The Standard Model of Particle Physics

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June 16, 2017

Particle physics

How the world works at *very small distances (and very high temperatures).*

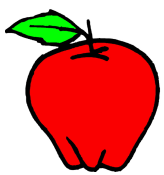
Earth 10^7 meters

Ratios of sizes

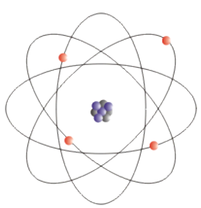
apple / earth is about the same as

atom / apple which is larger than

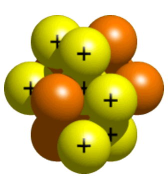
quark / atom



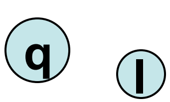
Apple 0.1 meters



Atom 10^{-10} meters



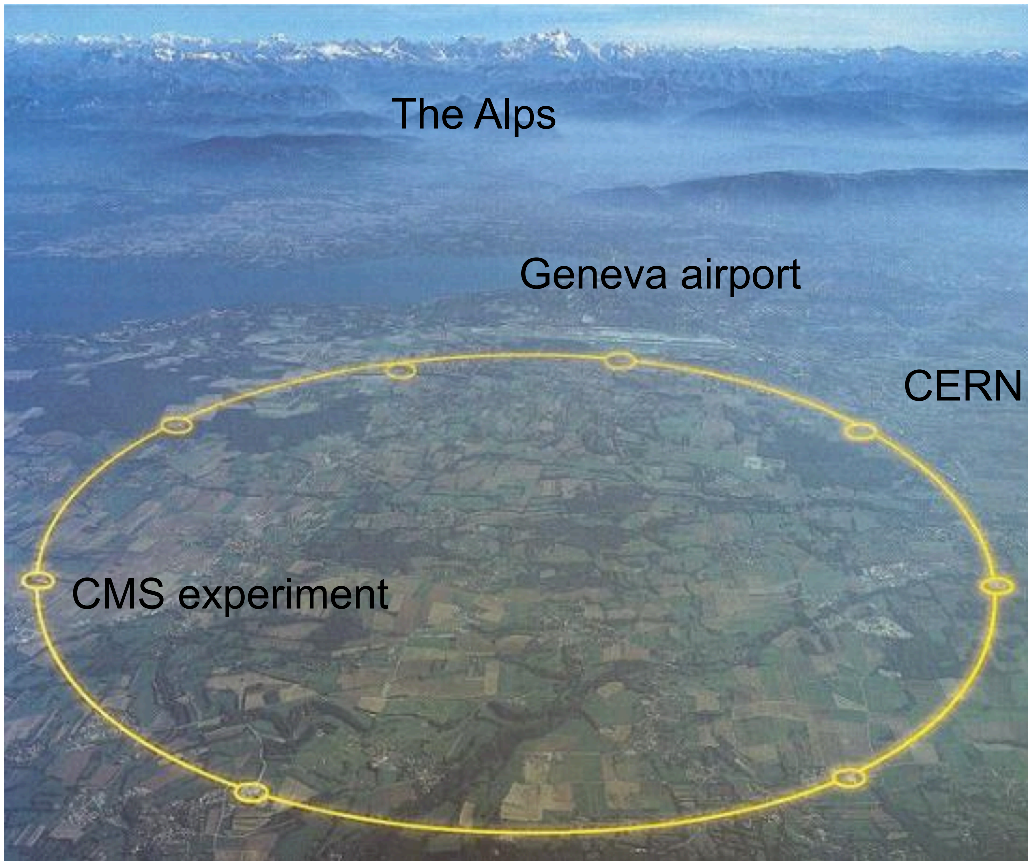
Nucleus 10^{-14} meters



Quarks & leptons $<10^{-18}$ meters

(We don't know exactly how small these are.)

The Large Hadron Collider



- World's highest energy accelerator.
- Circumference is 27 kilometers (17 miles).
- Crosses the French/ Swiss border (twice).
- Accelerator is about 100 meters underground.

The Large Hadron Collider

How much energy is in the proton beams?

(115 billion protons / bunch) x (2808 bunches / beam) x (2 beams) x
(7 trillion eV / proton) x (1.6 x 10^{-19} Joules / eV) = *723 million Joules !*

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Same as the kinetic energy of a Boeing 737 flying at 500 mph (230 m/s) !

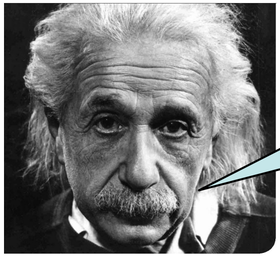
KE = (1/2) m v^2

KE = (1/2) (28,000 kg) $(230\ m/s)^2$

KE = 740 million Joules!

The Large Hadron Collider

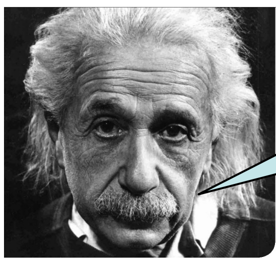
How fast are the beam protons moving?



The Large Hadron Collider

How fast are the beam protons moving?

My theory of special relativity says that nothing can move faster than the speed of light, which is 300 million meters per second (or 670 million mph).

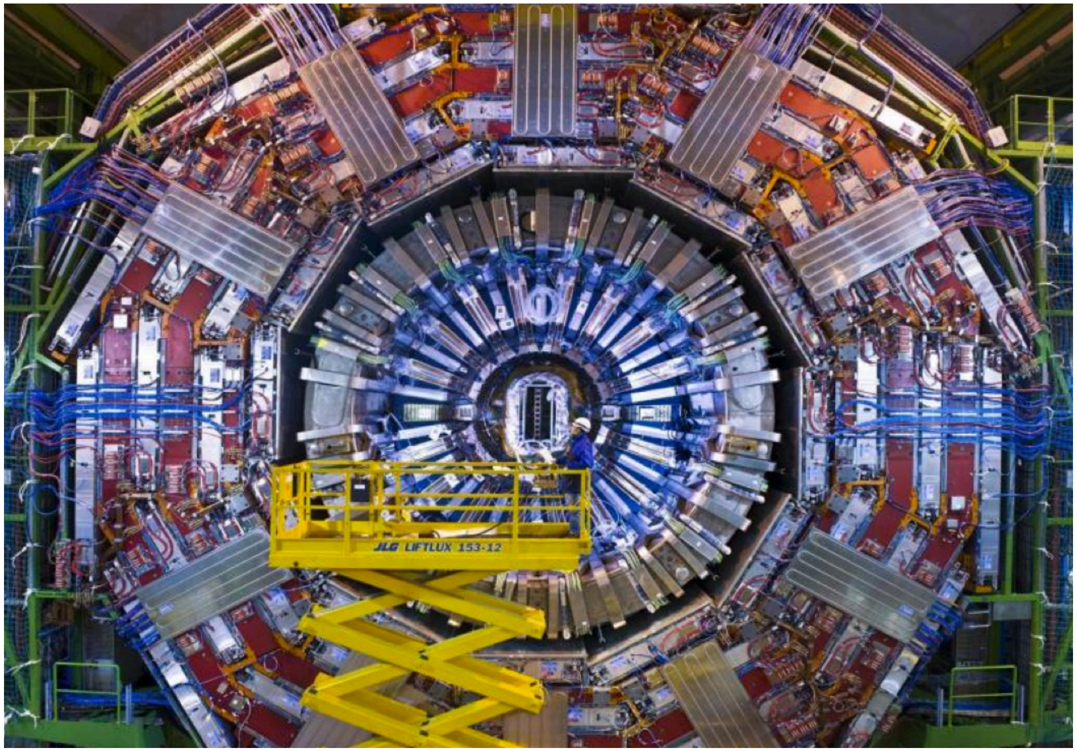


$$E = \gamma m c^2$$
$$\gamma = E/(mc^2) = (7000\ \text{GeV})/(0.940\ \text{GeV}) = 7450$$
$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}.$$
$$v/c = \sqrt{1 - 1/\gamma^2} = \sqrt{1 - 1/7450^2} = 0.999999991$$
$$c - v = c/(2\gamma^2) = (300000000\ \text{m/s})/(2 \times 7450^2) = 2.7\ \text{m/s}$$

If you race a LHC beam proton and a photon (particle of light), the photon is moving at about 300 million meters per second and the proton is only 2.7 meters per second slower!

