Why is it so hard to unify QM and GR?

Eugene A. Lim

KING'S College LONDON

New Scientist Live : Instant Expert

The Devil is in the details...

Unification

We want to *combine* the rules of Quantum Mechanics and General Relativity.

To understand the obstruction, we will learn about some wonderful consequences of **Quantum Mechanics**, **Special Relativity** and **General Relativity**.

The Devil is in the details...

A Personal Mandate

Rule #1: I will try to be as accurate as possible.

Rule #2 : If I gloss over things, I will tell you.

The Ingredients

Quantum Mechanics Rule 1 :

Heisenberg Uncertainty Principle

Quantum Mechanics Rule 2 :

Everything that can happen have a chance of happening

Special Relativity :

$E = mc^2$ *Energy is mass*

General Relativity :

You can make Black Holes by putting a lot of stuff in a small space.

Quantum Mechanics

Heisenberg Uncertainty Principle
Popular Version

You cannot *simultaneously* measure the momentum and the position of a particle to arbitrary accuracy.

Quantum Mechanics

Heisenberg Uncertainty Principle
"The Interest-Free Loan Version"

You can borrow free energy from empty space as long as you pay it back within a short period of time, and nobody's watching.

The more energy you borrow, the less time you can borrow it.

Quantum Mechanics

An electron traveling from left to right...

Quantum Mechanics

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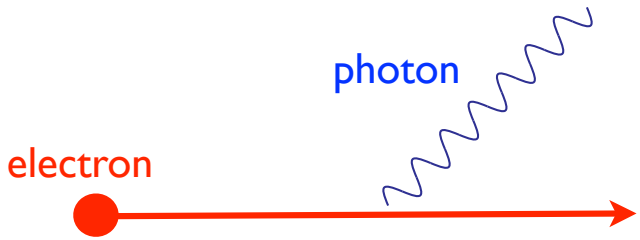
can spontaneously emit a photon!



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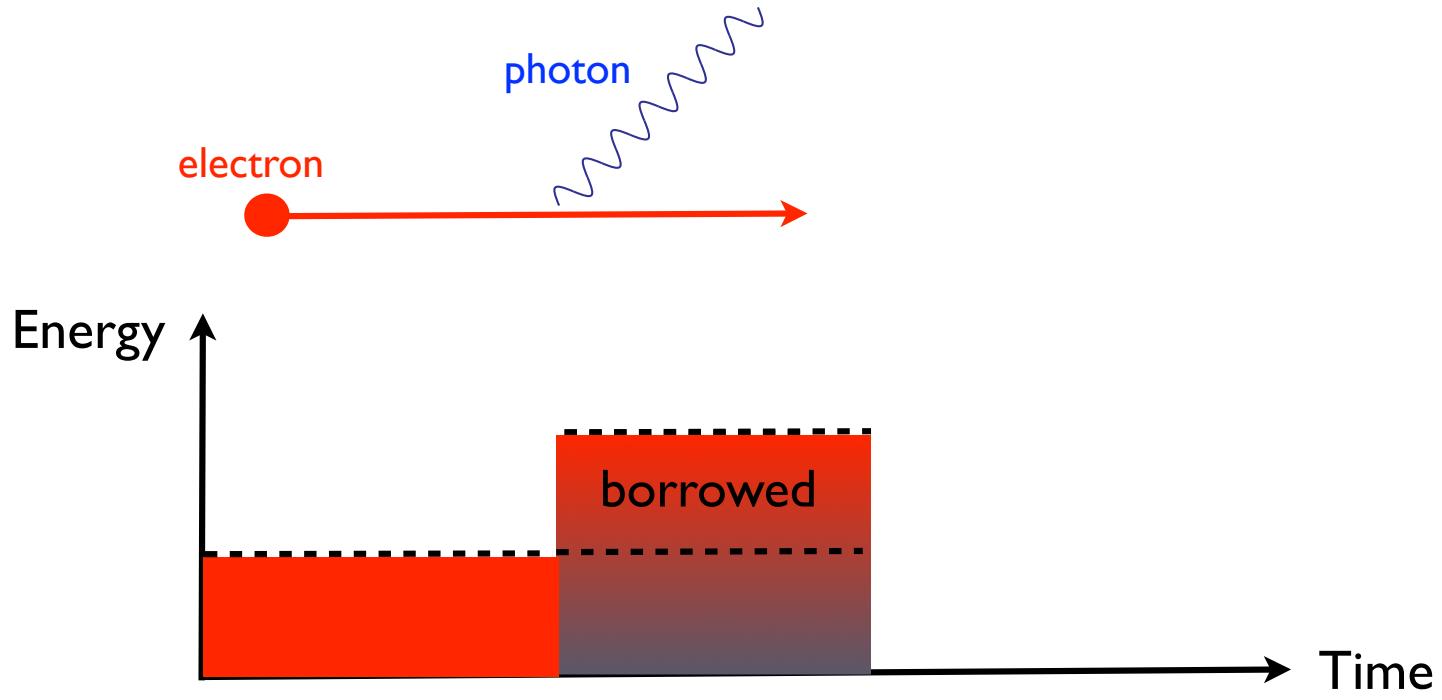

We borrowed energy to make a photon

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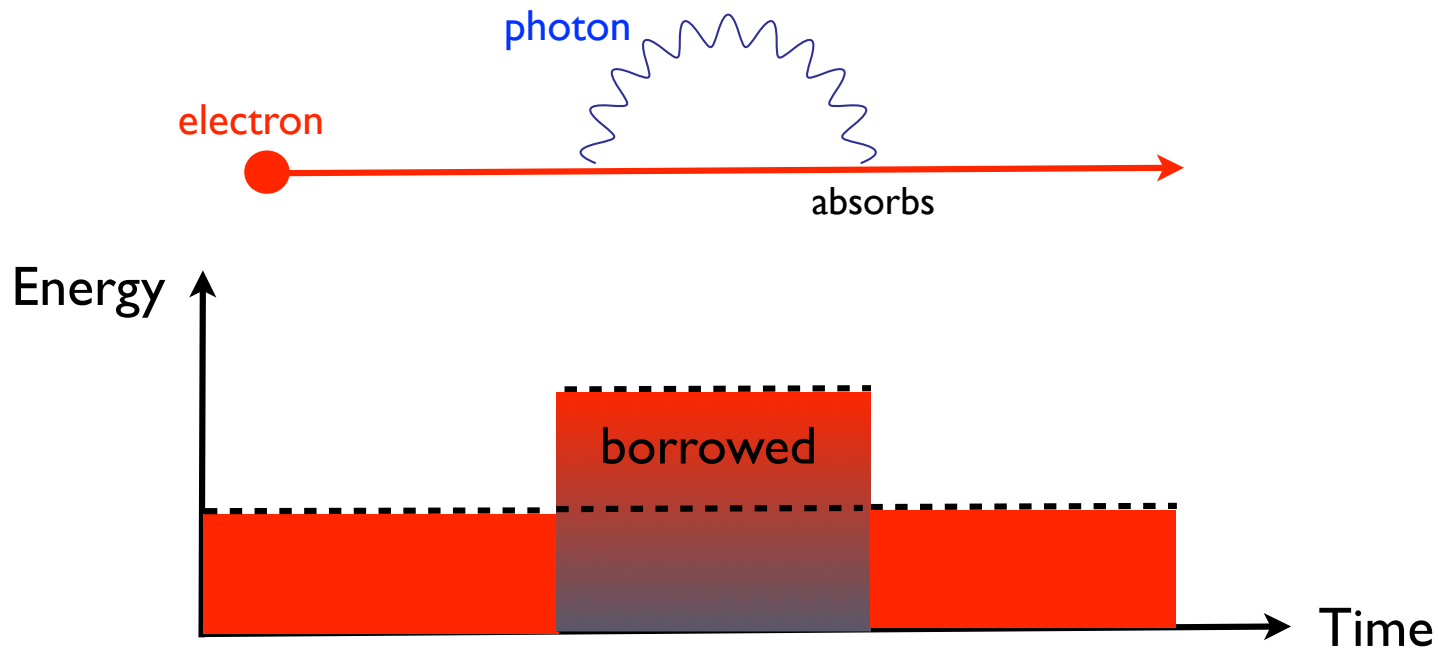
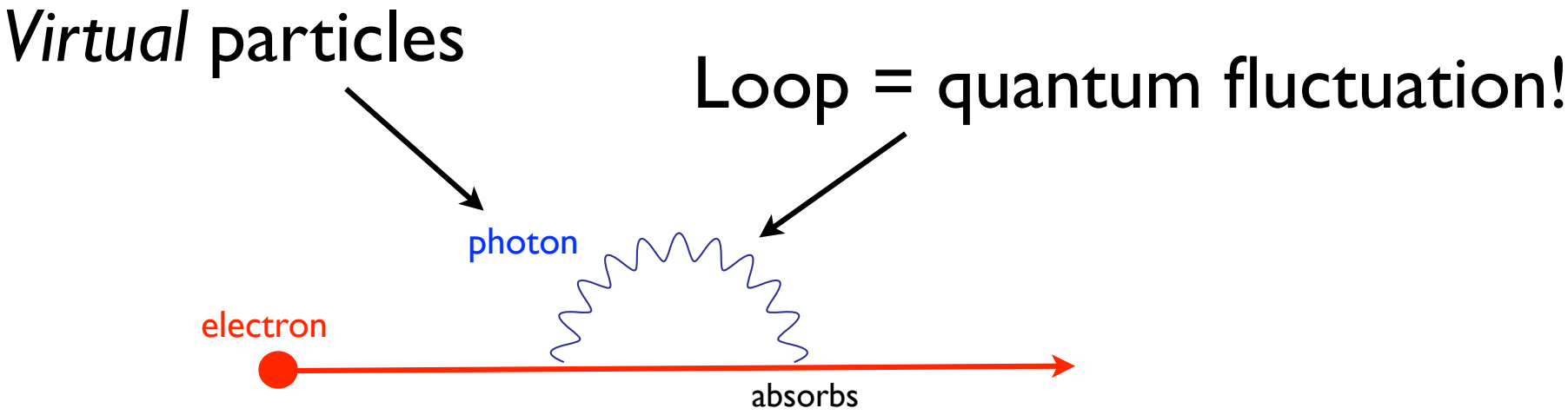


We borrowed energy to make a photon
and pay it back (interest-free) before anybody has a chance to watch it!

