

## 1 What this course is really about:

The course Title is: Introduction to Particle Physics. Technically correct, misses general philosophy. We are interested in how the world works. Turns out, one major lesson, probably the most important interesting scientific fact (which BTW didn't have to be this way.) things get easier/simpler at smaller scales. At these small scales things that naively seem to be totally unrelated are seen as aspects of the same thing.

Can all be explained by the interaction of particles. This is why "particles" is in the title of the class, we are forced to talk about interactions of particles when we look at nature at a scale where the laws of physics are their simplest.

## 2 Warnings:

Cutting edge field. - Way material presented only recently settled down. - Many theorems or equations/assumptions I won't be able to prove to you. - Most require advanced math, many lack formal proof. (downside of studying a cutting edge field) - Things can change rapidly. - Scope is incredibly broad.

extremely far-reaching mathematically dense and abstract topic,

Textbooks for undergraduates on particle physics are often organized historically, which can add to confusion.

All of the machinery, formalism, insight, and tools that you have gained as a physics student is essential for studying particle physics. quantum field theory is the framework in which three of the four fundamental forces of Nature are formulated

## 3 20th Century revolutions:

Special Relativity (SR) and Quantum Mechanics (QM). Radical departures from what came before them.

QM much more radical. SR took one guy (Einstein) few years to figure out. QM took an entire generation ~15-20 years to straighten out.

SR told us how to think clearly about ideas we were already using: space and time. QM threw everything out and invented a whole new framework/language with which physics had to be understood. Much more abstract: Hilbert spaces/state vectors/Hermitian operators/ etc/

Major gains in explanatory power and unification.

Concepts thought different, faces of same thing: Relativity: - Space and time - Energy and Mass (also momentum) - Electricity and Magnetism (also light) - (Gravity shown to be result of warping of space time)

Quantum Mechanics: - Waves and Particles - Chemistry and Physics

## 4 Mission Barely Possible: QM + SR

First 25 years of the 20th century two revolutions. 85 years since then, were all about putting these together.

Combining Relativity and Quantum Mechanics naively seems impossible. SR and QM use different basic languages.

QM: Time special (fundamental) role. Specify  $|\Psi\rangle$  at one time. Prescription for how to evolve to later times, .

Relativity: Time is not special! (can mix space and time by moving)

Turns out (just barely) possible: Quantum Field Theory - Basic framework for how the world works. - Dramatically restricts what a theory can possibly look like

### Consequences of Union

Anti-particles must exist

- Shocking / Unexpected
- Doubled everything in universe
- Makes the vacuum interesting

Key role of Spin:

- Relation between spin and particle type
- Dramatically limits types of particles can have

Major constraints on types of interactions allowed

- Only certain interaction will ever be important
- Always be a finite number of parameters that matter

## 5 Anti-Particles

### Causality

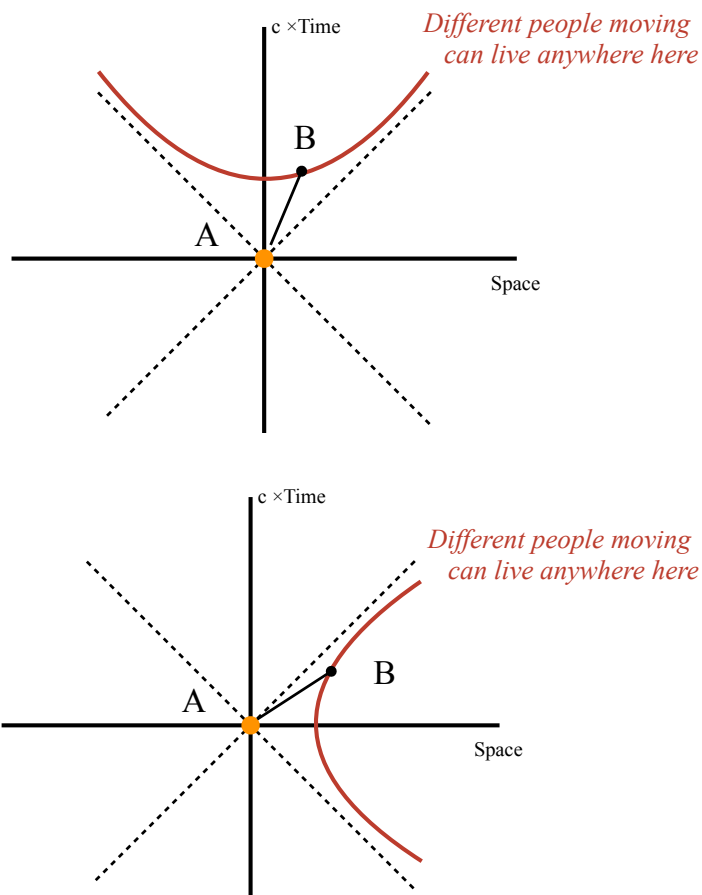
What happens next can only depend of what happened before (Does not depend on something that hasn't happened yet !) If someone dies from a gun shot, the gun must be shot first. Causality basic prerequisite to science !