One second after the start of the race, they have both traveled about 300 million meters, but the photon is only ahead by 2.7 meters!

The CMS Experient



- CMS stands for Compact Muon Solenoid.
- The size of a 5 story apartment building.
- Weights about 12,500 tons, about the same as this

Taking data with the CMS experiment

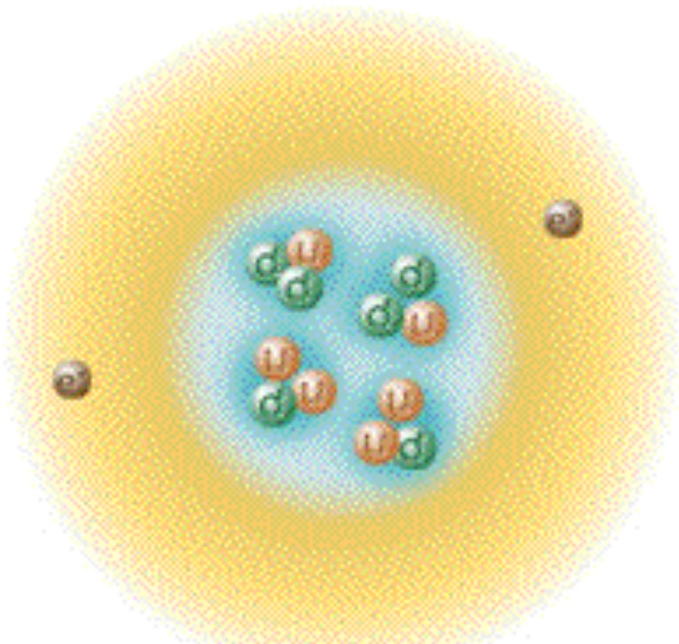
- The proton bunches collide every 25 nanoseconds.
  - Collisions per second : 1 / (25 nanoseconds / collision) = 1 / 25 x 10^{-9} = 40,000,000 collisions / second.
  - Light travels about 1 foot in 1 nanosecond.
    - distance = speed x time = (3 x 10^8 m/s) x (1 x 10^{-9} s) = 0.3 m = 1 foot.

- We can't possibly read out the detector and save *every* event (most are boring anyway).
  - Would be filling up 320 hard drives every second.

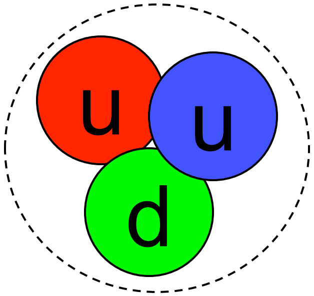
- We make decisions *very quickly*, on the fly, about which collision events to save
  - Look for unusual things: lots of energy coming out transverse to the beam, special particles produced, missing transverse energy, …

Your *every-day* particles and forces

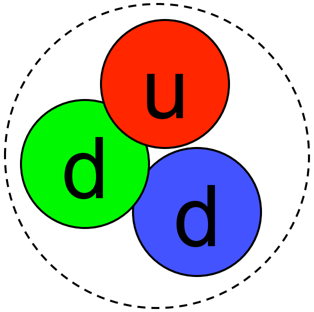
Helium atom:
Two electrons (-)
Two protons (+)
Two neutrons (0)



Atom held together by
electromagnetic force



Proton:
Two up quarks
One down quark

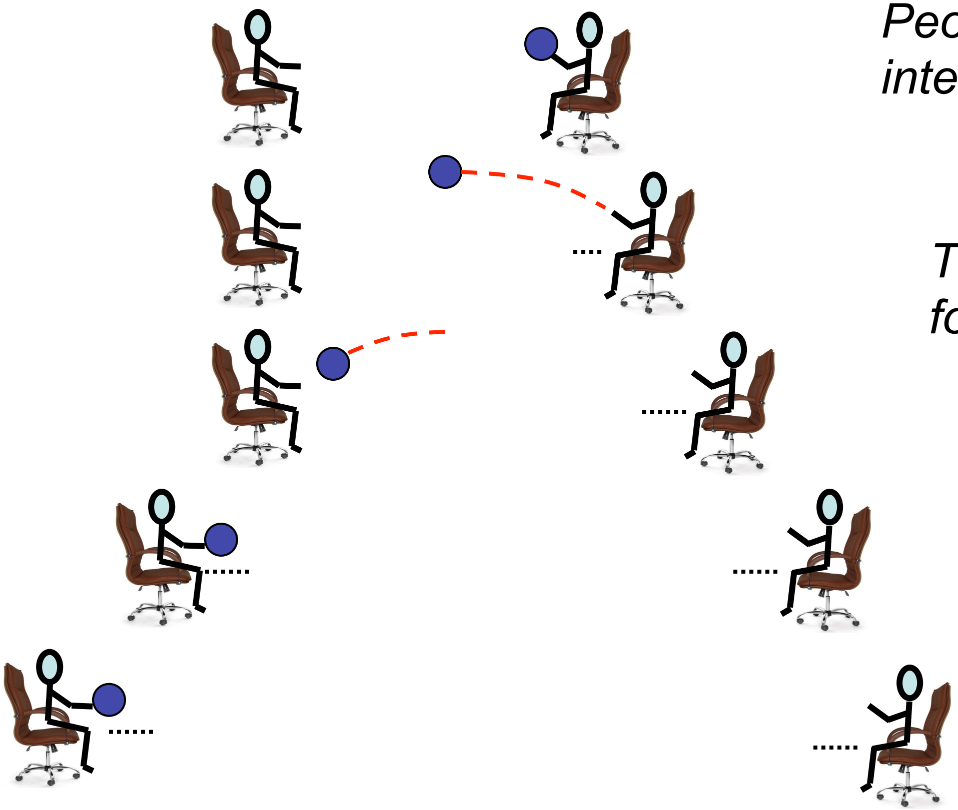


Neutron:
One up quark
Two down quarks

Proton, neutron, and nucleus held together by the ***strong force***

Force carriers

Particles interact by exchanging force carriers.
Example for a *repulsive* force



People in chairs are the interacting particles.

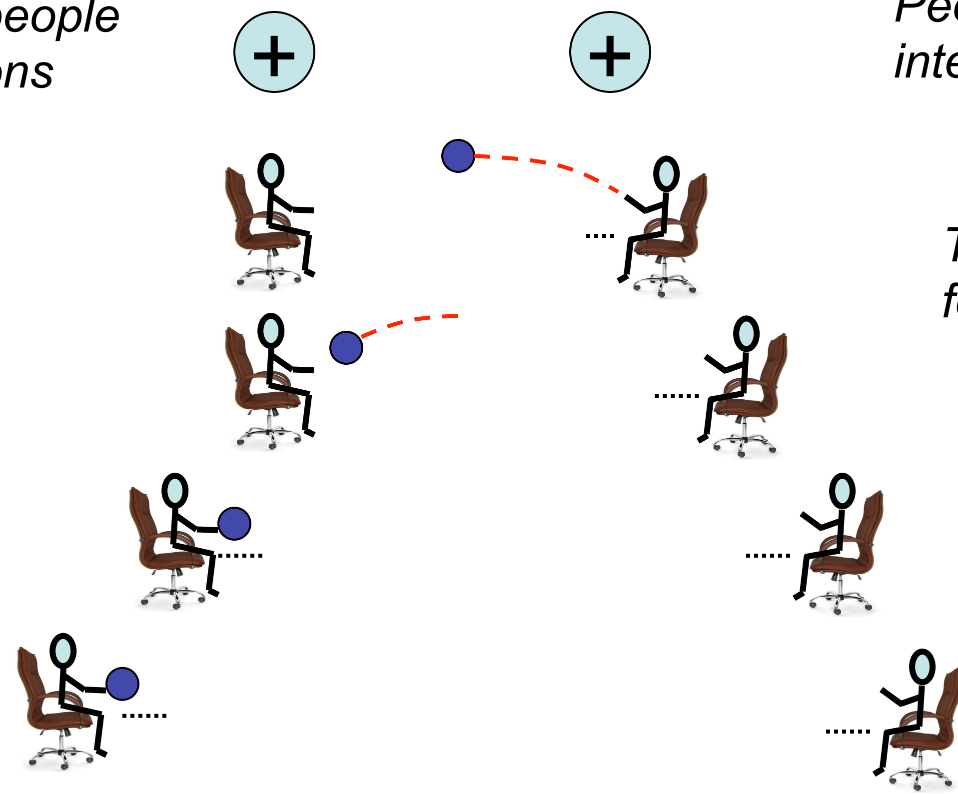
The blue ball is the force carrier.

