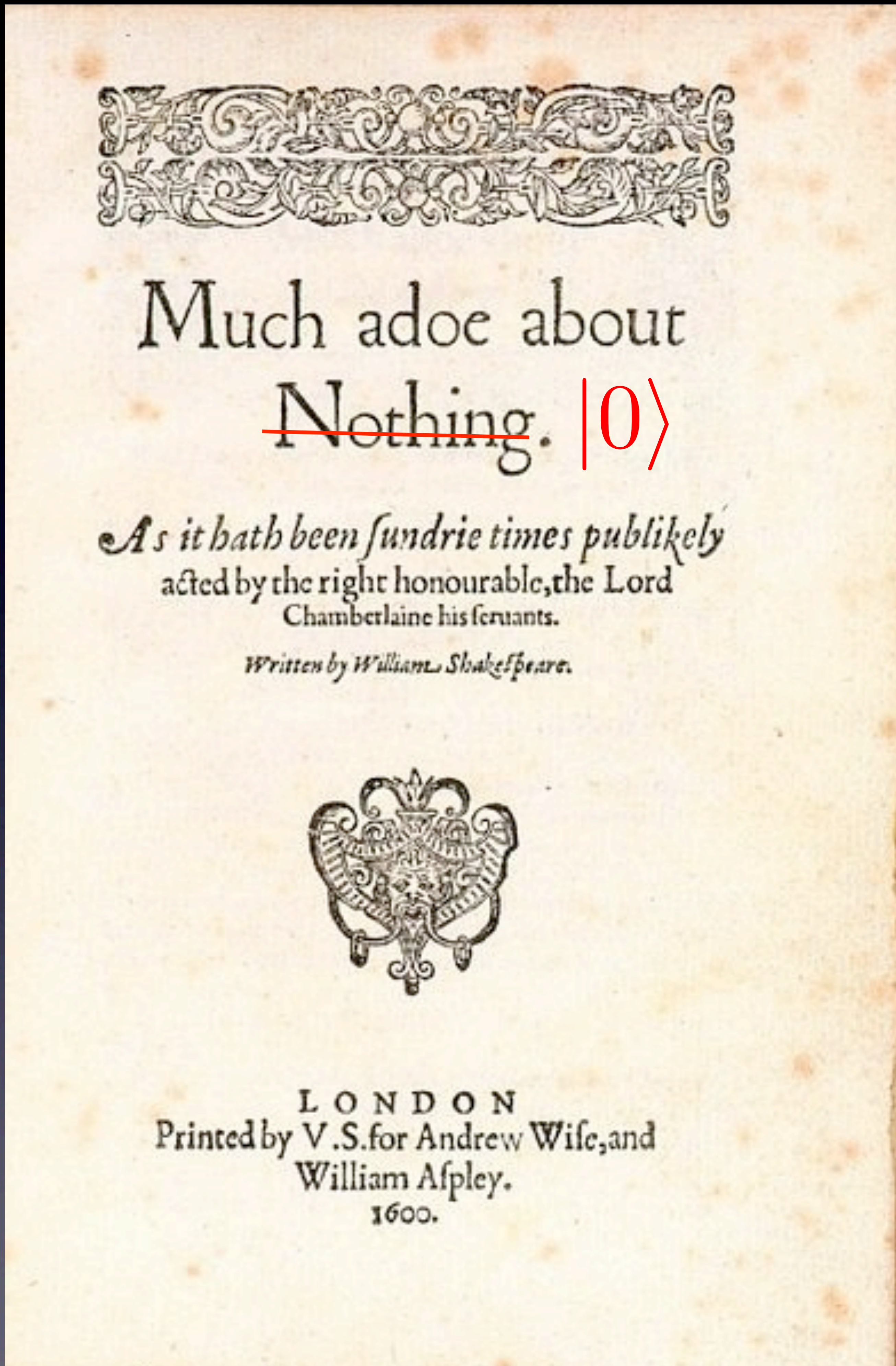

Much adoe about
~~Nothing~~. $|0\rangle$

As it hath been ſundrie times publikely
acted by the right honourable, the Lord
Chamberlaine his ſeruants.

Written by William Shakeſpeare.

LONDON
Printed by V.S. for Andrew Wiſe, and
William Aſpley.
1600.

A State of the Vacuum Address

SUPA

Jay Hubisz

11/7/2012

What is the vacuum?

The universe as “springs”

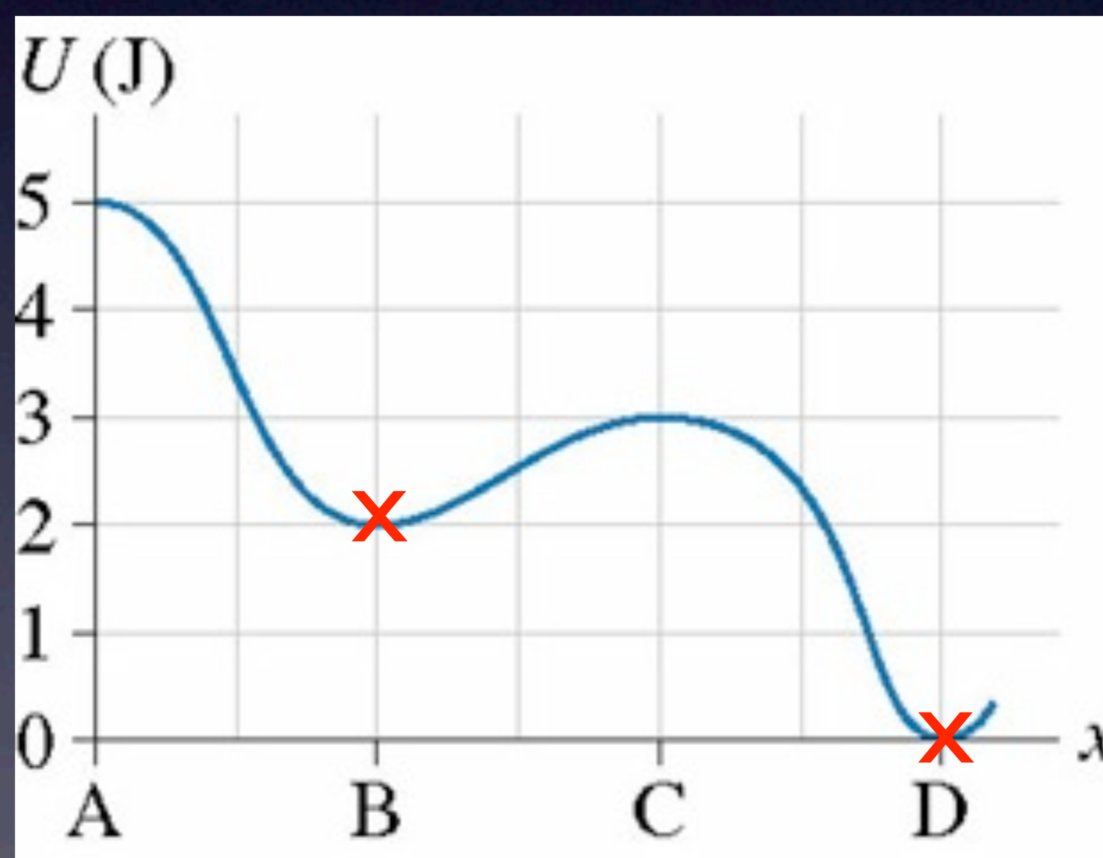
A system with a potential energy has a set of *stationary points*

Places where systems don’t move

Maxima/Minima of the potential

Near the minima, nearly all systems act like masses on springs!!

$$F = -kx$$

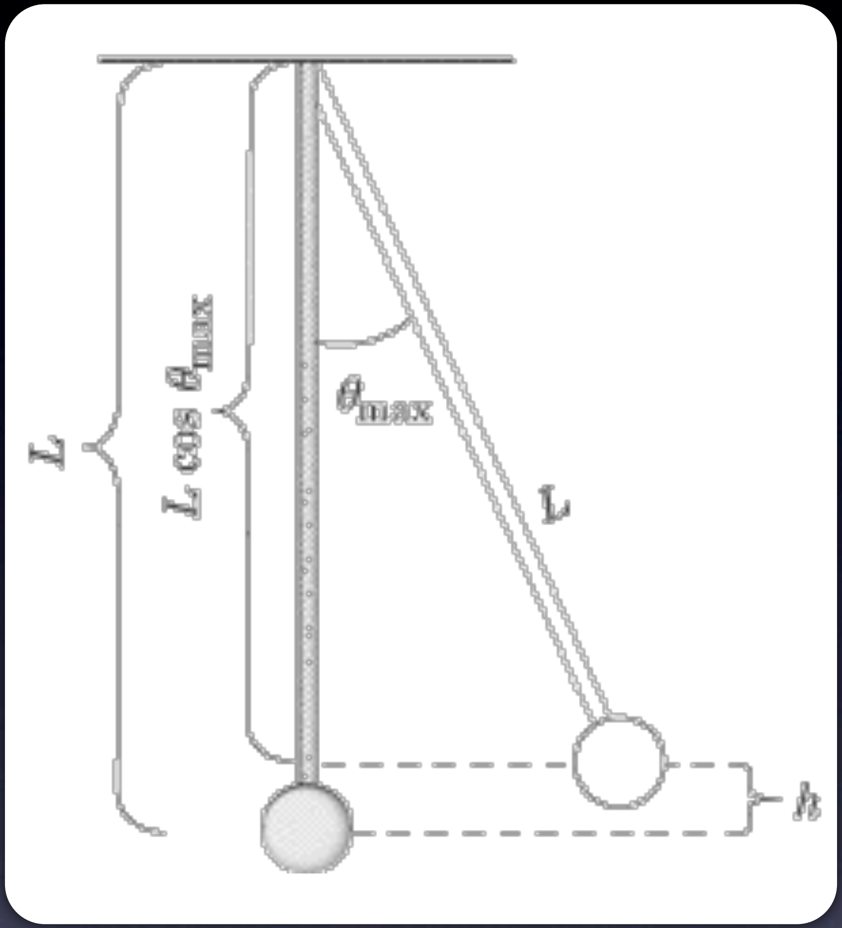


$$\frac{1}{2}kx^2$$

zero!

$$U(x_0 + \delta x) \approx U(x_0) + \cancel{\frac{dU}{dx}}(x_0)\delta x + \frac{1}{2}\frac{d^2U}{dx^2}(x_0)(\delta x)^2$$

The pendulum



$$U = mgh = mgL(1 - \cos\theta) \approx \frac{1}{2} mgL\theta^2$$

Quadratic in displacement near minimum!

