How and Why to go Beyond the Discovery of the Higgs Boson

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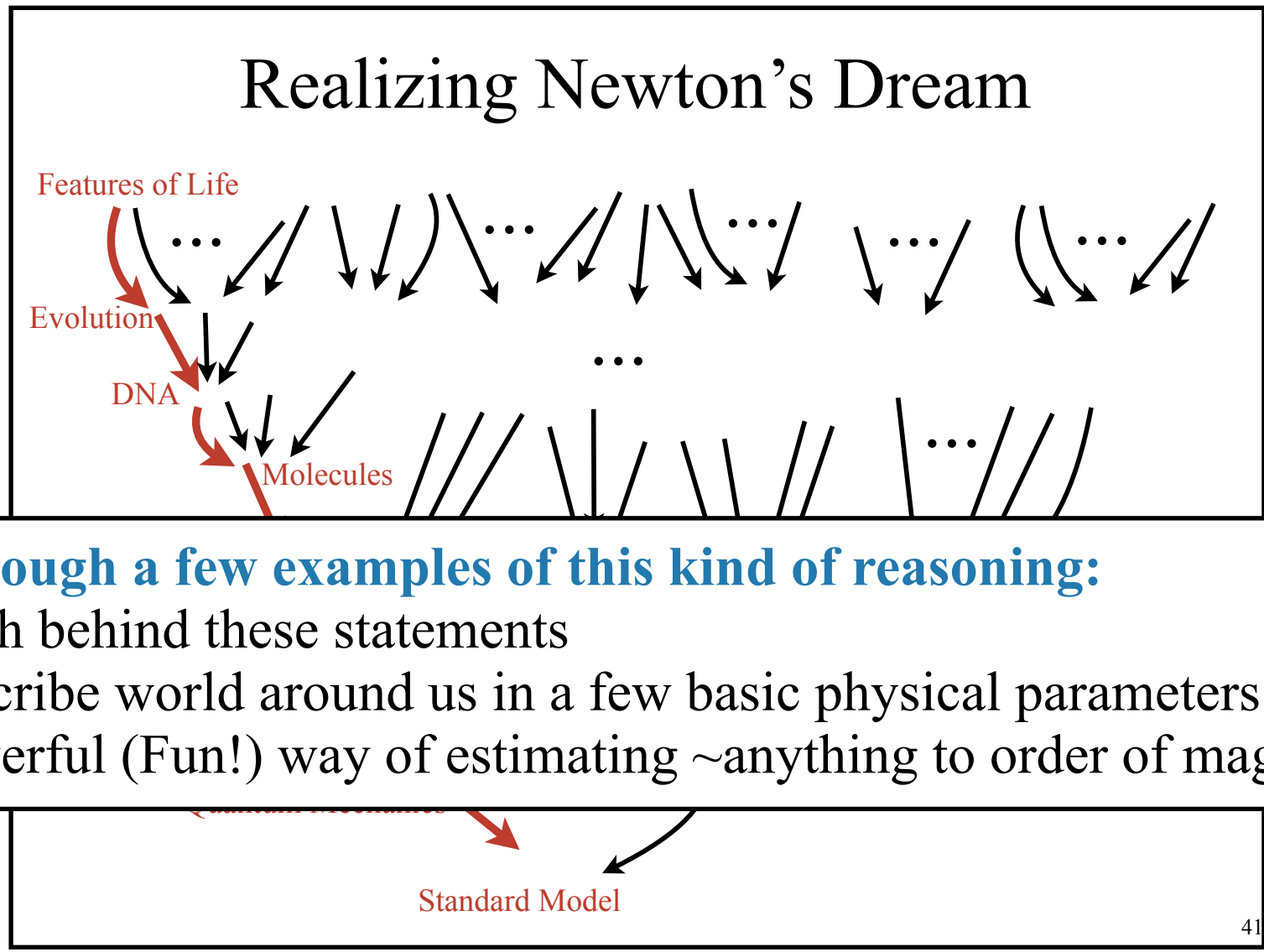
http://hep.uchicago.edu/~johnda/ComptonLectures.html

Intermezzo

Taking a lot of flak for remarks associated to:



Go through a few examples of this kind of reasoning:

- 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 "~"

Put in the right physics to get answers to within *"geometric factors"*

- Dont worry about factors of 2 or π etc
- Use "~" not "="

Examples (Volume of something) ~ $(\text{size})^3$

Cube $= R^3 \sim R^3$

Sphere $= 4/3\pi R^3 = 4.2\ R^3 \sim R^3$

$= 1/6\pi(D)^3 = 0.4\ D^3 \sim D^3$

Cylinder $= R \times \pi R^2 = \pi\ R^3 \sim R^3$ (if two scales use r^2R)

Kinematic energy $= 1/2\ mv^2 \sim mv^2$

Ive been doing this already: "$\Delta p \Delta x \geq h$"

(…it is really $\Delta p \Delta x \geq h/(4\pi)$)

Units

I hate units! All numbers are really unit-less
Always comparing some quantity relative to some standard
We will work in "Natural Units"

Natural Units

- The right way to about the world
  (How physicists think, what makes them seem smart to other people)
- Very easy. Much easier than Metric/British/cgm/mks …
- Standard is set by basic physical principles
  ⇒ numbers have direct physical interpretations

c ≡ 1: [Distance]/[Time] ≡ 1
- Time and distance have same units
- E = m

You are already familiar with this:
"Its about an hour from here"

h ≡ 1: [Energy]×[Time] = 1 and [Energy]×[Distance] = 1
- Energy (or Mass) is inversely related to distance or time.