Force carriers

Particles interact by exchanging force carriers.
Example for a *repulsive* force

Replace the people with two protons

People in chairs are the interacting particles.



The blue ball is the force carrier.

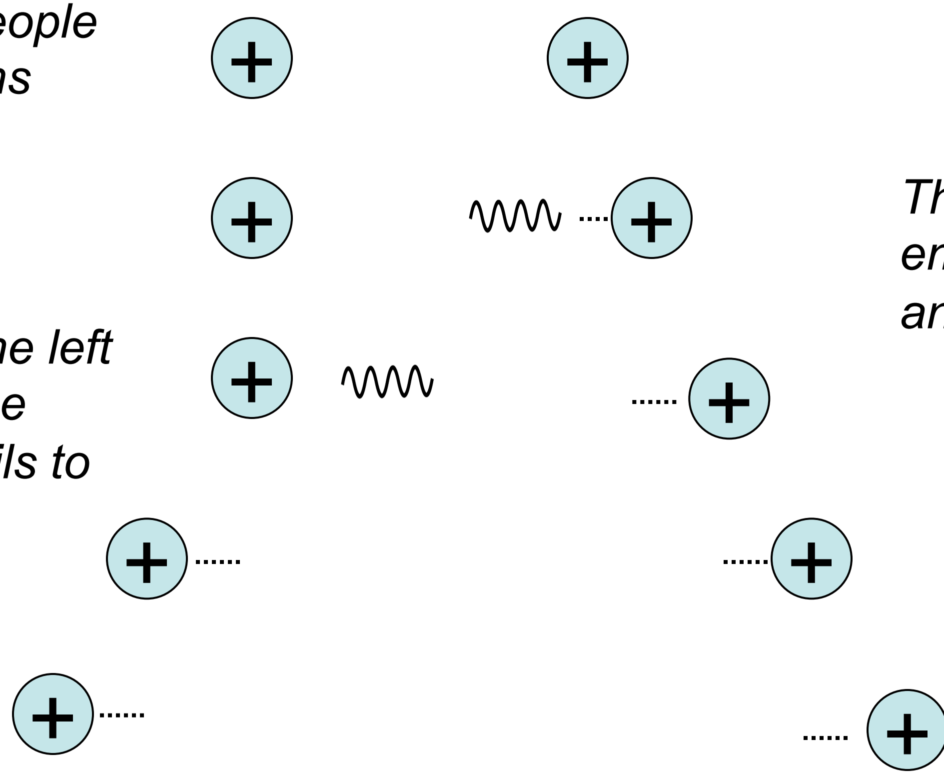
Force carriers

Particles interact by exchanging force carriers.
Example for a *repulsive* force

Replace the people with two protons

The proton on the right emits a force carrier and recoils to the right.

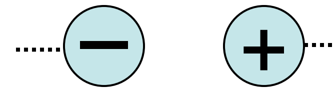
The proton on the left absorbs the force carrier and recoils to the left.



This is an electromagnetic interaction.
The force carrier is the ***photon***

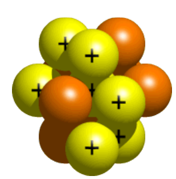
Electromagnetic and strong interactions

- ***Electromagnetic***: same charges repel, opposite charges attract. Force carrier is the *photon*.

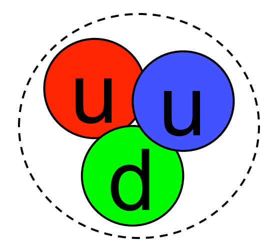


  – In an atom, the electrons (-) are attracted to the protons (+) in the nucleus. *This is what holds the atom together.*

- ***Strong***: quarks attract each other by exchanging force carriers called “gluons”. The strong force is *always attractive*.



nucleus



proton

Summary of *every-day* particles and forces

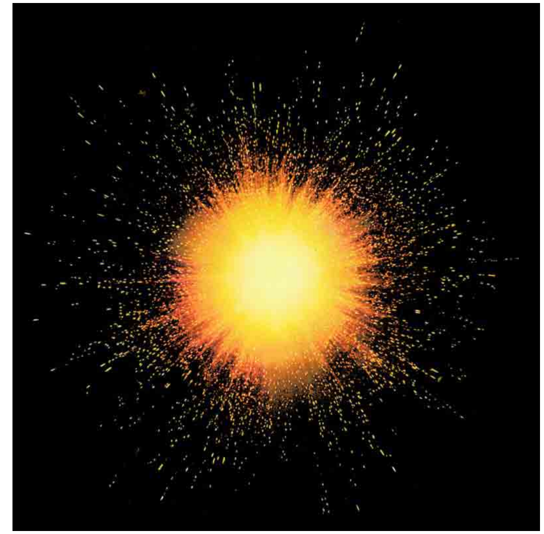
	Symbol	Electric charge	*Every-day* interactions (force carrier)
quarks	u	+2/3	Electromagnetic (photon γ)
	d	-1/3	Strong (gluon g)
leptons	e	-1	Electromagnetic (photon γ)

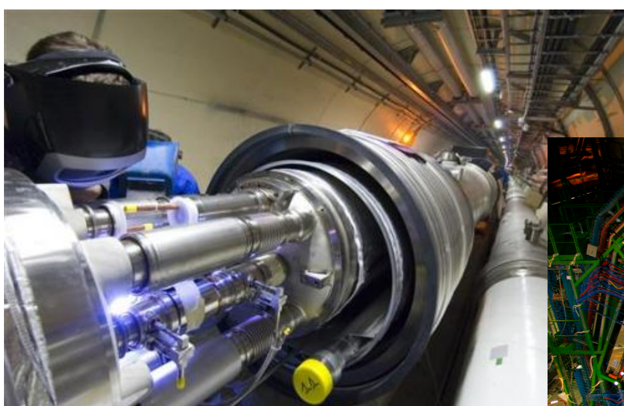
But, this is far from the full set of particles and forces…

