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

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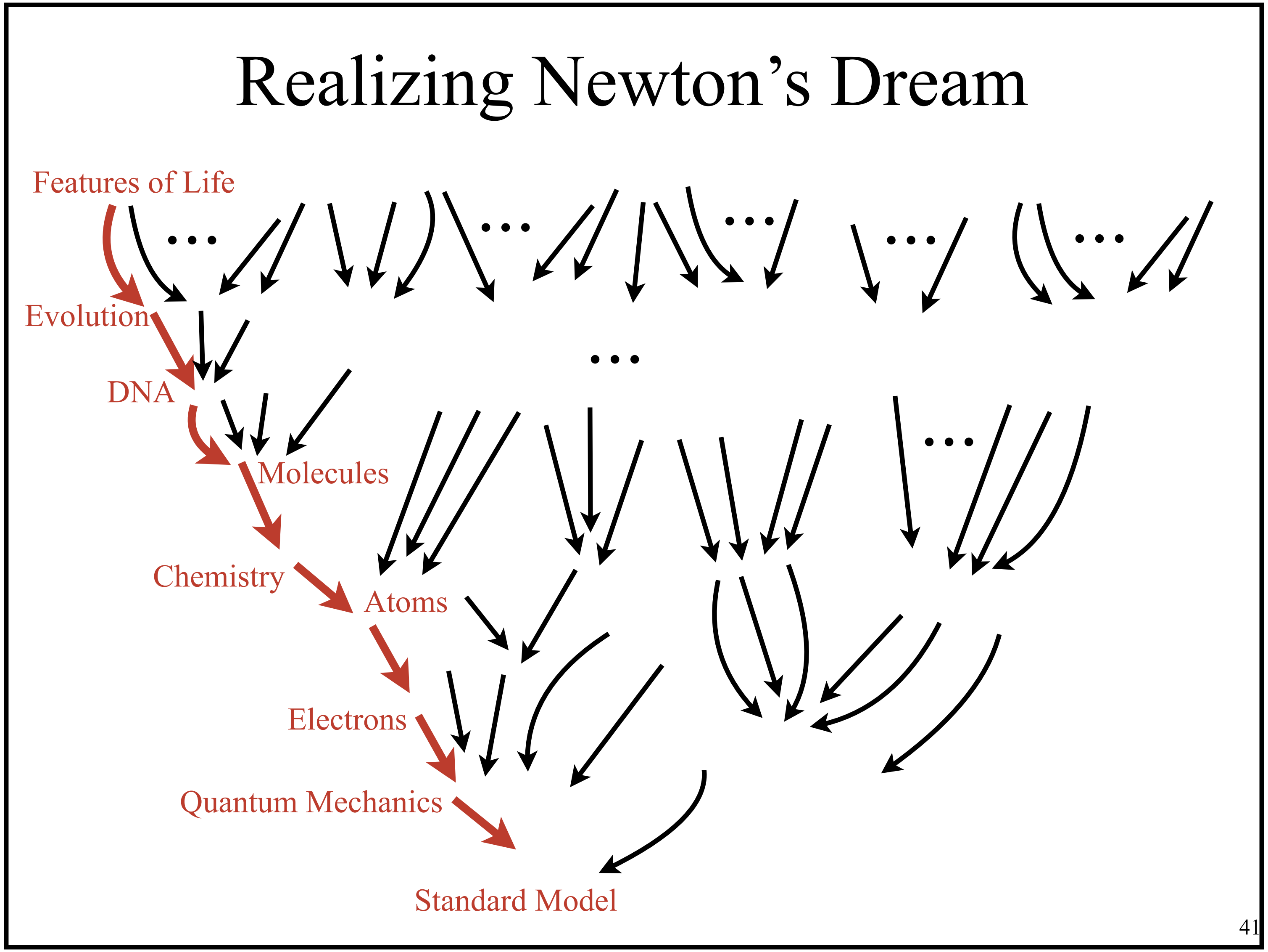
University of Chicago

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

Intermezzo

Taking a lot of flak for remarks associated to:



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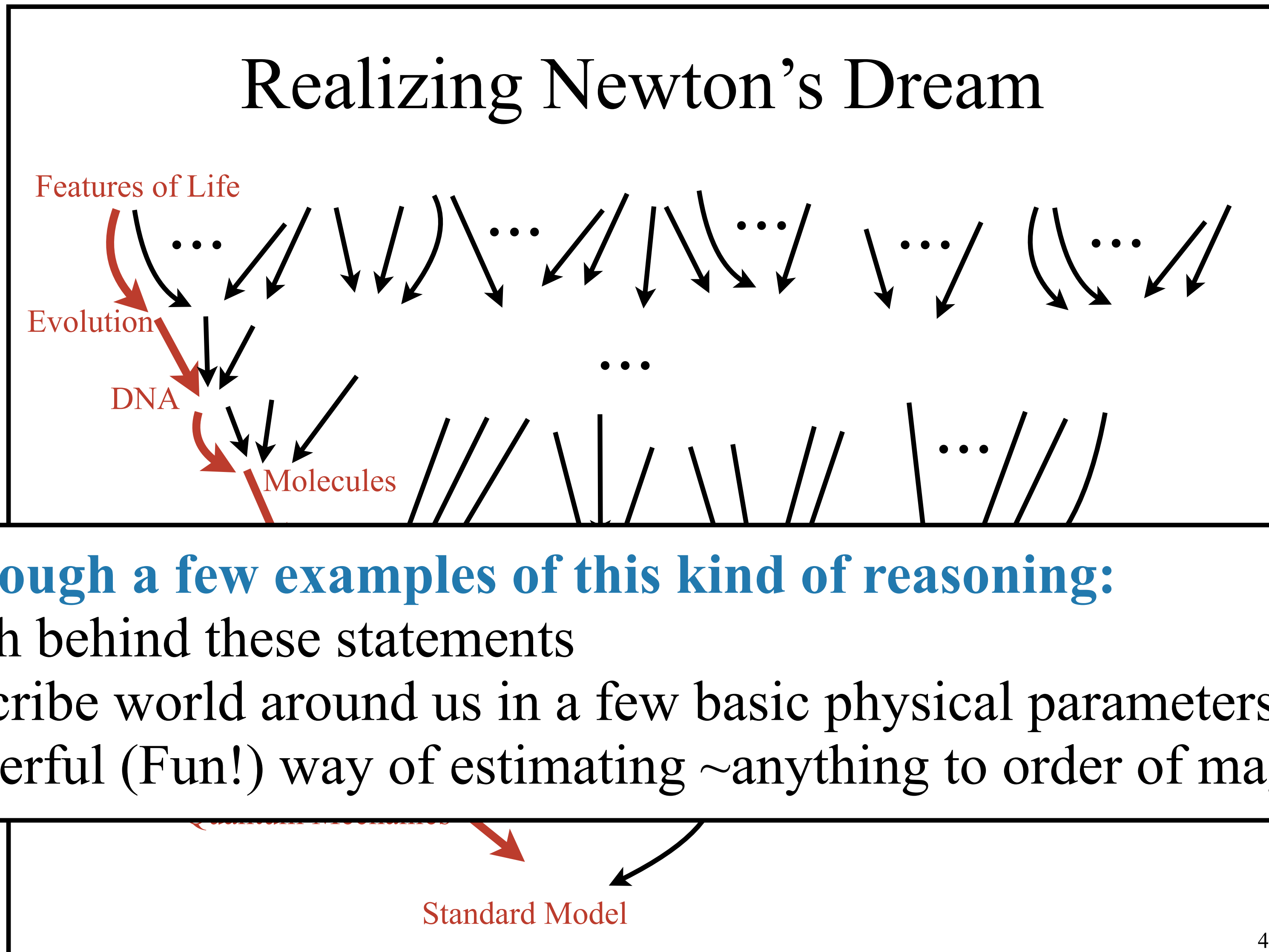

Go through a few examples of this kind of reasoning:

- 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 "=“

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Examples (Volume of something) ~ (size)^3

Cube = R^3 ~ R^3

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

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

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Cube	$= R^3$		$\sim R^3$
Sphere	$= 4/3\pi R^3$	$= 4.2\ R^3$	$\sim R^3$
	$= 1/6\pi(D)^3$	$= 0.4\ D^3$	$\sim D^3$

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

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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”

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Natural Units

- The right way to think 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

$\Rightarrow$ numbers have direct physical interpretations

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c ≡ 1: [Distance]/[Time] ≡ 1

- Time and distance have same units
- E = m

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$h \equiv 1$: [Energy]×[Time] = 1 and [Energy]×[Distance] = 1

- Energy (or Mass) is inversely related to distance or time.

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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:

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

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

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

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

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Proton Size:

I am as tall as 10^16 protons stacked on top of each other

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

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

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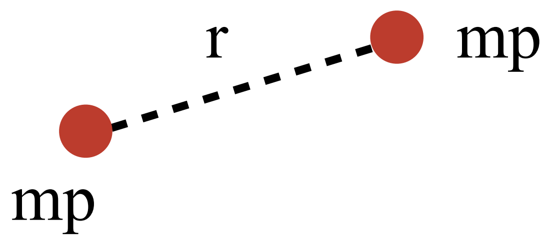
I am made of ~10^29 protons

EM and Gravitation Interactions



Electromagnetic Energy

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

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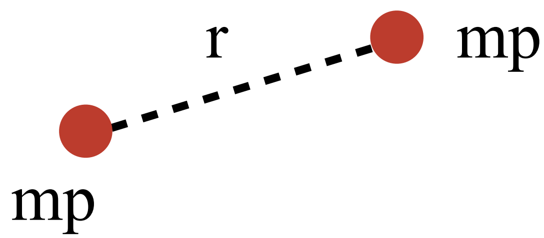

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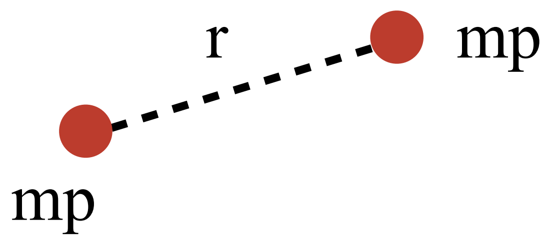

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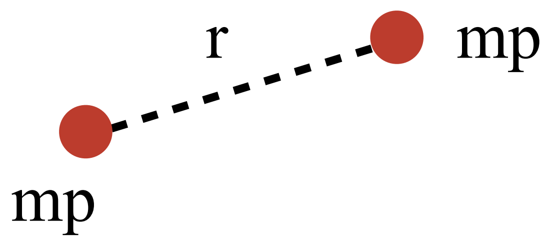

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Pure number: α
Its small: 1/137

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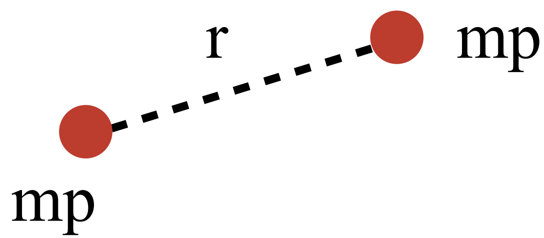

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Gravitational Energy

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

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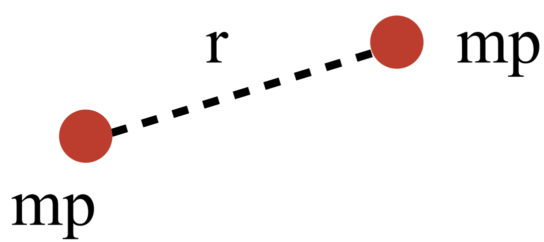

Electromagnetic Energy

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E → GeV

$\frac{e^2}{4\pi}$ →

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$\frac{1}{r}$ → GeV

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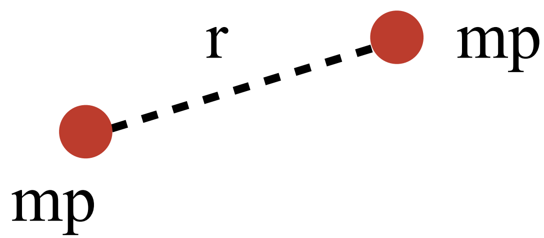
$$E = -G_N \frac{m_p^2}{r}$$

E → GeV

$\frac{m_p^2}{r}$ → GeV^3

EM and Gravitation Interactions



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

The world with 4 numbers

Claim: ~everything in world combination of these numbers

$$\mathrm{m_p} \sim 1\ \mathrm{GeV}$$

$$\alpha = \frac{1}{137} \sim 10^{-2}$$

$$\mathrm{m_e} \sim 10^{-3}\ \mathrm{GeV}$$

$$\alpha_\mathrm{G} \equiv \mathrm{G_N m_p^2} = 10^{-39}$$

Will work through some quick examples.

Atoms

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

Atoms

$$\mathrm{p} \times \mathrm{r} \sim 1$$

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

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

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$$\mathrm{r_{atom}} \sim \frac{1}{\mathrm{Z}\alpha \mathrm{m_e}}$$

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Z	Prediction	Actual Value
1	$\sim 10^{-11}\mathrm{m}$	$2.5 \cdot 10^{-11}\mathrm{m}$
10	$\sim 10^{-12}\mathrm{m}$	$4.0 \cdot 10^{-11}\mathrm{m}$
>10	$\sim 10^{-12}\mathrm{m}$	$\sim 10^{-10}\mathrm{m}$

Details of electron screening needed for high Z
(Will use 10^-10 when Z >10)

Atoms

$$\mathrm{p} \times \mathrm{r} \sim 1$$

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$$\frac{\mathrm{r_{nucleus}}}{\mathrm{r_{atom}}} \sim \frac{\alpha \mathrm{m_e}}{\mathrm{Z}^{2/3}\mathrm{m_p}} \sim 10^{-5}$$

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

Atoms

$$p \times r \sim 1$$

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

$$r_{atom} \sim \frac{1}{Z\alpha m_e} \qquad r_{nucleus} \sim \frac{Z^{1/3}}{m_p}$$

$$\frac{r_{nucleus}}{r_{atom}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10^{-[illegible]}$$

Number of different atoms $\sim 1/\alpha$

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

Atoms

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$$\frac{r_{nucleus}}{r_{atom}} \sim \frac{\alpha m_e}{Z^{2/3} m_p} \sim 10$$

Number of different atoms ~ 1/α

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

- Why we could do QM first with out relativity: (v << 1 for Z~1)
- Why electricity more stronger everyday than magnetism.

