hi

Lecture 25, 04.11.2017

Quantum Mechanics 5

housekeeping

Question about anything?

I'll make a movie for you:

Poster selection:

April 13, outline due April 20...read the instructions.

Homework:

For month of April, I've shifted due dates to Saturdays.

Readings:

There is a manuscript chapter on antimatter and Dirac...Antimatter, Paul Dirac's Second Big Score

Honors Project

Data due April 22. Paper due on May 4 (final day).

the dropbox instructions? Forget them. We'll be uploading files to a site in Norway. I'll let you know.

Read the Second of two sets of instructions:

`MinervaInstructions2_2017.pdf` in

www.pa.msu.edu/~brock/file_sharing/QSandBB/

Quantum Mechanics, so far:

Light has both wave and particle-like properties

Bohr Model:

- electrons are in atomic orbits
- fixed in radius and energy
- electrons make transitions - spectra

Electrons have both wave and particle-like properties

- for both light and electrons, $p = \frac{h}{\lambda}$
- standing wave patterns at Bohr radii worked

Electrons are represented by imaginary wavefunctions, ψ

- the square of the wavefunctions represent the probability of finding an electron at a point at a time

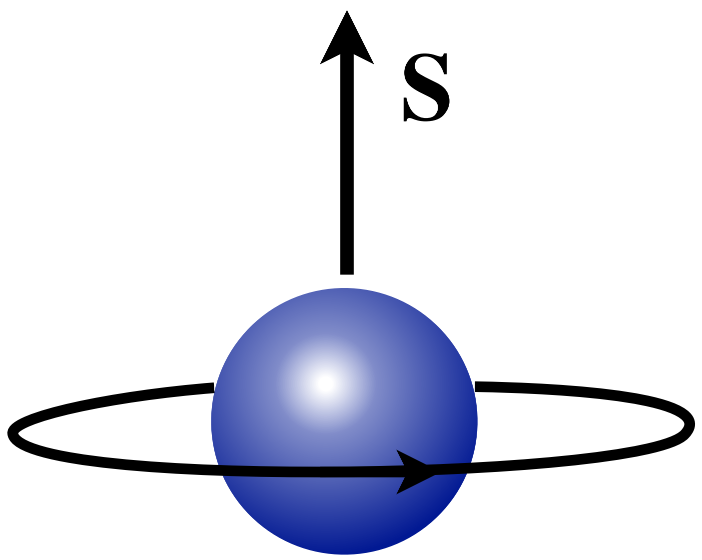
Heisenberg Uncertainty Principle:

- measuring a precision location of a quantum makes momentum imprecise
- measuring a precision time interval of a quantum makes energy imprecise

electrons are little magnets

They behave in a magnetic field as if they are little spinning current spheres

The electron **itself** is *like* a spinning charge...



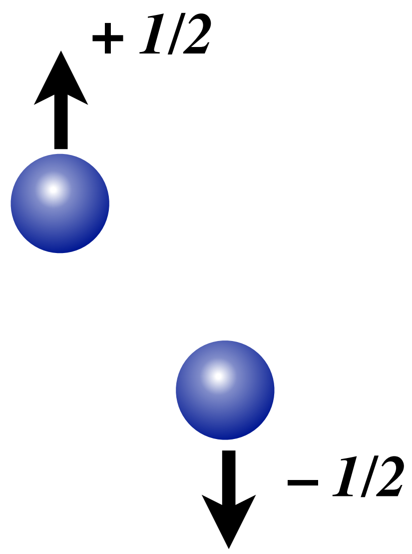
Electrons have an **intrinsic** angular momentum, "S": "spin"

$$S_z = m_s \frac{h}{2\pi}$$

But, the "spin" can only take on two values:

$$m_s = +\frac{1}{2} \quad \text{or} \quad m_s = -\frac{1}{2}$$

We say
"spin, plus 1/2" or "spin up"
and
"spin, minus 1/2" or "spin down"



Pauli Exclusion Principle:

No two electrons can be in the same quantum state

that is, have identical “quantum numbers”

…integers that characterize the atom

Relativistic Quantum Mechanics, so far:

Making Quantum mechanics relativistic was problematic:

- negative energies were inevitable $E_T = \pm\sqrt{(m_0c^2)^2 + (pc)^2}$
- negative probabilities seemed inevitable

Paul Dirac creatively changed Schrodinger's approach:

- Schrodinger Equation: one wavefunction…the electron, non relativistic
- Dirac Equation: 4 wavefunctions, completely relativistic
- two wavefunctions with positive energies, one spin up and one spin down
- two wavefunctions with negative energies, one spin up and one spin down
- "spin" came naturally out of Dirac's equation…a purely relativistic property with no classical analogue

Vacuum and antimatter

- Dirac embraced the negative energies and modeled the vacuum as full of negative energy electrons
- But he envisioned a multi-particle model in which a negative energy electron can be promoted to a positive energy electron and a negative energy, "anti-electron"
- The process was: photon $\rightarrow$ (-e, +E electron) + (+e, -E electron) = electron + anti-electron

Positron

- The anti-electron, aka Positron, was discovered soon after in cosmic rays jargon alert: **fermion**

refers to:	any particle with half-integer spin
entomology:	from Fermi's theoretical work on the behavior of large numbers of Fermions
example:	electron, proton, neutron

jargon alert: **boson**

refers to:	any quantum object with integer spin
entomology:	from Satyendra Nath Bose, who worked on the effects of multiple boson aggregates
example:	photon, pion, Higgs Boson

spin is a defining quality of an electron

electron

symbol: e

charge: $-1e$

mass: $m_e = 9.0 \times 10^{-31}$ kg ~ 0.0005 p

spin: 1/2

category: fermion, lepton

the bar over the top will mean "antiparticle"

anti-electron, aka "positron"

symbol: $\overline{e}$ or e^+

charge: +1e

mass: $m_e = 9.0 \times 10^{-31}$ kg ~ 0.0005 p

spin: *1/2*

category: anti-fermion, anti-lepton

particle:

proton

symbol:	p
charge:	$+1e$
mass:	$m_p = 1.6726\times10^{-27}$ kg = 1 p
spin:	1/2
category:	fermion, hadron

again, an inherent angular momentum and a defining property of photons

particle: **photon**

symbol: γ

charge: 0

mass: $m_{\gamma} = 0$

spin: 1

category: boson, aka Intermediate Vector Boson

Dirac's result

required: 4 quantum fields, rather than 1 $\psi_{up}(+E), \psi_{down}(+E)$

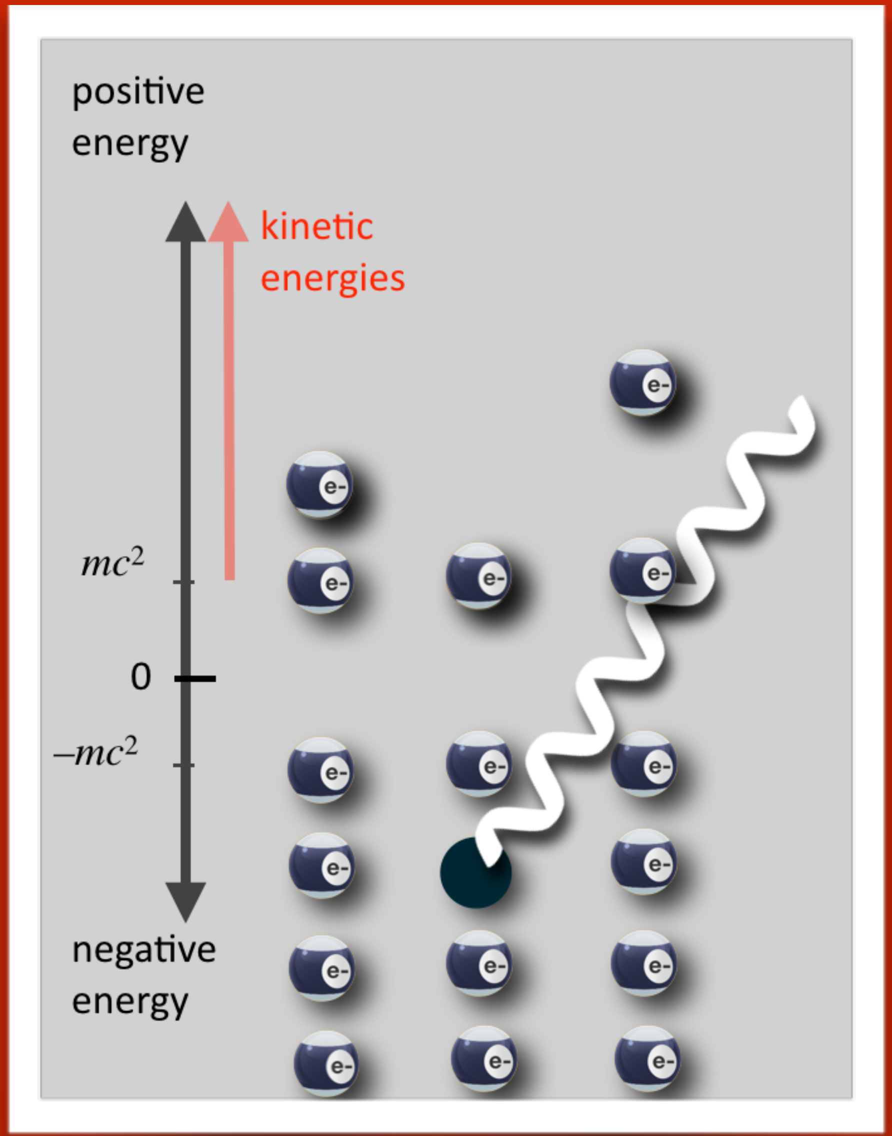
2 have positive energy, 2 have negative energy $\psi_{up}(-E), \psi_{down}(-E)$

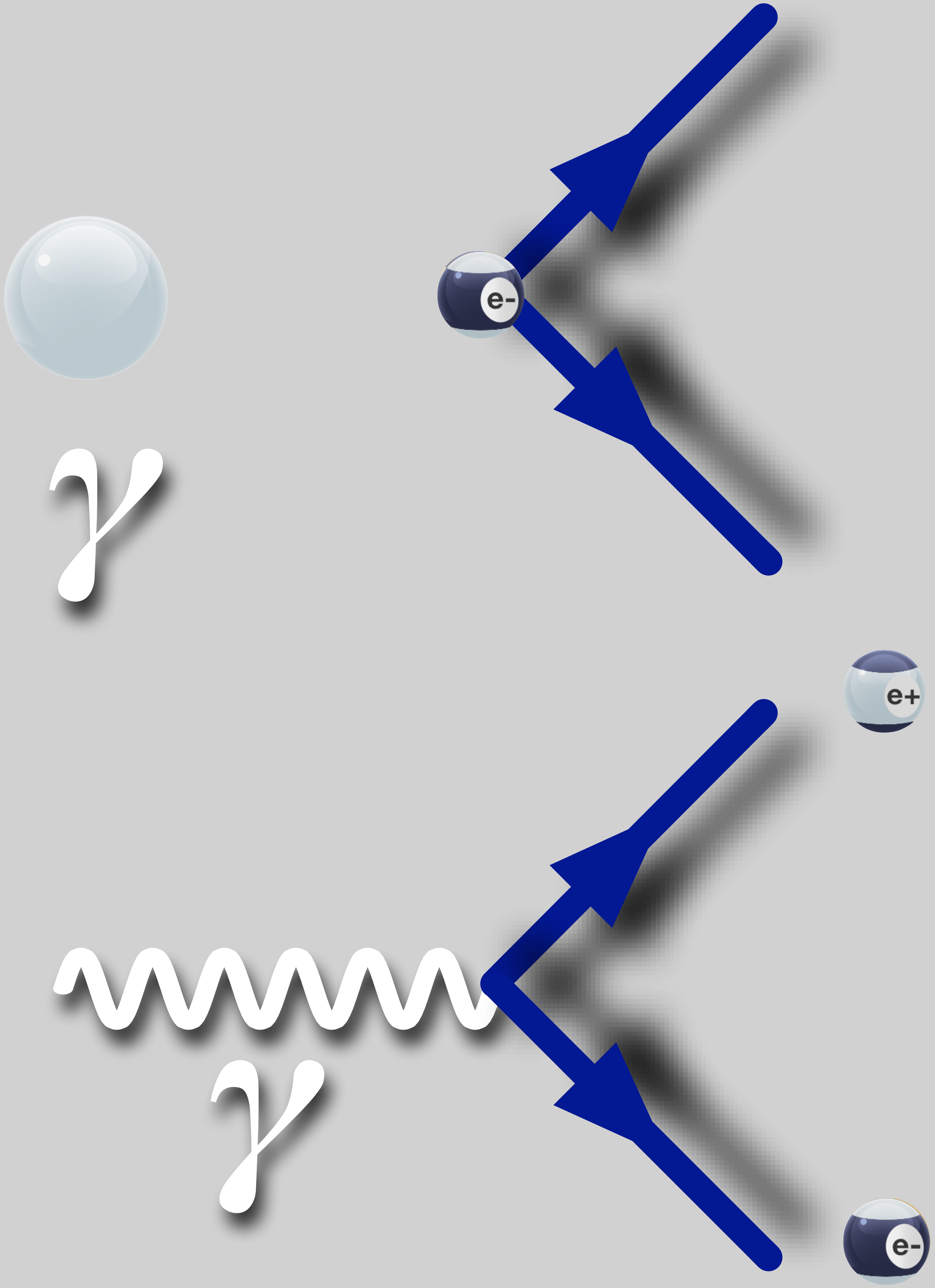
each pair is related precisely to spin

Dirac showed that spin is a wholly relativistic effect
...it just popped out of his equation.

modern intepretat

a photon poof-disappears





antimatter

is a fact of life

every particle has it’s anti-particle partner

same mass, different electrical charge

Dirac
Nobel

at the age of 31

Carl Anderson and Victor Hess

Anderson was 31

this is where it gets interesting

we need to establish a language for Dirac-like reactions

“Relativistic Quantum Field Theory”
essentially invented by Paul Dirac

notice a couple of things about what appears in Dirac's equation

1. it's about more than one thing: two electrons and a photon

   "regular" Quantum Mechanics is about single objects only

2. stuff appears and stuff disappears

`what's`

nothing.

what's nothing

you'd maybe say:

no objects (particles...quanta)

zero energy

the Heisenberg Uncertainty Principle:

there's no state of Nature that can possess any precise value of, say, energy

and that includes Zero.

the Heisenberg Uncertainty Principle

will not allow a **void**.

but we *still* have a notion of the **vacuum**

- it's the lowest energy state in Nature
- where there are no real particles

`understanding whatsgoingonhere`

requires some mental fortitude

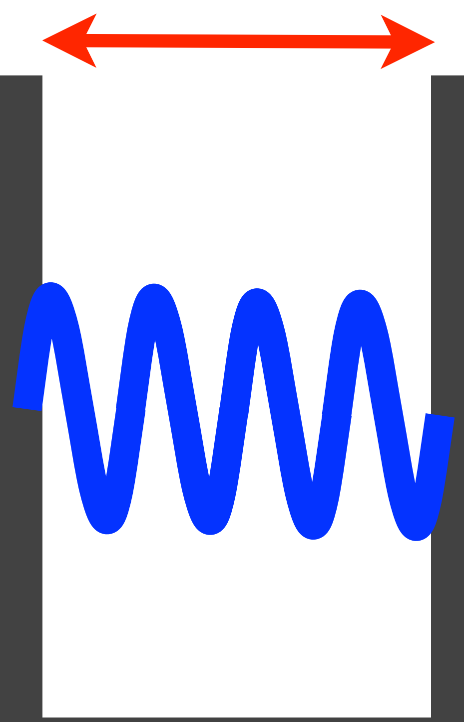
remember

trying to trap an electron?

let’s make it all about nothing.

What’s in Nothing?

nothing…somewhere here:



make the trap smaller

remember

What's in Nothing?

or nothing, somewhere here:

trying to trap an electron?

do nothing tighter

make the trap smaller to this value:

$$\Delta x \sim \frac{h}{m_e c}$$

$\sim 2.2 \text{ x } 10^{-12}$ m

The size of a Hydrogen atom... $5 \text{ x } 10^{-11}$ m

The size of a proton... $\sim 10^{-15}$ m

an important

but simple calculation about nothing

a very important "length"

Compton Wavelength

we consider this to be "the size of a particle"

$$\Delta x \sim \frac{h}{m_e c} = \lambda_{\text{Compton}} = \lambda_C$$

$$\Delta x \, \Delta p \quad \sim \quad h$$

$$\frac{h}{m_e c} \Delta p \sim h$$

$$\frac{1}{m_e c^2} \Delta pc \sim 1$$

$$\Delta pc \sim m_e c^2$$

Remember: $E_T^2 = (mc^2)^2 + (pc)^2$

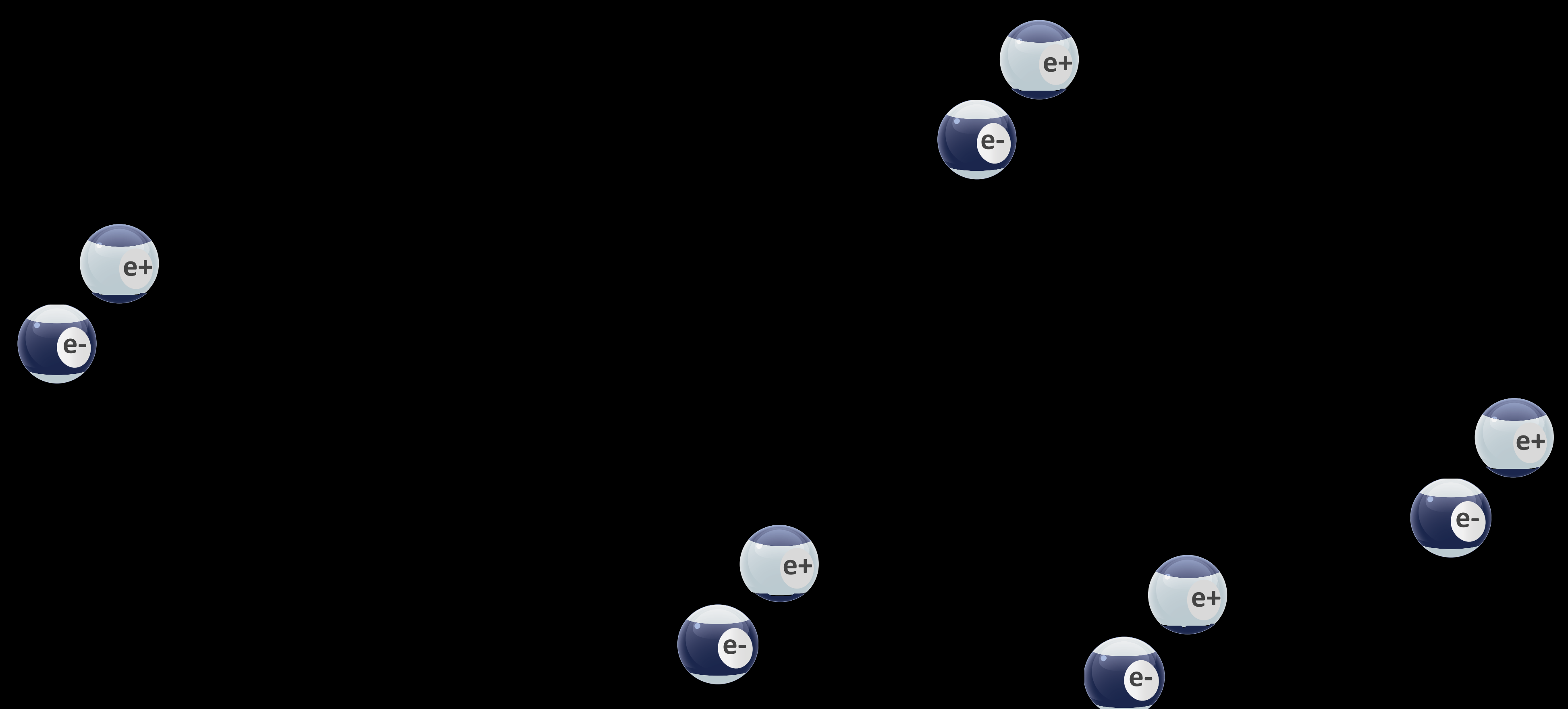
An energy equivalent to the mass energy...all by looking closely at nothing.

pop

the Uncertainty Principle requires

that particle-antiparticle pairs pop into and out of existence

all the time



`uncertainty principle`

+ the particular length of:

$$\lambda_C = \frac{h}{mc}$$

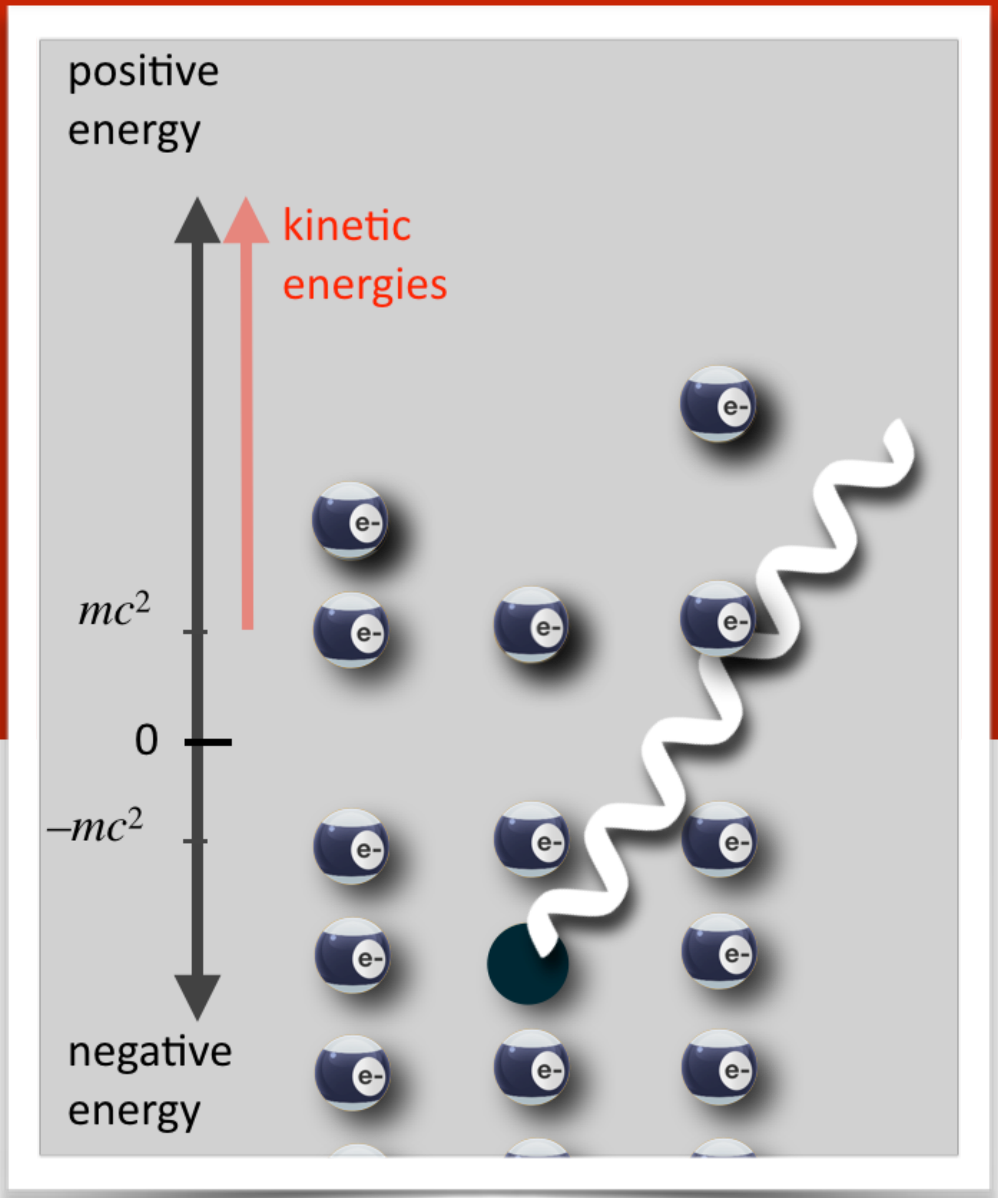
makes the vacuum very active.