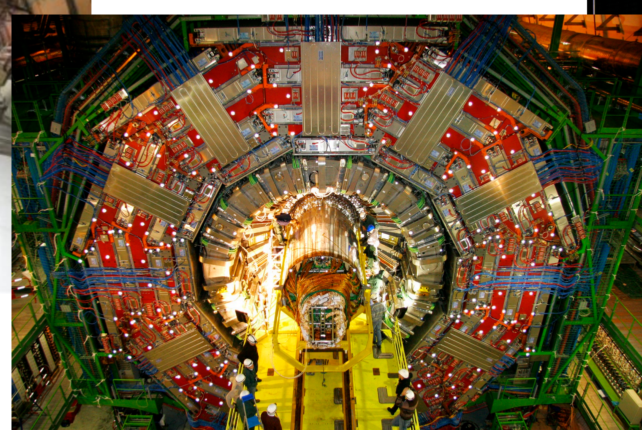
The full Standard Model

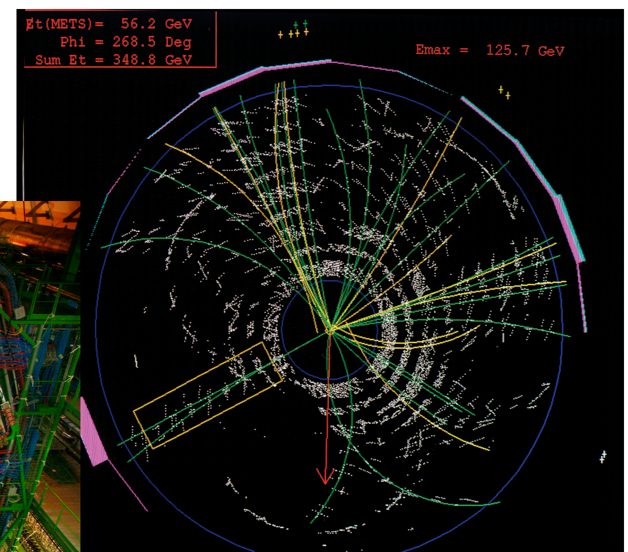
- A far richer set of particles and interactions were present in the early universe just after the big bang.

- We create them with our *accelerators* and study them with our *detectors*.









The full Standard Model

	Symbol			Electric charge	Interactions (force carrier)
quarks	u	c	t	+2/3	Electromagnetic (photon γ)
	d	s	b	-1/3	Strong (gluon g)
					Weak ($W^{\pm}$, Z^0)
leptons	ν_e	ν_μ	ν_τ	0	Weak ($W^{\pm}$, Z^0)
	e	μ	τ	-1	Electromagnetic (photon γ) *(only for e,μ,τ)*

- Three sets, or "***generations***", of particles, heavier with each generation.
- Each charged lepton has an associated nearly massless ***neutrino***.
- 3rd ***Weak force*** with massive force carriers: $W^{\pm}$, Z^0.
- *Every* particle has a corresponding ***antiparticle*** with the same mass but *opposite electric charge*.

The last missing piece?

- The **mass** of a particle is thought to be related to how strongly it interacts with the so-called *Higgs field*, which is *everywhere*.
  - The theory explains why the weak force is much weaker than the electromagnetic force.

- If this is correct, the theory predicts the existence of a particle called the ***Higgs Boson***.

- The theory also makes *predictions* about how the Higgs Boson is produced and how it decays that can be <u>tested by the LHC</u>.

- We are convinced that we have discovered the Higgs boson.
  - Angular analysis of decay distributions consistent with spin-zero particle.
  - Scaling of the Higgs boson couplings with mass look as expected.

- If the Standard Model is a complete theory, the Higgs is the last particle to be discovered. We don't *need* more particles.
  - If there's something beyond the Standard Model (such as Supersymmetry), there could be *many more particles* yet to be discovered...

The Bigger Picture

- The physics of the very small (particle physics) is also connected to the physics of the very big (astronomy and cosmology).

- It’s possible to measure how much energy there is in the entire universe and also divide it up into categories.

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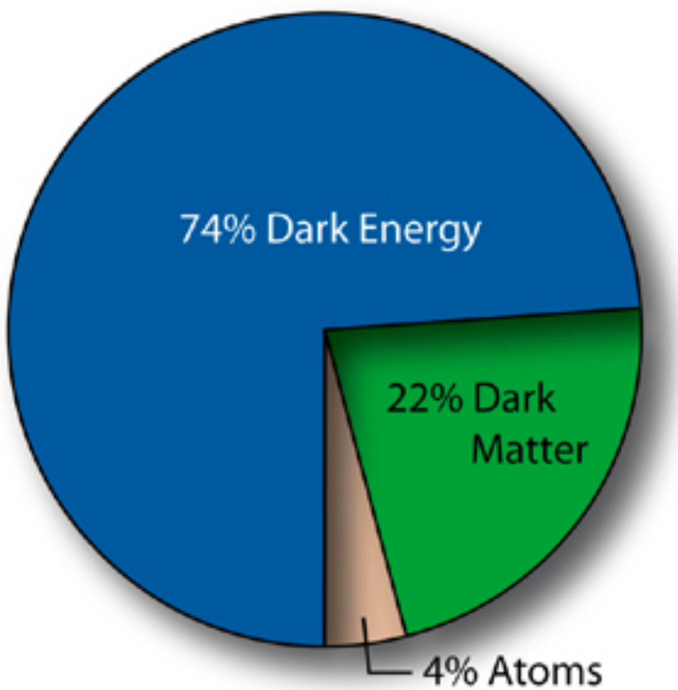


The stuff we are made of and everything we see is only 4% of the total!

Dark Matter might be Weakly Interacting Massive Particles (WIMPS). We might produce and detect these at the LHC.

We don't know what the heck Dark Energy is...

Types of particle reactions

- ***Creation and annihilation***
  - A particle and *its* antiparticle can transform into another particle, antiparticle pair through the exchange of a force carrier. The initial pair is "annihilated", the second pair is "created".
  - Examples:

$$e^+e^- \longrightarrow \mu^+\mu^-$$
$$e^+e^- \longrightarrow b\,\bar{b}$$
$$u\bar{u} \longrightarrow d\bar{d}$$

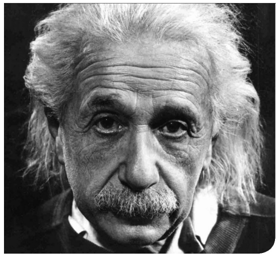
- ***Particle decay***
  - All of the particles in the 2nd and 3rd generation (*except the neutrinos*) spontaneously disintegrate (or "decay") into other lighter particles through the exchange of a W^+ or W^- boson.
  - Examples:

$$\tau^- \longrightarrow e^-\ \nu_\tau\bar{\nu}_e$$
$$b \longrightarrow c\,\mu\,\bar{\nu}_\mu$$
$$t \longrightarrow b\,u\,\bar{d}$$

Some rules for Particle reactions

Conservation laws: If something is "conserved" in a reaction, it means that it must be the *same before and after the reaction*.

- ***Energy conservation***
  - The total energy is conserved.
  - Mass is a from of energy : $\boldsymbol{E = mc^2}$
  - Heavy particles can *decay* into lighter particles, but ***not*** the other way around.



- ***Charge conservation***
  - The total electric charge is conserved.

- ***Lepton number and flavor conservation***
  - Leptons have lepton number +1, their antiparticles have lepton number -1. The total lepton number is conserved.
  - Each of the 3 generations has it's own "flavor" of leptons. Lepton number is conserved separately for each flavor.

An example

$$\tau^- \rightarrow e^- \ \nu_\tau \bar{\nu}_e$$

	τ^-	e^-	ν_τ	$\bar{\nu}_e$	
τ lepton number	+1	0	+1	0	✓
e lepton number	0	+1	0	-1	✓
Electric charge	-1	-1	0	0	✓
Energy	**heavy**	**light**	***Super light***	***Super light***	Allowed

Some of the mass energy (**E=mc²**) of the initial state is converted into kinetic energy of the final state, so we check that the *initial mass* is *greater* than the *final total mass.*

Decays of the Z boson

Is this decay allowed?

$$Z^0 \rightarrow e^+ e^+$$

Decays of the Z boson

Is this decay allowed?

$$Z^0 \rightarrow \cancel{e^+ e^+}$$

Decays of the Z boson

Is this decay allowed?

$$Z^0 \to \cancel{e^+ e^+}$$

e lepton number	0	-1	-1
Electric charge	0	+1	+1
Energy	**heavy**	**light**	**light**

Decays of the Z boson

Is this decay allowed?

$$Z^0 \to e^+ \mu^-$$

Decays of the Z boson

Is this decay allowed?

$$Z^0 \rightarrow \cancel{e^+\mu^-}$$

Decays of the Z boson

Is this decay allowed?

$$Z^0 \rightarrow \cancel{e^+\mu^-}$$

μ lepton number	0	0	+1	✗
e lepton number	0	-1	0	✗
Electric charge	0	+1	-1	✓
Energy	**heavy**	**light**	**light**	✓

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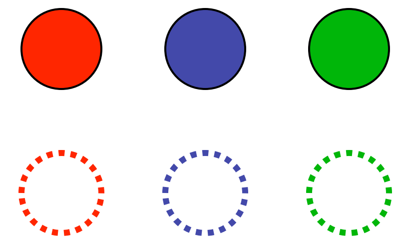
μ lepton number	0	-1	+1	✓
e lepton number	0	0	0	✓
Electric charge	0	+1	-1	✓
Energy	**heavy**	**light**	**light**	✓

This decay is also allowed $Z^0 \rightarrow e^+ e^-$

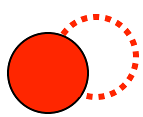
More about quarks and hadrons

- Quarks carry a property called color.
  - Three possibilities: red, blue, green.
- Antiquarks carry anticolor.
  - Three possibilities: antired, antiblue, or antigreen.