Atoms

$$\mathrm{p \times r \sim 1}$$

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

$$\mathrm{r_{atom} \sim \frac{1}{Z\alpha m_e}} \qquad \mathrm{r_{nucleus} \sim \frac{Z^{1/3}}{m_p}}$$

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Atoms

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For Hydrogen

10^{-4} 0.5 MeV $\sim$ 50 eV

(Actually is 13.6 eV)

Atoms

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

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

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

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Mass Density: Mass/Volume

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

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Pressure of Solid: Force/Area or Energy/Volume

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

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

(Ratio of two give the speed of sounds)

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

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

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

Planets

Solids where gravitational pressure balanced by solid pressure

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

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

Planets

Solids where gravitational pressure balanced by solid pressure

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

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

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

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

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

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α / G $\times\, r_{\text{atom}}$

Prediction:	$r_e \sim 10^7$m	$m_e \sim 10^{25}$kg
Actual:	$6.4 \cdot 10^6$m	$5.9 \cdot 10^{24}$kg

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Life

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

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$E_{\rm Fall} \sim E_{\rm B}$ [obscured by box]

L_A ~ 10 cm / M_A ~ 100 kg

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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 the Camera**

May 13th: **The Discovery of the Higgs Boson**

May 20th: **Problems with the Standard Model**

May 27th: **Memorial Day: No Lecture**

June 3rd: **Going beyond the Higgs: What comes next ?**

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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. & Relativity

<u>Constituents</u> *(Matter Particles)* **Spin = 1/2**

Leptons: Quarks:

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

<u>Interactions</u> Dictated by principles of symmetry **Spin = 1**

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

γ W Z g

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Consistent theory of electromagnetic, weak and strong forces ...
... provided <u>**massless**</u> *Matter* and *Force Carriers*

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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

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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)*

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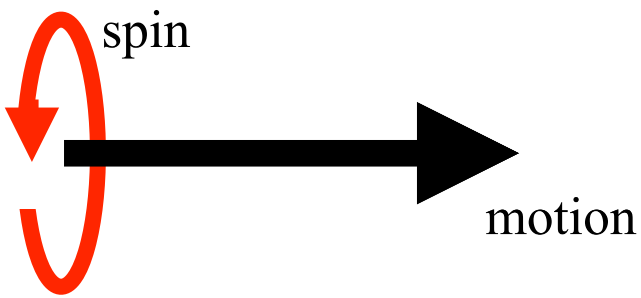
<u>Aligned with direction of motion</u>



"Right-handed"

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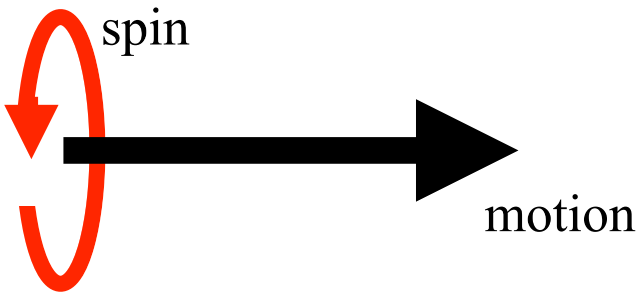

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"Left-handed"

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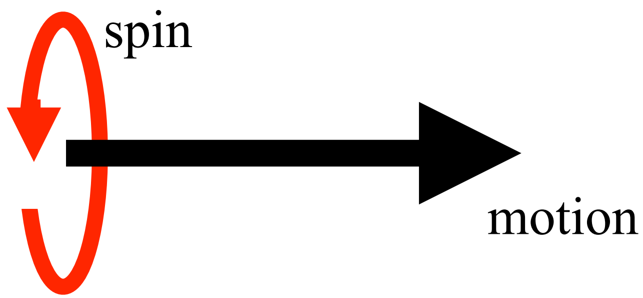

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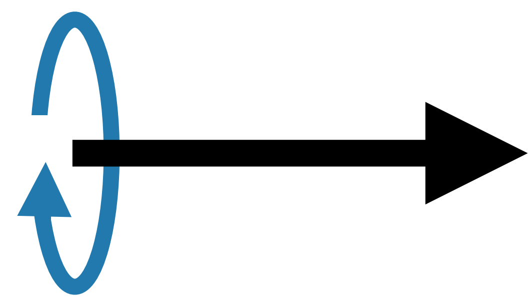

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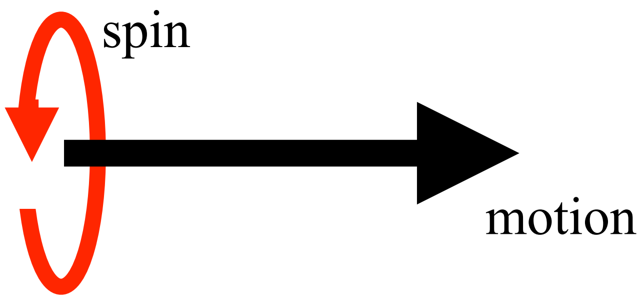

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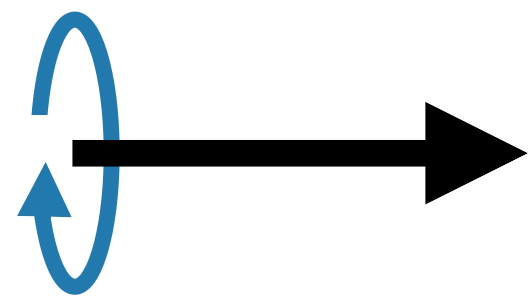

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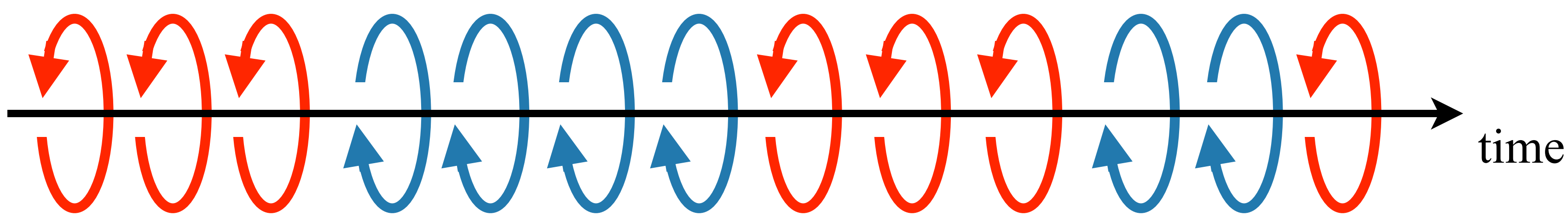

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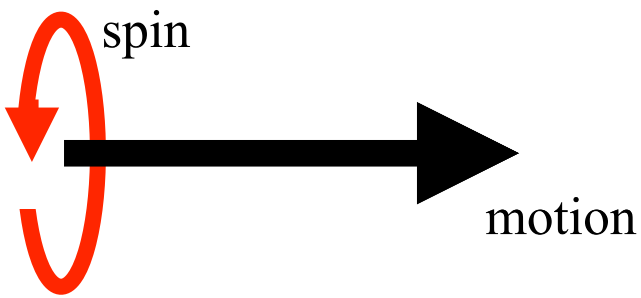

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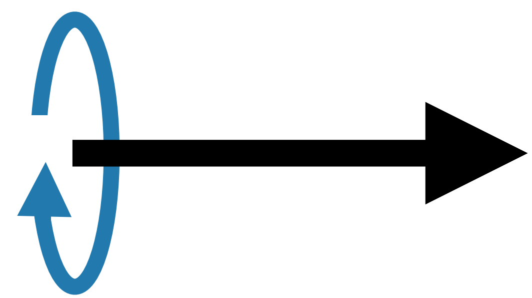

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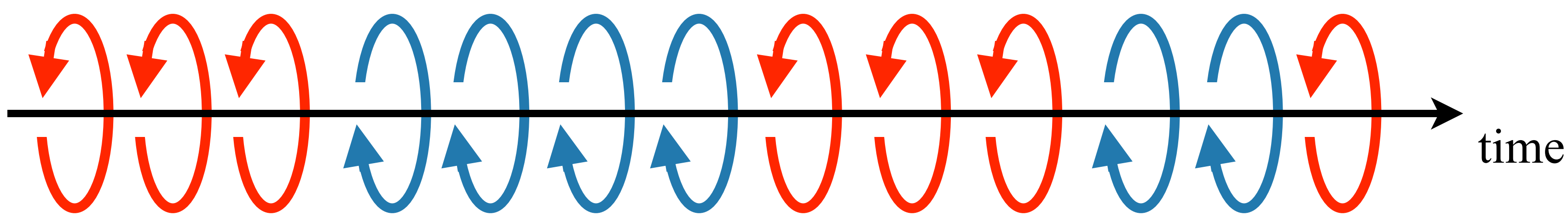

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The heavier the particle the more it flips.

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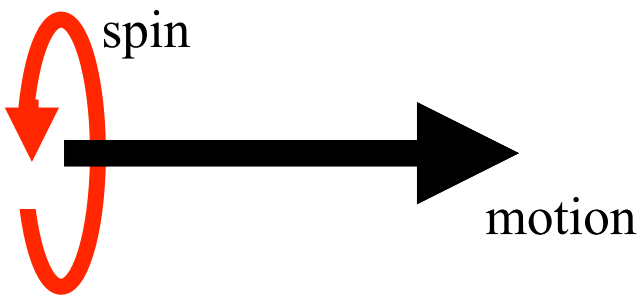

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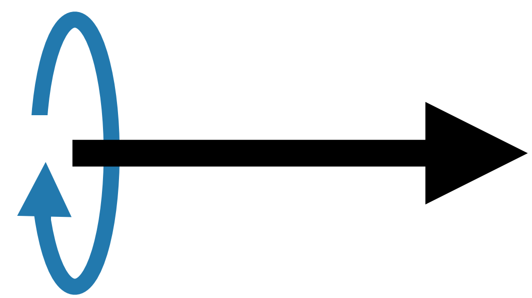

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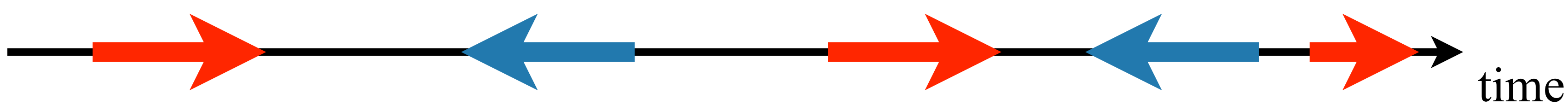

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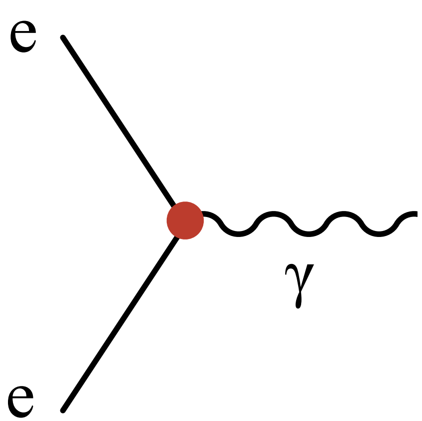

B/c electrons have
Charge

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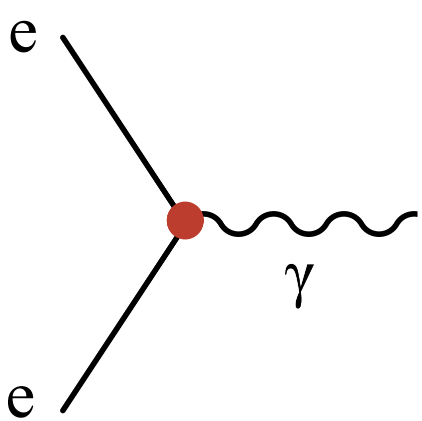

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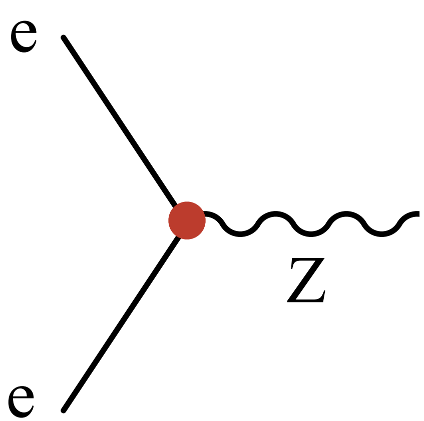

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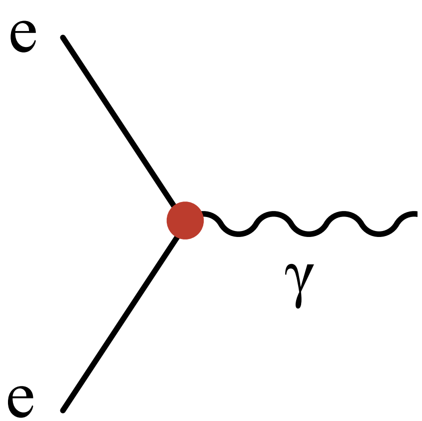

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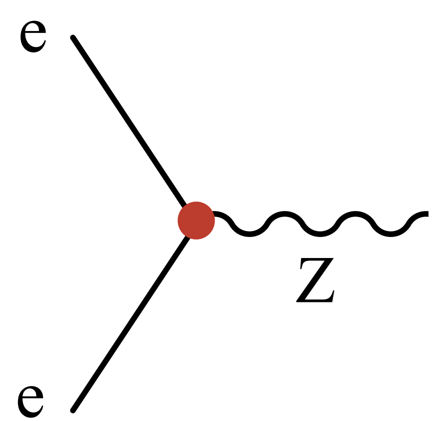

