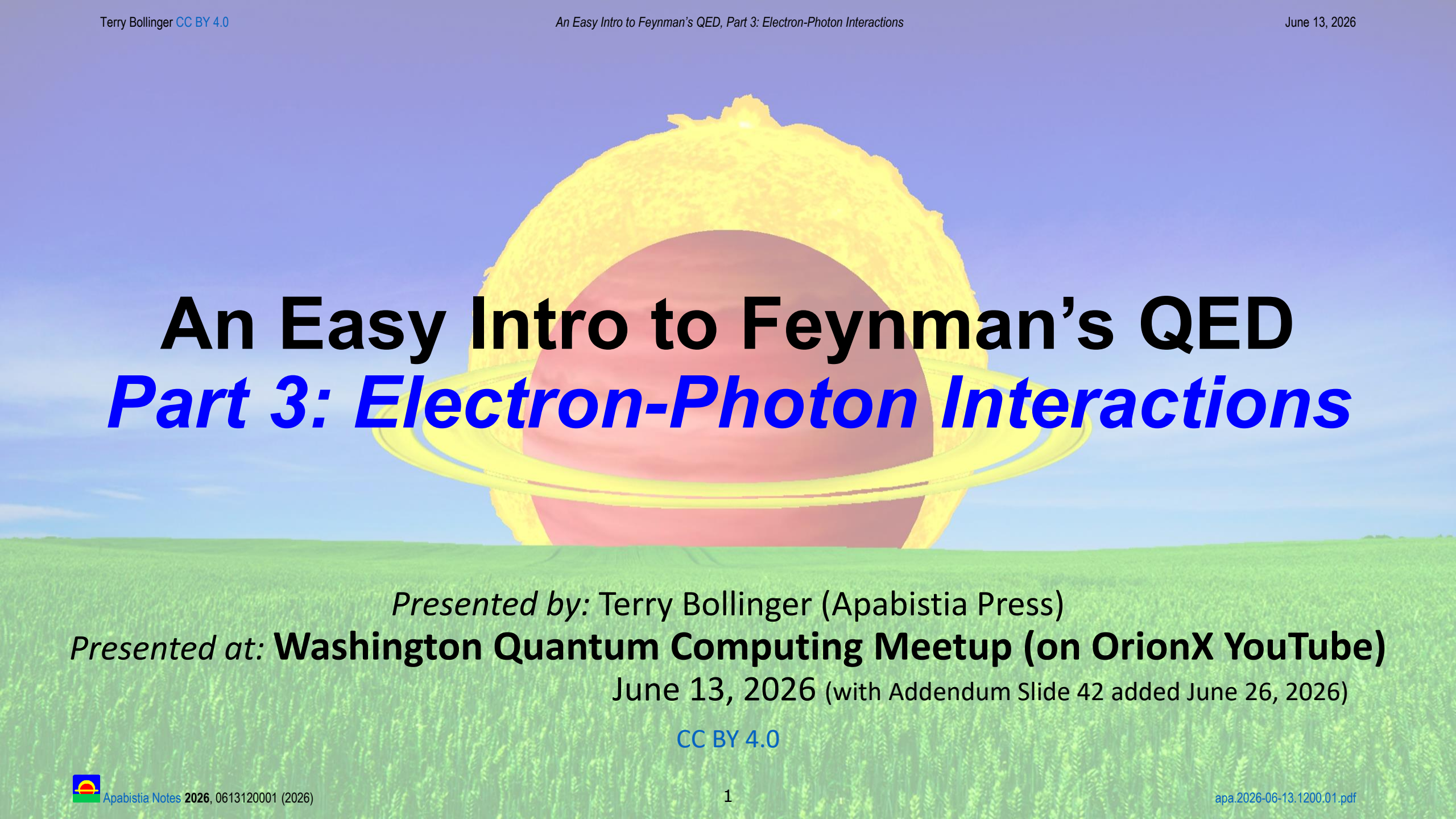

An Easy Intro to Feynman's QED
Part 3: Electron-Photon Interactions

Presented by: Terry Bollinger (Apabistia Press)

Presented at: **Washington Quantum Computing Meetup (on OrionX YouTube)**

June 13, 2026 (with Addendum Slide 42 added June 26, 2026)

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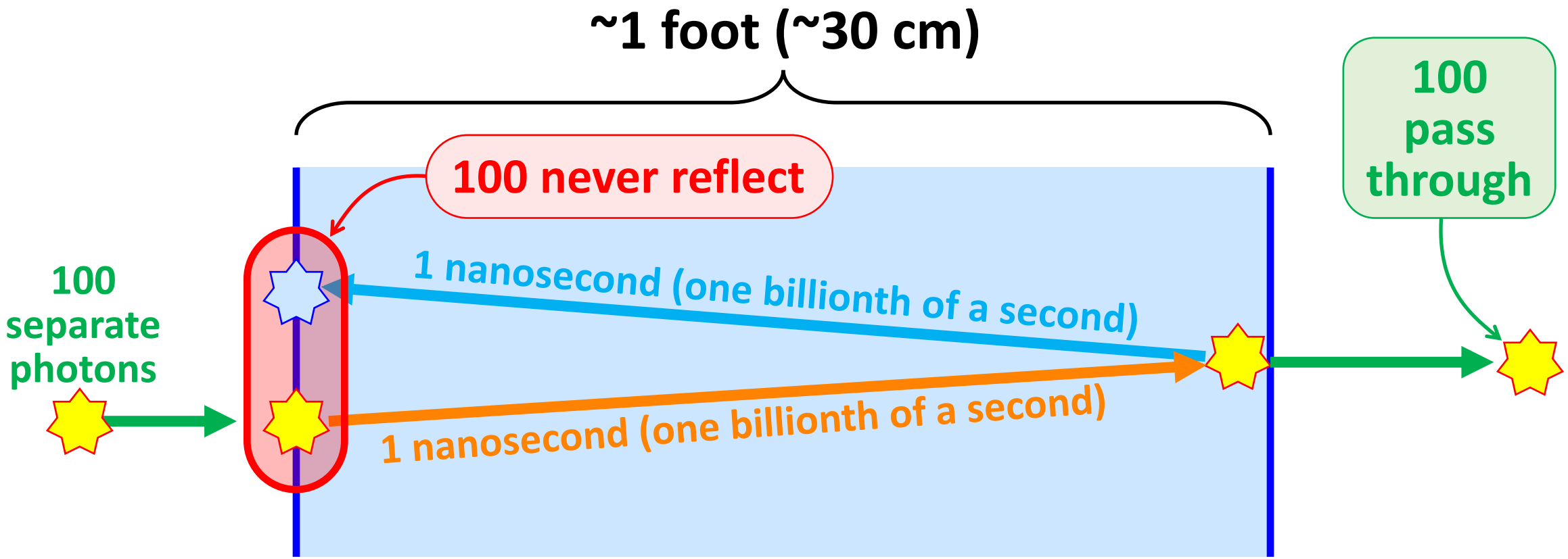
Overview

I. Photons Are Very Odd Ducks
II. Expanding the Game by Adding Electrons
III. Why Feynman Proposed the Impossible
IV. Why Feynman's Operator Cannot Exist
V. Mass Shells as Incompatible Universes
VI. More Complicated Feynman Diagrams
VII. Antimatter as Traveling Backward in Time
VIII. The Greatest Divide in Particle Physics
IX. Summary: What I Found Interesting

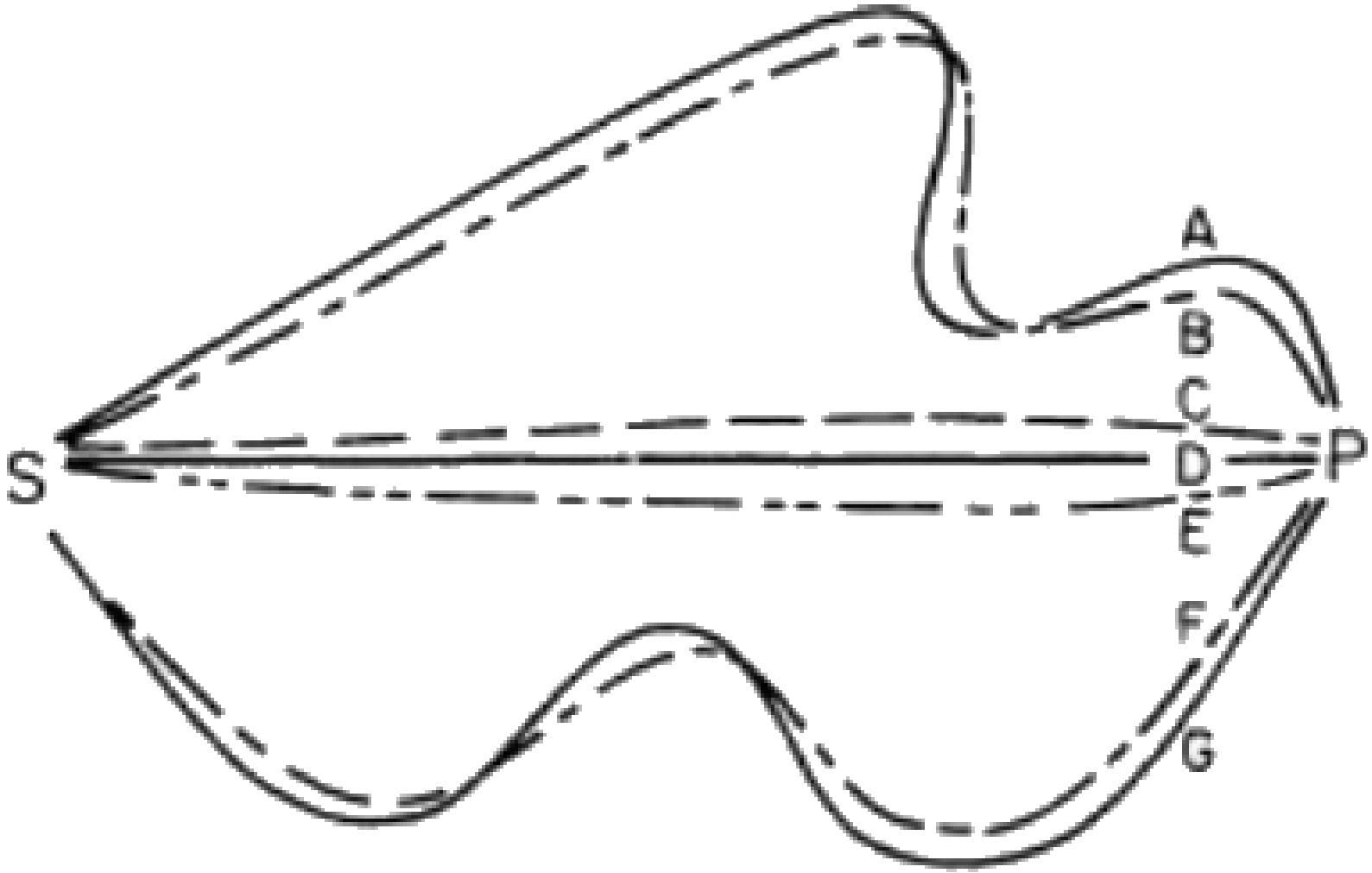
Part I.
Photons Are Very Odd Ducks

One Photon Can Act Like a Long Burst of Coherent Light



Two nanoseconds *after* the photon hits the glass front, its reflection from the far side of the glass cancels the existence of its reflection