Write everything in terms of **[Energy]:** use 1 GeV ~ mp as basic unit

Examples

Everything in terms of GeV. Use conversions to get back to human units

Conversions:

$$\text{GeV} = 10^{-27}\ \text{kg}$$

$$\text{GeV}^{-1} = 10^{-16}\ \text{m}$$

$$\text{GeV}^{-1} = 6 \cdot 10^{-25}\ \text{s}$$

Proton Weight: GeV

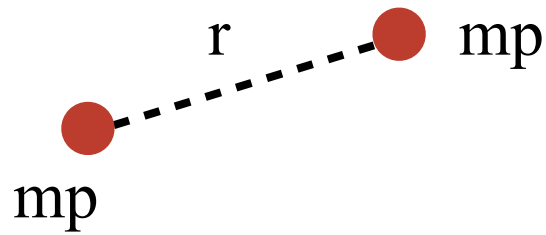
Proton Size: GeV^{-1}

My height: $1\text{m} \sim 10^{16}\ \text{GeV}^{-1}$

My weight: $100\ \text{kg} \sim 10^{29}\ \text{GeV}$

I am made of ~10^29 protons

EM and Gravitation Interactions



Electromagnetic Energy

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

GeV GeV

Pure number: α
Its small: 1/137

Gravitational Energy

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

GeV GeV^3

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

The world with 4 numbers

Claim: ~everything in world combination of these numbers

$$m_p \sim 1 \text{ GeV} \qquad \alpha = \frac{1}{137} \sim 10^{-2}$$

$$m_e \sim 10^{-3} \text{ GeV} \qquad \alpha_G \equiv G_N m_p^2 = 10^{-39}$$

Will work through some quick examples.

Atoms

For Atoms Electron mass is king!
(mp doesn't make an appearance)

$$p \times r \sim 1$$

$$E \sim -\frac{Z\alpha}{r} + \frac{p^2}{m_e} \qquad E \sim -\frac{Z\alpha}{r} + \frac{1}{m_e r^2}$$

$$r_{atom} \sim \frac{1}{Z\alpha m_e} \qquad r_{nucleus} \sim \frac{1}{Z m_p}$$

$$\frac{r_{nucleus}}{r_{atom}} \sim \frac{\alpha m_e}{m_p} \sim 10^{-5}$$

$$p_e \sim \frac{1}{r_{atom}} \sim m_e(Z\alpha) \qquad v_e \sim (Z\alpha)$$

$$E_{atom} \sim \frac{Z\alpha}{r_{atom}} \sim Z^2\alpha^2 m_e$$

For Hydrogen

10^{-4} 0.5 MeV $\sim$ 50 eV
(Actually is 13.6 eV)

Solids

(To within our ~) Solids just atoms stacked next to each other

Mass Density: Mass/Volume

$$\rho_{\rm solid} \sim \frac{Z m_p}{(r_{\rm atom})^3} \sim Z^4 \alpha^3 m_p m_e^3$$

Pressure of Solid: Force/Area or Energy/Volume

$$P_{\rm solid} \sim \frac{Z^2 \alpha^2 m_e}{(r_{\rm atom})^3} \sim Z^5 \alpha^5 m_e^4$$

(Ratio of two give the speed of sounds)

$$v_{\rm sound} \sim \sqrt{\frac{P_{\rm solid}}{\rho_{\rm solid}}} \sim \sqrt{\frac{\alpha}{m_p r_{\rm atom}}}$$

Predict: ~25,000 m/s

Beryllium	12,890 m/s
Diamond	12,000 m/s
Steel	6000 m/s

Planets

Solids where gravitational pressure balanced by solid pressure

$$E_{Gravity} \sim \frac{G_N M_p^2}{R_p} \qquad P_{Gravity} \sim \frac{E_{Gravity}}{V_{Planet}} \sim \frac{G_N M_p^2}{R_p^4}$$

$$M_{Planet} \sim \rho_{solid} \times R_P^3 \sim \frac{Z m_p R_P^3}{r_{atom}^3}$$

$$P_{Gravity} \sim \frac{G_N Z^2 m_p^2 R_P^2}{r_{atom}^6}$$

$$P_{Gravity} \sim P_{solid}$$

Planets/atoms relative size direct result of EM vs gravity strength

r_{atom}^0 r_{atom}^1

$$R_{Planet} \sim \sqrt{\frac{1}{G_N m_p^2 Z^3 \alpha m_e^2}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{atom}$$

This is why things are big, despite being governed by microscopic laws

Life

Estimate limit on size of life: Require dont break bones when fall

$$E_{fall} \sim M_A g_{local} L_A$$

$$g_{local} \sim G_N \frac{M_P}{R_P^2} \sim \sqrt{\alpha_G \alpha} \frac{1}{m_p r_{atom}^2}$$

Prediction:	~5	m/s/s
Actual:	9.8	m/s/s

Break bones along cross sectional areas

$$E_{\text{Break Bones}} \sim N_{\text{atoms cross-section}} \times E_{atom}$$

$$\sim \left(\frac{L_A}{r_{atom}}\right)^2 \times \frac{Z\alpha}{r_{atom}}$$

$$E_{Fall} \sim E_{Bi}$$

$L_A \sim 10$ cm / $M_A \sim 100$ kg

$$L_A \sim \left(\frac{\alpha}{\alpha_G}\right)^{\frac{1}{4}} \times r_{atom} \qquad M_A \sim \left(\frac{\alpha}{\alpha_G}\right)^{\frac{3}{4}} \times Z m_p$$

Lecture Outline

April 1st: **Newton's dream & 20th Century Revolution**

April 8th: **Mission Barely Possible: QM + SR**

April 15th: **The Standard Model**

April 22nd: ***Importance of the Higgs***

April 29th: **Guest Lecture**

May 6th: **The Cannon and**

May 13th: **The Discovery of**

May 20th: **Experimental Ch**

May 27th: **Memorial Day: N**

June 3rd: **Going beyond th**

Sources:

- **Nima Arkani-Hamed**
- **John Barrow**
- **Matt Strassler**
- **Leonard Susskind**
- **Frank Tipler**
- **Steven Weinberg**

I will keep this list up to date as we go along.