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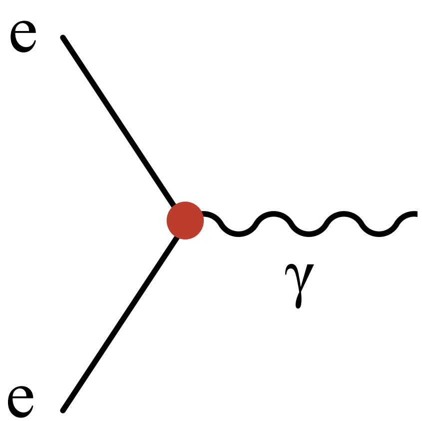

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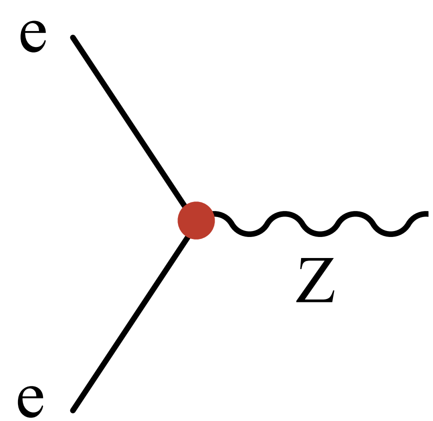

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Left -handed particles have Hyper-charge = 1
Right-handed particles have Hyper-charge = 0

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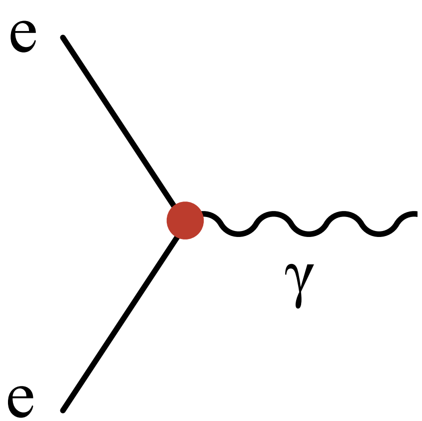

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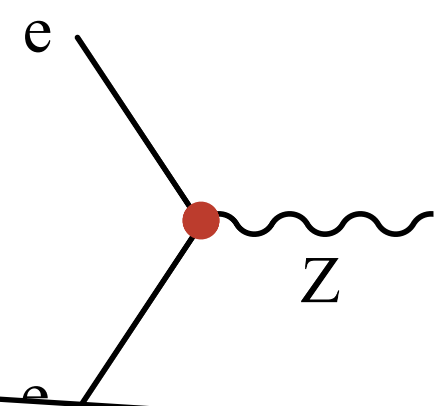

B/c electrons have
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Only left-handed particles have hyper-charge change !

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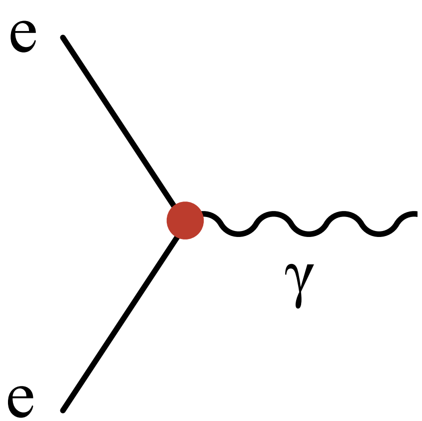

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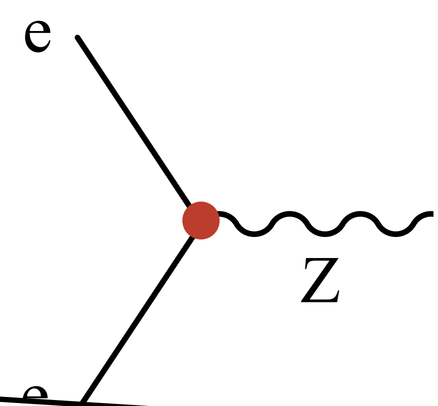

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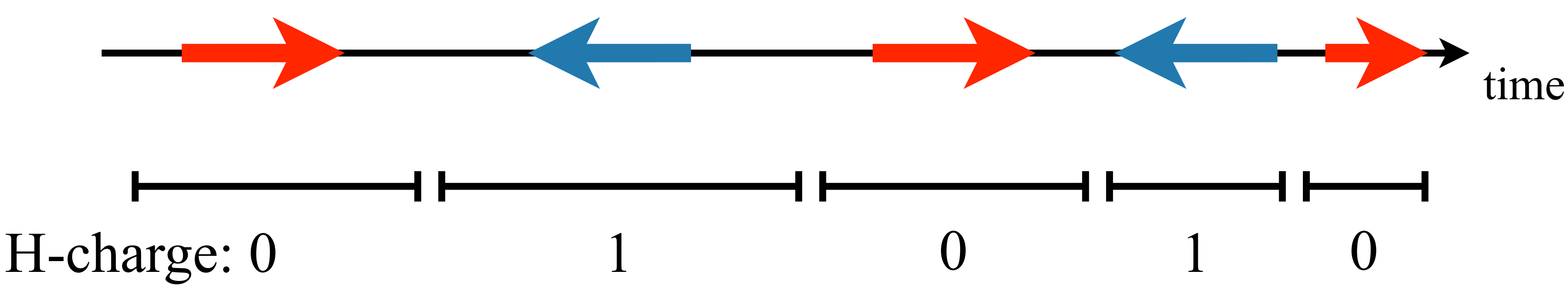
This + particle masses immediately leads to contradiction:



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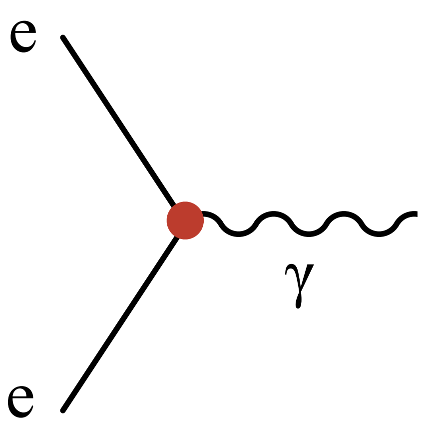

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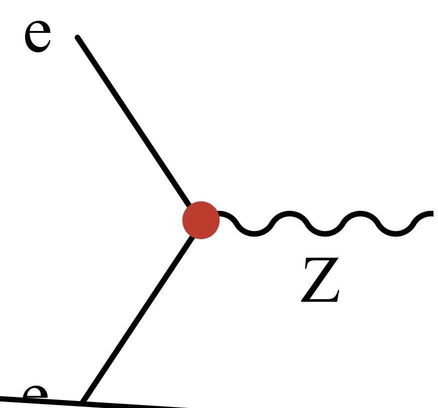

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<u>One hand:</u>
QFT tells us that ***massive*** particles can flip back and forth.
SM these have different H-charges ⇒ ***H-charge <u>not</u> conserved***

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

H-charge: 0 1 0 1 0

Get around this with the Higgs *Field*

Get around this with the Higgs *Field*

What is a field?

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

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:

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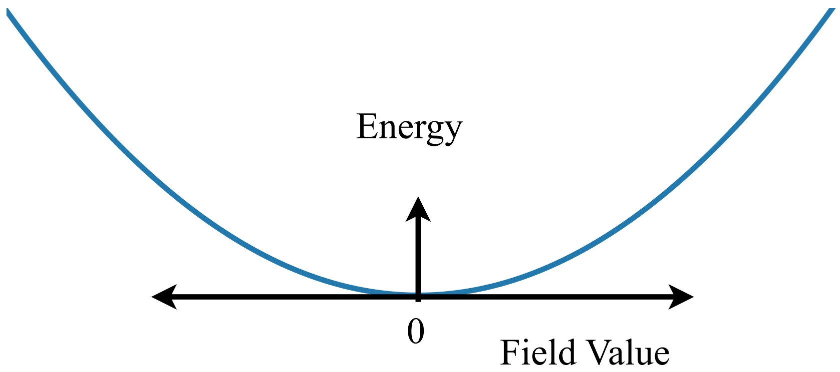

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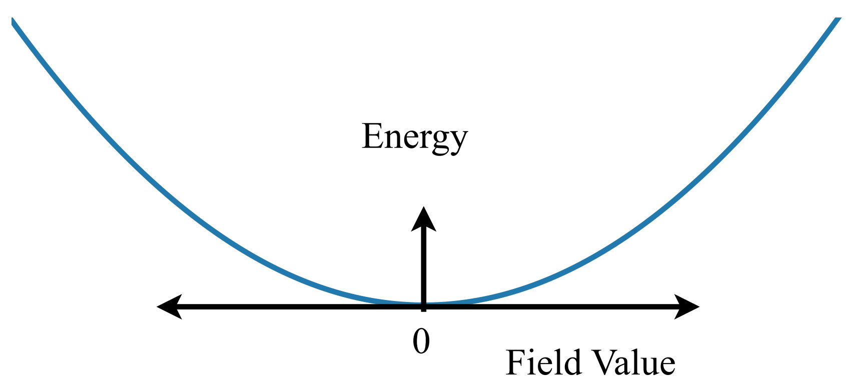
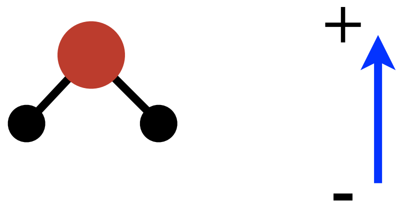


Warm-up with example of how a field can affect mass

Mass from Field: *Example*

Water molecules are little dipoles:



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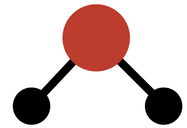

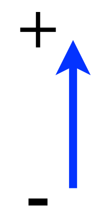

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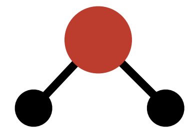

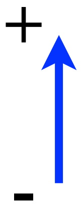

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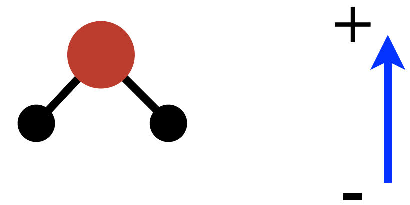

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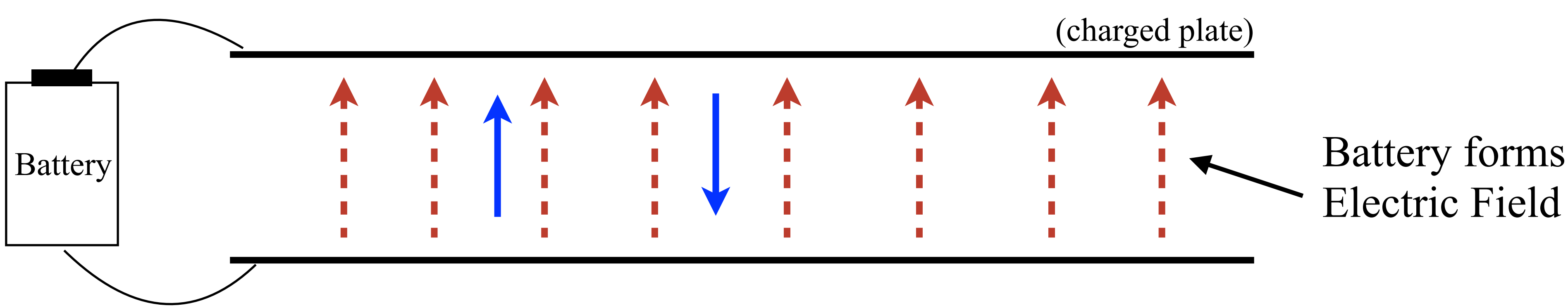

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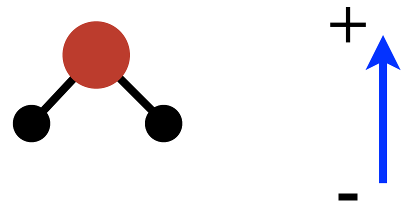

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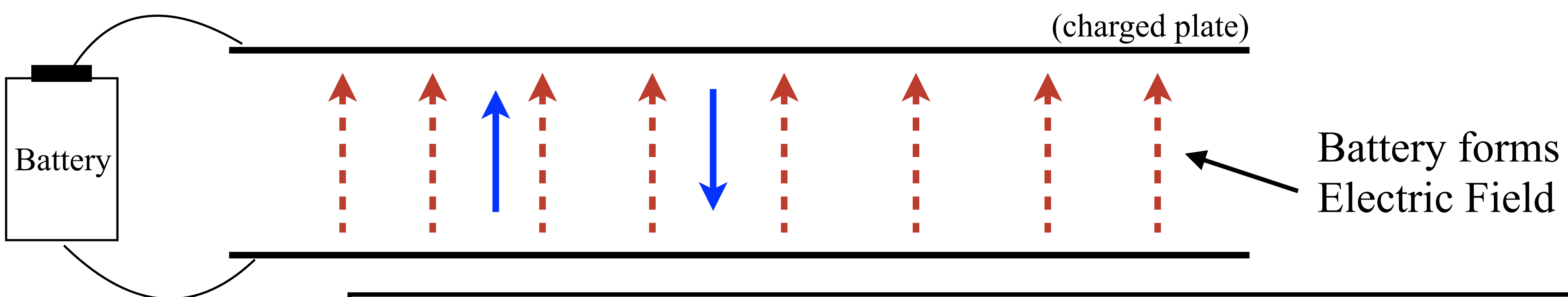

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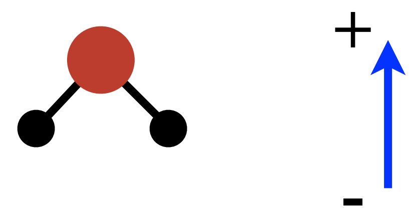

