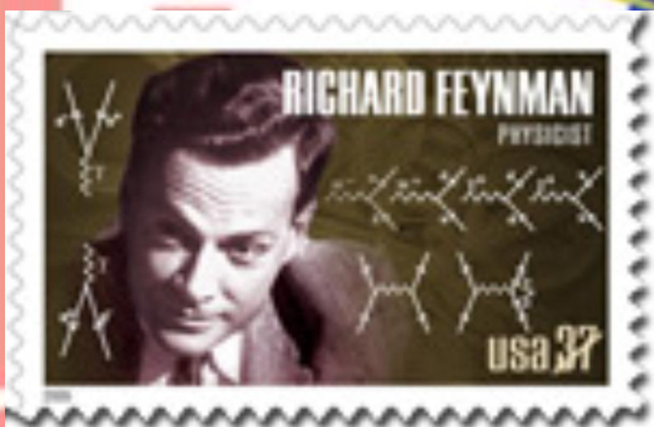
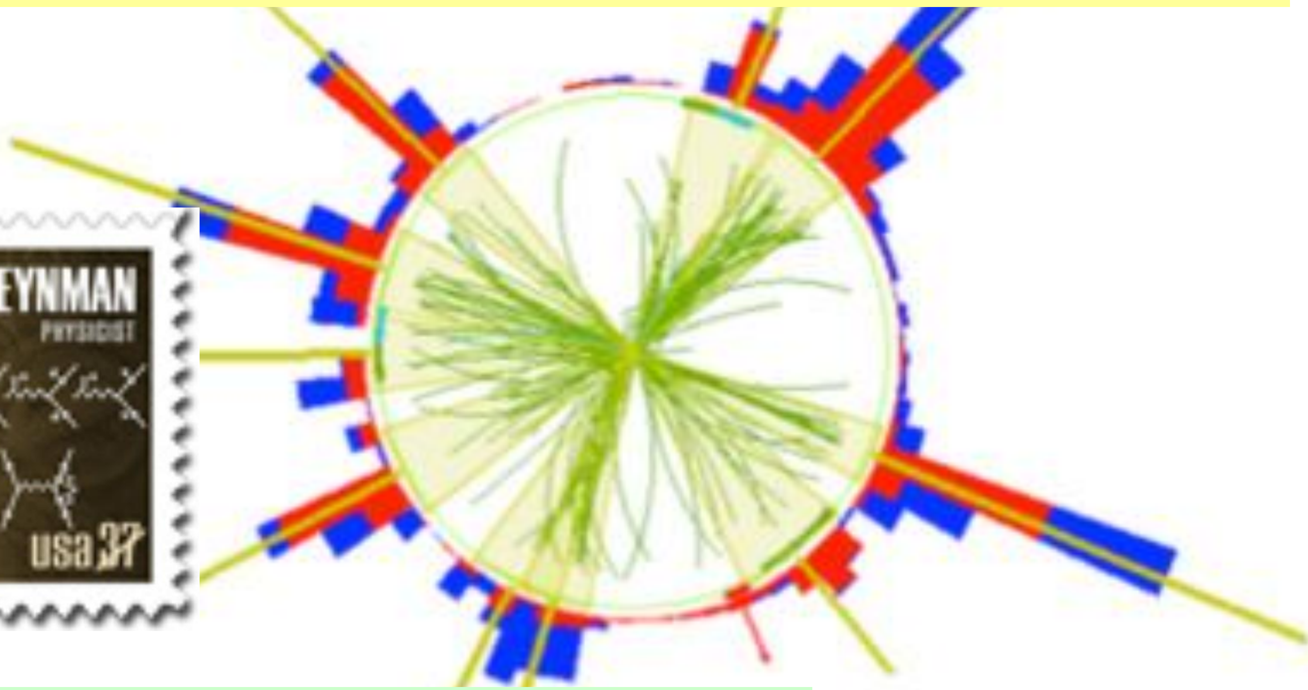
Richard Feynman at 100

Feynman Diagrams and Beyond





Lance Dixon (SLAC)