Spring Theory

Generalizes to "smooth" systems

(string, gas, electromagnetic fields)
infinite set of masses with springs connecting them

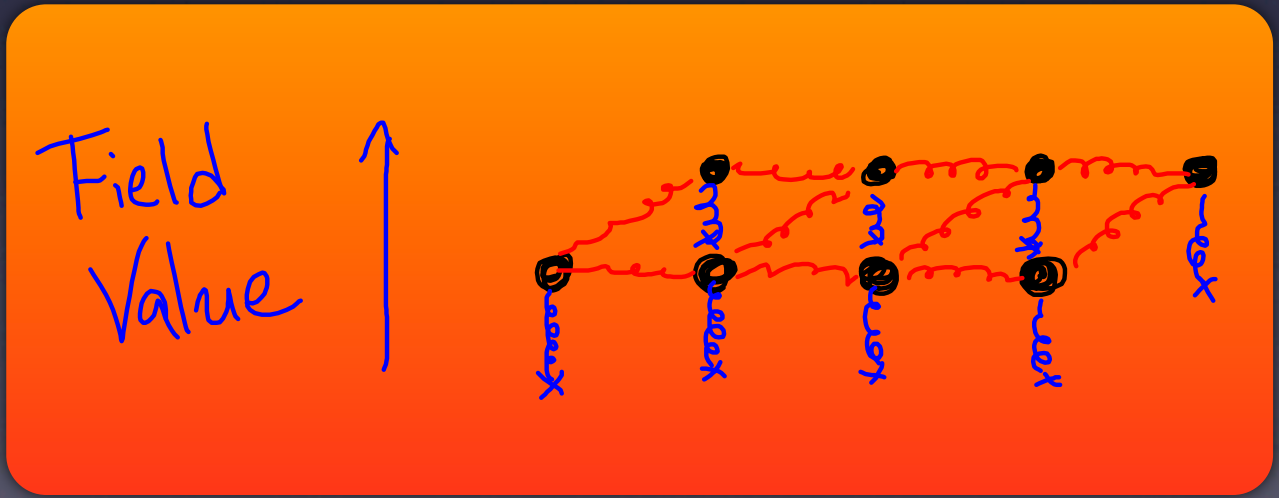
Field Theory

Particle physics is very well described by relativistic field theory

relativistic field - an infinite set of coupled quantum springs

one for each point in space-time

Only showing a 2D slice

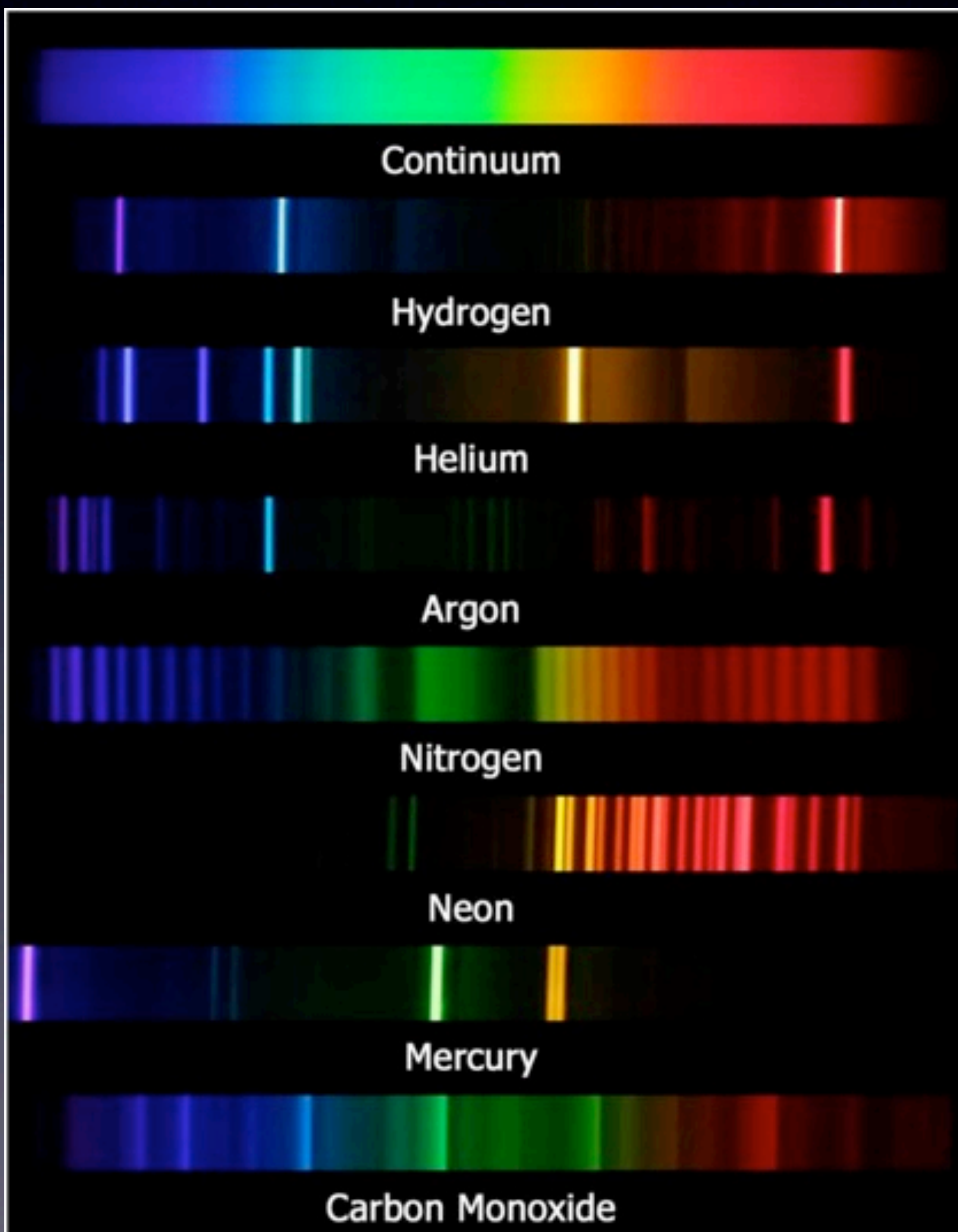


Blue springs - universal displacement

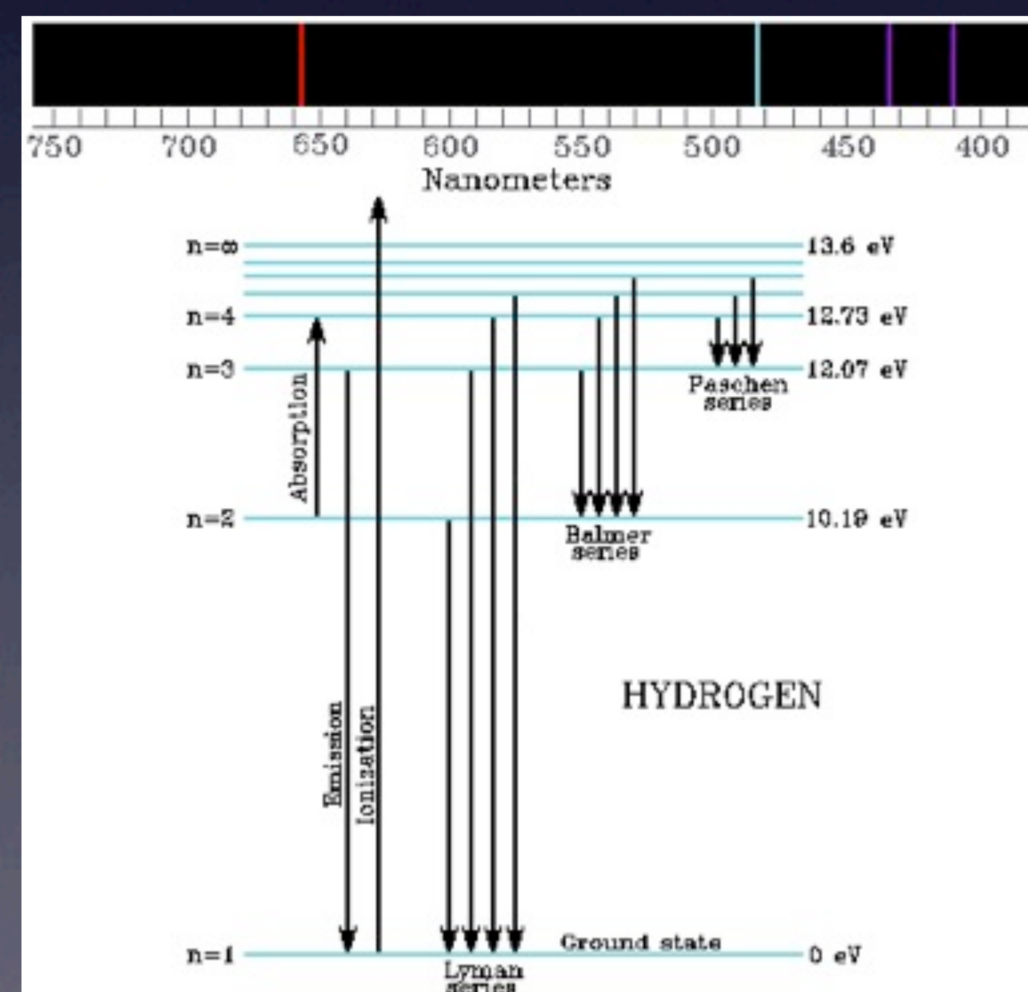
Red springs - nearest neighbor coupling

Quantum World

Recall the energy levels of atoms

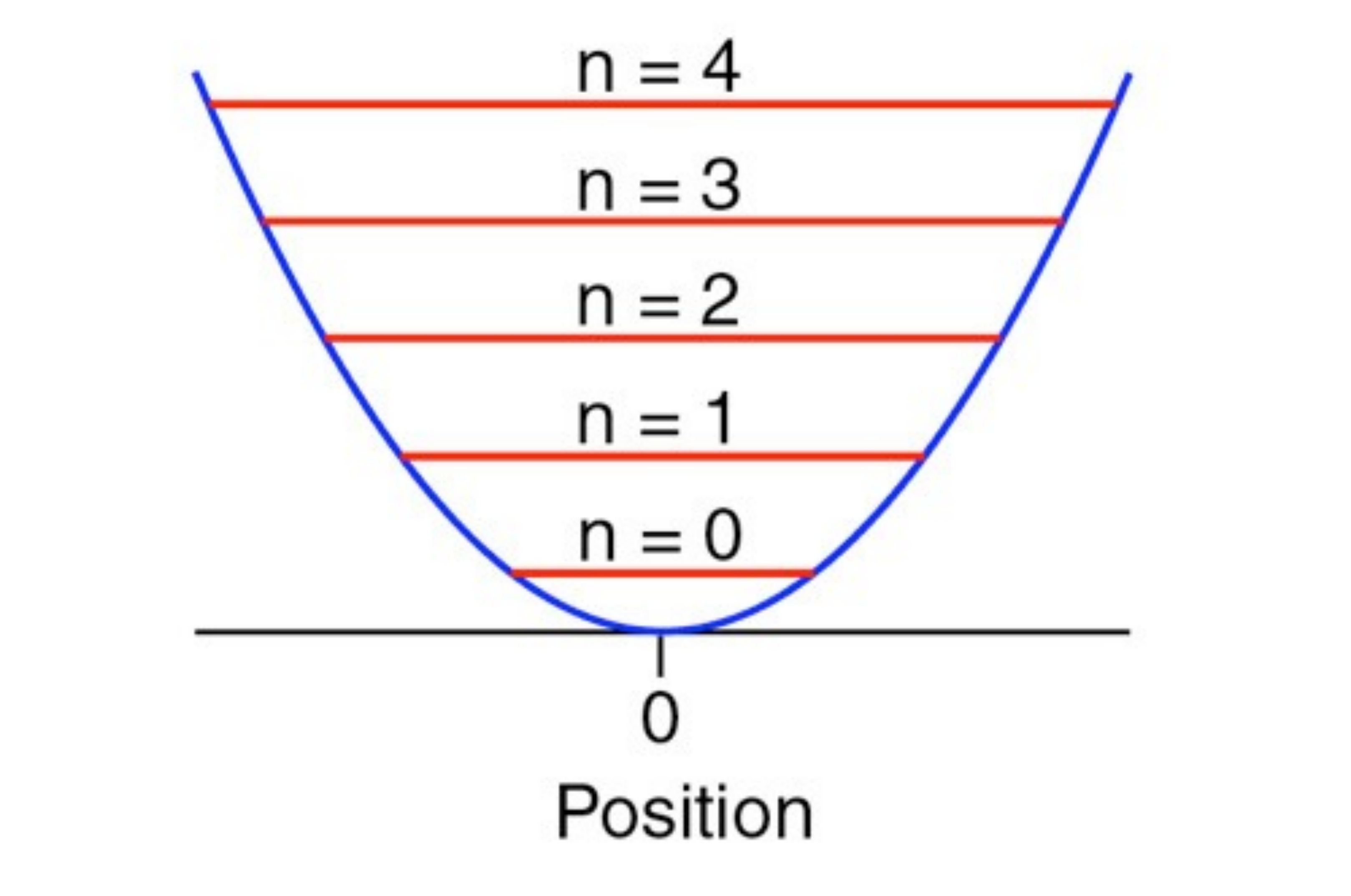


Pure samples of atoms emit light at very specific wavelengths/energies



Quantum springs

Much simpler than hydrogen



$$E = \frac{1}{2}\hbar\omega(n + 1/2)$$

Allowed energies are evenly spaced!