Quantum Fluctuations

This is called a ***Quantum Fluctuation***



Quantum Fluctuations

Heisenberg

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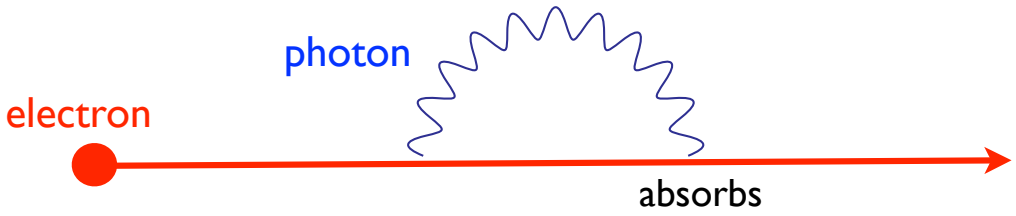
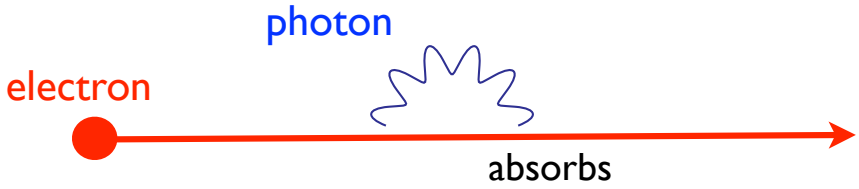


bigger loop = less energy



smaller loop = more energy

Everything can happen...

Quantum fluctuations occur in *all possible energies including infinite energy*.

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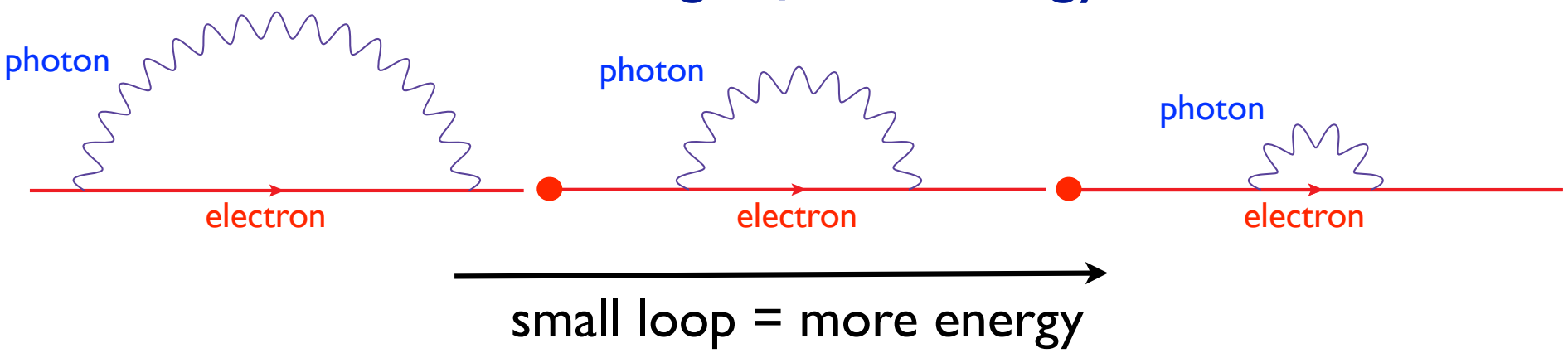

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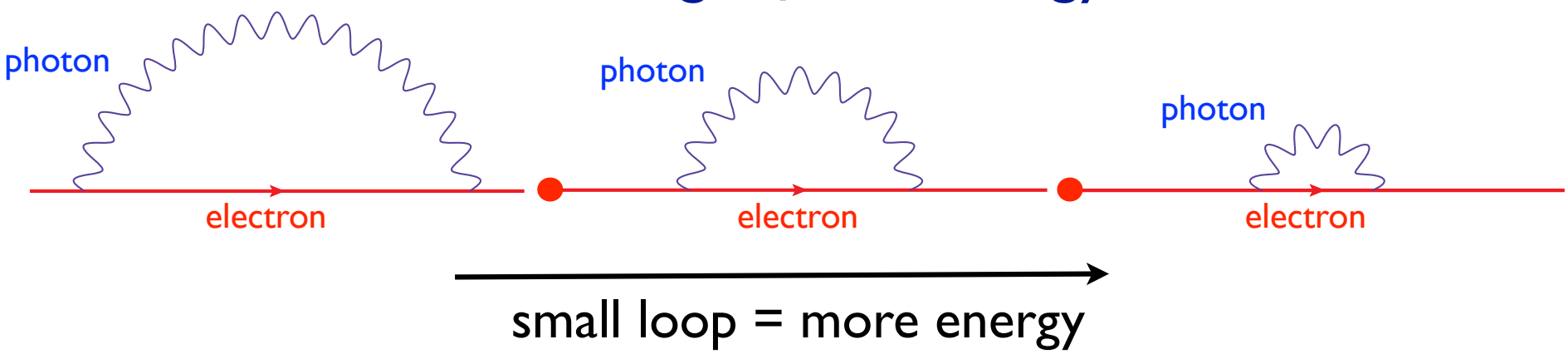
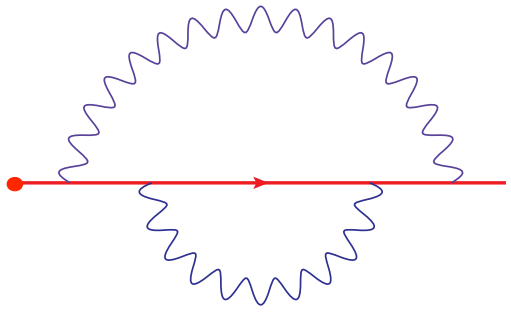


and particles can emit other virtual particles *in all other possible ways*.



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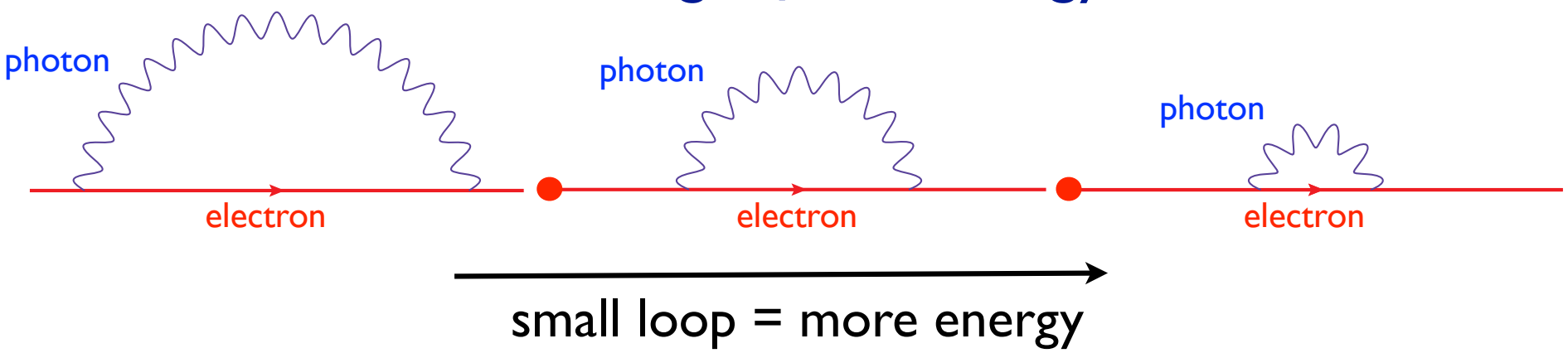

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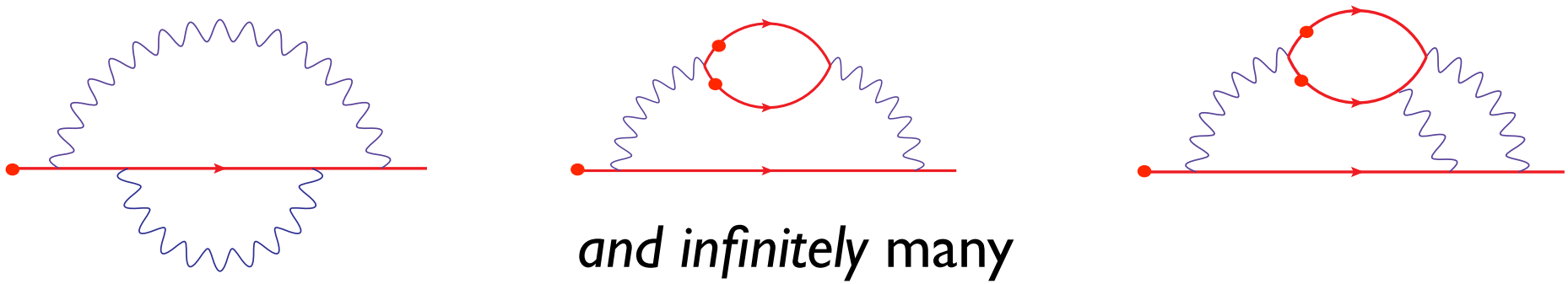

and infinitely many other combinations...

Reality is Democratic

So, from all these possibilities...which one actually *happened*?

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Answer : all of them at once!

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Fundamental Rule of QM

the **probability** of any process is a
sum over all possibilities.

