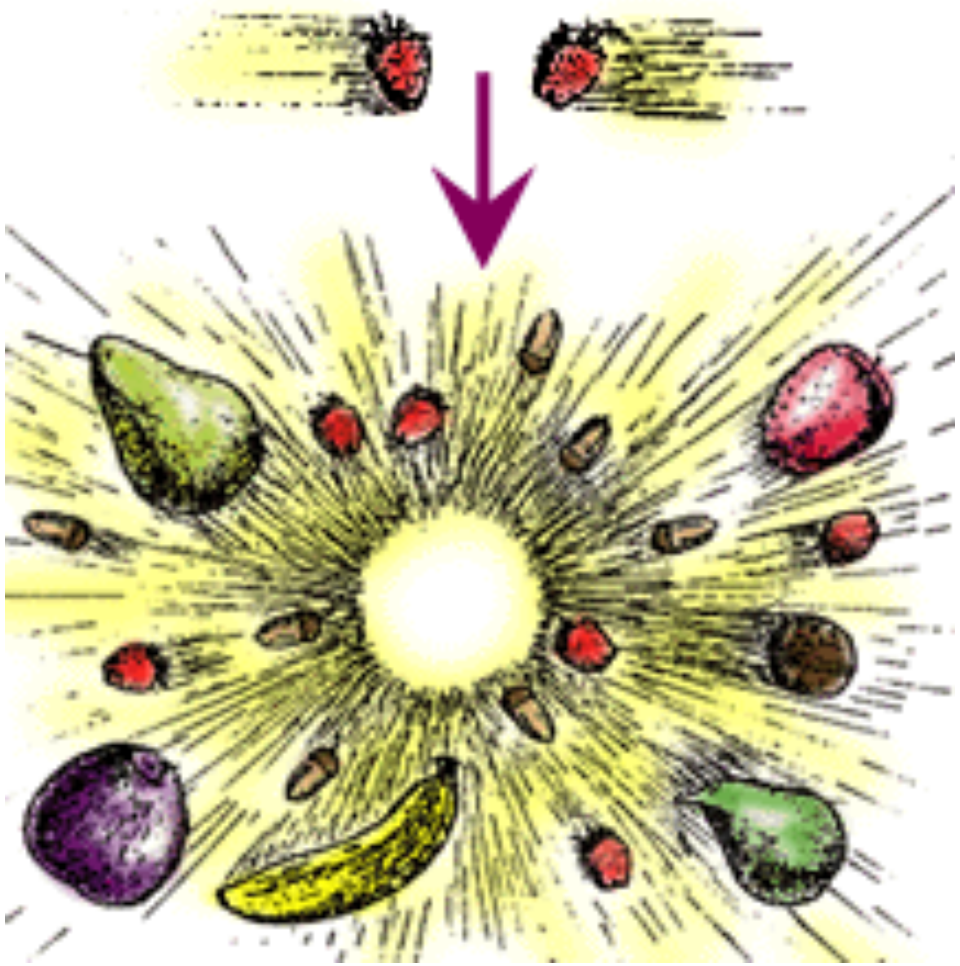


$E = mc^2$

- How can we use protons (mass = 1 GeV) to study the properties of particles with higher masses?

  -> When we collide protons that each have 6.5 TeV of energy, a lot of that energy (E) gets converted into mass (m)

- Each collision between accelerated particles is called an EVENT
  - Many particles are created in an event
  - Most decay immediately into new stable particles



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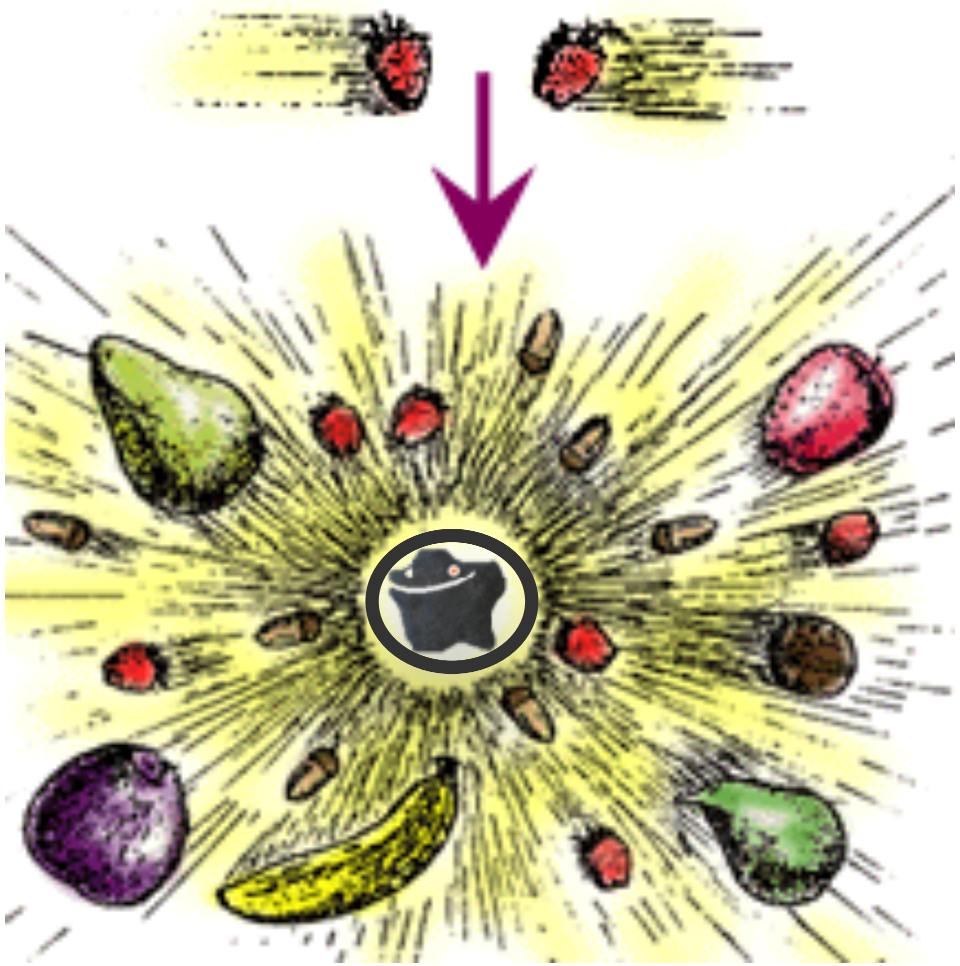


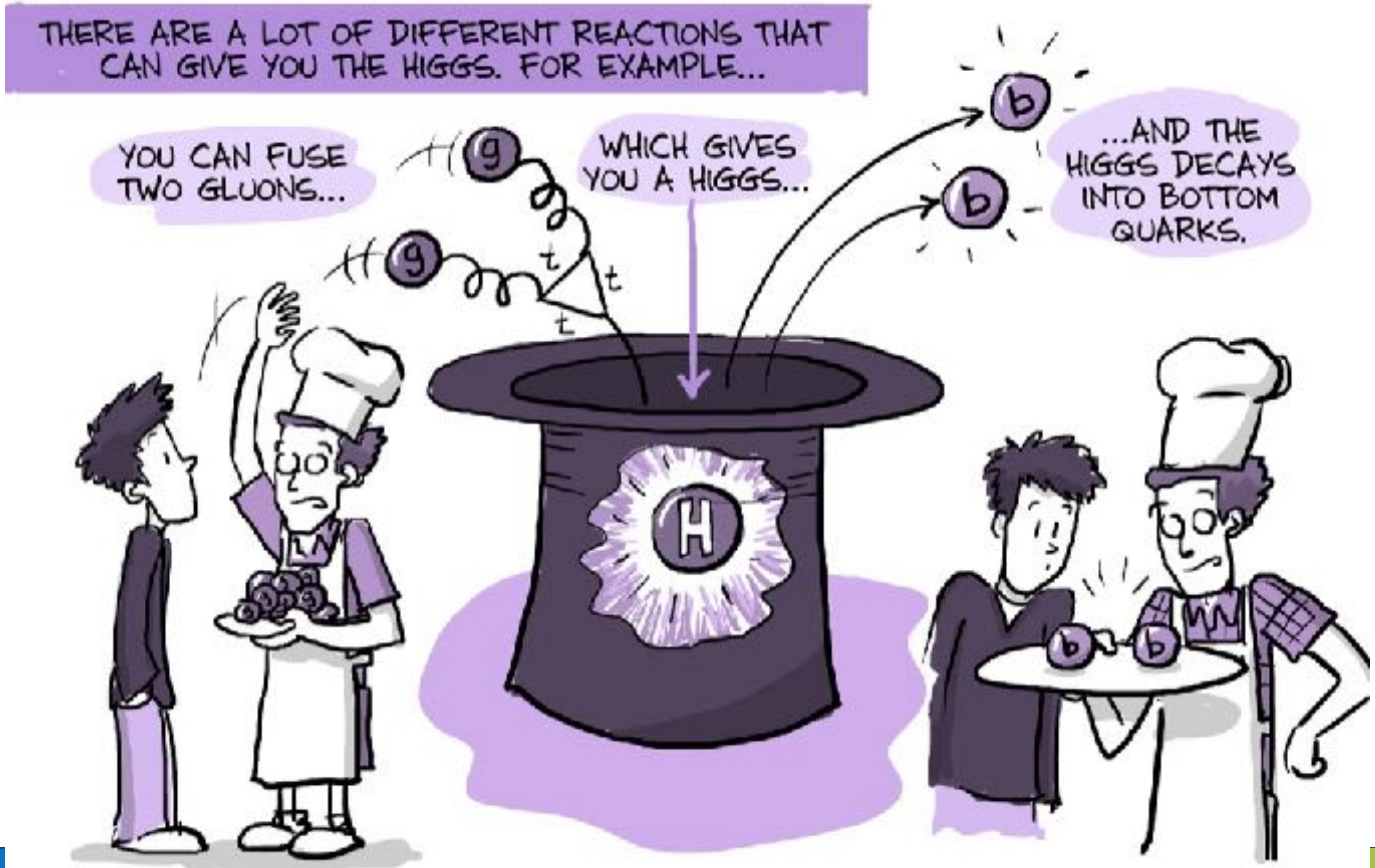
How a Higgs boson decays

- 1 in 10 billion collisions will contain a Higgs boson
- Higgs bosons decay to other particles immediately after they are produced. Each possible way is called a decay channel