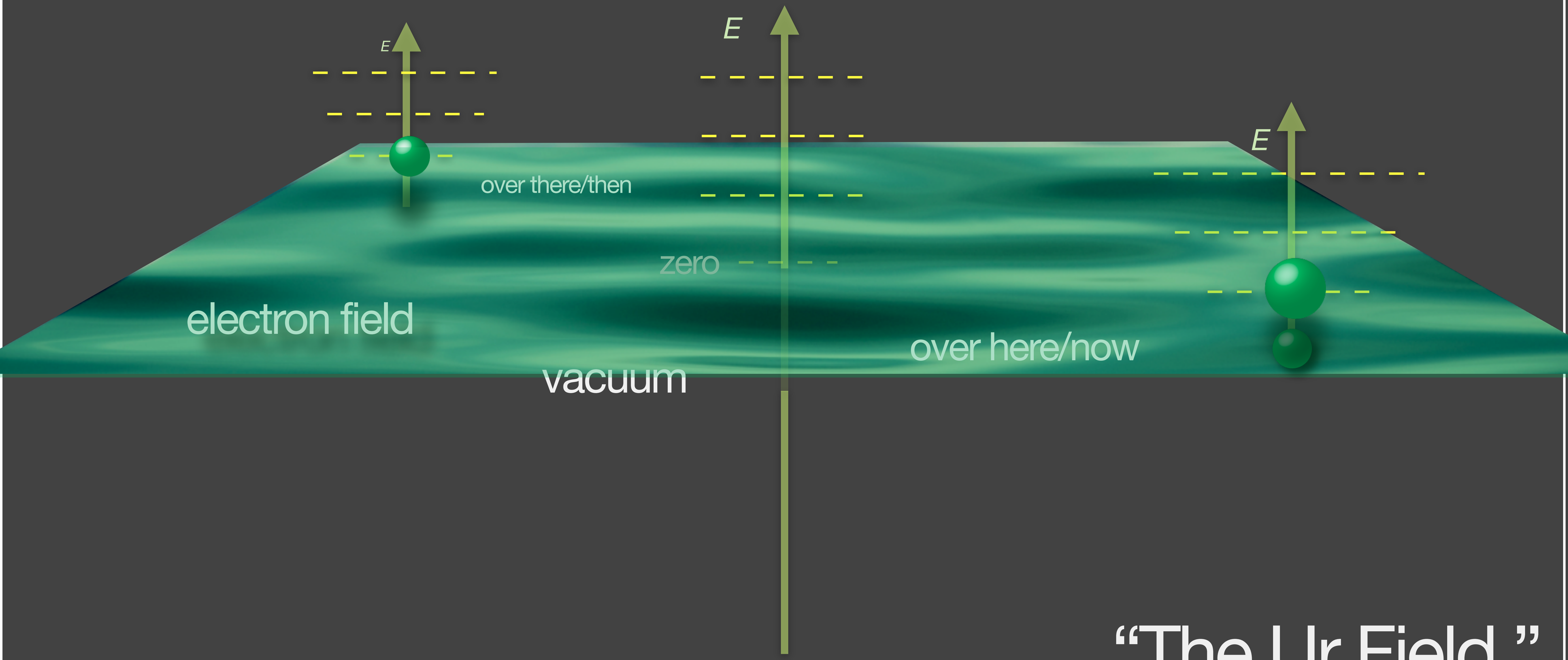
they are all popped out of the same stuff

the vacuum Field of the electron

electrons appear because they're coerced out of the vacuum

like by a photon



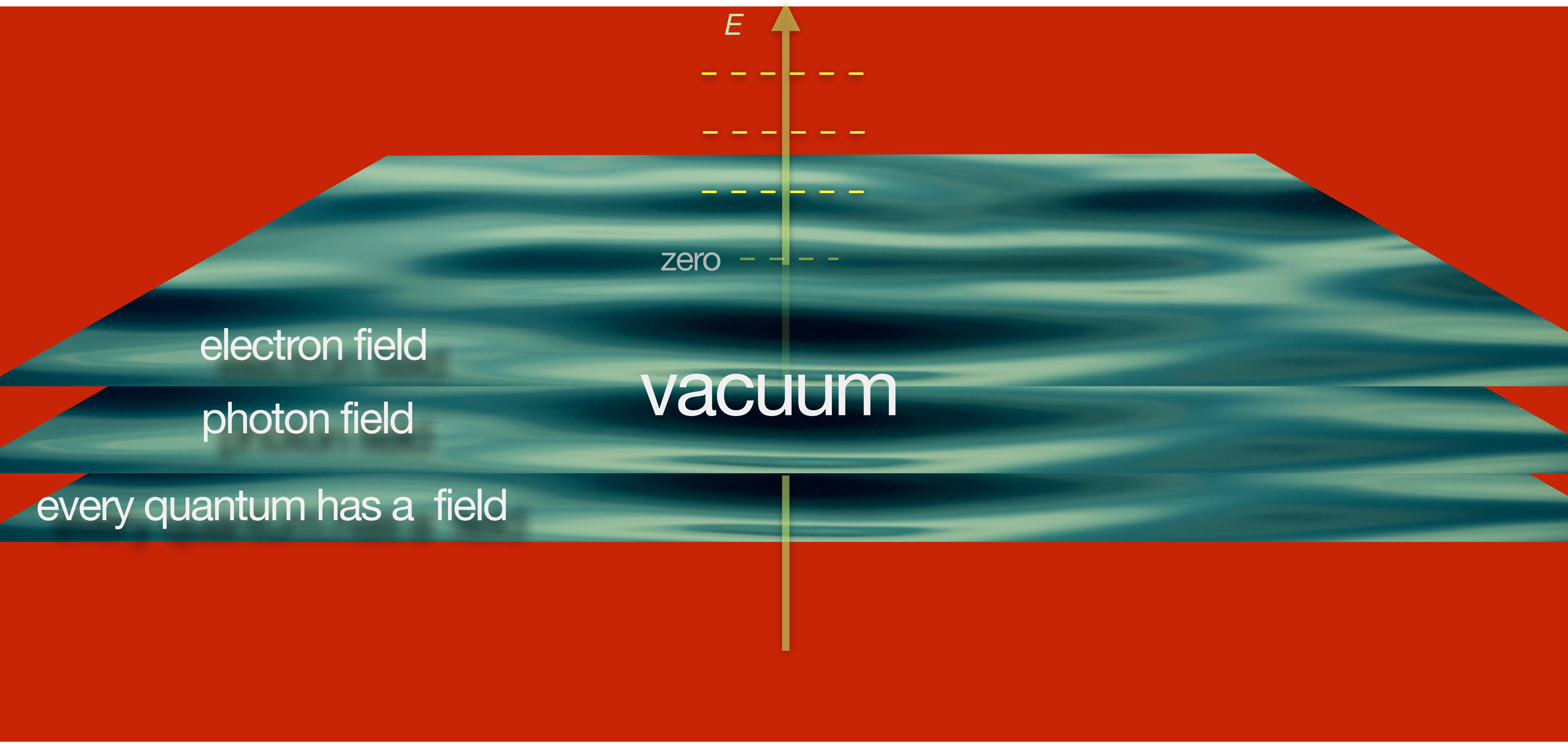


“The Ur Field.”

ur- |ʊ(ə)r| |ʊə| combining form primitive; original; earliest : *urtext.* ORIGIN from German.

but wait, there’s more

an Ur Field for every quantum


E
zero
electron field
photon field
every quantum has a field
vacuum

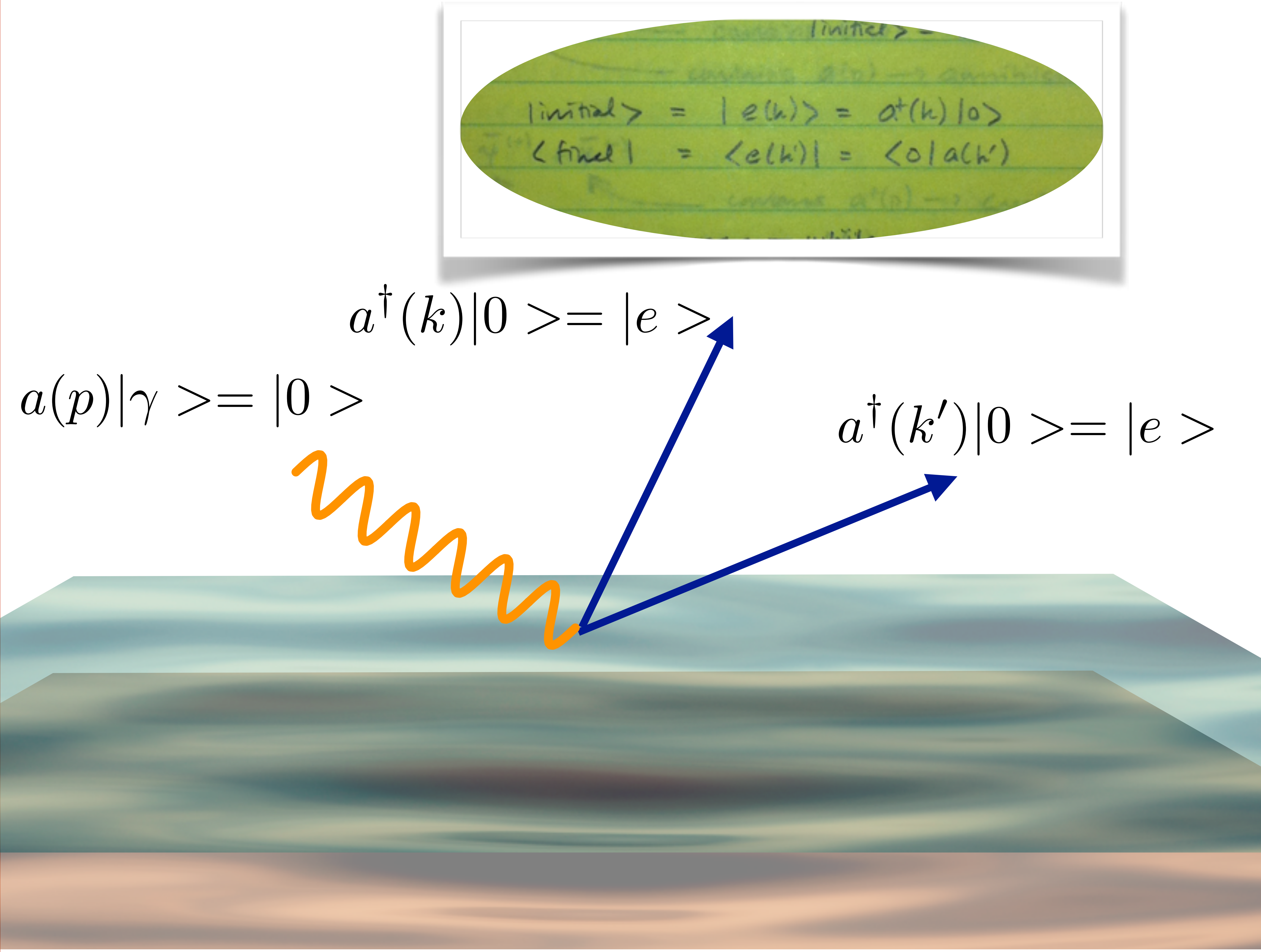
this was first understood for the EM field

Dirac put all particles on the same footing

a Field <---> quanta of that Field

the vacuum is a complicated place

what the mathematics tells us

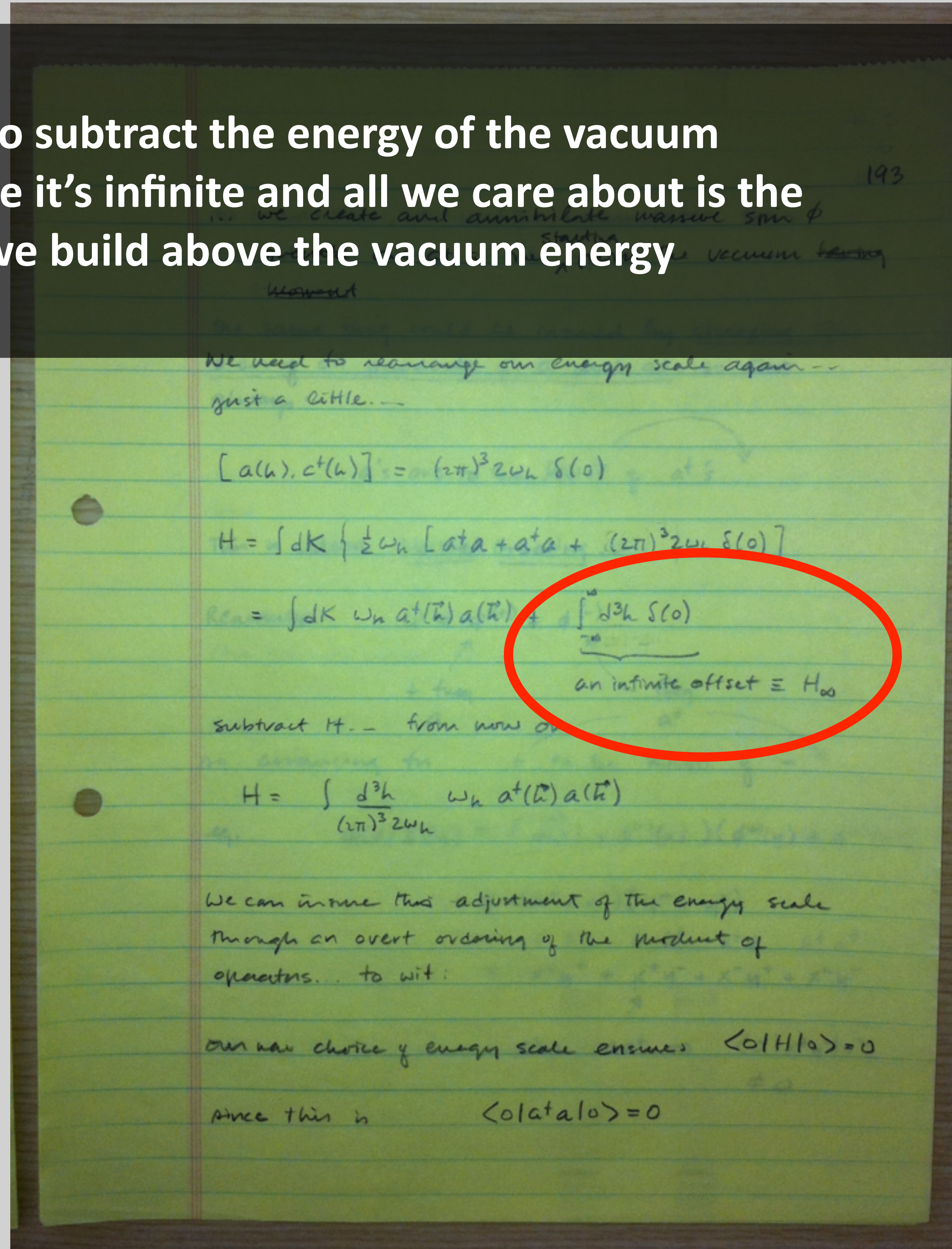


it’s not like the photon is now “in” the electron

the photon pops the electron- positron pair out of the Ur electron field
and itself disappears back into the Ur photon field.

but what does that mean?

we have to subtract the energy of the vacuum away...because it's infinite and all we care about is the states we build above the vacuum energy



it means that the vacuum is full of energy

like a reservoir

particles are created out of the vacuum

Okay. So we don’t like infinity

we subtract it away and worry about the difference between

infinity and finite energies of real particles

Seriously?

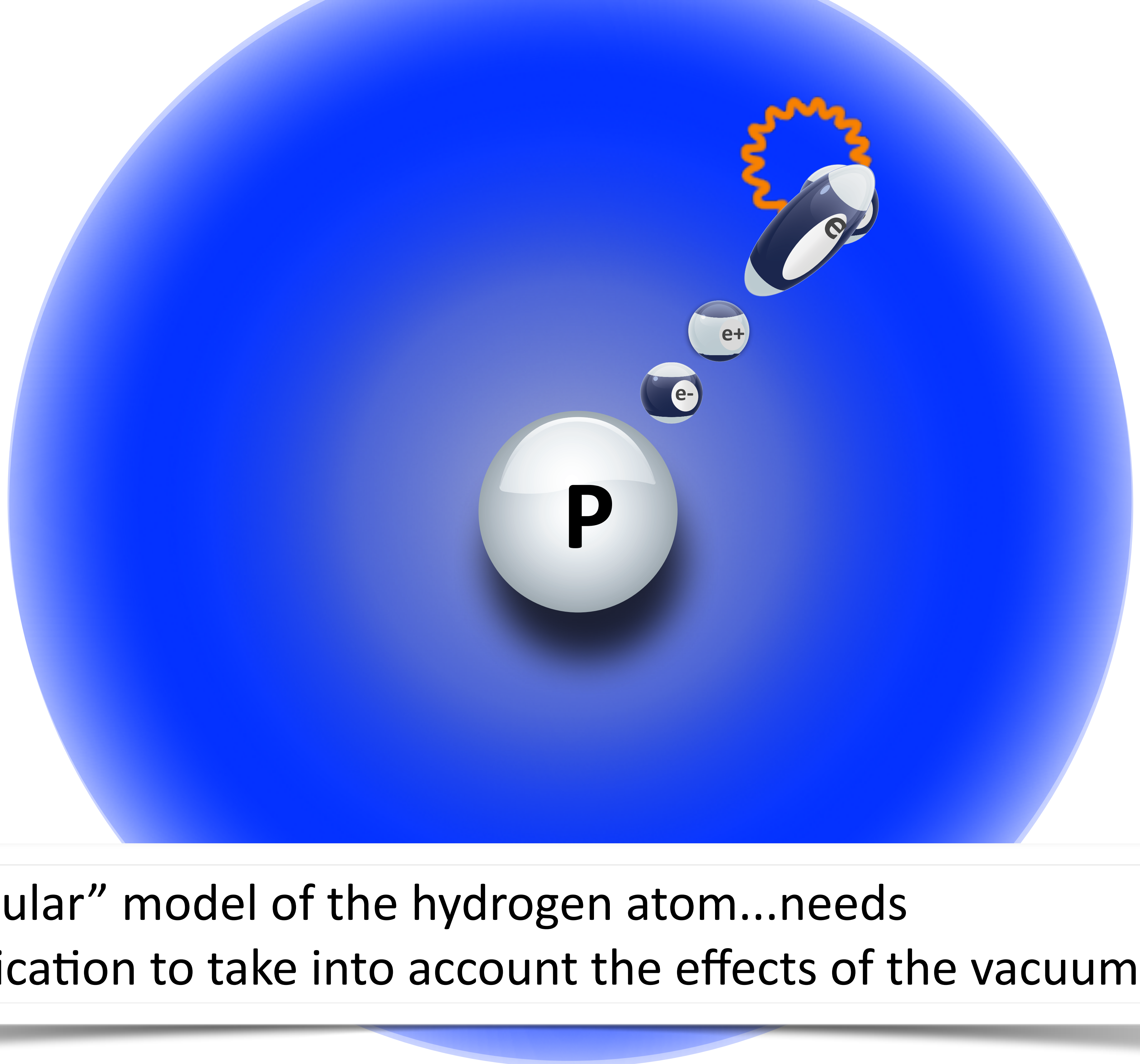
That seems to be the case.