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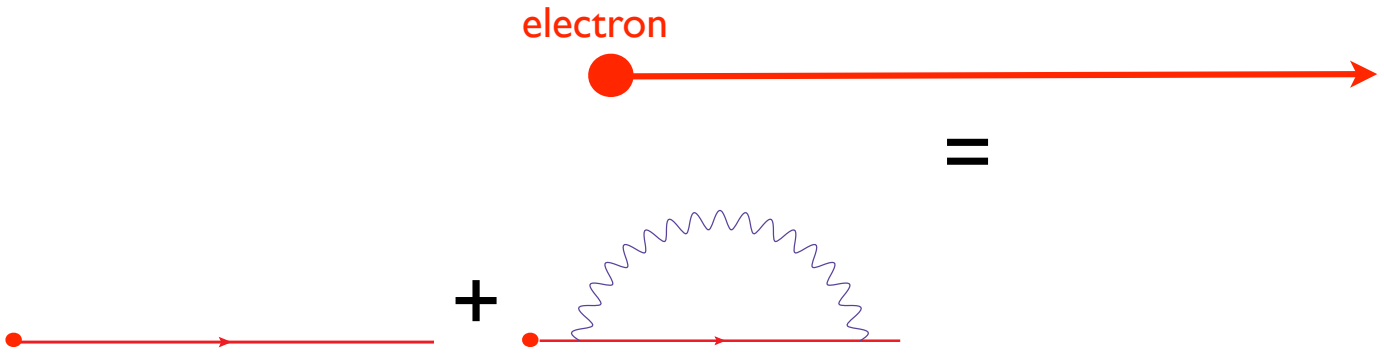

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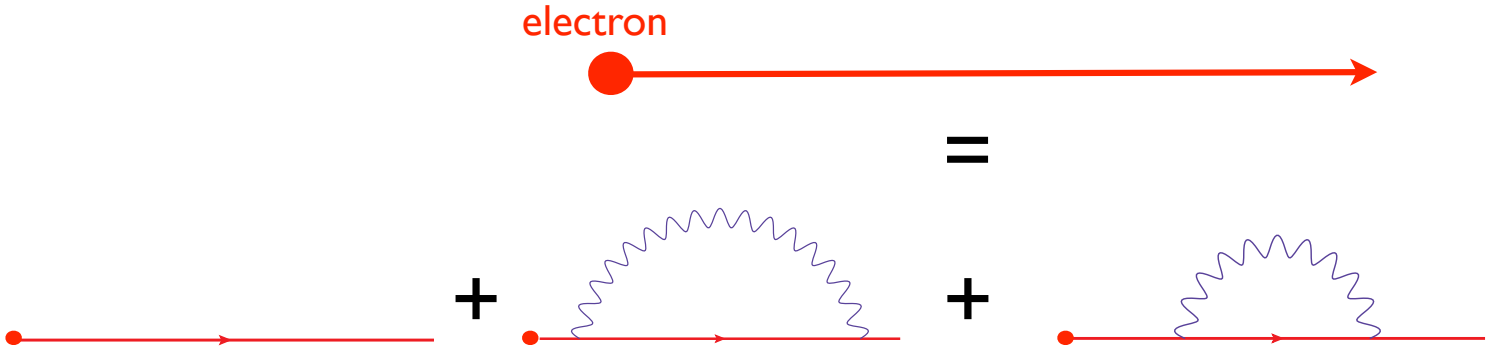

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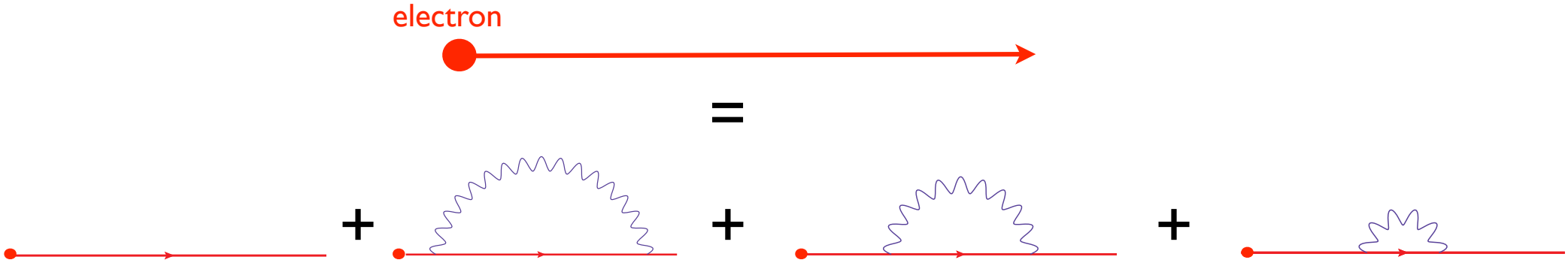

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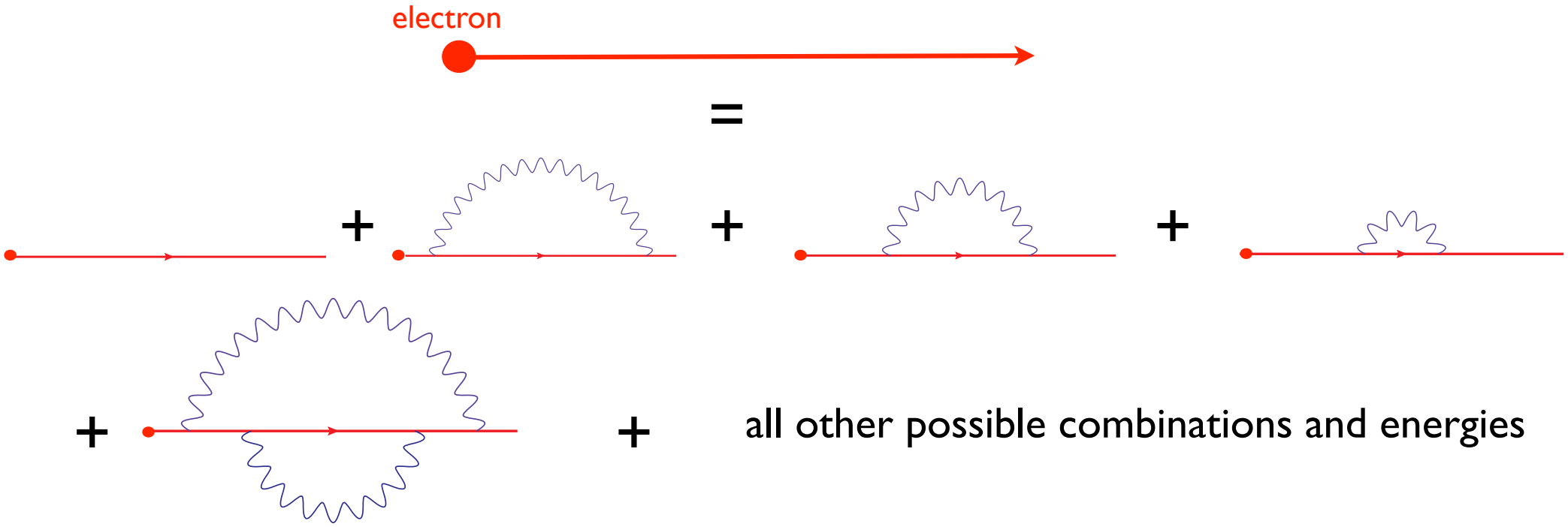

Summing up infinities...

For any given theory, two possibilities when you sum up an infinite number of terms:

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If you get an finite number

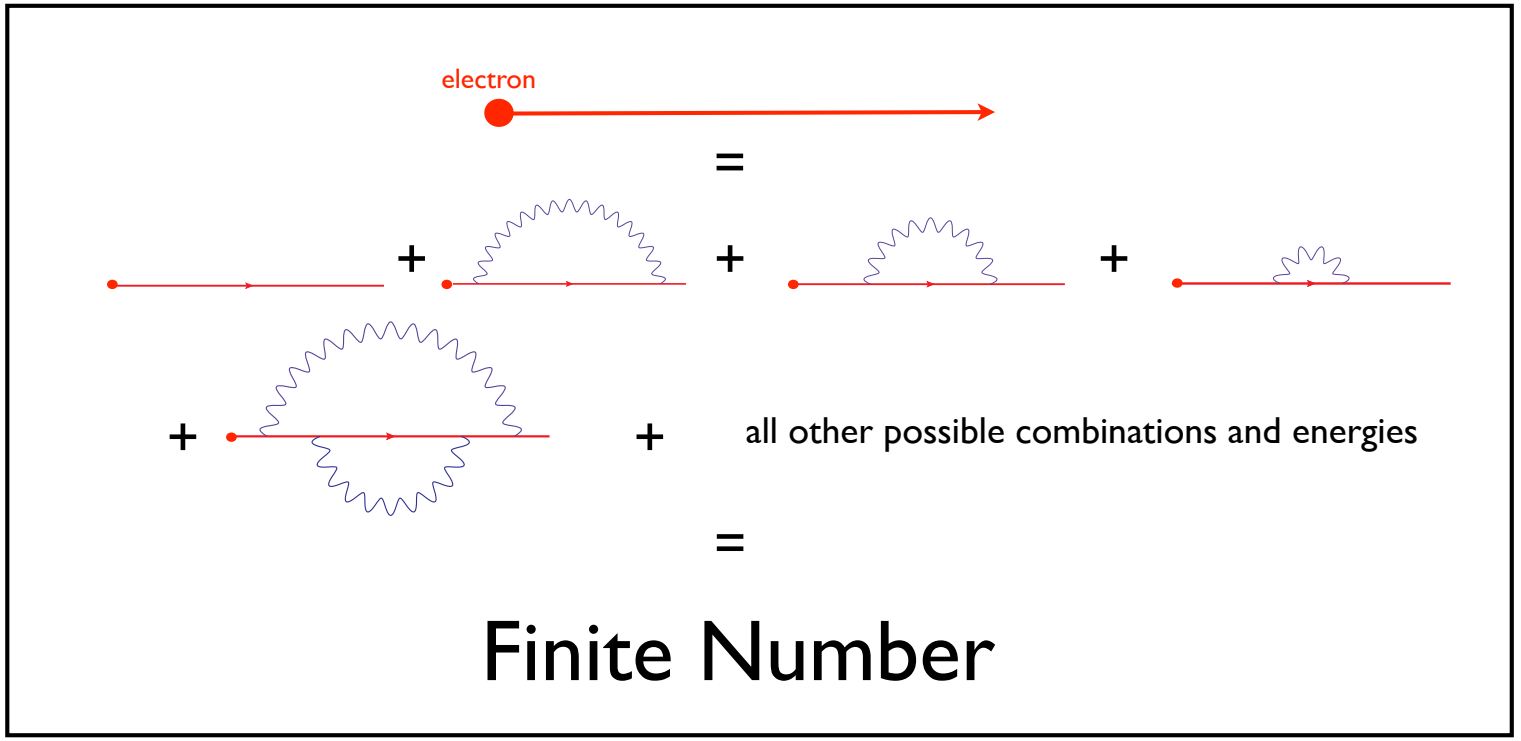
CONGRATULATIONS

your theory is *complete*.

(Pass it on to your experimentalist friends to check if it matches reality.)

Summing up infinities...

Quantum Electrodynamics (theory of photons and electrons) is a complete theory.



Tested to one part to 10,000,000,000 : our most successful and predictive theory.

Summing up infinities...