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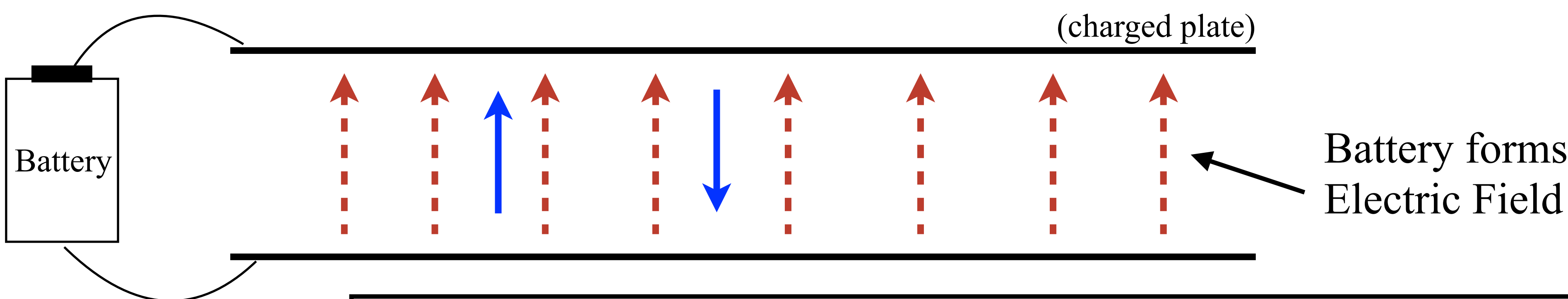

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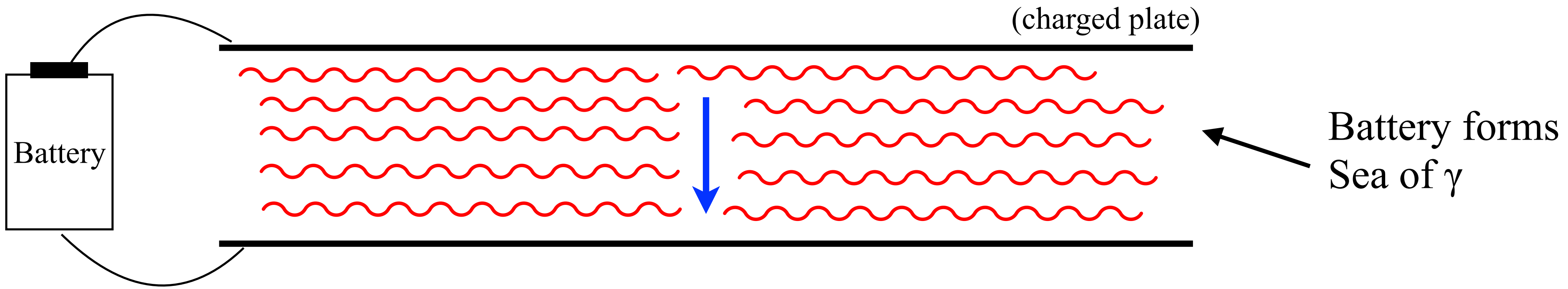
Example of how a field can creates mass for a particle

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



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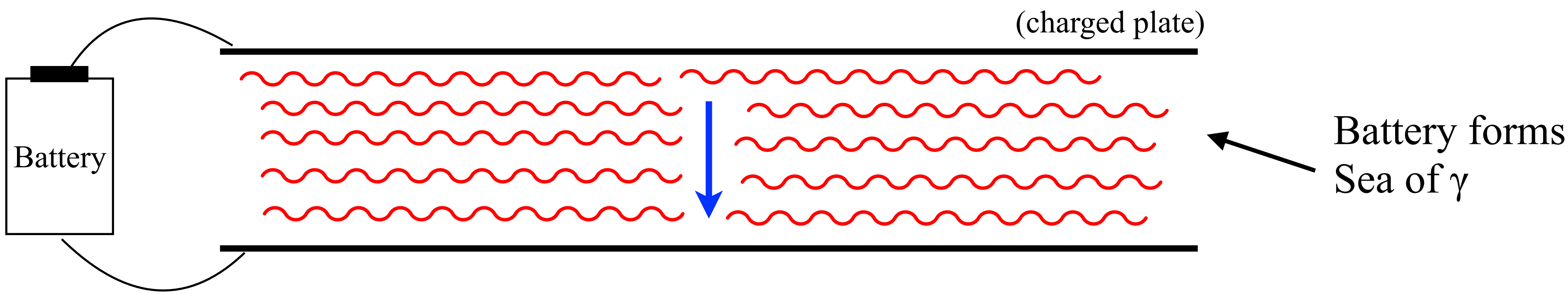

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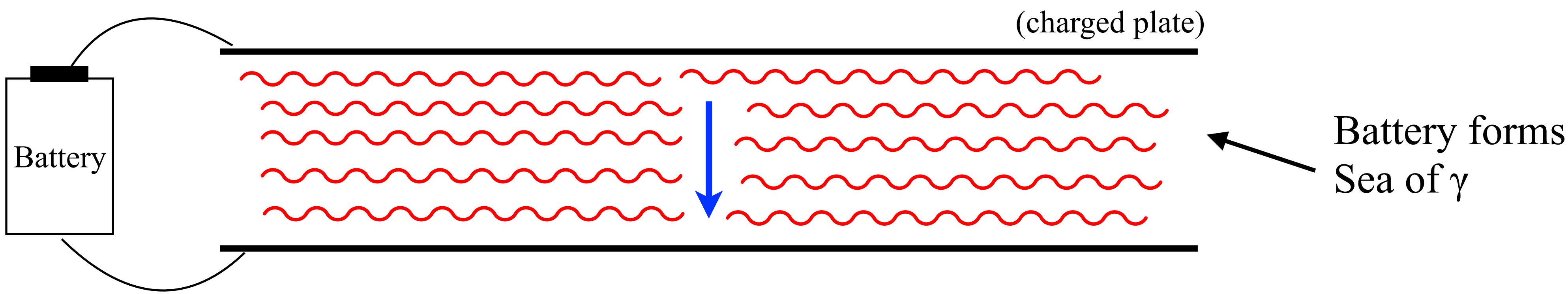

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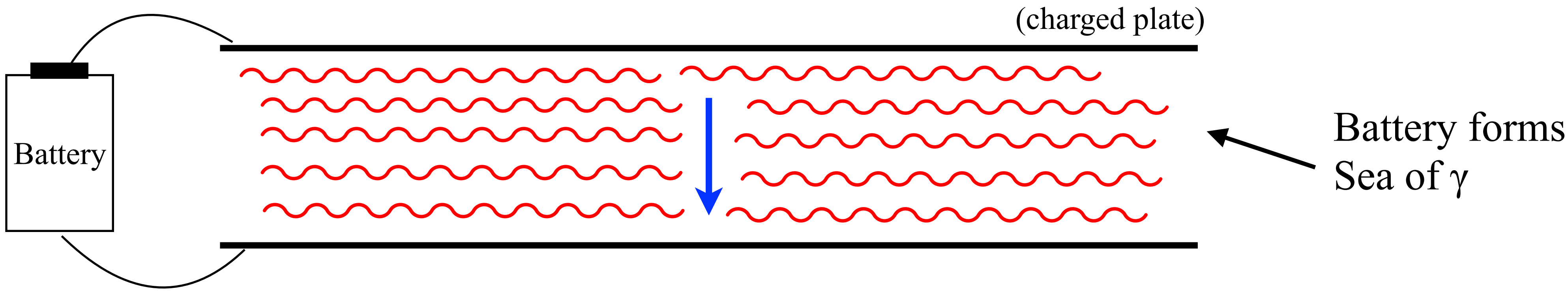

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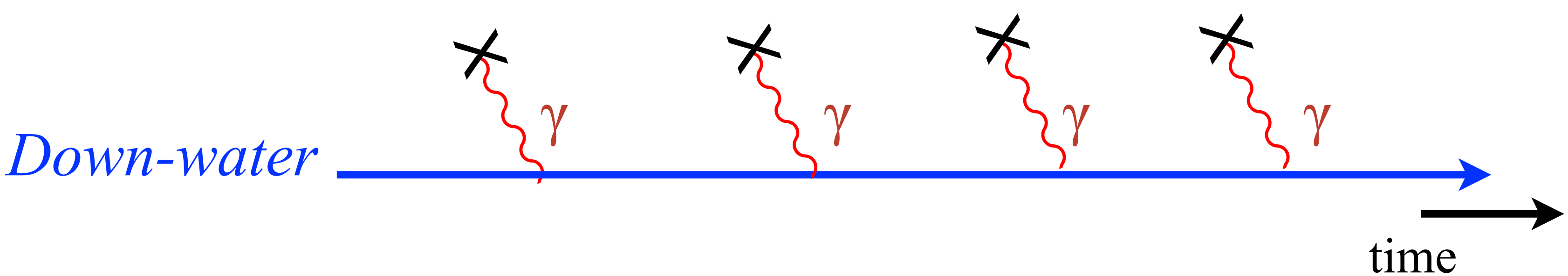

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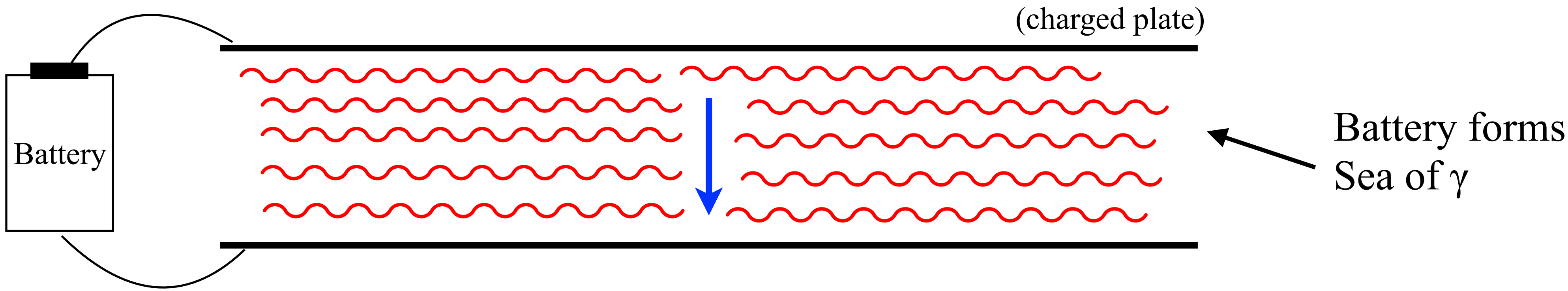

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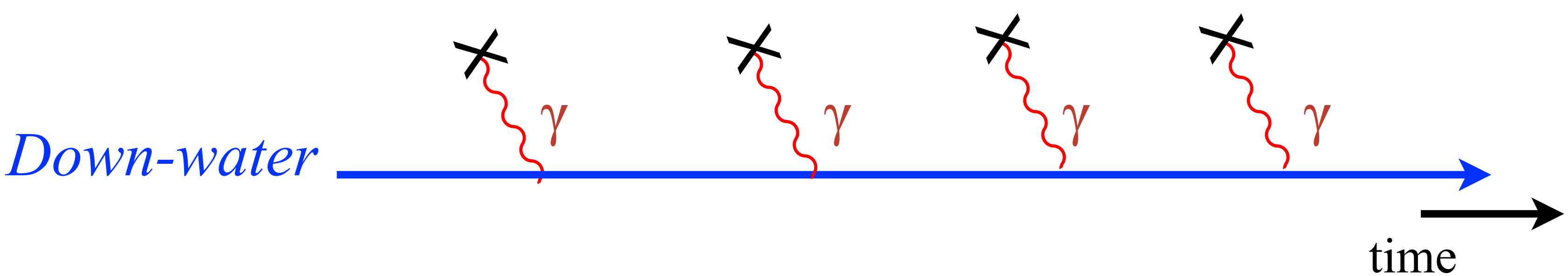

In this example, γ ***condensate*** is created by the battery ("Turns field On")

Turning the Higgs Field On

For the Higgs field don't use batteries or charged plate, instead…
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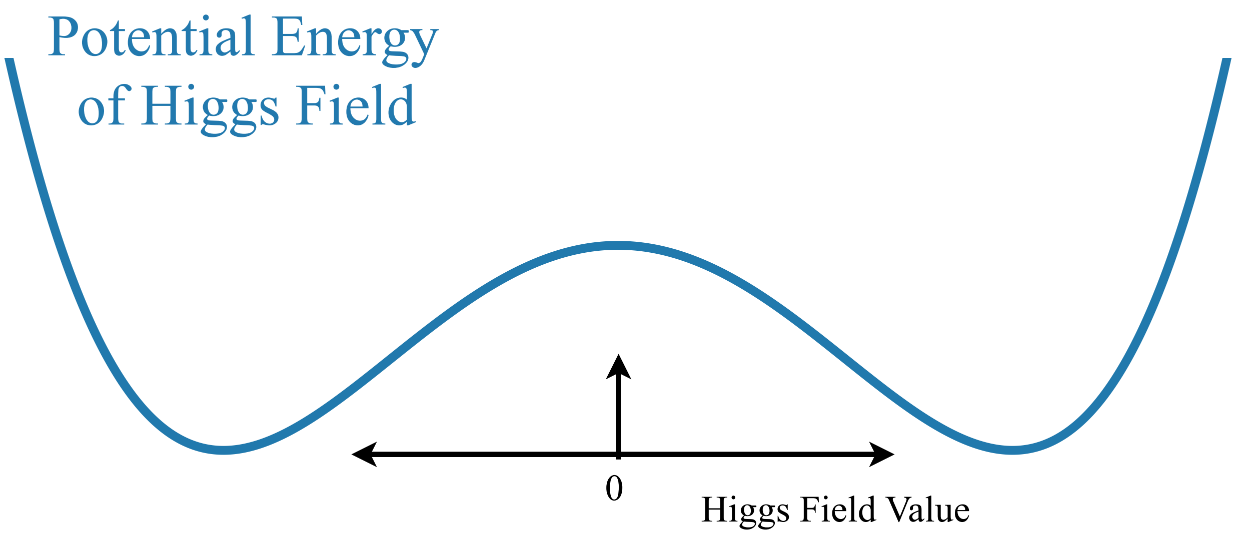