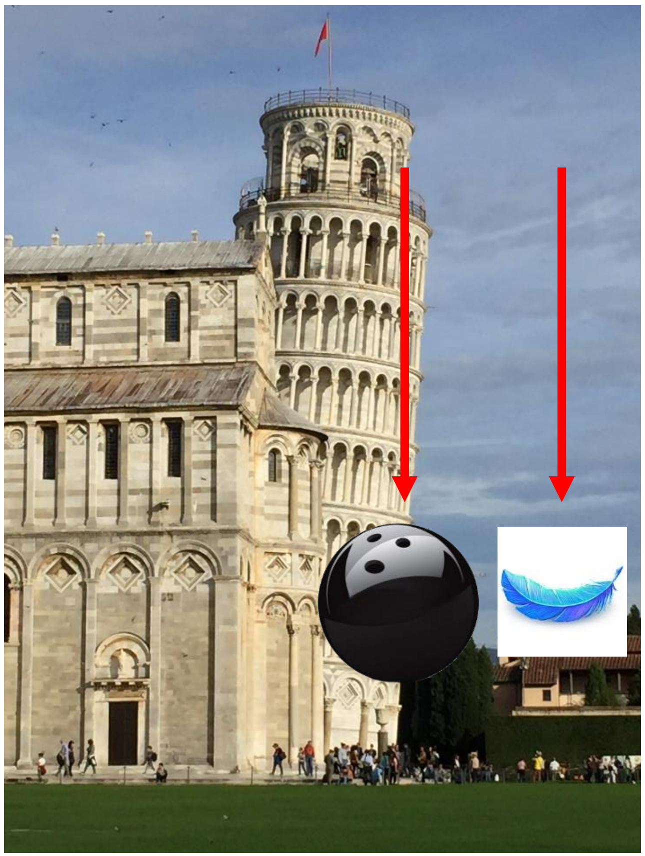
Galileo’s Villa, Arcetri

November 9, 2018

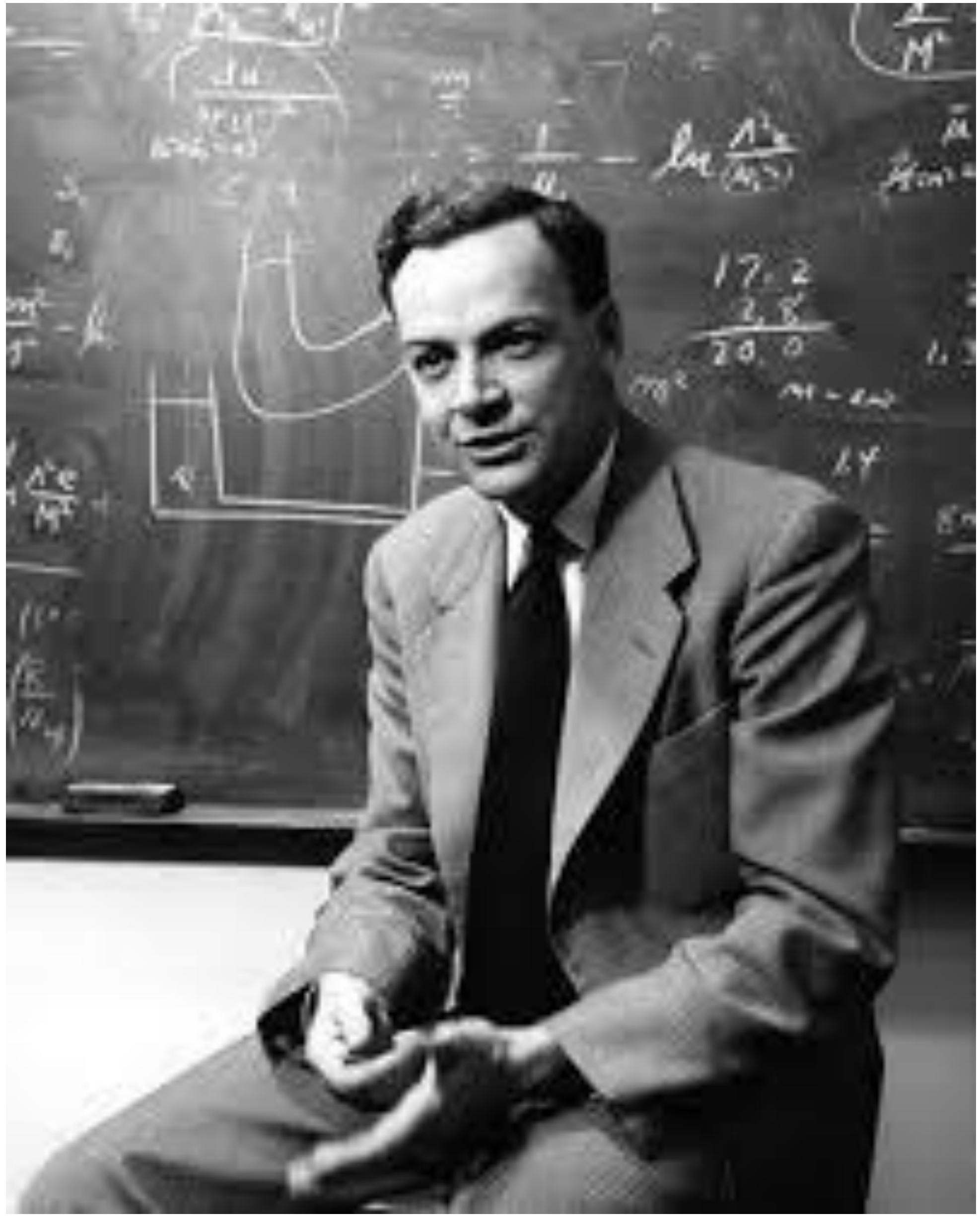
NATIONAL ACCELERATOR LABORATORY

Before Feynman, there was Galileo

- Renaissance man, theorist and experimenter

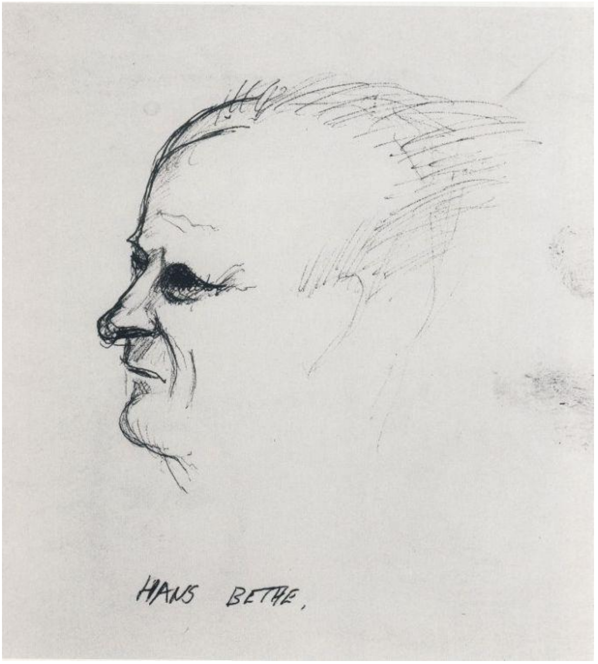


Also found in Pisa:



Feynman also a Renaissance man

- Besides his science, Feynman also left a legacy in art

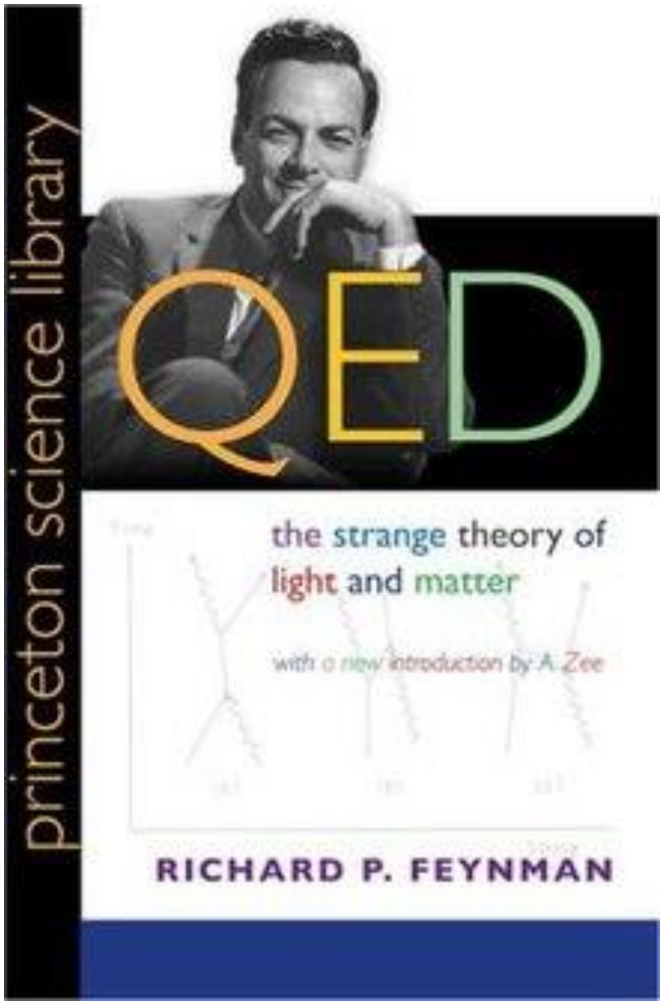


“At least as good as Rembrandt’s physics” - Curt Callan

Outline

- Feynman, Feynman diagrams and QED
- Feynman and early QCD
- Feynman and the weak interactions
- Feynman and quantum gravity
- Feynman and biology

Feynman's revolutionary insights into scattering of quantum particles



were initially for Quantum ElectroDynamics

Theory of how electrons interact with the particles associated with light or electromagnetism = photons

The most precise theory of all
– good to a part per trillion!

Shelter Island, June 1947

NAS
Archives

Dirac theory of electron incomplete:

- Willis Lamb reports on Lamb shift between 2S and 2P hydrogen
- Isadore Rabi reports on electron anomaly [Nafe, Nelson, Rabi]

Feynman's thesis work
birthplace of the path integral

$$\int [D\phi(t,x)] \exp\left\{\frac{i}{\hbar} S[\phi(t,x)]\right\}$$

REVIEWS OF
MODERN PHYSICS

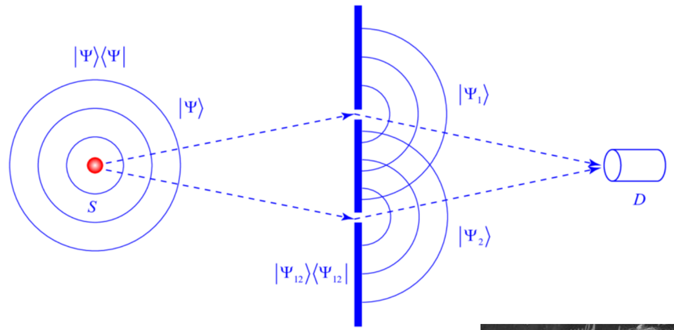
VOLUME 20, NUMBER 2 APRIL, 1948

Space-Time Approach to Non-Relativistic Quantum Mechanics

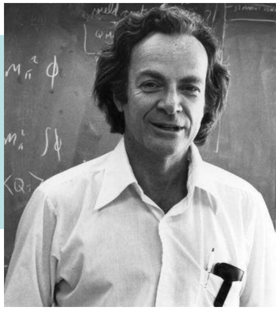
R. P. FEYNMAN

Cornell University, Ithaca, New York

Non-relativistic quantum mechanics is formulated here in a different way. It is, however, mathematically equivalent to the familiar formulation. In quantum mechanics the probability of an event which can happen in several different ways is the absolute square of a sum of complex contributions, one from each alternative way. The probability that a particle will be found to have a path $x(t)$ lying somewhere within a region of space time is the square of a sum of contributions, one from each path in the region. The contribution from a single path is postulated to be an exponential whose (imaginary) phase is the classical action (in units of $\hbar$) for the path in question. The total contribution from all paths reaching x, t from the past is the wave function $\psi(x, t)$. This is shown to satisfy Schroedinger's equation. The relation to matrix and operator algebra is discussed. Applications are indicated, in particular to eliminate the coordinates of the field oscillators from the equations of quantum electrodynamics.



~ How Feynman introduced quantum mechanics to us Caltech undergrads in 1979



The beginning of Feynman diagrams

PHYSICAL REVIEW VOLUME 76, NUMBER 6 SEPTEMBER 15, 1949

The Theory of Positrons

R. P. Feynman
Department of Physics, Cornell University, Ithaca, New York

(Received April 8, 1949)