Last Time: *The Standard Model*

Description fundamental constituents of Universe and their interactions

Triumph of the 20th century

Quantum Field Theory: Combines principles of Q.M. & Special Relativity

Constituents *(Matter Fields/Particle)* Spin = 1/2

Leptons: Quarks:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Interactions Dictated by principles of symmetry Spin = 1

QFT $\Rightarrow$ Field/Particle associated w/each interaction *(Force Carriers)*

γ W Z g

Consistent theory of electromagnetic, weak and strong forces ...

... provided **massless** *Matter* and *Force Carriers*

Serious problem: matter and W, Z carriers have Mass !

Today's Lecture

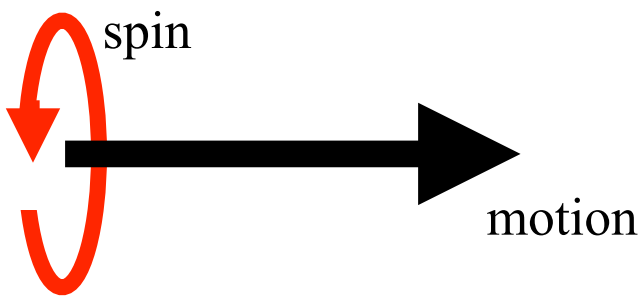
The Importance of the Higgs

"The Higgs Boson (or "God Particle") is Responsible For All Mass in the Universe"

What's the Problem with Mass ?

All goes back spin *(Forced on us by QM+R)*
Matter particles have spin 1/2. *QM ⇒ Only two ways they can spin*

Aligned with direction of motion



"Right-handed"

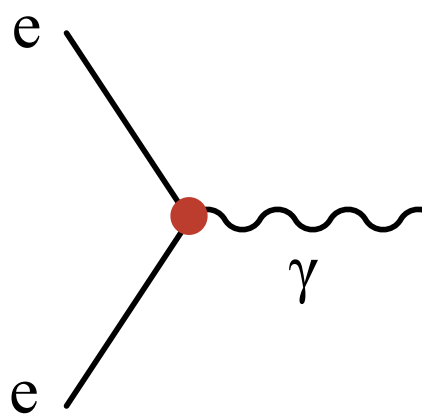
Against with direction of motion

"Left-handed"

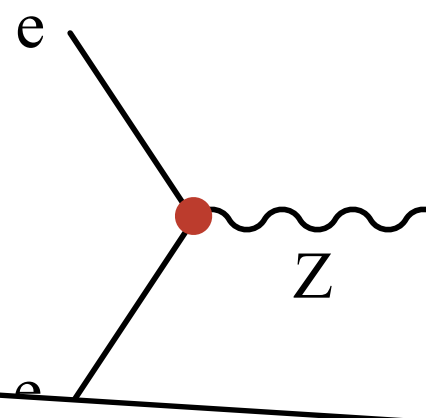
QFT tells us that ***massive*** particles can flip back and forth…

… and the size of the mass sets the rate (probability) for flipping.
The heavier the particle the more it flips.

What's the Problem with Mass ?



B/c electrons have
Charge



B/c electrons have
Hyper-charge

Only left-handed particles have hyper-charge change !

Now the crazy part…

Left -handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

One hand:
QFT tells us that ***massive*** particles can flip back and forth.
SM these have different H-charges ⇒ ***H-charge not conserved***

Other hand:
QFT tells us that all ***charge must be conserved!*** (Basic conseq. QM+R)

H-charge: 0 1 0 1 0

Get around this with the Higgs Field

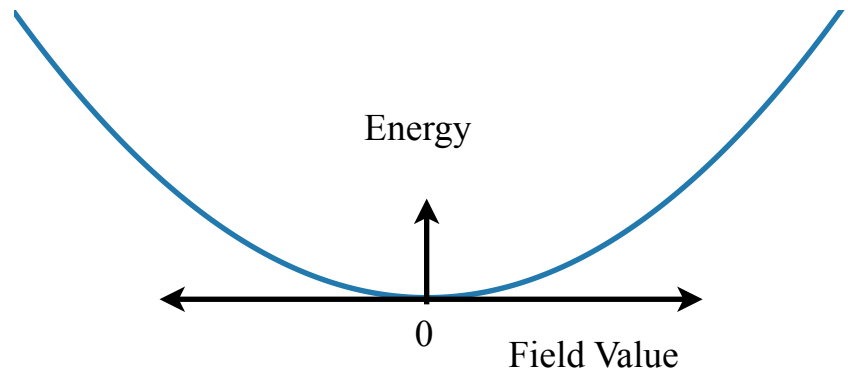
What is a field?

