Intro-to- Particle Physics

LifeLab Foundation QuarkNet India

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Fermilab

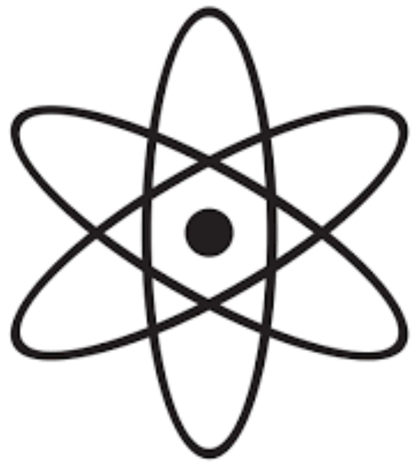
A little about me

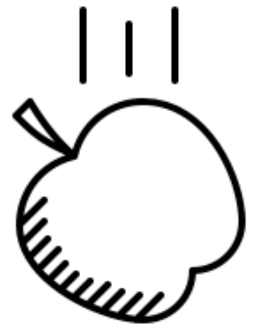
- Born in Ecuador (also undergrad there)
- PhD @ Johns Hopkins, 2020, now Fermilab postdoc
- I like Higgs boson physics, particle jet physics and particle dark matter in accelerators

The “visible” universe

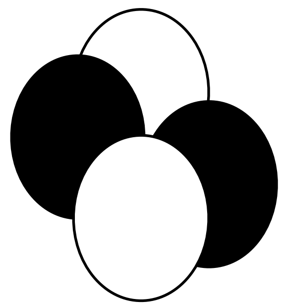
Our current understanding

Protons/
neutrons



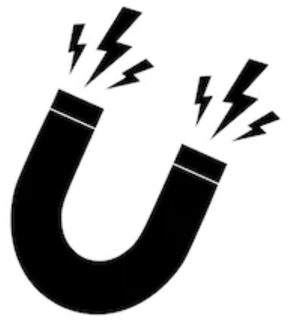


Gravitational
force



Strong
force

Weak
force



Electro
-magnetic
force

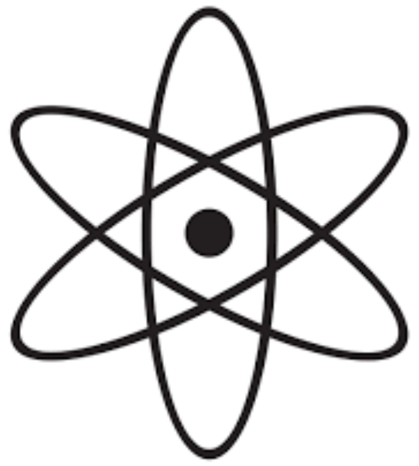
The "visible" universe

Our current understanding

u

d

Protons/
neutrons



e

Particles of matter

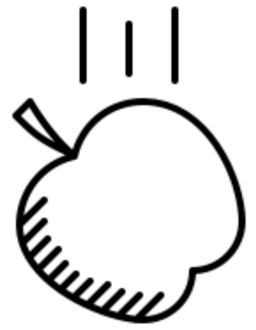
g

W

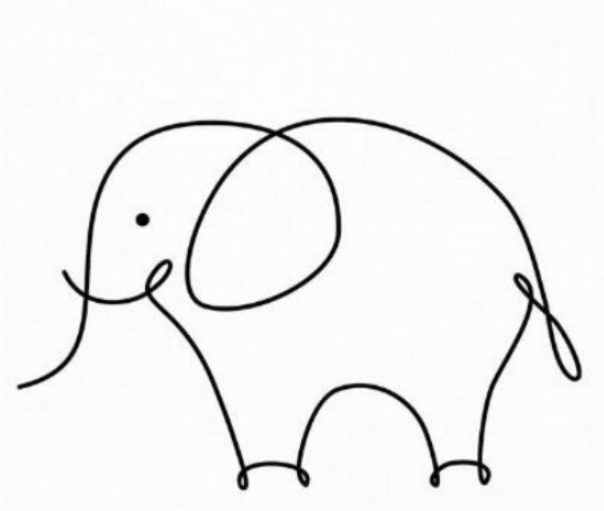
ν_e

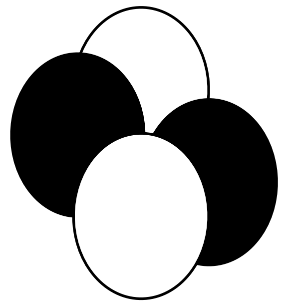
γ

Force carriers



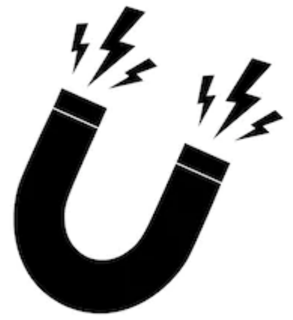
Gravitational
force





Strong
force

Weak
force



Electro
-magnetic
force

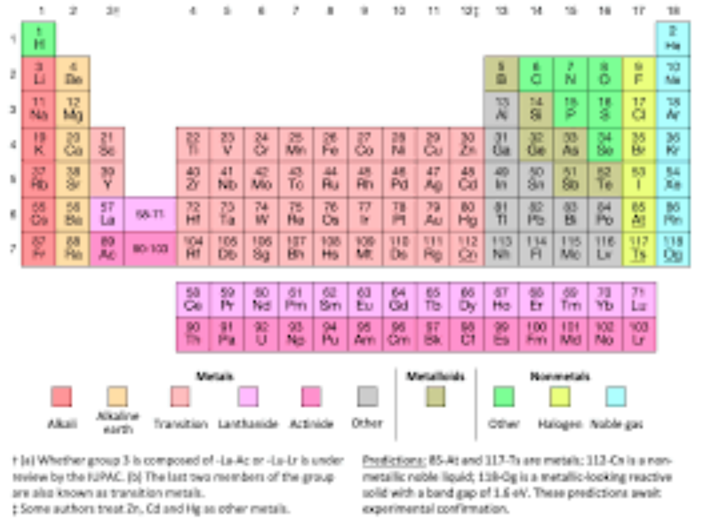
How did we get here?

Our concept of “elementary” particles

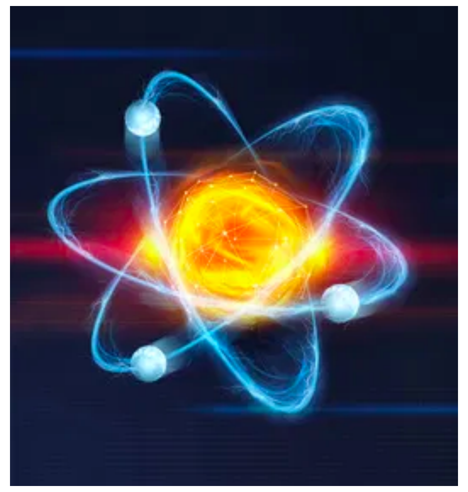
1000 BC | 1500 AC | 1900 | 1960 | 2012 | 2021