PHYSICAL REVIEW VOLUME 76, NUMBER 6 SEPTEMBER 15, 1949

Space-Time Approach to Quantum Electrodynamics

R. P. Feynman
Department of Physics, Cornell University, Ithaca, New York

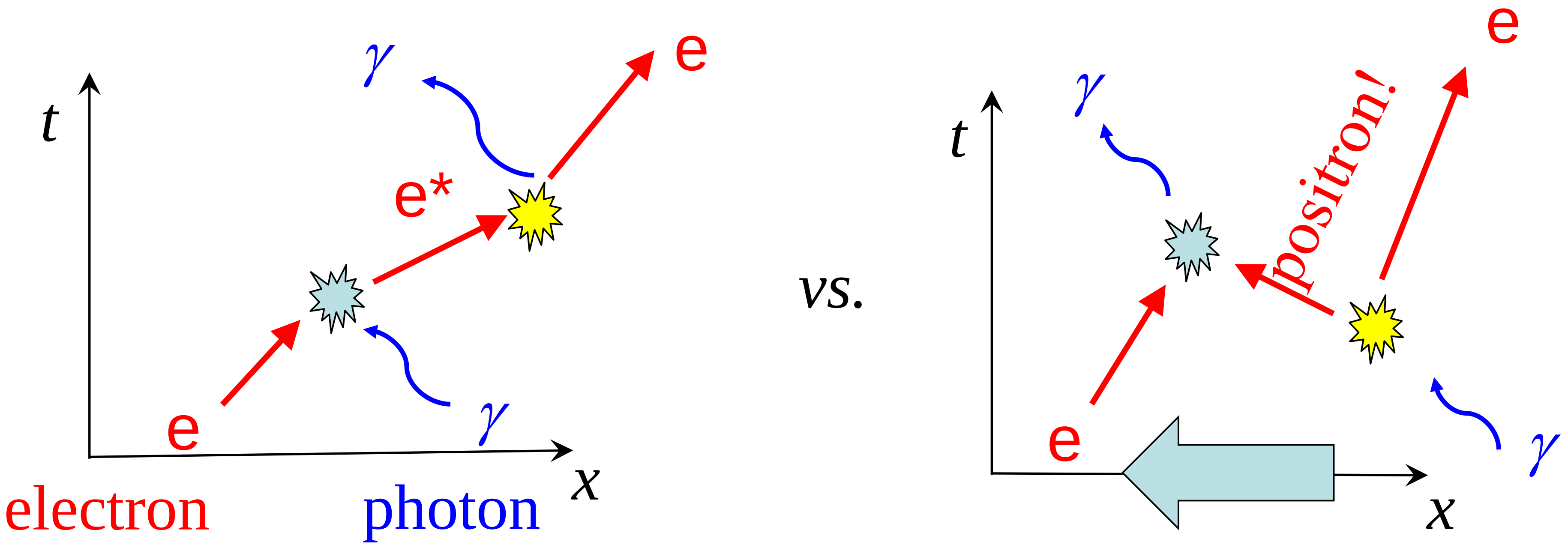
(Received May 9, 1949)

- Before Feynman, quantum-mechanical calculations were strictly ***time-ordered***, based on the Hamiltonian *H* which evolves states forward in time:

$$|\psi(t)\rangle = \exp(-iHt/\hbar)|\psi(0)\rangle$$

Covariance and positrons

Feynman realized that time ordering is ***ambiguous*** in special relativity: Two observers moving with respect to each other can see the same two events happen in different order.



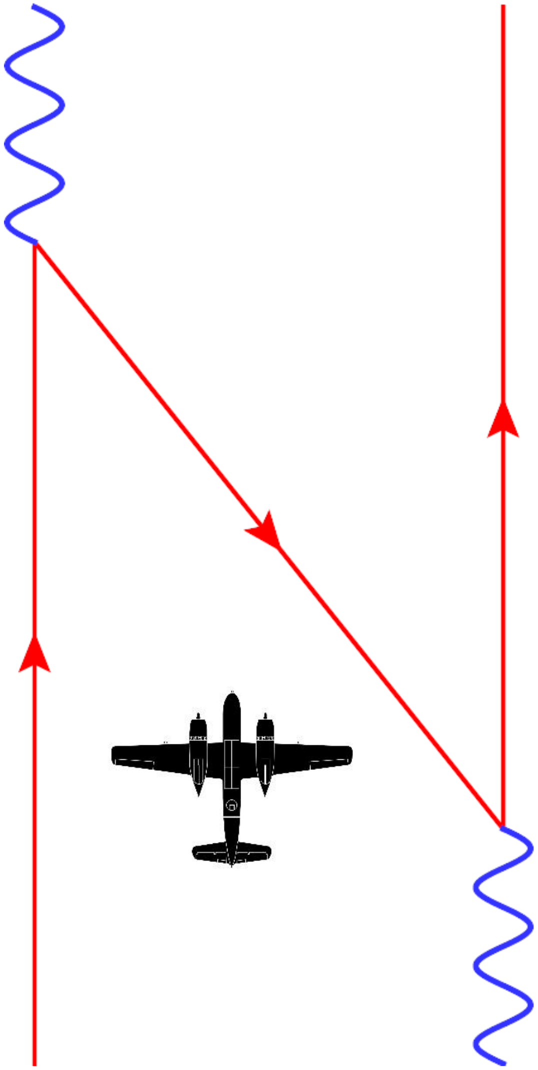
A positron is an electron moving backward in time

Wheeler

These two **time-ordered** contributions naturally belong together!

A holistic view

Following the charge rather than the particles corresponds to considering this continuous world line as a whole rather than breaking it up into its pieces. 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.



On and off the "mass shell"

- Einstein: energy of a particle at rest is $E = mc^2$
- Energy of a particle in motion with momentum $\mathbf{p}$:
  $E^2 = (\mathbf{p}c)^2 + (mc^2)^2 = \mathbf{p}^2 + m^2$ for $c = 1.$
- Energy & momentum form a relativistic four vector, $p^\mu = (p^0, p^1, p^2, p^3) = (E,\mathbf{p})$
- Its relativistically invariant "length" is its mass:

$$p^2 = p^\mu p_\mu = E^2 - \mathbf{p}^2 = m^2$$

- Real particles are on-shell, $p^2 = m^2$
- Virtual particles are off-shell, $p^2 \neq m^2$

Neither advanced nor retarded

In order to combine the two contributions, Feynman needed to construct a new “propagator” – the rule for how the electron gets from point A to point B. It also had to move positrons (sometimes called negative energy solutions) backward in time from point B to point A.