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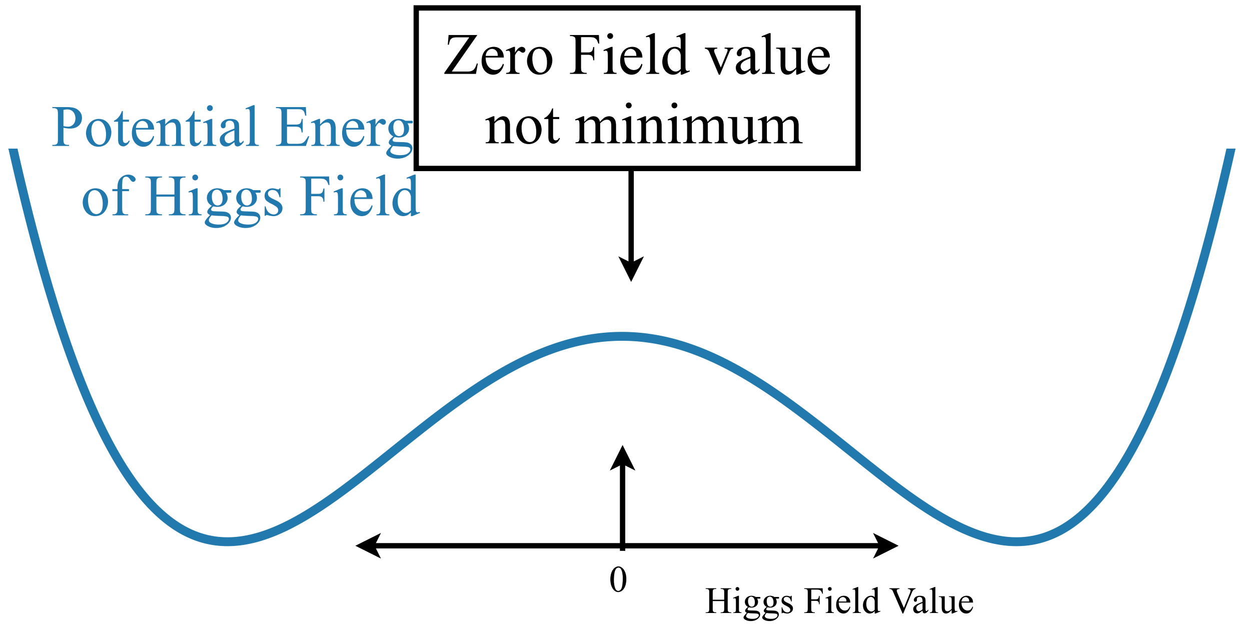

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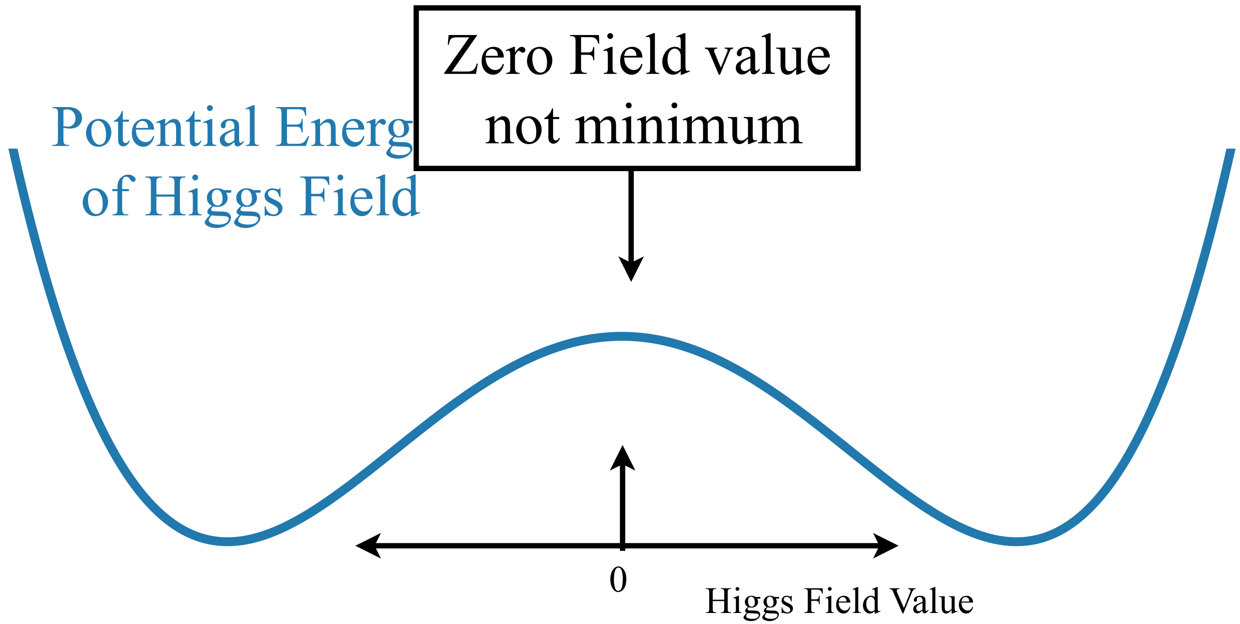

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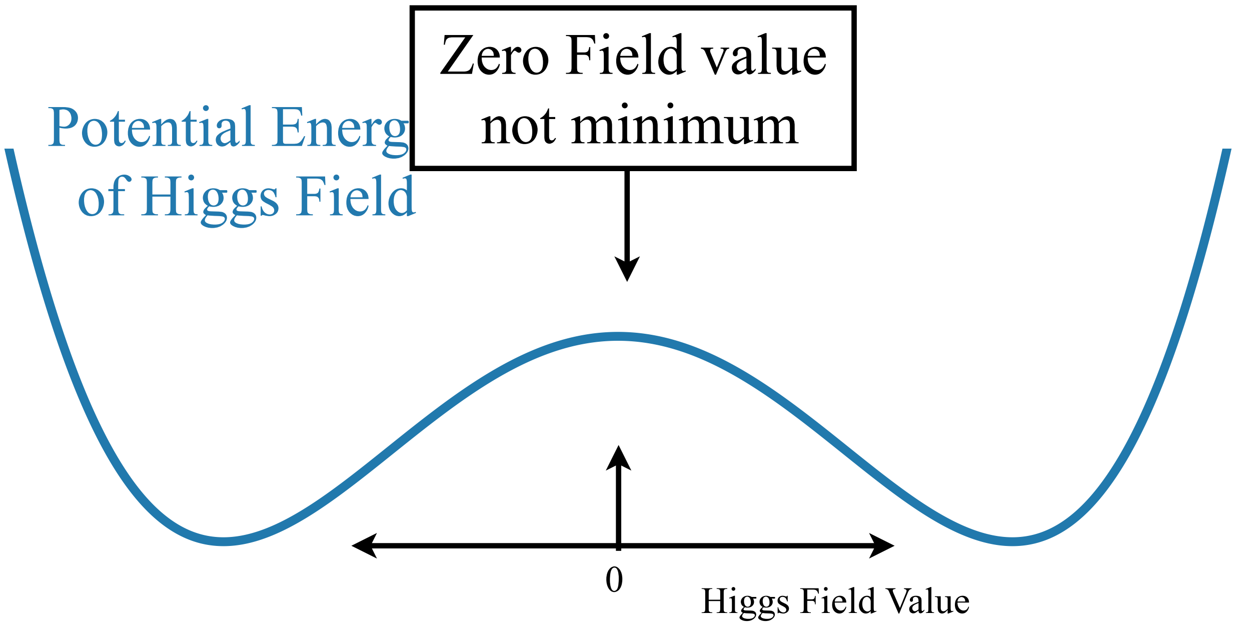

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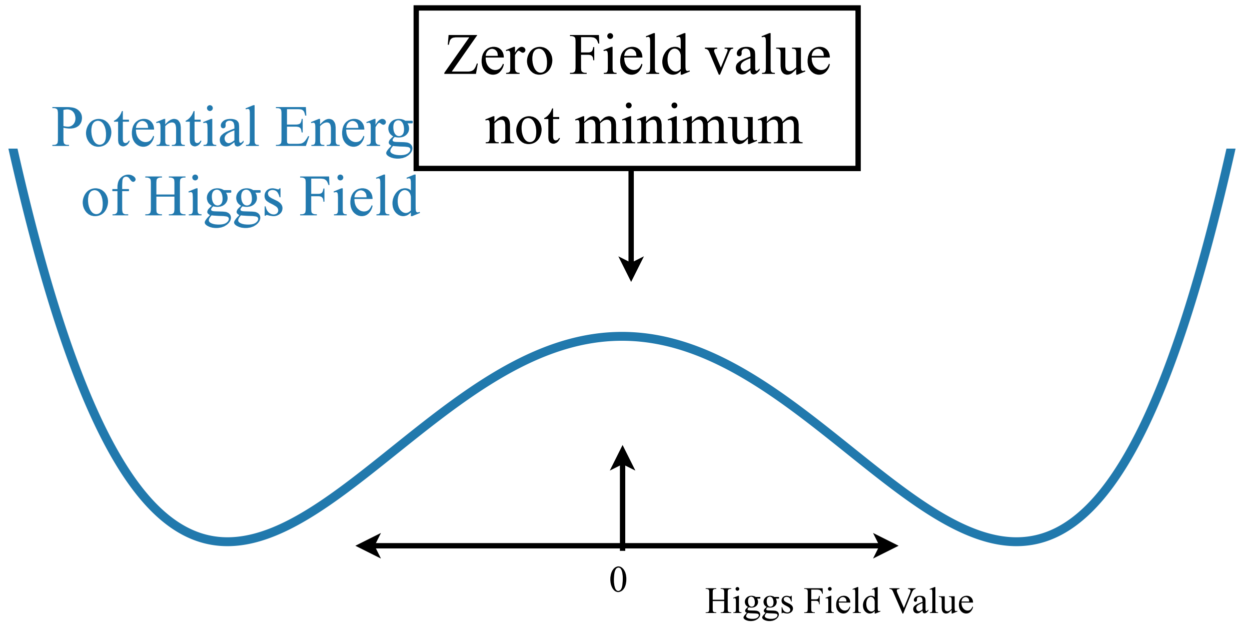

The form of the Higgs potential energy enough to turn the field on
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Form a condensate (***v-condensate***) just as in our previous example
QM effect related to shape of potential. *(Analogous to Superconductivity)*

Does all mass come from Higgs Field?

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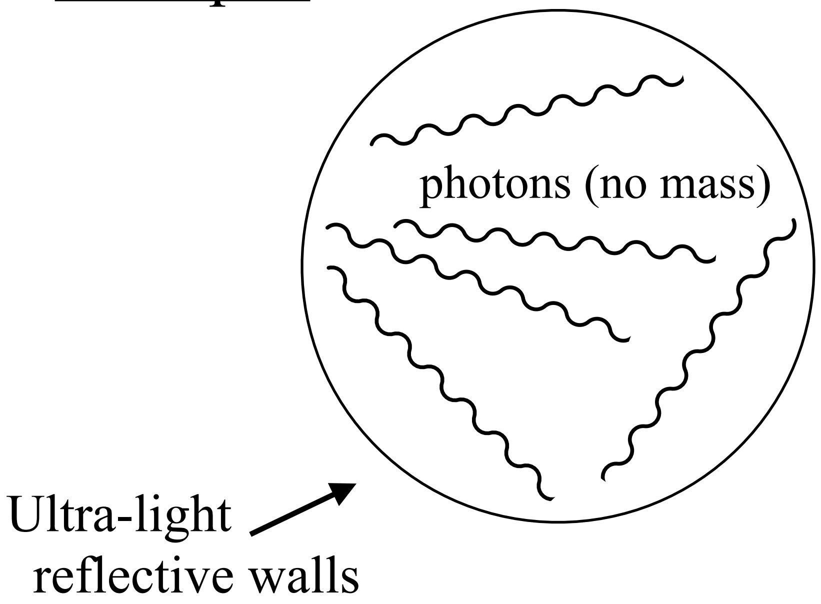
No !

Example:



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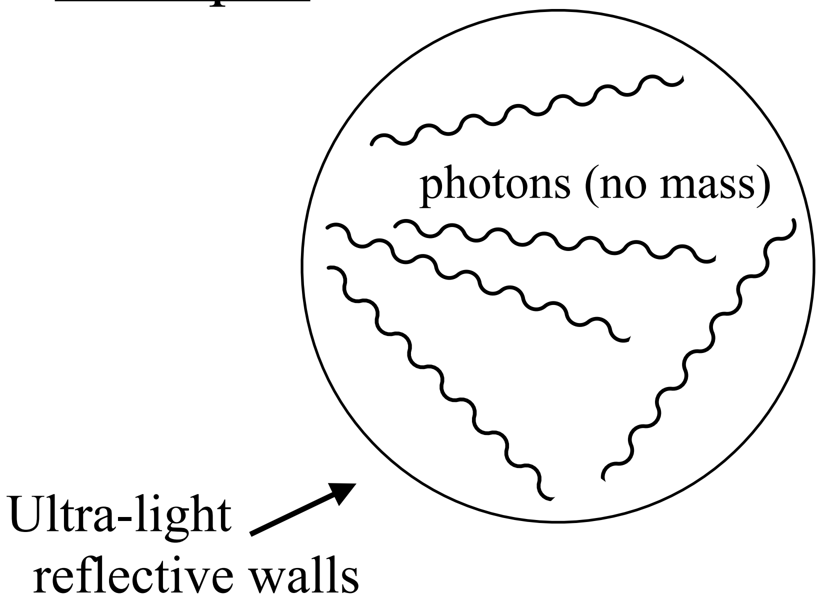

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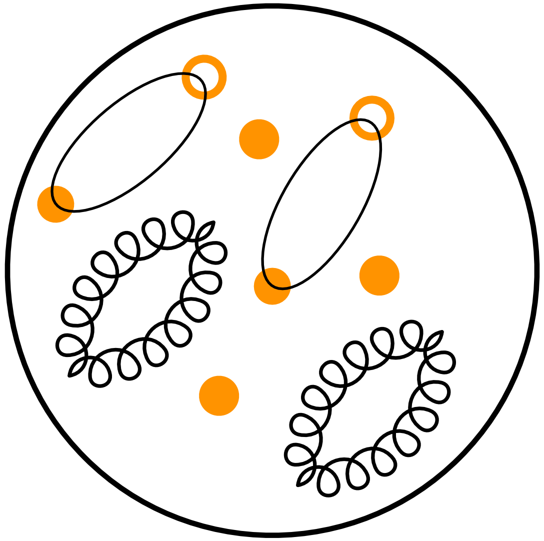