Higgs $\rightarrow b + \bar{b}$	(b quark and its antiquark)
Higgs $\rightarrow \tau^+ + \tau^-$	(τ lepton and its antiparticle)
Higgs $\rightarrow \gamma + \gamma$	(two photons, also called gammas)
Higgs $\rightarrow W^+ + W^-$	(W boson and its antiparticle)
Higgs $\rightarrow Z^0 + Z^0$	(Two Z bosons)

- Different strategies and tools are used to search for the Higgs in each of these channels

How to find a Higgs boson



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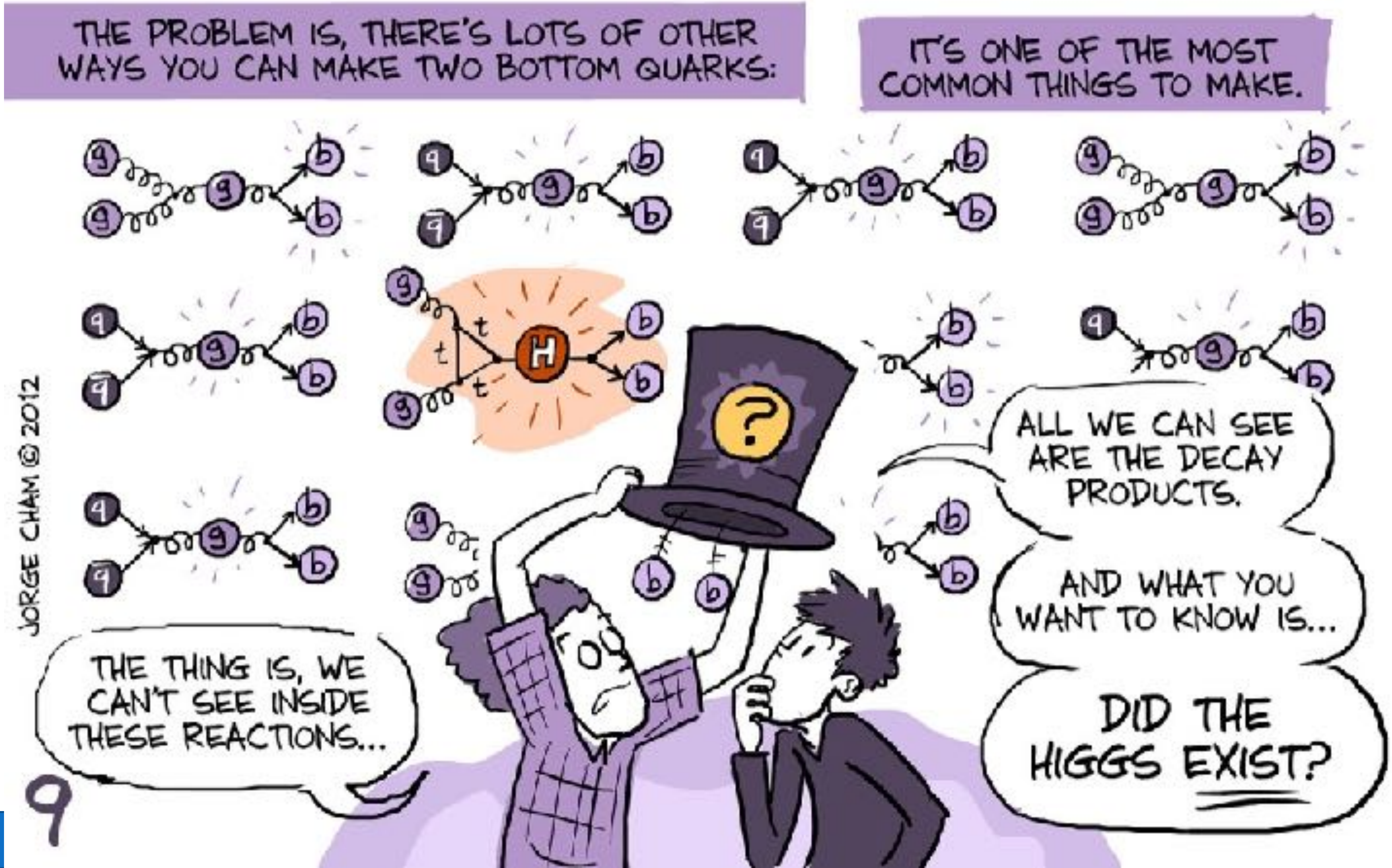