Retarded propagator only propagates effects to later time, it is causal.

$$G_{\text{ret}}(p) = \frac{1}{(p^0 + i\varepsilon)^2 - \mathbf{p}^2 - m^2}$$

Advanced propagator only propagates effects to earlier time, it’s anti-causal

$$G_{\text{adv}}(p) = \frac{1}{(p^0 - i\varepsilon)^2 - \mathbf{p}^2 - m^2}$$

Feynman propagator does either, depending on energy, it’s covariant

$$G_F(p) = \frac{1}{p^2 - m^2 + i\varepsilon}$$

Freeman Dyson, interlocutor

PHYSICAL REVIEW VOLUME 75, NUMBER 3 FEBRUARY 1, 1949

The Radiation Theories of Tomonaga, Schwinger, and Feynman

F. J. Dyson
Institute for Advanced Study, Princeton, New Jersey

(Received October 6, 1948)

A unified development of the subject of quantum electrodynamics is outlined, embodying the main features both of the Tomonaga-Schwinger and of the Feynman radiation theory. The theory is carried to a point further than that reached by these authors, in the discussion of higher order radiative reactions and vacuum polarization phenomena. However, the theory of these higher order processes is a program rather than a definitive theory, since no general proof of the convergence of these effects is attempted.

The chief results obtained are (a) a demonstration of the equivalence of the Feynman and Schwinger theories, and (b) a considerable simplification of the procedure involved in applying the Schwinger theory to particular problems, the simplification being the greater the more complicated the problem.

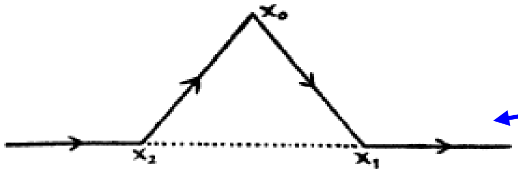


Fig. 1.

First Feynman diagram in print!

Dyson as Ben Jonson to Feynman's Shakespeare

"Nature herself was proud of his designs, and joyed to wear the dressing of his lines."

The most iconic Feynman diagram

772 Phys. Rev. 76, 769 R. P. FEYNMAN

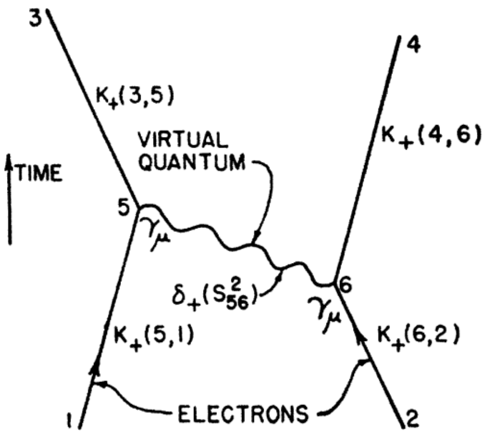


FIG. 1. The fundamental interaction Eq. (4). Exchange of one quantum between two electrons.

electron-electron scattering in QED

But it can be repurposed to also describe the most important processes in the Standard Model

Carved in stone in Tuva (courtesy of Glen Cowan, Ralph Leighton)

Feynman parameters

RPF, Phys. Rev. 76, 769

The integrals so far only contain one factor in the denominator. To obtain results for two factors we make use of the identity

$$a^{-1}b^{-1}=\int_0^1 dx(ax+b(1-x))^{-2}, \tag{14a}$$

(suggested by some work of Schwinger's involving Gaussian integrals). This represents the product of two reciprocals as a parametric integral over one and will therefore permit integrals with two factors to be expressed in terms of one. For other powers of a, b, we make use of all of the identities, such as

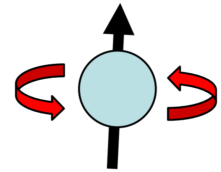
$$a^{-2}b^{-1}=\int_0^1 2xdx(ax+b(1-x))^{-3}, \tag{15a}$$

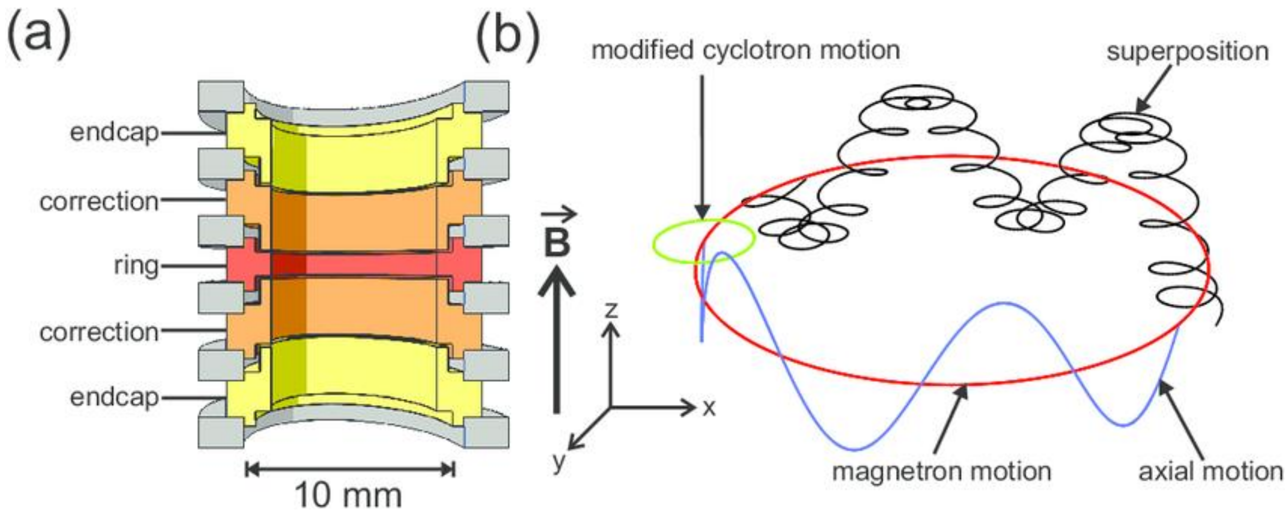
deducible from (14a) by successive differentiations with respect to a or b.