The Vacuum

There are many different quantum fields in the Standard Model

Many oscillators at each coordinate

The vacuum is the state in which every spring, at every spacetime point, is in its own ground state

(zero particle state - no wiggles of the fields)

We characterize this vacuum state by the field content and with a description of the equilibrium position of the fields

The Standard Model

Building a Field Theory

We start with the symmetries of special relativity

We only add fields that have well-defined behavior under these transformations

Simplest ones are:

Scalar fields → spin-0 particles

Spinor fields → spin-1/2 particles (fermions)

massless LH and RH

- can join them to make 1 massive

Vector fields → spin-1 particles A^μ μ=0,4

vectors have 4 components

We construct a theory from these fields that obeys Einstein's theory of special relativity

The Standard Model Fermions

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

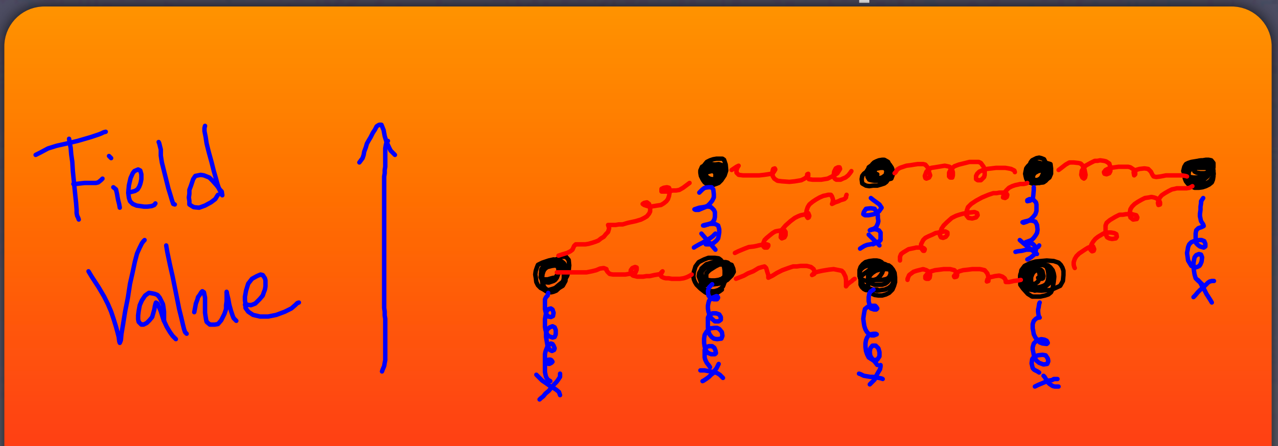
Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Their masses span an enormous range! ~12 OOM



masses are values of blue spring constants

Standard Model Bosons

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

These three are massive!

Their mass sets the distance at which the weak interaction ‘turns off’

These are all spin-1 (vector fields)

Gauge invariance

In electromagnetism:

Can shift the photon by derivatives of an *arbitrary* function of t,x,y,z without changing *anything*

$$A^\mu \to A^\mu + \frac{\partial}{\partial x^\mu}\alpha(x)$$

E and B-fields (which come from A) remain the same

If this were not the case, we could never have a "quantum" photon!

Gauge Invariance & Mass

Vectors have a problem

A^t has "negative norm"
Means negative probabilities :-(

NONSENSE

That's Bad!

electromagnetism is gauge invariant

A^t never appears anywhere in quantum case!

That's Good!

Theory *must* be gauge invariant

conserved charges

Mass term: $m_A^2 A^\mu A_\mu$
Not gauge invariant - neg norm states creep in and wreck the theory

That's Bad!

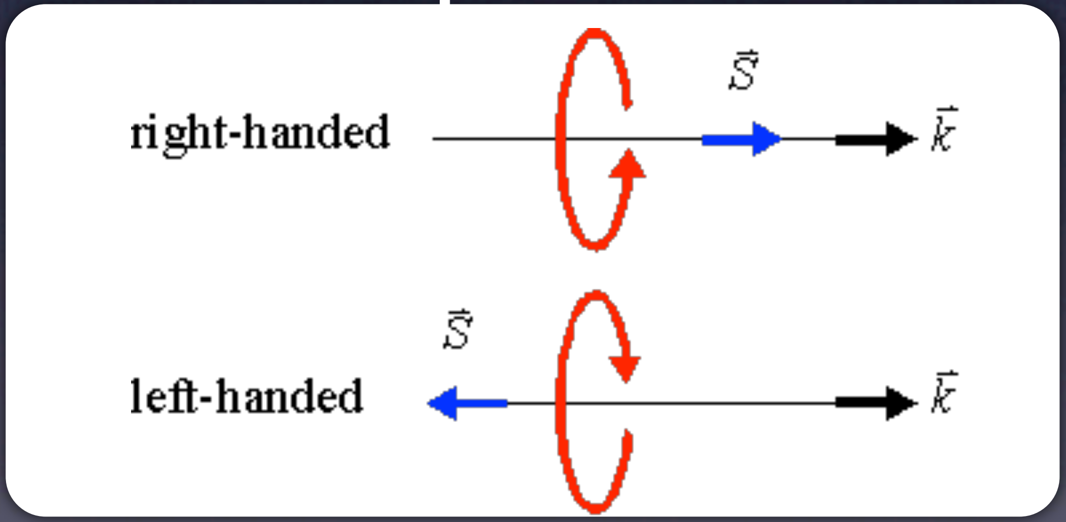
Parity

Under a parity transformation, we look at the universe through a mirror

$$x \to -x, \quad y \to -y, \quad z \to -z$$

Massless fermions move at speed of light

Can use right-hand-rule to see if spin is parallel or anti-parallel to the direction of the velocity



$$\vec{L} = \vec{r} \times \vec{p}$$

Both flip sign under parity! L doesn't change

But overall velocity flips sign!

Parity turns RH fermion into LH fermion

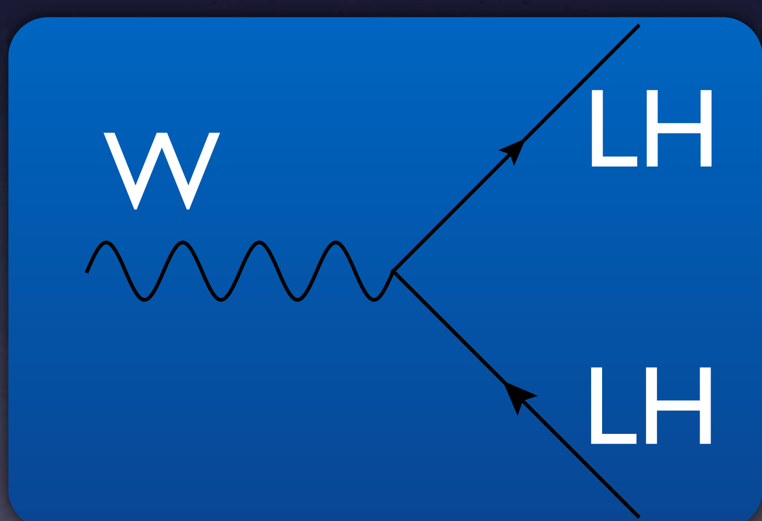
Charges and mass

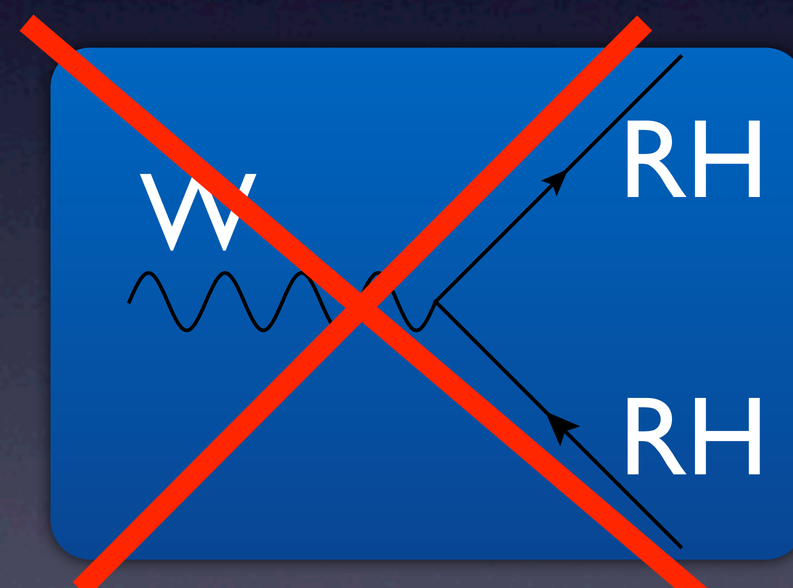
There are conserved charges for the weak and strong forces

some fermions carry these, some don't

As Lee and Yang postulated, and Wu showed to be the case experimentally, the weak interactions badly violate parity

Text



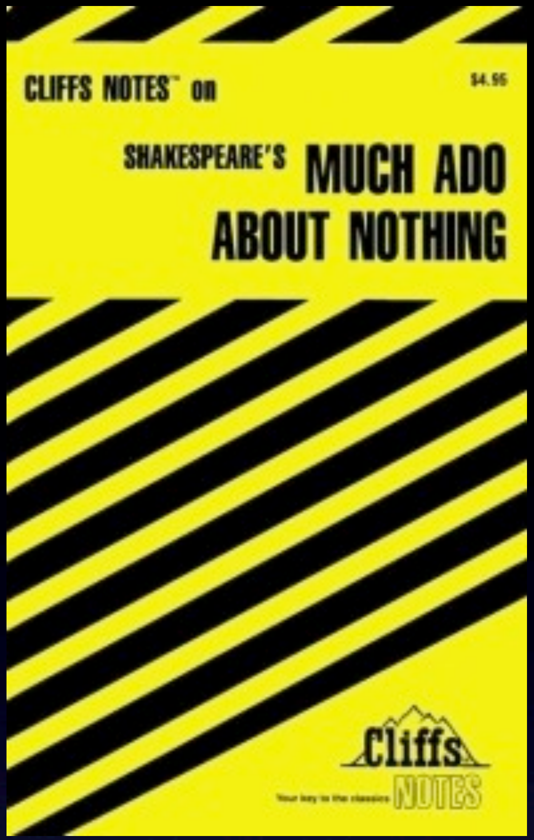


In SM - All LH spinor fields carry weak charge, RH fields do not

$q_L \neq 0$

fermion mass term: $m_f \psi_L \psi_R$ mass term violates charge conservation/G.I.

$q_R = 0$

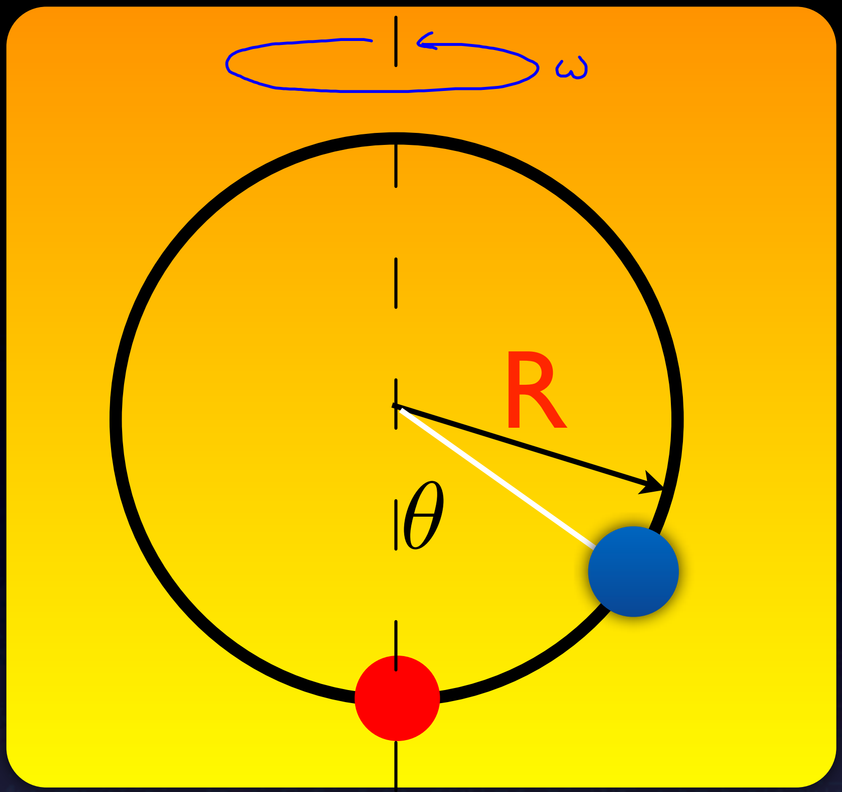


Cliff's Notes

- Quantum field theory - infinite collection of masses on springs
- Vacuum - state in which all springs are in their ground state
  - characterized by field content, minima of potential
- standard model fields spin-1 and spin-1/2
- gauge invariance required for sensible predictions
  - forbids any mass terms!