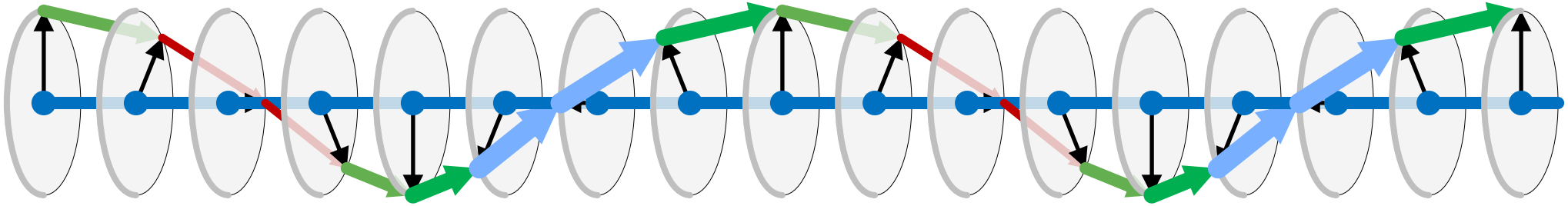
Photons *Do Not* Always Go in Straight Lines



QED Fig 32

Review: Photon Paths Resemble Bendable Springs

- Each "possible photon path" resembles a long, flexible spring:



- Hidden assumptions:
  - This skips over the issue of optical polarization (e.g., linear or circular)
  - The path exists "all at once" along a path of length and time
  - Feynman assumes S and D are static points within a *single* inertial frame
  - The length of a very curvy spring matters, since lightspeed limits apply
  - When elaborated over infinitely many paths with D endings that correspond to "now", the results always converge into a wave model
  - A carefully done wave model thus predicts the same results as QED

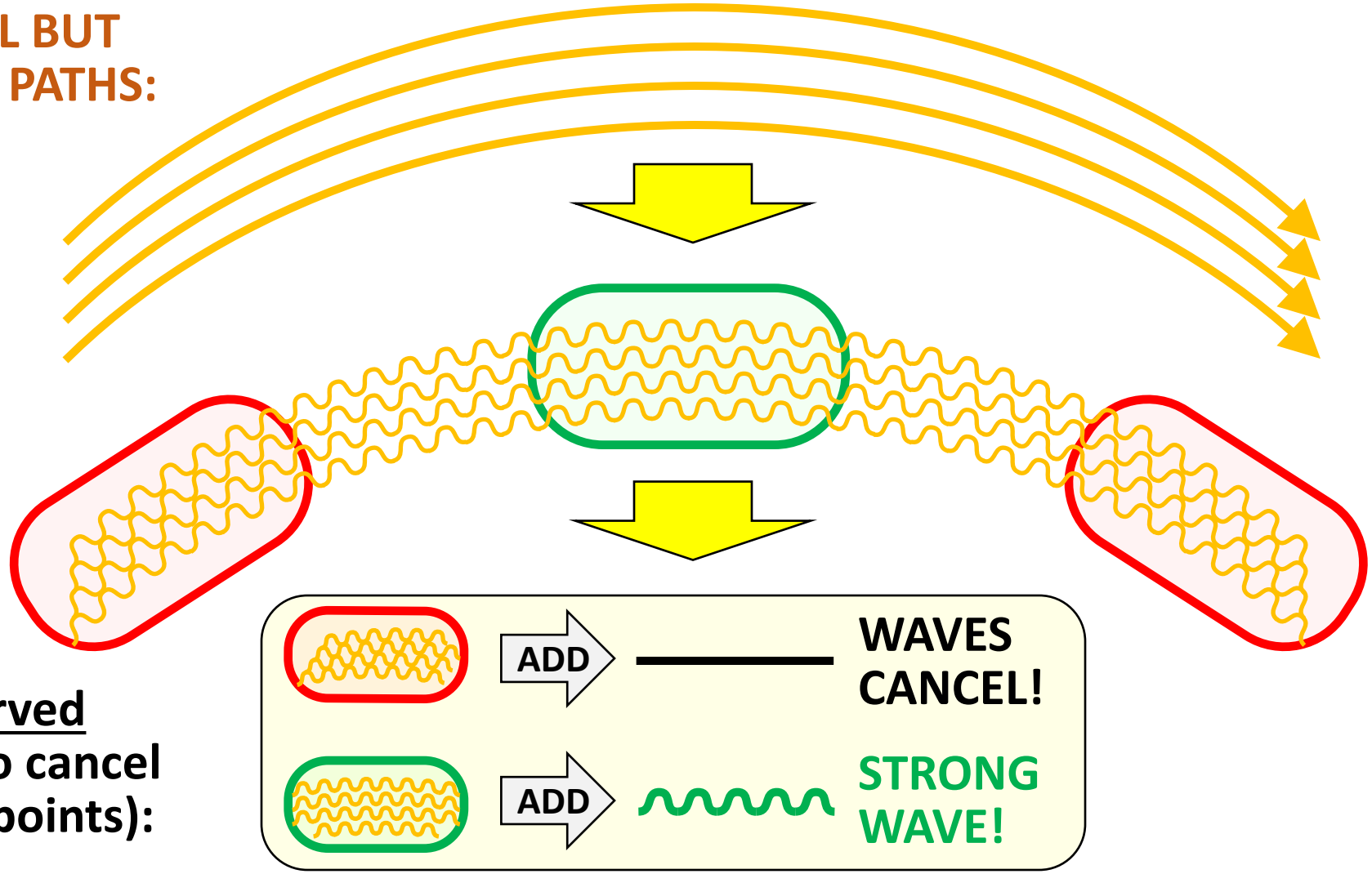
Feynman Path Integrals Dislike Curves

FOUR PARALLEL BUT CURVED LIGHT PATHS:

1. Classical ray analysis:

2. Feynman wave-path analysis:

3. Feynman curved paths tend to cancel (at multiple points):

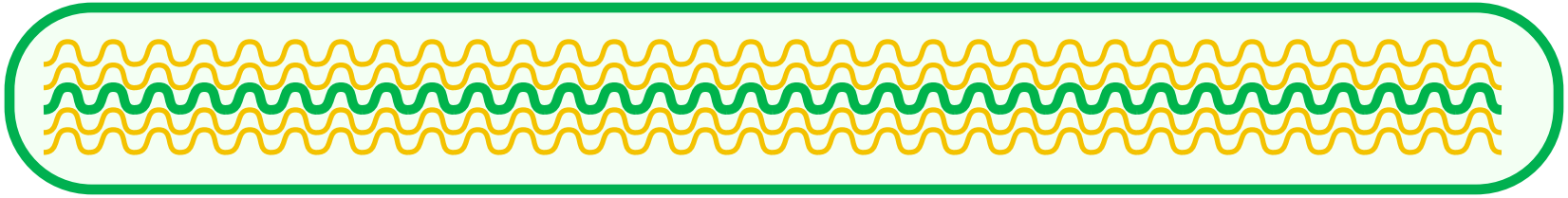


Feynman Path Integrals *Mostly* Prefer Straight Lines

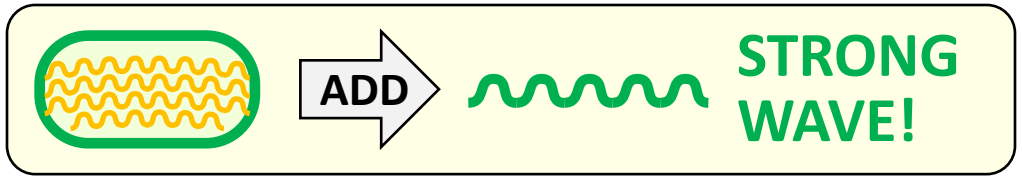
FOUR PARALLEL BUT STRAIGHT LIGHT PATHS:

1. Classical ray analysis:

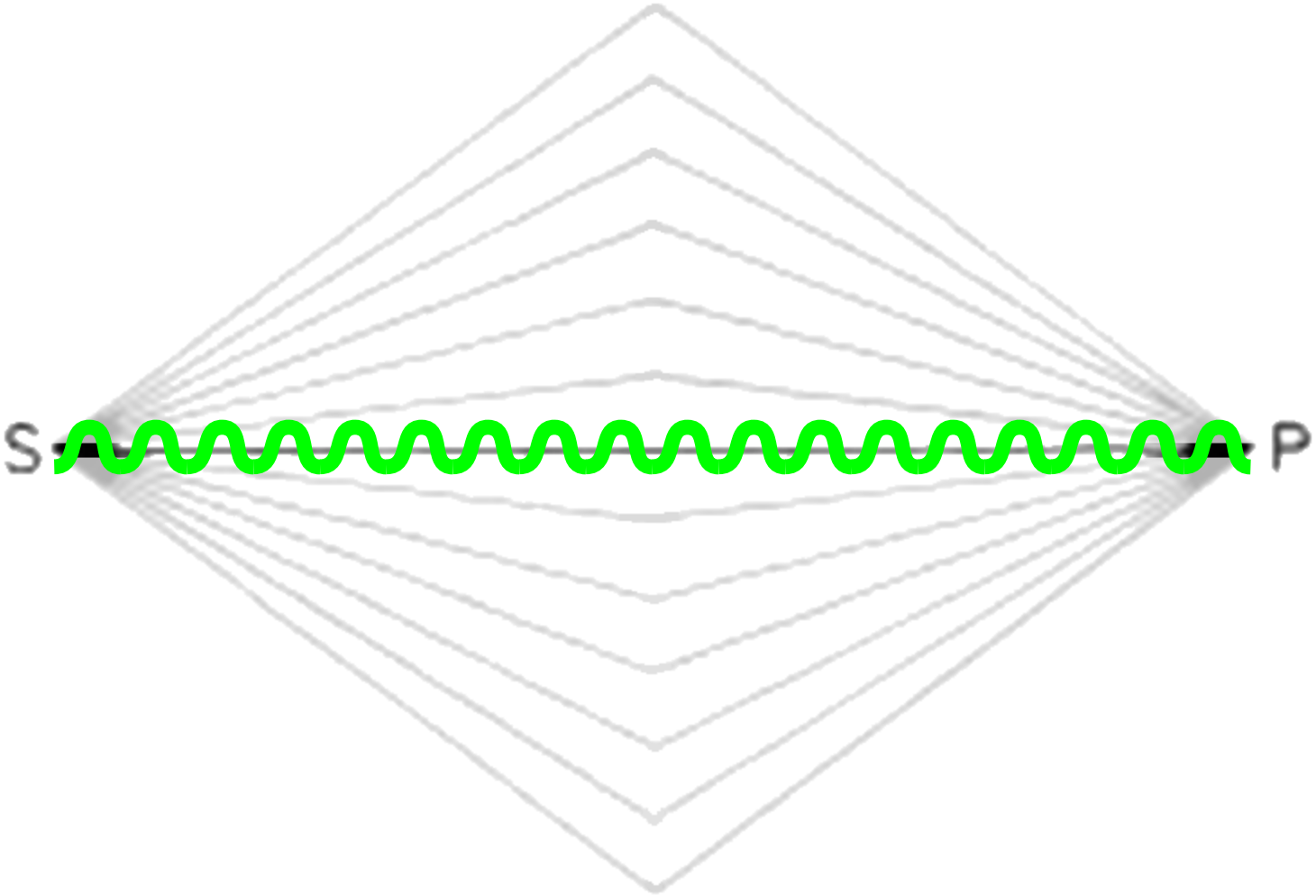
2. Feynman wave path analysis:



3. Feynman straight paths tend to add up:

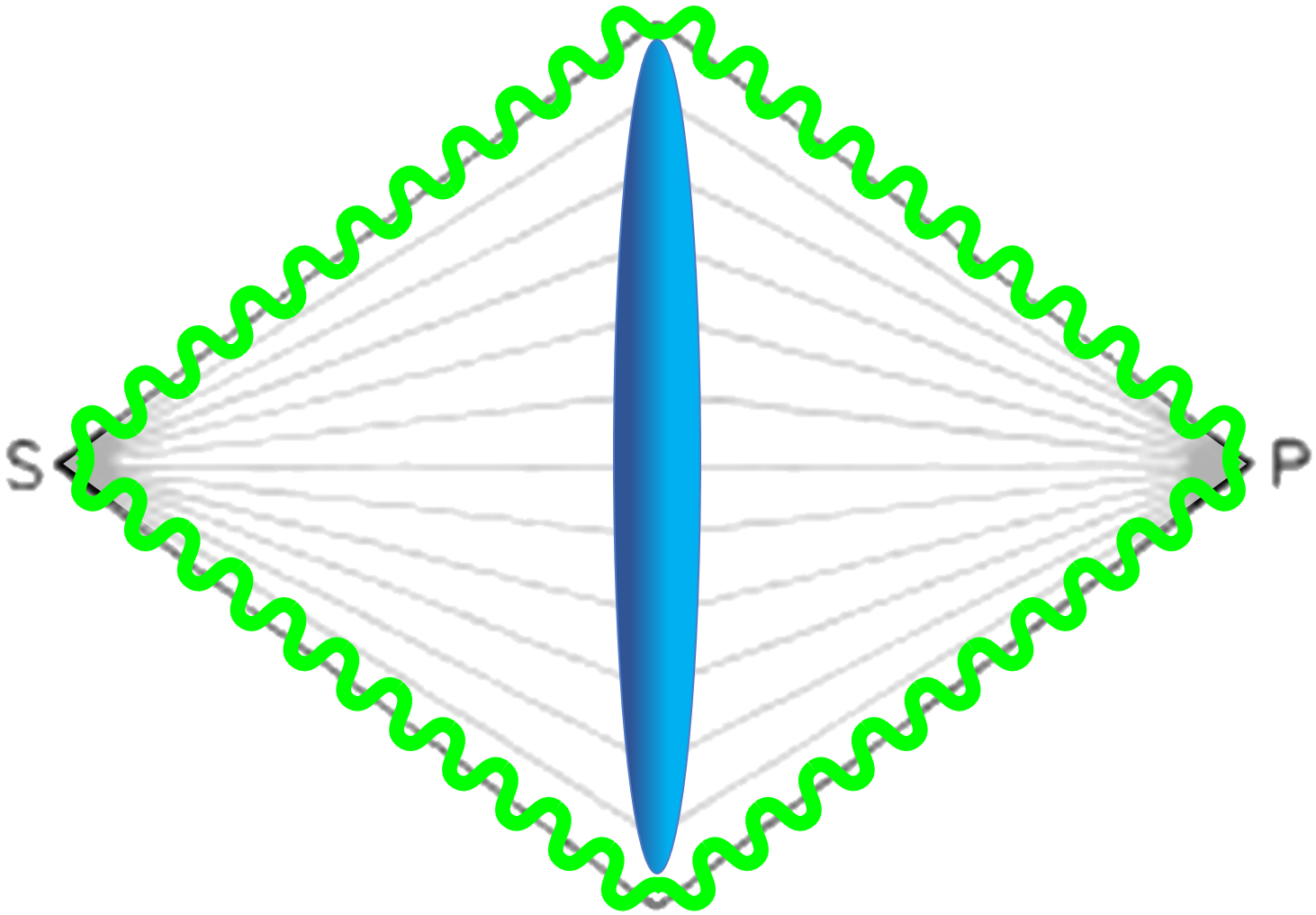


But Without Lenses, Light Never Bends… Right?



QED Fig 35

Surprise! Light Bends Around Disks (Arago's Spot)



QED Fig 35

Part II.
Expanding the Game by Adding Electrons

First, A Better Way to Compare Time and Length

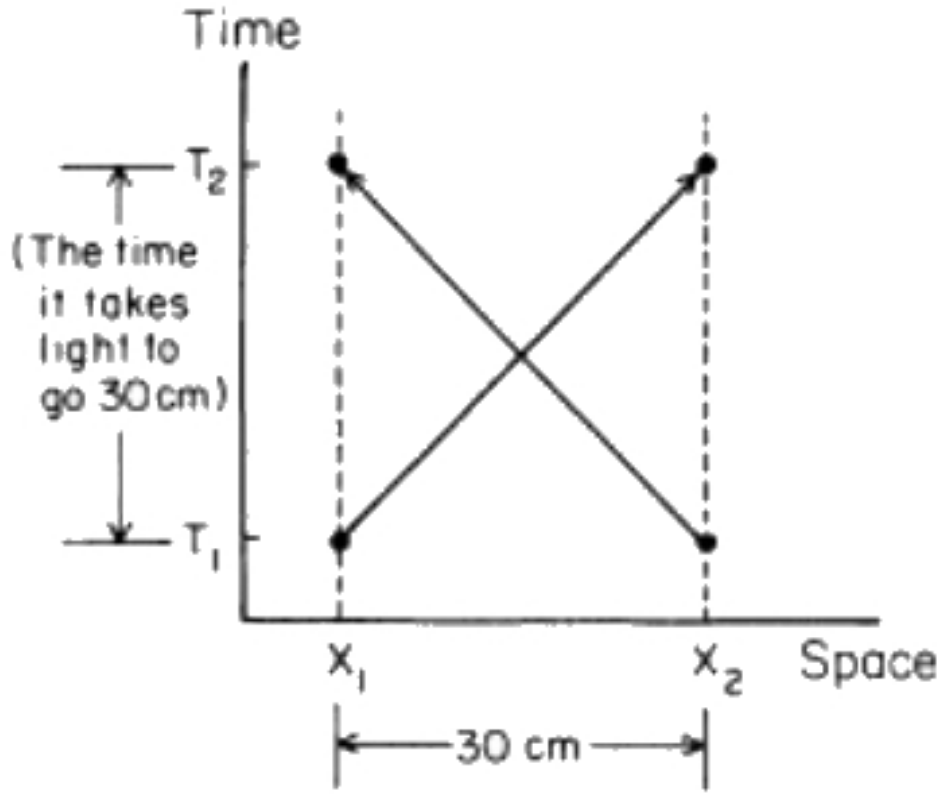


FIGURE 54. The time scale I will use in these graphs will show particles going at the speed of light to be travelling at a 45-degree angle through space-time. The amount of time it takes light to go 30 centimeters — from X^1 to X^2, or from X^2 to X^1 — is about one-billionth of a second.

The Three Basic Actions of Light and Electrons

So now, I present to you the three basic actions, from which all the phenomena of light and electrons arise.

—ACTION #1: A photon goes from place to place.

—ACTION #2: An electron goes from place to place.

—ACTION #3: An electron emits or absorbs a photon.

Each of these actions has an amplitude—an arrow—that can be calculated according to certain rules.