This picture works with exquisite precision and accuracy.

but the vacuum

is roiling with particle-antiparticle "virtual pairs" popping into and out of existence

multiple ways we know this.



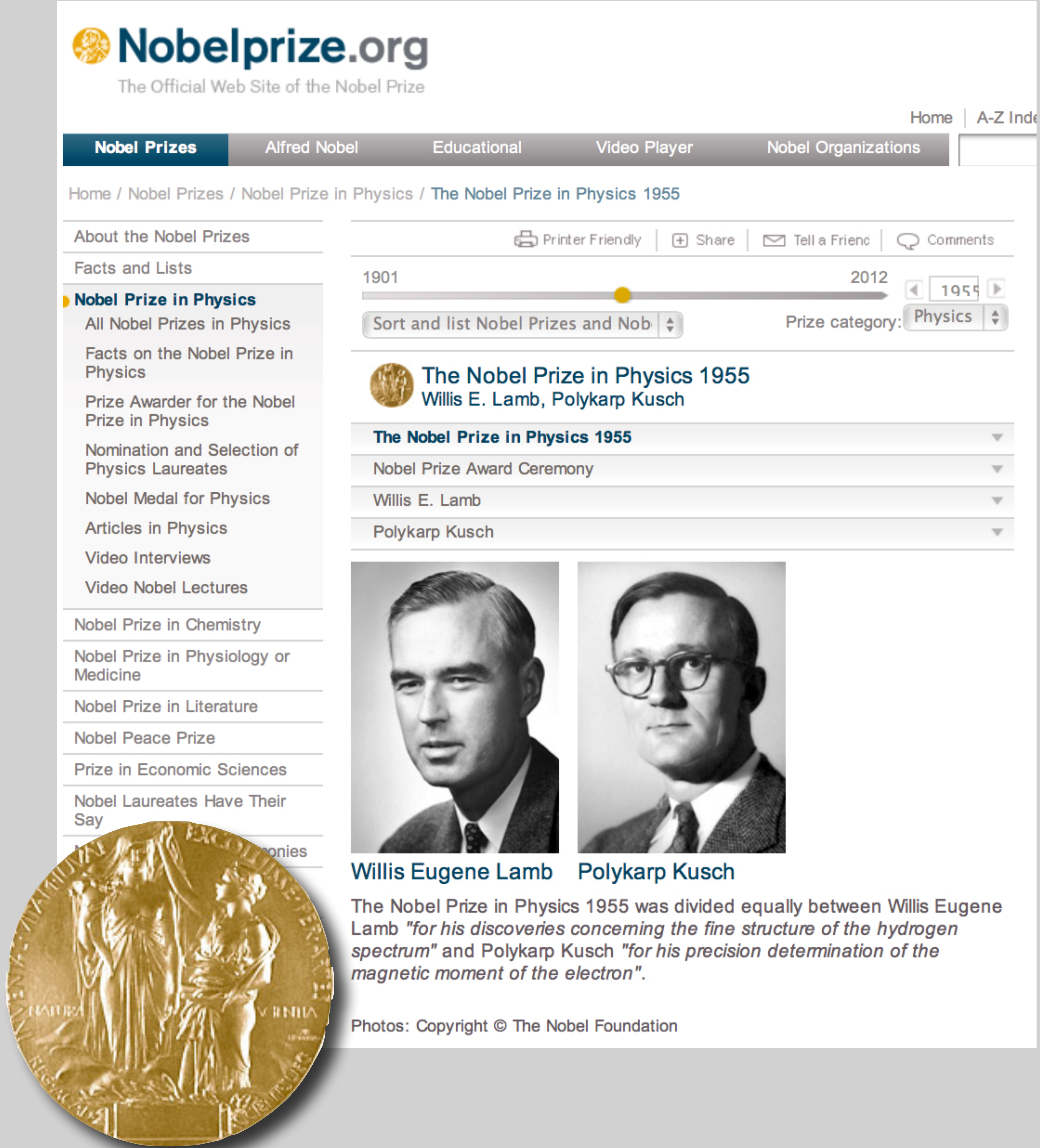
A "regular" model of the hydrogen atom...needs modification to take into account the effects of the vacuum

The electron cloud is spread out by the virtual photon and the positron's effects...and that changes the emission spectrum of hydrogen:
The **"Lamb Shift"**...measured after WWII with microwave technologies

1955 Nobel Prize

Willis E. Lamb

died just a few years ago at the University of Arizona

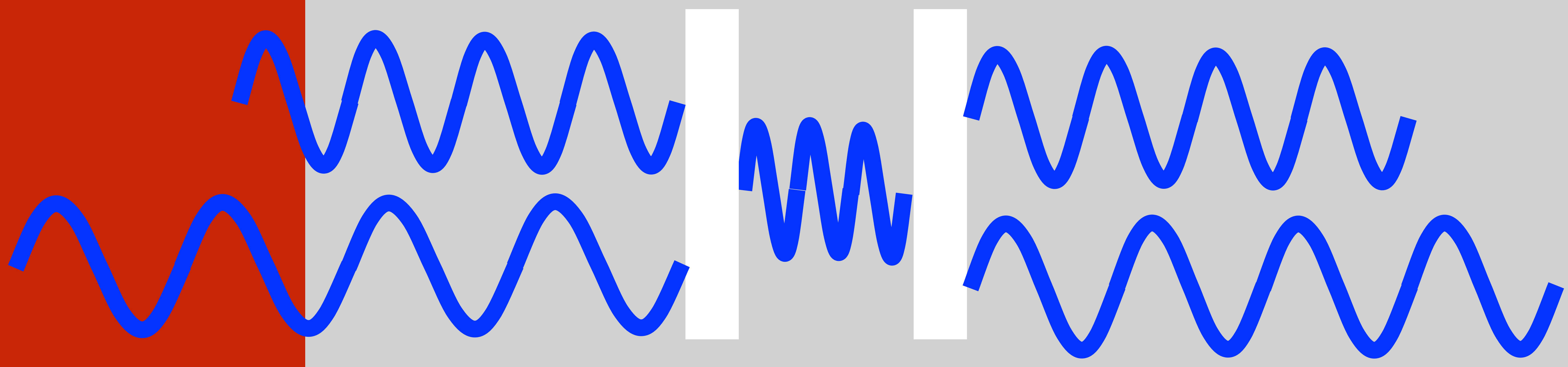


the "Casimir Effect"

two highly polished mirrors isolated from all external effects

The vacuum has all wavelengths of virtual waves from particles and fields...but fewer can fit between the walls

...and the pressure from the outside, moves them closer together



The amount is precisely predicted...and a few years ago the experiments confirmed it convincingly in 2001

the vacuum

is a very complicated thing

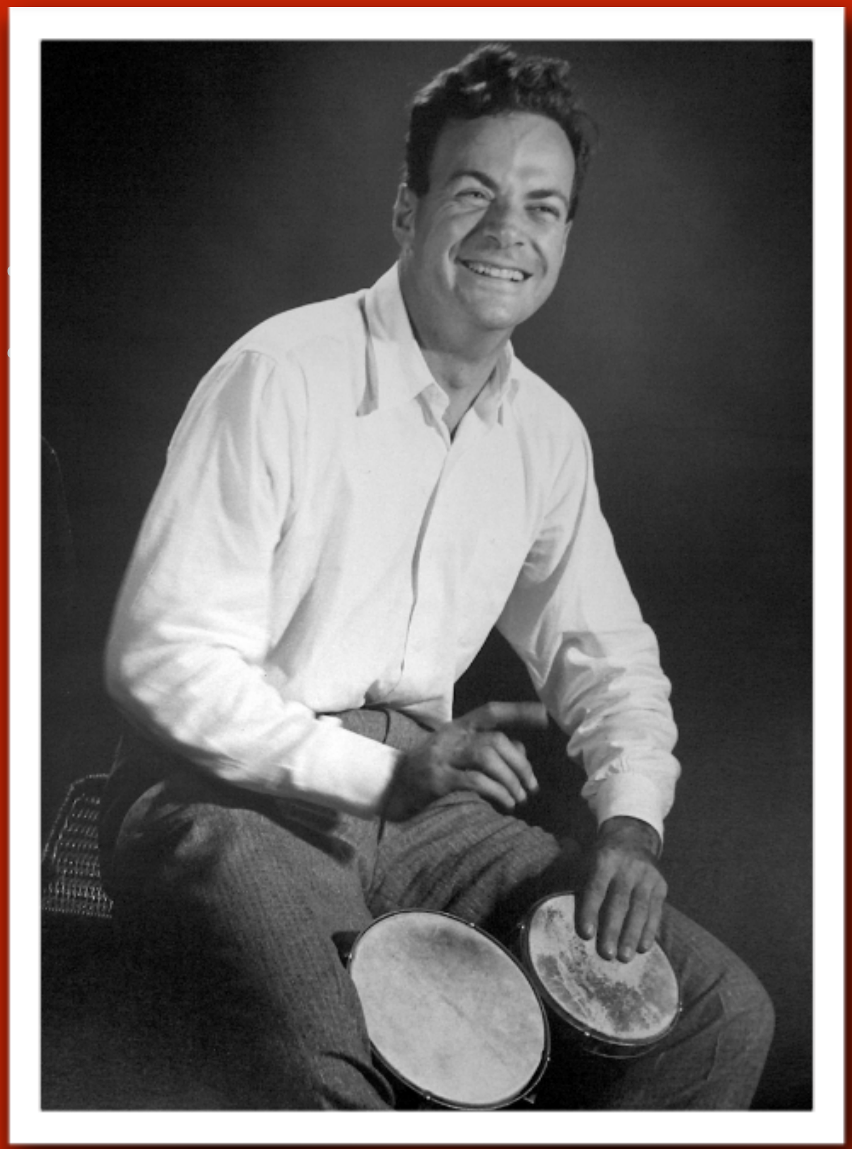
as we'll see when we get back to cosmology

Feynman Diagrams

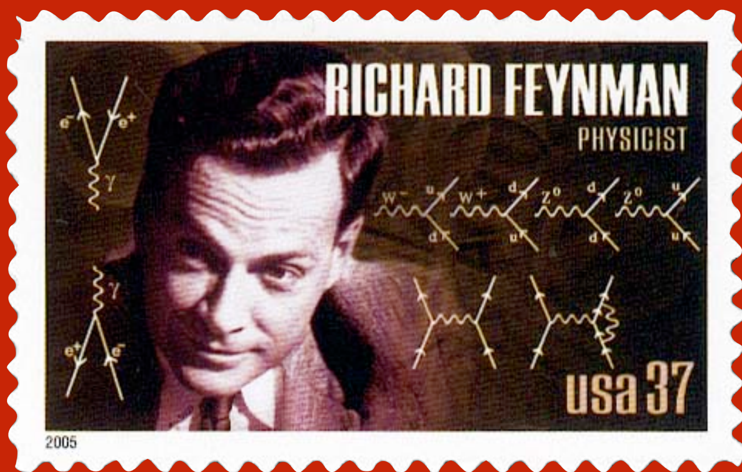
now for real.