Field: mapping of number (or set of numbers) to each point in space

You are familiar with fields:

- Temperature map: number at each location
- Wind map: arrow (pair of numbers) at each location

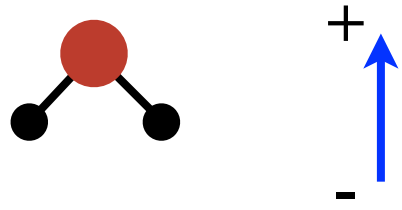
Most fields cost energy for being on:



Warm-up with example of how a field can affect mass

Mass from Field: *Example*

Water molecules are little dipoles:

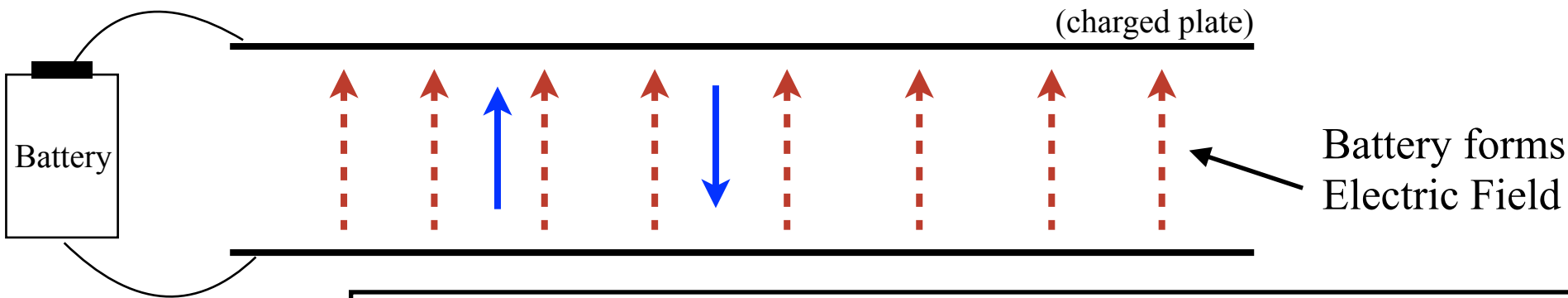


Consider only two orientations

↑ - ***Up-water*** ↓ - ***Down-water***

- Mass of ***Up*** and ***Down*** water same
- Space is symmetric

Now, break the symmetry by external electric field pointing up:



- Now, ***Down*** water more energy (= mass) than ***Up*** water

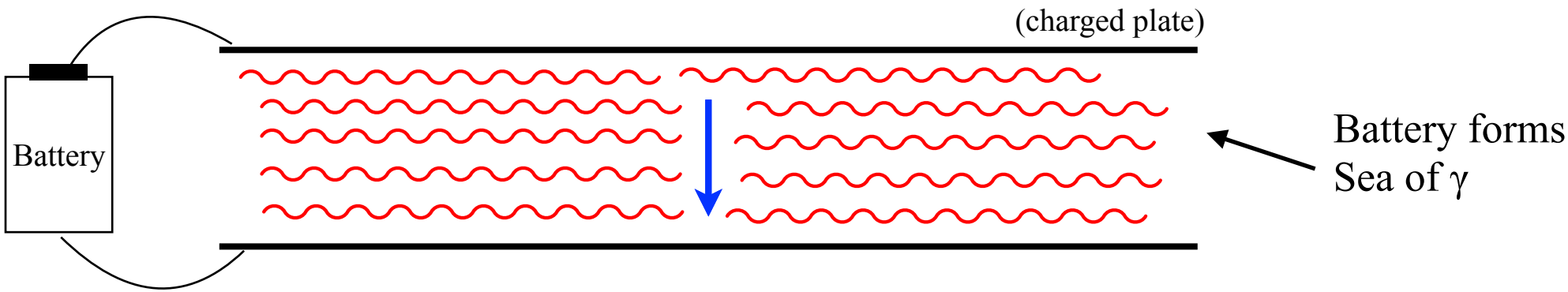
Example of how a field can creates mass for a particle

Note: No net force on the water molecule

Not like the water getting stuck in some kind of molasses !

Mass from Field: *Example*

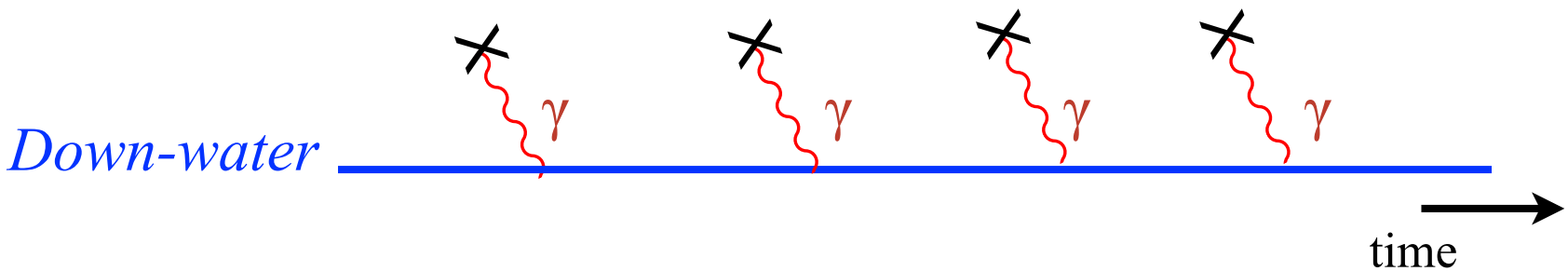
We know this electric force mediated by photons γ



Photons are constantly being created/absorbed by the charged plates

Point of view of water molecule:

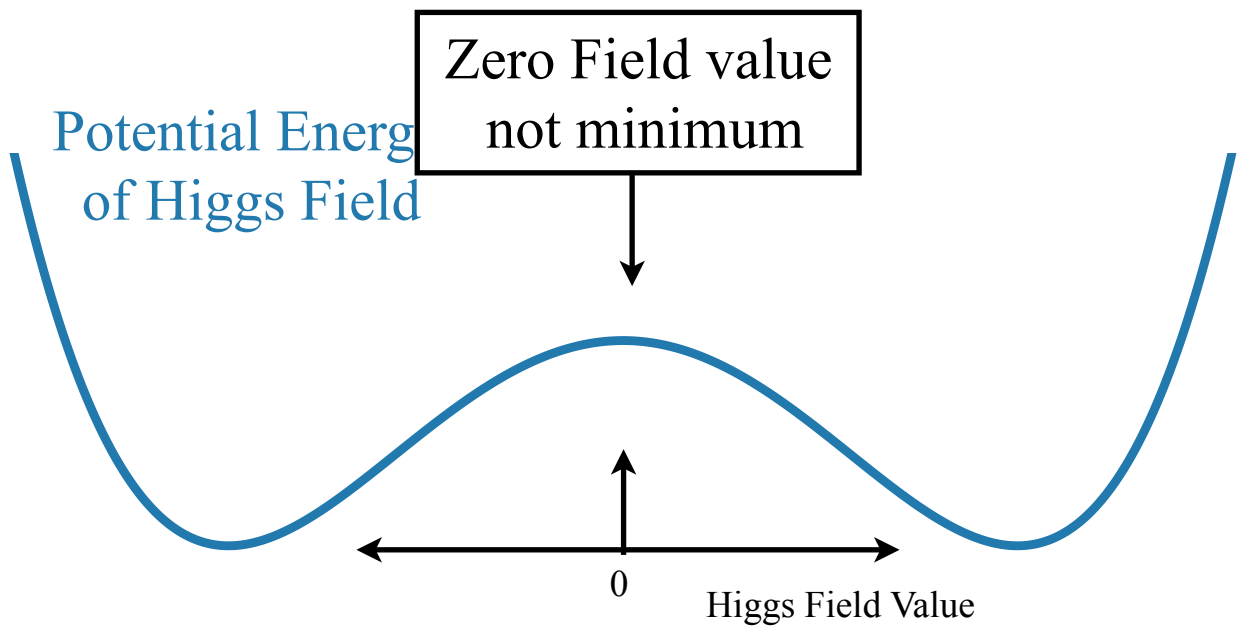
- Lives in place where can add or remove γ with changing anything
- Space ("vacuum") filled with ***Condensate*** of photons



In this example, γ c***ondensate*** is created by the battery ("Turns field On")

Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead…
Use a trick called "Spontaneous Symmetry Breaking"



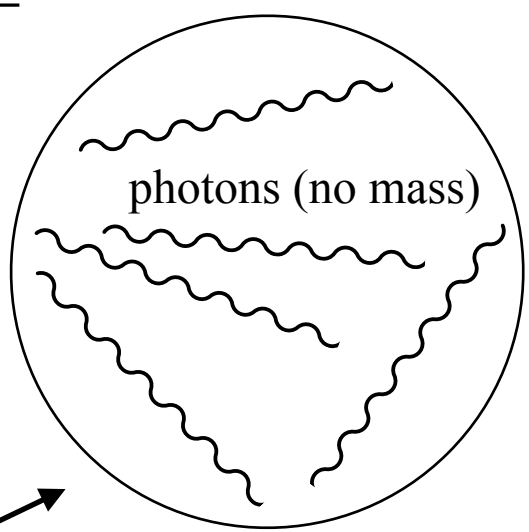
The form of the Higgs potential energy enough to turn the field on
This functional form is also an *input* to the theory

Form a condensate ("v-condensate") just as in our previous example
QM effect related to shape of potential. *(Analogous to Superconductivity)*

Does all mass come from Higgs Field?

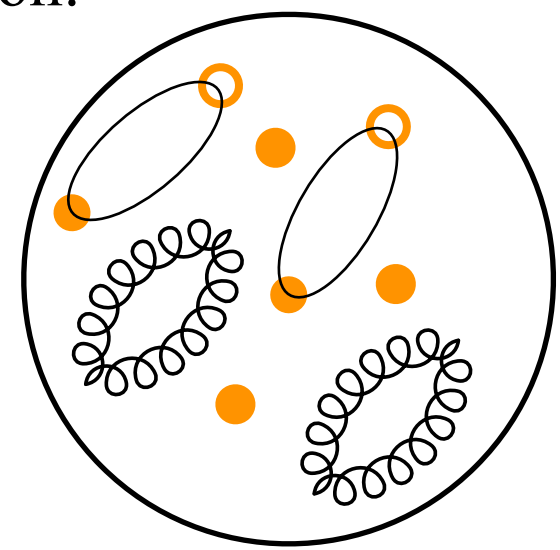
No !