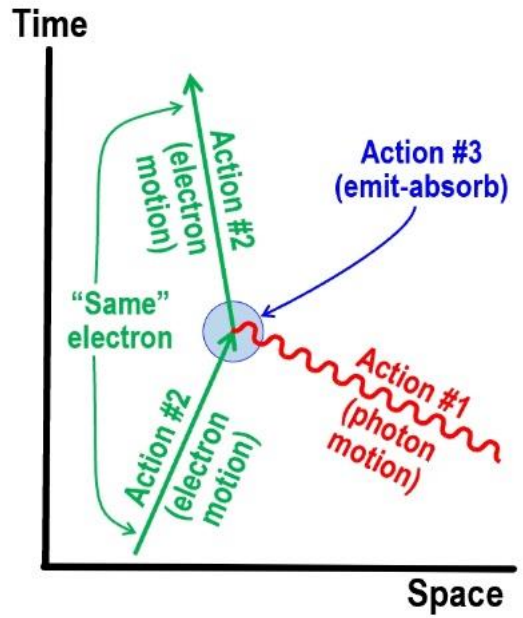


FIGURE 51.5. [TB] All phenomena involving light and electrons arise from three basic actions. Two are lines showing motion, and the third is a junction where three such lines connect. We've already seen Action #1, which is a photon going from one location to another location. Action #2 adds a new particle, the electron, which also goes from one location to another. Action #3 is something new. Instead of a path, it is a point in space and time at which an electron *emits* or *absorbs* a photon. Each of these actions has an amplitude, and you can use those amplitudes to figure out the likelihood of any involving light and electrons.

Like "Straightness," the Speed of Light is *Emergent*

FIGURE 56. When light goes at the speed c, the "interval", I, equals zero, and there is a large contribution in the 12 o'clock direction. When I is greater than zero, there is a small contribution in the three o'clock direction, one inversely proportional to I; when I is less than zero, there is a similar contribution in the nine o'clock direction. Thus, light has an amplitude to go faster or slower than speed c, but these amplitudes cancel out over long distances.

Unlike Photons, Electrons "Hop" Along Their Paths

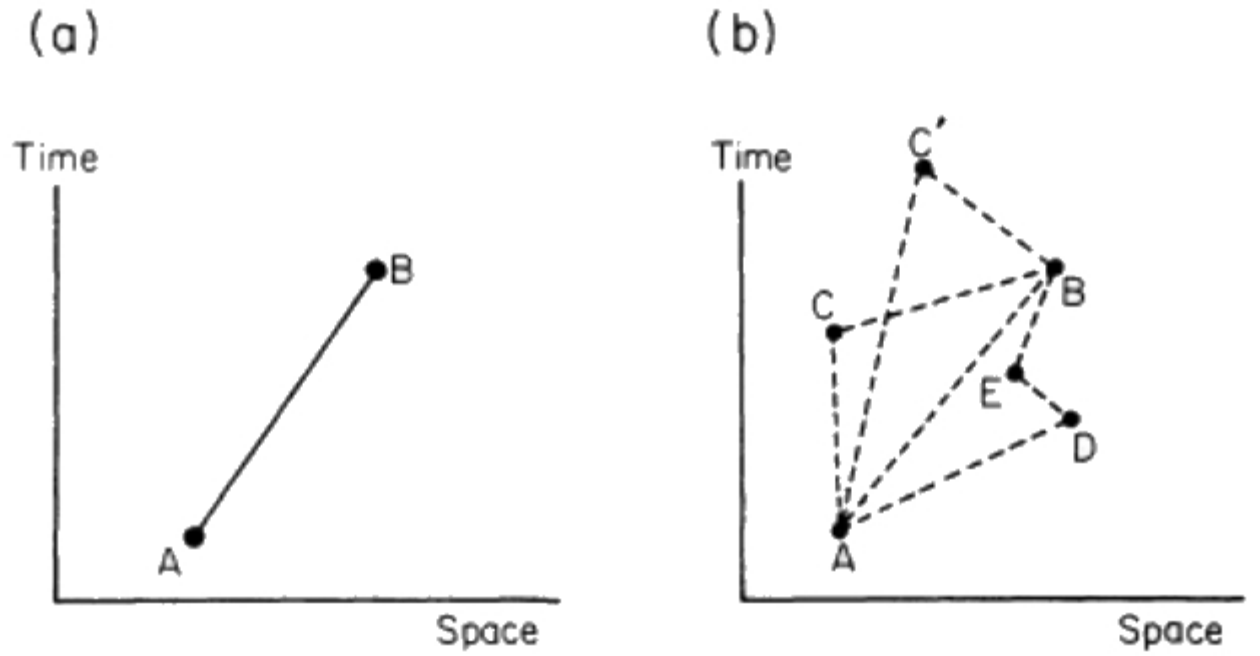


FIGURE 57. An electron has an amplitude to go from point to point in space-time, which I will call "$E(A\ to\ B)$." Although I will represent $E(A\ to\ B)$ as a straight line between two points (a), we can think of it as the sum of many amplitudes (b) — among them, the amplitude for the electron to change direction at points C or C on a "two-hop path," and the amplitude to change direction at D and E on a "three-hop" path — in addition to the direct path from A to B. The number of times an electron can change direction is anywhere from zero to infinity, and the points at which the electron can change direction on its way from A to B in space-time are infinite. All are included in $E(A\ to\ B)$.

An Electron Has an Amplitude *j* for Absorbing a Photon

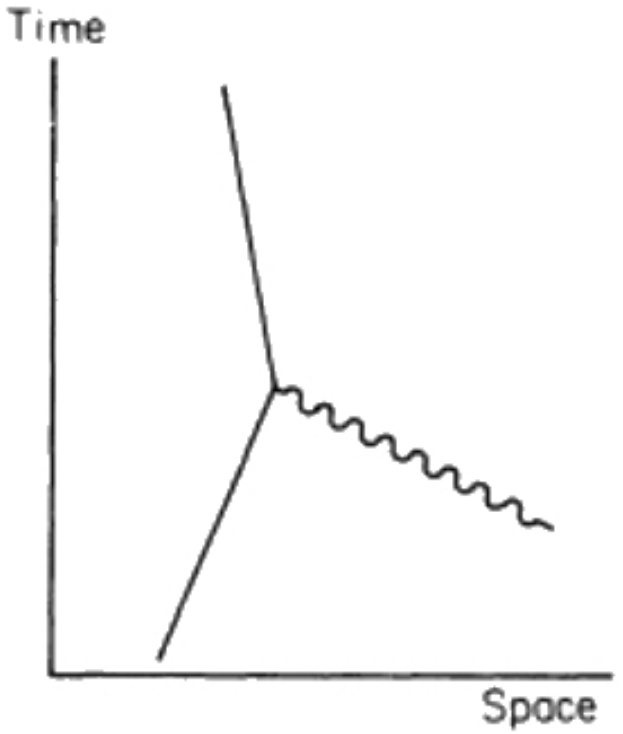


FIGURE 58. An electron, depicted by a straight line, has a certain amplitude to emit or absorb a photon, shown by a wavy line. Since the amplitude to emit or absorb is the same, I will call either case a "coupling." The amplitude for a coupling is a number that I will call *j*; it is about -0.1 for the electron (this number is sometimes called the "charge"). [TB: There's a problem folks forget to mention!]

Part III.
Why Feynman Proposed the Impossible

Young Feynman's Views on Photon Absorption

- While writing his 1942 Ph.D. dissertation on the Principle of Least Action in quantum mechanics, Feynman conspicuously did not assume that electrons can absorb photons.
- To conserve momentum, he sent his photons between atoms

> *Page 10:* ... We are then led to the possibility that the spontaneous radiation of an atom in quantum mechanics also, may not be spontaneous at all, but induced by the interaction with other atoms, and that all of the apparent quantum properties of light and the existence of photons may be nothing more than the result of matter interacting with matter directly, and according to the laws of quantum mechanics.

R. P. Feynman, *The Principle of Least Action in Quantum Mechanics* (Ph.D. Dissertation). Princeton University Department of Physics **1942**, 0504 [May 4] (1942). https://cds.cern.ch/record/101498/files/Thesis-1942-Feynman.pdf

Feynman's Deepest Insight: Atoms Are Unnecessary

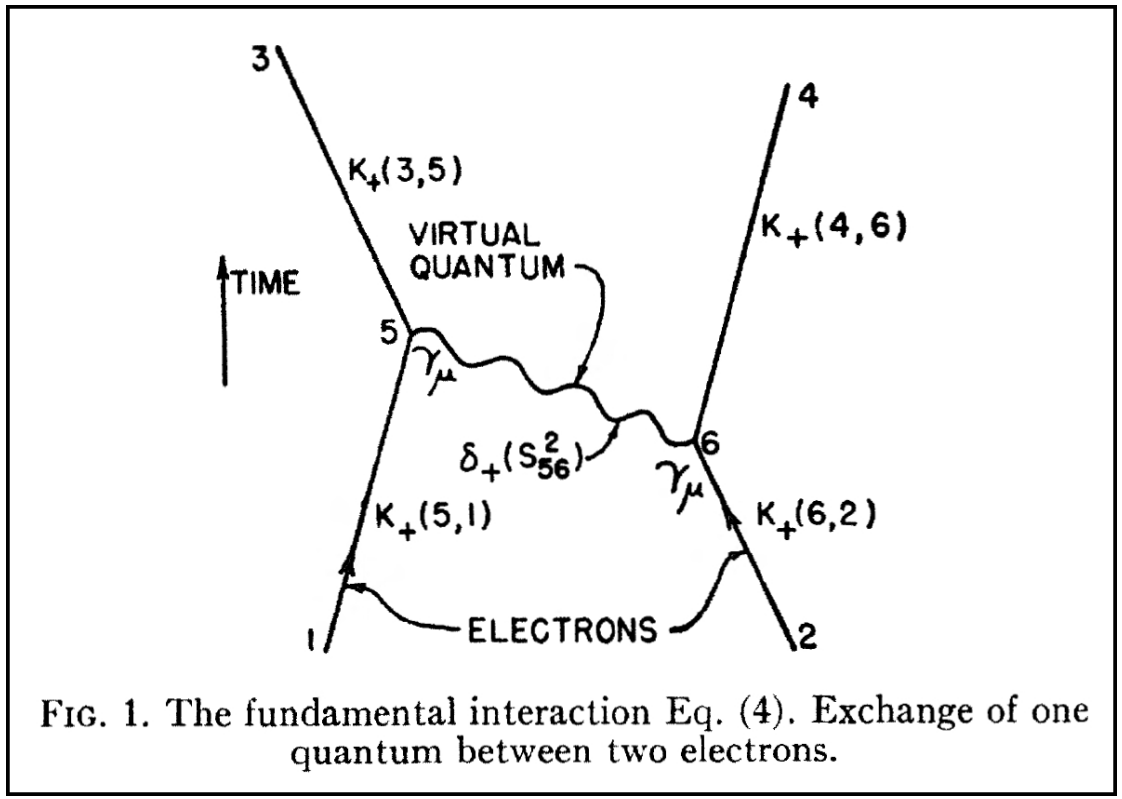


FIG. 1. The fundamental interaction Eq. (4). Exchange of one quantum between two electrons.