Earth
Fire
Water
Air

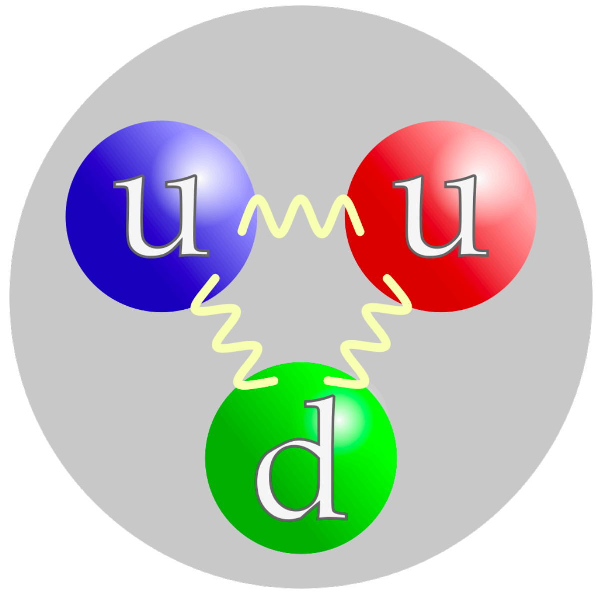
Sulfur
Salt
mercury
…



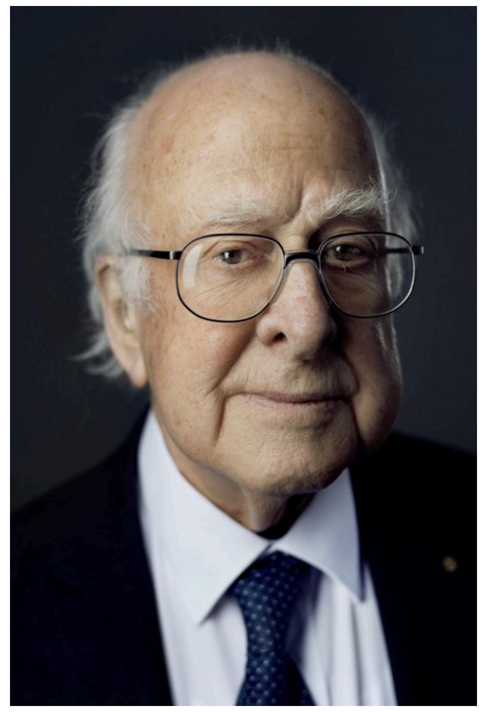
Chemical
elements



Electron
Proton



Quarks
Leptons

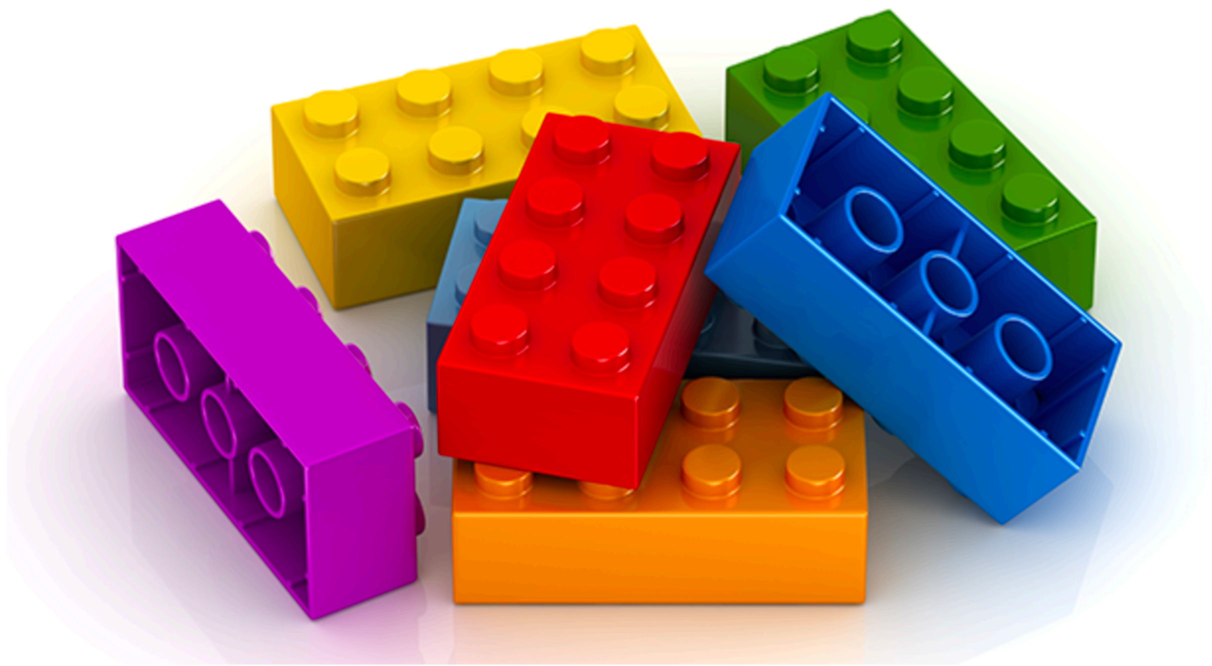


Higgs
Boson

Today!

How did we get here?

Our concept of "elementary" particles



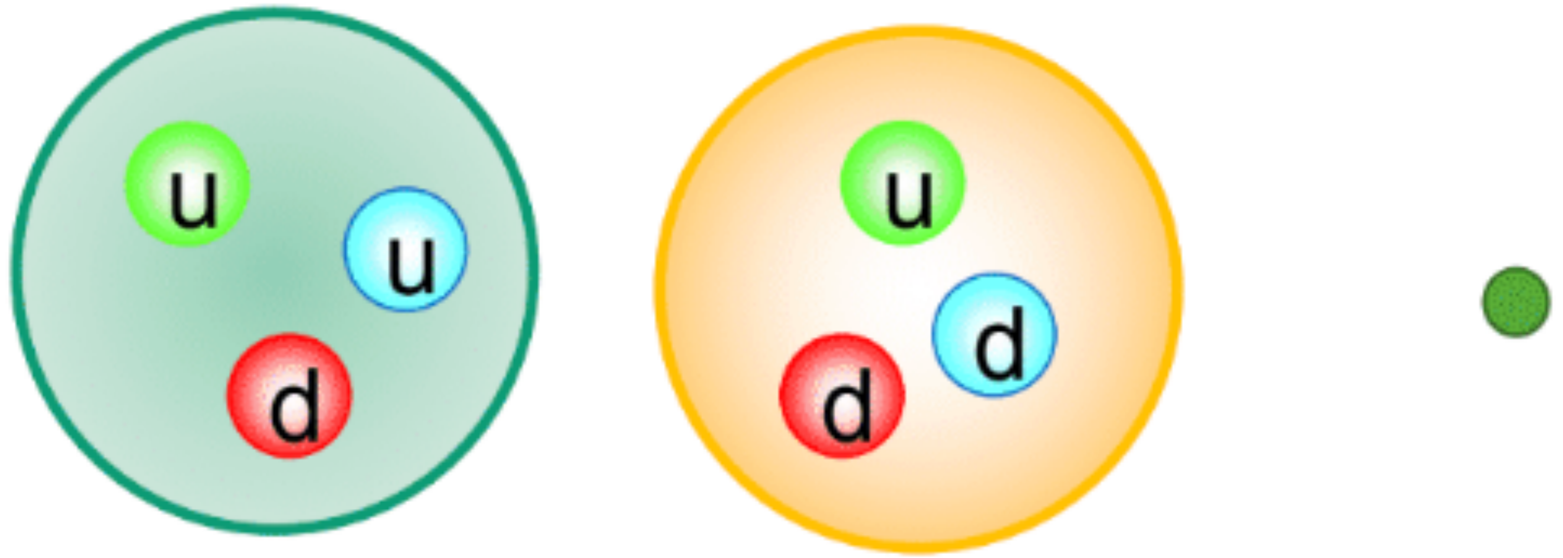
- **Foundational**: everything is made out of this
- **Impenetrable**: cannot be broken apart
- **Indistinguishable**: every electron identical to every other electron

By 1930s: protons, neutrons, electrons: *life is good*

e p n

Earth’s building blocks

All ordinary matter in our universe is made of:

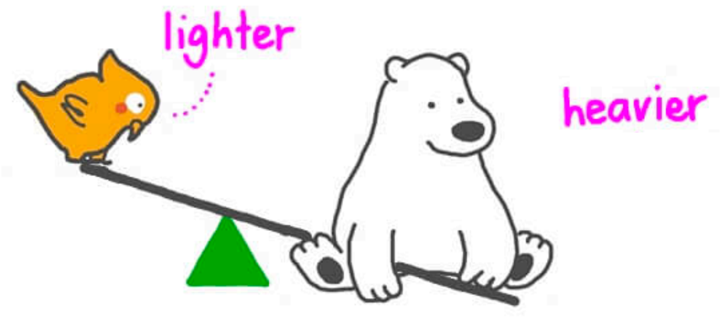


p n e

Protons and neutrons are not elementary… but *up* and *down quarks* are:

u d e

Quarks



	Up	Charm	Top
	~2.2 MeV/c^2	~1.28 GeV/c^2	~173 GeV/c^2
Quarks			
+2/3 charge	u	c	t
-1/3 charge	d	s	b
	~4.7 MeV/c^2	~96 MeV/c^2	~4.18 GeV/c^2
	Down	Strange	Bottom

There are 3 generations: same properties only heavier

Leptons

The most known ones are the electron and the muon.

We often say that the muon is a cousin of the electron but only heavier.

0.511 MeV/c² 105.6 MeV/c² 1.77 GeV/c²

Leptons

e	μ	τ
Electron	Muon	Tau

We often see muons in cosmic rays (build a cloud chamber!)

Neutrinos

Neutrinos are a type of leptons.

They also come in three types - one for each generation.

Neutrinos have very little mass and interact only via the weak force

This means that you would need a light year of lead nuclei to have a 50% of interacting

Leptons

Electron neutrino	Muon neutrino	Tau neutrino
ν_e	ν_μ	ν_τ
< 2.2eV/c^2	< 0.17 MeV/c^2	< 18.2 GeV/c^2

Antimatter

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

Neutral particles (zero charge) are their only antiparticle.