INTERMISSION

James Watt's Governor



Bead sliding without friction on spinning hoop in uniform gravitational field - can be done with FBD

$$\ddot{\theta} = -\omega^2 \sin\theta \left(\frac{g}{\omega^2 R} - \cos\theta \right)$$

Find the stationary points!
(values of θ for which the RHS is zero)

Stationary points

Find the stationary points

$$\ddot{\theta} = -\omega^2 \sin\theta \left(\frac{g}{\omega^2 R} - \cos\theta \right)$$

2 easy ones:

$$\sin\theta = 0 \implies \theta = 0, \pi$$

bottom top

What about these?

$$\cos\theta = \frac{g}{\omega^2 R}$$

Can only occur when:

$$\frac{g}{\omega^2 R} \leq 1$$

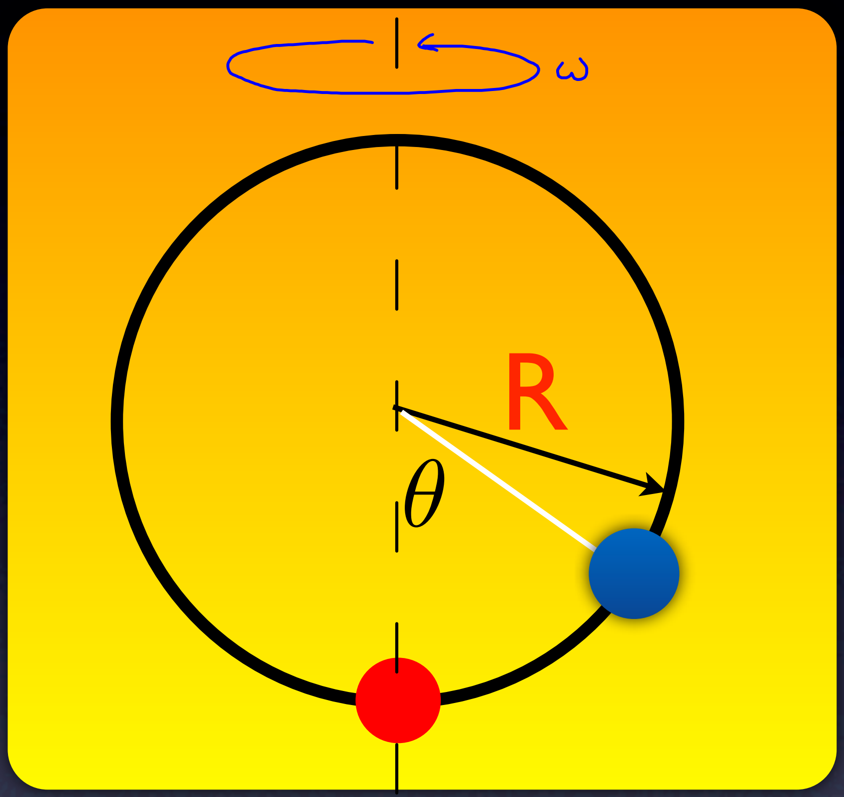
Critical value of ω over which behavior changes drastically!

Many stationary points

Two Scenarios:

Small ω	Big ω	
$\theta = \pi$ Unstable	$\theta = \pi$ Unstable	$\theta = \pm \arccos \frac{g}{\omega^2 R}$ Stable!
$\theta = 0$ Stable	$\theta = 0$ Unstable!	

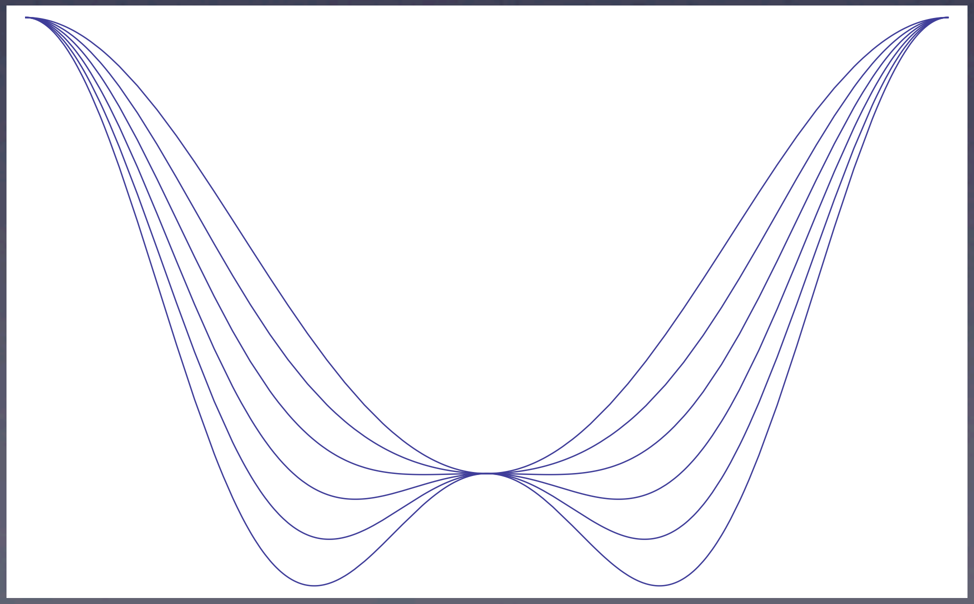
The Governor



As omega grows, one stable stationary point passes criticality - bifurcates into one unstable, two stable stationary points

"BROKEN" L-R SYMMETRY

Potential energy



The Higgs Field

In the standard model without a Higgs field, there are NO MASS TERMS

Such mass terms violate the conservation laws for the charges associated with the electromagnetic and weak forces - gauge invariance broken (negative probabilities!)

Higgs field is different! - H can have charge AND mass

$$m^2 H^\dagger H \to m^2 H^\dagger e^{-i\alpha(x)} e^{i\alpha(x)} H = m^2 H^\dagger H$$

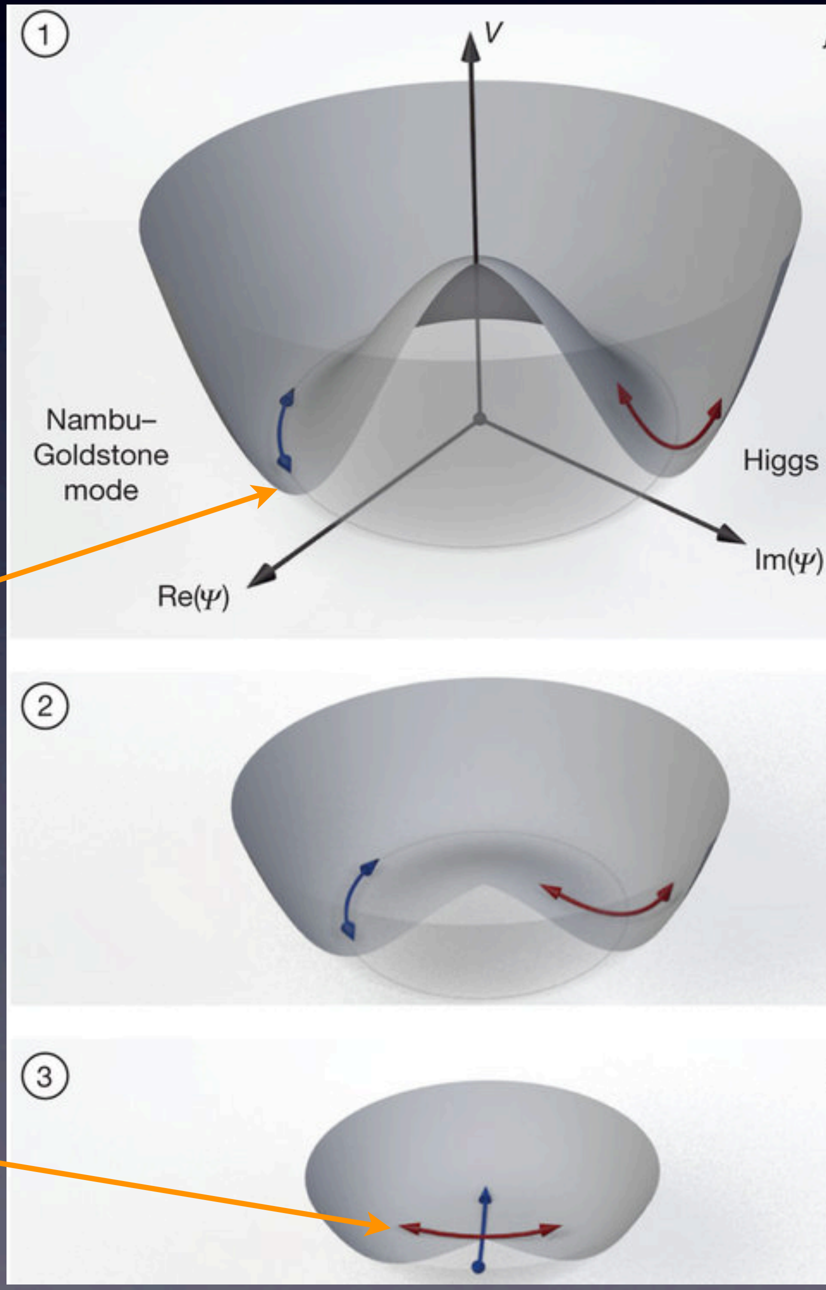
The Higgs *just has* a mass
it does not come from somewhere else
(at least not in the Standard Model)

The Higgs Potential

In fact, it has more than just a mass - it has a full potential

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

As you vary μ, you get very different behavior!



$\mu^2 > 0$, minimum away from H=0

$$|H|^2_{\min} = \frac{\mu^2}{2\lambda}$$ "vacuum expectation value"

$\mu^2 < 0$, minimum at H=0

Higgs interactions

Can add gauge invariant interactions with H

$$\lambda H \psi_L \psi_R \qquad q_H = -q_L; \quad q_R = 0$$

$$e^2 |H|^2 A_\mu A^\mu$$

When H finds its minimum, and everything is SHO's again:

$$\boxed{\lambda v \psi_L \psi_R} + \lambda h \psi_L \psi_R + \pi \text{ stuff}$$

mass!

$$\boxed{e^2 v^2 A_\mu A^\mu} + 2e^2 v h A_\mu A^\mu + e^2 h^2 A_\mu A^\mu + \pi \text{ stuff}$$

mass!