R. P. Feynman, *Space-Time Approach to Quantum Electrodynamics* [First use of a Feynman diagram], Physical Review **76** (6), 769–789 [Sep. 15] (1949). https://journals.aps.org/pr/pdf/10.1103/PhysRev.76.769

- Seven years later, Feynman dropped all use of atoms to absorb photons
- He instead went with the vastly simpler — and arguably more fundamental — approach of having *electrons* absorb photons
- The simplification enabled more precise mathematical models
- One "little" problem: The photon absorption he proposed cannot happen in classical physics
- This is why Feynman calls the quantity that is emitted and absorbed a "virtual" photon

How Is Choosing an Impossible Process "Progress"?

- Feynman's most critical insight between 1942 and 1949 was this:
  - *All* absorptions of photons by matter violate conservation (!)
  - That is, an atom residing in a hard vacuum with no interacting fields *also* violates energy-momentum conservation, and so *also* "cannot exist"
  - The larger the body, the smaller the deviation becomes, but…
  - … it never *fully* disappears
  - The photon is like a "hot potato" that each body must pass along, at least in part, to yet another body (think entropy)
- By recognizing that atoms *also* violate energy-momentum conservation, Feynman eliminated any need to use atoms
- Focusing *only* on electrons and photons allowed him to create a method, QED, that could calculate in new, more precise ways

Part IV.
Why Feynman's Operator Cannot Exist

Adding Pure Momentum to Rest Mass Is Paradoxical

Here is Dibyajyoti Das's equation for the energy and momentum of an electron after it absorbs a photon (Feynman Action #3, a "coupling"):

$$2m_0c^2h\nu = 0$$

> "[The above] equation [describes the energy and momentum of an electron after it fully absorbs a photon.] The rest mass energy [of the electron-photon combination cannot be] equal to zero, [and] the [photon] frequency of the [electron-photon combination] also [cannot] equal … zero [since] the … photon [cannot] exist [if its frequency is zero]. … The … equation is not possible [because] this process [cannot] … conserve momentum and energy simultaneously. **The only way [an] electron can … absorb a … photon is when the electron is in a bound system [where something] nearby … like a nucleus … can absorb some of the recoil and conserve [total] momentum** in [the] process."

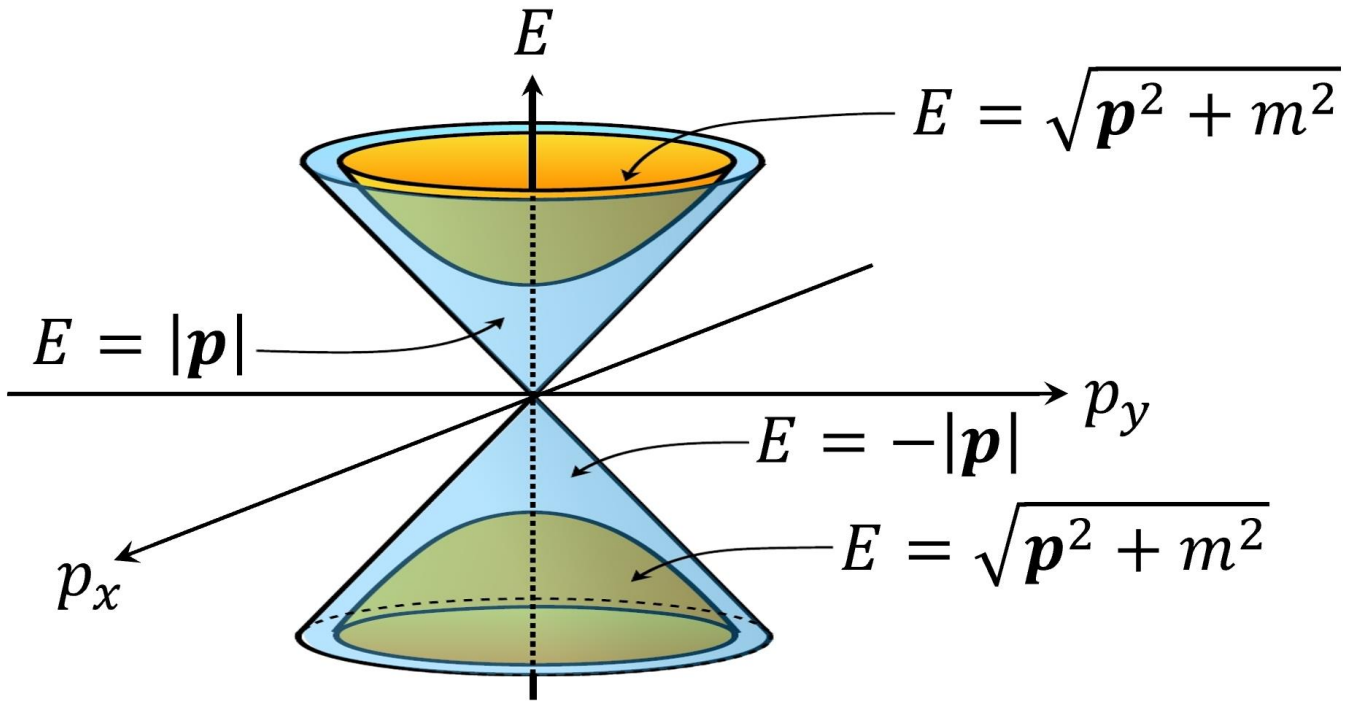
[1] Dibyajyoti Das, *Can a free electron absorb a photon?* For the Love of Physics (YouTube) **2019**, 0611 [Jun. 11] (2019). https://youtu.be/QRCSlbOhMFU?t=06m45s

Describing What Is and Is Not Possible

- When Young Feynman used atoms as photon absorbers in his dissertation, he was following a decades-long perspective
- To describe what is and is not possible when photons and electrons (and other particles) interact, physicists used a method called *mass shells* to create a surface (a "shell") of valid outcomes
- The "shell" is a shape in 4D space that fully conserves all energy and momentum
- The *classical* world is ferociously "on shell"
- The *quantum* world is… another story entirely
- In a nutshell, Feynman's most important insight was that he could device a mathematical theory that operated almost entirely *off shell*

Part V.
Mass Shells as Incompatible Universes

The Energy-Momentum Shells of Electrons and Photons



GOLD SHELL: The 4D hyperboloid showing all permitted energy-momentum combinations for a **massive particle** (e.g., for an electron).

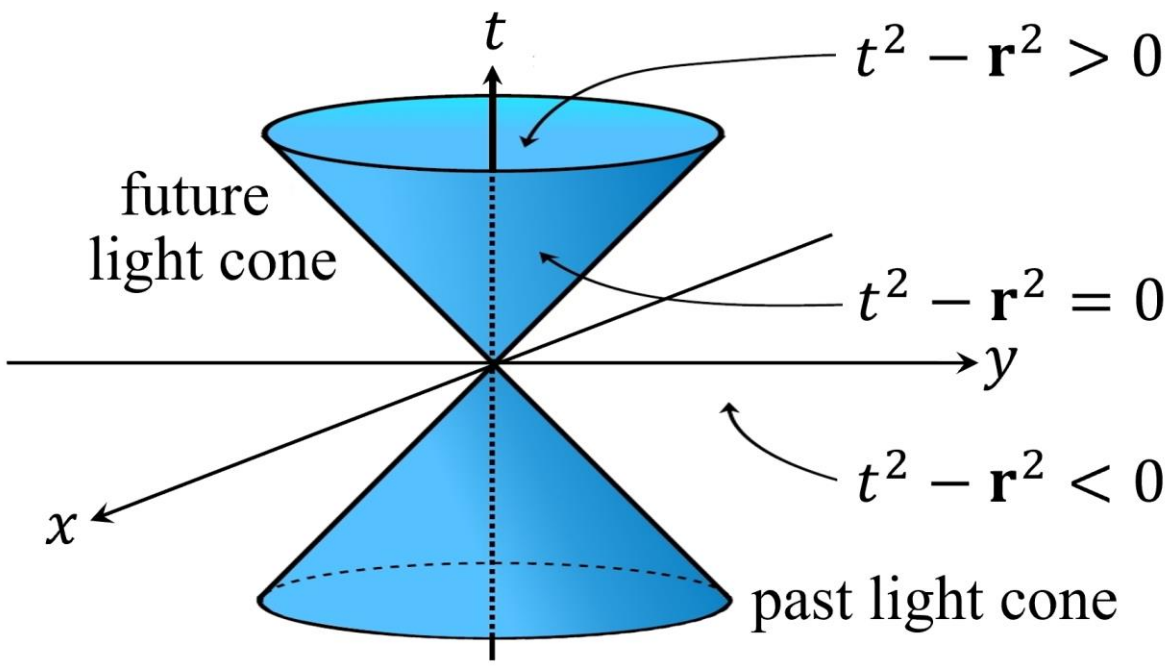
BLUE SHELL: The 4D double cone (extreme hyperboloid) showing all permitted energy-momentum combinations for a particle with **no rest mass** (e.g., a photon).

L. Álvarez-Gaumé and M. Á. Vázquez-Mozo, "Field theory and the Standard Model: A symmetry-oriented approach," in *Proceedings of the 2022 European School of High-Energy Physics*, 2022. (Figure 3.) https://cds.cern.ch/record/2926918/files/Publication.pdf, CC BY 4.0

The Two Mass Shells Never Intersect

- One of the simple but striking features of the massless and massive shells is that *they never intersect*
- Instead, as the energies and momentums grow large, the shells of massless and massive particles grow increasingly close
- This asymptotic approach is a vital part of why the classical world works the ways it does:
  - While the two shells never *quite* intersect, they get close enough that they can be treated "as if" they are fully interoperable
  - Young Feynman's use of atoms as absorbers and emitters is an example, since, at first, they seemed large enough to treat as fully classical
- However, the fact that these shells *do not* intersect is also why events such as photon emission remain stubbornly unstable

An Oddly Similar Figure: Special Relativity Light Cones



The joined tips of the cones define a point-like historical event.