`creation and annihilation of`

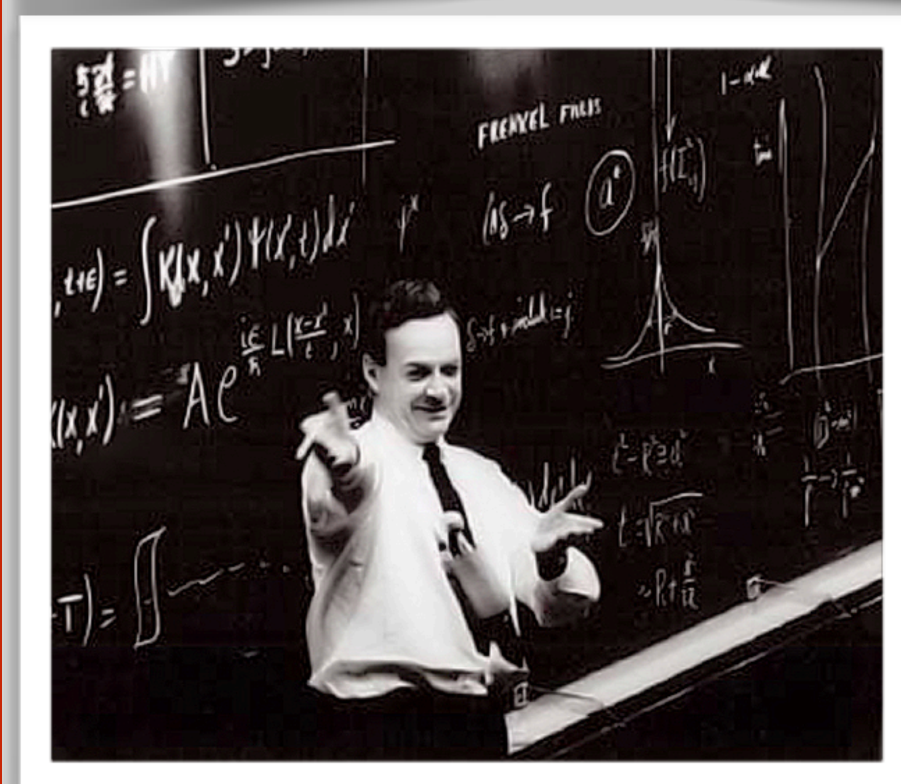
can be embodied in Feynman Diagrams

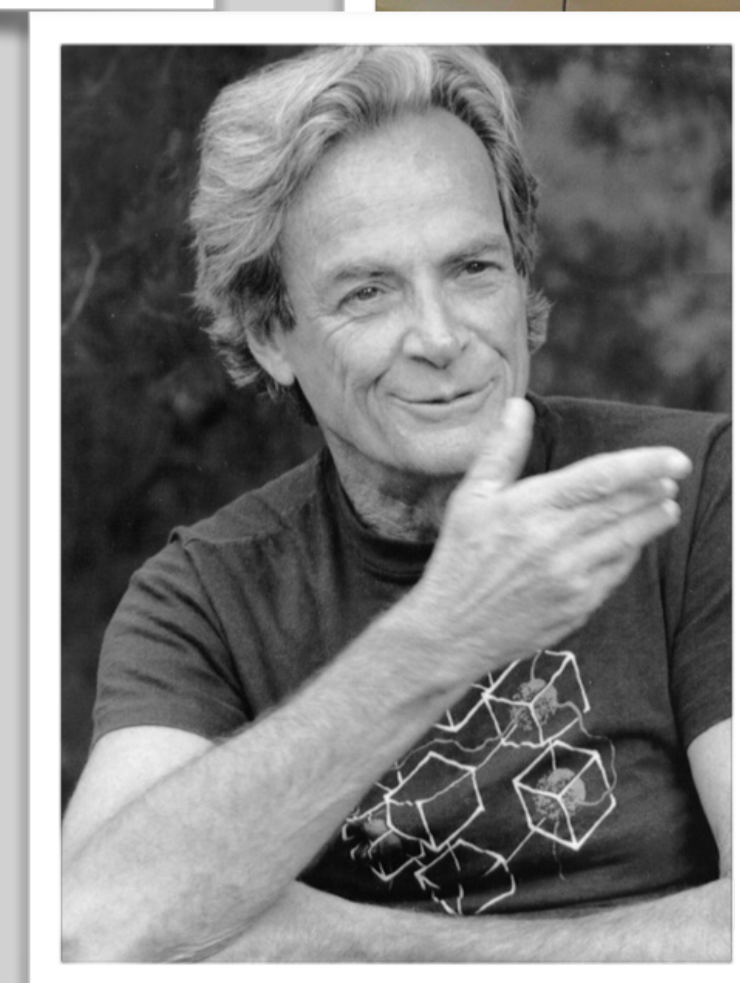


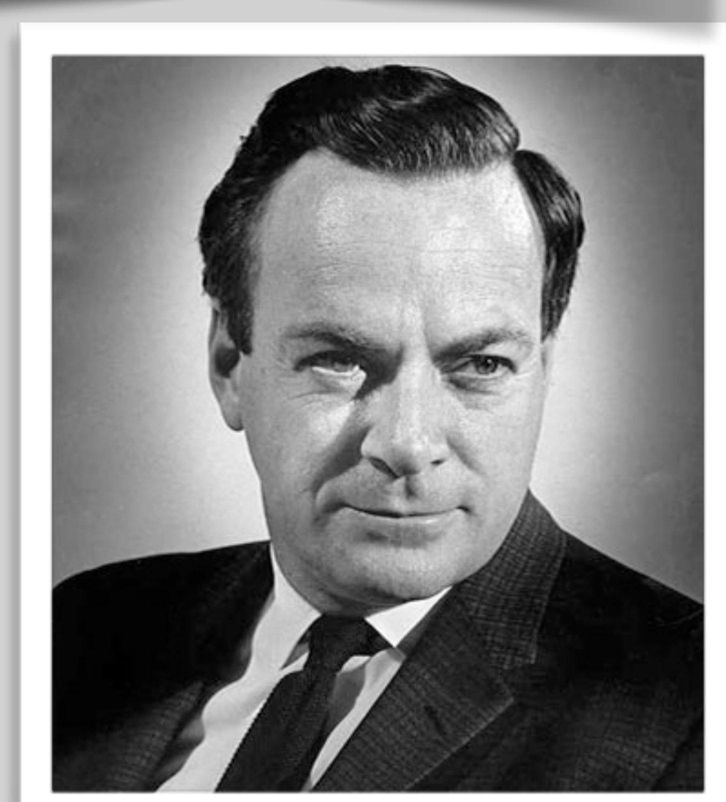
hero worship



about as close as we come

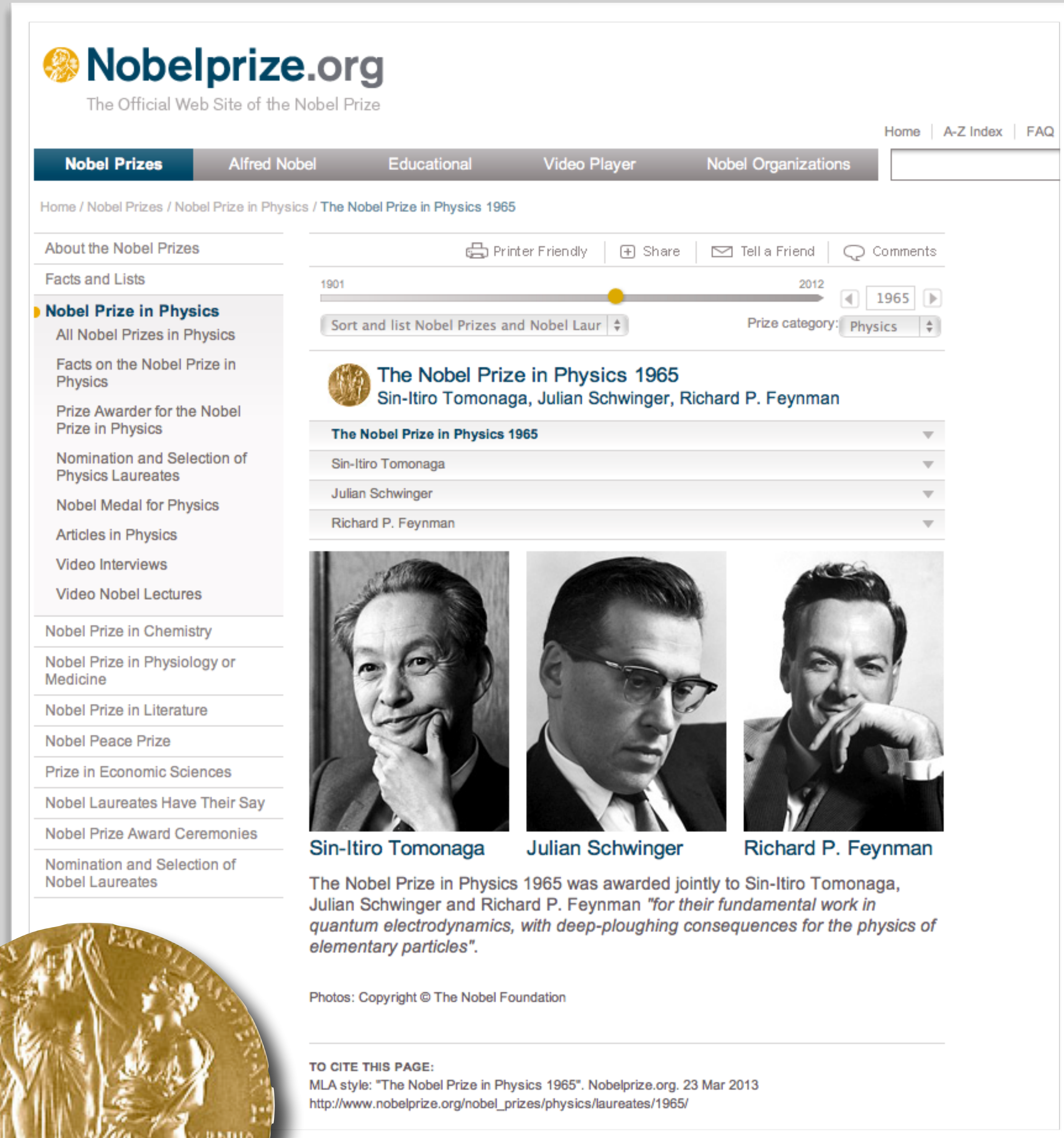






Richard Feynman, Sin-Itiro Tomonaga, Julian Schwinger

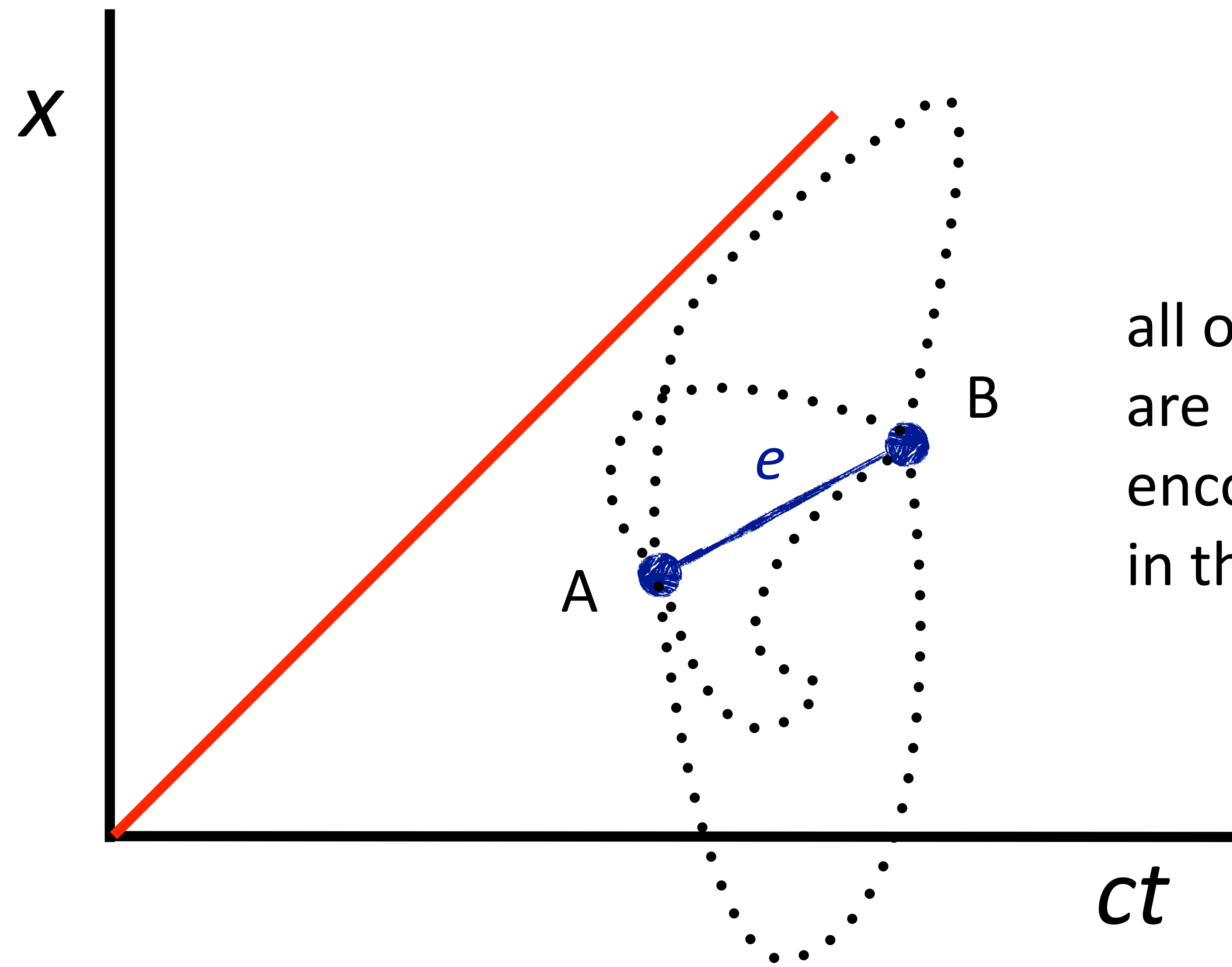
1965 Nobel



the symbols of Feynman Diagrams

each line represents an entire "history" of trajectories

to go from A to B, represent all histories with a single line.



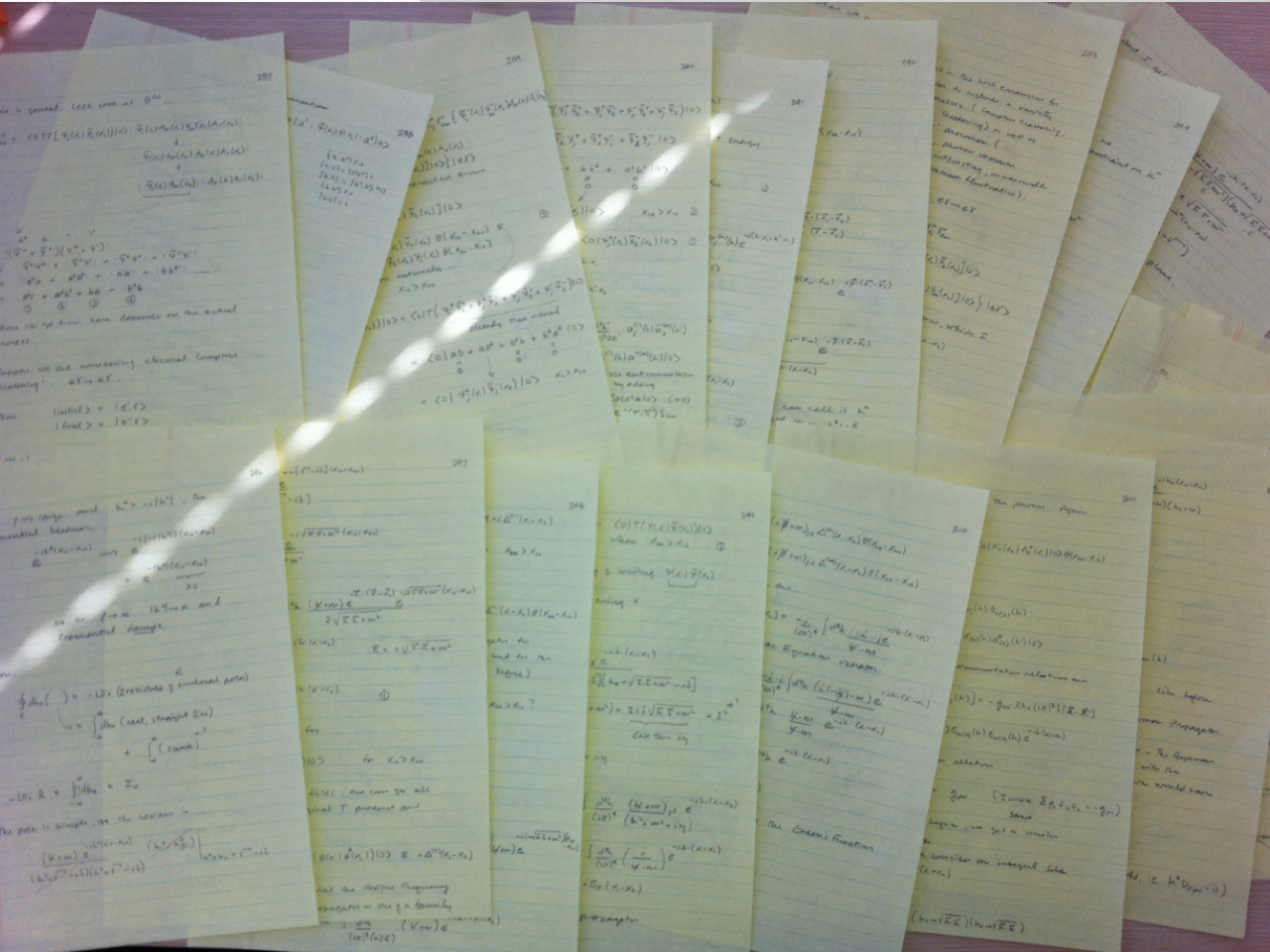
all of the paths are encompassed in the one line

Feynman's lines include rules on how to calculate the possibilities in a relativistically consistent way.

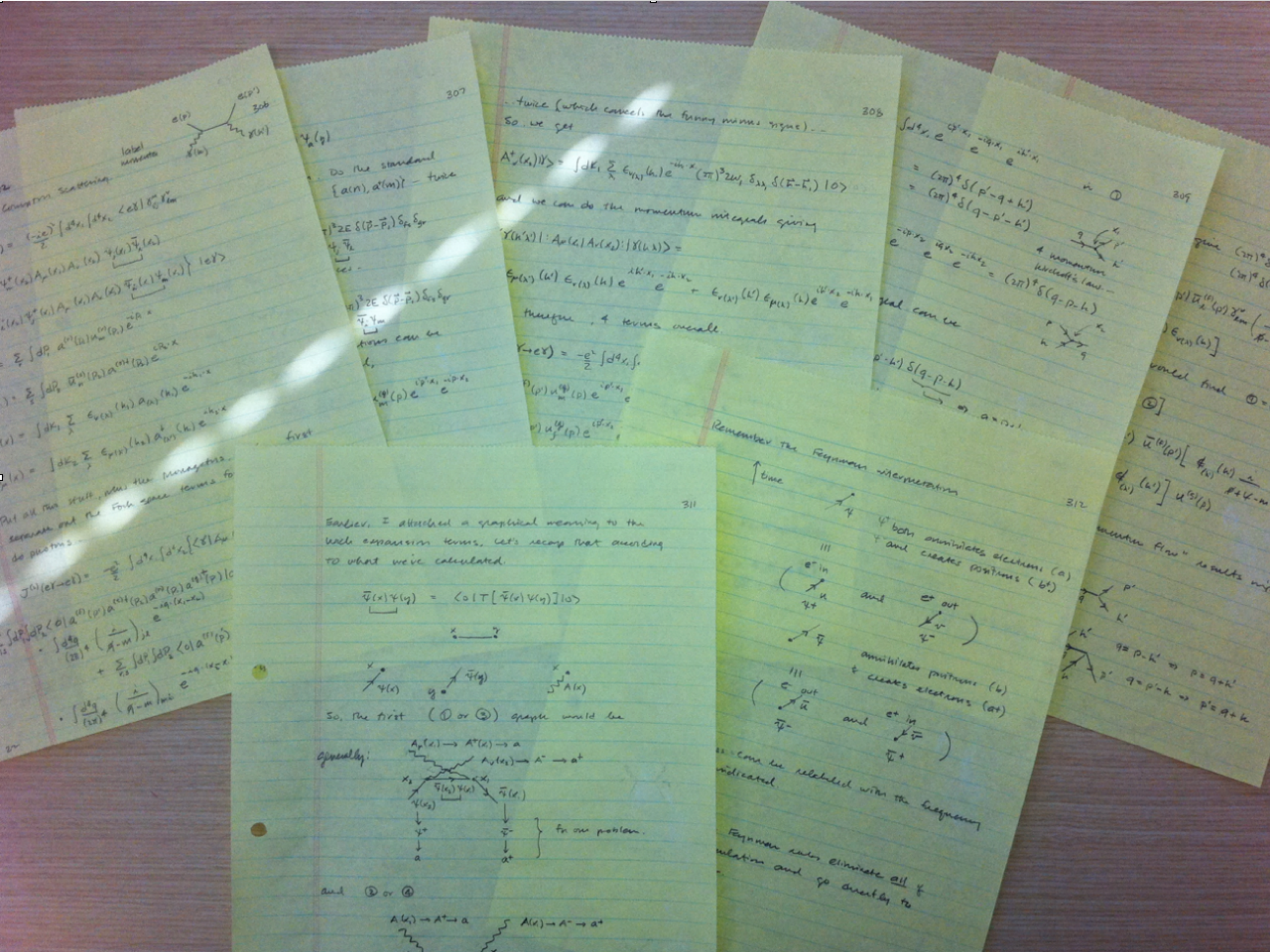
very efficient

avoids lots of technicalities.

When I teach these techniques to second year graduate students, I first do the calculation of Compton Scattering and do it without Feynman’s tools.



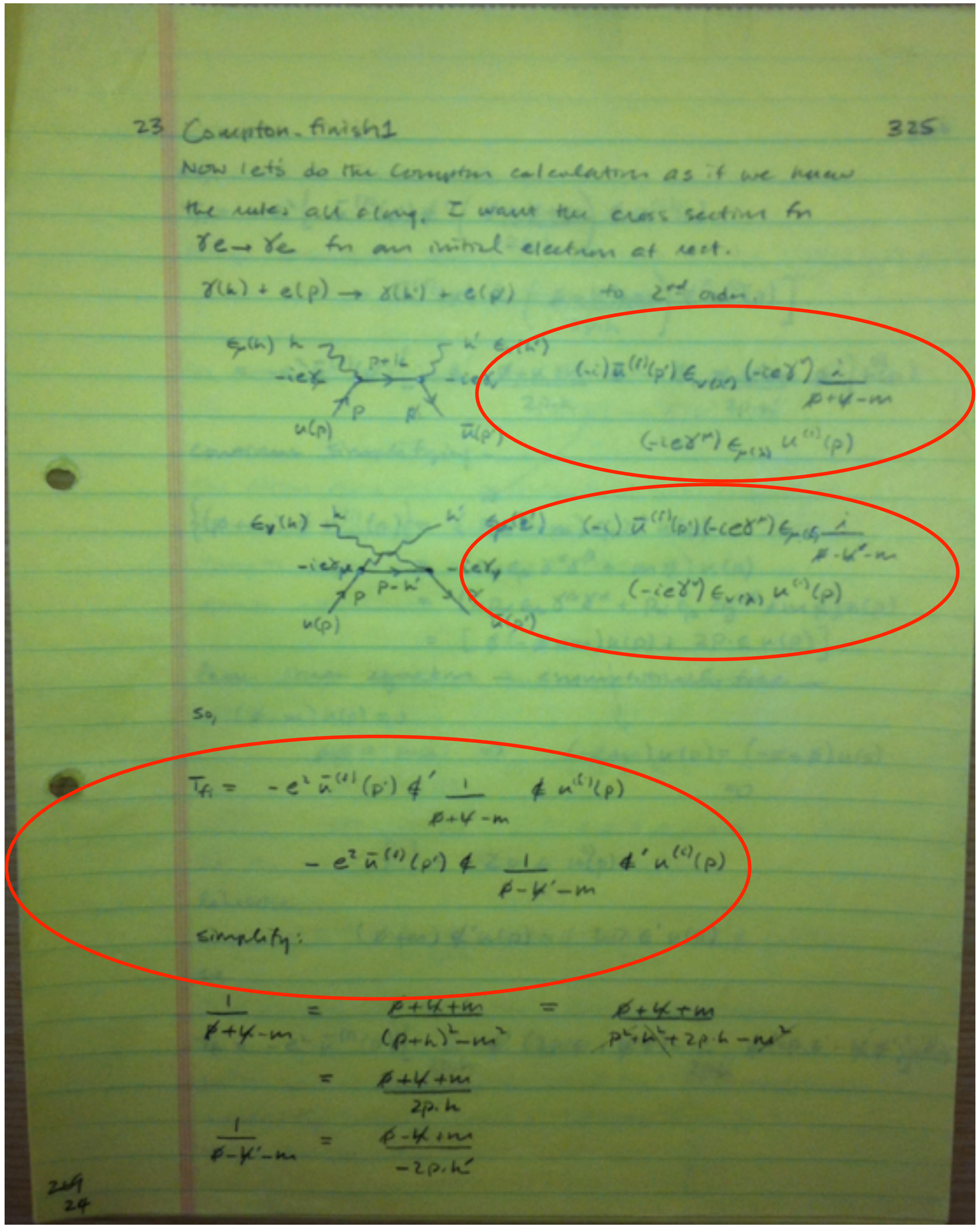
Call this $i\eta$
the Green's Function


307
Do the standard
308
twice (which cancels the funny minus signs)...
So we get
and we can do the momentum integrals giving
therefore, 4 terms overall.
309
4 momentum
conservation...
311
Earlier, I attached a graphical meaning to the
Wick expansion terms. Let's recap that according
to what we've calculated.
So, the first (① or ③) graph would be
Generally:
for our problem.
and ② or ④
312
Remember the Feynman interpretation
time
both annihilates electrons (a)
and creates positrons (b†)
e⁻ in
and
e⁺ out
annihilates positrons (b)
& creates electrons (a†)
e⁻ out
and
e⁺ in
can be relabeled with the frequency
indicated.
Feynman rules eliminate all
calculation and go directly to
Compton Scattering
label
momenta
first
momentum flow" results in

his rules eliminate all of that

and I can just write down the "answer"

appropriately labeled, each line tells us what to put into a long equation for further solving



our papers are full of diagrams

experimental ones:

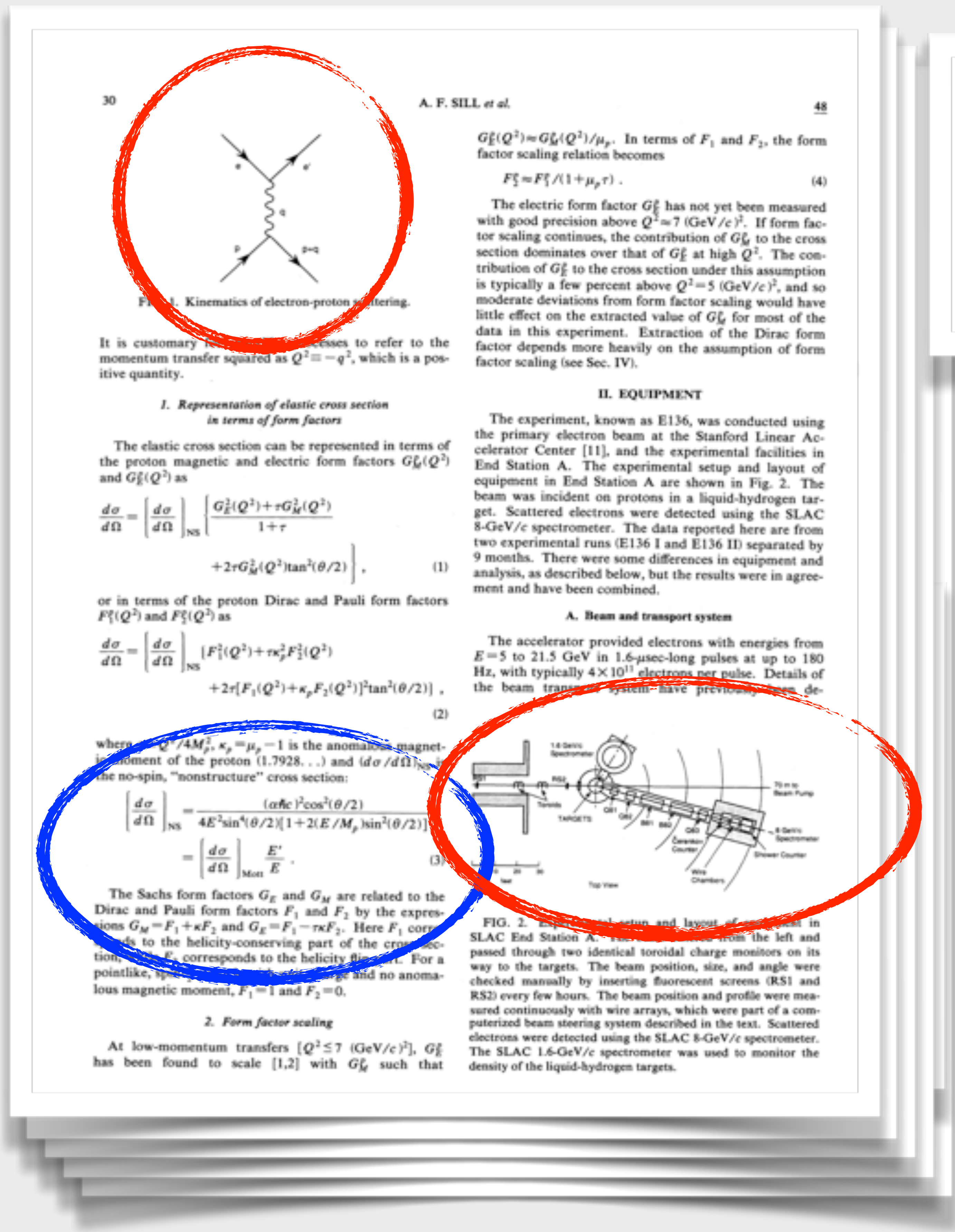


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FIG. 1. Kinematics of electron-proton scattering.