The gauge invariance is still there, manifest in the shift symmetry of π - this dof accounts for 3rd polarization

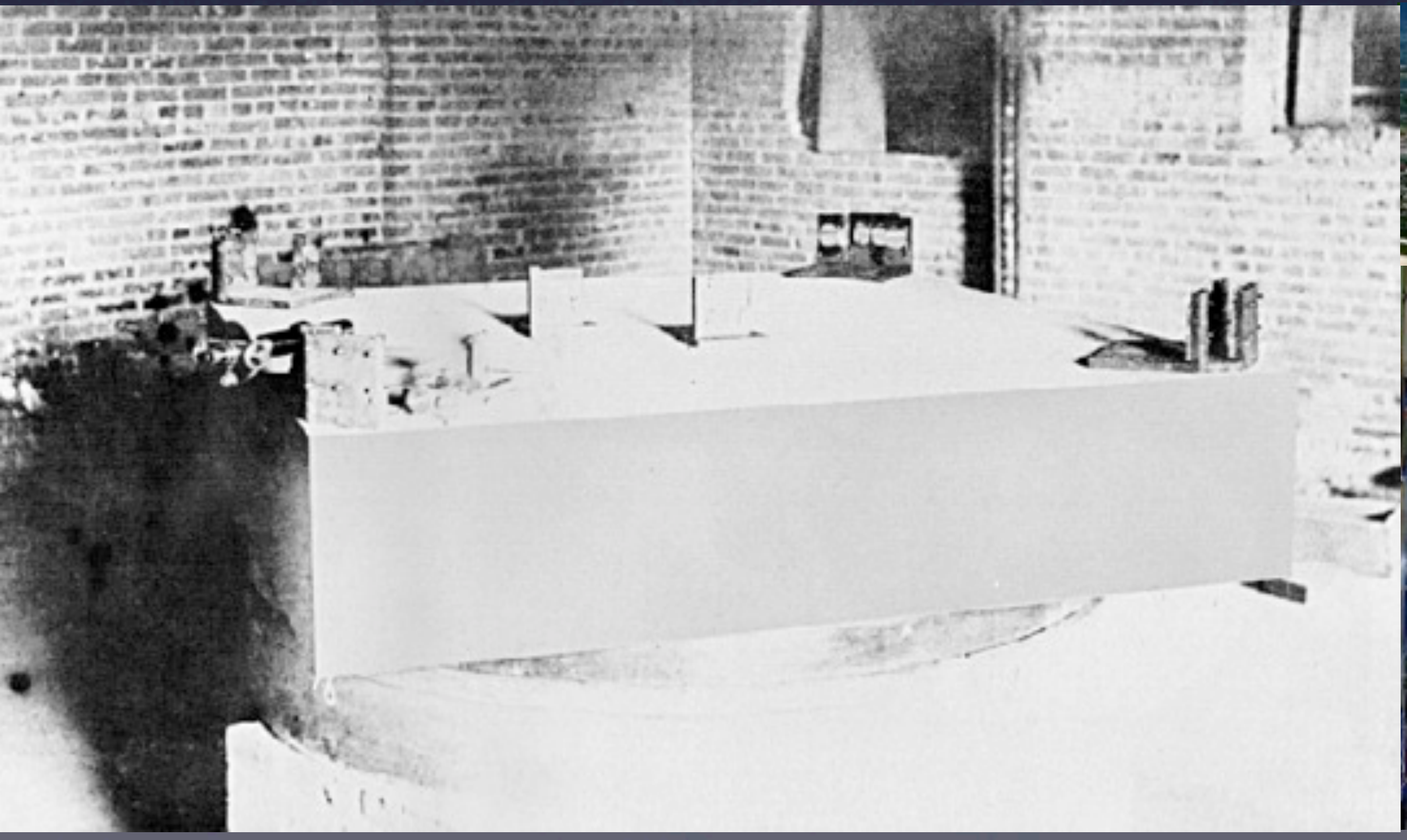
Ether 2.0

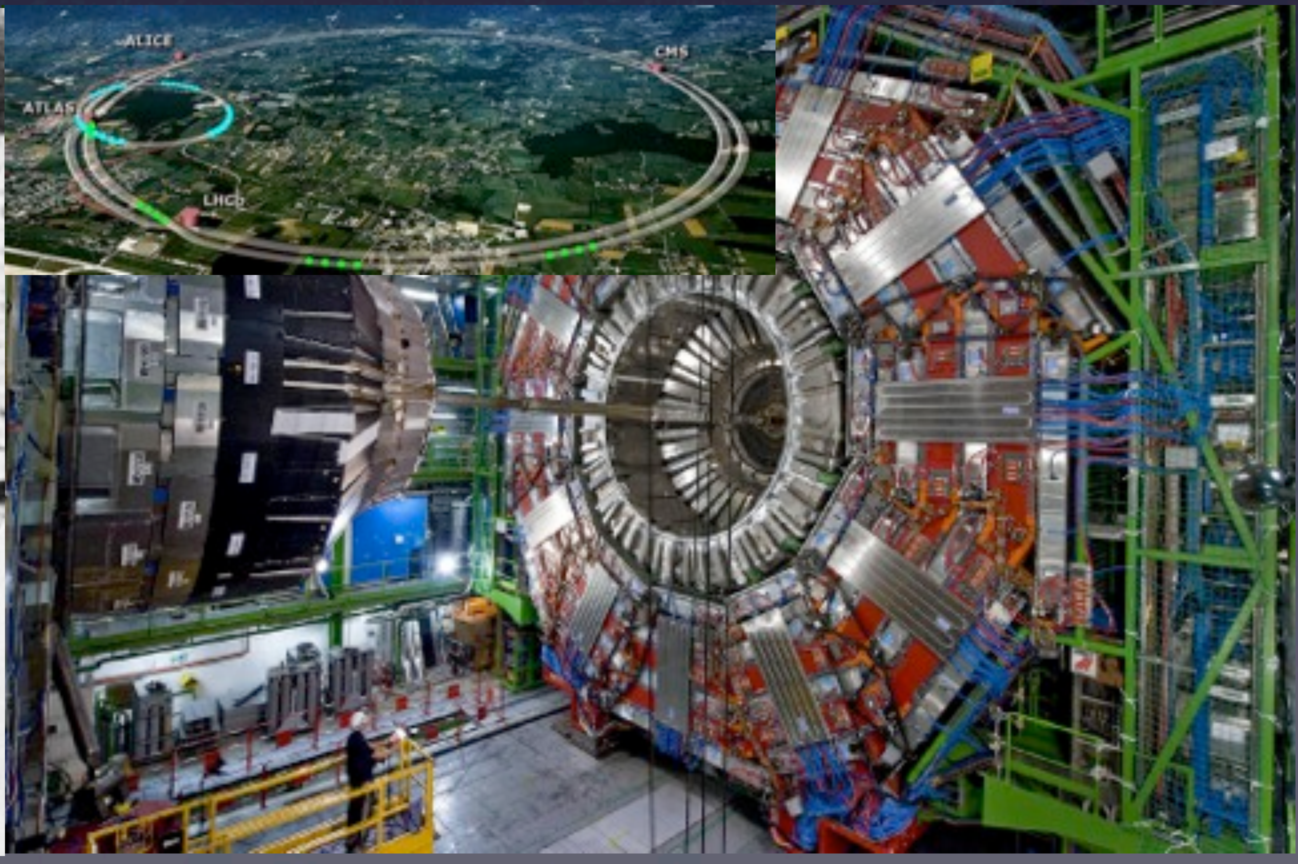
The stationary point for H is away from 0
the charge of the vacuum is non-vanishing!

Empty space-time is filled with charge
a form of 'ether' consistent with Einstein's special relativity

higgs particles are wiggles of this ether

The LHC is in part a (massively) upgraded ether inspector





The Higgs Interactions and Decays

Higgs to taus

$$m_\tau \bar{\tau}\tau \implies \frac{m_\tau}{v} h\bar{\tau}\tau \implies h \to \bar{\tau}\tau$$

Higgs to b's

$$m_b \bar{b}b \implies \frac{m_b}{v} h\bar{b}b \implies h \to \bar{b}b$$

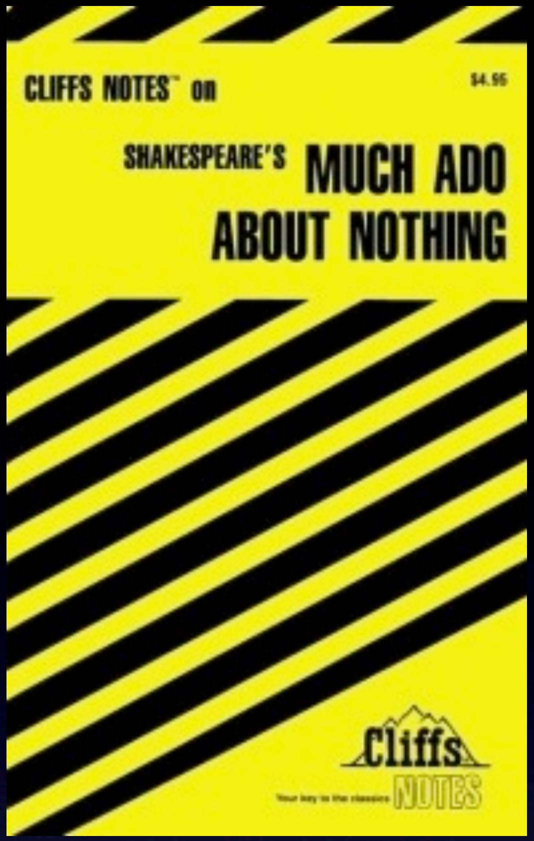
Higgs to Z's

$$m_Z^2 Z_\mu Z^\mu \implies 2\frac{m_Z^2}{v} hZ_\mu Z^\mu \implies h \to Z^* Z \to 2l^+ 2l^-$$

Higgs to W's

$$m_W^2 W_\mu^+ W^{-\mu} \implies 2\frac{m_W^2}{v} hW_\mu^+ W^{-\mu} \implies h \to W^+ W^- \to l^+ \nu l^- \nu$$

Bottom Line: Once you have the masses, you know exactly how the Higgs will show up