Mass = 0.511 MeV/c^2
Spin = 1/2

e^-

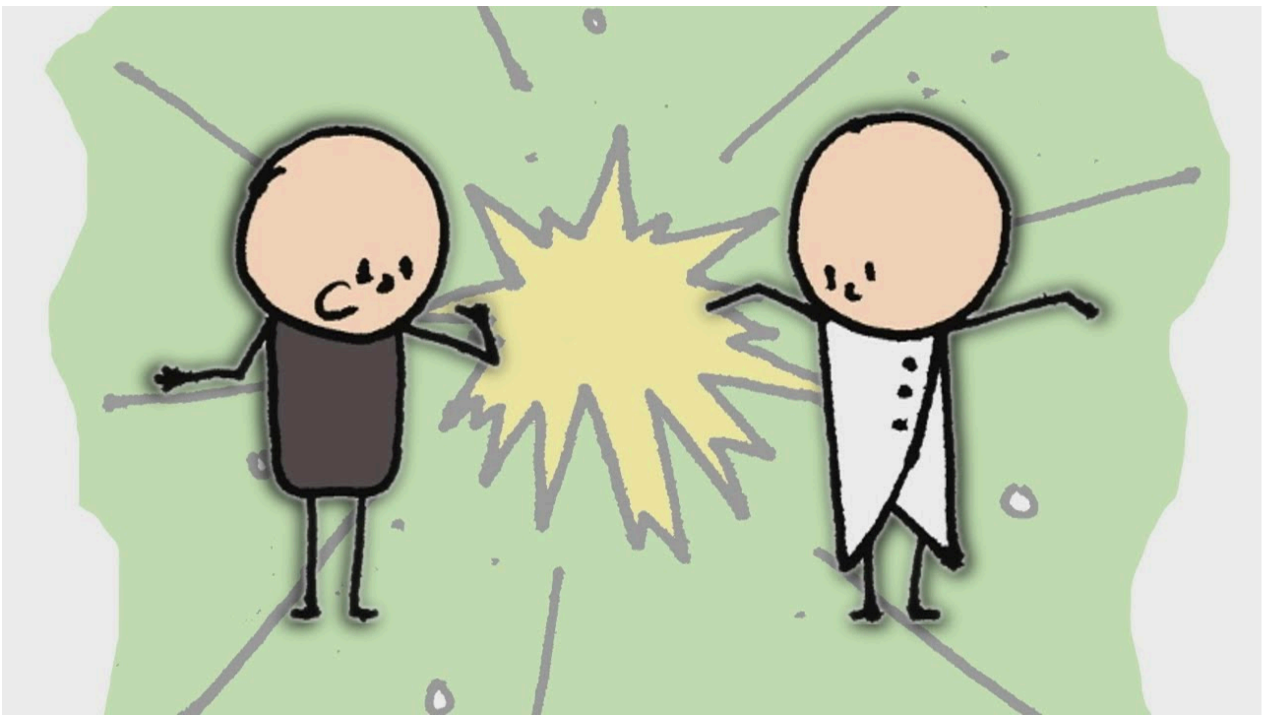
Electron

e^+

Positron

Matter and anti-matter particles always come in pairs

They annihilate each other if they are in contact



Antimatter

How do we produce it?

Some antimatter is easier to produce than others...

Potassium-40 can produce positrons when it decays

A banana (lots of potassium) produces a positron (e+) ~ every 75 min

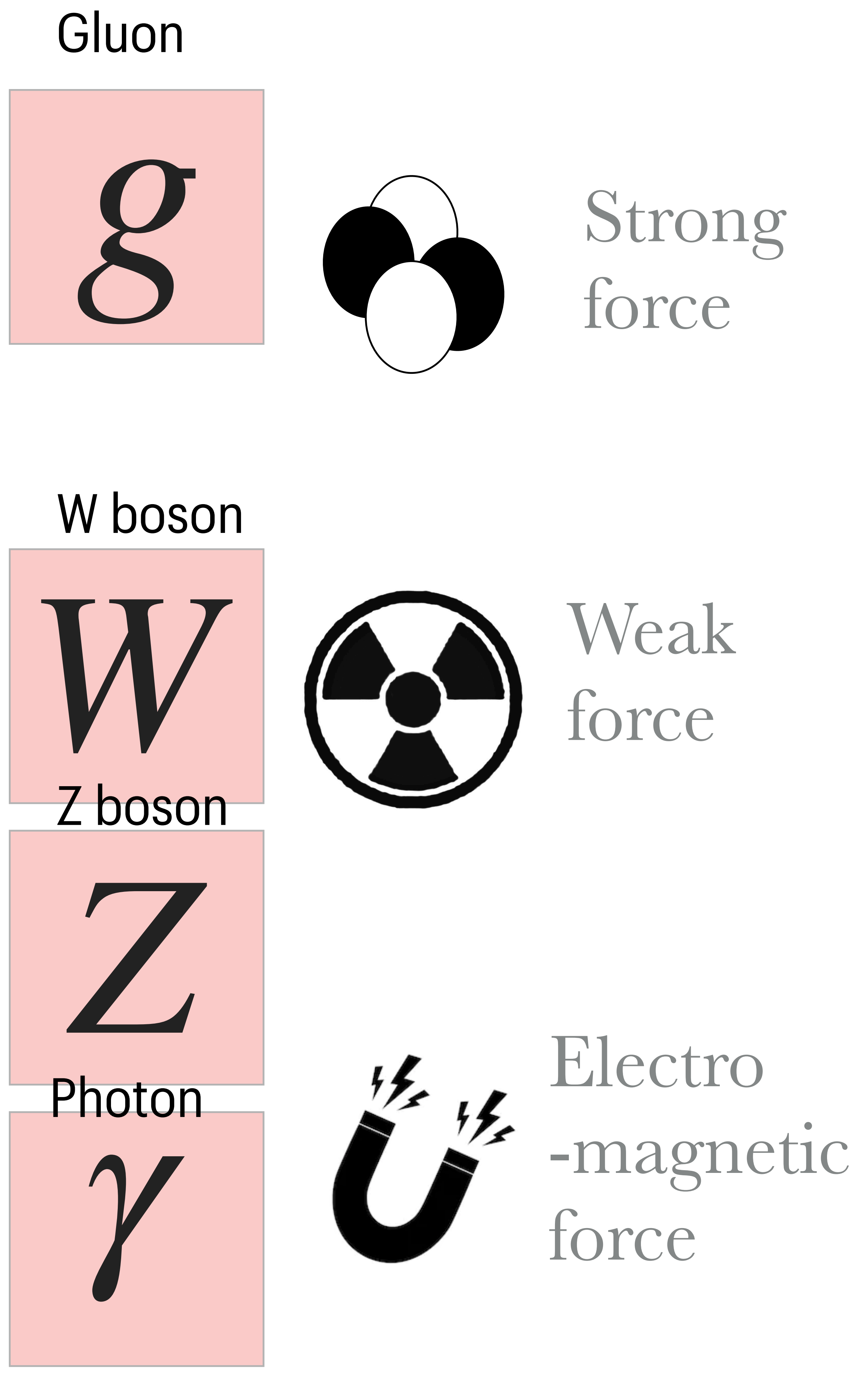
Colliding protons on a fixed target of metal

$$p + p \rightarrow \bar{p} + p + p + p$$

Force carriers

Force carriers: particles that give rise to interactions between particles

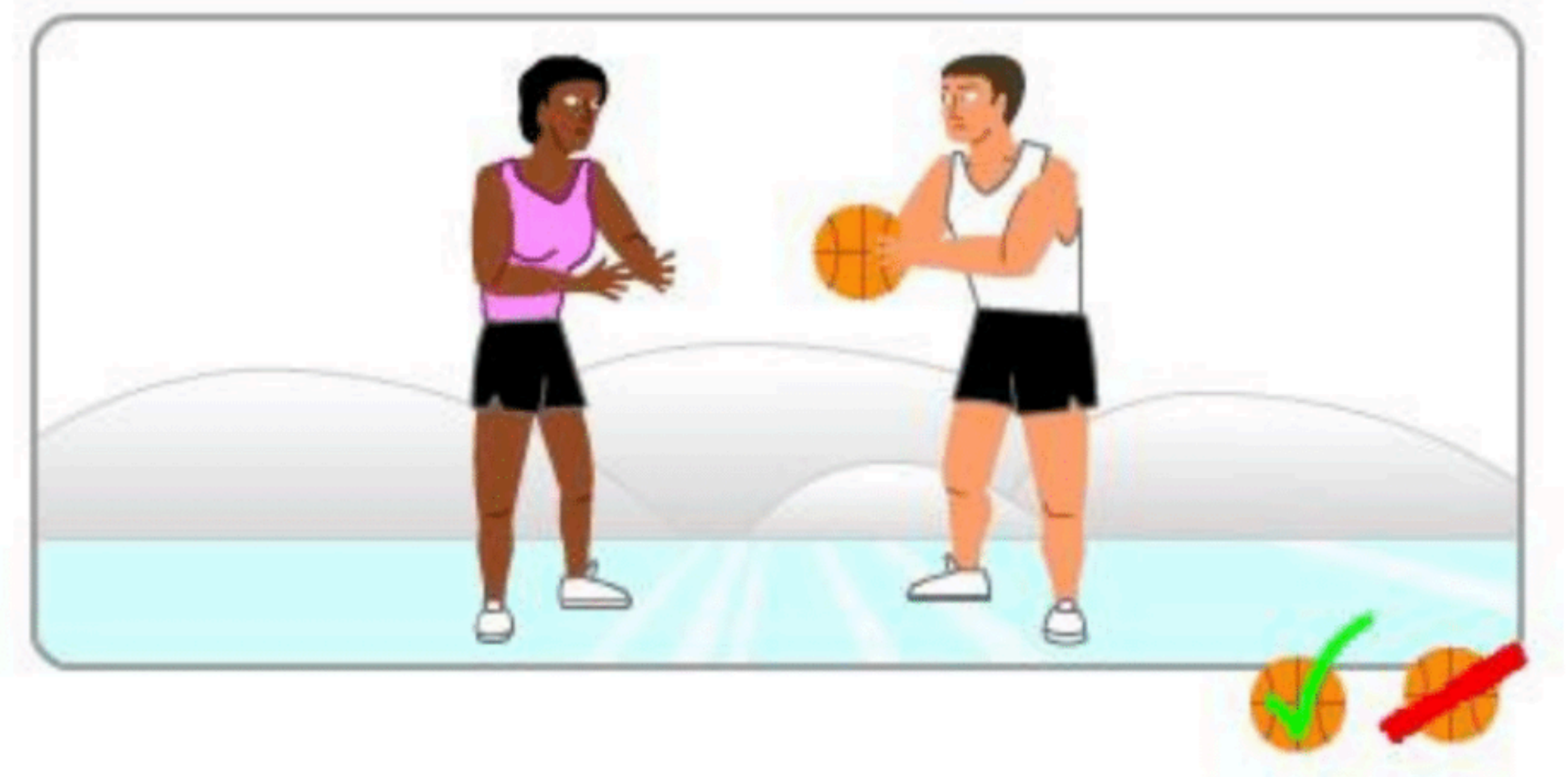
Forces: the effects of the force carrier particles on matter particles