It is customary ... to refer to the momentum transfer squared as $Q^2 \equiv -q^2$, which is a positive quantity.

1. Representation of elastic cross section in terms of form factors

The elastic cross section can be represented in terms of the proton magnetic and electric form factors $G_M^p(Q^2)$ and $G_E^p(Q^2)$ as

$$\frac{d\sigma}{d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]_{NS} \left\{ \frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2(\theta/2) \right\}, \quad (1)$$

or in terms of the proton Dirac and Pauli form factors $F_1^p(Q^2)$ and $F_2^p(Q^2)$ as

$$\frac{d\sigma}{d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]_{NS} \{F_1^2(Q^2)+\tau\kappa_p^2 F_2^2(Q^2) + 2\tau[F_1(Q^2)+\kappa_p F_2(Q^2)]^2\tan^2(\theta/2)\}, \quad (2)$$

where ... $Q^2/4M_p^2$, $\kappa_p=\mu_p-1$ is the anomalous magnetic moment of the proton (1.7928...) and $(d\sigma/d\Omega)_{NS}$ is the no-spin, "nonstructure" cross section:

$$\left[\frac{d\sigma}{d\Omega}\right]_{NS} = \frac{(\alpha\hbar c)^2\cos^2(\theta/2)}{4E^2\sin^4(\theta/2)[1+2(E/M_p)\sin^2(\theta/2)]} = \left[\frac{d\sigma}{d\Omega}\right]_{Mott}\frac{E'}{E}. \quad (3)$$

The Sachs form factors G_E and G_M are related to the Dirac and Pauli form factors F_1 and F_2 by the expressions $G_M=F_1+\kappa F_2$ and $G_E=F_1-\tau\kappa F_2$. Here F_1 corresponds to the helicity-conserving part of the cross section, ... F_2 corresponds to the helicity flip part. For a pointlike, ... and no anomalous magnetic moment, $F_1=1$ and $F_2=0$.

2. Form factor scaling

At low-momentum transfers [$Q^2 \le 7$ (GeV/c)^2], G_E^p has been found to scale [1,2] with G_M^p such that $G_E^p(Q^2) \approx G_M^p(Q^2)/\mu_p$. In terms of F_1 and F_2, the form factor scaling relation becomes

$$F_2^p \approx F_1^p/(1+\mu_p\tau). \quad (4)$$

The electric form factor G_E^p has not yet been measured with good precision above $Q^2 \approx 7$ (GeV/c)^2. If form factor scaling continues, the contribution of G_M^p to the cross section dominates over that of G_E^p at high Q^2. The contribution of G_E^p to the cross section under this assumption is typically a few percent above $Q^2=5$ (GeV/c)^2, and so moderate deviations from form factor scaling would have little effect on the extracted value of G_M^p for most of the data in this experiment. Extraction of the Dirac form factor depends more heavily on the assumption of form factor scaling (see Sec. IV).

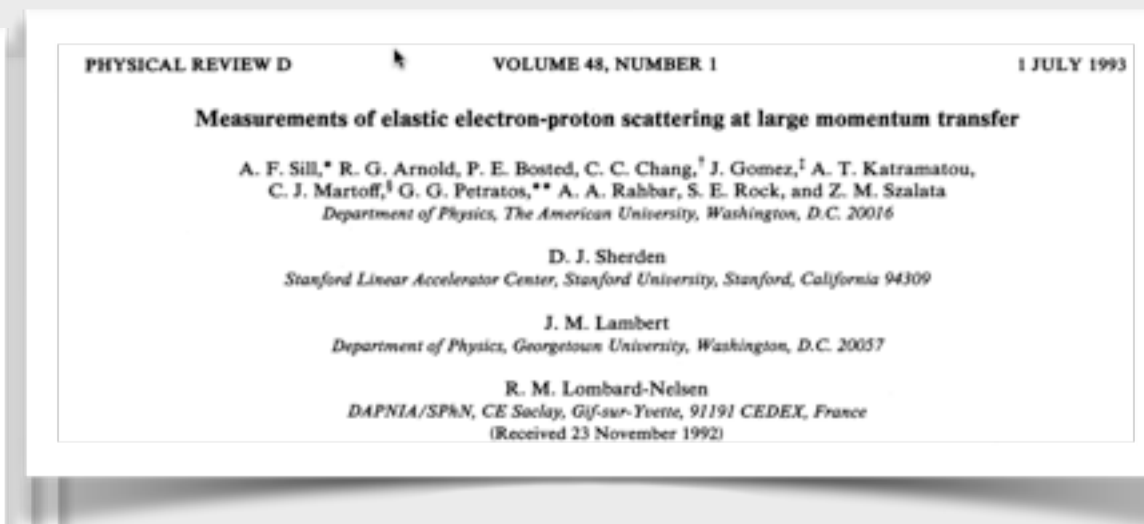
II. EQUIPMENT

The experiment, known as E136, was conducted using the primary electron beam at the Stanford Linear Accelerator Center [11], and the experimental facilities in End Station A. The experimental setup and layout of equipment in End Station A are shown in Fig. 2. The beam was incident on protons in a liquid-hydrogen target. Scattered electrons were detected using the SLAC 8-GeV/c spectrometer. The data reported here are from two experimental runs (E136 I and E136 II) separated by 9 months. There were some differences in equipment and analysis, as described below, but the results were in agreement and have been combined.

A. Beam and transport system

The accelerator provided electrons with energies from $E=5$ to 21.5 GeV in 1.6-μsec-long pulses at up to 180 Hz, with typically 4×10^{11} electrons per pulse. Details of the beam ... have previously been de-

FIG. 2. ... setup and layout of ... in SLAC End Station A. ... from the left and passed through two identical toroidal charge monitors on its way to the targets. The beam position, size, and angle were checked manually by inserting fluorescent screens (RS1 and RS2) every few hours. The beam position and profile were measured continuously with wire arrays, which were part of a computerized beam steering system described in the text. Scattered electrons were detected using the SLAC 8-GeV/c spectrometer. The SLAC 1.6-GeV/c spectrometer was used to monitor the density of the liquid-hydrogen targets.



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Measurements of elastic electron-proton scattering at large momentum transfer

A. F. Sill,* R. G. Arnold, P. E. Bosted, C. C. Chang,† J. Gomez,‡ A. T. Katramatou, C. J. Martoff,§ G. G. Petratos,** A. A. Rahbar, S. E. Rock, and Z. M. Szalata
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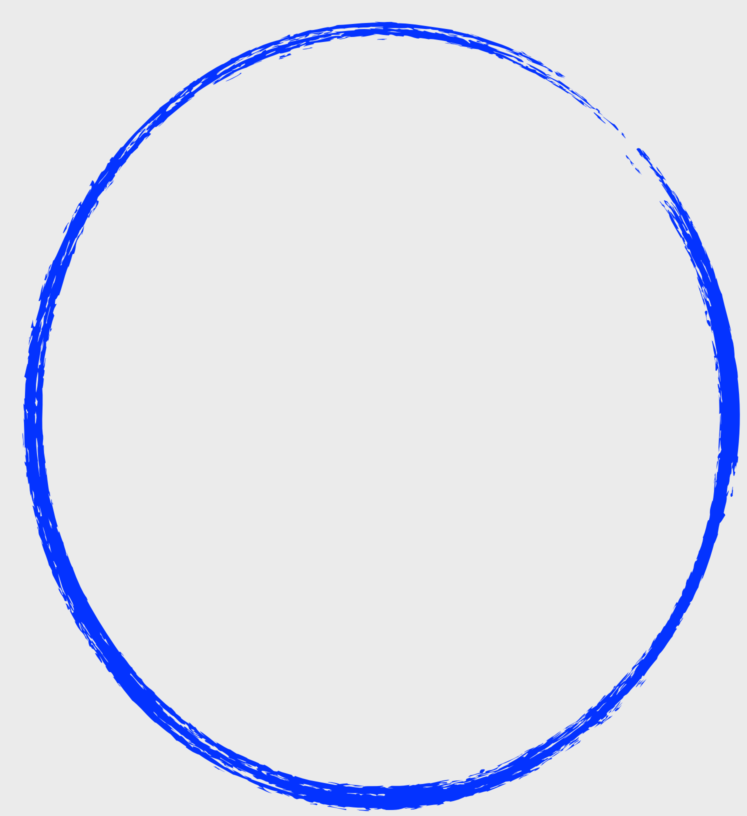
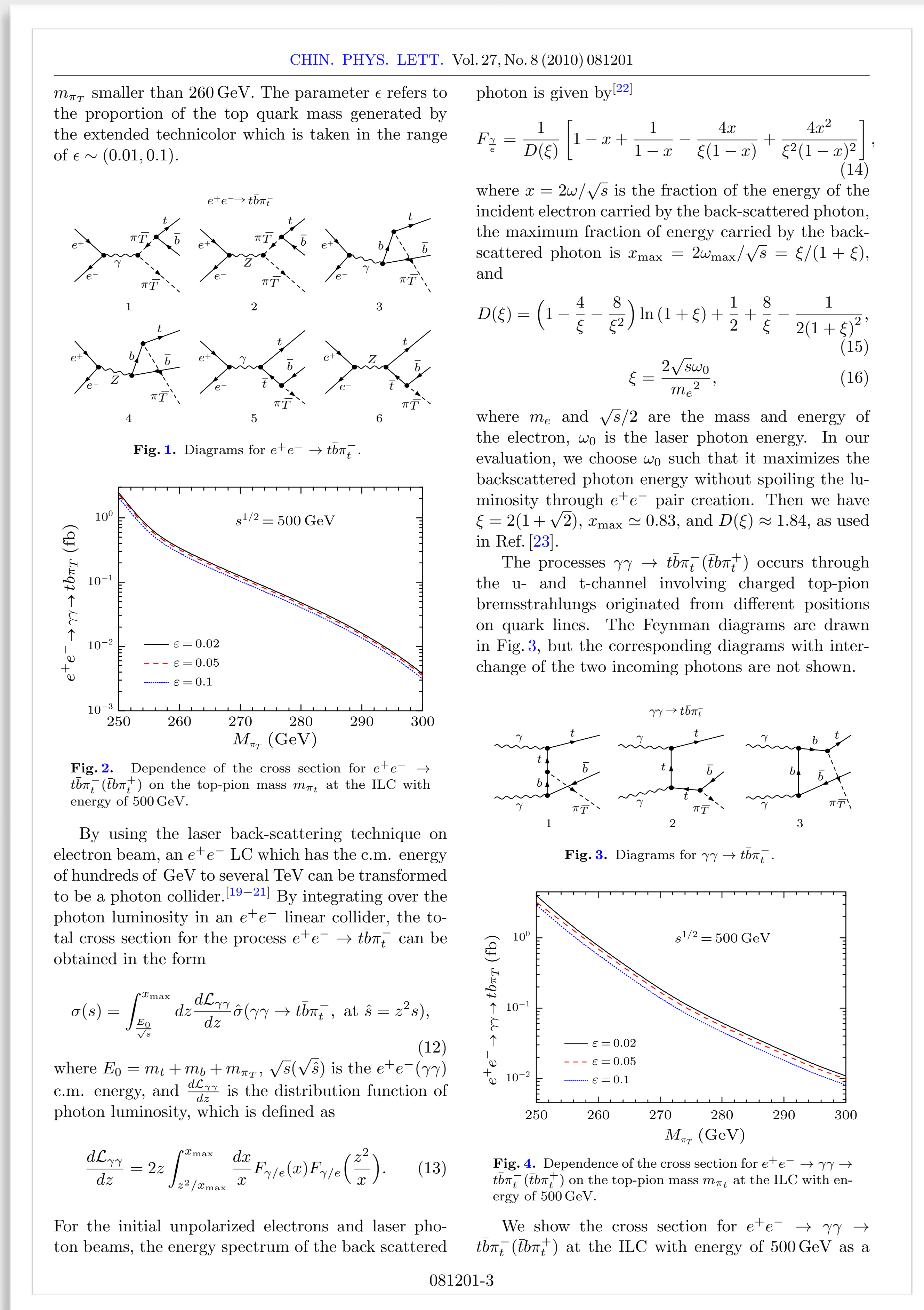
(Received 23 November 1992)



theoretical papers

each diagram is a complicated calculation



CHIN. PHYS. LETT. Vol. 27, No. 8 (2010) 081201

m_{π_T} smaller than 260 GeV. The parameter ϵ refers to the proportion of the top quark mass generated by the extended technicolor which is taken in the range of $\epsilon \sim (0.01, 0.1)$.

Fig. 1. Diagrams for $e^+e^- \to t\bar{b}\pi_t^-$.

Fig. 2. Dependence of the cross section for $e^+e^- \to t\bar{b}\pi_t^-\,(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

By using the laser back-scattering technique on electron beam, an e^+e^- LC which has the c.m. energy of hundreds of GeV to several TeV can be transformed to be a photon collider.[19–21] By integrating over the photon luminosity in an e^+e^- linear collider, the total cross section for the process $e^+e^- \to t\bar{b}\pi_t^-$ can be obtained in the form

$$\sigma(s) = \int_{\frac{E_0}{\sqrt{s}}}^{x_{\max}} dz \frac{d\mathcal{L}_{\gamma\gamma}}{dz} \hat{\sigma}(\gamma\gamma \to t\bar{b}\pi_t^-, \text{ at } \hat{s} = z^2 s), \tag{12}$$

where $E_0 = m_t + m_b + m_{\pi_T}$, $\sqrt{s}(\sqrt{\hat{s}})$ is the $e^+e^-(\gamma\gamma)$ c.m. energy, and $\frac{d\mathcal{L}_{\gamma\gamma}}{dz}$ is the distribution function of photon luminosity, which is defined as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = 2z \int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}\Big(\frac{z^2}{x}\Big). \tag{13}$$

For the initial unpolarized electrons and laser photon beams, the energy spectrum of the back scattered photon is given by[22]

$$F_{\frac{\gamma}{e}} = \frac{1}{D(\xi)}\Big[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\Big], \tag{14}$$

where $x = 2\omega/\sqrt{s}$ is the fraction of the energy of the incident electron carried by the back-scattered photon, the maximum fraction of energy carried by the back-scattered photon is $x_{\max} = 2\omega_{\max}/\sqrt{s} = \xi/(1+\xi)$, and

$$D(\xi) = \Big(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\Big)\ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2}, \tag{15}$$

$$\xi = \frac{2\sqrt{s}\omega_0}{{m_e}^2}, \tag{16}$$

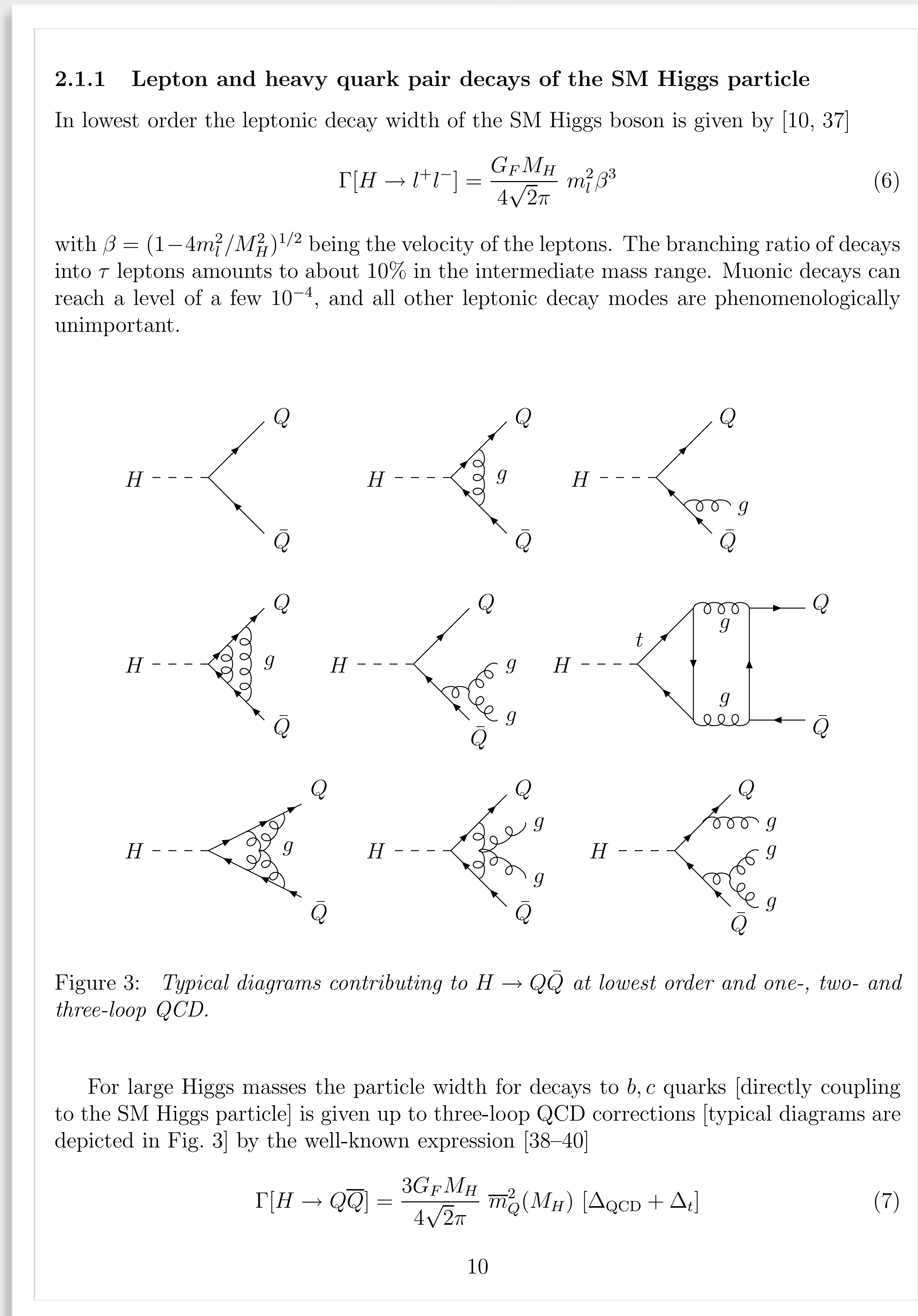
where m_e and $\sqrt{s}/2$ are the mass and energy of the electron, ω_0 is the laser photon energy. In our evaluation, we choose ω_0 such that it maximizes the backscattered photon energy without spoiling the luminosity through e^+e^- pair creation. Then we have $\xi = 2(1+\sqrt{2})$, $x_{\max} \simeq 0.83$, and $D(\xi) \approx 1.84$, as used in Ref. [23].

The processes $\gamma\gamma \to t\bar{b}\pi_t^-\,(\bar{t}b\pi_t^+)$ occurs through the u- and t-channel involving charged top-pion bremsstrahlungs originated from different positions on quark lines. The Feynman diagrams are drawn in Fig. 3, but the corresponding diagrams with interchange of the two incoming photons are not shown.

Fig. 3. Diagrams for $\gamma\gamma \to t\bar{b}\pi_t^-$.