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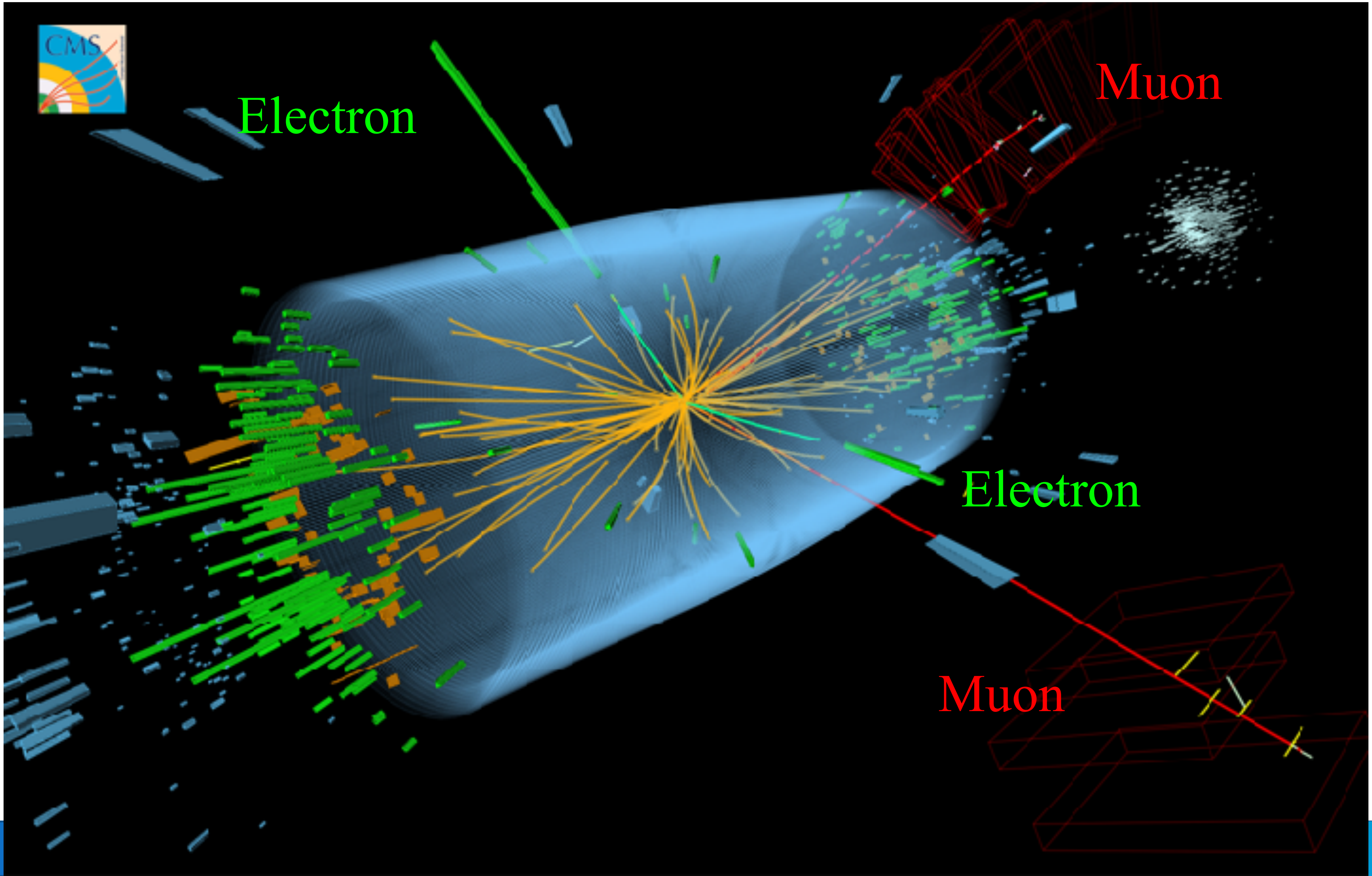
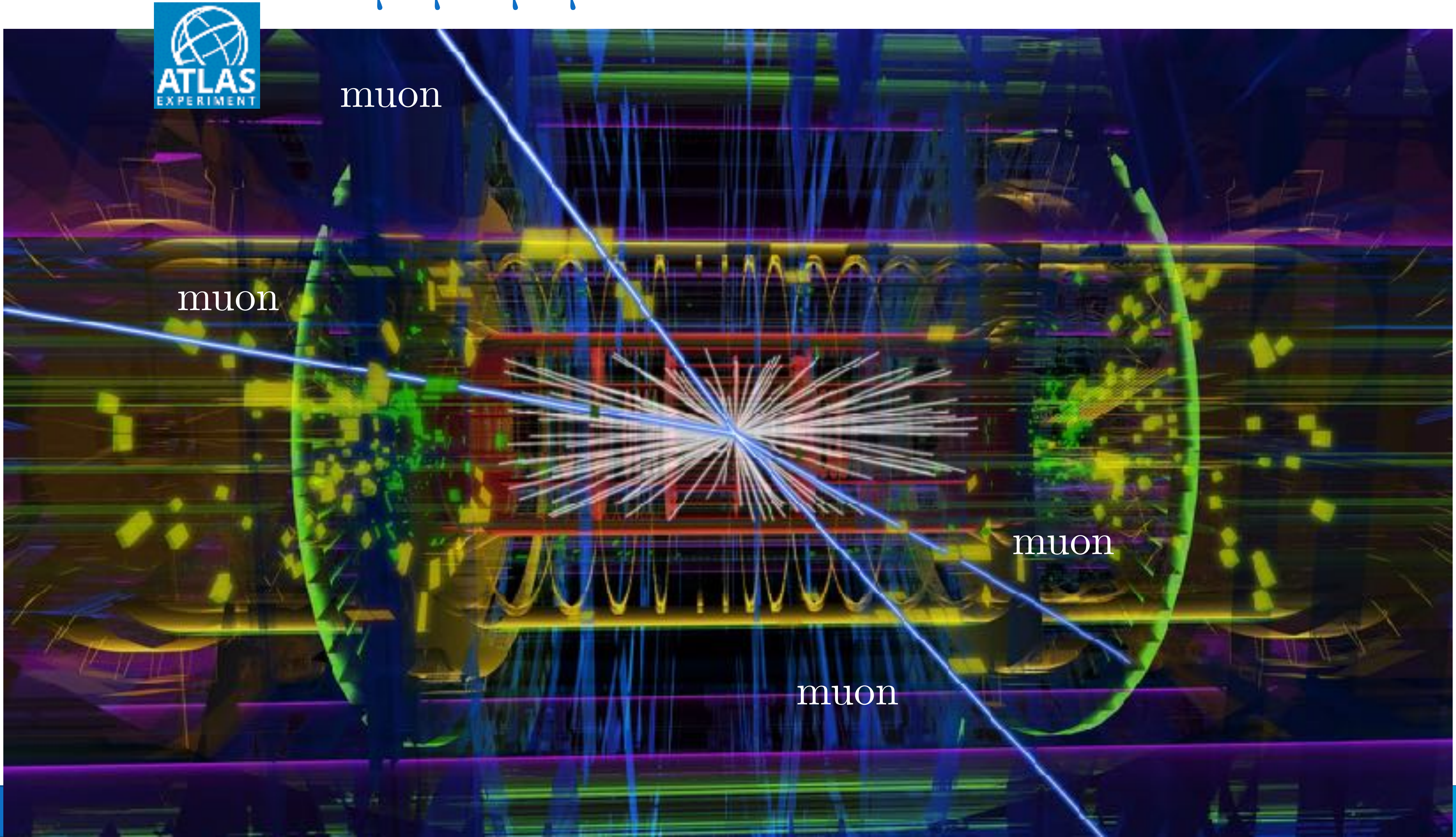
$H \rightarrow ZZ \rightarrow e^+e^- \mu^+\mu^-$ candidate event



$H \rightarrow ZZ \rightarrow \mu^+\mu^- \mu^+\mu^-$ Candidate

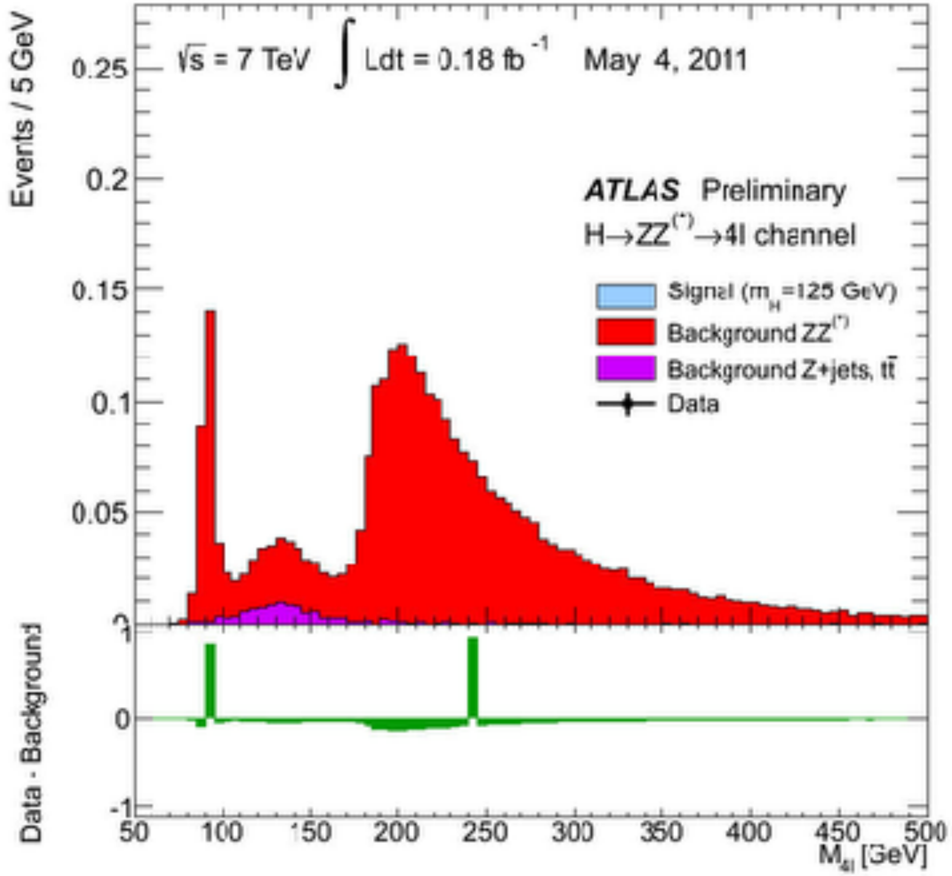


The Mass Histogram

- For H to ZZ decays, end up with 4 leptons in the *final state*
- The four possible decay product combinations could come from the decay of a Higgs boson or from the decay of other processes (background)
- Need to look at a large number of events and plot the number of times each value of the m