Force carriers

The unseen effect

Two people exchanging a basketball ~ two particles exchanging a force carrier



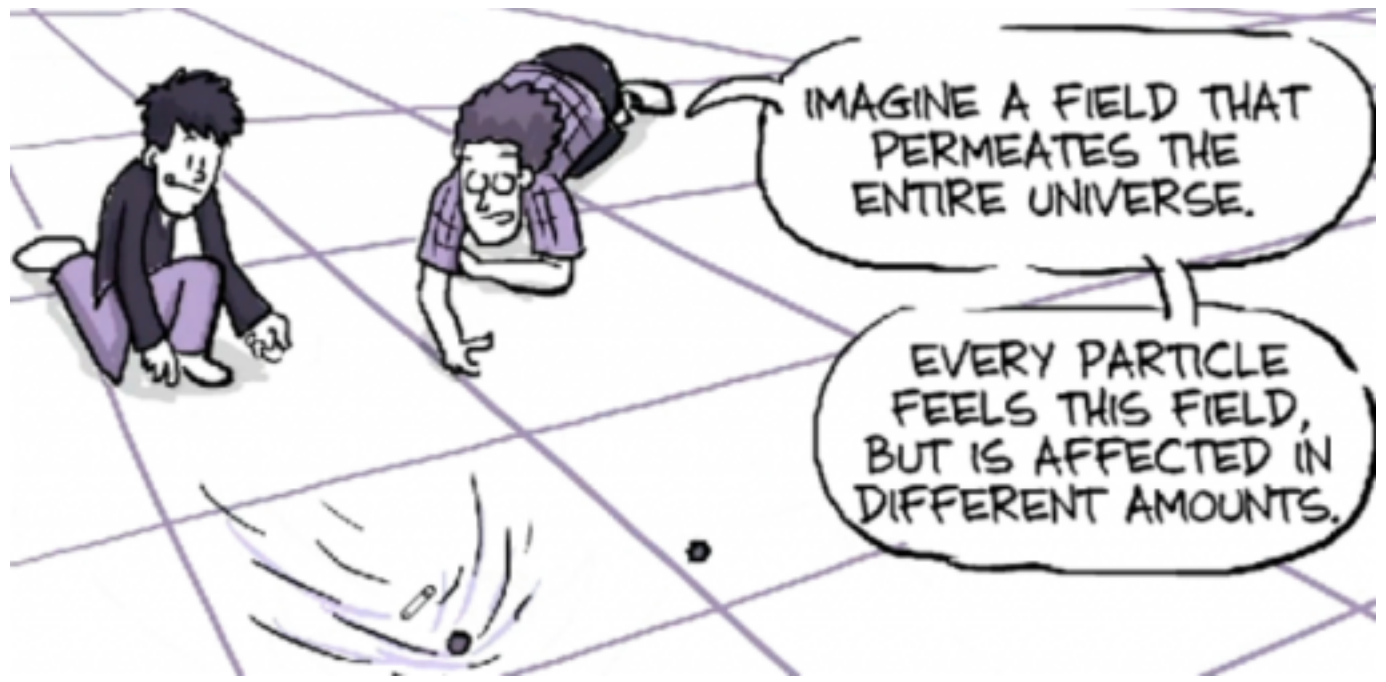
All the interactions that affect matter particles are due to the exchange of force carrier particles

The Higgs boson

Our last piece

The Higgs mechanism explains how elementary particles get their mass

1. Higgs field permeates the universe



Massive particles interact a lot with this field

2. New particle predicted: the Higgs boson

Discovered at Large Hadron Collider @ 2012

The Standard Model of Particle Physics

Quarks

u c t

d s b

Leptons

e μ τ

ν_e ν_μ ν_τ

g

W

Z

γ

Force carriers

H

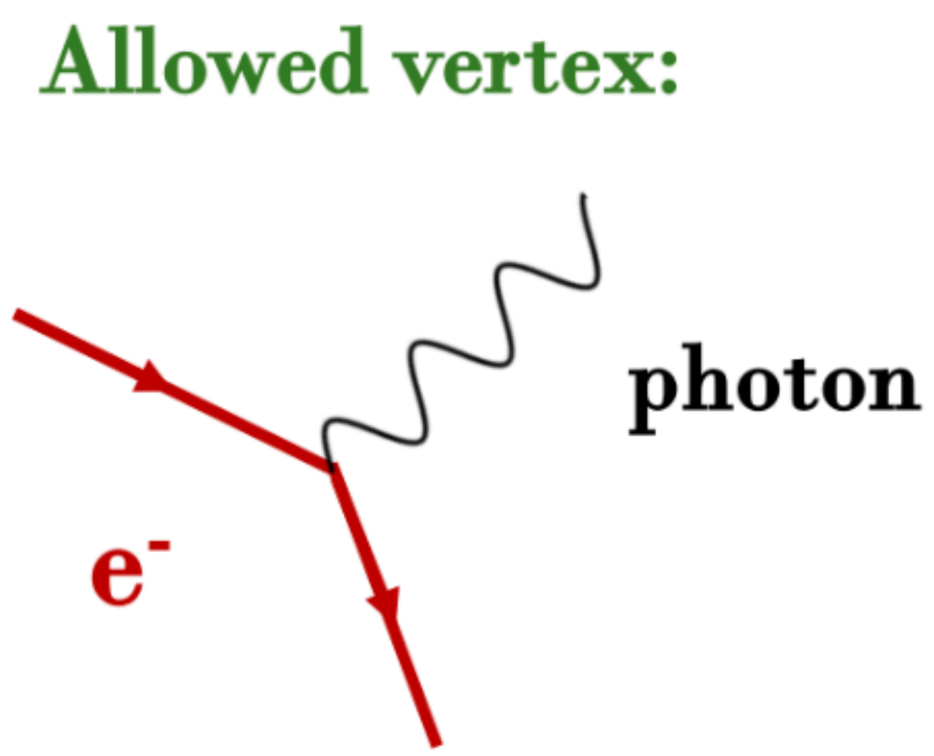
The Higgs boson

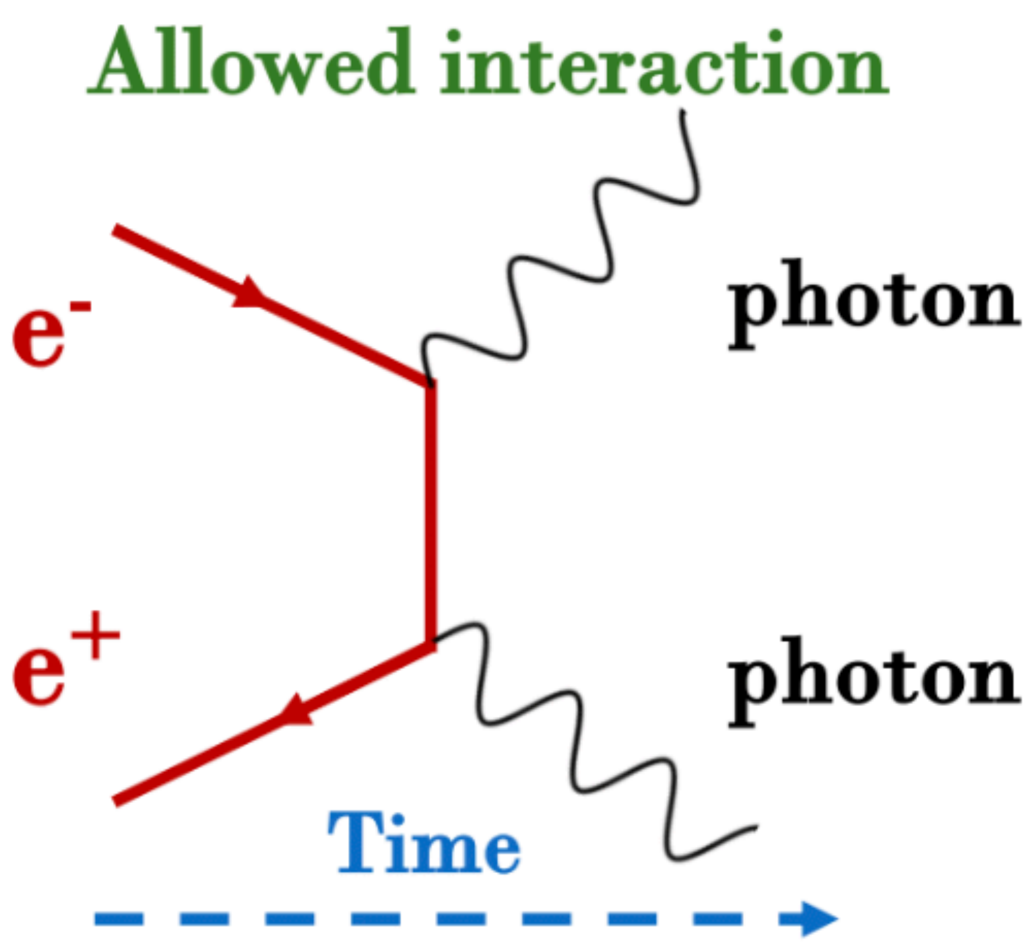
Some extra miscellaneous info

1. How we draw our particles?

Feynman diagrams

A nice way to explain particle interactions (also essential in Quantum Field Theory)
e.g. electron-positron annihilation