If you get infinity, then your theory is not predictive.

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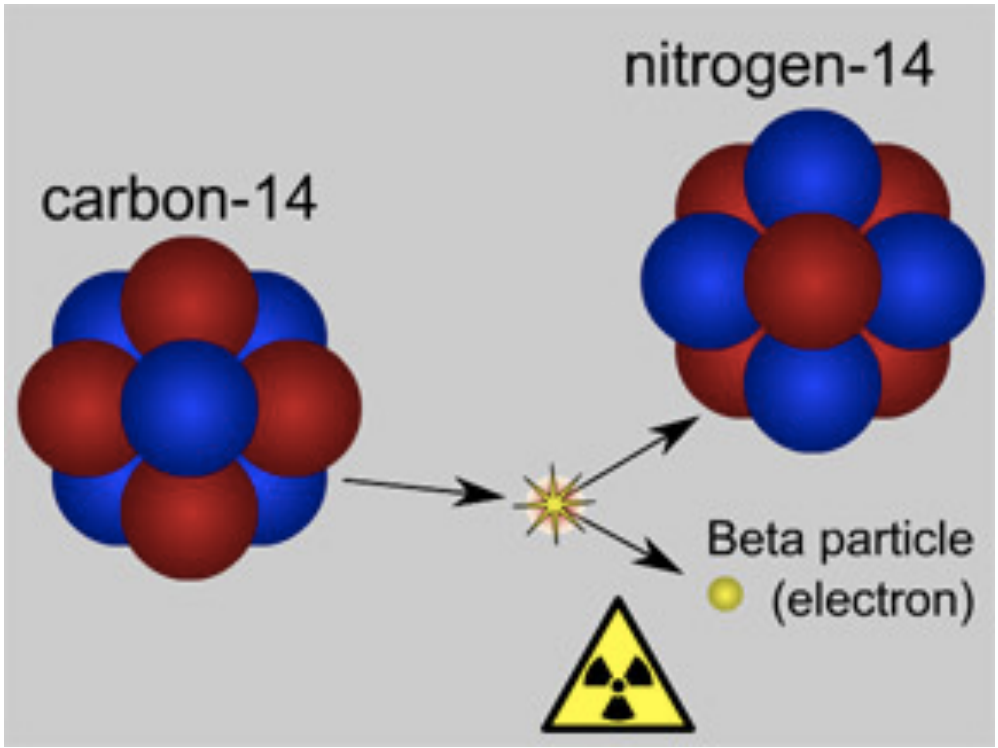
example: Radioactive Decay

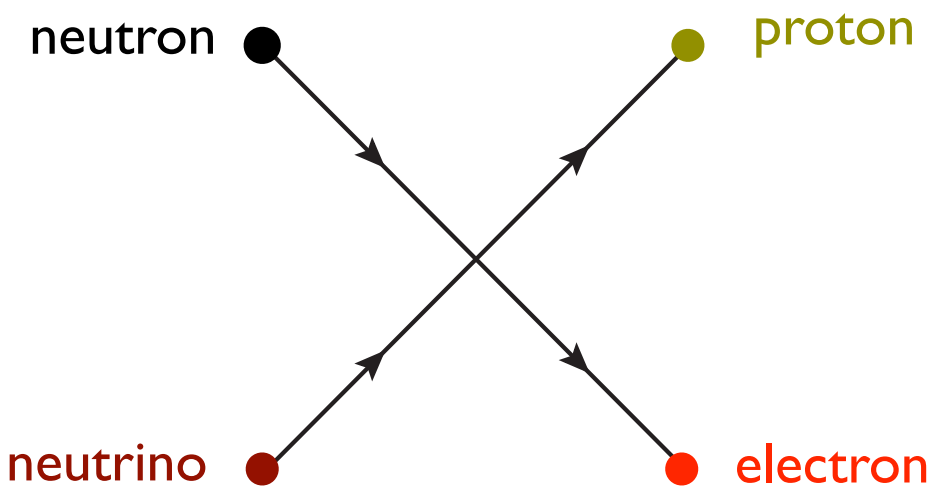


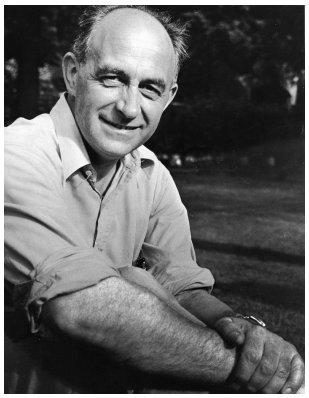
A neutron can decay into a proton, emitting an electron.

Summing up infinities...

Fermi's theory of Radioactive Decay

How a neutron can decay into a proton (and *vice versa*)





Enrico Fermi

If we ignore quantum fluctuations, this theory can make predictions up to a certain limit of energy.

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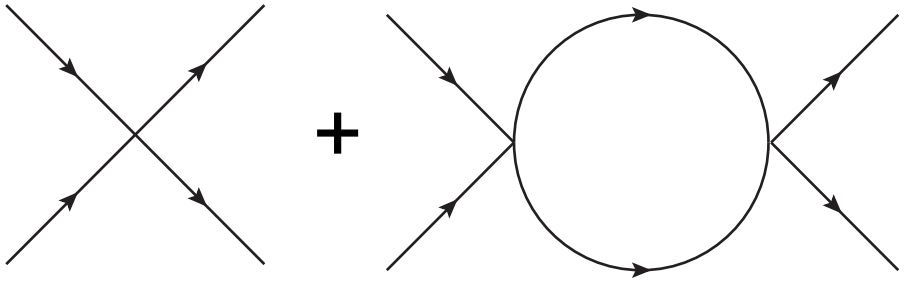
Let's ignore the particle type (just details):

the **probability** of a beta decay process is the *sum over all possibilities*:



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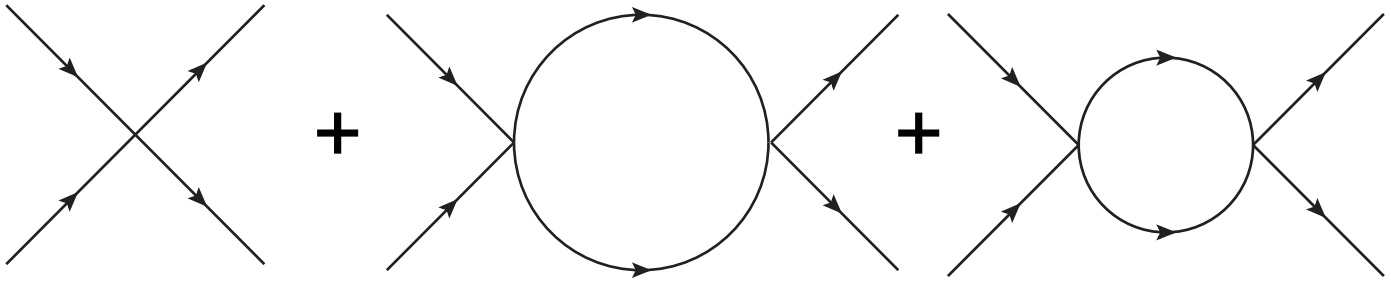

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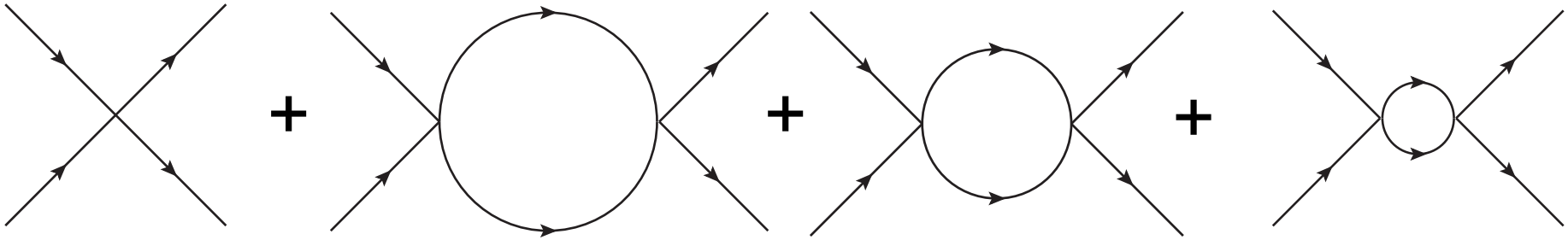

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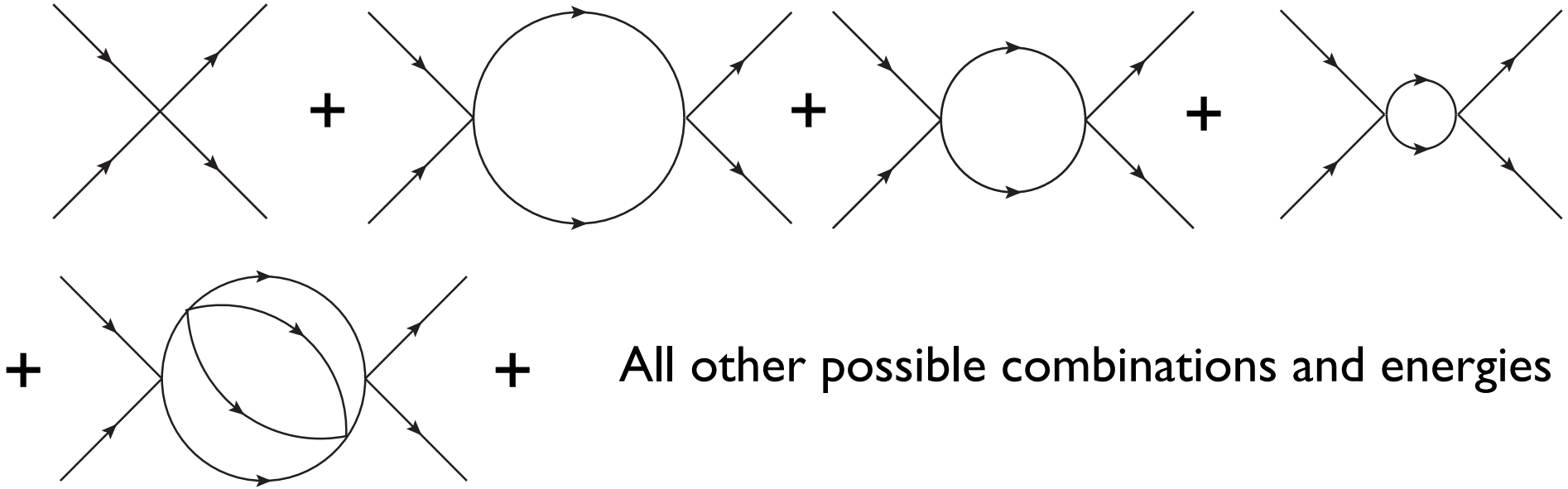