Causality in Relativity

Cant send signals faster than maximum speed All moving observers agree that A happens before B Can say safely say: "A causes B"

However, If you could go faster than  $c$ , things go wrong... Depending about how you move, disagree about what comes first. Causality is violated. Bullet hits B before A pulls trigger.

Causality in Relativistic QM



w/QM always some non-zero probability of getting out. Problem, looks like current is going backwards in time from A to B. Way out, if interpret this as B sending something to A. But B has to send something with opposite charge. (know A lost charge)

For the theory to have a prayer of being both quantum mechanical and relativistic there must exist particles that are identical to proton (say) except with opposite charge. Anti-particles !

## 6 Vacuum

Anti-matter in turn has major impact on nothing, ie the vacuum.

What does it take to study empty space ("the vacuum") ? Nothing special...until try to check small regions

**Before QM:** Build tiny robots. (Get tiny robots to build tinier robots, who ..)

**With QM:** At small distances, uncertainty principle kicks in. Need large  $\Delta p$  (or equivalently large  $\Delta E$ ). Smaller and smaller distances, need higher and higher energies

Empty Space Interesting

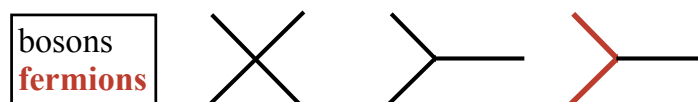
When eventually get to small enough distances to need  $\Delta E \sim 2m_e c^2$  Nothing prevents creation of particle - anti-particle pair - Everything is conserved (energy/charge/...) - Some probability for this to happen

Completely changes our picture of the vacuum - Simple act of looking at it creates something - No sense in which the vacuum is empty

Often here accelerator as world's most powerful microscopes Looking at the vacuum

## 7 Other Implications Combining SR & QM

**Spin** QM: QM + R: Could accommodate spin Any  $1/2$  integer value allowed Forced to talk spin (Something special w/massless particles) Integer spin = Bosons / Half-integer = Fermions Can only have: 0  $1/2$  1  $3/2$  2 Interactions QM: Any conceivable interaction possible QM + R: Charge is conserved Local (no more action at a distance) Only finite number of specific interactions allowed :



In this course we will outline this basic framework for any possible theory. And then talk about the particular version that we actually observe.

## 8 Our world

Stuff in the world made of atoms:

Matter:

Electrons: Negatively charged Responsible for volume of atom Thought to be fundamental

Nucleus: Positively charged Responsible for the mass of an atom Made of, protons and neutrons, which are made of quarks Quarks also thought to be fundamental

Matter particles (electrons/quarks) fermions Large collections behave like classical particles

Forces

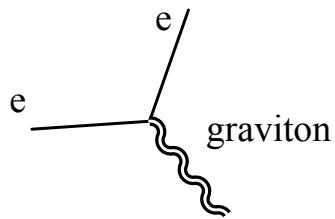
Gravity: Known since antiquity / Inverse square law Always attractive / Irrelevant for atomic/sub-atomic interactions Electromagnetism: Known since antiquity / Inverse square law Attractive or repulsive / Holds electrons within atoms Strong: Discovered early 1900s / Short distances / No simple relationship Responsible for holding together the nucleus Weak: Discovered just before turn of 20th century / Looks nothing like others Radioactive decay. Heats the sun / earth

Our world both Relativistic and Quantum Mechanical  $\Rightarrow$  described in terms of a Quantum Field Theory (QFT)

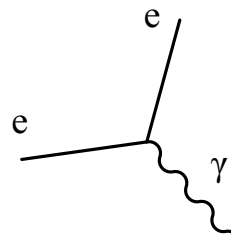
The particular version of QFT that was found to describe our universe developed in the 1960-70s.

All forces as important. Look very different from one another

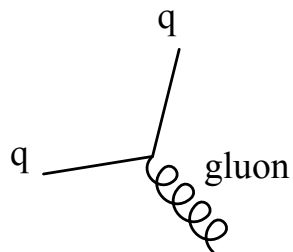
### Gravitational Interaction



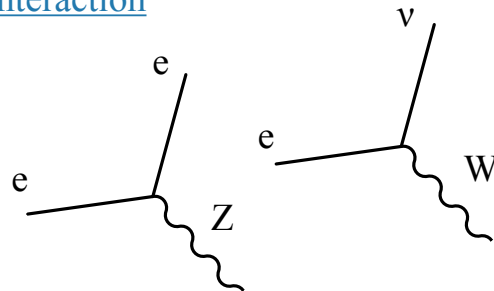
### Electromagnetic Interaction



### Strong Interaction



### Weak Interaction



First time that we see that all forces described in same basic way. Forces look very different to us... is a long distance illusion!