- Quarks are not allowed to show their color! Quarks must cluster together to form color-neutral objects.

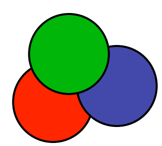
Meson



example

$$u\bar{d} = \pi^+$$

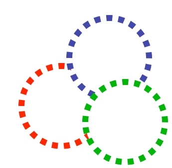
Baryon



example

$$uud = p$$

Antibaryon



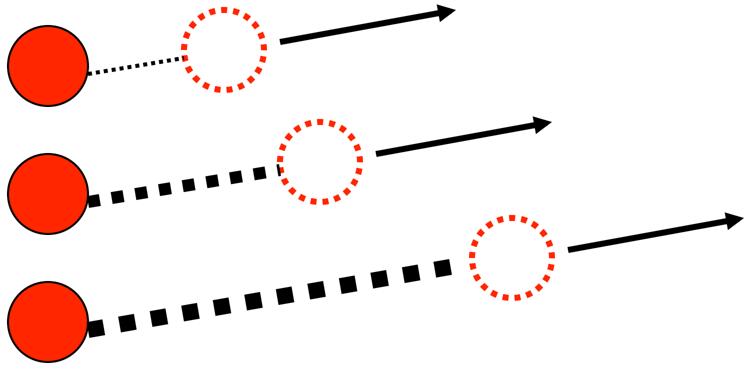
example

$$\bar{u}\bar{d}\bar{d} = \bar{n}$$

All of these combinations are called hadrons.

Quark jets

If you try to separate a quark-antiquark pair, the strong force *resists like a spring or a rubber band*. More separation gives more resistance.



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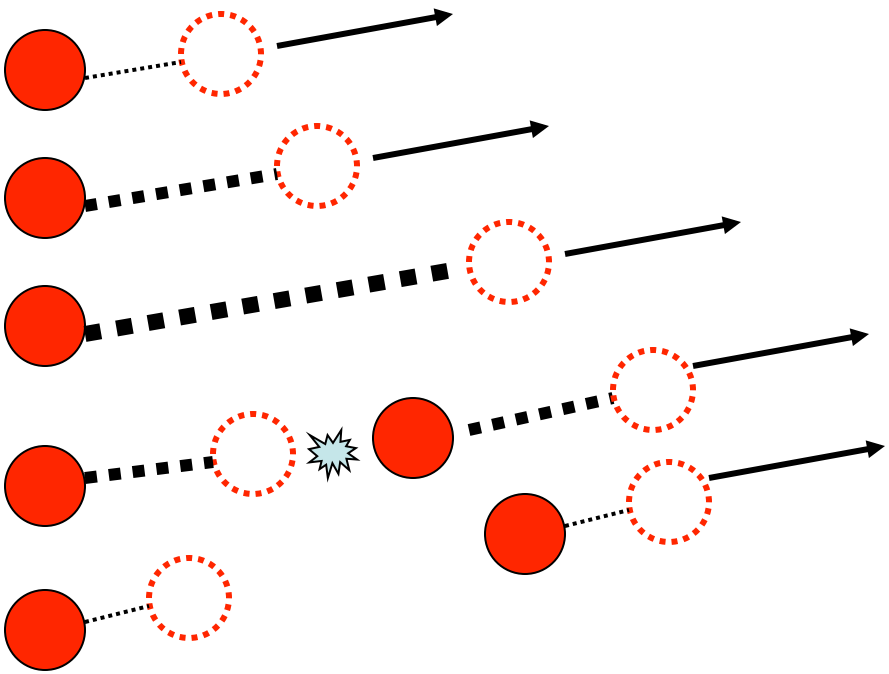
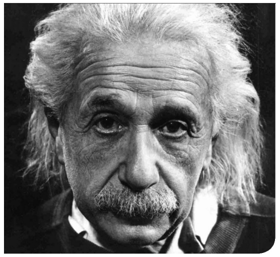




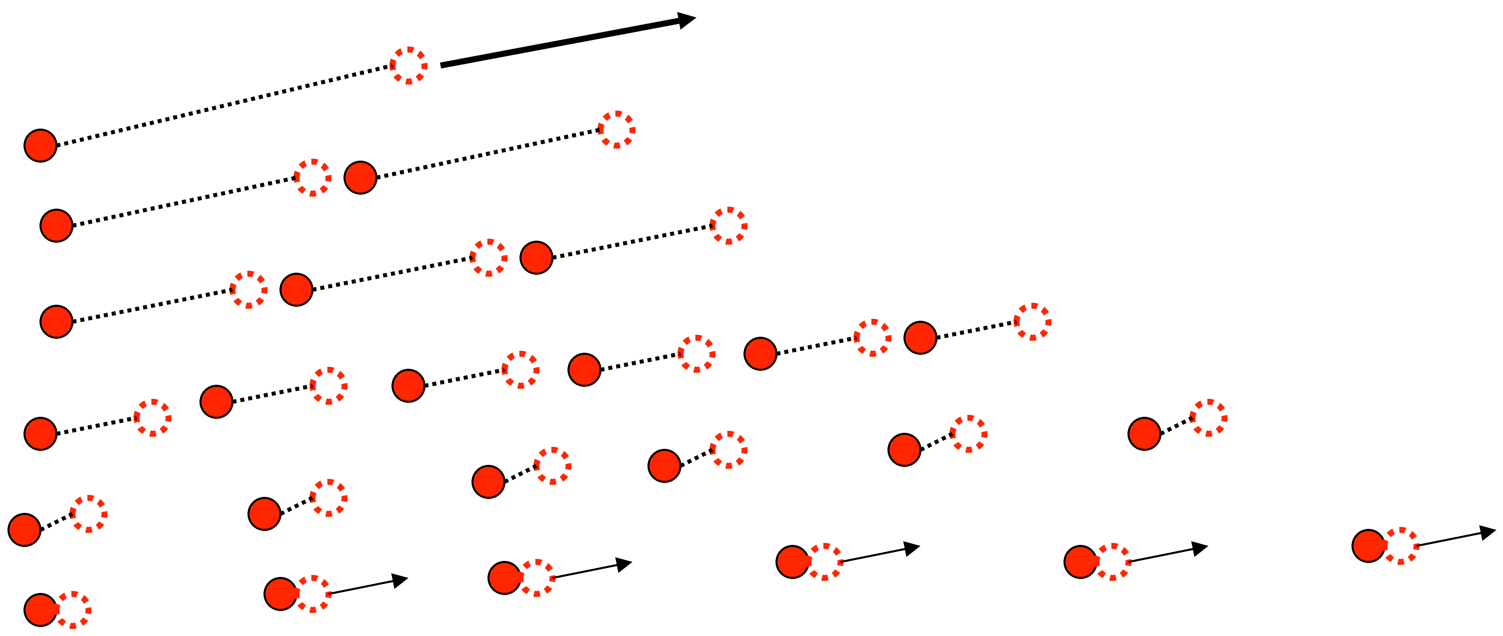
Eventually, the rubber band (color field) will snap into two pieces.