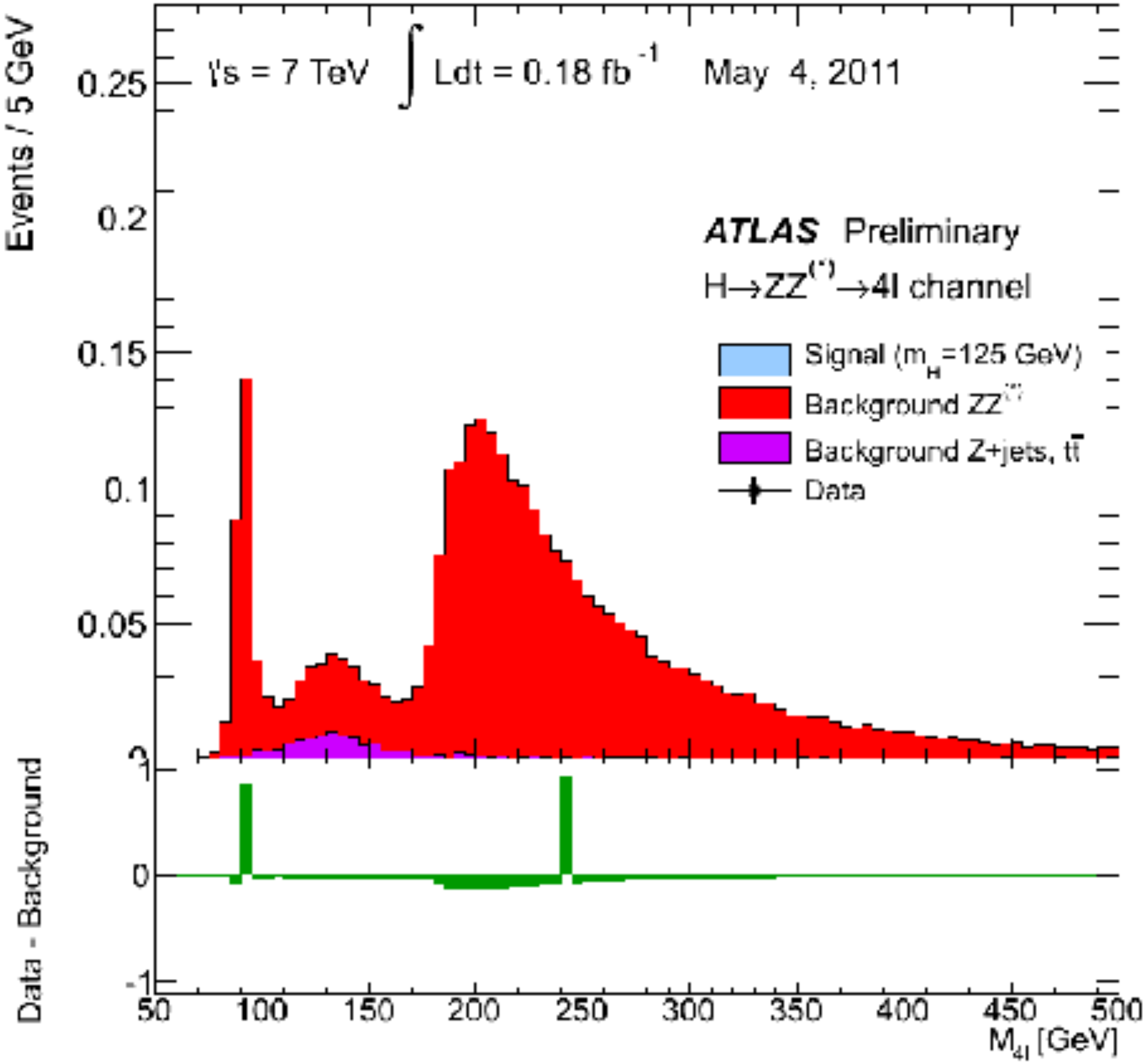
$$e^+ + e^- + e^+ + e^-$$
$$e^+ + e^- + \mu^+ + \mu^-$$
$$\mu^+ + \mu^- + e^+ + e^-$$
$$\mu^+ + \mu^- + \mu^+ + \mu^-$$

$$E^2 = p^2c^2 + m^2c^4$$

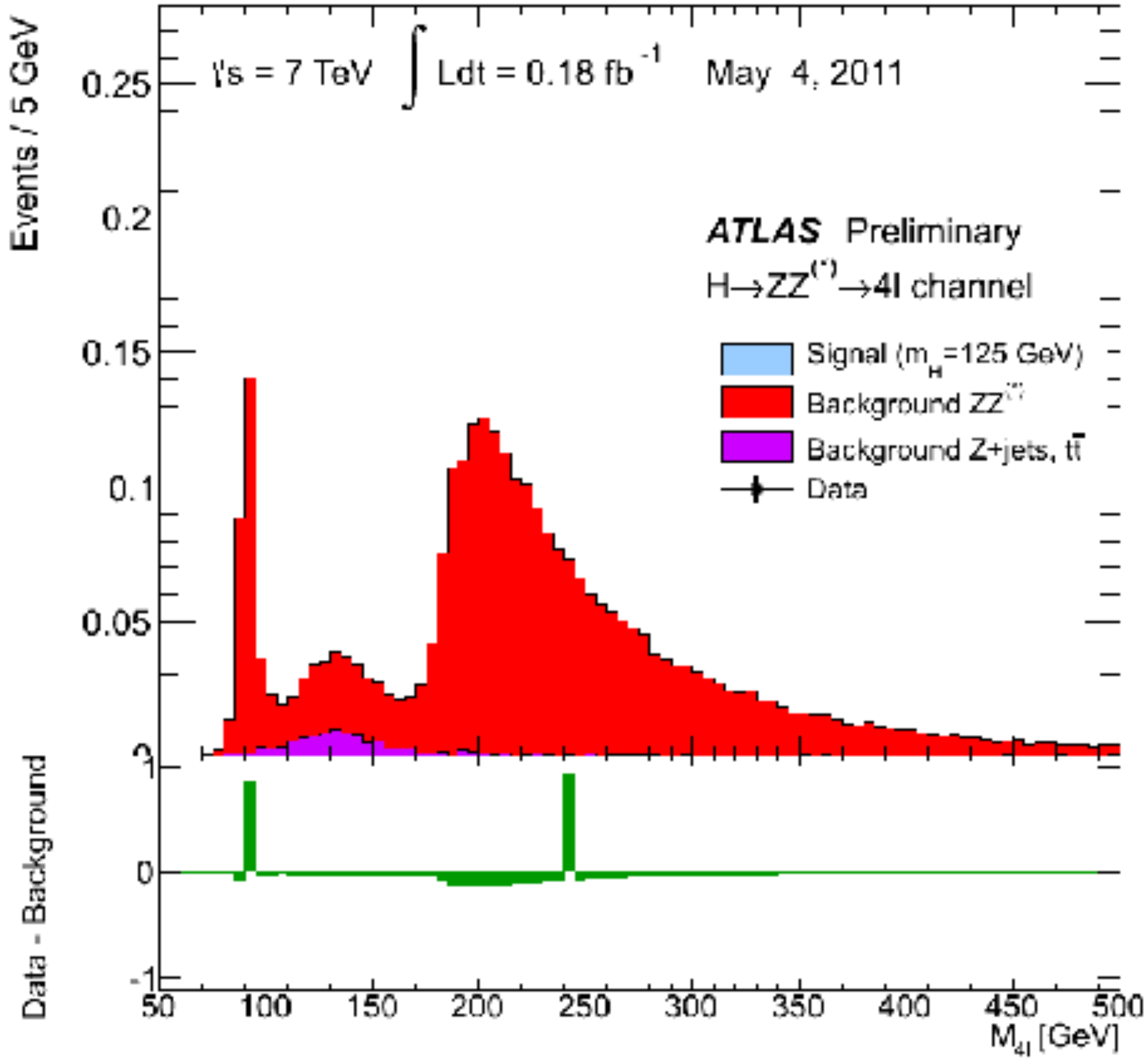


Predicted Background: number of 4 lepton events we expect to occur from decays not involving a Higgs boson