Fig. 4. Dependence of the cross section for $e^+e^- \to \gamma\gamma \to t\bar{b}\pi_t^-\,(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

We show the cross section for $e^+e^- \to \gamma\gamma \to t\bar{b}\pi_t^-\,(\bar{t}b\pi_t^+)$ at the ILC with energy of 500 GeV as a



2.1.1 Lepton and heavy quark pair decays of the SM Higgs particle

In lowest order the leptonic decay width of the SM Higgs boson is given by [10, 37]

$$\Gamma[H \to l^+l^-] = \frac{G_F M_H}{4\sqrt{2}\pi}\, m_l^2 \beta^3 \tag{6}$$

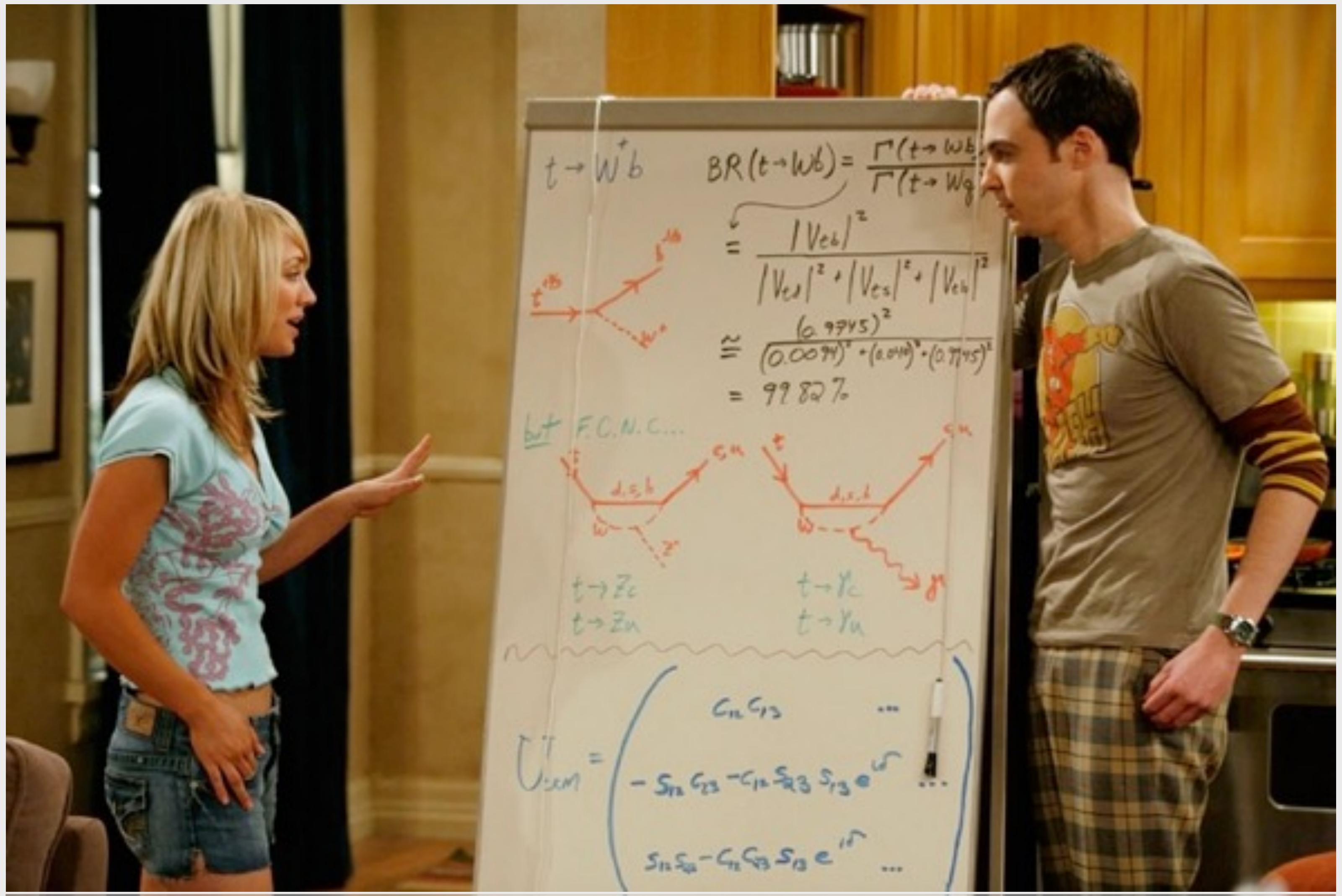
with $\beta = (1 - 4m_l^2/M_H^2)^{1/2}$ being the velocity of the leptons. The branching ratio of decays into τ leptons amounts to about 10% in the intermediate mass range. Muonic decays can reach a level of a few 10^{-4}, and all other leptonic decay modes are phenomenologically unimportant.

Figure 3: *Typical diagrams contributing to $H \to Q\bar{Q}$ at lowest order and one-, two- and three-loop QCD.*

For large Higgs masses the particle width for decays to b, c quarks [directly coupling to the SM Higgs particle] is given up to three-loop QCD corrections [typical diagrams are depicted in Fig. 3] by the well-known expression [38–40]

$$\Gamma[H \to Q\overline{Q}] = \frac{3G_F M_H}{4\sqrt{2}\pi}\, \overline{m}_Q^2(M_H)\, [\Delta_{\rm QCD} + \Delta_t] \tag{7}$$

we really do use Feynman Diagrams



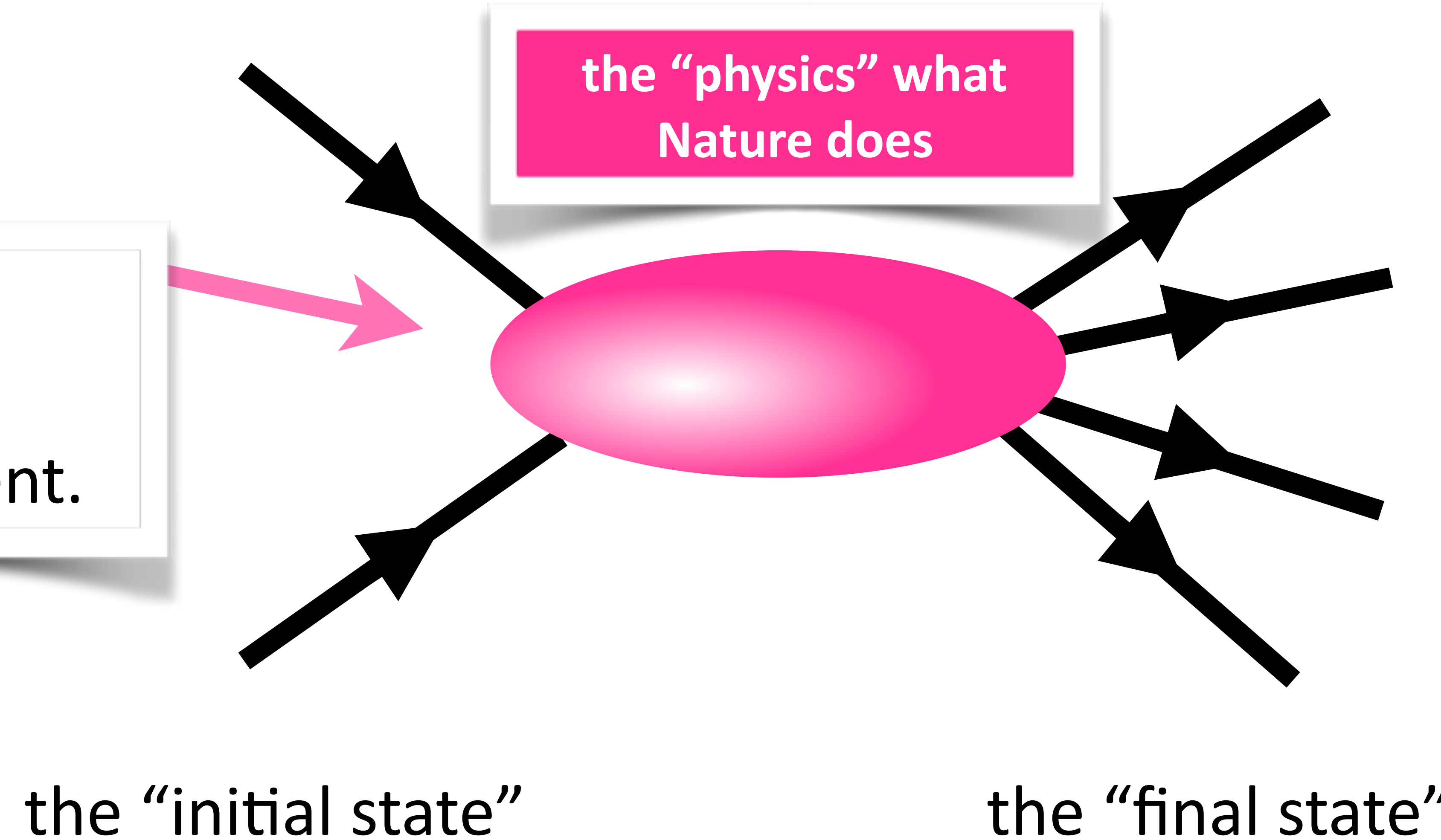
always the same thing

initial "state"

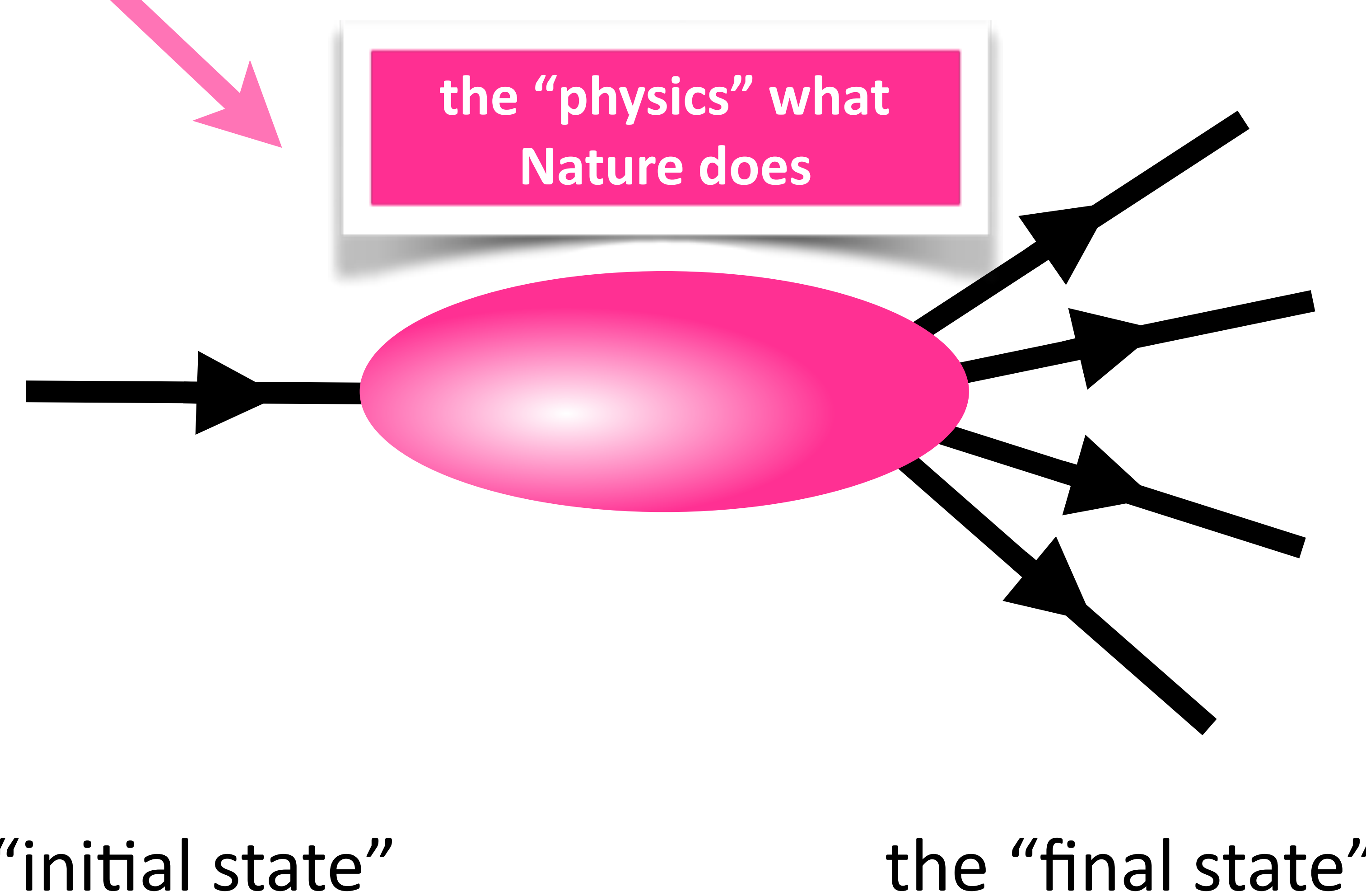
final "state"

in-between

A collision
or
scattering event.



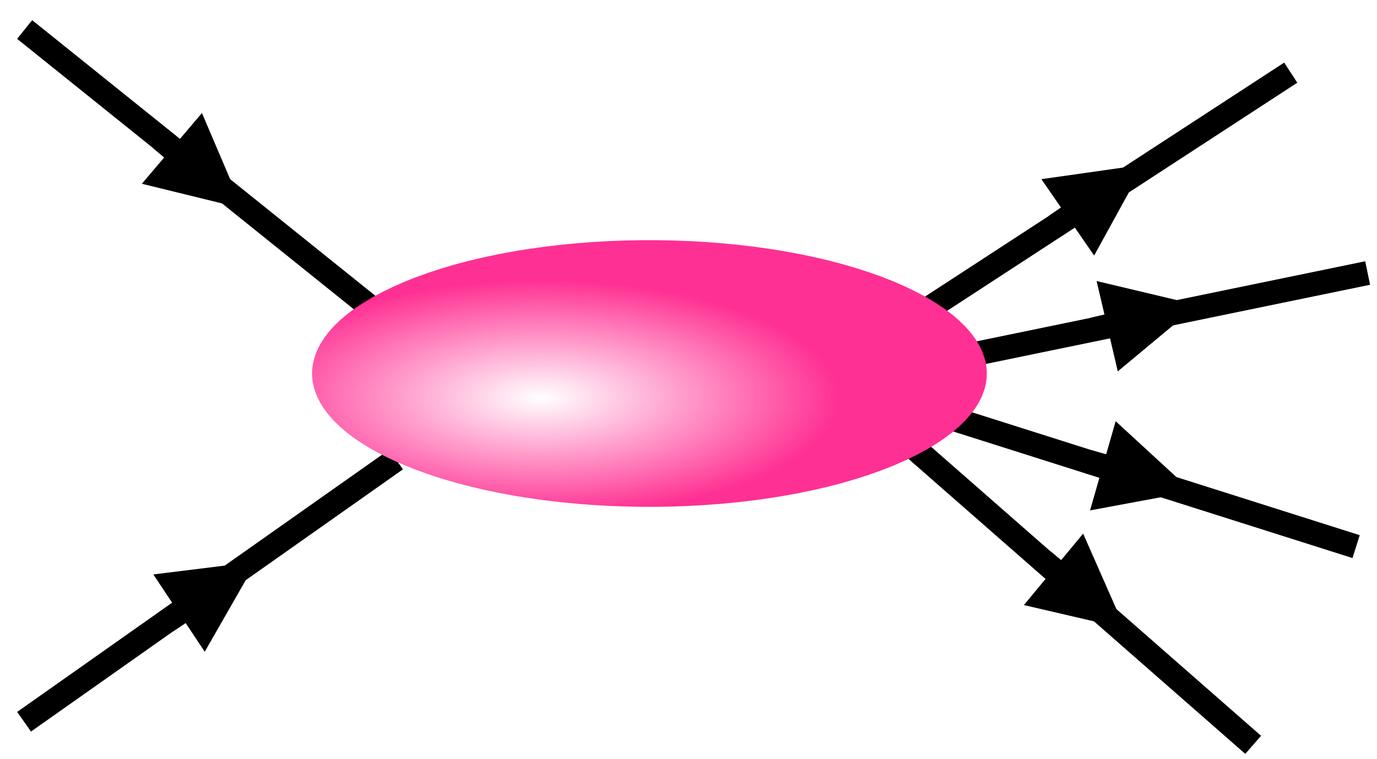
A decay.



like cooking

probably lousy metaphor

the "initial state" | the chemistry of cooking | the "final state"



the "initial state" | the "final state"

Feynman's approach is really sneaky and really cute

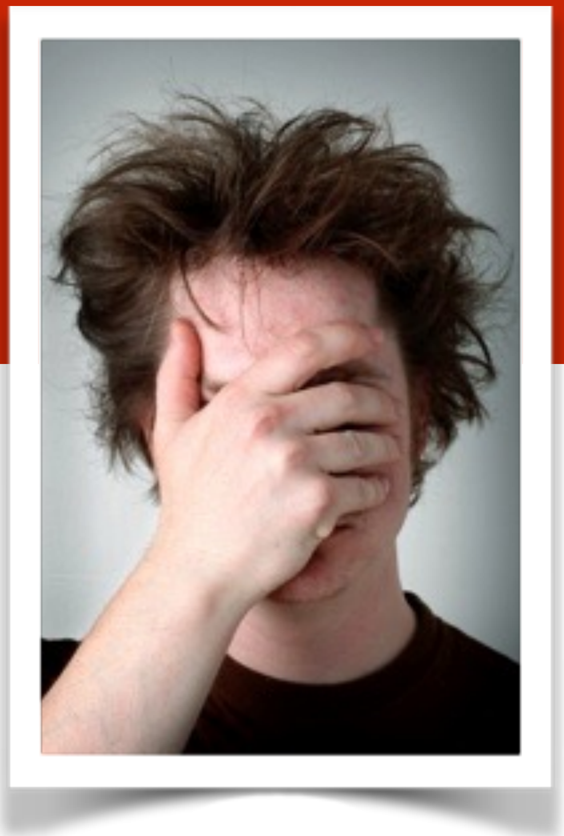
energy and time appear together in the equations:

In essence, this:

either energy solution: $(\pm E)(t)$

just the -E solution: $(-E)(t)$

move the – sign: $(E)(-t)$



Get a whole new interpretation of antimatter

antiparticles

can be intepreted as particles moving backwards in time.

that’s it.

and visa versa

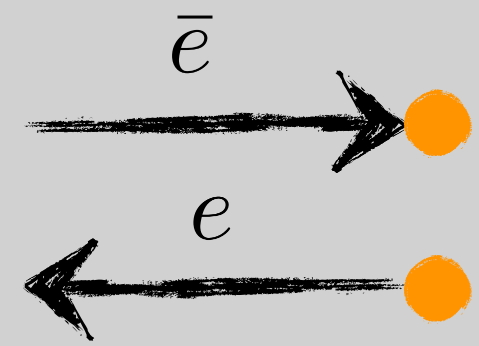
we'll do this in

two steps

1. I'll show you how spacetime can be manipulated to predict new physical processes out of old ones

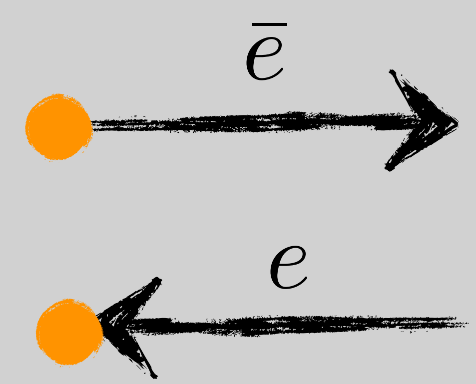
making use of the Feynman idea that antiparticles moving forward in time are the same as particles moving backwards in time

An anti-electron...coming **forwards into** an **initial** state:



is the same thing as
An electron coming
backwards out of an **initial** state

An anti-electron...coming **forwards out** of a **final** state:



is the same thing as
An electron coming
backwards into a **final** state

2. But *the vast majority of our use* will be to develop the handful (11) of "Primitive Diagrams" that we'll put together like a puzzle

to predict all possible physical processes in the "Standard Model" of particle physics jargon alert: **fermion**

refers to:	any particle with half-integer spin
entomology:	from Fermi's theoretical work on the behavior of large numbers of Fermions
example:	electron, proton, neutron

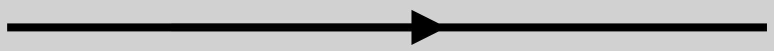
jargon alert: **bosons**

refers to:	any quantum object with integer spin
entomology:	from Satyendra Nath Bose, who worked on the effects of multiple boson aggregates
example:	photon, pion, Higgs Boson