The **FUTURE LIGHT CONE** interior (the top of two $t^2 - \mathbf{r}^2 > 0$ regions) is the only future that this event can ever influence.

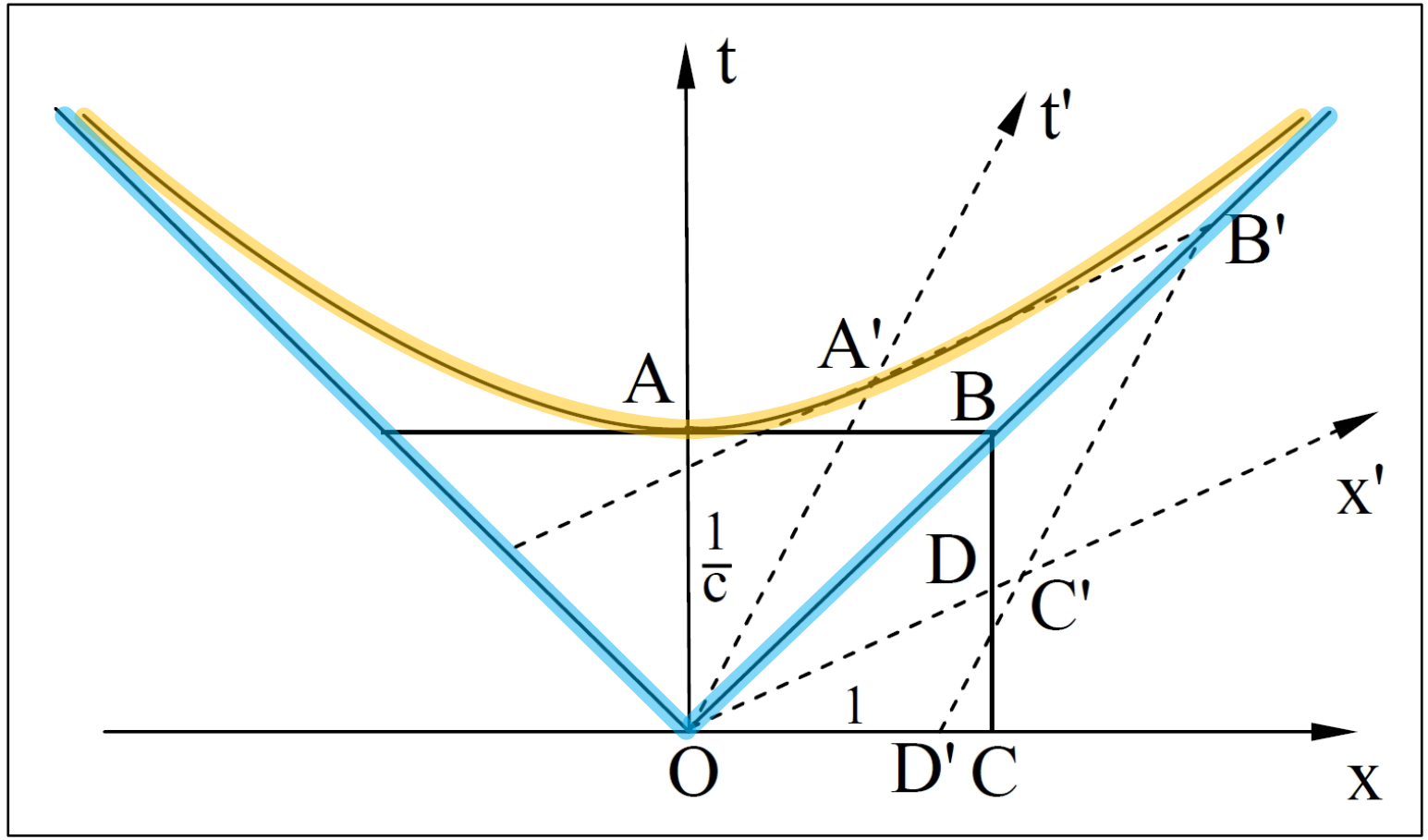
The **PAST LIGHT CONE** interior (the bottom $t^2 - \mathbf{r}^2 > 0$ region) defines all past activities that can impact the event

Light in the vacuum defines the $t^2 - r^2 = 0$ surfaces of both of the cones

Anything outside the light cone interiors (the vast surrounding space-like $t^2 - r^2 < 0$ region) can impact the future cone, but cannot be known at the time of the event

L. Álvarez-Gaumé and M. Á. Vázquez-Mozo, "Field theory and the Standard Model: A symmetry-oriented approach," in *Proceedings of the 2022 European School of High-Energy Physics*, 2022. (Fig. 3)

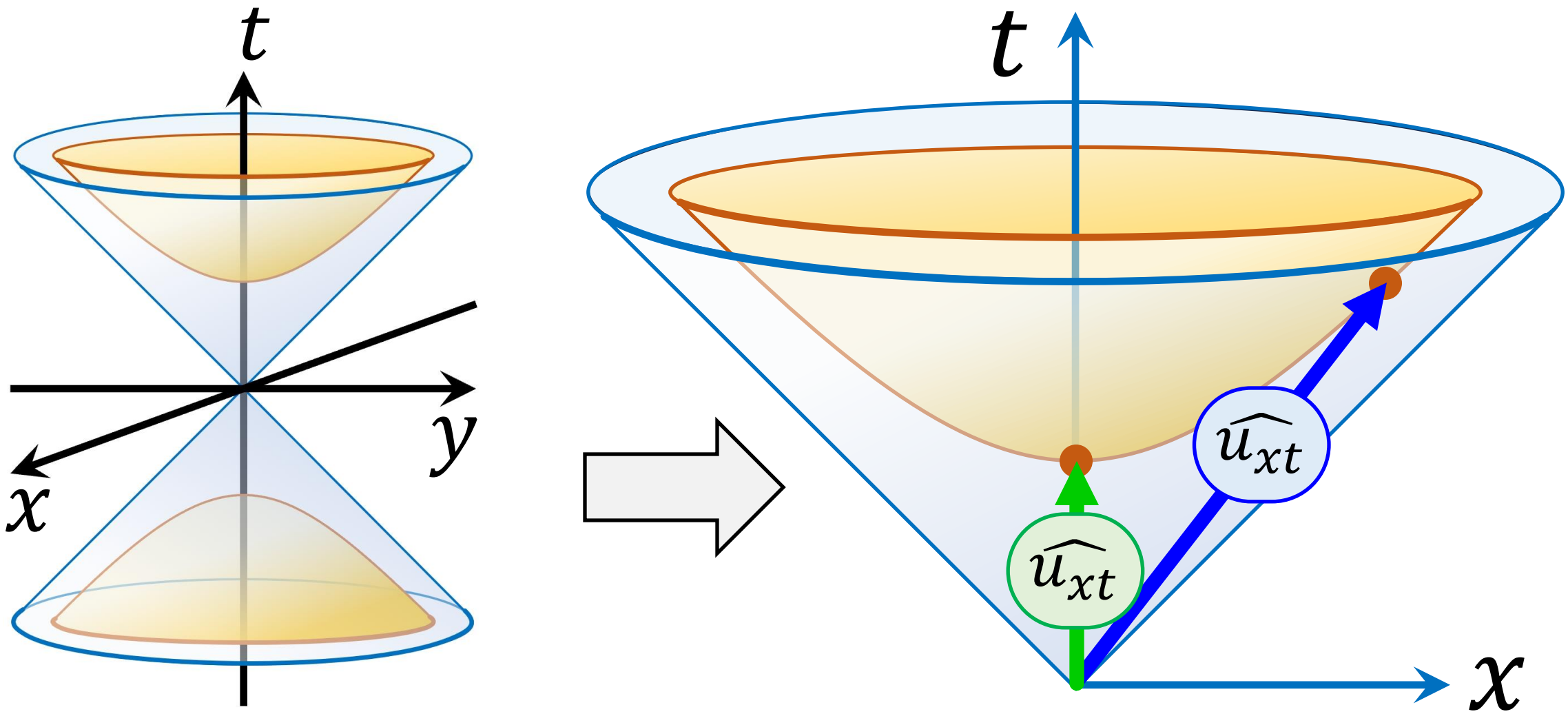
Special Relativity Also Has Convergent Shells



H. Minkowski, *Space and Time*. 80th Assembly of German Natural Scientists and Physicians, Sep. 21, 1908. (Fig. 1) http://www.minkowskiinstitute.org/mip/books/minkowski.html

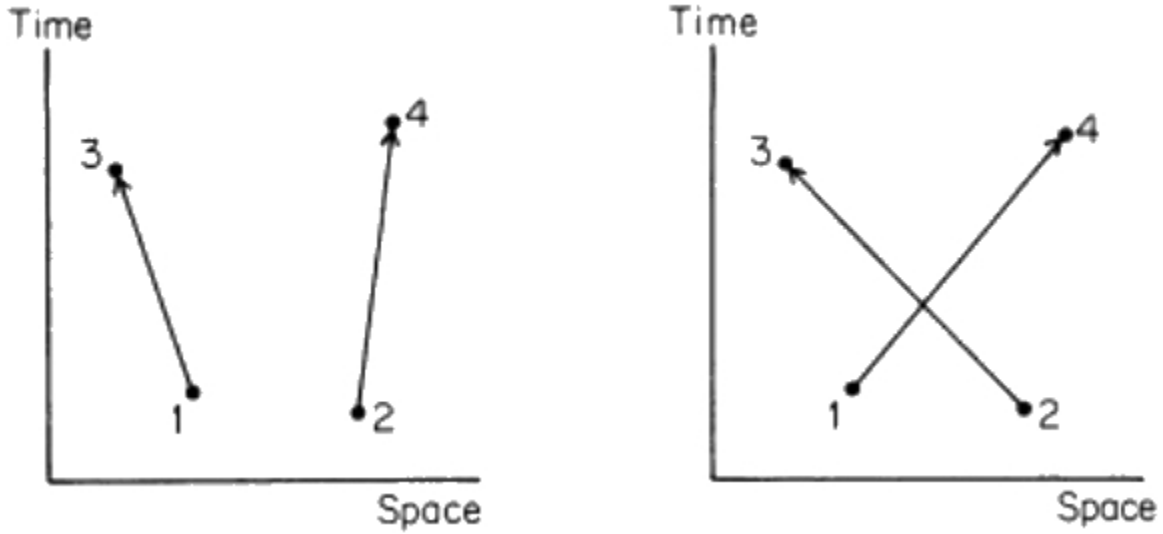
- Hermann Minkowski famously reinterpreted Einstein's 1905 paper on special relativity by placing it into a 4D spacetime continuum
- Within Minkowski's forward light cone (the blue-highlighted lines), one line (gold) of a 4D hyperboloid emerges
- The time-location coordinates of special relativity differ from the (conjugate!) energy-momentum coordinates of mass shells, but the geometry stays the same