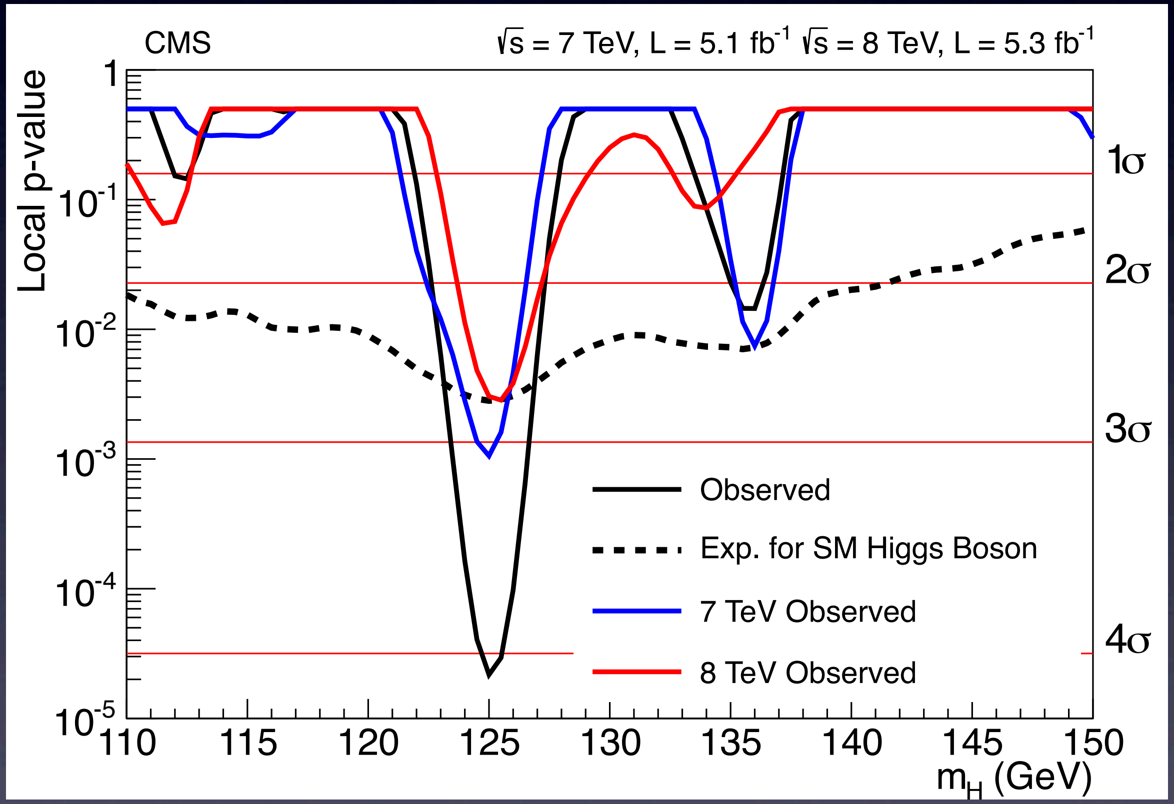
Cliff's Notes

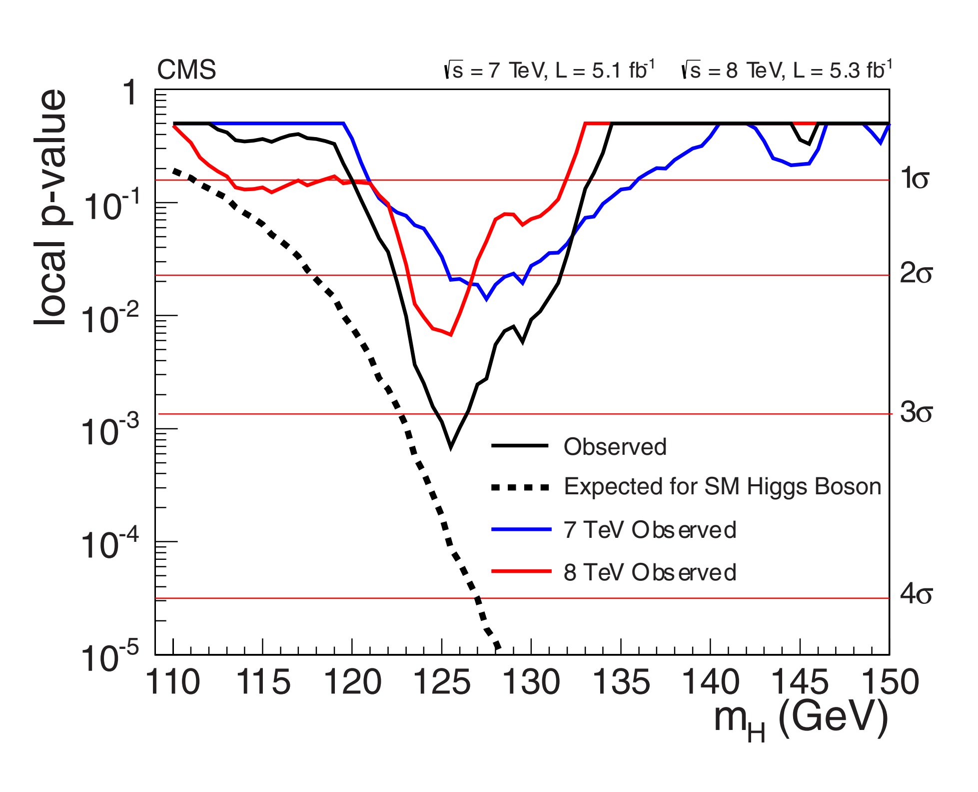
- The Higgs mechanism is a gauge invariant method of generating masses for standard model fields
- It predicts a Higgs particle - wiggles in the ether
- It is extremely predictive, once you measure the masses

One More Boson!

The July 4th "revolution"

CMS Higgs Discovery at ~125 GeV



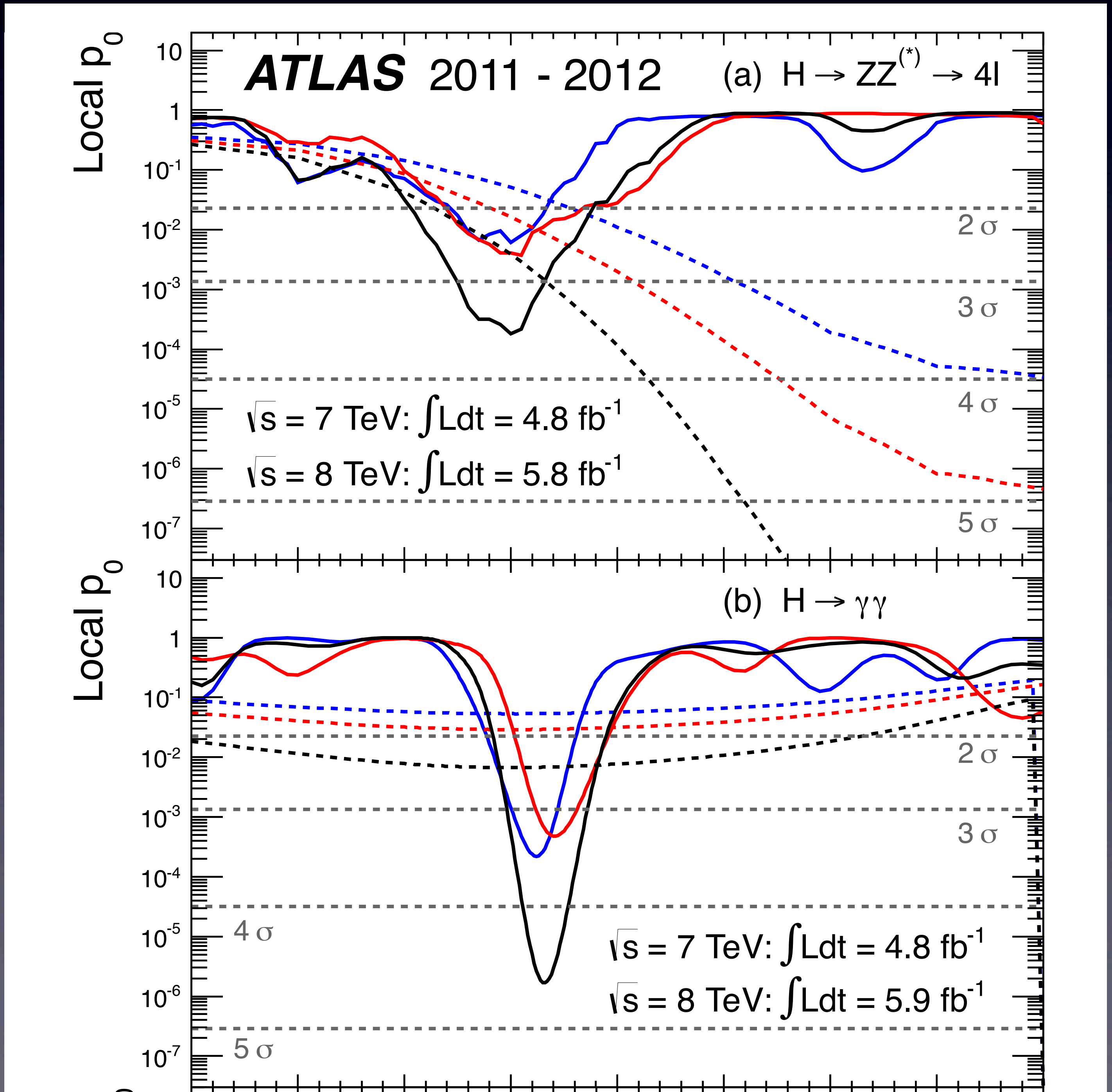


$h \rightarrow \gamma\gamma$ $\qquad$ $h \rightarrow ZZ^* \rightarrow 2l^+2l^-$

These are high resolution channels - low resolution push it beyond 5 sigma

One More Boson!