- Strong force: anti-screening / confinement - Weak force: massive force carriers At short distance ( $1/m_Z$ ) all look the forces start to look the same

This is the reason we build colliders! Unity at small scales.

## 9 Standard Model

Niavely you might only expect one generation.

The Standard Model took on modern form in 60s - 70s. Makes very precise predictions, shown to be highly accurate. Consistent theory of electromagnetic, weak and strong forces ... provided massless Matter and Force Carriers

Serious problem as matter and W, Z known to be massive ! We will come back to this problem later in the semester.

# The Standard Model

Matter Particles (Fermions)

Spin = 1/2

Leptons:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

$$\begin{pmatrix} c \\ s \end{pmatrix}$$

$$\begin{pmatrix} t \\ b \end{pmatrix}$$

Interactions “Force carriers” (Bosons)

Spin = 1

Gauge bosons:

$\gamma$

W

Z

g

Beautiful (complicated) mathematics governs nature interactions

Dictated by principles of symmetry (*Much direct consequence QM + R*)

## 10 The right way to think about the world

Not often taught even in gradschool, easy and extremely powerful.

Go through a few examples of this kind of reasoning: Atoms Electrons Quantum Mechanics Chemistry - Teeth behind these statements - Describe world around us in a few basic physical parameters - Powerful (Fun!) way of estimating anything to order of magnitude

Dimensional Analysis and “ $\sim$ ”

Put in the right physics to get answers to within “geometric factors” - Don't worry about factors of 2 or  $\pi$  etc - Use “ $\sim$ ” not “=”

Examples (Volume of something) (size)<sup>3</sup>

Cube =  $R^3$  Sphere =  $4/3\pi R^3 = 4.2 R^3 = 1/6\pi(D)^3 = 0.4 D^3$  Cylinder =  $R \times \pi R^2 = \pi R^3 \sim R^3 \sim R^3 \sim D^3$   
 $\sim R^3$  (if two scales use  $r \sim R$ ) Kinematic energy =  $1/2 mv^2 \sim mv^2$  I've been doing this already: “ $\Delta p \Delta x \geq h$ ” (...it is really  $\Delta p \Delta x \geq h/(4\pi)$ )

$c \equiv 1$ : [Distance]/[Time]  $\equiv 1$  - Time and distance have same units -  $E = mc^2$   $\hbar \equiv 1$ : [Energy]  $\times$  [Time] = 1 and [Energy]  $\times$  [Distance] = 1 - Energy (or Mass) is inversely related to distance or time. Write everything in terms of [Energy]: use 1 GeV  $\sim mp$  as basic unit “Its about an hour from here”

Everything in terms of GeV. Use conversions to get back to human units Conversions: GeV = 1027 kg  
GeV = 1016 m GeV = 6  $\cdot$  1025 s

Examples:

Proton Weight: GeV Proton Size: GeV<sup>-1</sup>

My height: 1m  $\sim 10^{16}$  GeV<sup>-1</sup> (I am as tall as  $10^{19}$  protons stacked on top of each other) My weight: 100kg  $\sim 10^{29}$  GeV (I am made of  $10^{29}$  protons)

The world with 4 numbers Claim:  $\sim$ everything in world combination of these numbers  $mp = 1$  GeV  $\alpha = 1/137$   $m_e = 10^{-3}$  GeV  $G = 10^{-39}$  GeV m<sup>2</sup>

Will work through some quick examples.

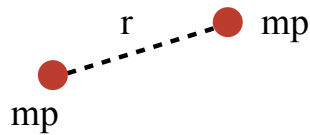
Atoms

Solids

Planets

Life ect. Homework: calculate global in terms of

# EM and Gravitation Interactions



## Electromagnetic Energy

$$E = -\frac{e^2}{4\pi} \frac{1}{r}$$

$\swarrow$                        $\underbrace{\hspace{1cm}}$                        $\searrow$   
 GeV                                      GeV

Pure number: $\alpha$ Its small: $1/137$
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## Gravitational Energy

$$E = -G_N \frac{m_p^2}{r}$$

$\swarrow$                        $\underbrace{\hspace{1cm}}$                        $\searrow$   
 GeV                                      GeV<sup>3</sup>

Dimensionful number $G_N m_p^2 = 10^{-39}$
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