Spacetime Hyperboloids Define Clock Units for All Frames



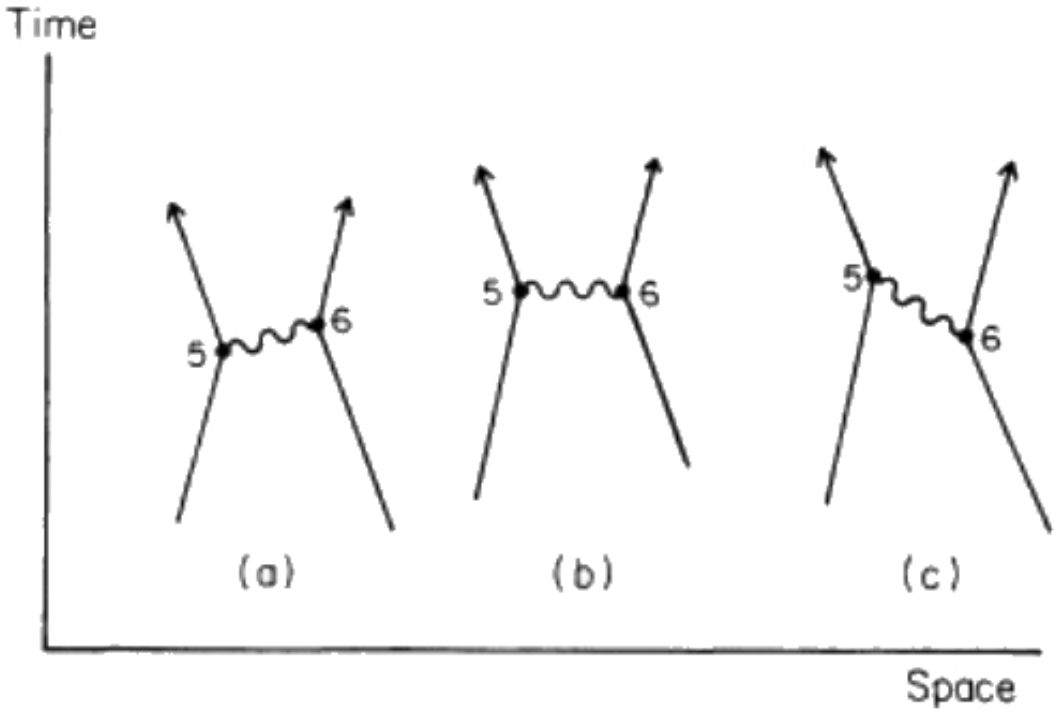
Part VI.
More Complicated Feynman Diagrams

To Cross or Not to Cross: This is Important in QED!



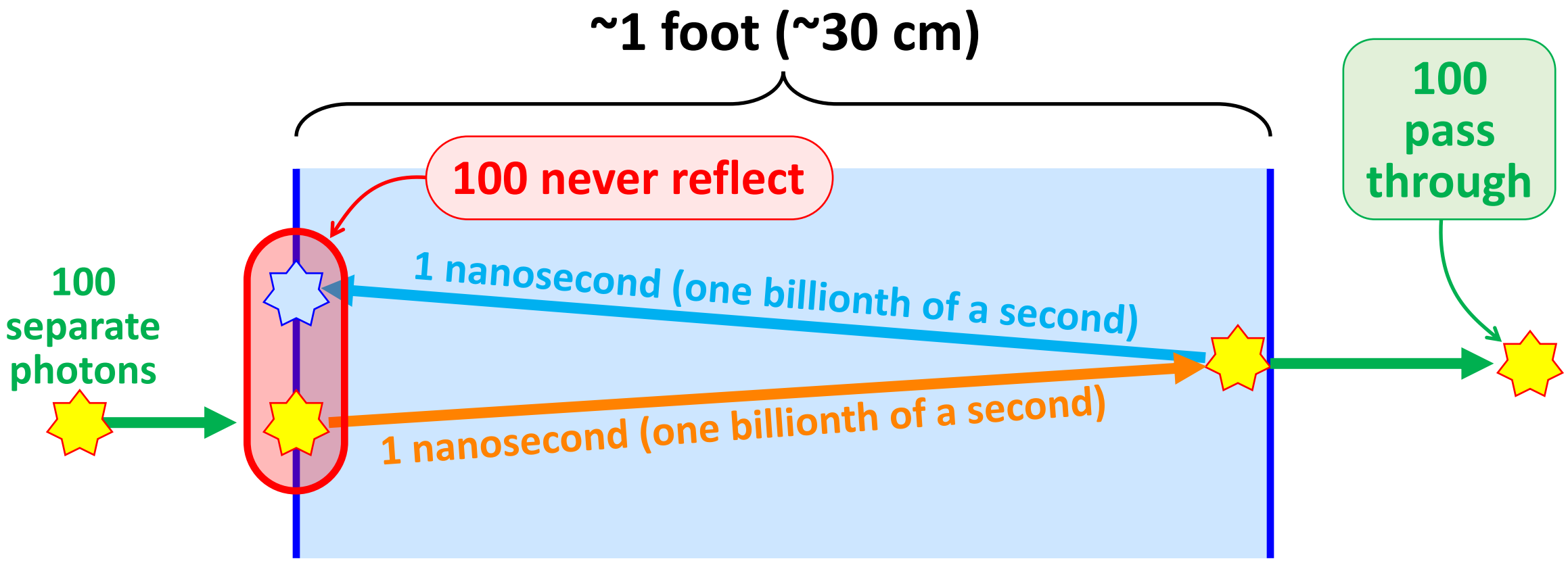
- In Figure 59, Feynman begins "prepping" for an especially important difference between two classes of particles, bosons (like photons) and fermions (like electrons)
- What distinguishes the two groups is strangely simple: How do they behave when their paths cross?
- Particles that don't like to cross transform into what we call matter

Time Gets Wonky in Feynman Diagrams



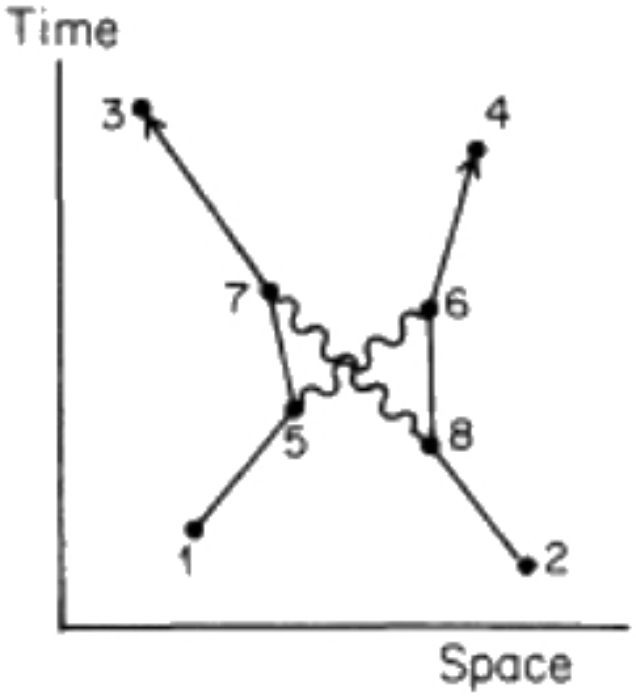
- Fig. 61: Since the speed of light *emerges* from summing many photon paths, ordinary time takes a big hit in Feynman diagrams
- The implications affect more than just calculations
- For example, recall the example of photons getting "lost" for 2 ns.

One Photon Can Be "All Over" a Lengthy Time Period



Two nanoseconds *after* the photon hits the glass front, its reflection from the far side of the glass cancels the existence of its reflection

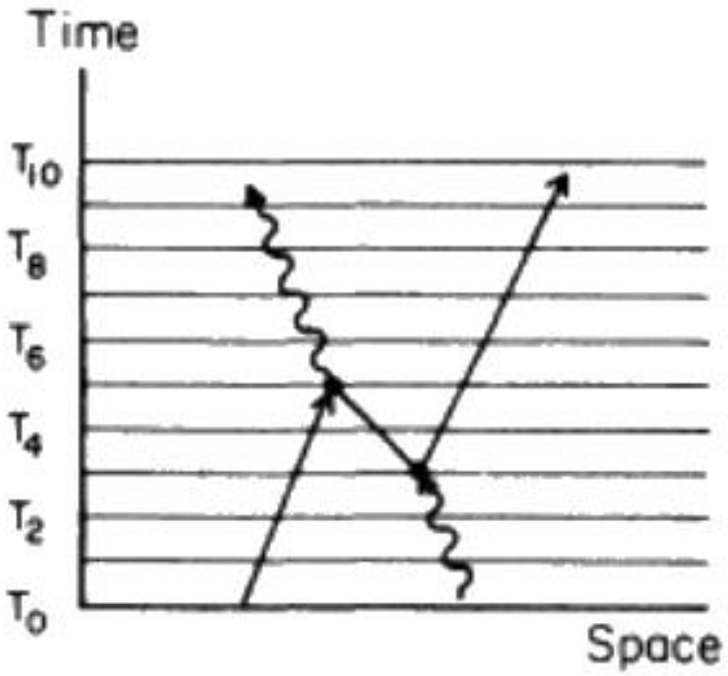
High-Accuracy Feynman Diagrams Get *Very* Complicated