Example:



Ultra-light
reflective walls

Proton:



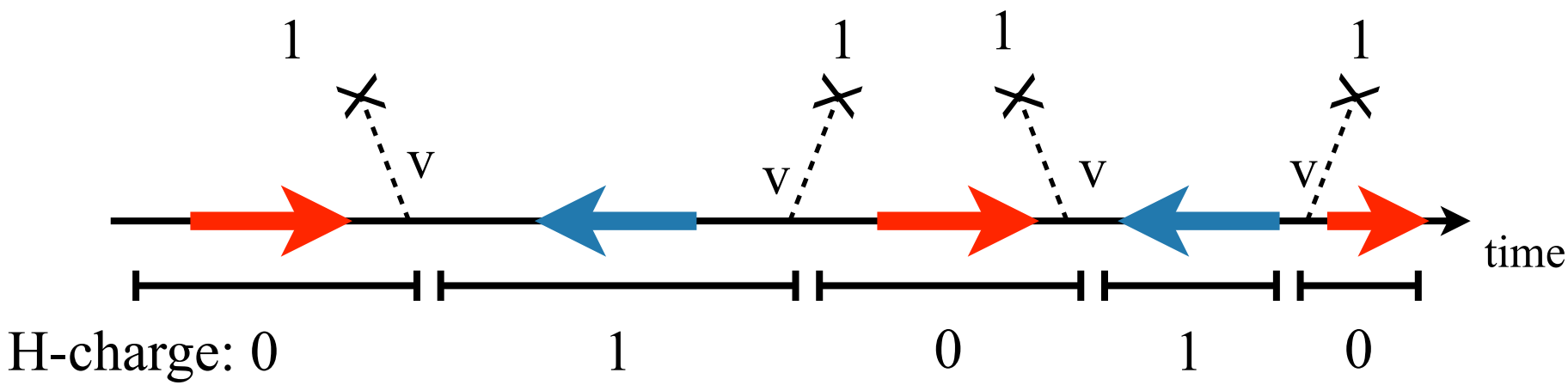
Most of the mass in the universe (protons)
not from the Higgs Field!

Higgs Field: Mass to Matter

How does it work for matter particles ?

As in the example, but using the v-condensate

Critical Point: v-condensate has hyper-charge = 1



Interaction of matter particles w/v-condensate that allows mass

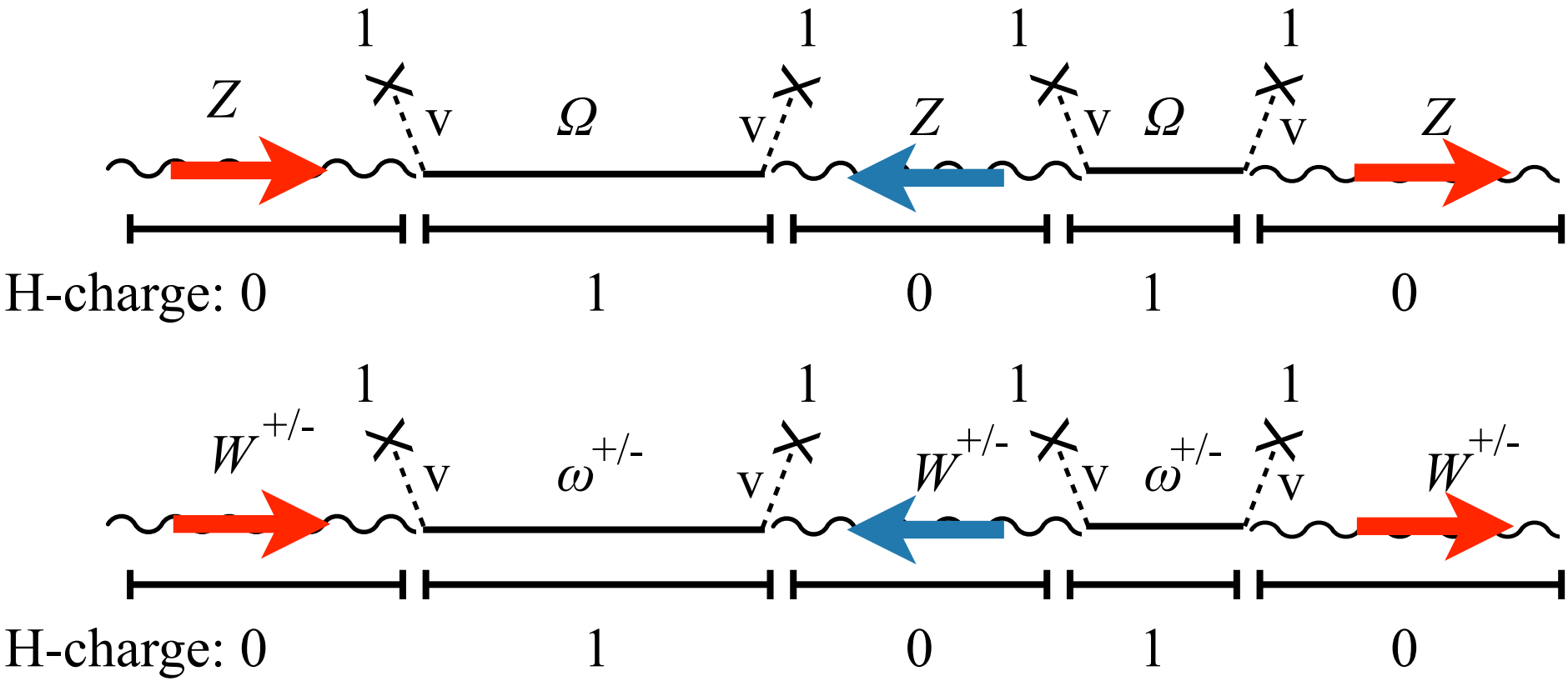
Can change between right and left-handed in a way that conserves charge

Higgs Field: Mass to W & Z

Similar effect gives mass to W/Z particles: One crucial difference.