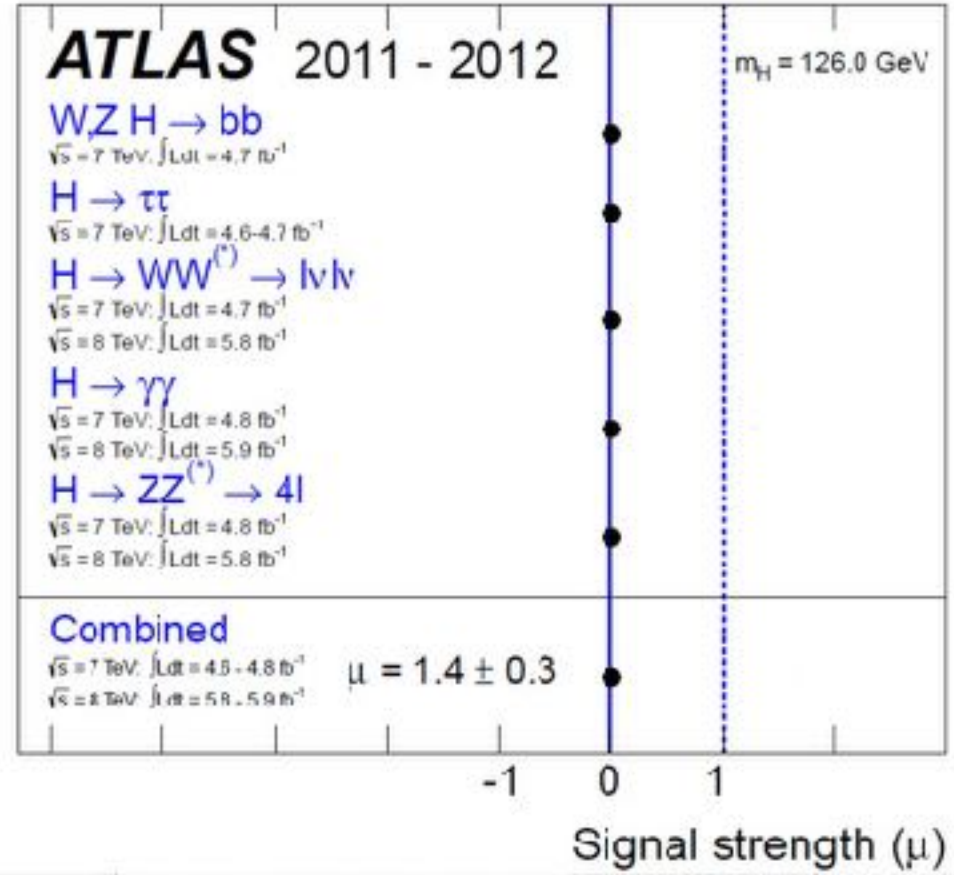
Time Evolution of Higgs Boson Data

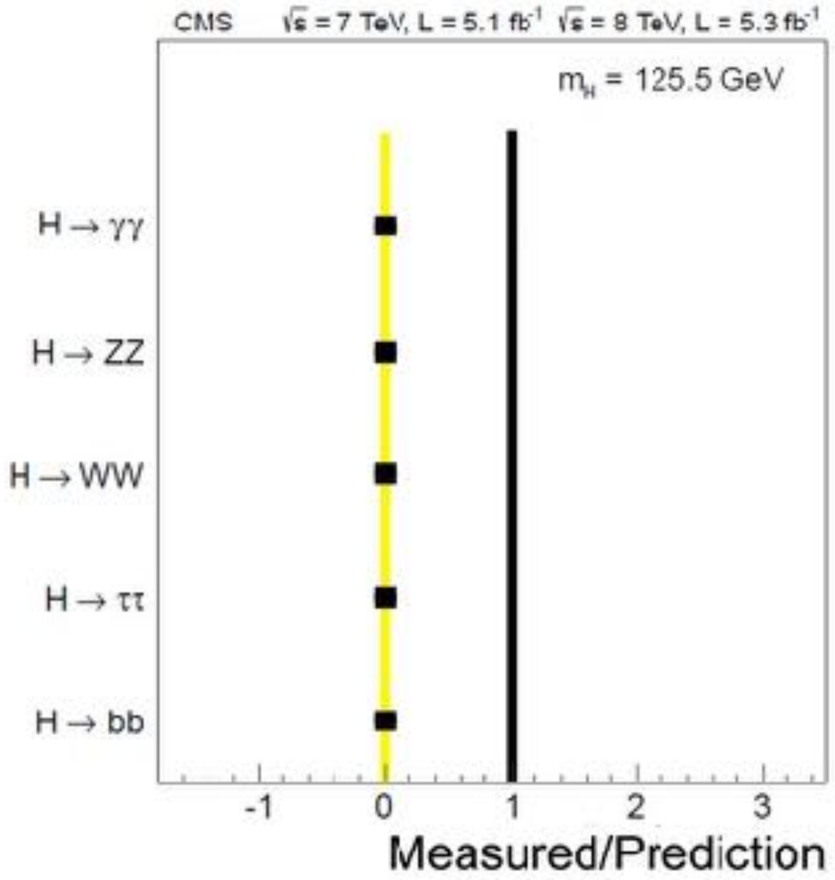


Time Evolution of Higgs Boson Data



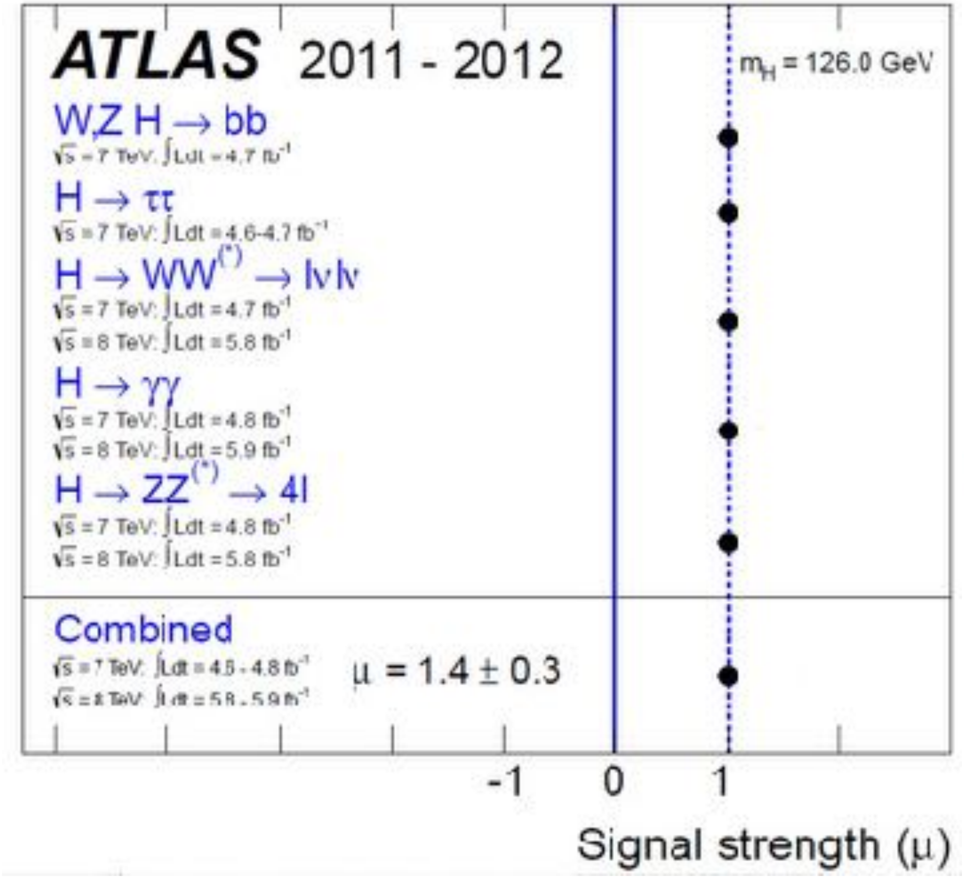
Results if no Higgs

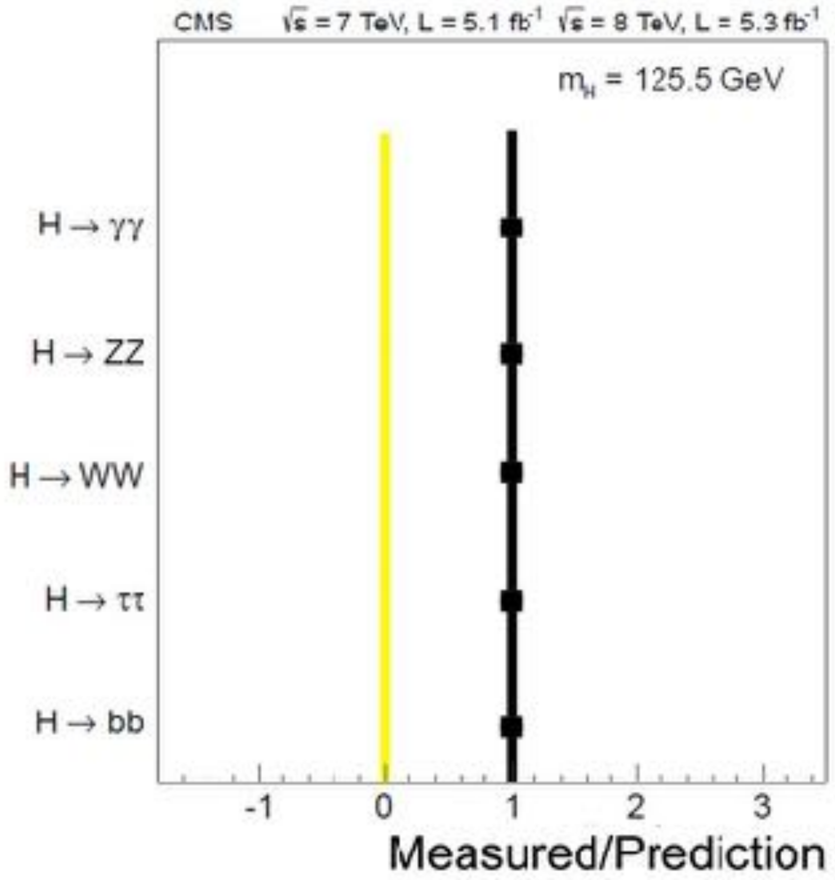




Ratio of Measurement to Standard Model Prediction