- Fig. 62: First-whack Feynman diagrams are easy. Figures for making more detailed predictions are not easy at all!
- The problem is that the model *increases* probabilities for more lines and vertices as you get smaller in scale

Part VII.
Antimatter as Traveling Backward in Time

An Iconic Image: An Electron "Bouncing" Back in Time



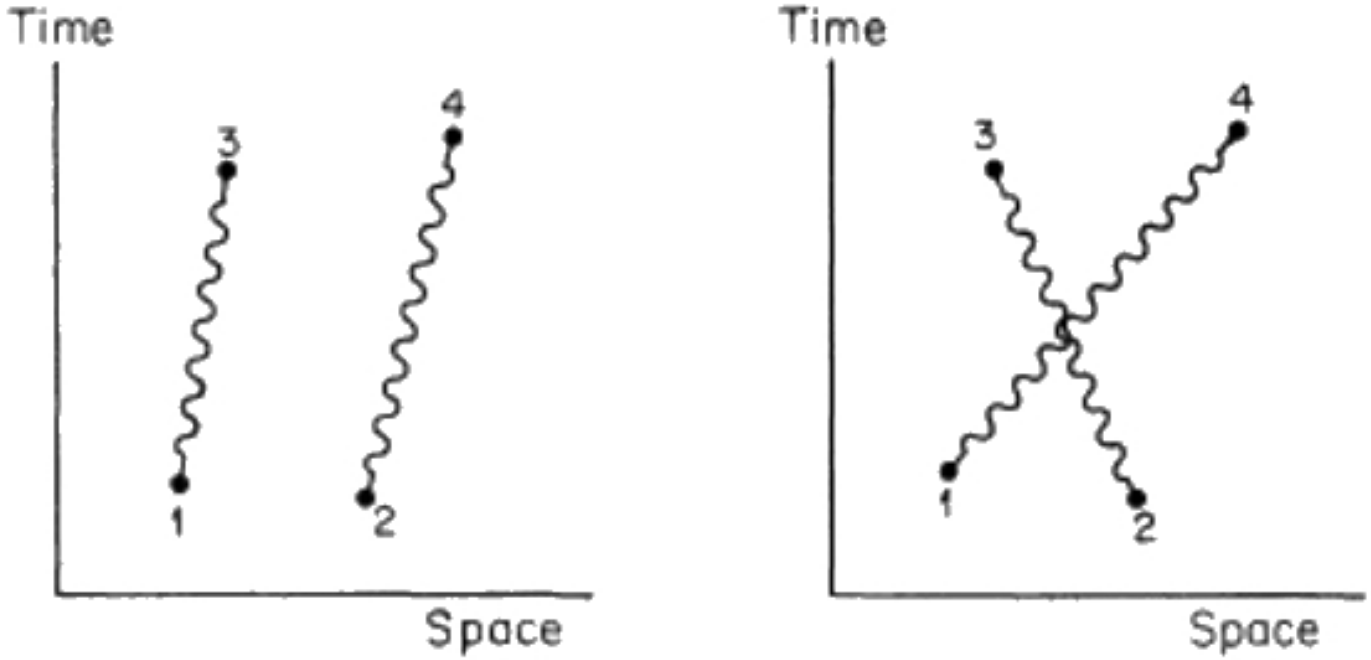
> It is as though a bombardier flying low over a road suddenly sees three roads and it is only when two of them come together and disappear again that he realizes that he has simply passed over a long switchback in a single road.

R. P. Feynman, The Theory of Positrons. Physical Review 76 (6), 749–759 [Sep. 15] (1949). https://authors.library.caltech.edu/records/vysv7-c2b63

- (Fig. 64) One of Feynman's memorable images is an electron "bouncing" off an energy event, traveling backward in time as a positron, then returning to its electron state after another bounce
- This observable event has inspired a great deal of science fiction.

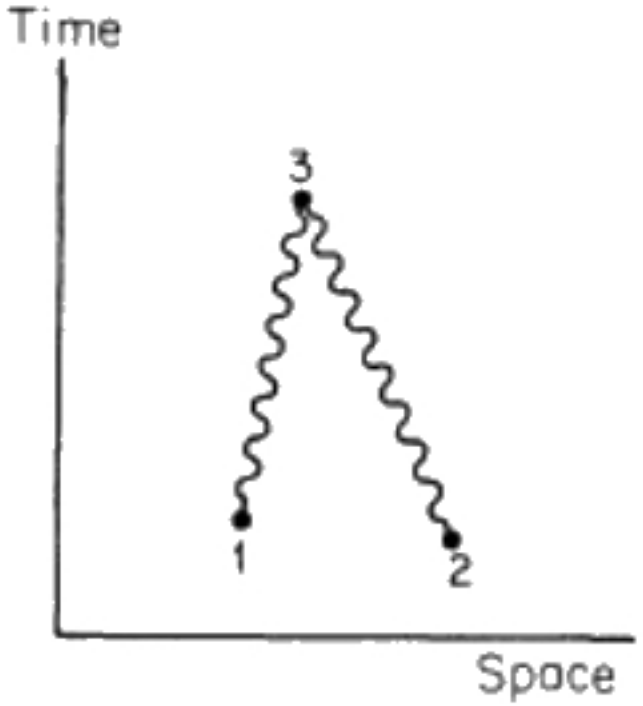
Part VIII.
The Greatest Divide in Particle Physics

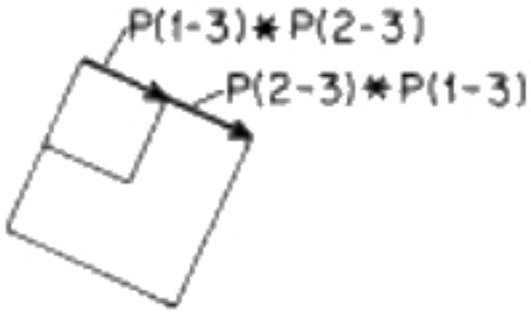
Mentioned, But Not Really Covered



- (Fig. 70) As mentioned earlier, Feynman notes that some particles (e.g., light beams) like crossing paths, while others (e.g., water streams from hoses) don't like to be in the same place at all
- Repelling gives rise to matter; cooperating gives rise to energy

A Final Odd Figure: This is Not a Laser Beam!





- (Fig. 71) Feynman provides a strong explanation for why additive probability makes lasers possible, but laser photons don't cross
- The diffuse model of photons sharing a single large space captures this form of addition much better

Part IX.
Summary: What I Found Interesting

Summary: What Did I Find Most Interesting?

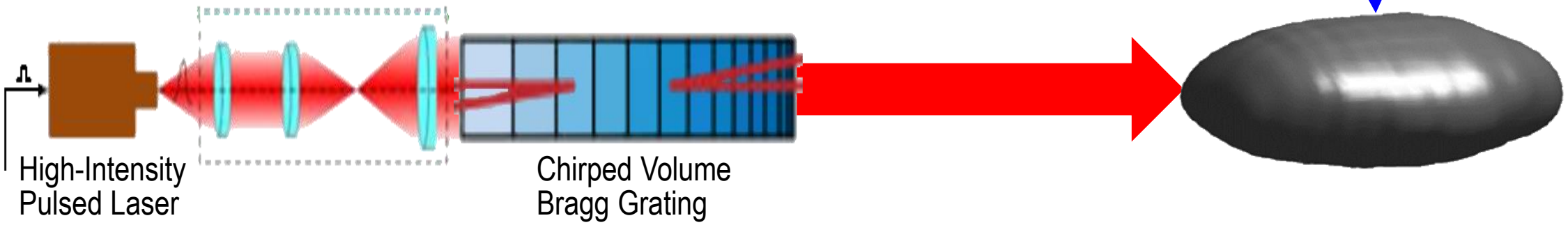
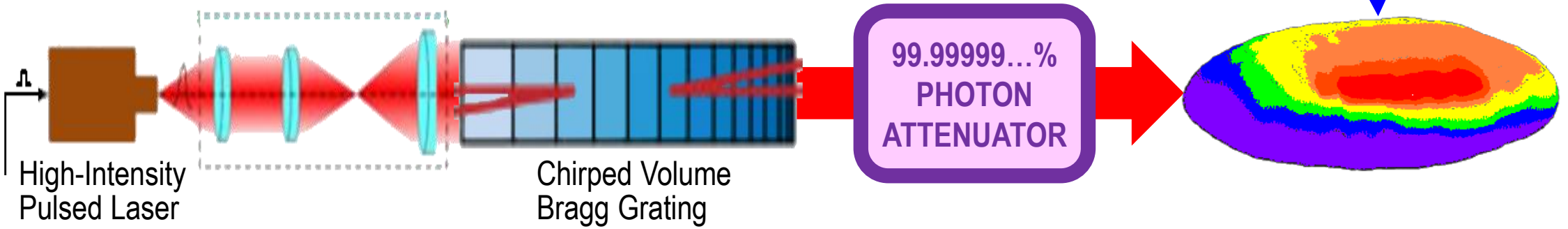
- I was deeply surprised that Feynman's most impactful insight is the one almost no one talks about
- His transition from atoms-absorbing-photons to electrons-absorbing-photons is well documented in his dissertation and subsequent papers
- If Feynman had *not* realized that the instability of photons applies to all forms of matter, it is unlikely he ever would have come up with as effective a model for calculating as he did.
- The associated issue of the existence of two distinct and non-intersecting energy-momentum shells feels deeply important
- In effect, we have two universes in parallel, with quantum mechanics acting as the reconciliation interface between the two

Addendum: What is the Shape of a Photon?

Q: What is the **3D size and shape of a single photon**?

A: *Whatever you want it to be* (**Pulse Attenuation Photon Shaping**)

OUTPUT: A Well-Bounded, Well-Shaped, High-Intensity Chirped Pulse



OUTPUT: A Well-Bounded, Well-Shaped, *Single-Photon* Wave Packet