Both Left and Right states of W/Z have hyper charge 0

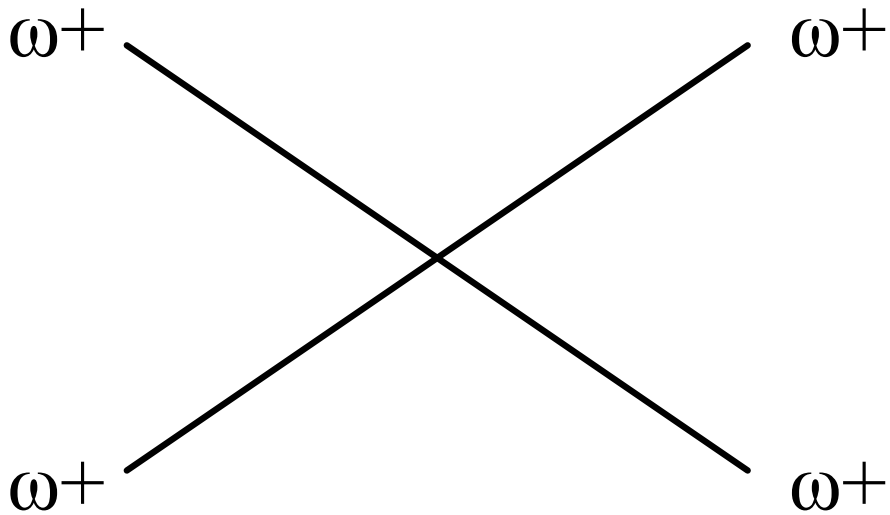
Need new particles: "Ω" and "ω"



Ω and ω are also referred to as "Longitudinal polarizations of W/Z"

What about the Higgs Boson ?

What is the probability to scatter ω+/-



$$\psi = \quad \sim \quad \frac{1}{50}\frac{\text{Energy}}{m_W}$$

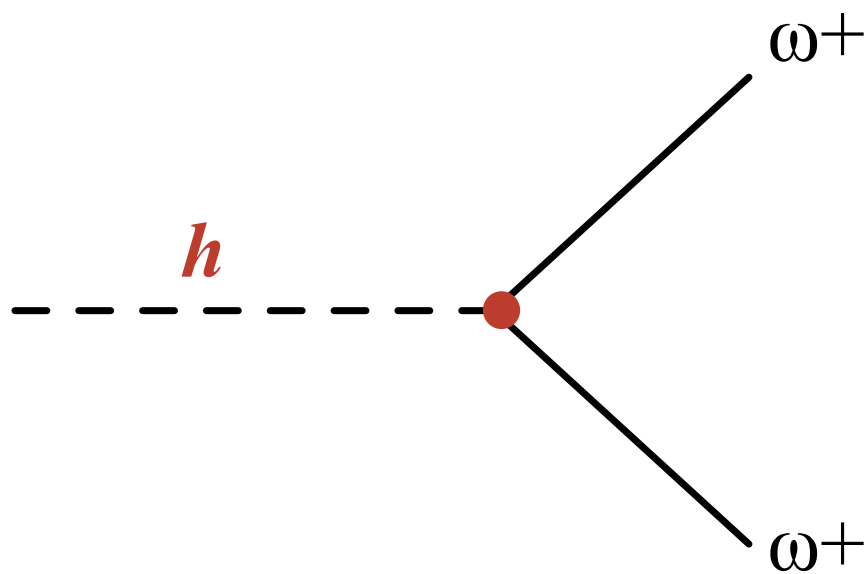
$$P = |\psi|^2 = \left(\frac{1}{50}\frac{\text{Energy}}{m_W}\right)^2$$ **> 1 at high E**

(putting all the correct factors)

- P > 1when E ~1200 GeV
- Theory breaking down at ~1 TeV
- Something clearly missing when we get to 1 TeV

The Higgs Boson

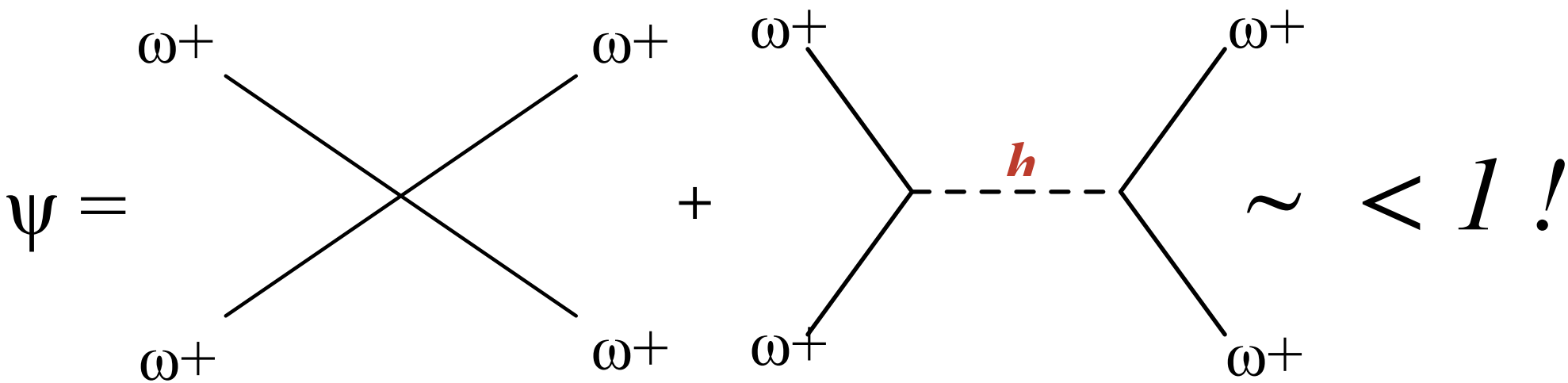
Requires another new particle: ***h***
That couples to ω+



h sound waves is the Higgs field condensate

What about the Higgs Boson ?