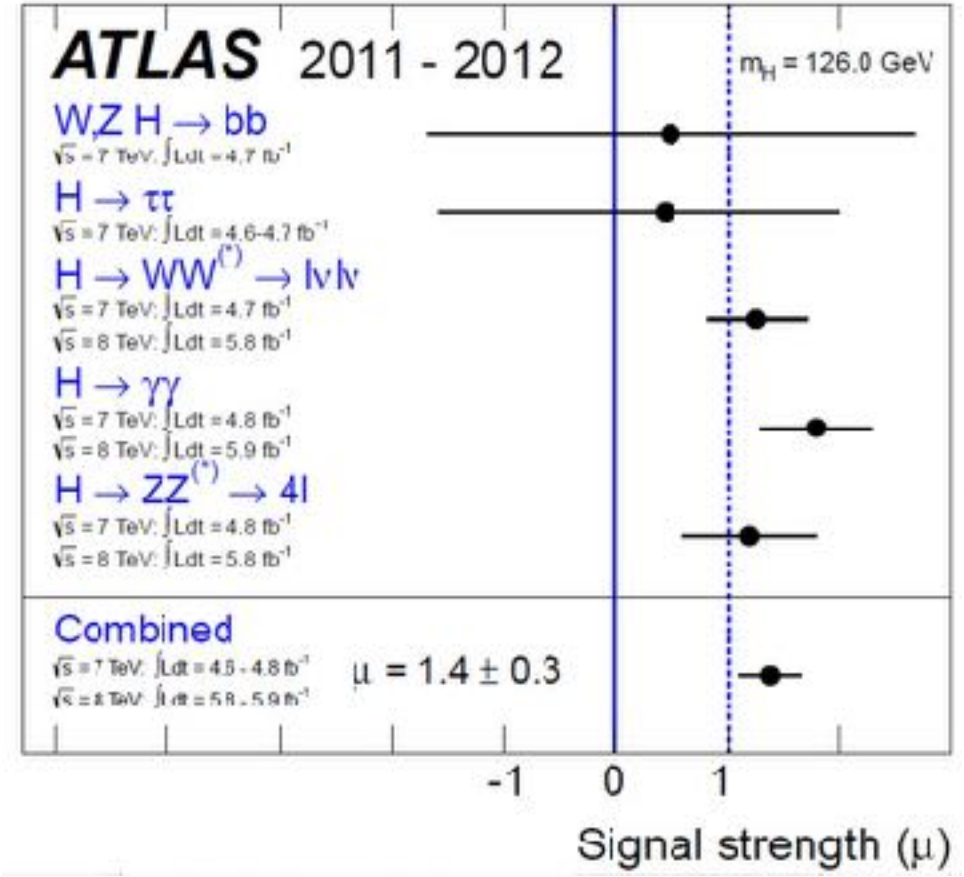
Results with Higgs

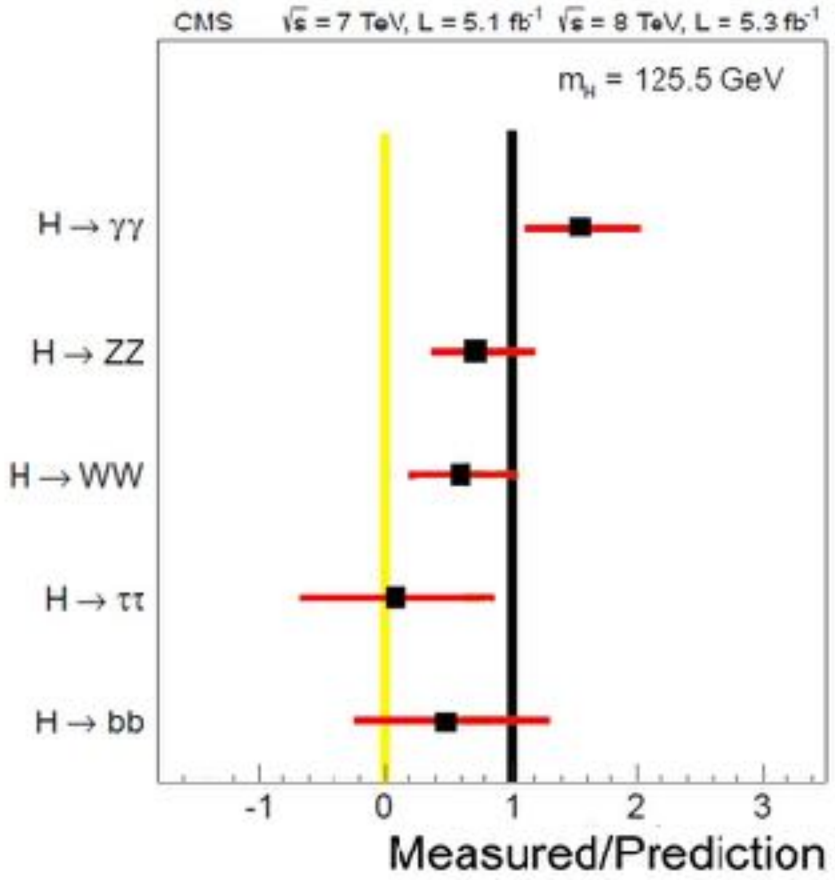




Ratio of Measurement to Standard Model Prediction

July 2012 Results





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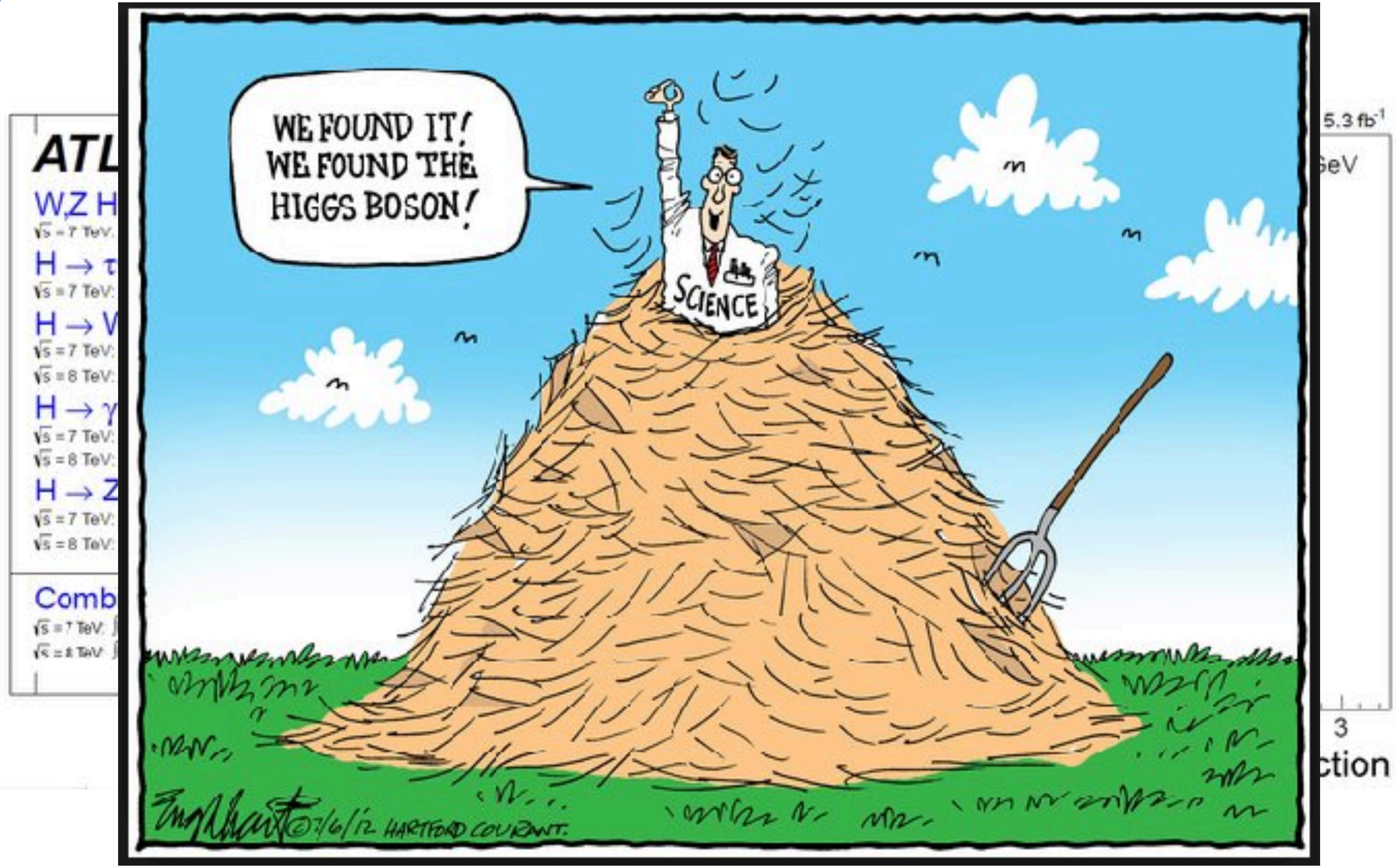
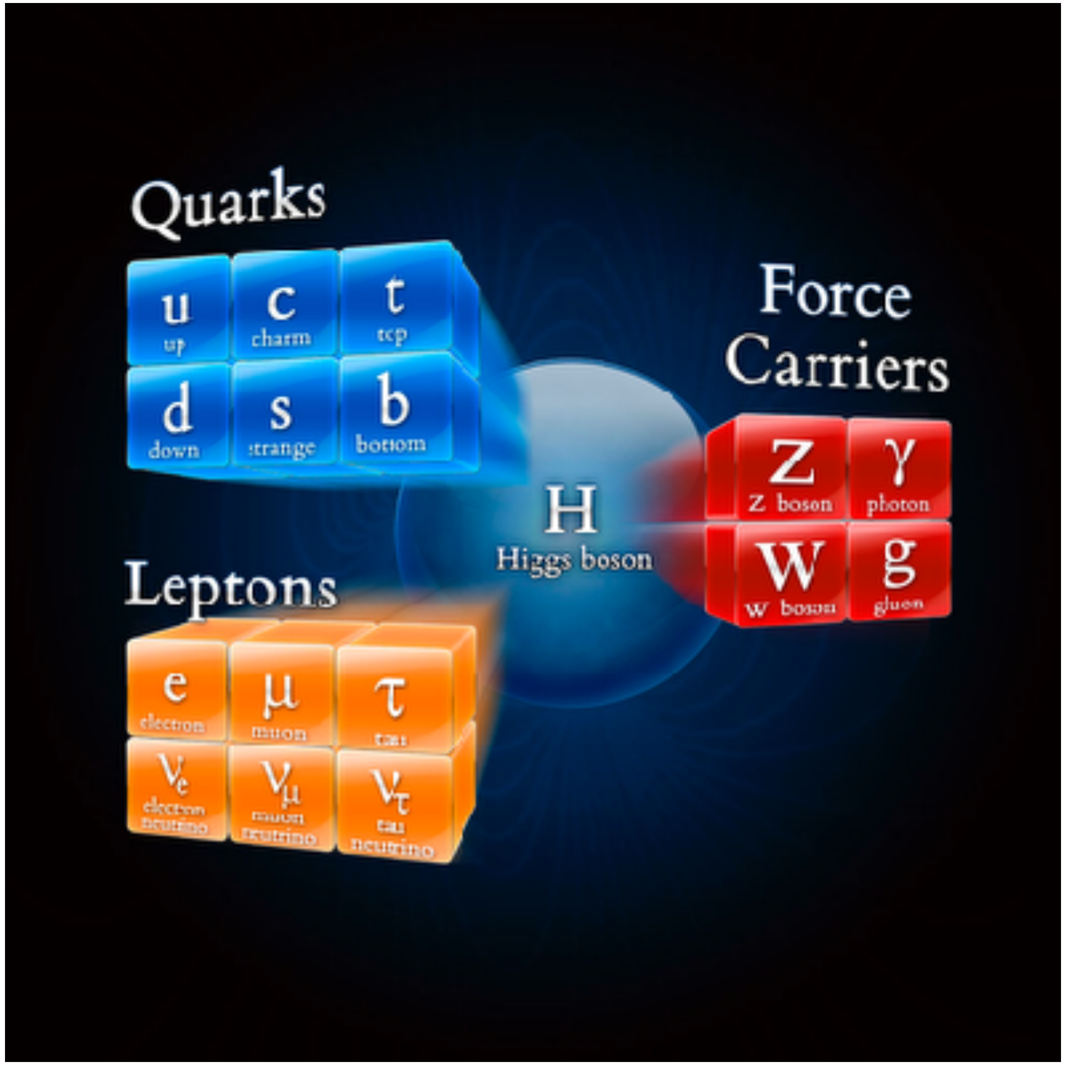