Vertices can be combined to produce allowed interactions

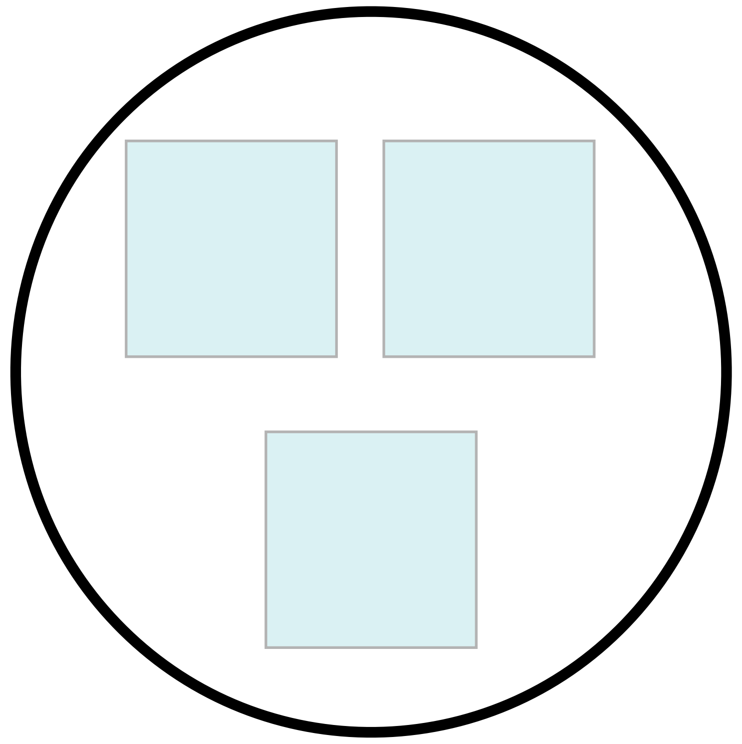
Antimatter is shown with arrows backwards in time

A weird property of the strong force

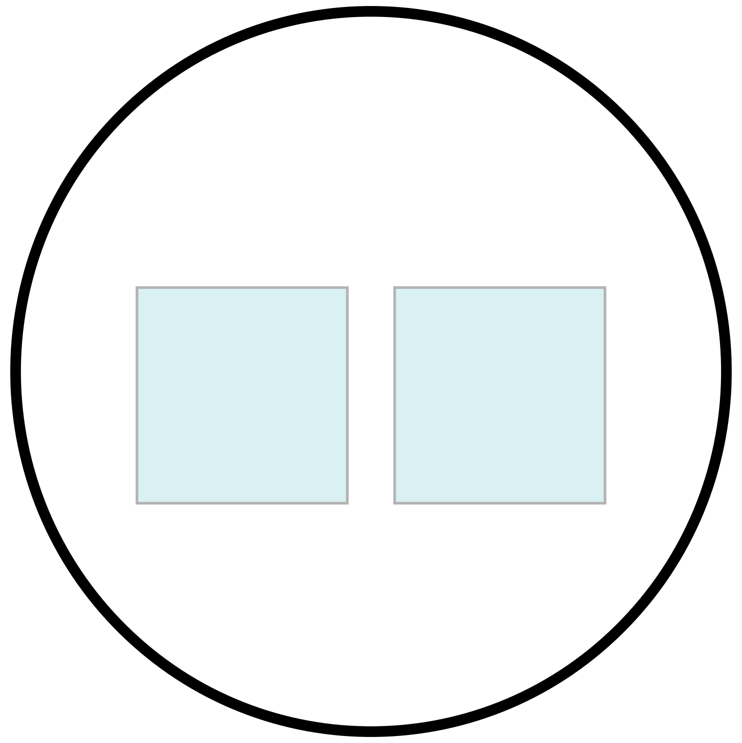
The dynamics of quarks and gluons is governed by the strong force.

Quarks and gluons cannot be found individually in nature

They are confined to groups of particles called: hadrons



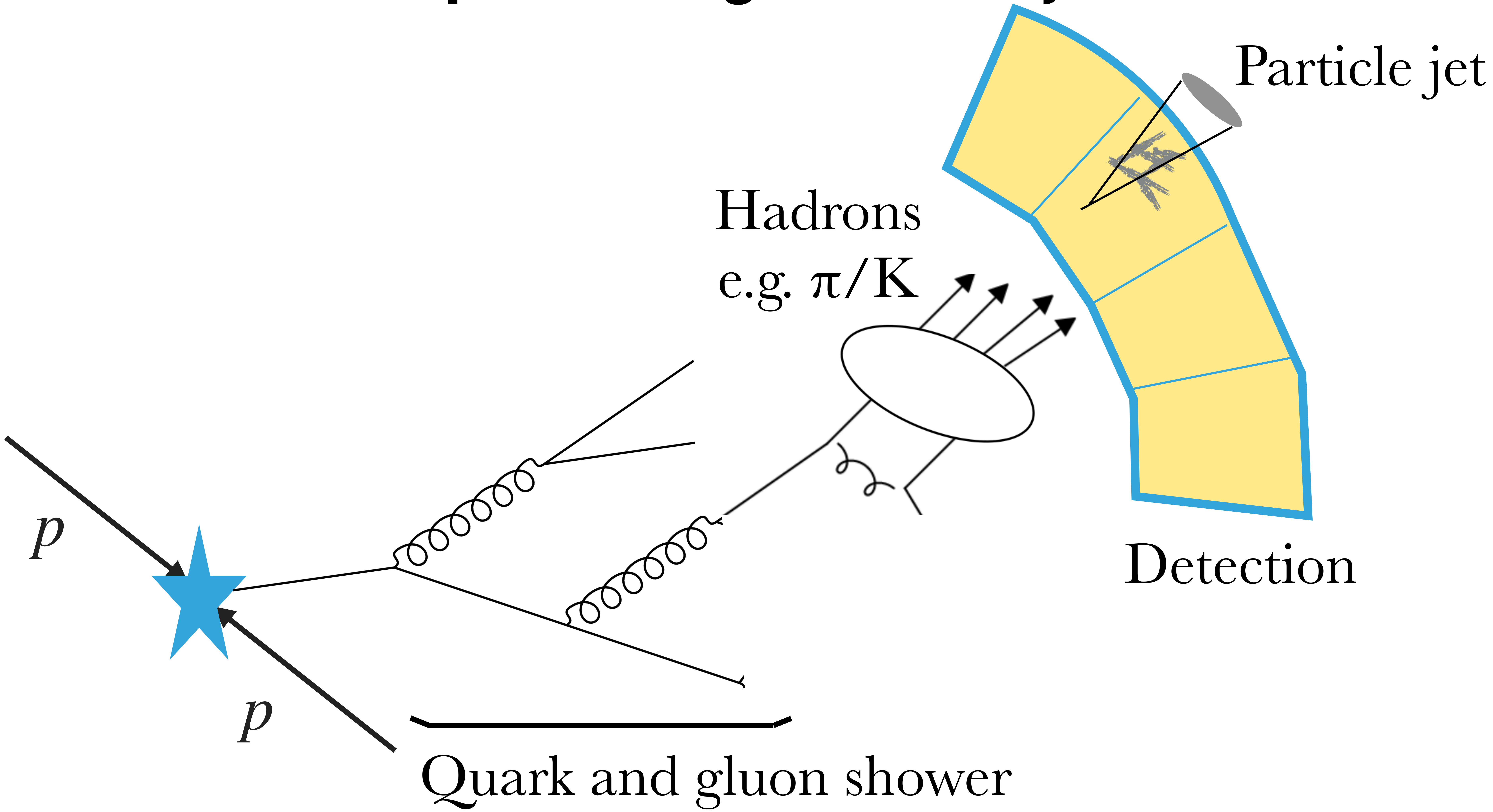
Baryons



Mesons

Particle Jets

In our particle detectors quarks and gluons form jets




$H \to b\bar{b}$
b-jet
b-jet
$Z \to e^+e^-$
e
e


CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-20 03:55:39.135168 GMT
Run / Event / LS: 305313 / 624767783 / 361
q-jet or g-jet
$H \to b\bar{b}$
b-jet
b-jet

Summary of what we have learned

- The **Standard Model** is the most complete explanation of fundamental particles and their interactions
- Quarks and leptons are **matter particles**
- Each force has **force carrier particles** associated with it
- The **Higgs mechanism** is responsible for the masses of elementary particles