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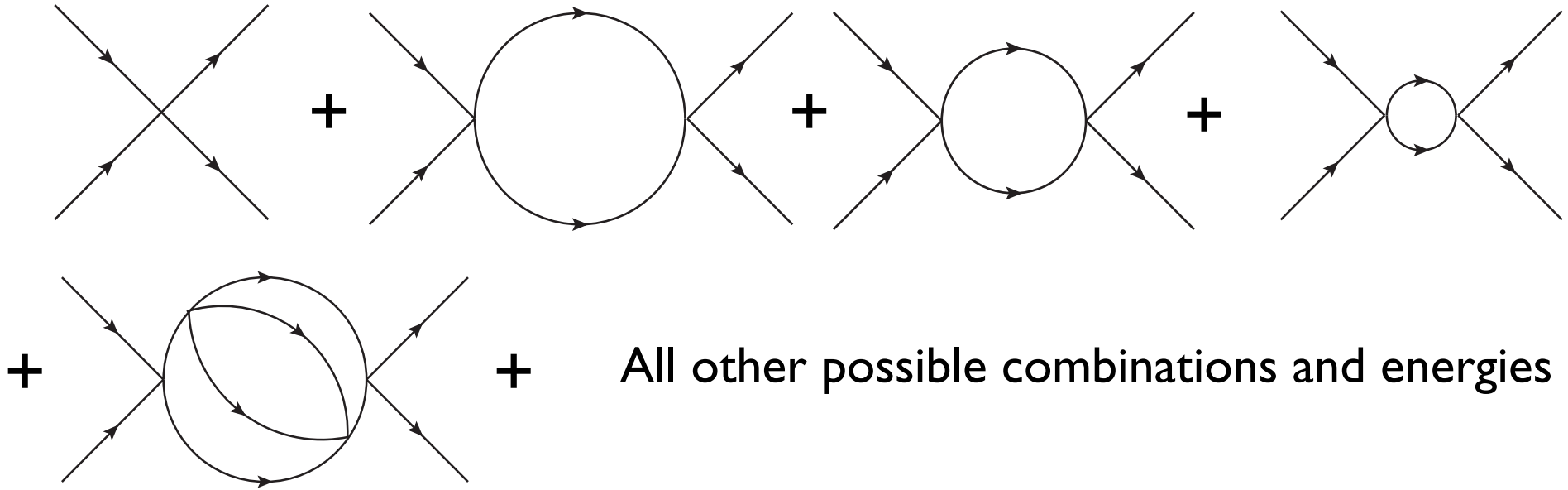


All other possible combinations and energies

= infinity

What now?

All is not lost...

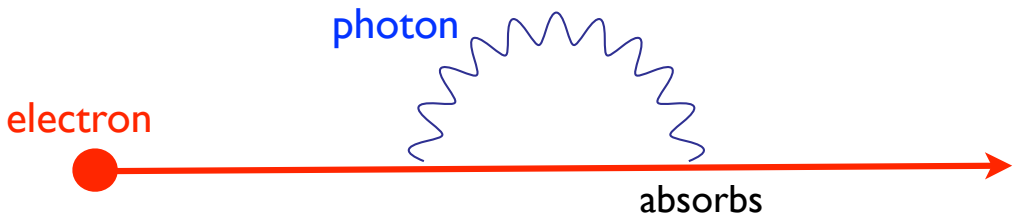
If you ignore the quantum fluctuations, the theory is actually very good and predictive up to a certain limit in collision energy.

So maybe it's not wrong, it's just *incomplete*.

Radiation Decay occurs: so what is missing in our theory?

Fixing a theory

Let's consider an electron with a virtual photon again



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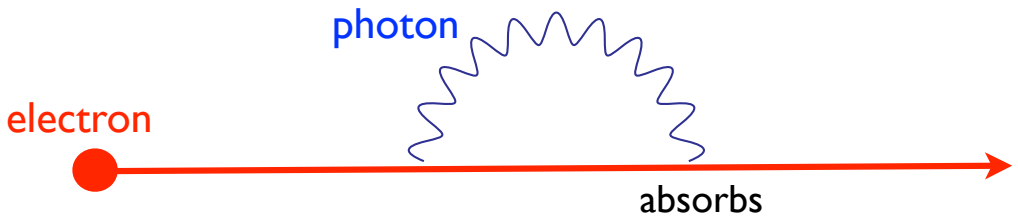
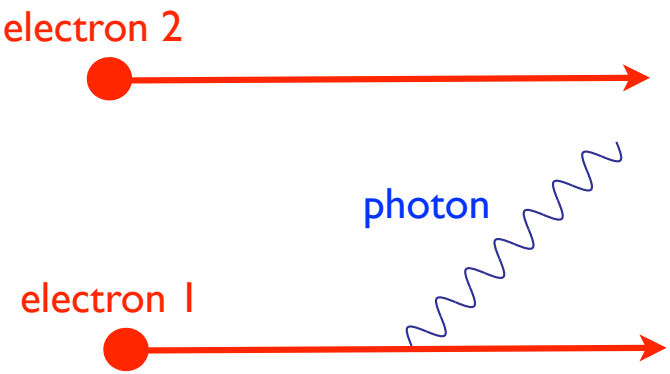


If there is another electron nearby...



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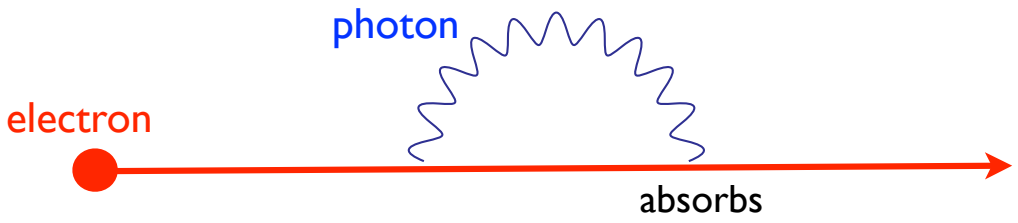

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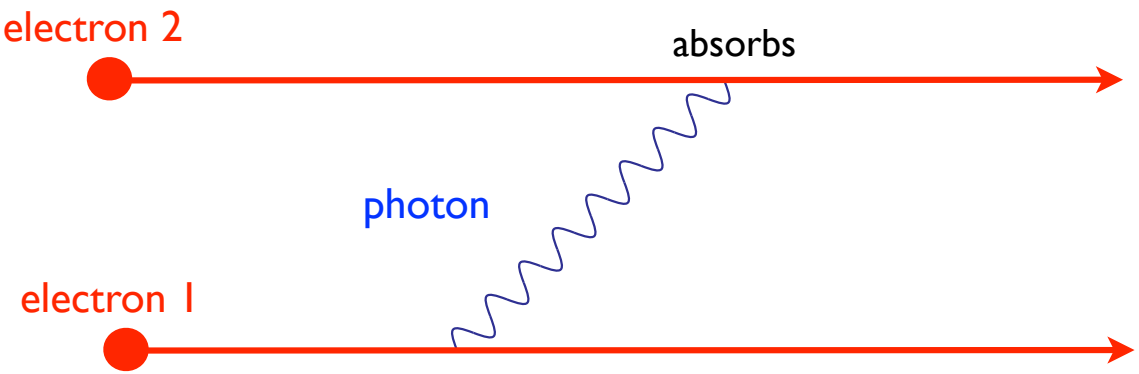
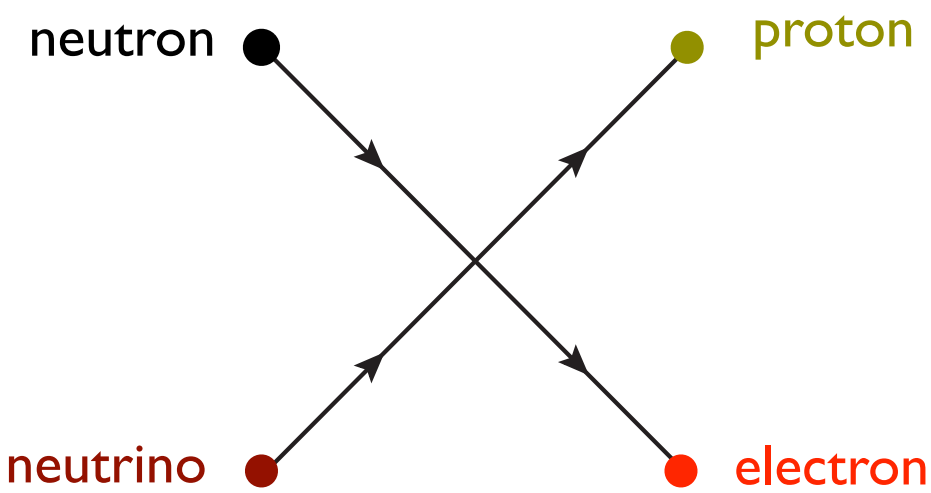


it can absorbs the virtual photon instead!