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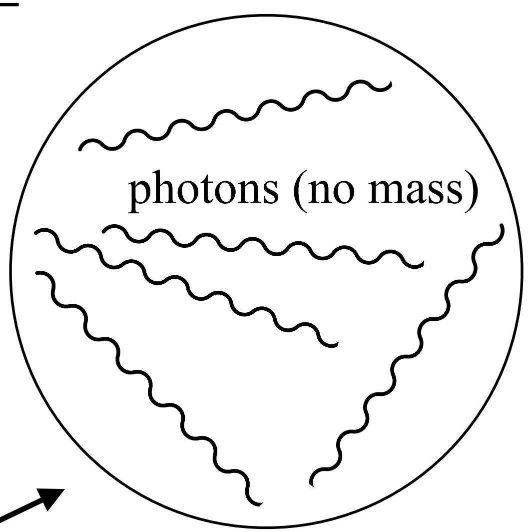
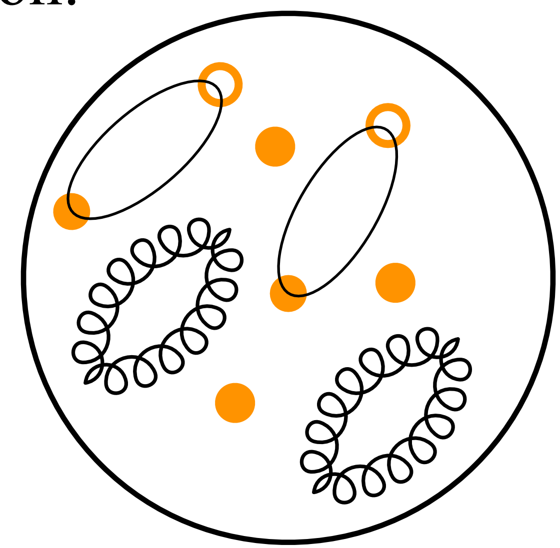


Ultra-light reflective walls

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

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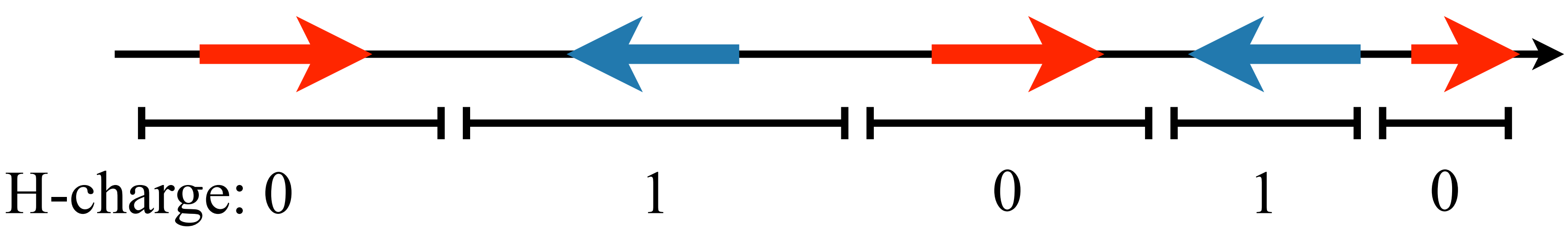

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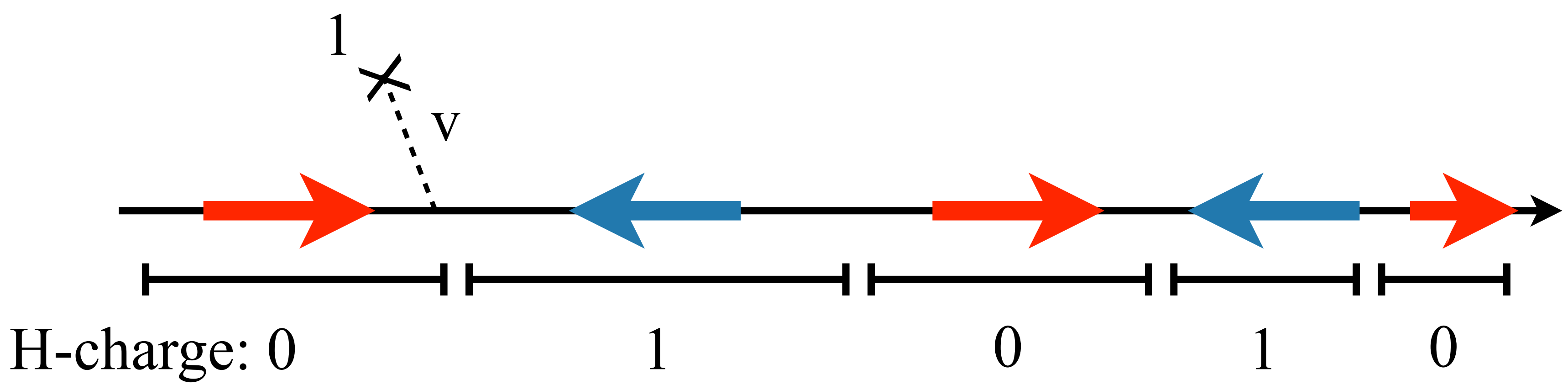

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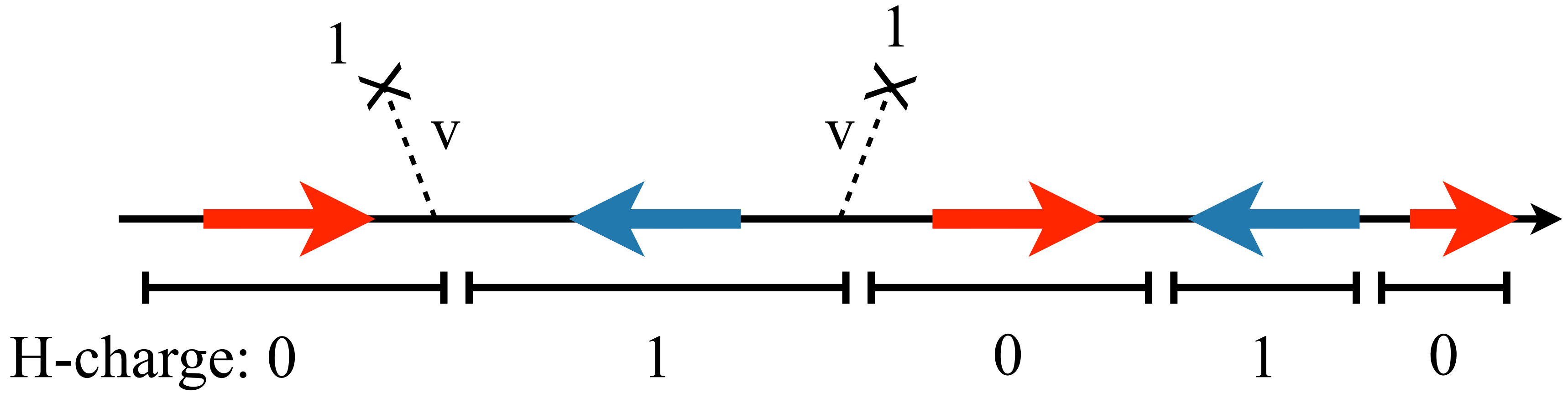

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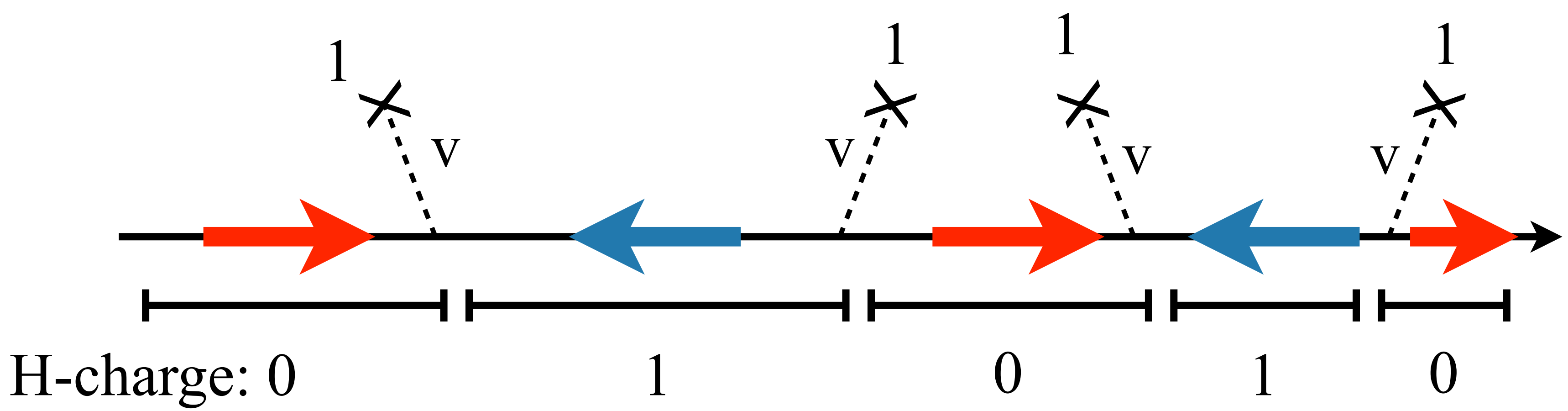

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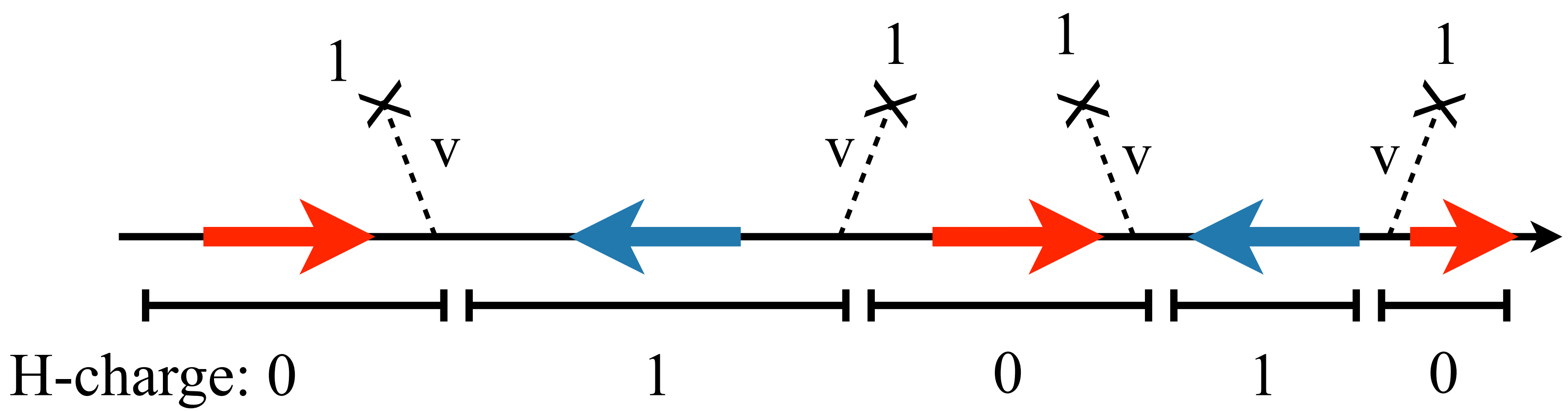

Interaction of matter particles w/v-condensate that allows mass

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

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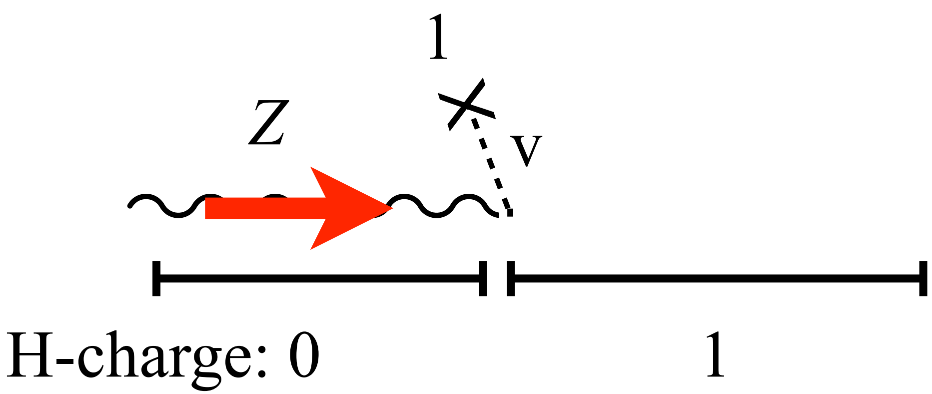

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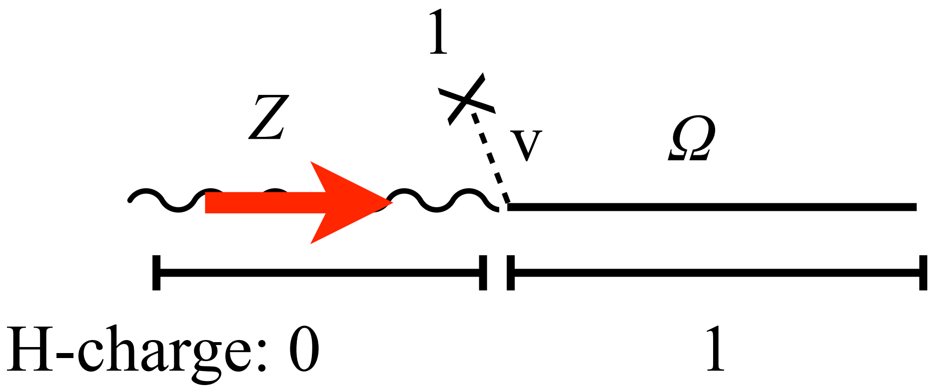