The energy of the color field creates a particle antiparticle pair!

$$E = mc^2$$

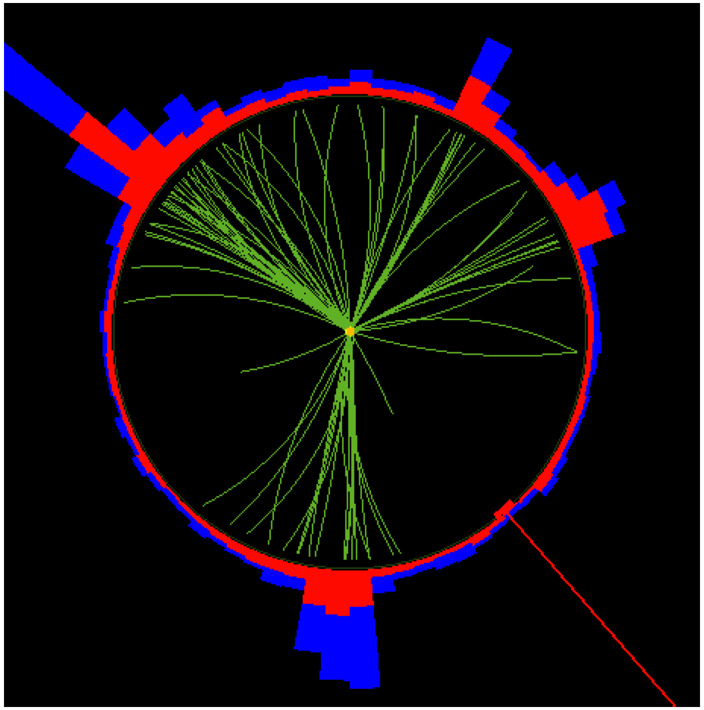
Quark jets

This can happen several times. The result is a *group of hadrons* all moving in about the *same direction*.

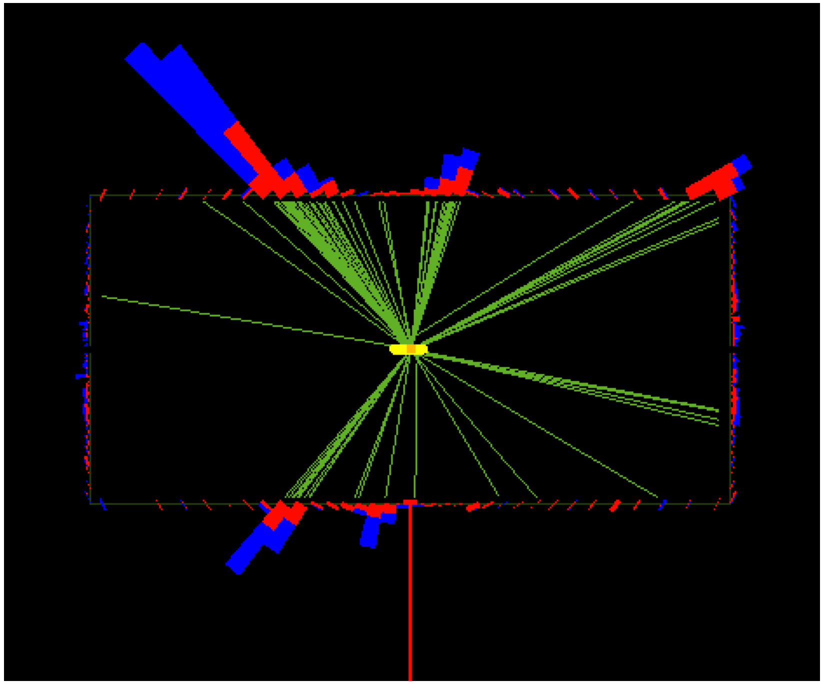


When we see this pattern in our detectors, we call it a "jet".

CMS experiment event displays



End view.
Beams are going in to and out of the screen.



Side view.
Beams coming in from the left and the right.

Decays of the Higgs boson

Higgs decay mode	**Probability of Higgs decaying this way**
H to jets	0.70 most likely
H to $\gamma\gamma$	0.0023 rare
H to ZZ* to $l^+l^-l^+l^-$ $e^+e^-e^+e^-$ $e^+e^-\mu^+\mu^-$ $\mu^+\mu^-\mu^+\mu^-$	0.000126 very rare