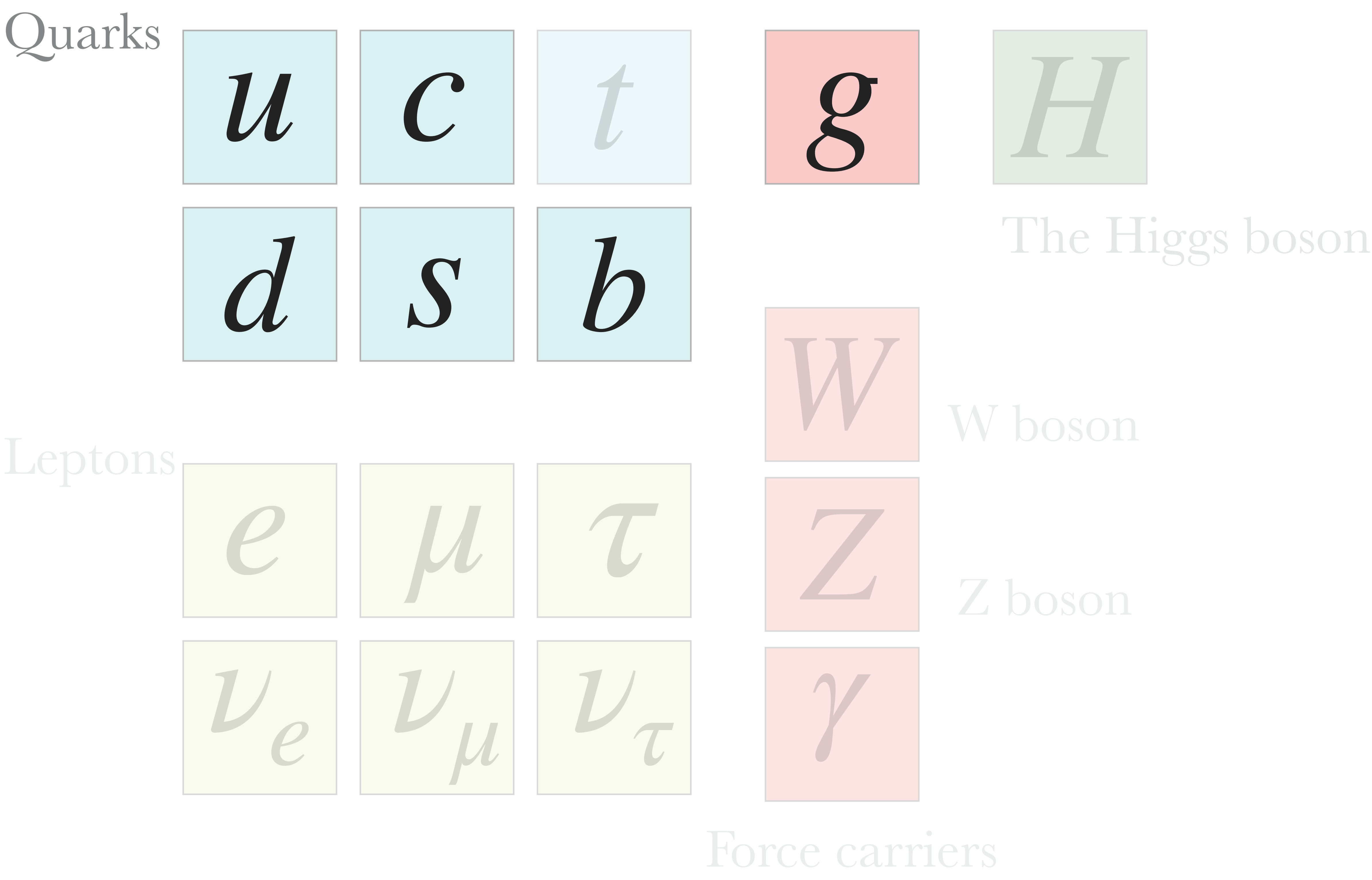
Some questions for the future

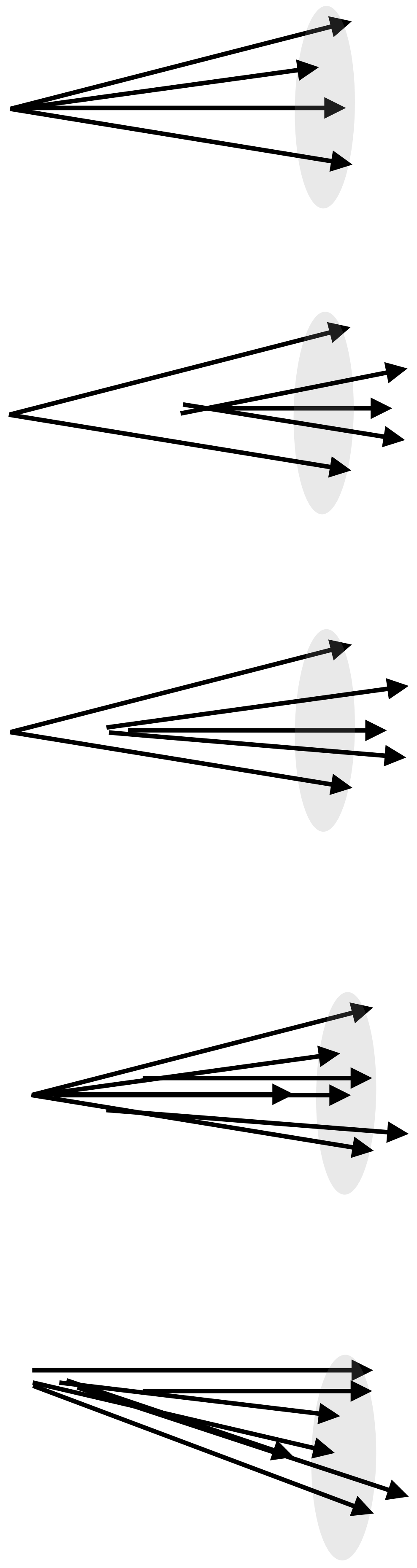
- Why is there more matter than antimatter?
- What is dark matter? Is it a particle?
- Is there any evidence for other particles? e.g. supersymmetry?
- Why do the three generations have different masses?
- Where does gravity fall in?

Questions?