Summary of what we learned

- The Standard Model is the most complete explanation of fundamental particles and their interactions to date
- The building blocks of matter are quarks and leptons
- There are force carrier particles (bosons) associated with each force
- The Higgs mechanism is responsible for the mass of the particles



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Many things left to discover and understand!

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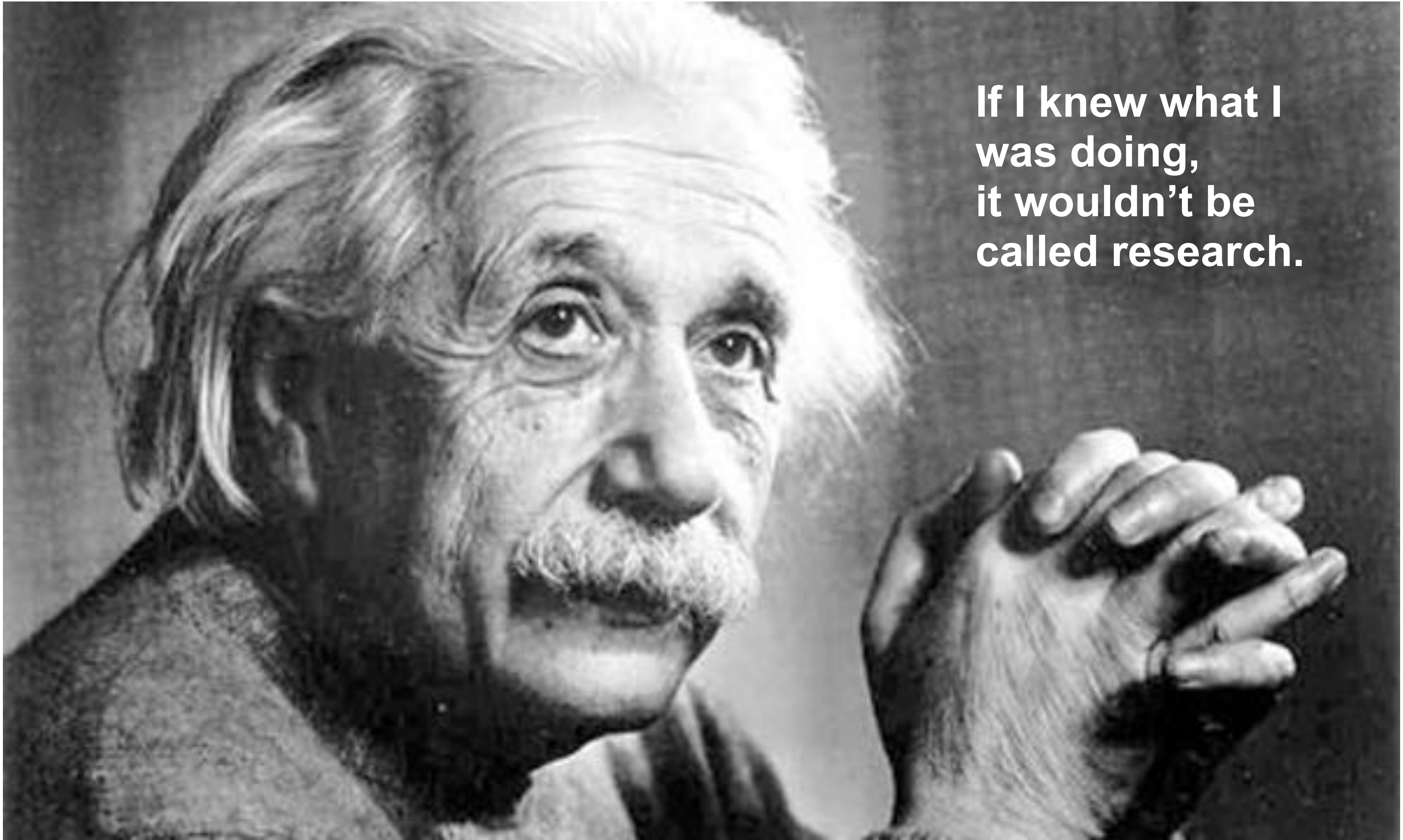
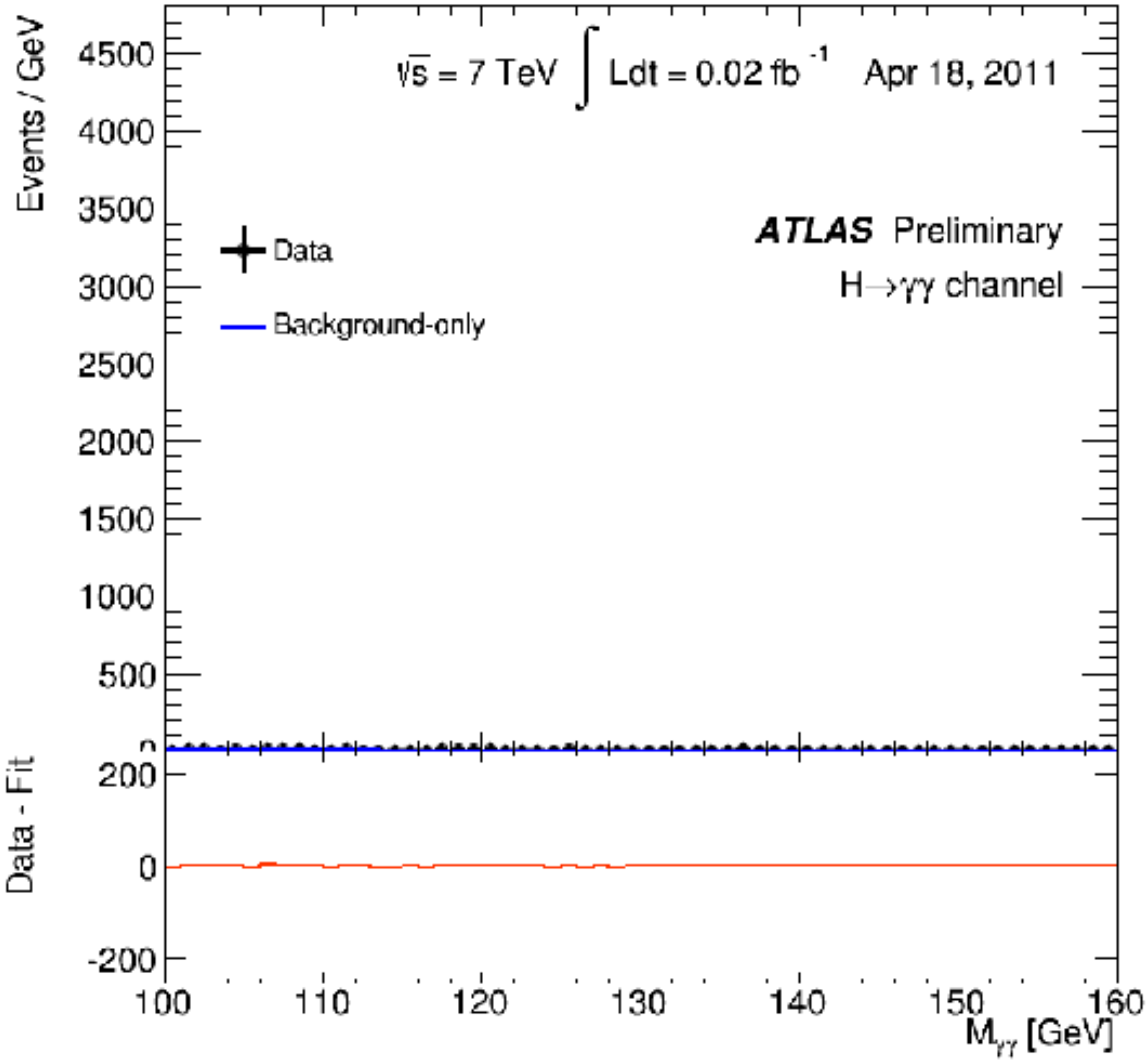
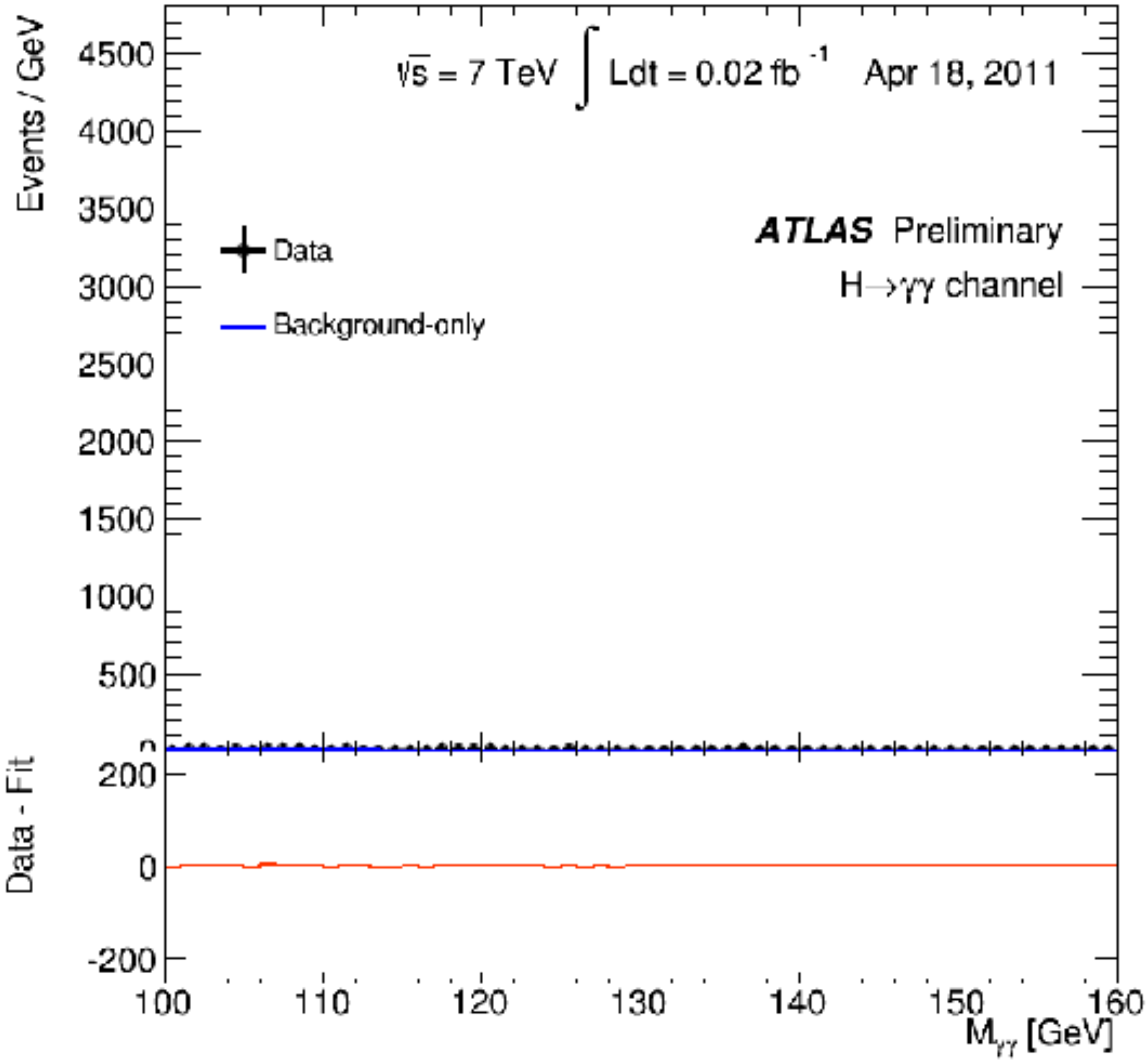
We could find the answers to these questions, or discover something totally unexpected!