A mathematical trick, but an incredibly useful one.

The electron anomalous magnetic moment, a (precious) “baby” scattering amplitude

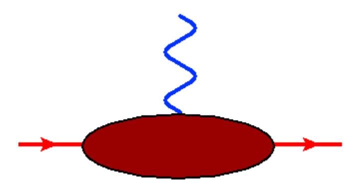
$$\vec{\mu}_e = g_e \frac{e\hbar}{2m_e c} \vec{S}_e$$





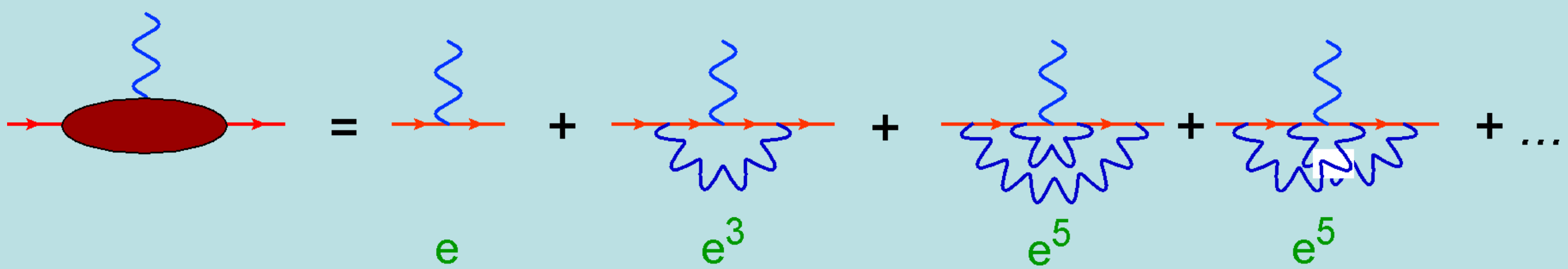
BASE, Eur. Phys. J. ST 224, 16, 3055 (2015)

Measurement doesn’t look much like particle scattering, but $a_e = (g_e - 2)/2$ can be computed from spin-flip part of $\gamma e \to e$ process as photon momentum → 0.



The loop expansion

- **Feynman:** Draw all diagrams with specified incoming and outgoing particles, weight them by coupling factors at each vertex. For a given process, extra powers of coupling for each closed loop.



In QED, each additional loop suppressed by the fine structure constant

$$\frac{e^2}{4\pi\hbar c} \equiv \alpha = \frac{1}{137.035999\ldots}$$

By 3 loops, 72 diagrams!

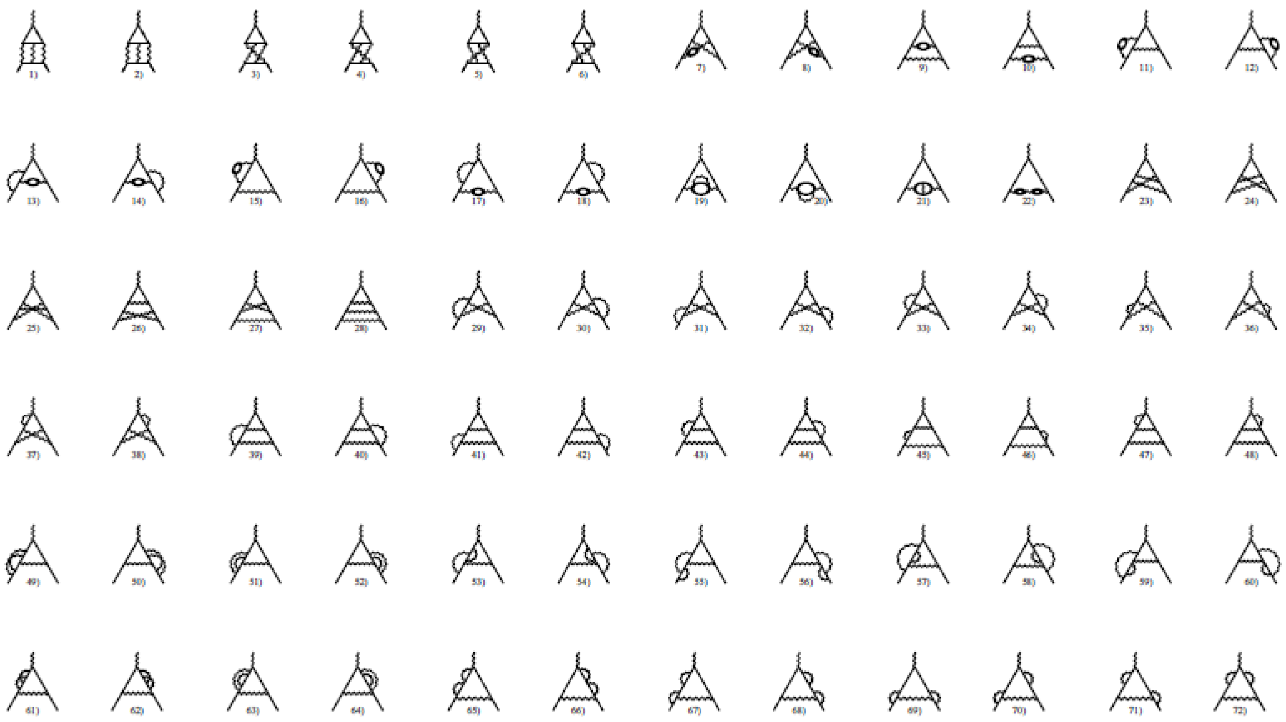


Fig. 7. The universal third order contribution to a_μ. All fermion loops here are muon–loops (first 22 diagrams). All non-universal contributions follow by replacing at least one muon in a closed loop by some other fermion

Without Feynman's methods, hopeless.