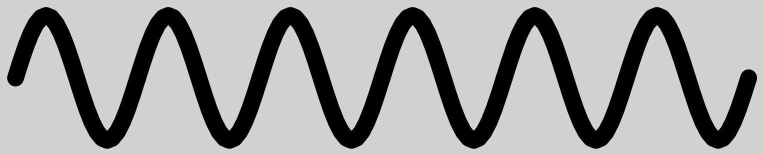
the key

the different kinds of lines

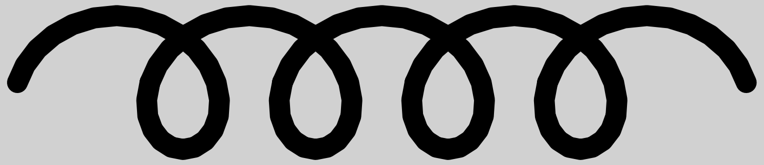
look at your Primitive Diagram Sheet



fermion, spin 1/2, e.g., electron



Vector Boson, spin 1, e.g., photon



gluon, spin 1

scalar Boson, spin 0, e.g., Higgs Boson

the first theory of Feynman's

"Quantum Electrodynamics" or "QED"

the full theory of the physics of photons and electrons

`strap in`

with pencil in hand

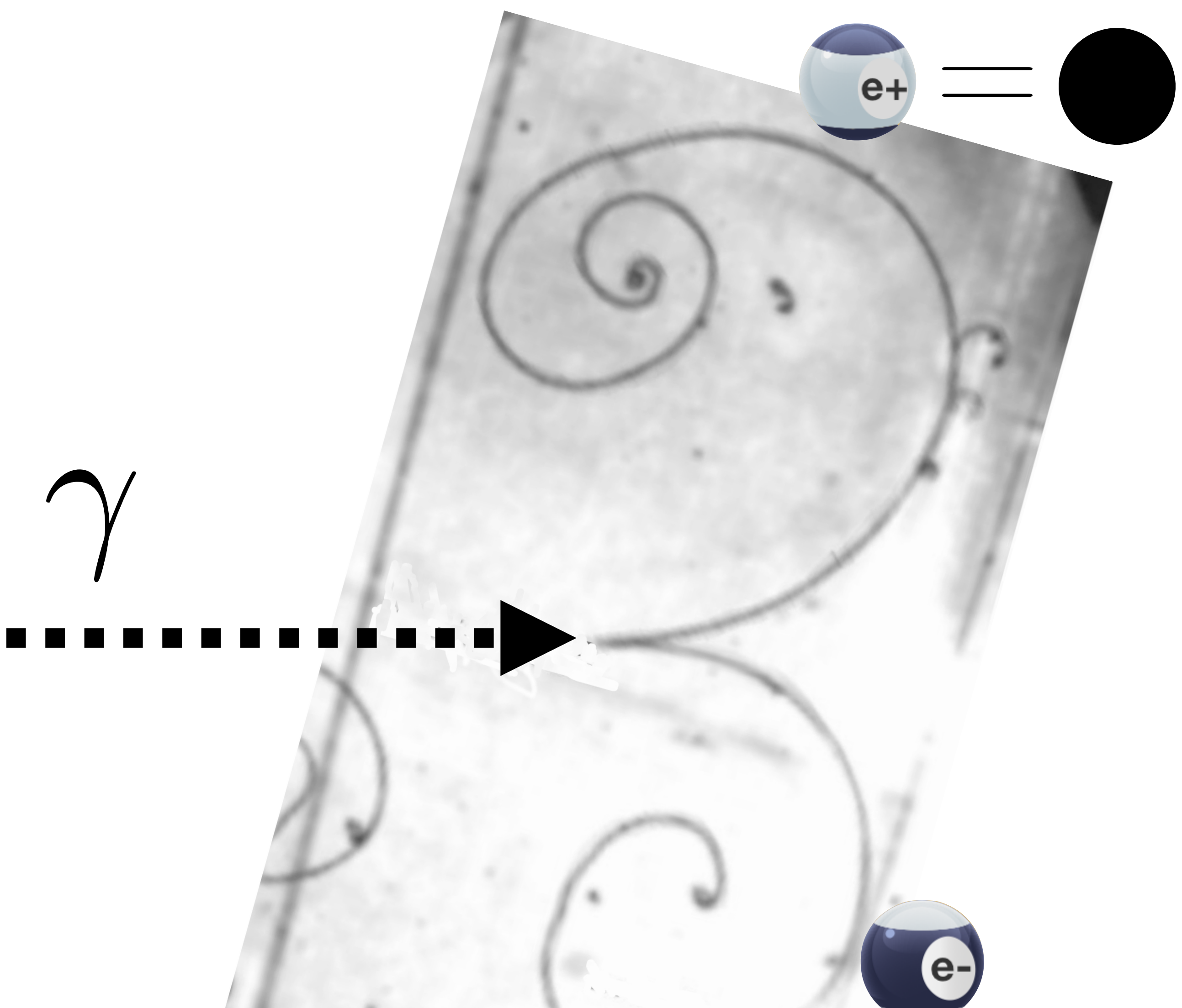
first idea

one can take a single Feynman Diagram that describes a process

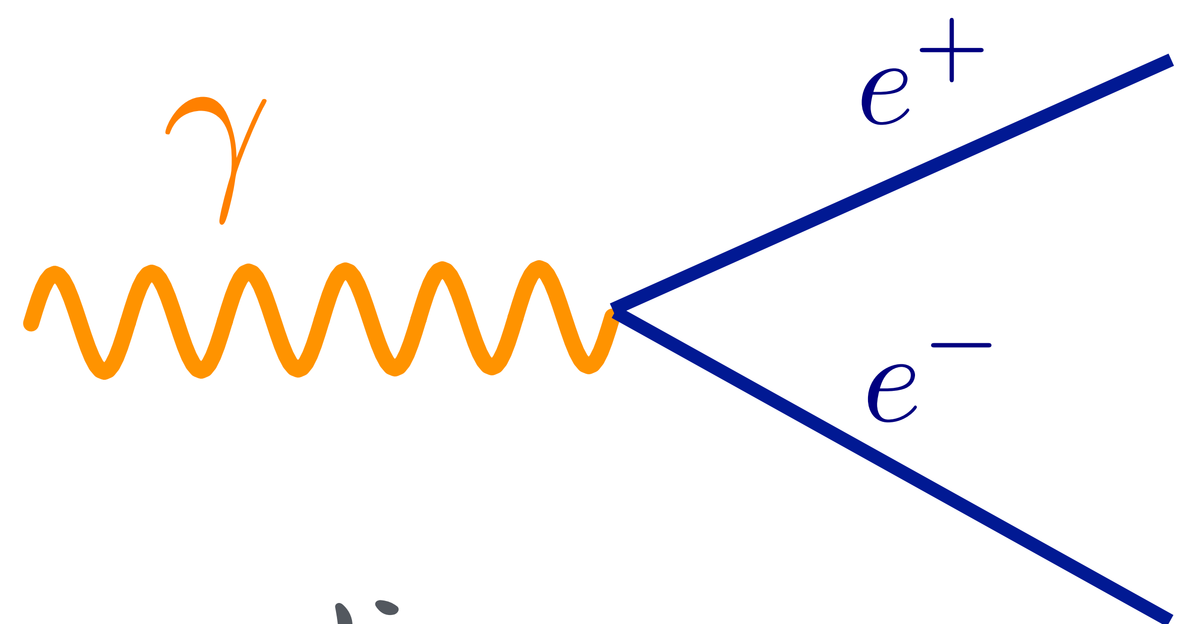
and by rearranging it in spacetime, “predict” additional physical processes

Dirac’s story

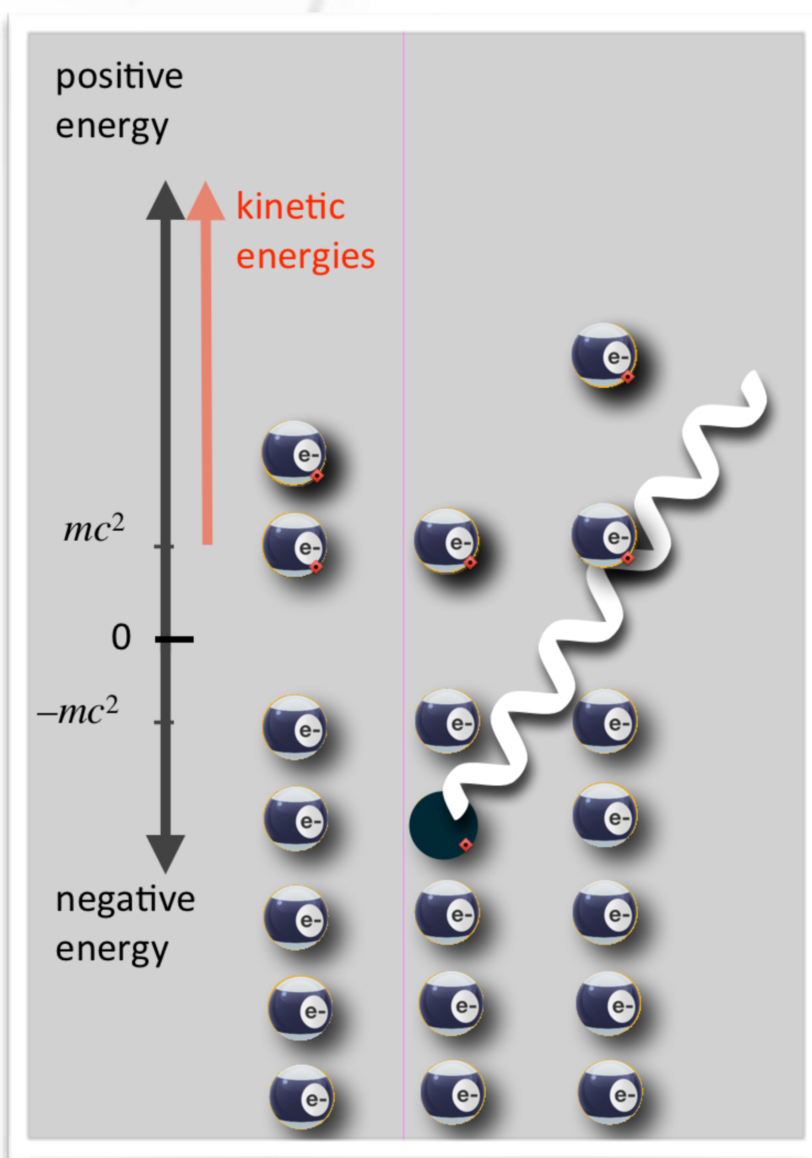
& Feynman’s picture



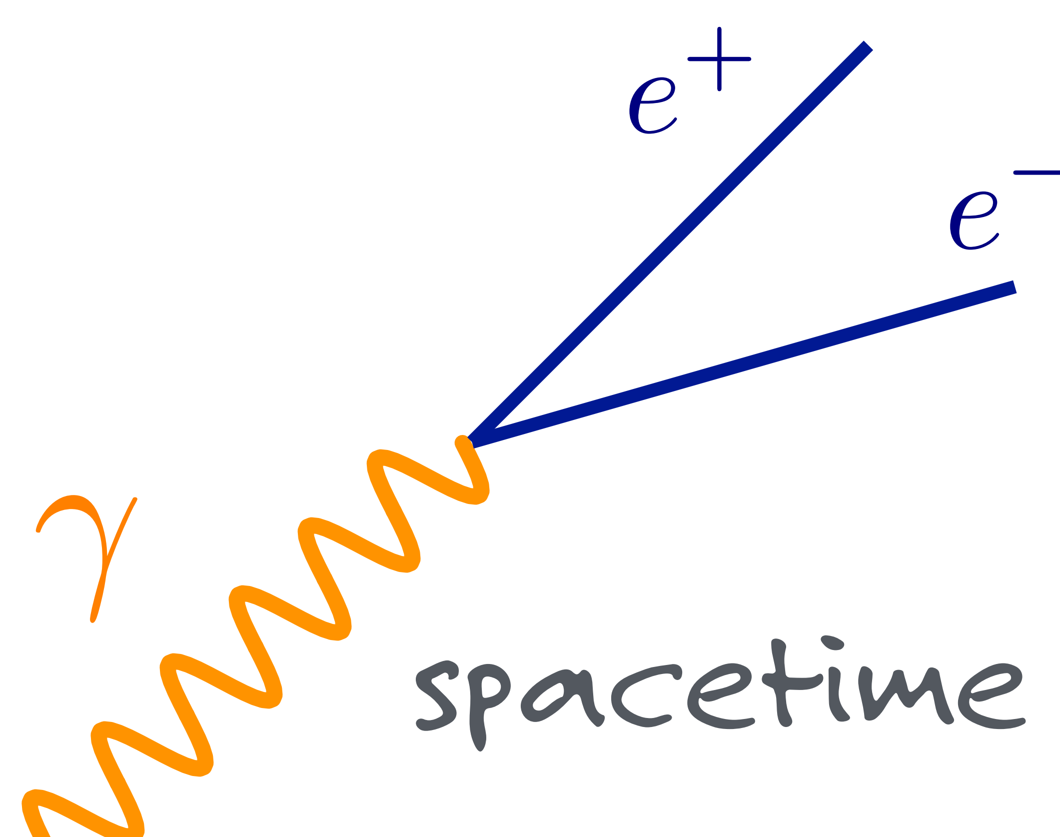
photograph



space diagram



cartoon



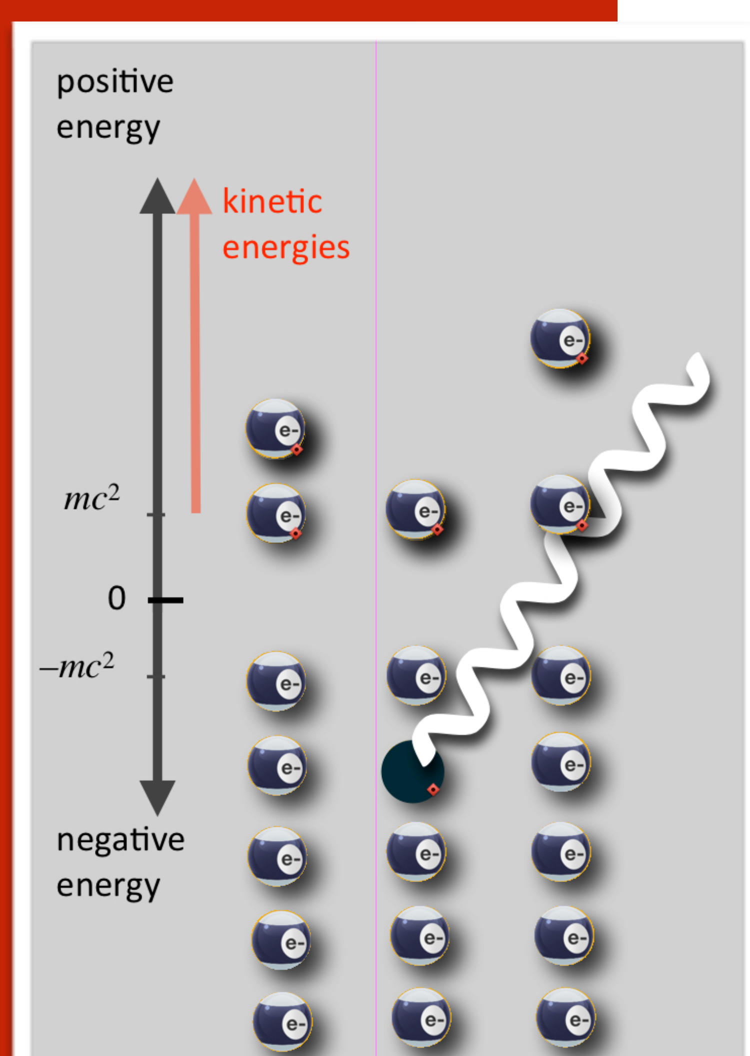
spacetime diagram

Feynman diagram

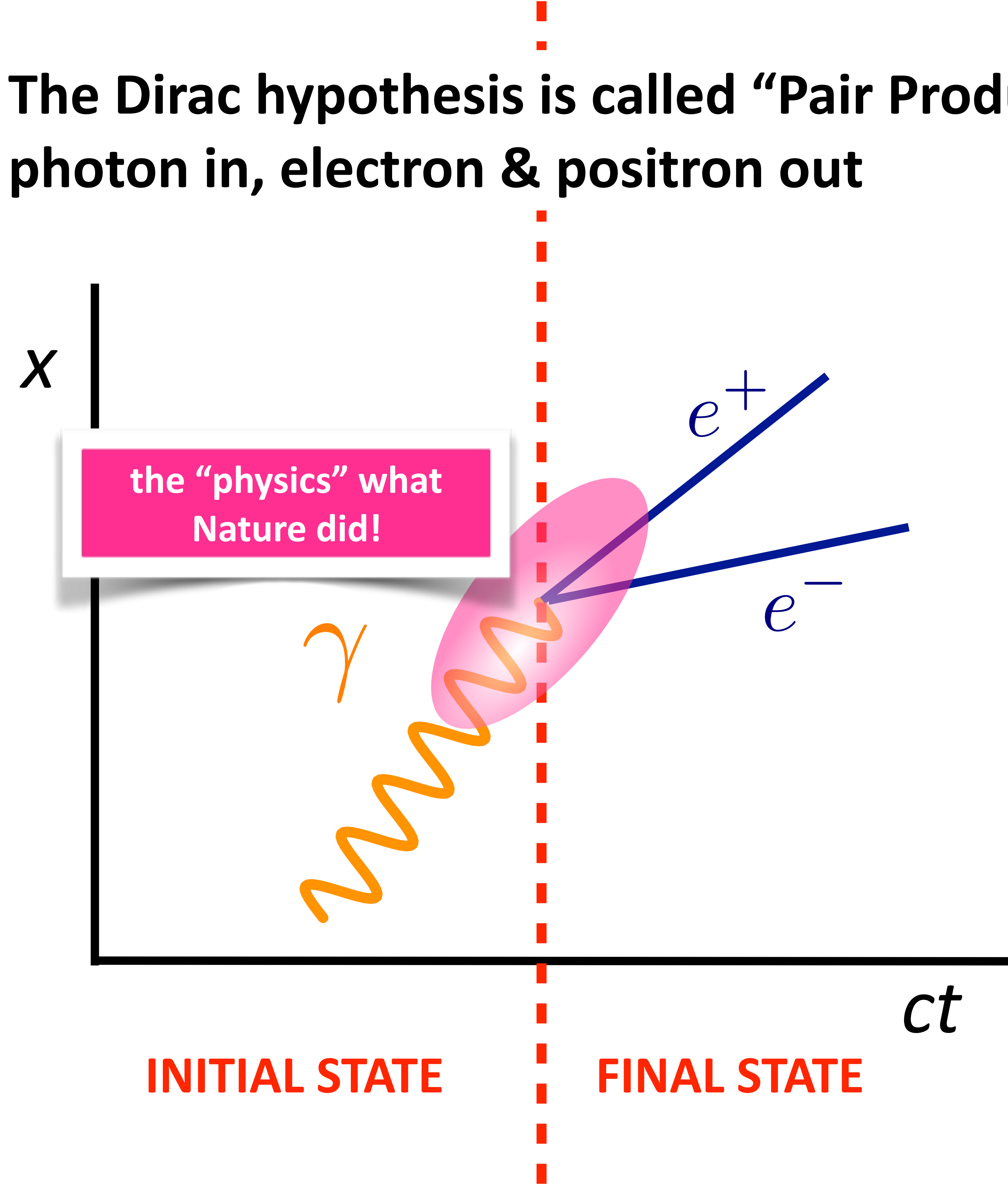
Dirac had photons creating an electron

Feynman's calculus allows that

and more



The Dirac hypothesis is called "Pair Production": photon in, electron & positron out



Now, remember that we treat *ct* and *x* identically...

The physics does not care which orientation is which.

note:

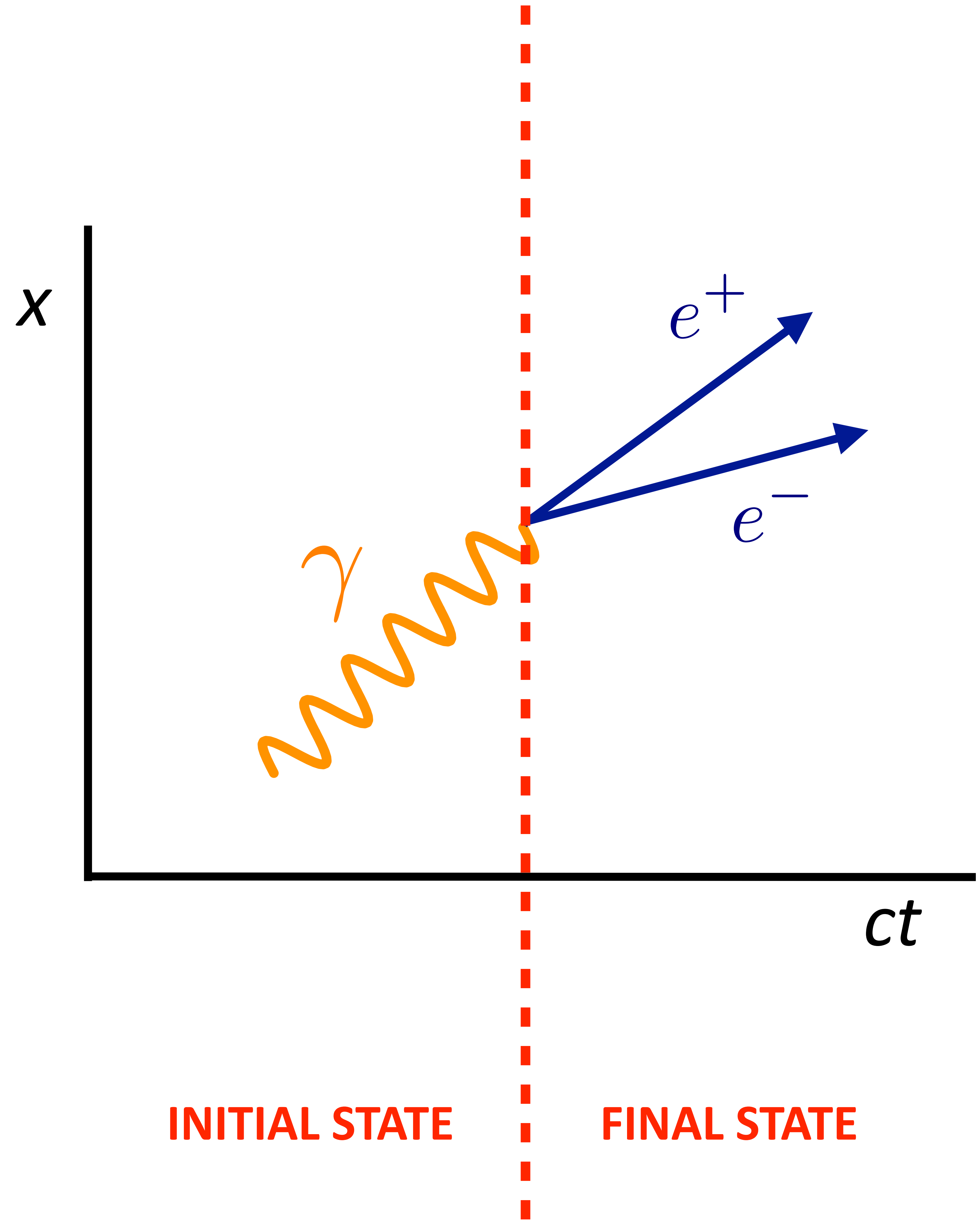
I’ve been banging on you to keep the slopes right

you know, photons have slope associated with c

We’ll relax that now.

can always rotate any Feynman Graph

and get a new one



BUT

We don’t deal with particles moving backwards in time

when it happens…we fix it!