Have to include all terms:



Fixes the inconsistent behavior at high Energy

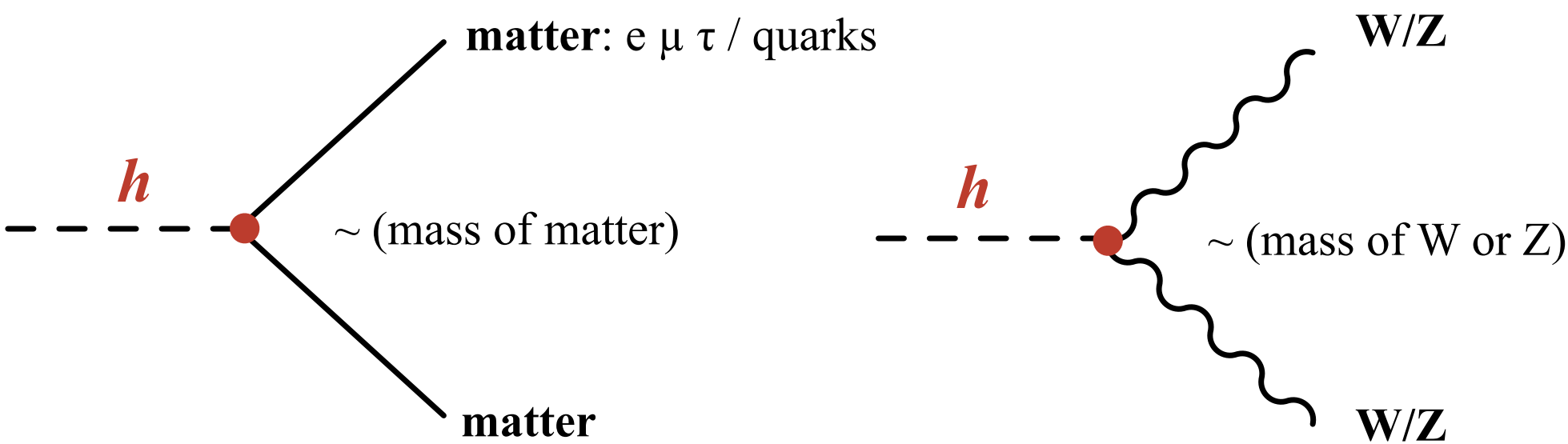
- Have sensible theory again.

The Higgs Boson

What do we know about the Higgs Particle: ***A Lot***

Higgs is excitations of v-condensate

$\Rightarrow$ Couples to matter / W/Z just like v



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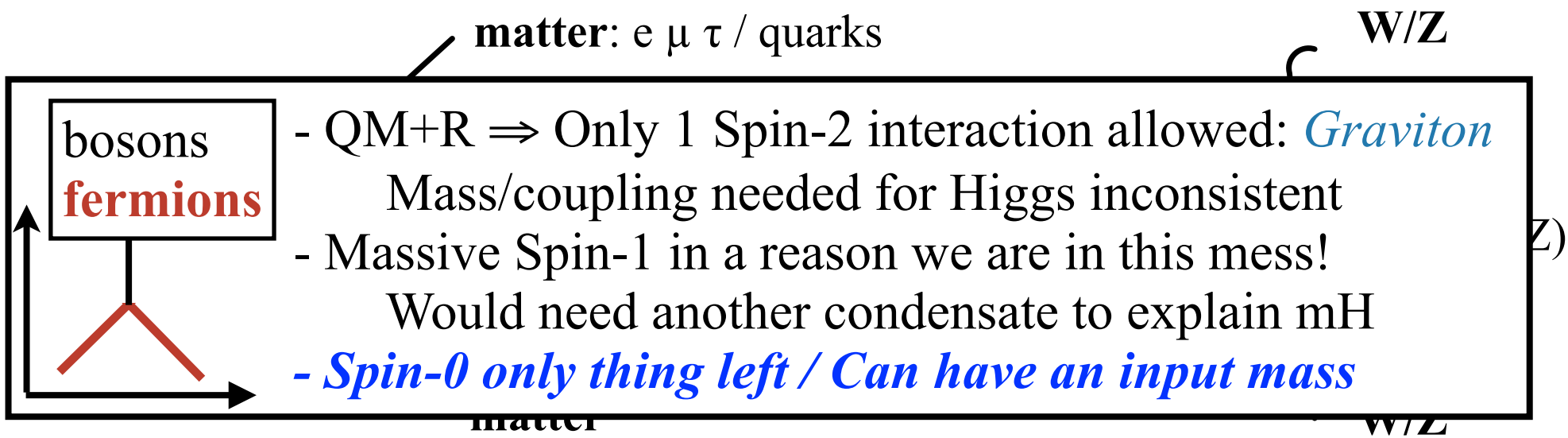

Spin: 0 ~~1/2~~ ~~1~~ ~~3/2~~ ~~2~~

Only thing we don't (*didn't!*) know was the value of mH

Field

^

"The Higgs Boson (or "God Particle") is Responsible For All Mass in the Universe"

v

Some (*Very Important!*) Mass

$$L_A \sim \left(\frac{\alpha}{\alpha_G}\right)^{\frac{1}{4}} \times \frac{1}{Z\alpha m_e}$$