Even with Feynman diagrams, reaching this precision would take decades.

QED state of art today:
5 loops, 12,672 diagrams

30 gauge invariant sets

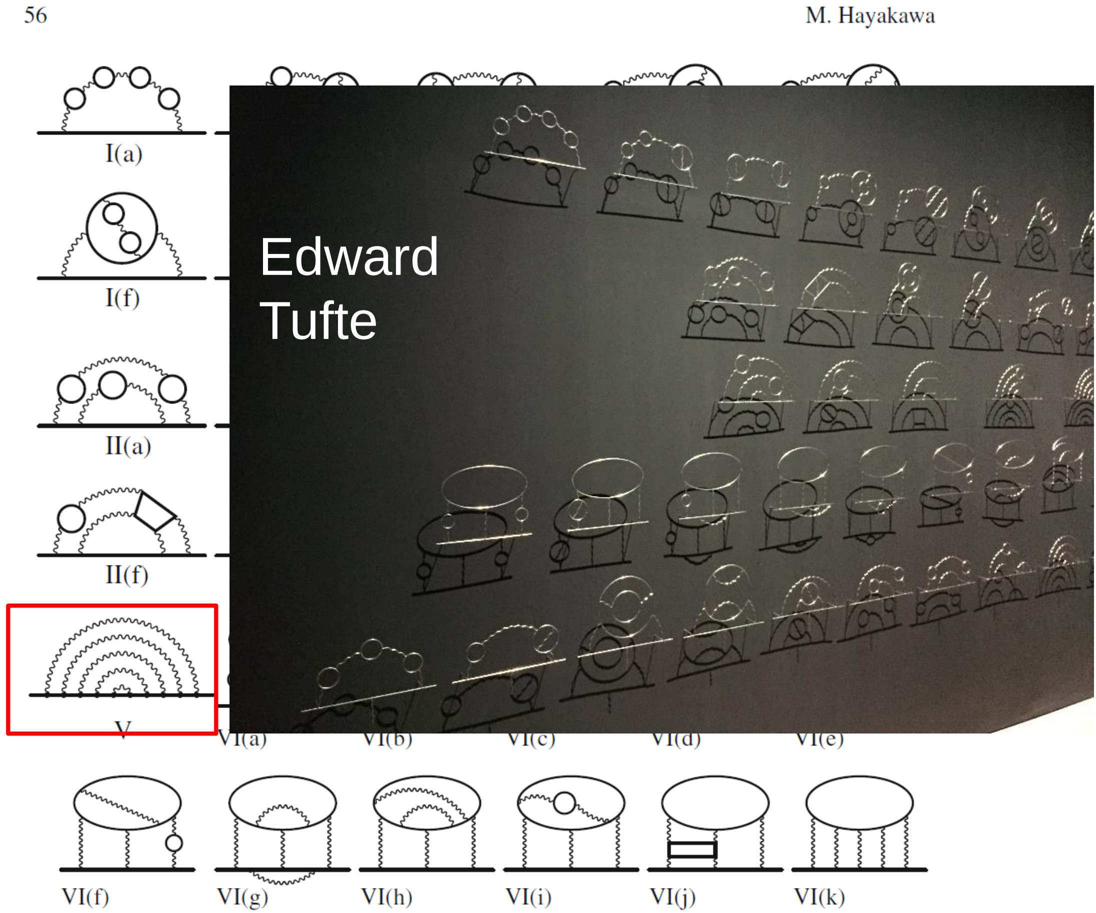


Fig. 2.7 Gauge-invariant subsets of self-energy-like diagrams at the tenth order

The most difficult set,
6354 diagrams,
leading to 389 integrals.
Evaluated numerically
after Feynman
Parameterization.

Aoyama, Hayakawa, Kinoshita, Nio, Watanabe, 2006-2017

7 decades of g_e-2 theory

fully analytic

$$\zeta_p = \sum_{k=1}^{\infty} \frac{1}{k^p}$$

$$\mathrm{Li}_4(\tfrac{1}{2}) = \sum_{k=1}^{\infty} \frac{1}{2^k\, k^4}$$

$$\begin{aligned}
a_e &= \frac{\alpha}{\pi}\cdot\frac{1}{2} \\
&+ \left(\frac{\alpha}{\pi}\right)^2 \left[\frac{197}{144} + \frac{\pi^2}{12} - \frac{\pi^2}{2}\ln 2 + \frac{3}{4}\zeta_3\right] \\
&+ \left(\frac{\alpha}{\pi}\right)^3 \left[\frac{28259}{5184} + \frac{17101}{810}\pi^2 - \frac{298}{9}\pi^2\ln 2 + \frac{139}{18}\zeta_3\right. \\
&\qquad - \frac{239}{2160}\pi^4 + \frac{100}{3}\left\{\mathrm{Li}_4\left(\frac{1}{2}\right) + \frac{1}{24}(\ln^4 2 - \pi^2\ln^2 2)\right\} \\
&\qquad \left. + \frac{83}{72}\pi^2\zeta_3 - \frac{215}{24}\zeta_5\right] + \ldots \\
&= 0.5\frac{\alpha}{\pi} \\
&\quad - 0.328478965579 1\ldots \left(\frac{\alpha}{\pi}\right)^2 \\
&\quad + 1.181241456587 2\ldots \left(\frac{\alpha}{\pi}\right)^3 \\
&\quad - 1.912245764926 4\ldots \left(\frac{\alpha}{\pi}\right)^4 \\
&\quad + 6.7(\pm 0.2)\left(\frac{\alpha}{\pi}\right)^5
\end{aligned}$$

Schwinger 1948

Karplus, Kroll 1950
Petermann 1957
Sommerfield 1957

Kinoshita, Cvitanovic 1972
Laporta, Remiddi 1996

numerical

Aoyama, Hayakawa, Kinoshita, Nio, 2005-2007
Laporta arXiv:1704.06996

(+ mass-dep.)