If I knew what I
was doing,
it wouldn’t be
called research.

Backup


√s = 7 TeV ∫ Ldt = 0.02 fb⁻¹ Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
M_γγ [GeV]
4500
4000
3500
3000
2500
2000
1500
1000
500
200
0
-200
100
110
120
130
140
150
160



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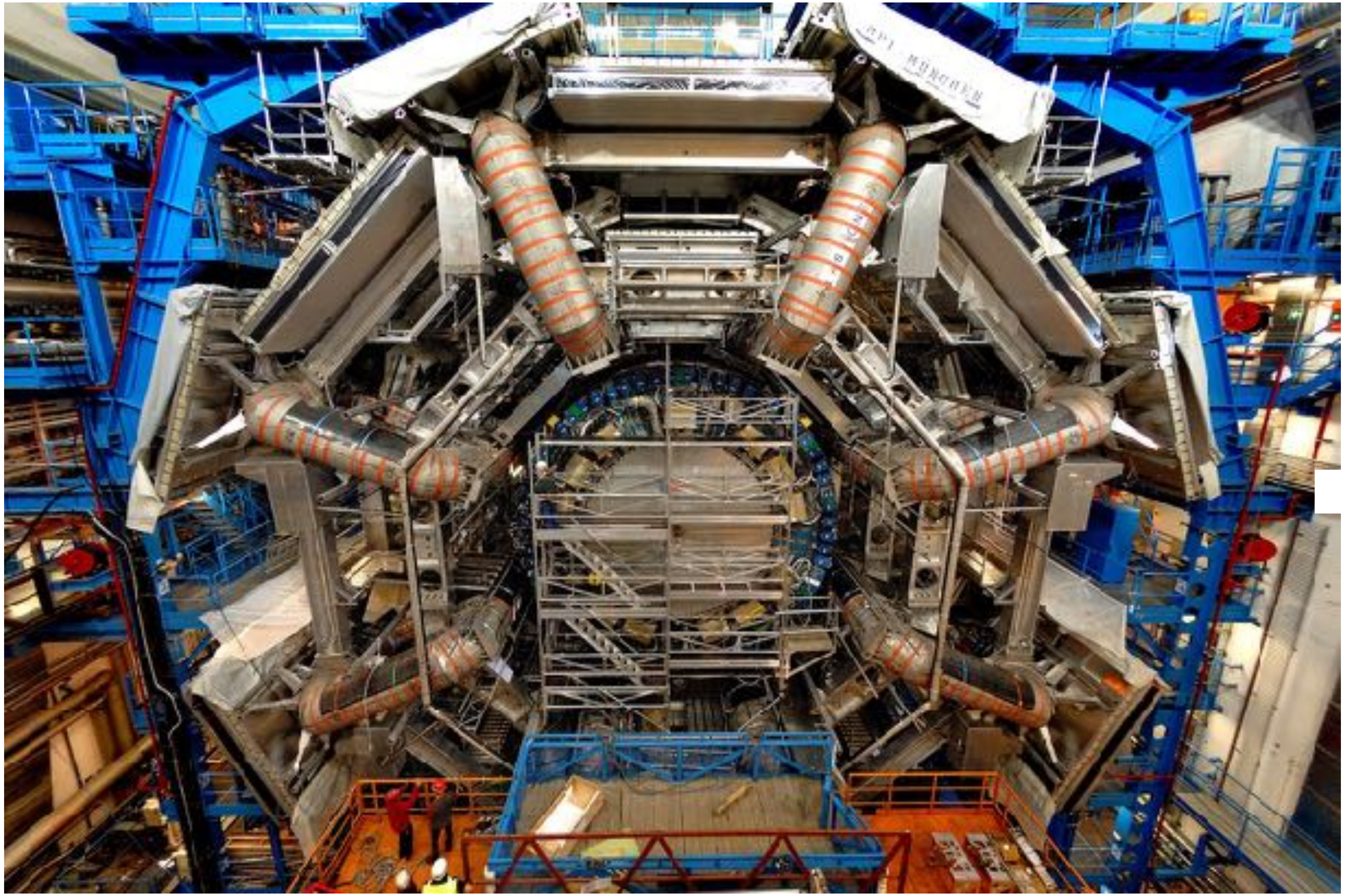
Mγγ [GeV]

The ATLAS Detector @ the LHC



The CMS Detector @ the LHC