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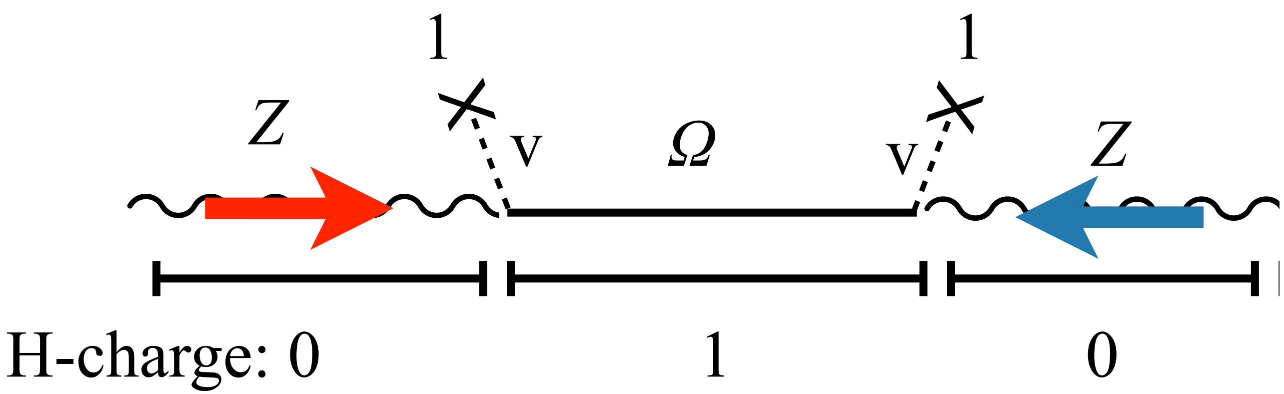

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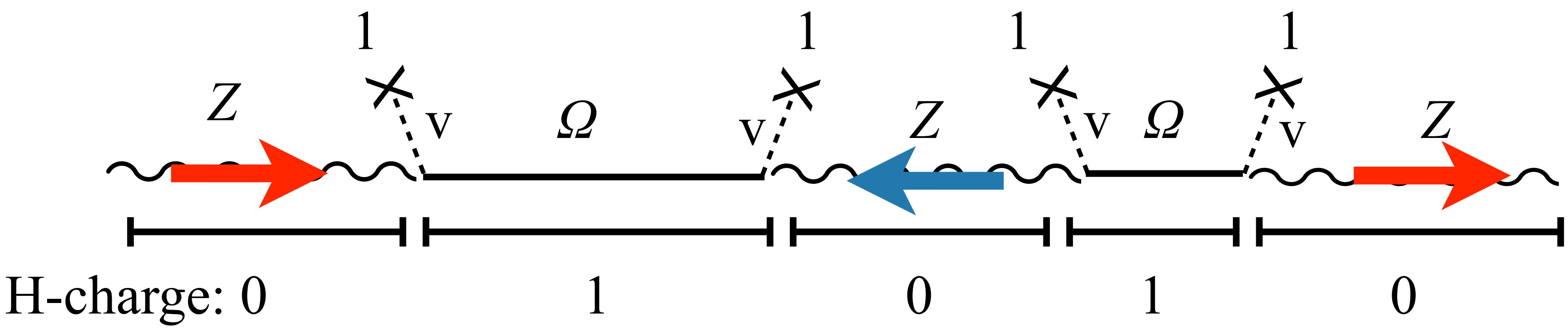

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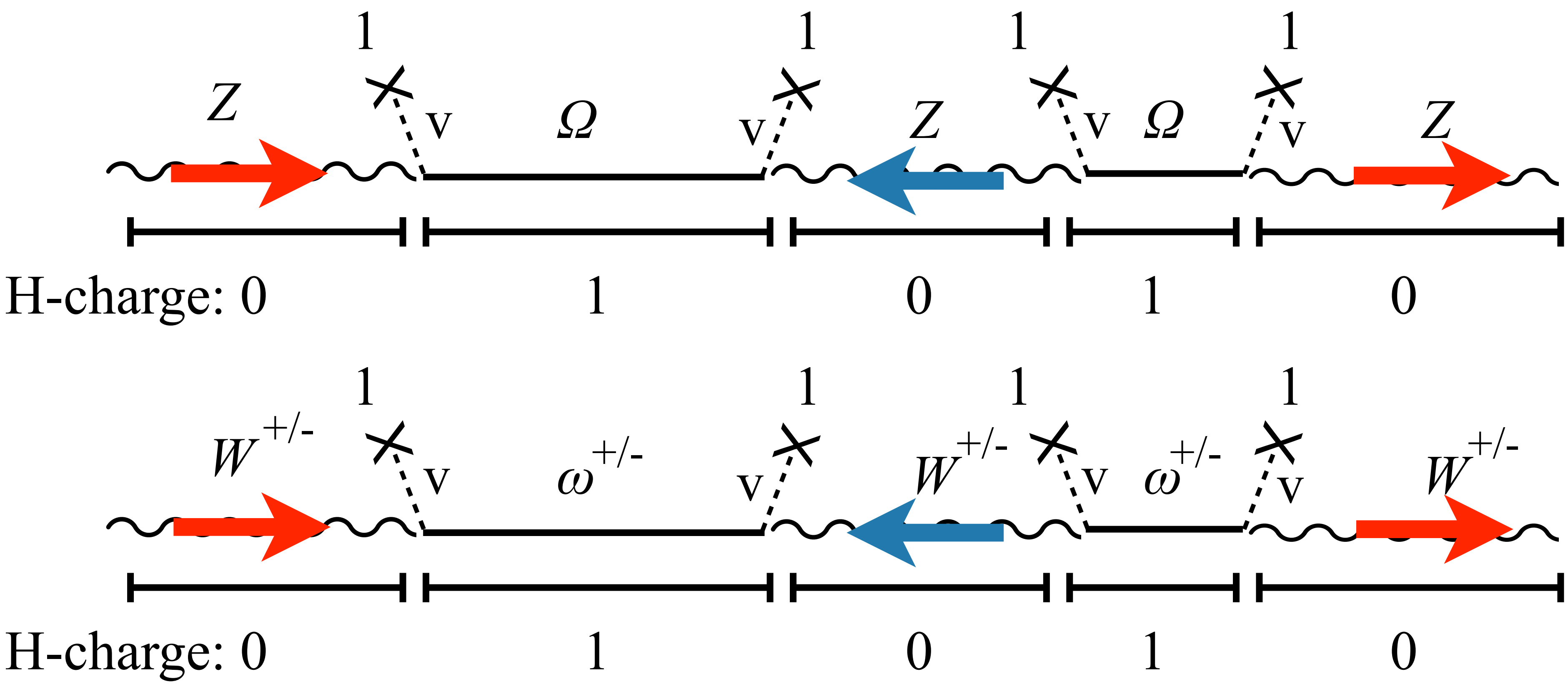

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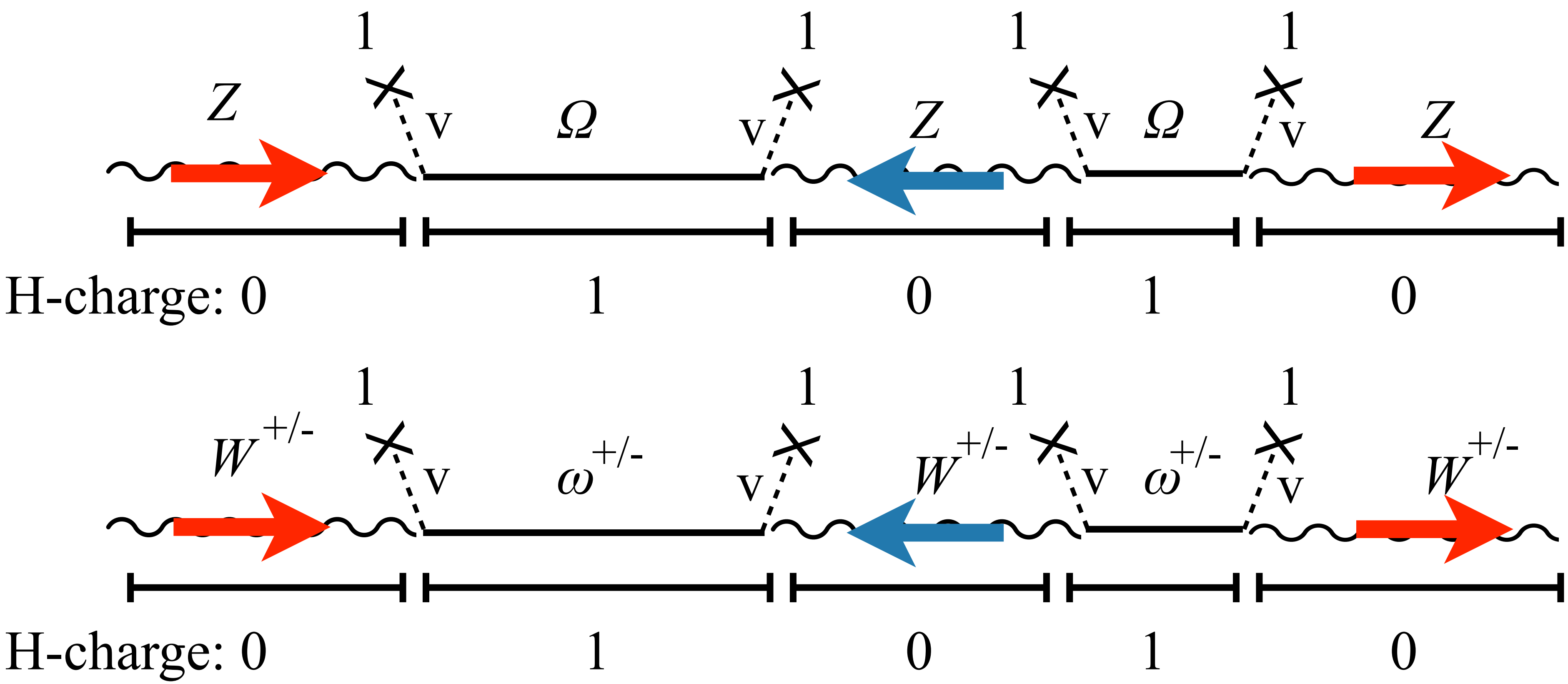

Ω and *ω* are also referred to as "Longitudinal polarizations of W/Z"

What about the Higgs Boson ?

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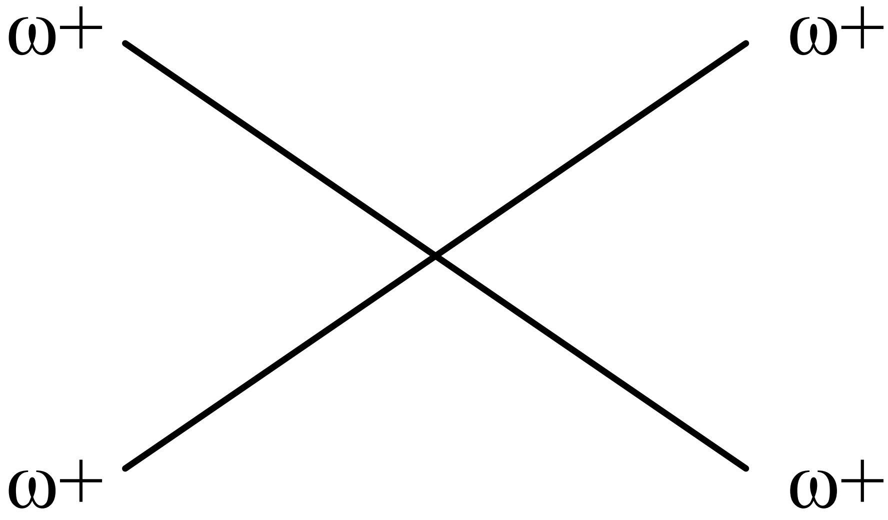
What is the probability to scatter ω+/- ?

$\psi =$



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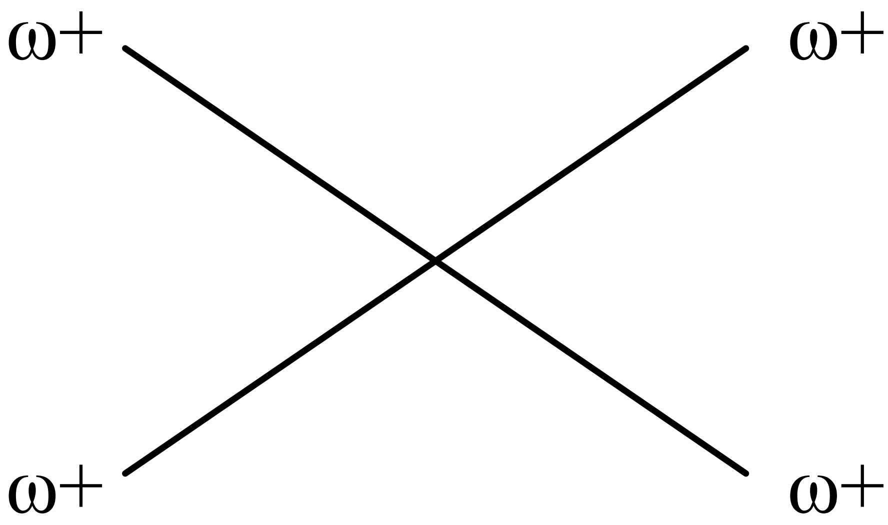

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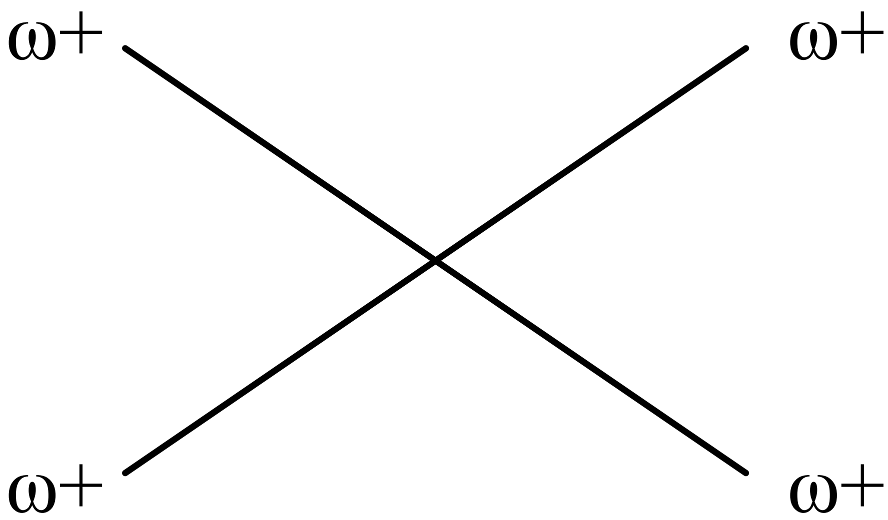