Jets in our detector

Jets of the Standard Model





quark jet
u, d, s
100 MeV
+ gluon radiation

b-jet
4.2 GeV
+ gluon radiation

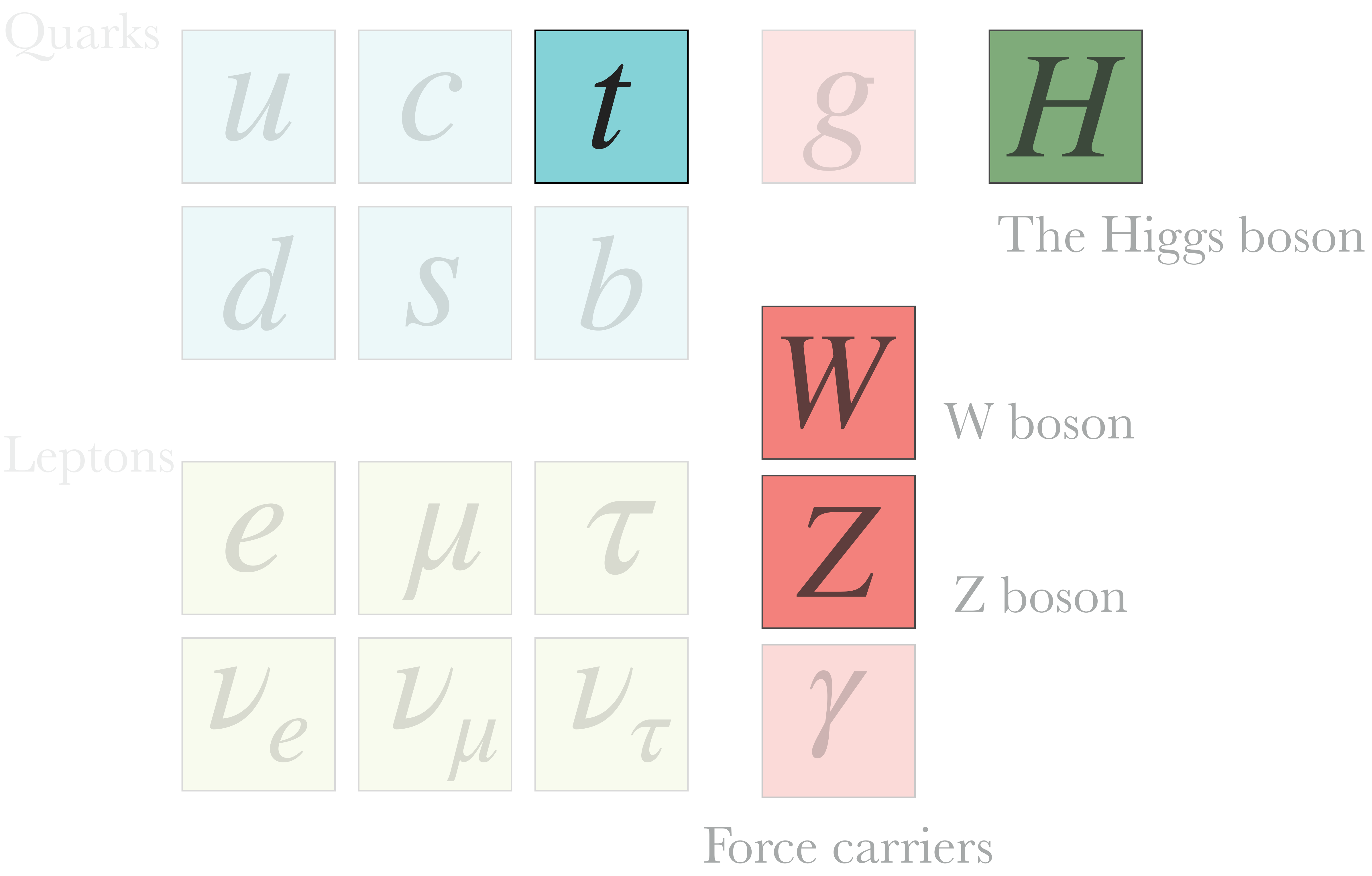
c-jet
1.3 GeV
+ gluon radiation

gluon-jet
0 GeV
+ gluon radiation

pileup jet
1 GeV

Jets in our detector

Jets of the Standard Model

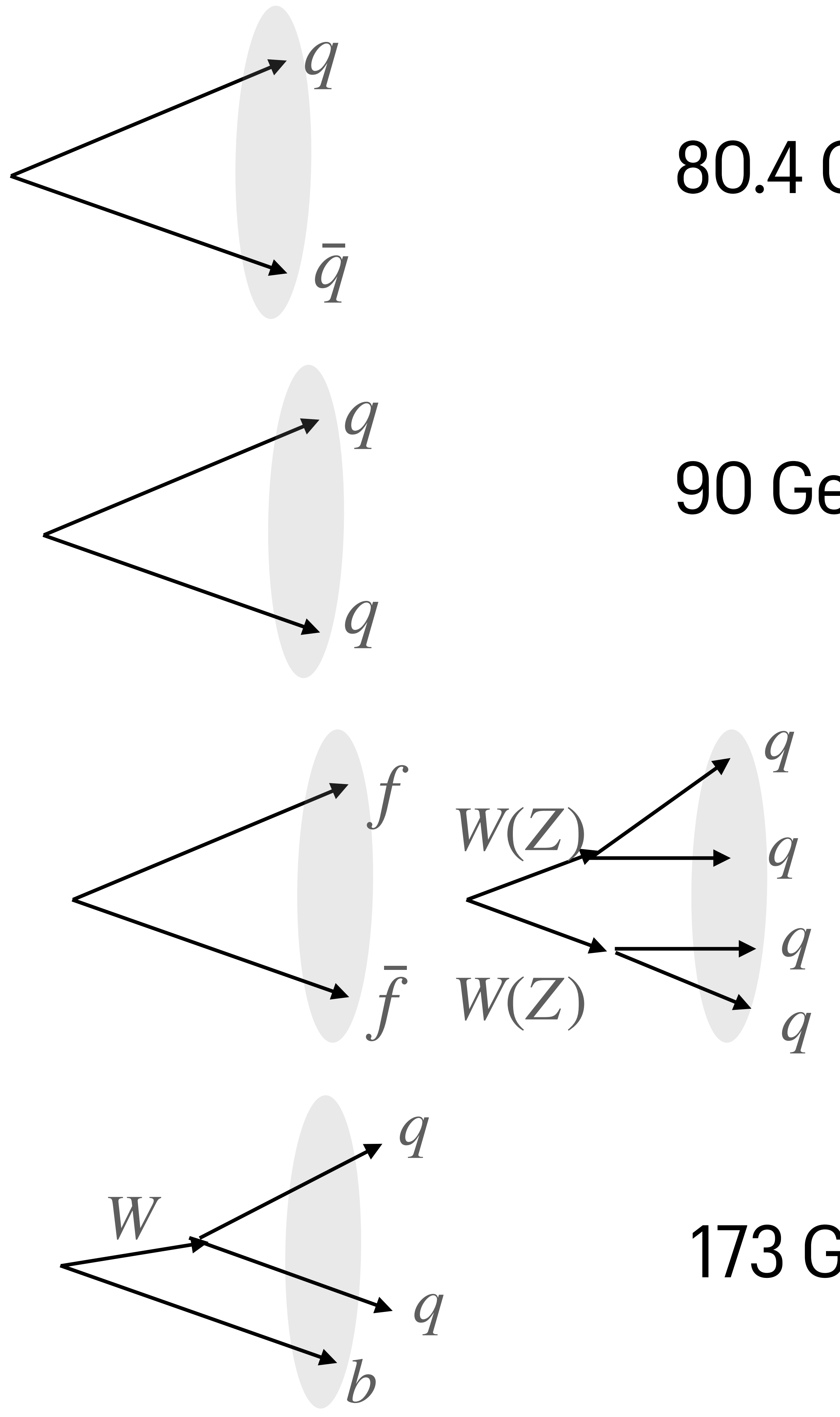


W-jet
~70%
80.4 GeV