Decays of the Higgs boson

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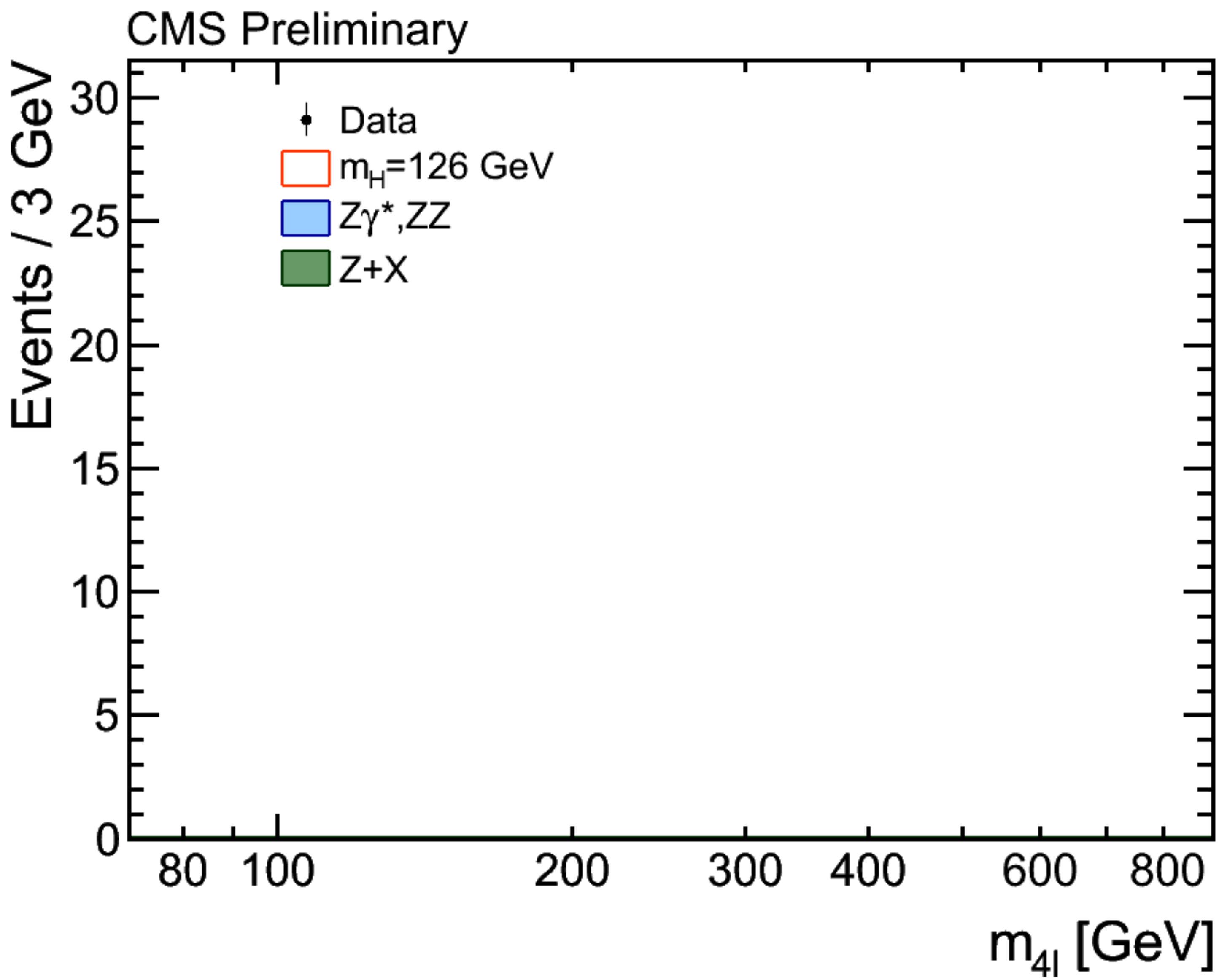
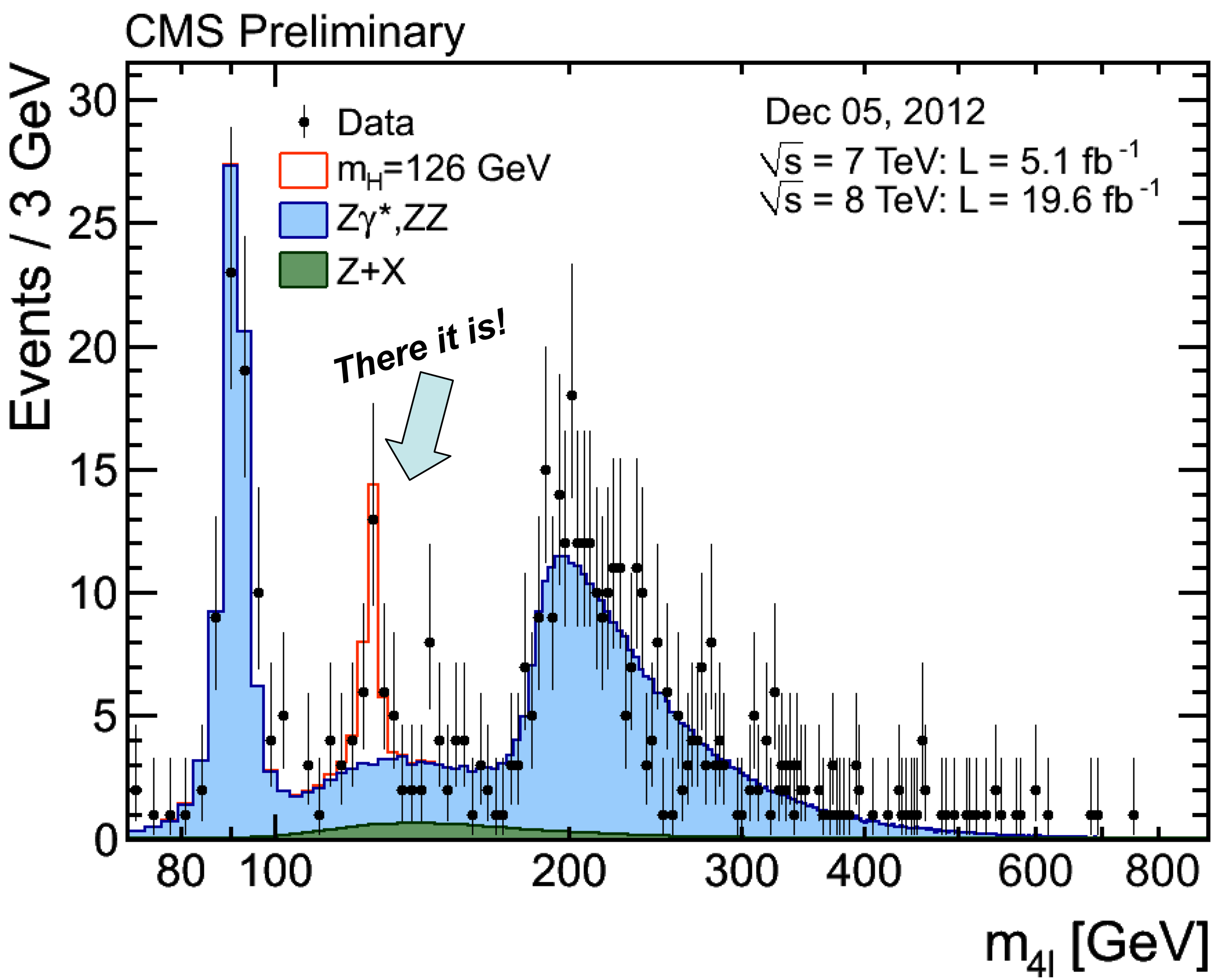
H to $\gamma\gamma$	0.0023 rare	These Higgs decays are rare, but it's also rare for other things to produce events that look like these. We will search for the Higgs in these decay modes.
H to ZZ* to $l^+l^-l^+l^-$ $e^+e^-e^+e^-$ $e^+e^-\mu^+\mu^-$ $\mu^+\mu^-\mu^+\mu^-$	0.000126 very rare	

Finding the Higgs boson

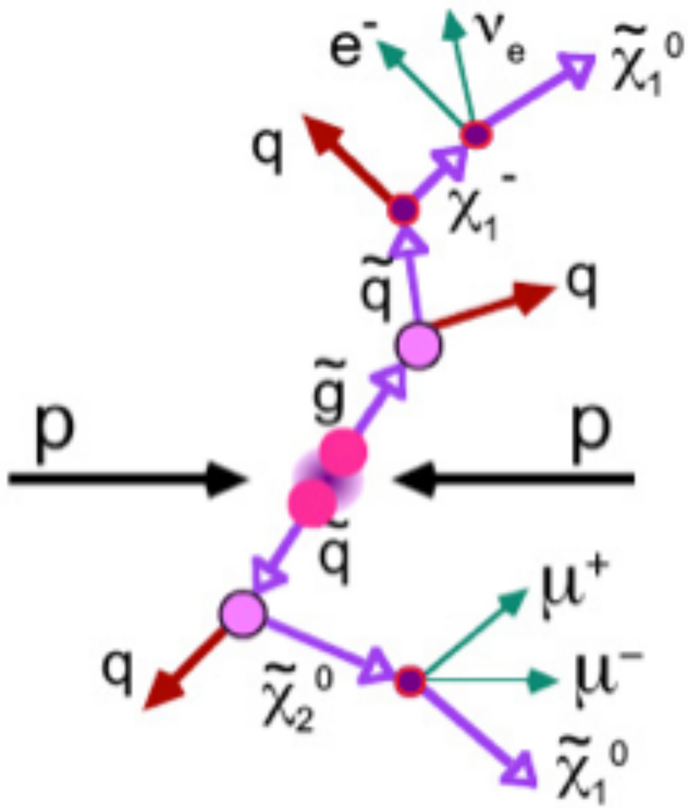


Finding the Higgs boson



Supersymmetry and the CMS experiment

Why Supersymmetry?