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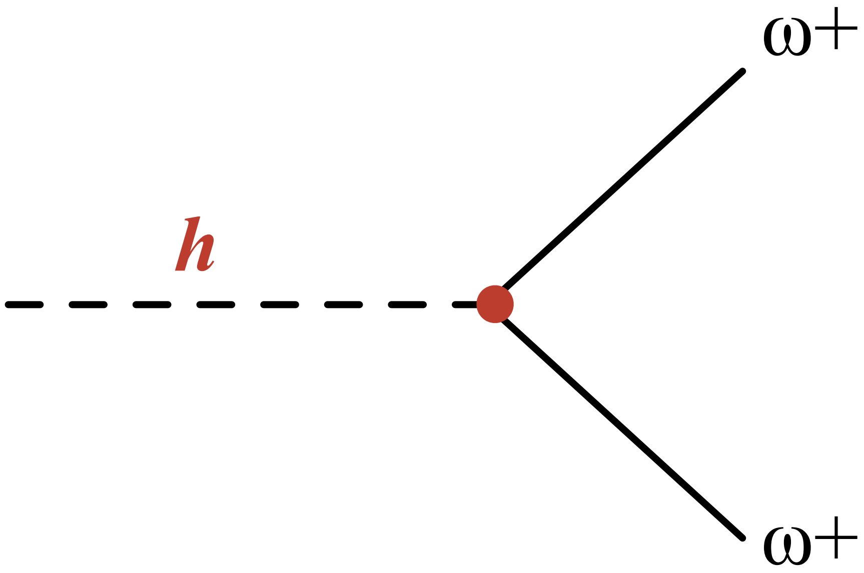
$$P = |\psi|^2 = \left(\frac{1}{50}\frac{\text{Energy}}{m_W}\right)^2$$ **> 1 at high E**

(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+

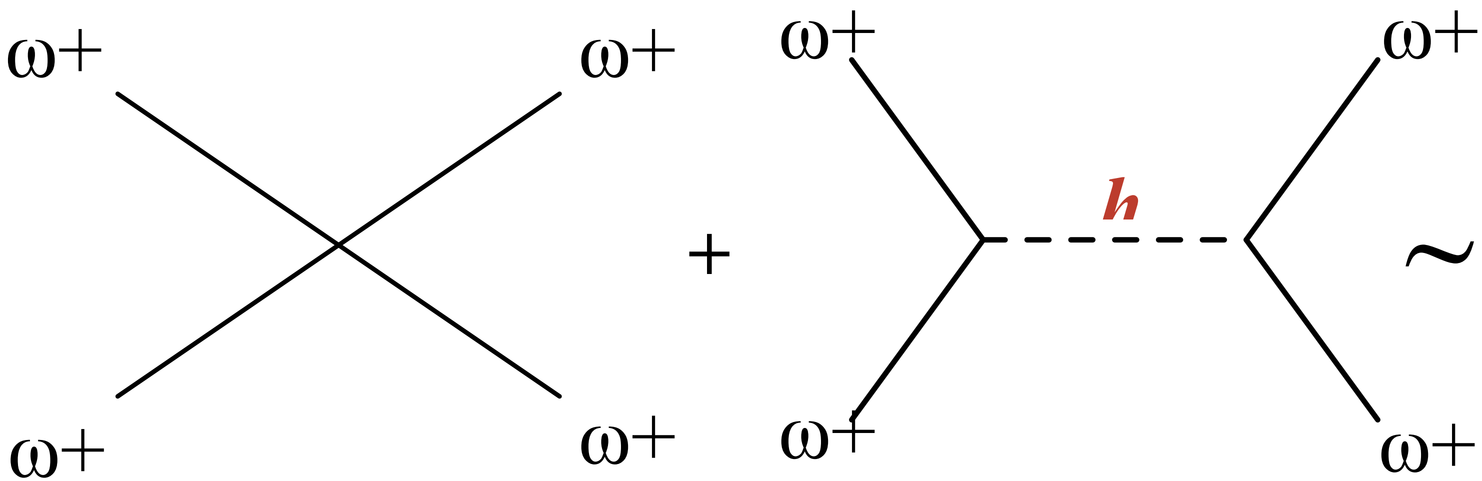


h sound waves is the Higgs field condensate

What about the Higgs Boson ?

Have to include all terms:

$\psi =$



$\sim\ < 1\ !$

Fixes the inconsistent behavior at high Energy

Have sensible theory again !

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

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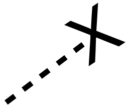
$\Rightarrow$ Couples to matter / W/Z just like v 

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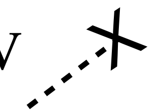
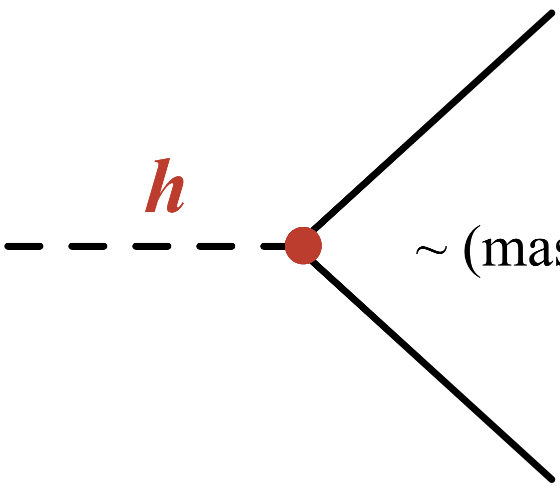
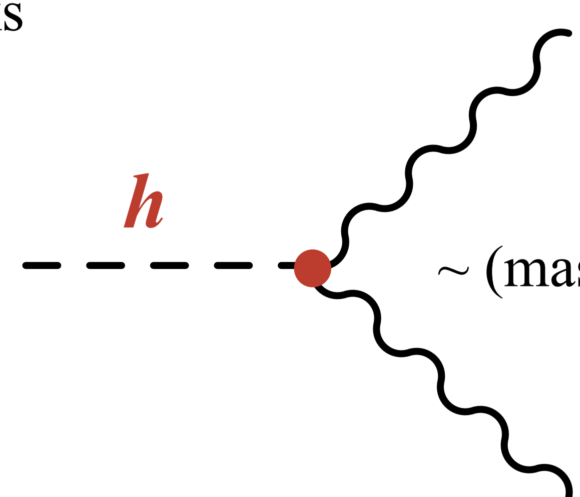
$\Rightarrow$ Couples to matter / W/Z just like v 





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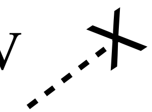
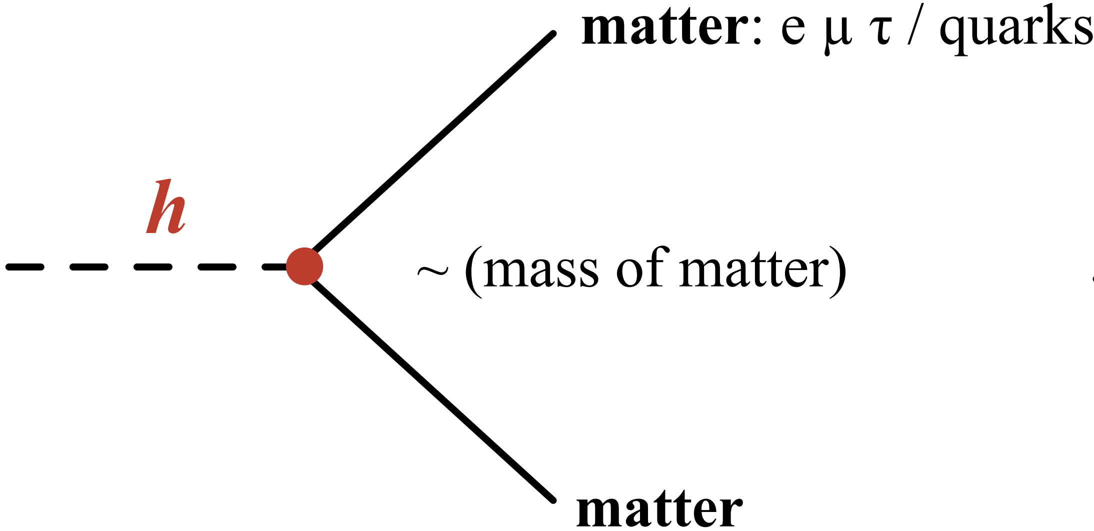
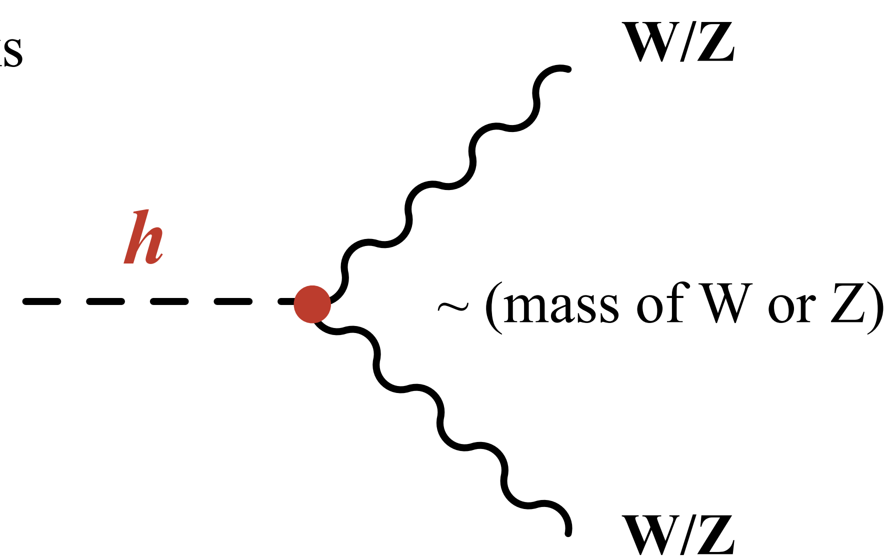
$\Rightarrow$ Couples to matter / W/Z just like v 





Spin: 0 1/2 1 3/2 2

The Higgs Boson

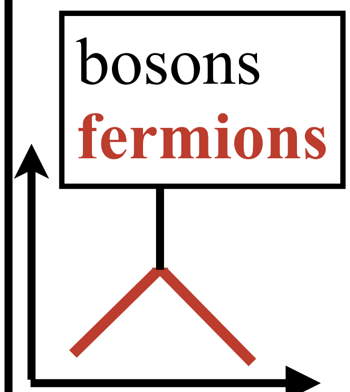
What do we know about the Higgs Particle: ***<u>A Lot</u>***

Higgs is excitations of v-condensate

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

matter: e μ τ / quarks

W/Z



matter

W/Z

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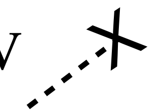
⇒ Couples to matter / W/Z just like v 

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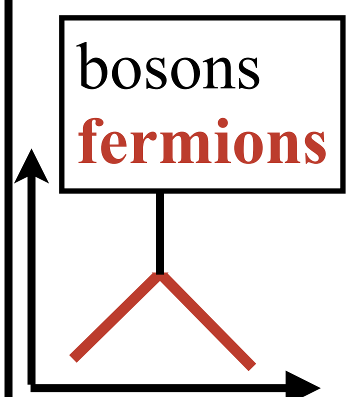

- QM+R ⇒ Only 1 Spin-2 interaction allowed: *Graviton*

Mass/coupling needed for Higgs inconsistent

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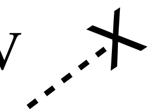
$\Rightarrow$ Couples to matter / W/Z just like v 

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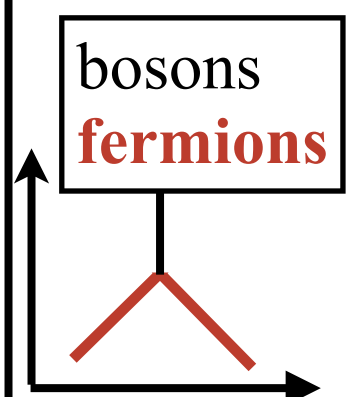

- QM+R $\Rightarrow$ Only 1 Spin-2 interaction allowed: *Graviton*
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- Massive Spin-1 in a reason we are in this mess!
  Would need another condensate to explain mH

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

The Higgs Boson

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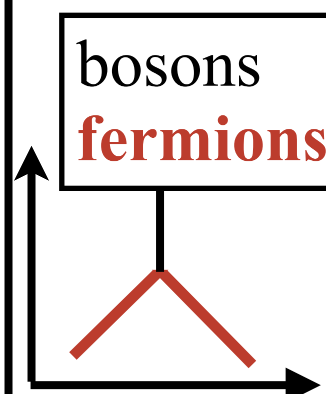

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Spin: 0 1/2 1 3/2 2

The Higgs Boson

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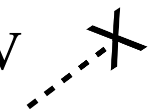
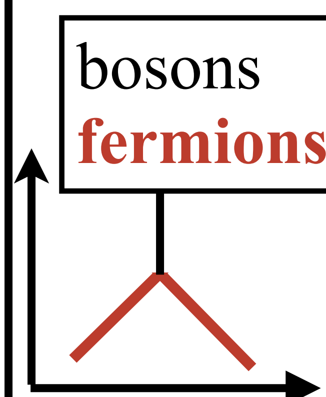
⇒ Couples to matter / W/Z just like v 

matter: e μ τ / quarks **W/Z**



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Z)

matter **W/Z**

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

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

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

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

Field

^

"The Higgs ~~Boson~~ ~~(or "God Particle")~~ is Responsible

For All Mass in the Universe"

Field

^

"The Higgs ~~Boson~~ (~~or "God Particle"~~) is Responsible

For ~~All Mass~~ in the Universe"

v

Some (*Very Important!*) Mass

Field

^

“The Higgs ~~Boson~~ (~~or “God Particle”~~) is Responsible

For ~~All Mass~~ in the Universe”

v

Some (*Very Important!*) Mass

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