ATLAS Higgs Discovery

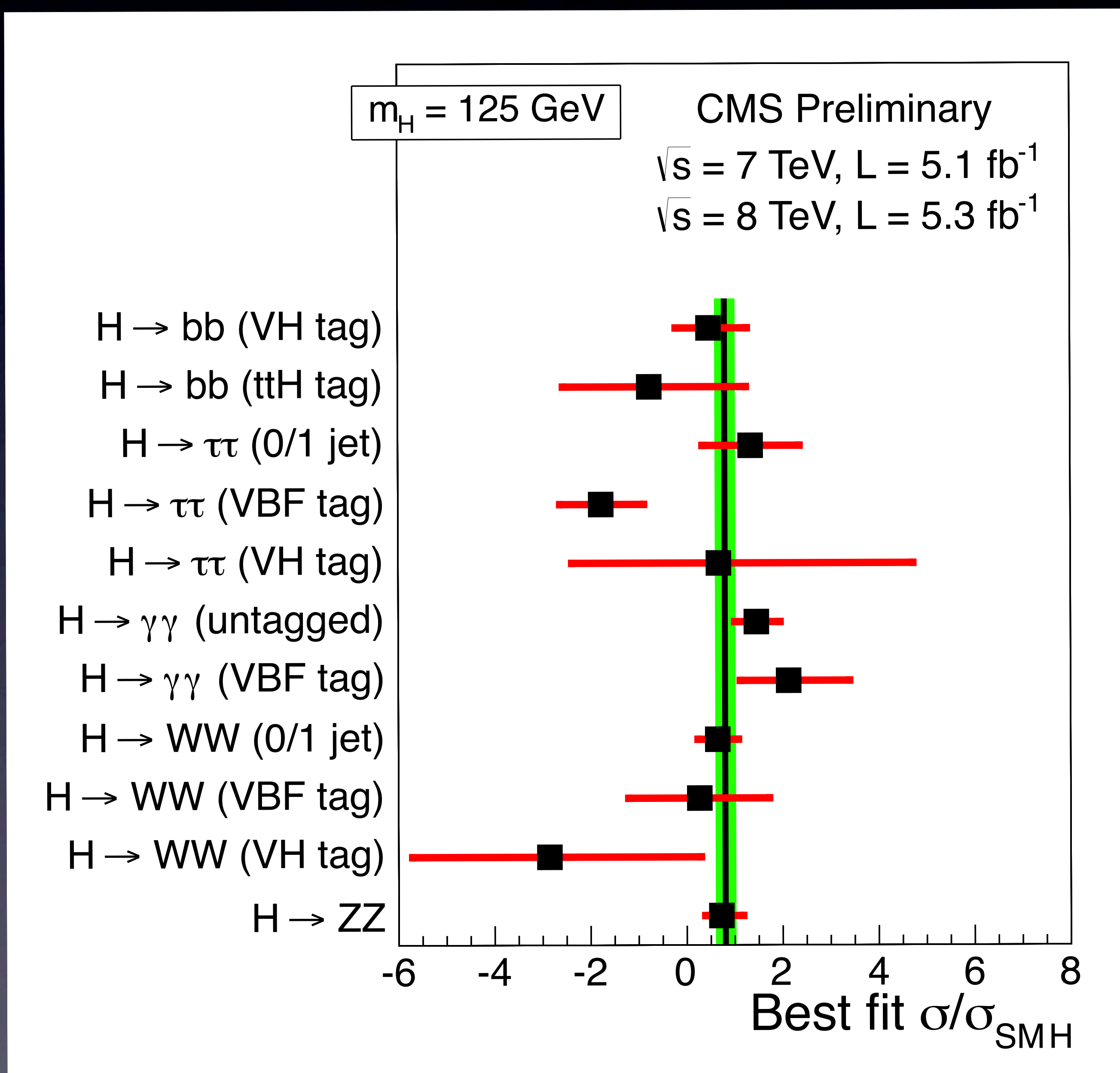


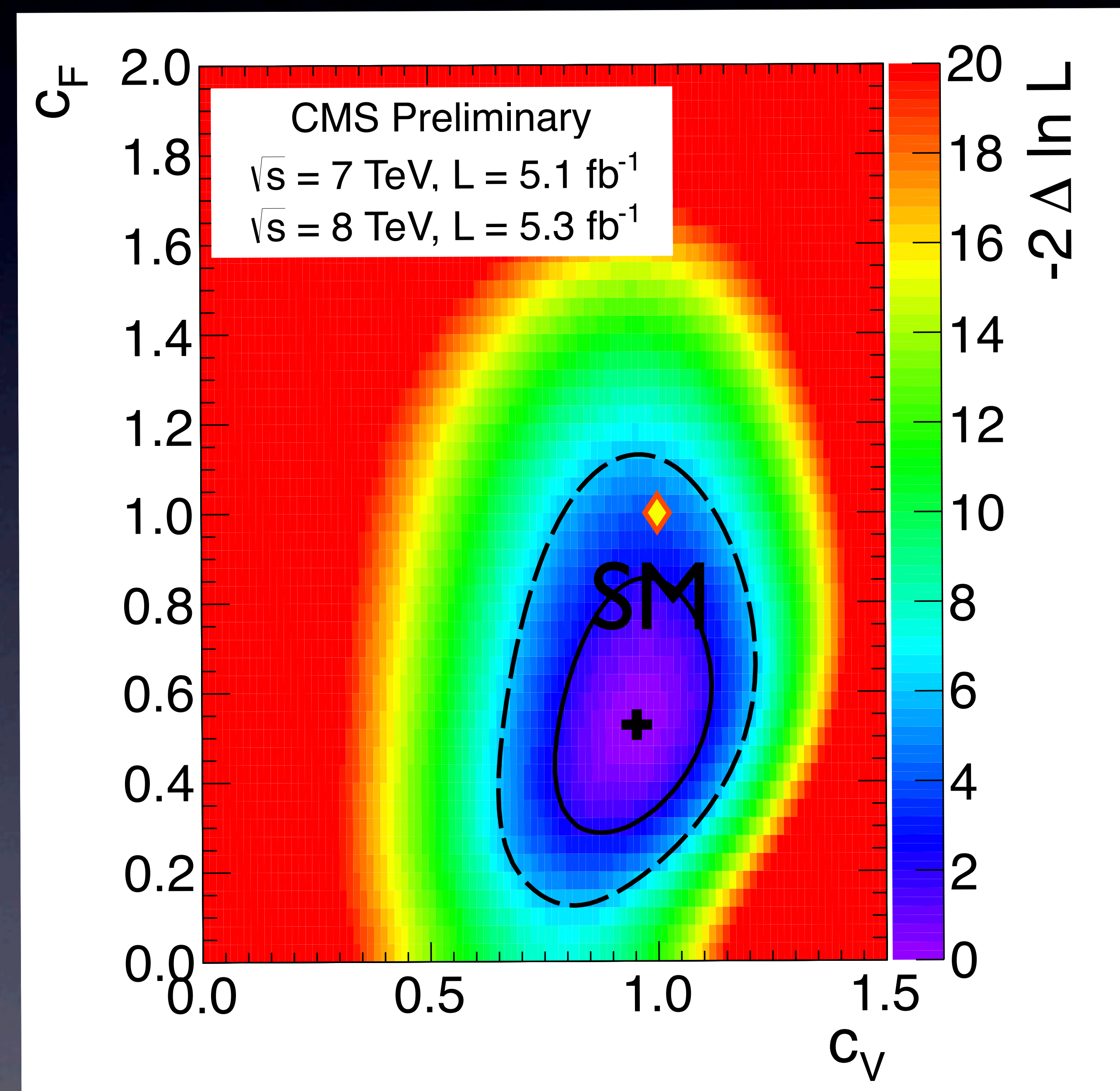
$$h \to ZZ^* \to 2l^+2l^-$$

$$h \to \gamma\gamma$$

Higgs fit - CMS

Is it the Higgs of the Standard Model?



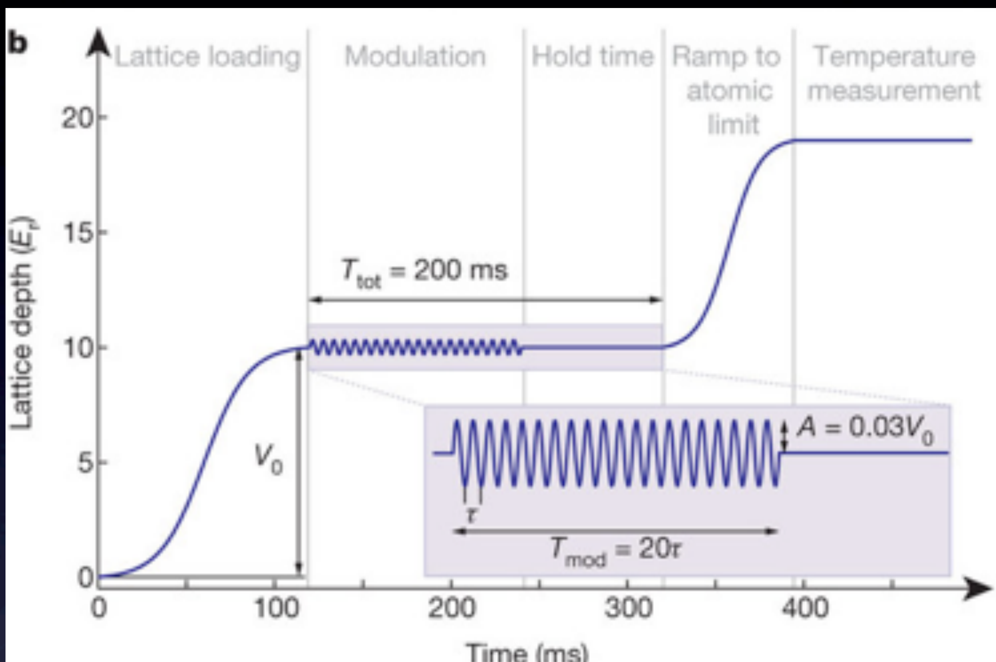


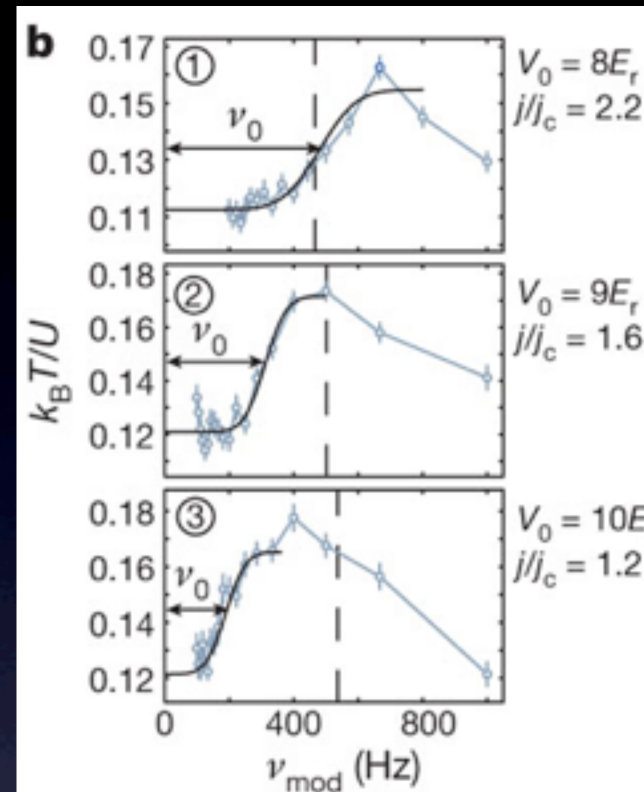
We have many reasons to believe the answer is NO.

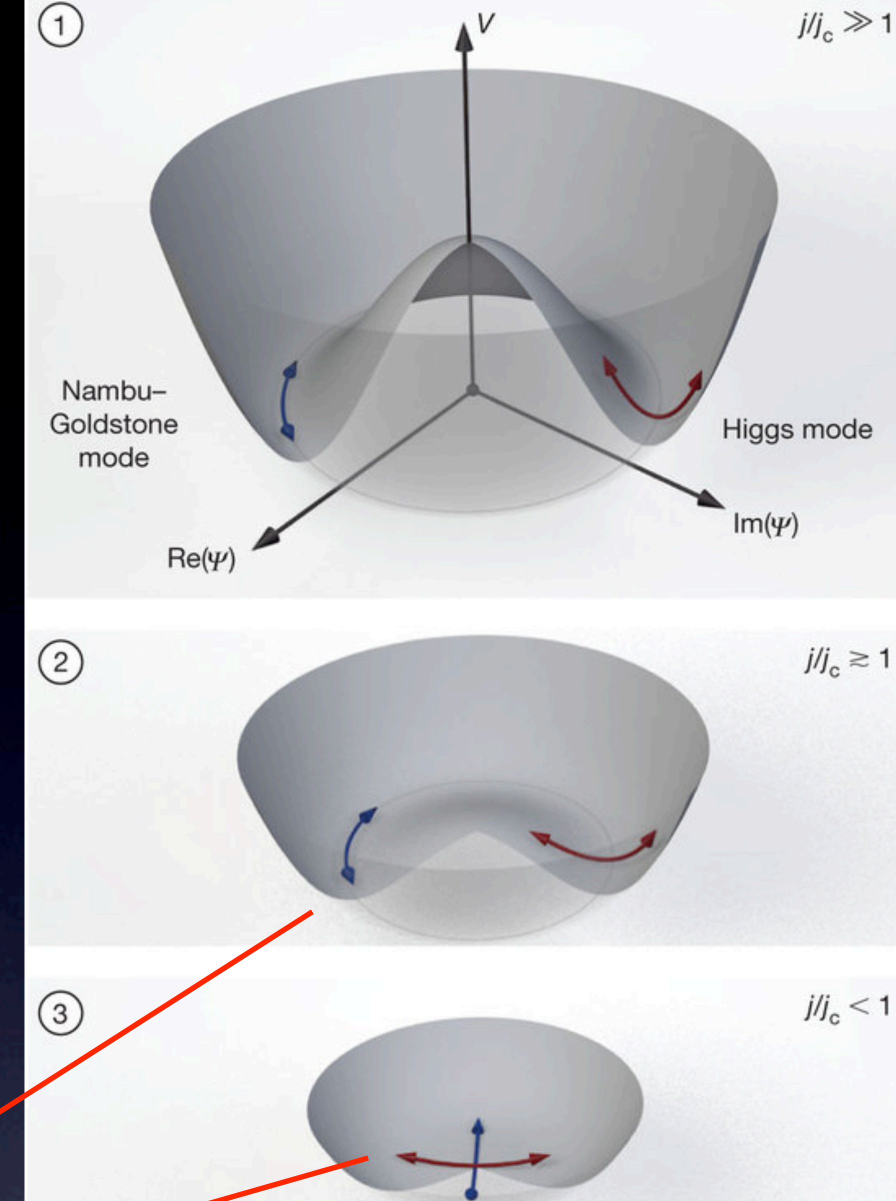
The Particle you love to hate

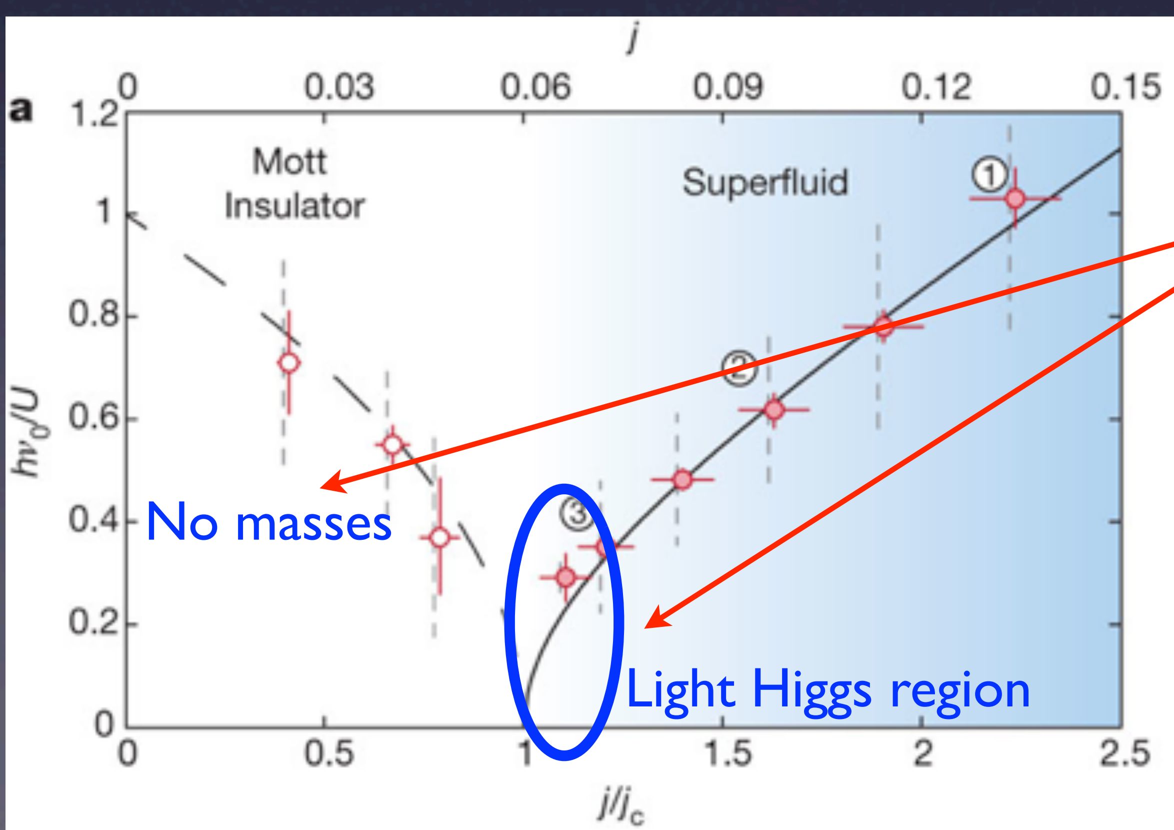
Fine Tuning

In the lab, you get to play "God":