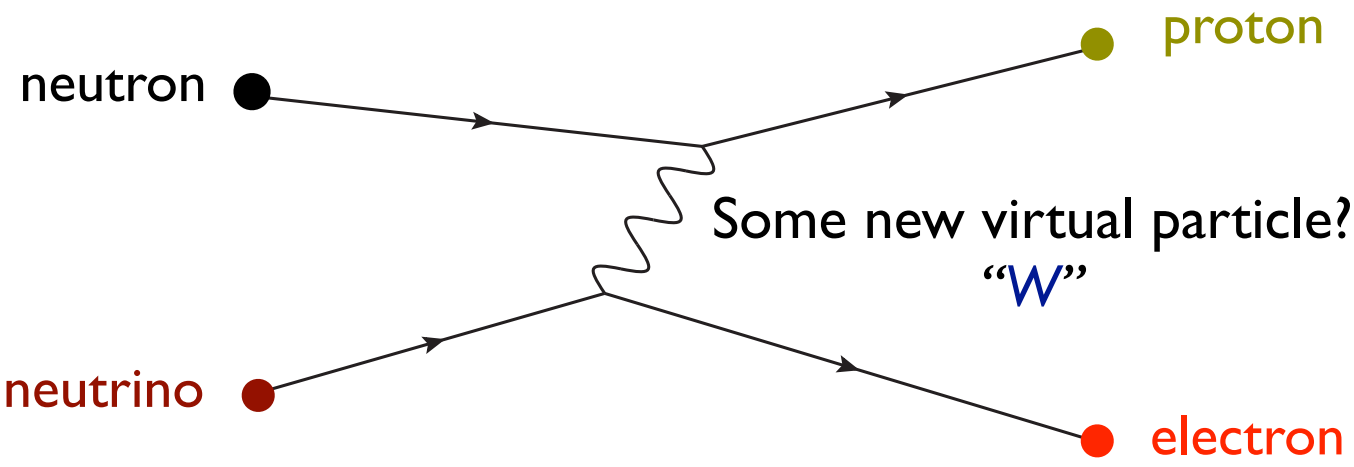
(This is actually the *origin of forces*, but we digress...)

Fixing a theory

Suppose something similar happen to the Fermi Theory



becomes



Fixing a theory

Special Relativity (energy *is* mass)

$$E = mc^2$$

Fixing a theory

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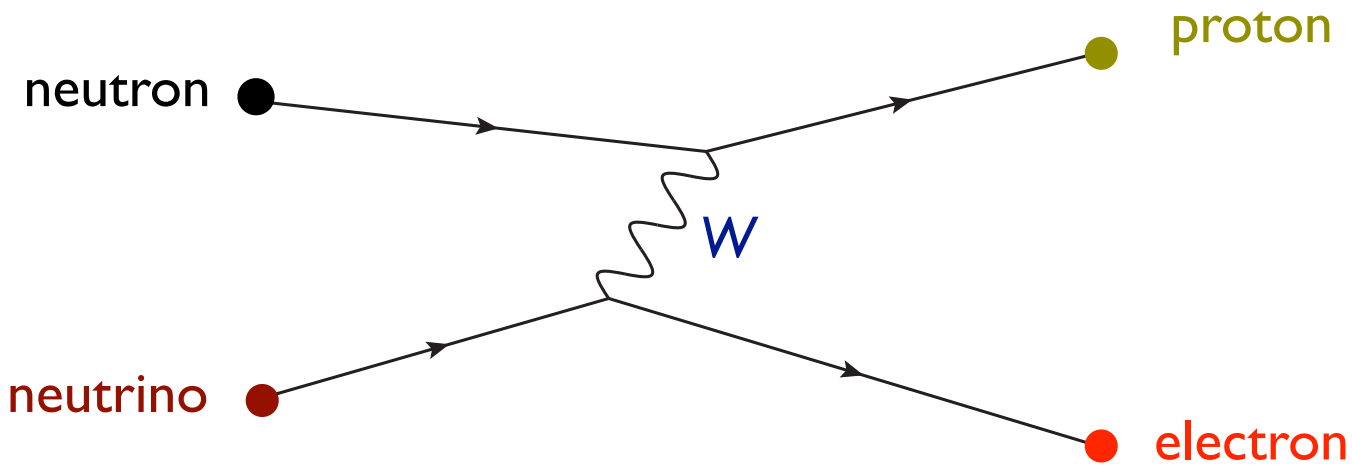
If the Quantum Fluctuation energy is *more* than the mass of the particle *W* then it can pop into virtual existence!

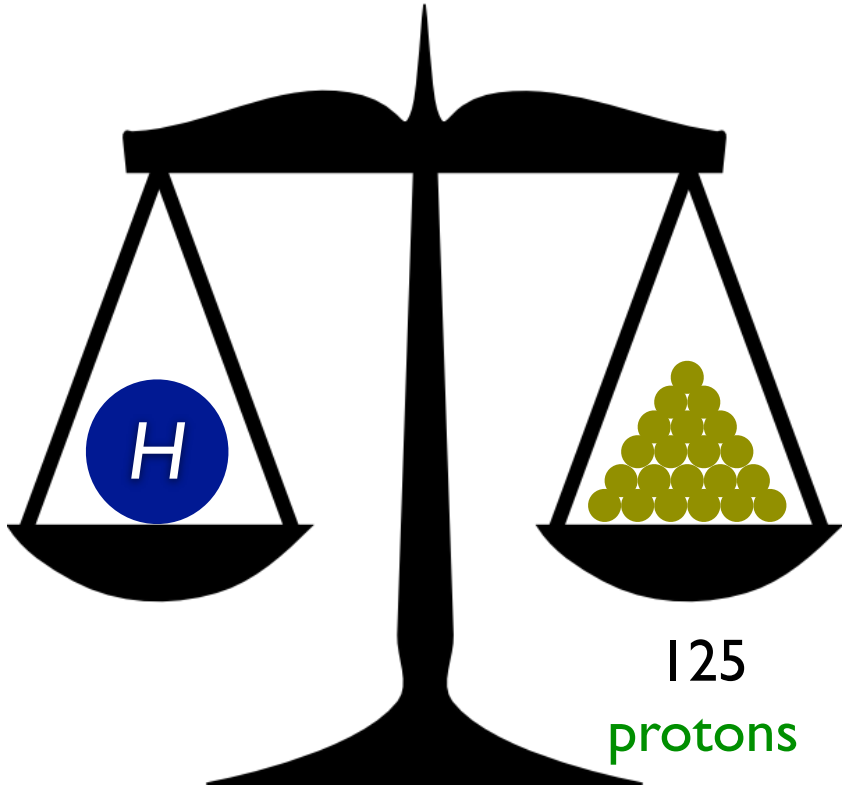


If *W* exists, it *will* pop into virtual existence.

Fixing a theory

It turns out that, if *we postulate* the existence of *W*, *Z* and the *Higgs H*, recalculate everything, the infinities disappear! Your theory is now *complete*!

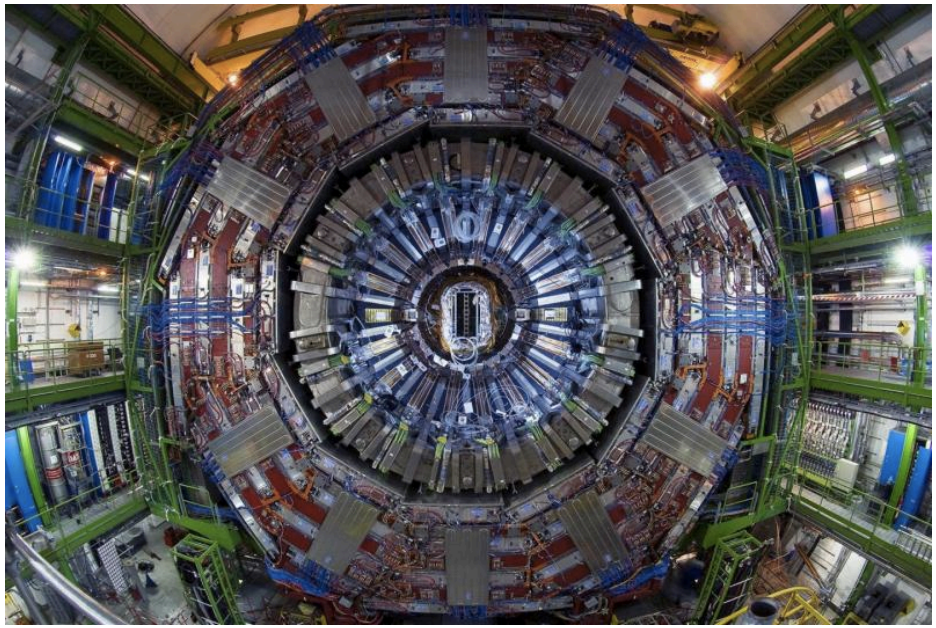
These particles are very massive.



Virtual become Real

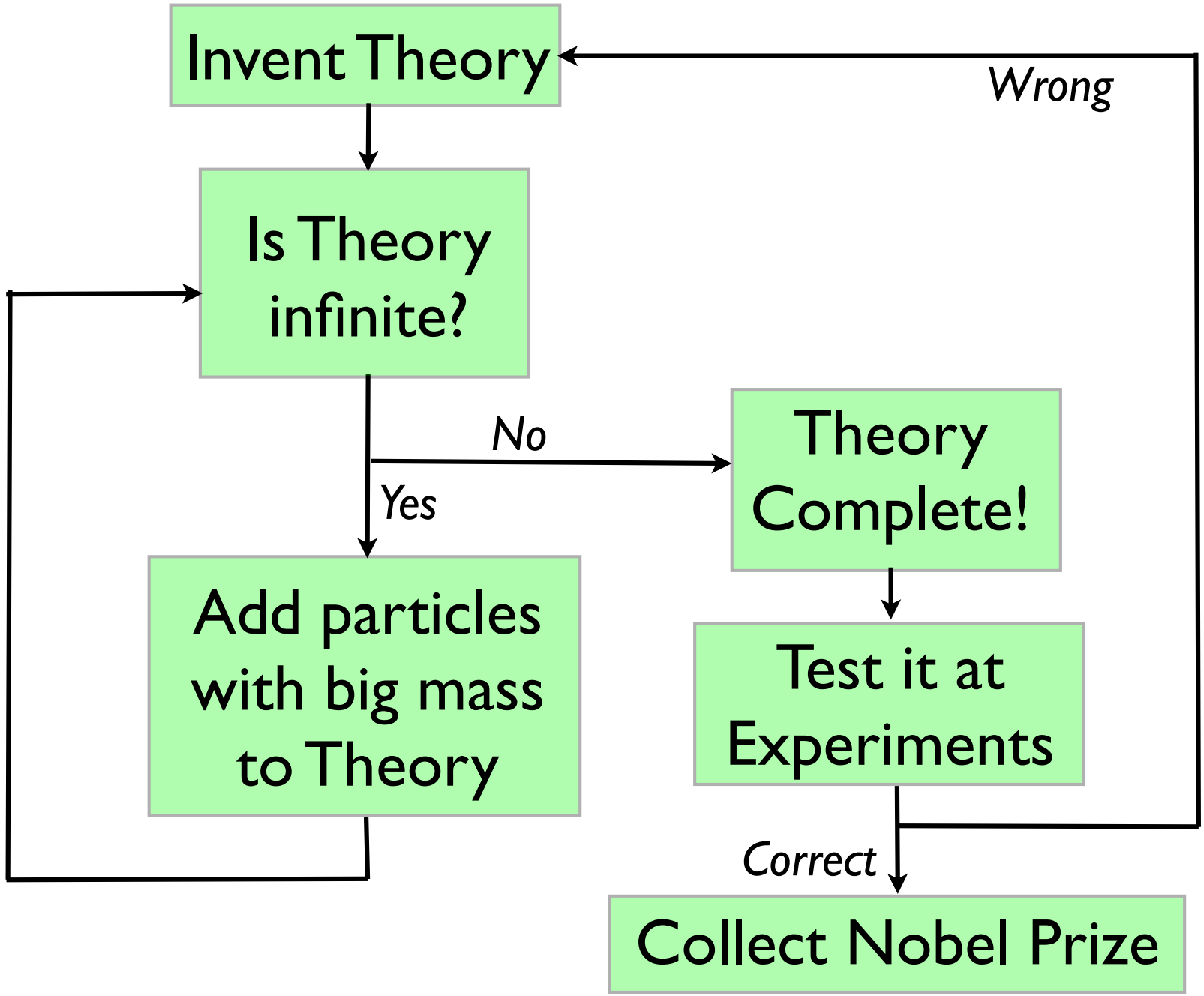
Z and *W* were discovered by the Super Proton Synchrotron particle collider at CERN in 1983.