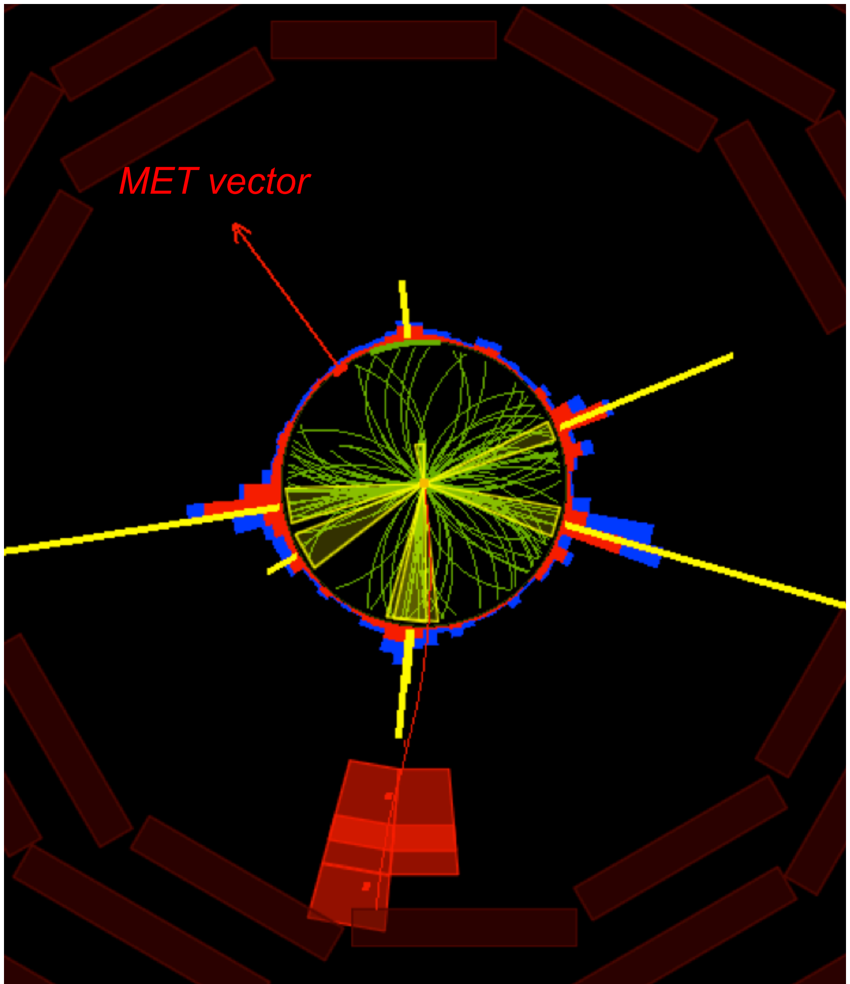


- It might be some of the Dark Matter out there.
  - A new quantum number called ***R-parity*** is conserved.
    - Motivated by non-observation of proton decay.
    - SUSY particles can only be created (or destroyed) in pairs or decay to lighter SUSY particles.
    - A decay chain of SUSY particles ends in the lightest one (the "LSP"), which is *STABLE*.
- The Dark Matter might be a sea of LSPs!

See arXiv:hep-ph/0312096 for a very readable review.

Looking for Supersymmetry

An actual CMS event

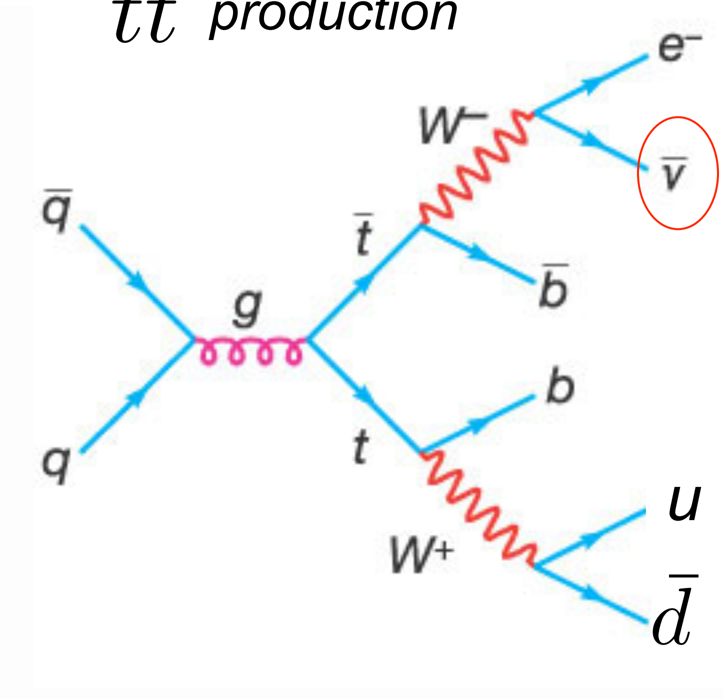


- A common technique is to look for significant missing transverse momentum.
  - Simple momentum conservation in the plane transverse to the beam direction.
- The LSP is stable, electrically neutral, and weakly interacting.
  - It goes right through the detector without interacting.
- Have to distinguish SUSY from other sources of missing transverse energy (neutrinos).

Looking for Supersymmetry

Standard Model background:

$t\bar{t}$ *production*



- A major background in most SUSY searches is from the production and decay of pairs of top quarks.
  - The top quark is very heavy (172 GeV), same as SUSY mass scale.
  - On-shell W bosons (80 GeV) decay leptonically with a ***neutrino*** 30% of the time.
  - Each neutrino carries away significant momentum.
  - The neutrino does not interact with the detector *AT ALL*.

- Similar signature to SUSY
  - High transverse momentum jets.
  - ***b quark jets***.
  - Lots of missing transverse momentum.

UCR QuarkNet workshop

- We will be running a 2-day QuarkNet workshop July 27-28.

- Workshop activities
  - Presentations on particle physics
  - Learn how to do an analysis of LHC data

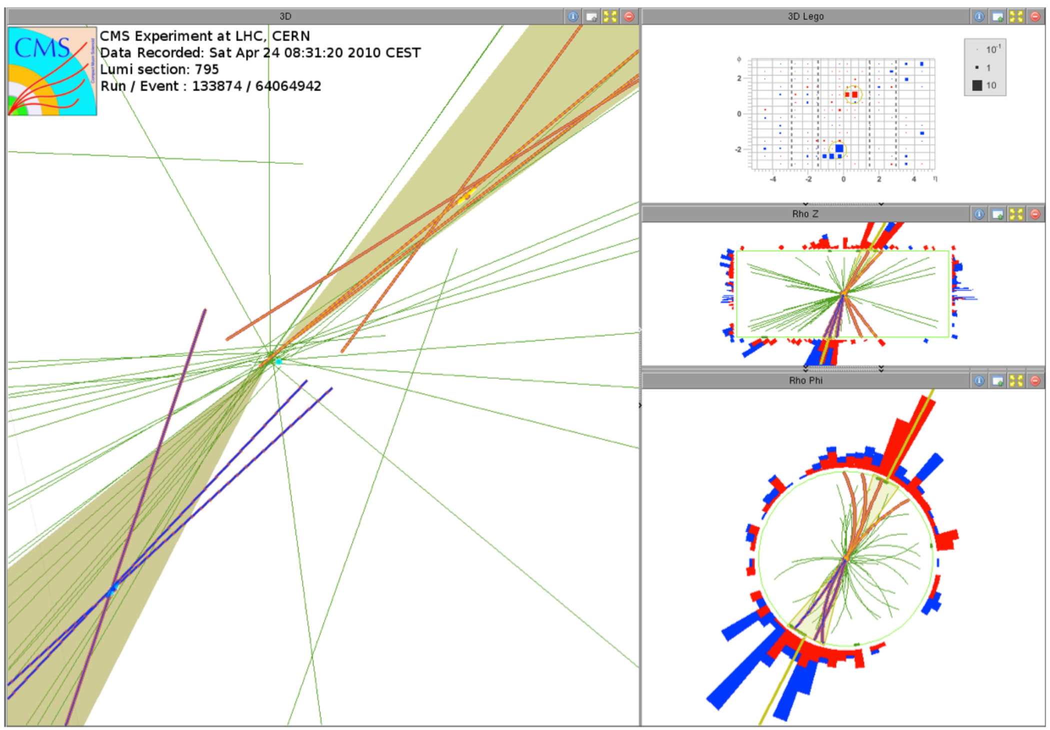
- We have a couple of spots available for the workshop, so if you are interested, please see me (Owen Long, owen.long@ucr.edu).

Extra Slides

Role of the 3rd generation and b-jet tagging

- SUSY models that do not require fine tuning predict that the stop and/or the sbottom to be relatively light (~ 1 TeV or less).

- Both the stop and sbottom will produce **b-quarks** in their decay chains.



b-quarks decay via the weak interaction and have a relatively long lifetime (1.5 ps).

Accounting for time dilation, the b-quark hadron can fly a few millimeters before decaying.

We tag b-quark jets by looking for a displaced vertex within the jet.

- Bonus videos
  - Funny cartoon: https://www.youtube.com/watch?v=BEnaEMMAO_s
  - More realistic animation, which you can download here: http://www.atlas.ch/multimedia/proton-event.html