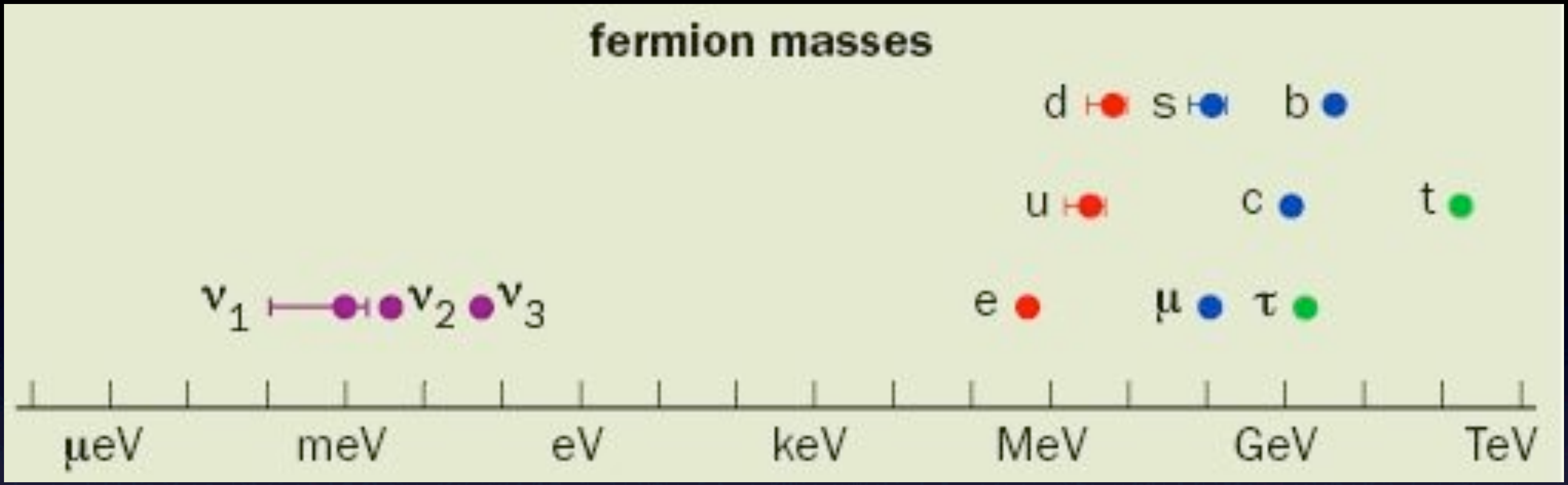
In particle physics:

$$\frac{j}{j_c} - 1 \sim 10^{-32} \sim \left(\frac{M_{\rm weak}}{M_{\rm planck}}\right)^2$$

Masses would generically be of order $M_{\rm Planck}$ or $M_{\rm GUT}$

Nature **487**, 454–458 (26 July 2012)

Fermion masses

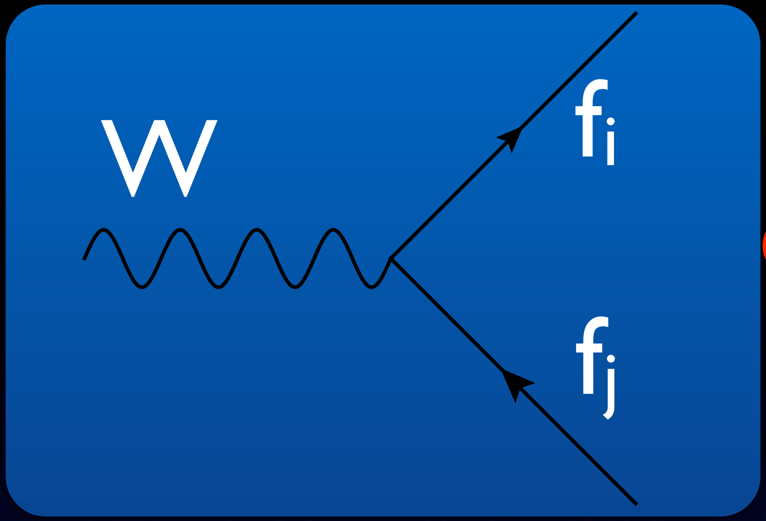


These come from the Higgs

$$\sum \lambda_{ij} H \psi_L^i \psi_R^j$$

Values are all over the map!! WHY?!

"Flavor physics"



e.g. top-bottom, top-strange, top-down

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

$$J = (2.91^{+0.19}_{-0.11}) \times 10^{-5}$$

This is close to the identity matrix, and very hierarchical off-diagonals quantify amount of flavor changing in weak force

More small numbers!!

Strong CP Problem

QCD generically violates Time reversal (or “CP”)

neutron electric dipole moment - sensitive to both strong and weak CP violating phases

$\bar{\theta} = \theta - \arg\det M_q$ This part is from the Higgs!

must be $< 10^{-11}$!

Yet another inexplicably small number!

Cosmological Constant

Universe is expanding, and that expansion is *accelerating*

Explained by presence of small "cosmological constant"

Energy density that permeates all space

$$\Lambda_{cc} \simeq (10^{-12}\ \mathrm{GeV})^4$$

Higgs contributes $\simeq (10^2\ \mathrm{GeV})^4$

55 orders of magnitude too big!!??

What does the Higgs not do?

- It doesn't give masses of order M_{Planck}
  - It should
- It doesn't give huge contribution to cosmo. constant
  - It should
- It doesn't give huge contribution to strong CP violation
  - It should
- It doesn't give generically large flavor changing couplings
  - It should
- It doesn't give fermions masses of the same scale
  - It should

It’s getting to be a bit much

I can hold up the cup
And the milk and the cake!
I can hold up these books! And the fish on a rake!
I can hold the toy ship! And a little toy man!
And look! With my tail I can hold a red fan!
I can fan with the fan As I hop on the ball!
But that is not all. Oh, no. That is not all....

Add to this:

- It doesn’t explain dark matter, which we KNOW is there
- More ingredients are necessary for neutrino masses
- Not enough CP violation for baryon assymetry
- ...

Is it *THE* Higgs?

Don Pedro: ... I think this is your daughter.
Leonato: Her mother hath many times told me so.
Benedick: Were you in doubt, sir, that you ask'd her?

What is the 'parentage' of the Higgs particle?

Have we tested all the ways that the ether wiggles?

Supersymmetry

Higgs comes with opposite spin partners

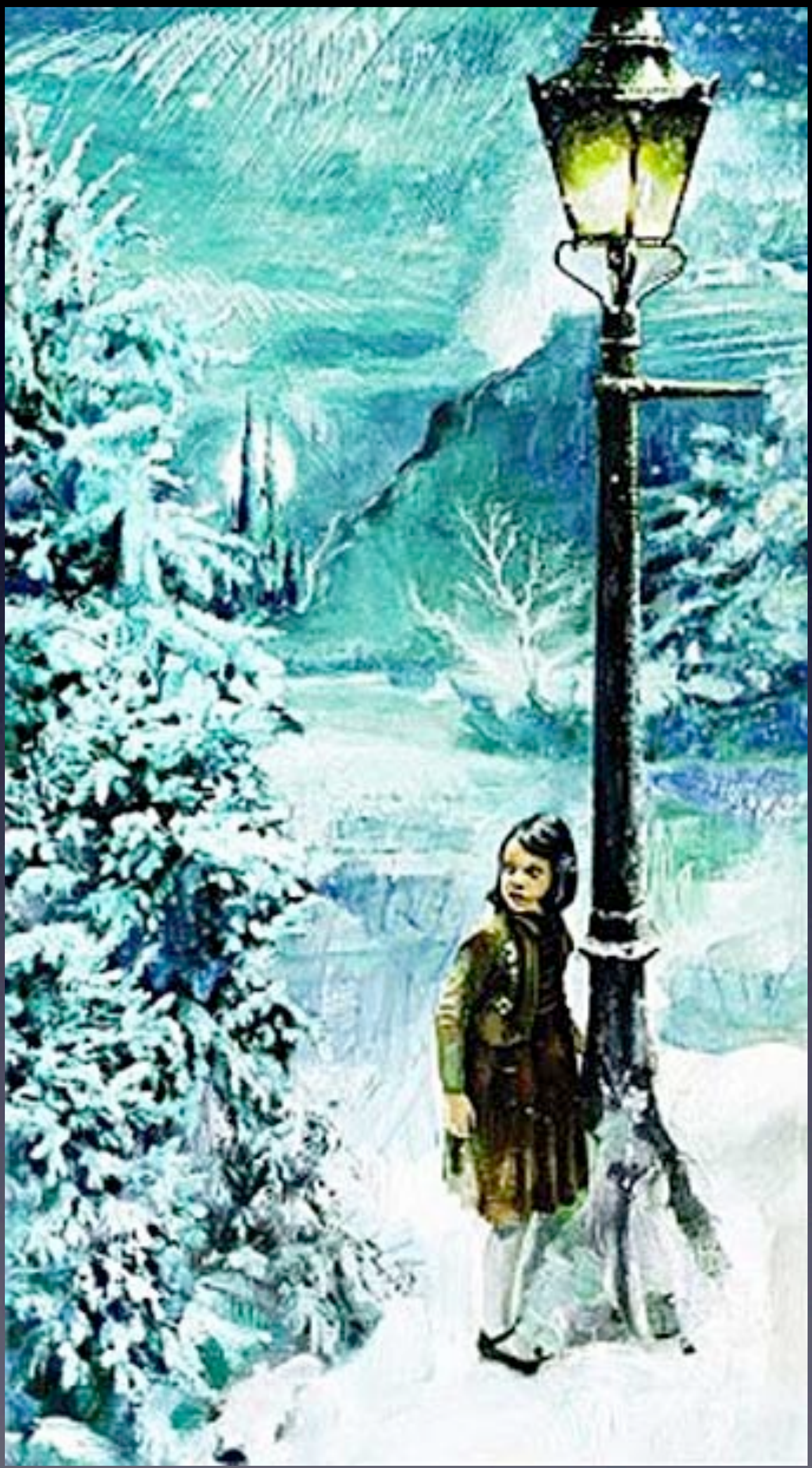
Composite Higgs

Higgs is made of other stuff

Combination of both?

The Lamp Post "problem"

Beatrice: I have a good eye, uncle; I can see a church by daylight.



We're great at seeing the things that are easy to see...

"spring" theory has been our guide

is the spring paradigm overstretched?

In some instances, we have been able to brighten the lamp...

rephrase strongly coupled theory in terms of weakly coupled one

Beyond standard model lattice studies vitally important!

(put space and time on the computer)

Conclusions

- We've likely found some ripples in an electroweak ether
  - have we found all of them?
- Many serious issues of the SM remain unsolved
  - the ether likely needs another upgrade