The Higgs *H* was discovered at the Large Hadron Collider at CERN in 2012.



This *complete* theory is called *Electroweak Interaction* and is highly successful and predictive.

A Powerful Principle



A Powerful Principle

Adding *W*, *Z*, and the Higgs to Fermi Theory is not the unique way to fix the theory.

But when discovered *W* and *Z* in 1983, we become super confident that we must discover the Higgs at the Large Hadron Collider.

How about GR?

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A traveling gravitational wave (“graviton”) going from left to right

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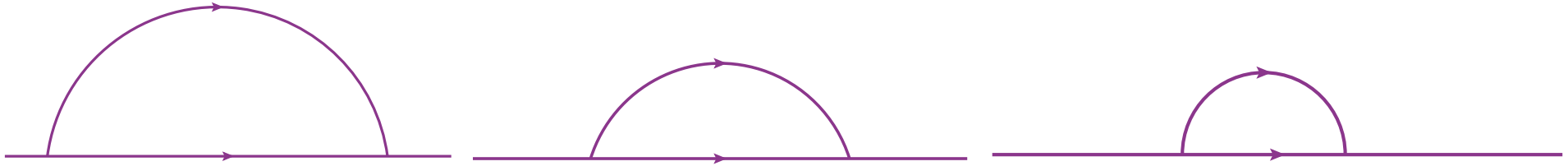
Quantum fluctuations allow virtual gravitons to pop in and out at all different energies as usual...



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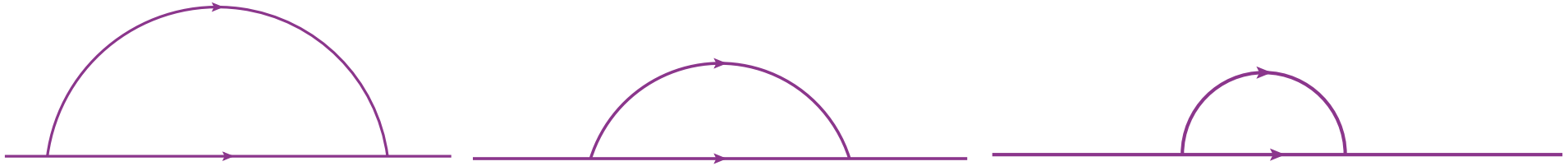
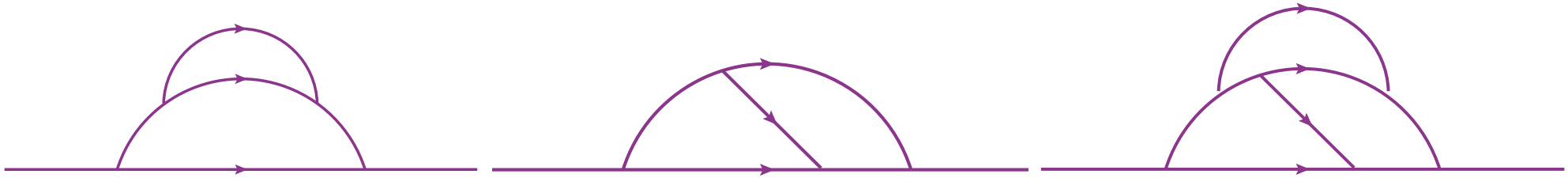
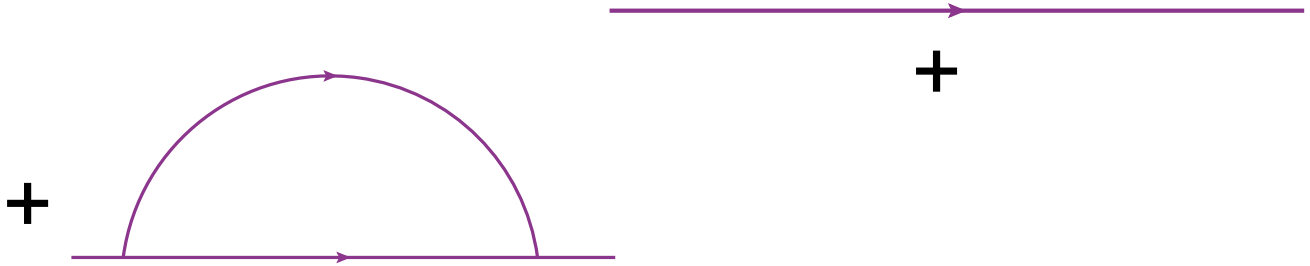


and other more complicated possibilities...



How about GR?

Summing them up as Quantum Mechanics tells us to...



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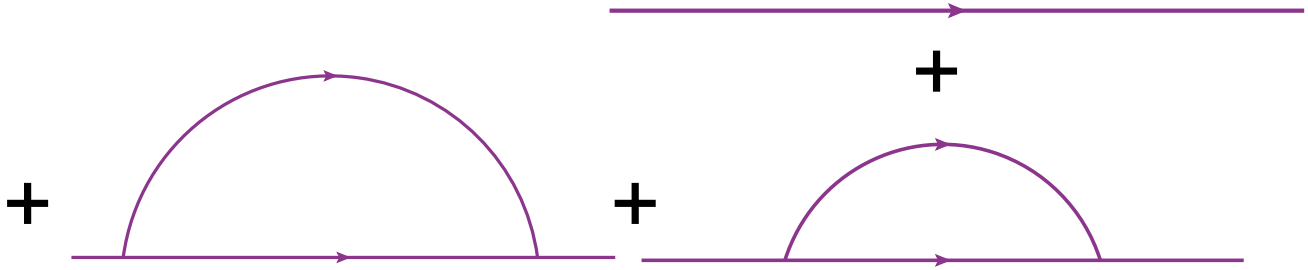

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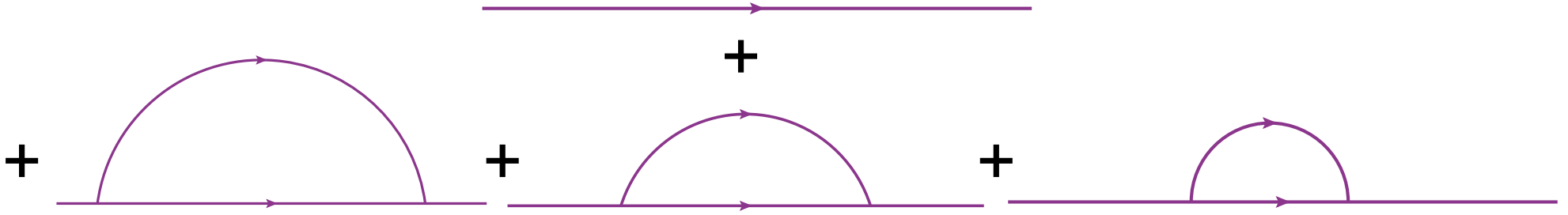

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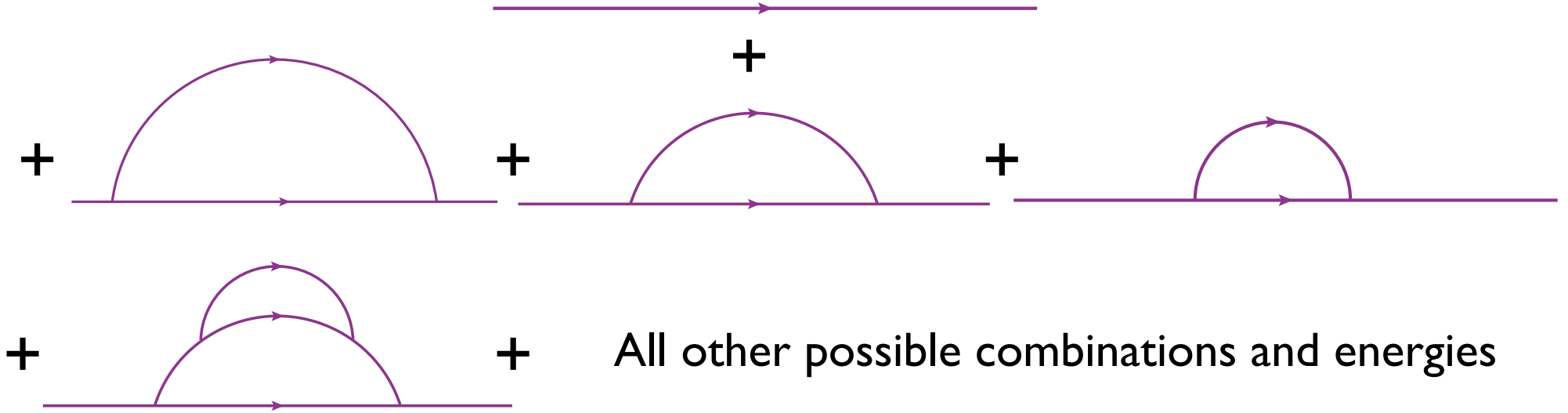