Feynman's trick

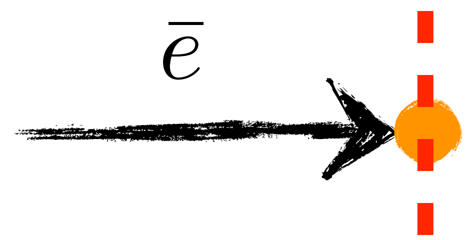
depends on the in and out states.

if some manipulation leaves you with particles going the "wrong" direction?

fix it.

particles in time

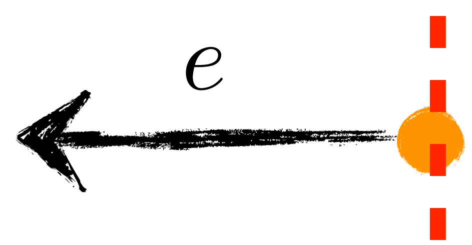
An anti-electron...coming **into** an **initial** state to a node:



Yes, this makes sense

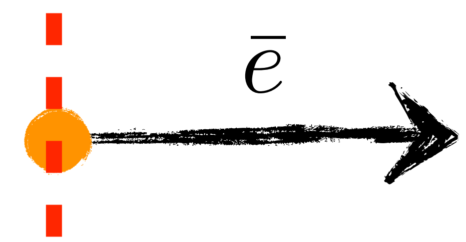
is the same thing as

An electron coming **out** of an **initial** state (?)



Nope, this makes no sense...time-backwards

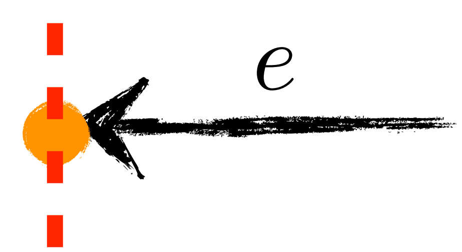
An anti-electron...coming **out** of a **final** state:



Yes, this makes sense

is the same thing as

An electron coming **into** a **final** state (?)



Nope, this makes no sense...time-backwards

Feynman had rules

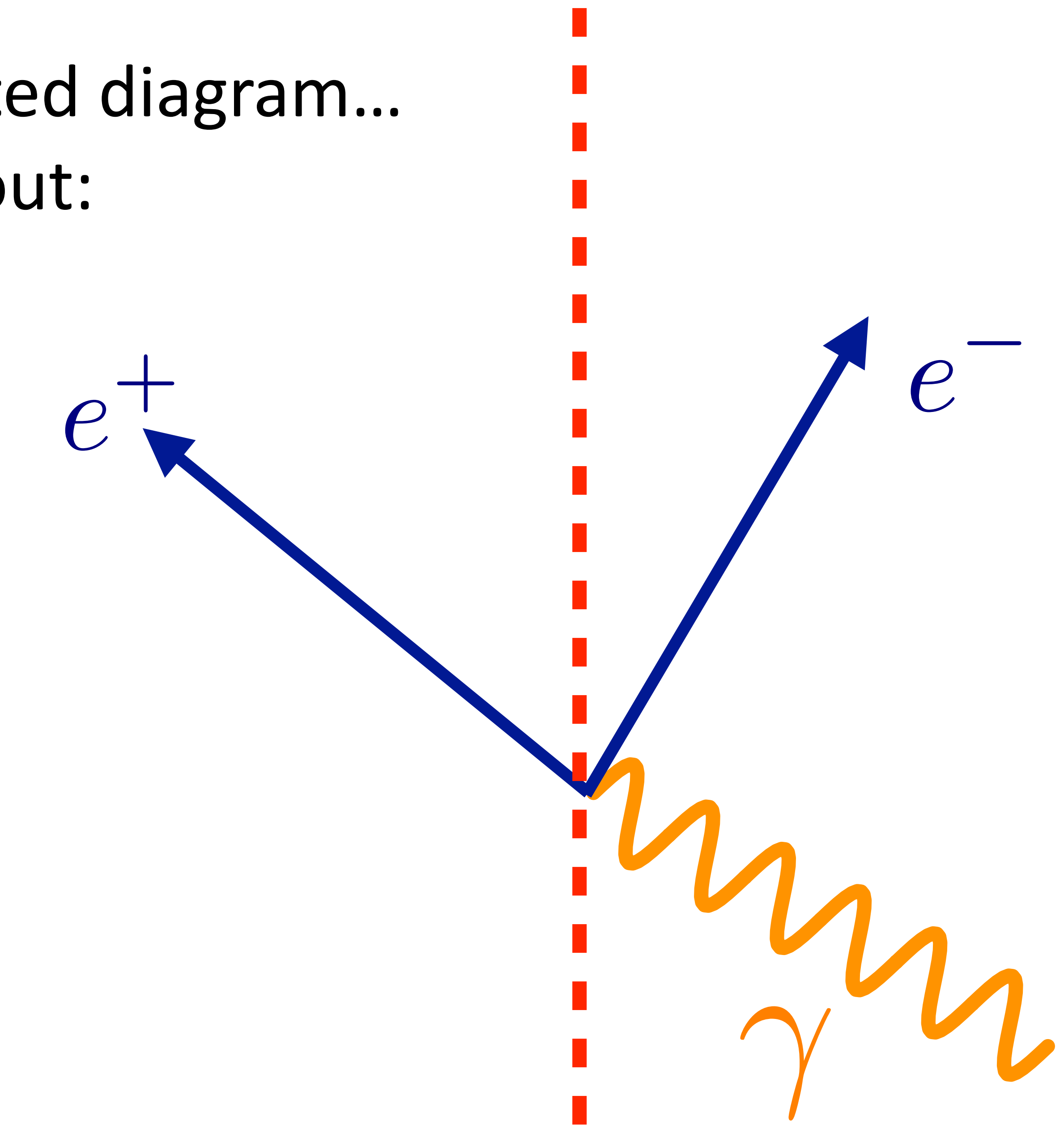
We'll have slightly different rules

but similar in spirit

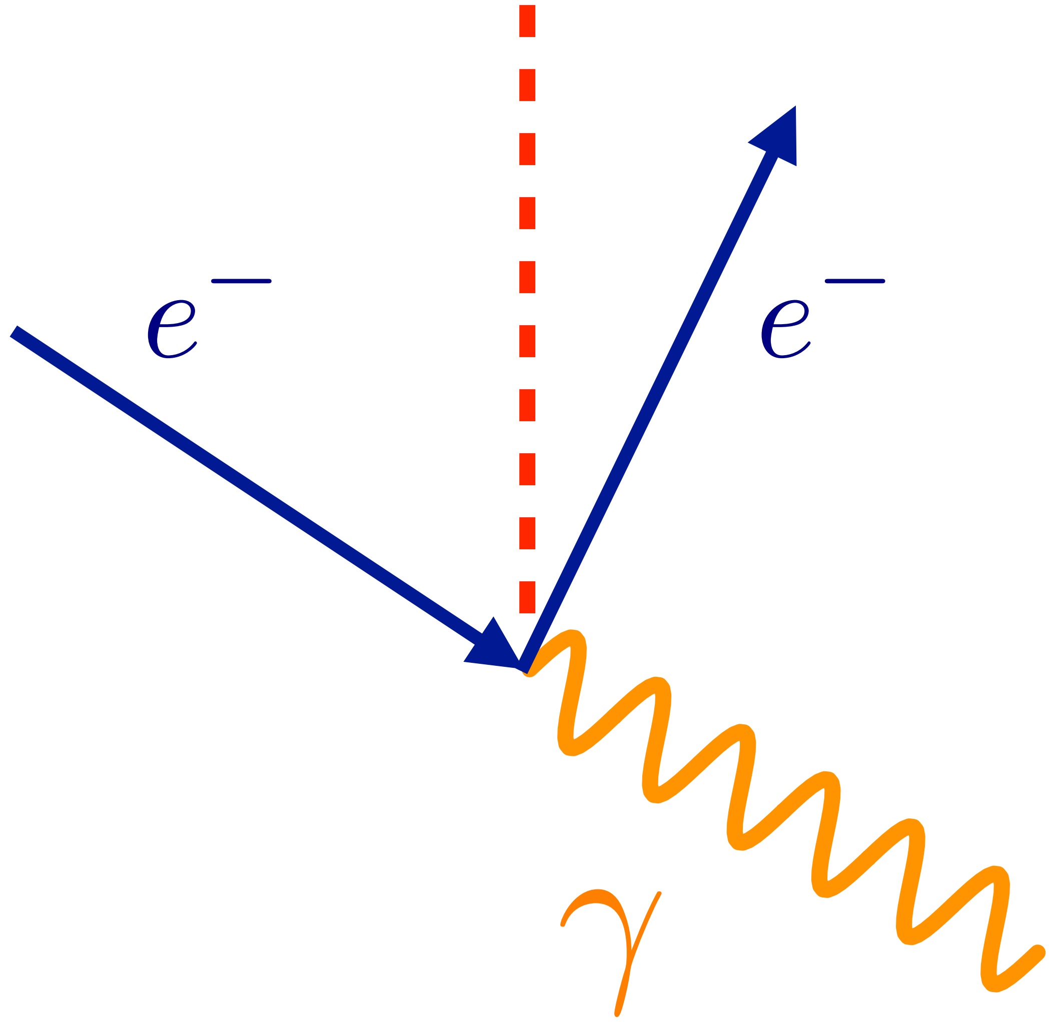
Rule 1.

If you flip a line's arrow forward or backward in time, you change the particle to antiparticle or antiparticle to particle

my rotated diagram… spread out:



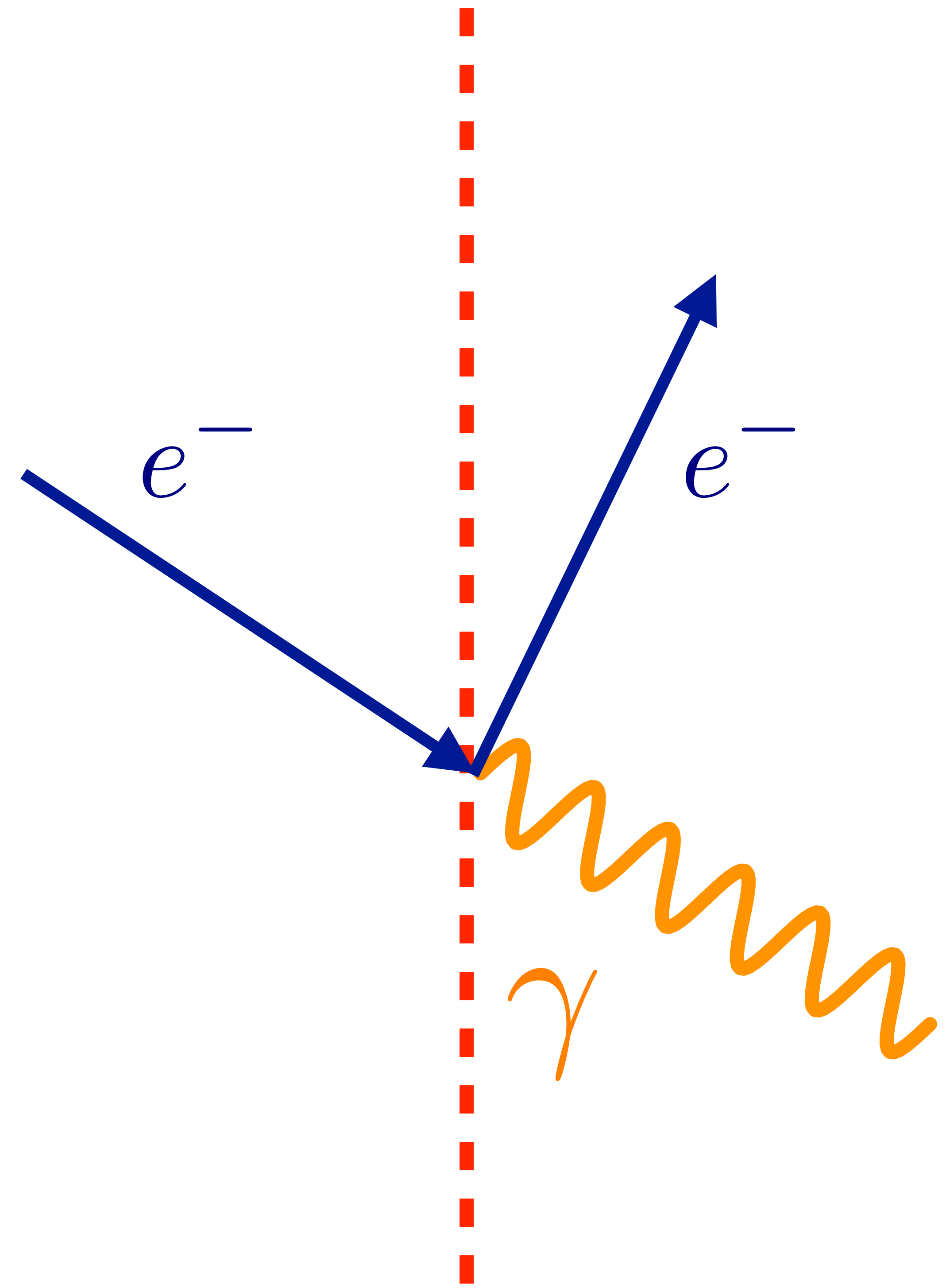
this is the same thing as:



look at this

you know this.

familiar:



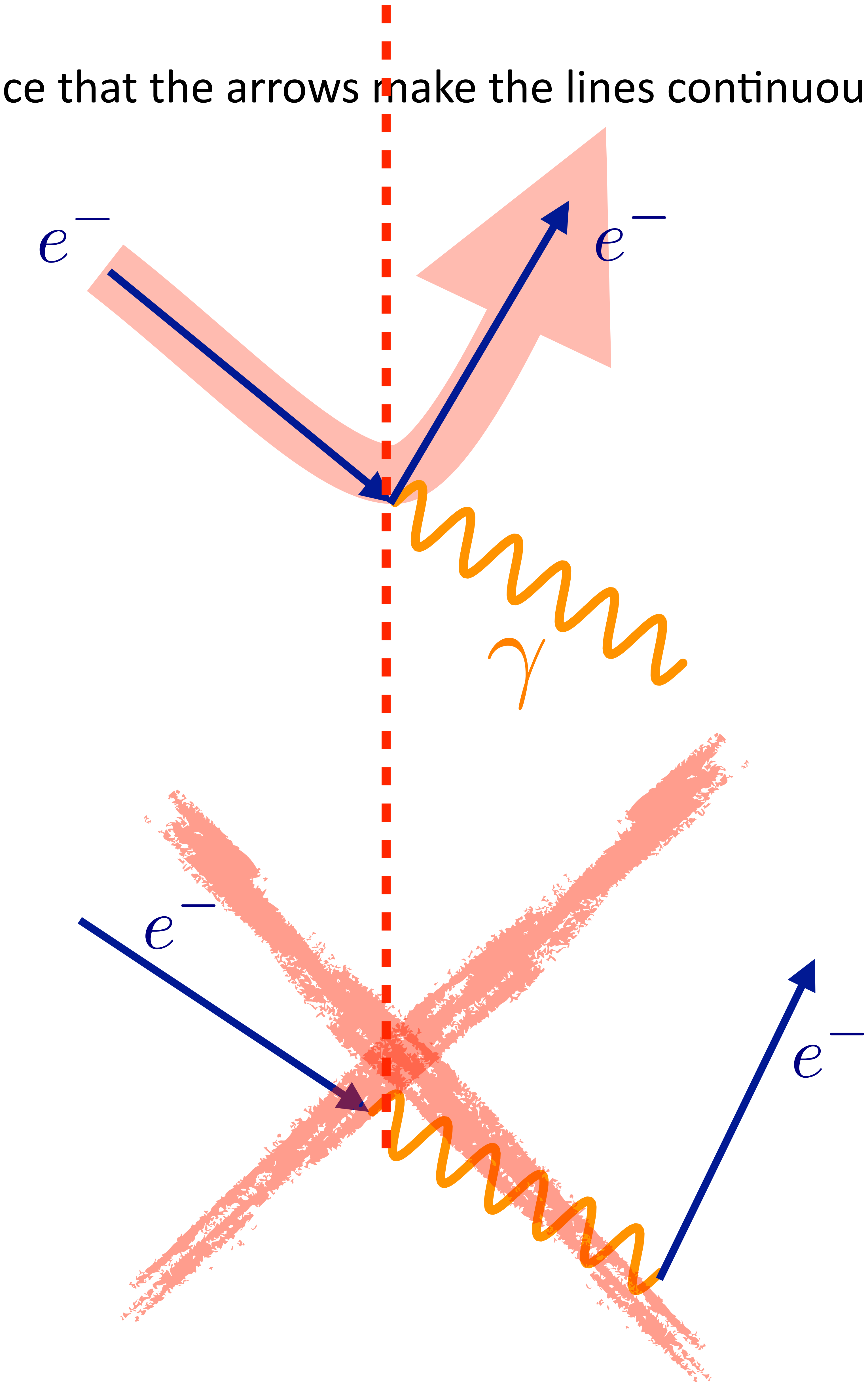
electron comes along and spits out a photon, recoils and goes on its way

regular old radiation

Rule 2.

fermion lines
must be
continuous

notice that the arrows make the lines continuous



now, let's do it in real-time

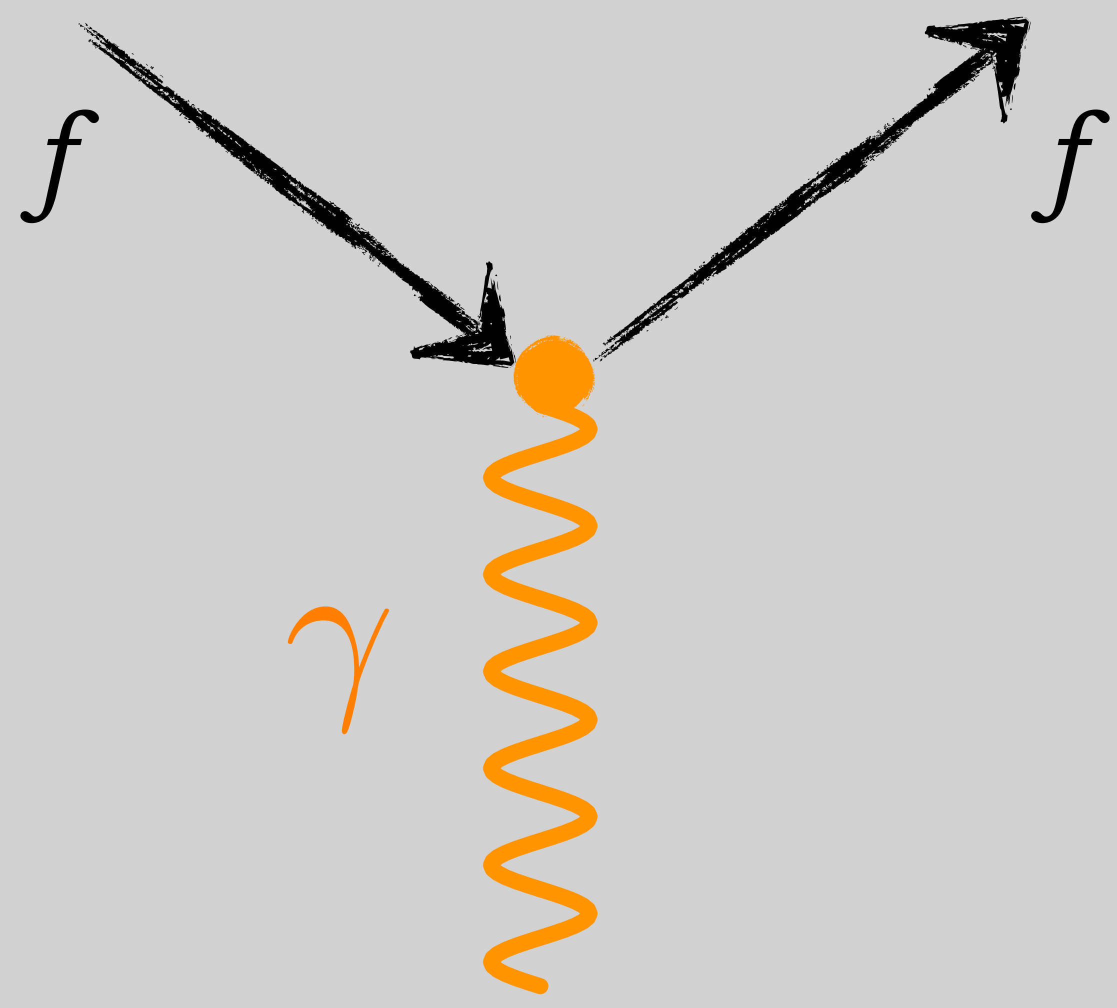
repeating a bit, so you can write

(first)

primitive diagrams

are general

but this is completely general...for any charged fermion:



f could be electron, positron, proton, antiproton...and more – any electrically charged **f**ermion.

Their diagrams are identical.

Primitive Diagram Scorecard

your first entry