Z-jet
~70%
90 GeV

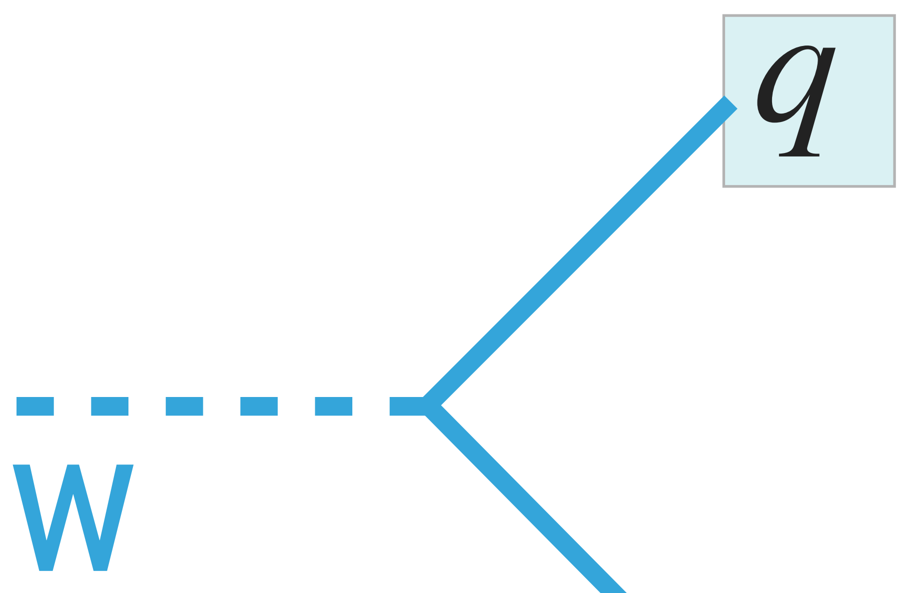
Higgs jet
>60%
125 GeV

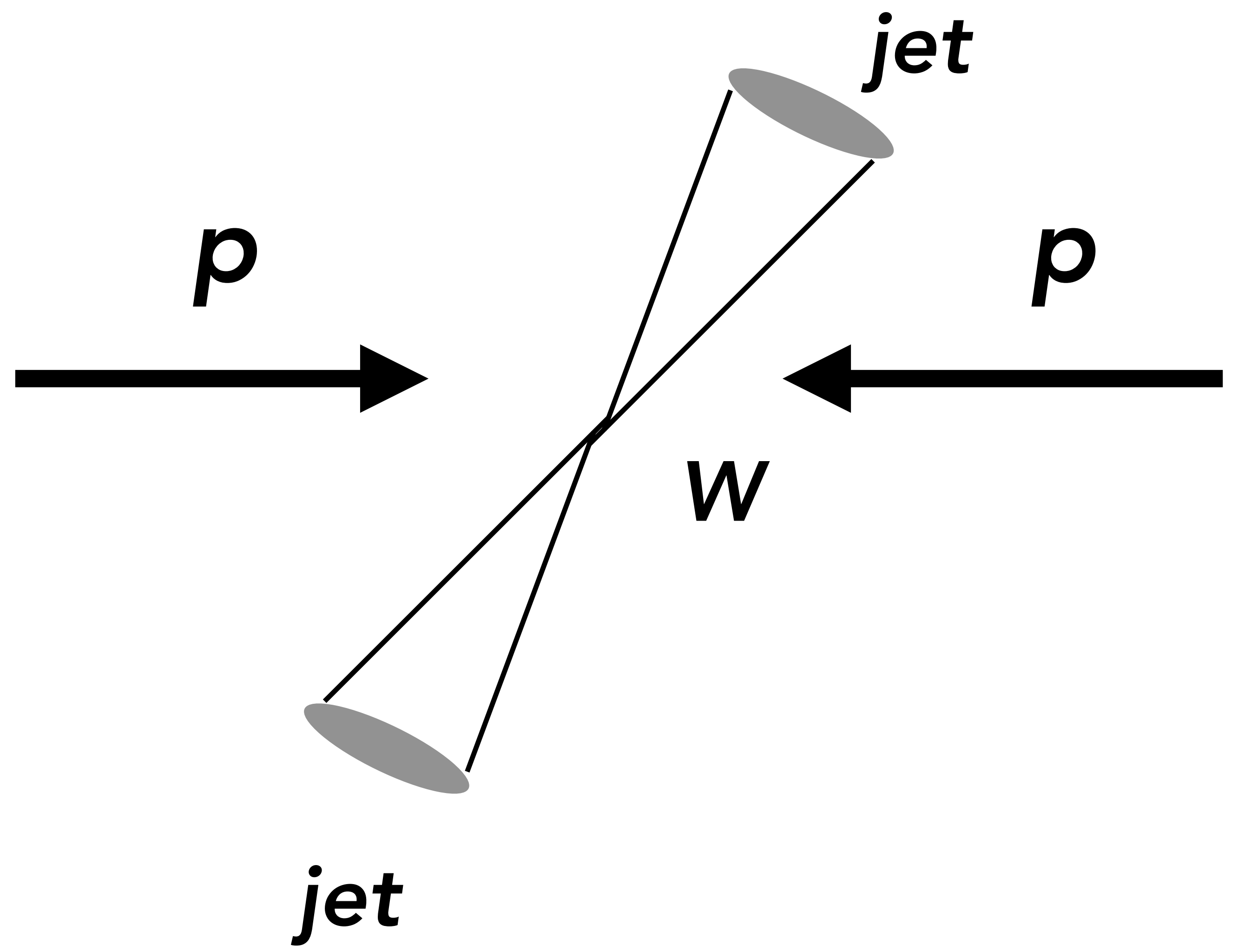
Top jet
~70%
173 GeV

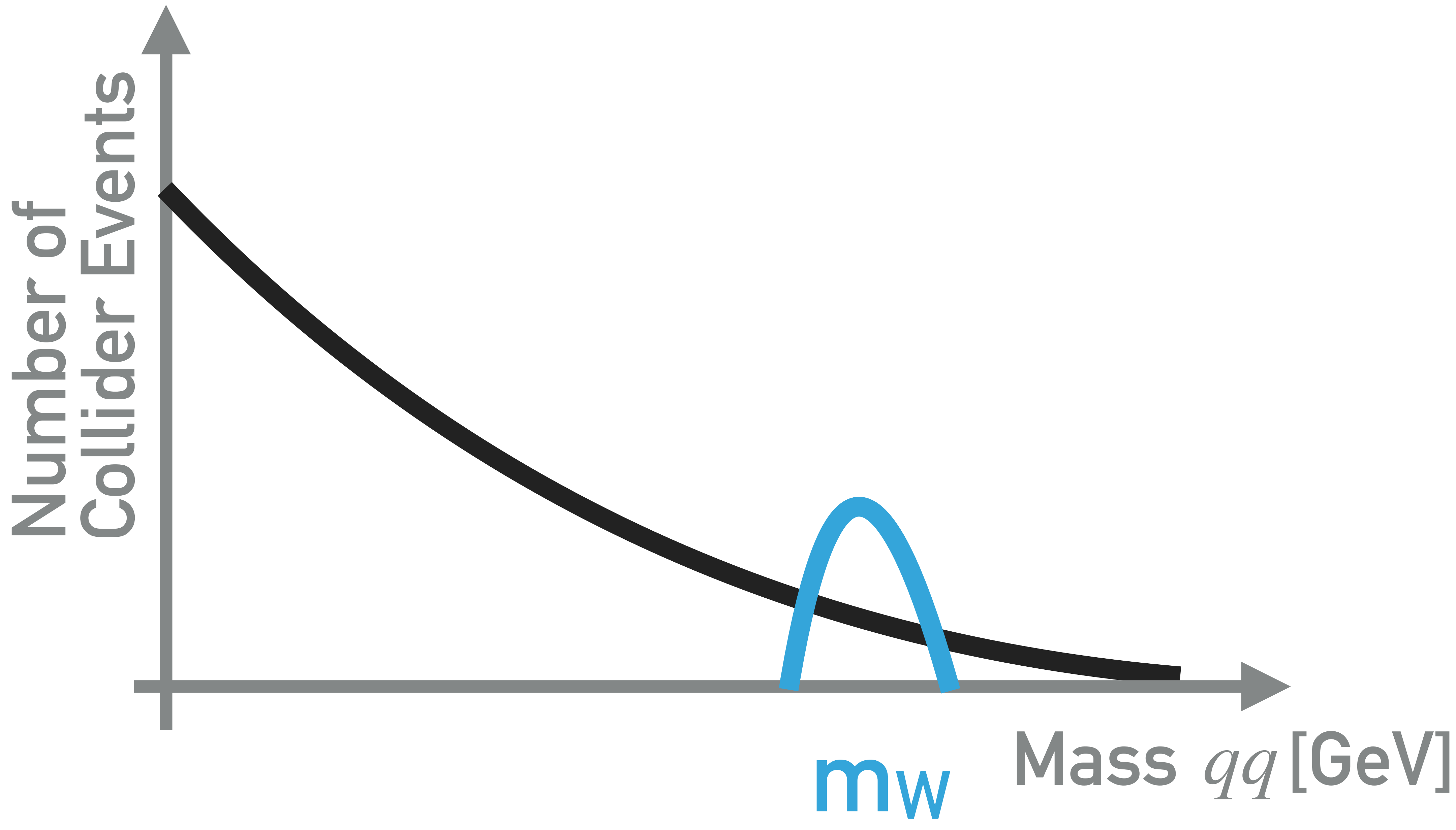


Looking for a resonance

At the LHC







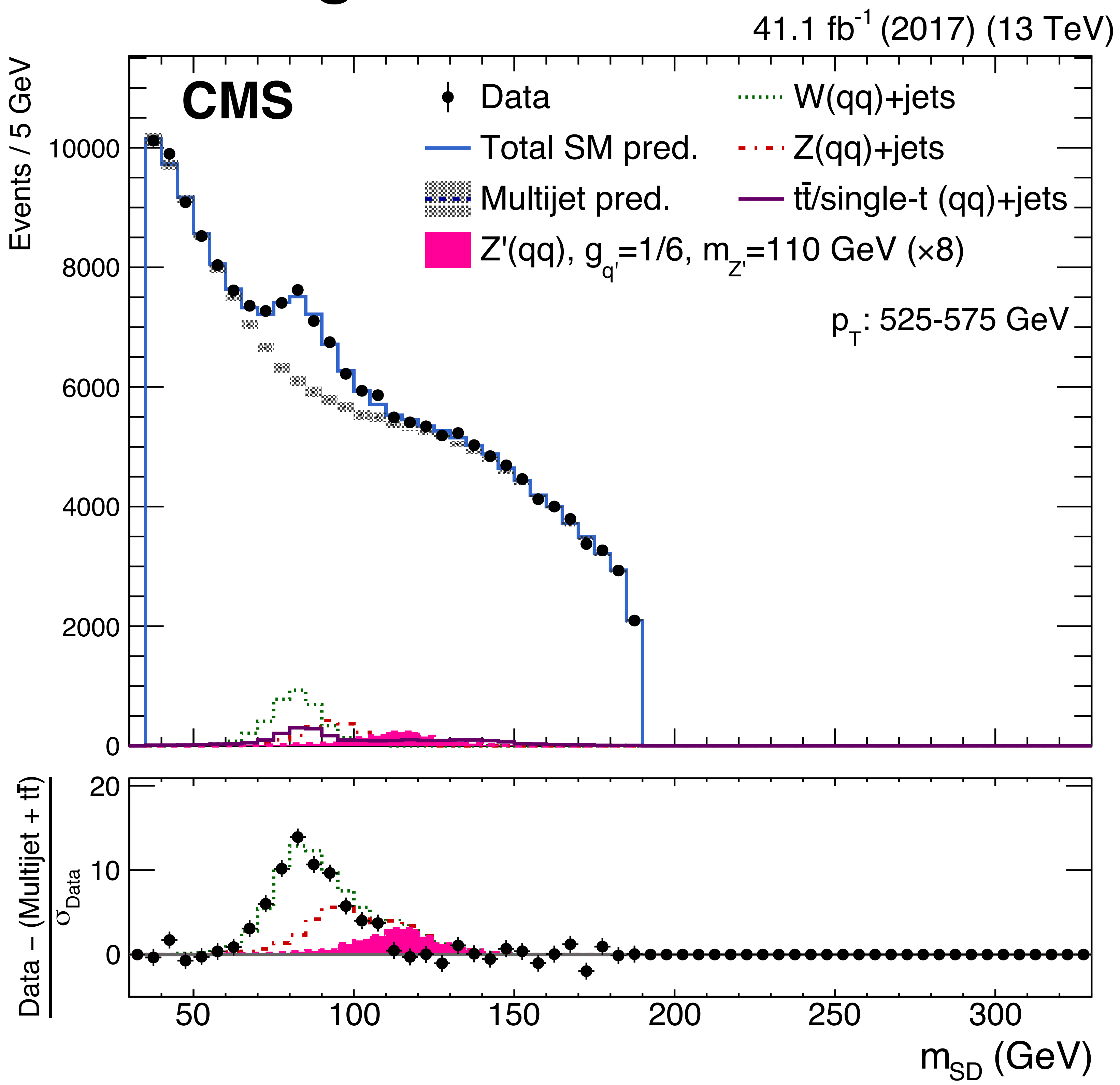
$p_T < 200$ GeV

$m_W \sim 80$ GeV

LHC results

Looking for a resonance

Finding W



Finding Z