All other possible combinations and energies

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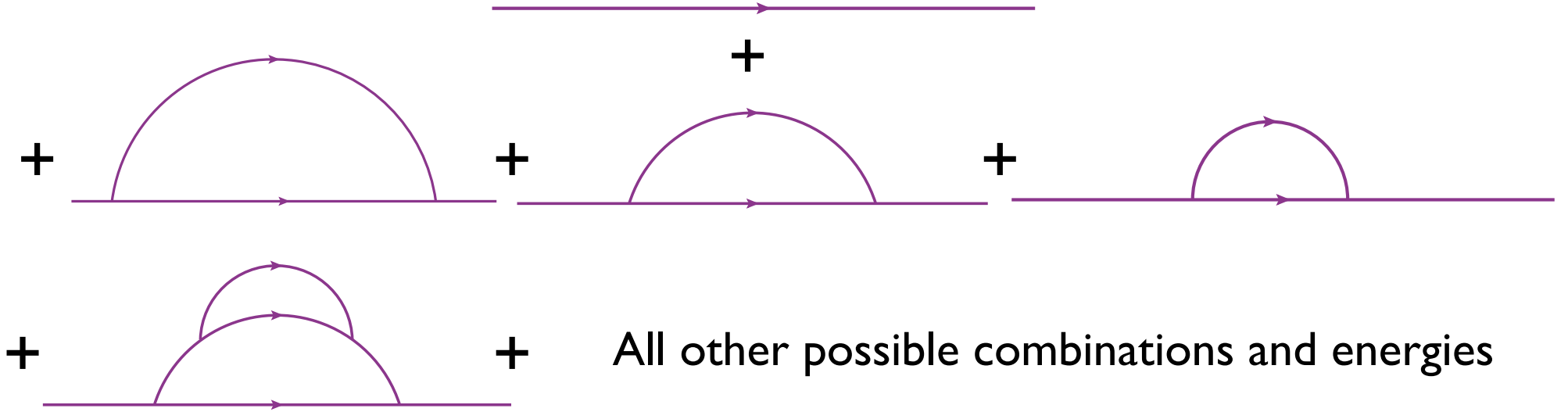


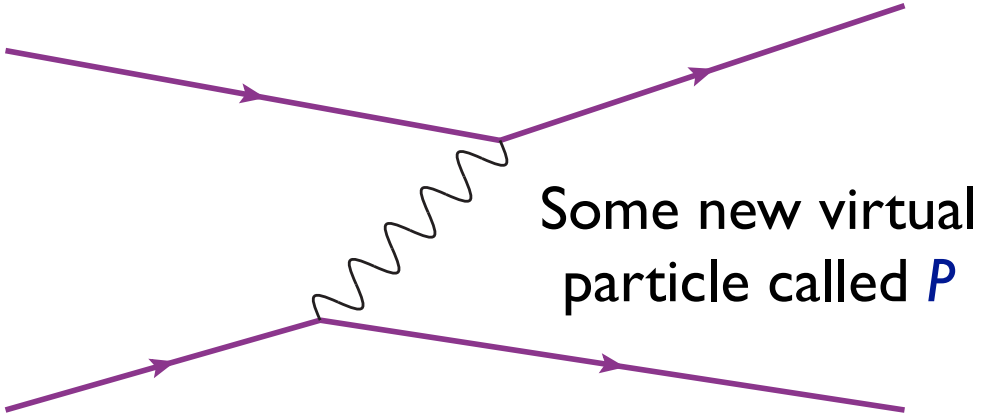
All other possible combinations and energies

= infinity 

General Relativity obviously works if we ignore quantum fluctuations, so maybe it's just *incomplete*?

Can we Fix GR?

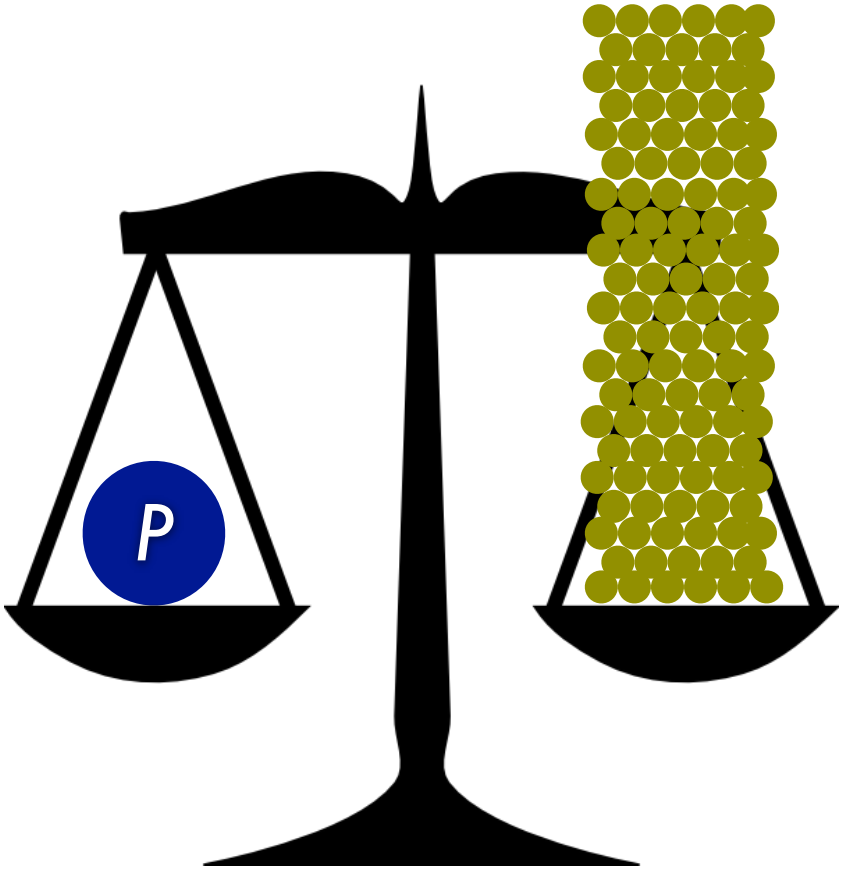
Let's try to fix gravity by adding extra species of massive particles at high energies like we did previously



The mass of this hypothetical virtual particle *P* can be estimated by combining the physics of Quantum Mechanics, Special Relativity, and General Relativity.

Can we Fix GR?

This mass is ginormous.



10,000,000,000,000,000,000 protons

So to make a virtual particle of this mass, we need a ***huge*** quantum fluctuation of energy!!

For want of a nail...

General Relativity (mass curves space)

If we put a lot of mass in a small area, the space will curve so much that it becomes a **Black Hole.**

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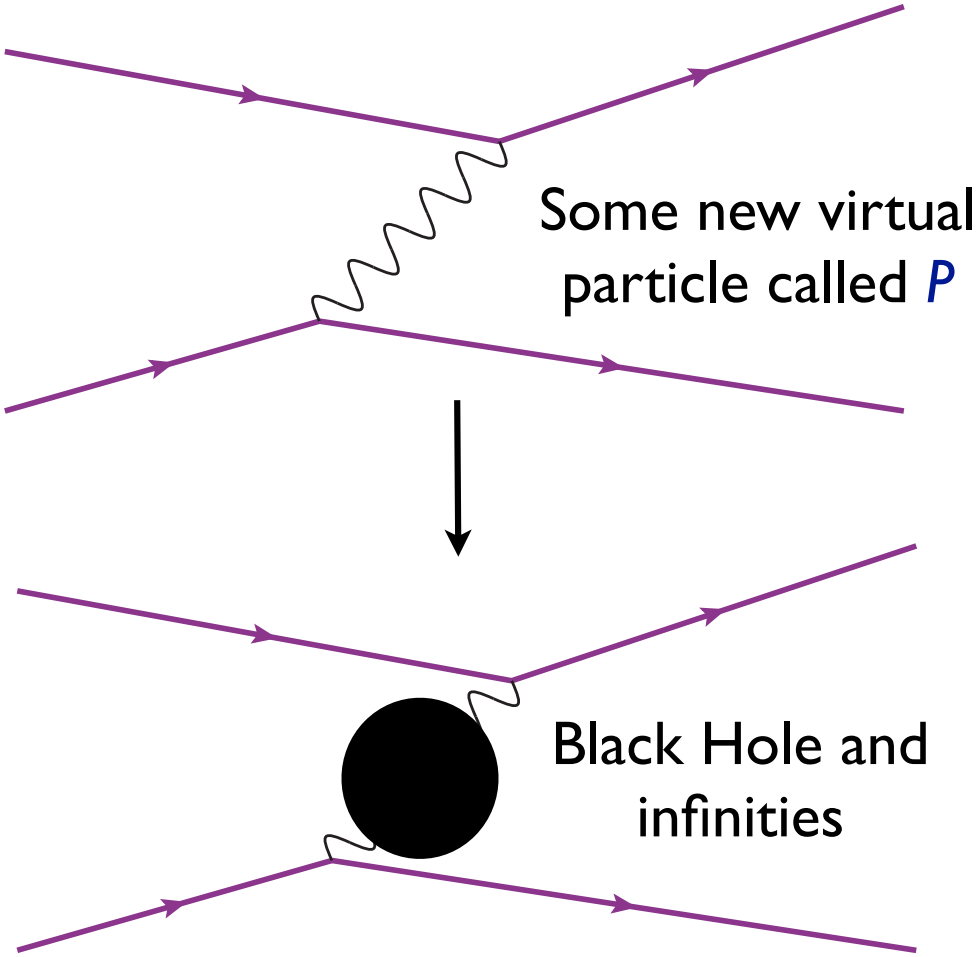
This amount of Quantum Fluctuation required to fix GR is exactly the amount needed to form a Black Hole.
So if we try save GR from these infinities,
it collapses into a Black Hole and forms a singularity.

A singularity = an infinity

For want of a nail...



Black holes exist, but their existence make our quantum theory of GR non-predictive.

The Devil is in the details...

When we *combine* the rules of Quantum Mechanics and General Relativity, we get a non-predictive theory.

And it's hard to unify QM and GR because Quantum Mechanics, Special Relativity, and General Relativity *are so well tested experimentally.*

Your Party Piece

So...why is it so hard to unify QM and GR?

Because QM says that you can borrow so much free energy from empty space that GR says you will make a black hole.

Your Party Piece

What's wrong with Black Holes? They exist right?

Yes. But the existence of these Black Holes make QM non-predictive because they have singularities and infinities.

Your Party Piece

I think I am in the wrong party.

THANK YOU!