Aoyama, Hayakawa, Kinoshita, Nio, Watanabe, 2006-2017

Laporta 4 loop result in "co-action" form

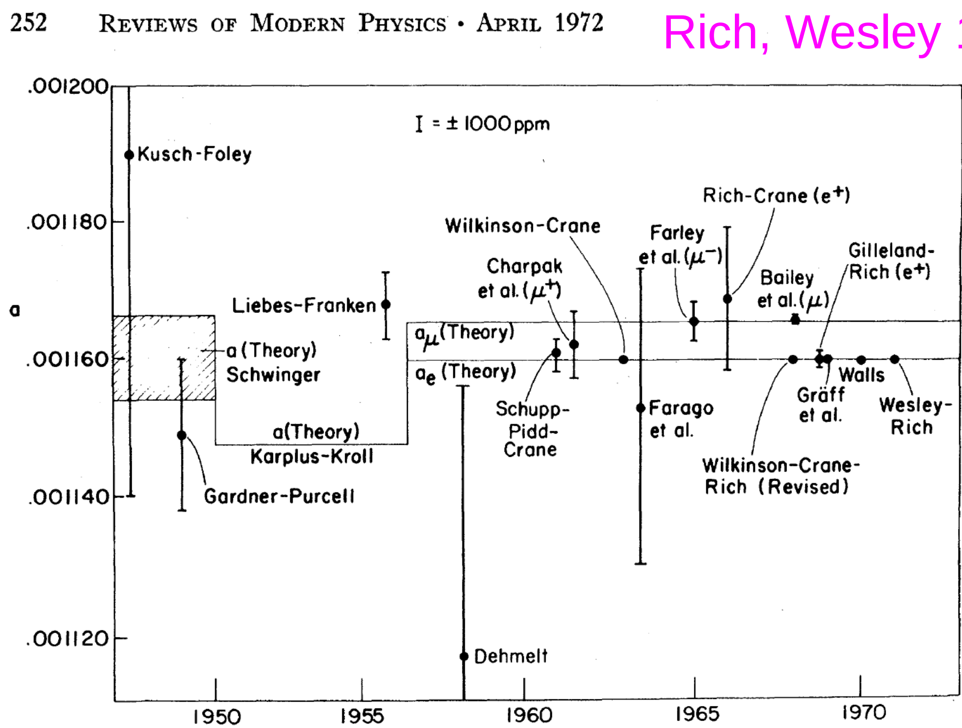
Schnetz arXiv:1711.05118

$$
\begin{aligned}
a_e \;\cong\;& \frac{1}{2}\left(\frac{\alpha}{\pi}\right) \\
&+ \left(\frac{197}{144} + \frac{1}{12}\pi^2 + \frac{27}{32}f_3^6 - \frac{1}{4}g_1^6\pi^2\right)\left(\frac{\alpha}{\pi}\right)^2 \\
&+ \left(\frac{28259}{5184} + \frac{17101}{810}\pi^2 + \frac{139}{16}f_3^6 - \frac{149}{9}g_1^6\pi^2 - \frac{525}{32}g_1^6 f_3^6 + \frac{1969}{8640}\pi^4 - \frac{1161}{128}f_5^6\right. \\
&\quad \left. + \frac{83}{64}f_3^6\pi^2\right)\left(\frac{\alpha}{\pi}\right)^3 \\
&+ \left(\frac{1243127611}{130636800} + \frac{30180451}{155520}\pi^2 - \frac{255842141}{2419200}f_3^6 - \frac{8873}{36}g_1^6\pi^2 + \frac{126909}{2560}\frac{f_4^6}{\mathrm{i}\sqrt{3}}\right. \\
&\quad - \frac{84679}{1280}g_1^6 f_3^6 + \frac{169703}{3840}\frac{f_2^6\pi^2}{\mathrm{i}\sqrt{3}} + \frac{779}{108}g_1^6 g_1^6\pi^2 + \frac{112537679}{3110400}\pi^4 - \frac{2284263}{25600}f_5^6 \\
&\quad + \frac{8449}{96}g_1^6 g_1^6 f_3^6 - \frac{12720907}{345600}f_3^6\pi^2 - \frac{231919}{97200}g_1^6\pi^4 + \frac{150371}{256}\frac{f_6^6}{\mathrm{i}\sqrt{3}} + \frac{313131}{1280}g_1^6 f_5^6 \\
&\quad - \frac{121383}{1280}f_2^6 f_4^6 - \frac{14662107}{51200}f_3^6 f_3^6 + \frac{8645}{128}\frac{f_2^6 g_1^6 f_3^6}{\mathrm{i}\sqrt{3}} - \frac{231}{4}g_1^6 g_1^6 g_1^6 f_3^6 - \frac{16025}{48}\frac{f_4^6\pi^2}{\mathrm{i}\sqrt{3}} \\
&\quad + \frac{4403}{384}g_1^6 f_3^6\pi^2 - \frac{136781}{1920}f_2^6 f_2^6\pi^2 + \frac{7069}{75}f_2^4 f_2^4\pi^2 - \frac{1061123}{14400}f_3^6 g_1^6\pi^2 \\
&\quad + \frac{1115}{72}\frac{f_2^6 g_1^6 g_1^6\pi^2}{\mathrm{i}\sqrt{3}} + \frac{781181}{20736}\frac{f_2^6\pi^4}{\mathrm{i}\sqrt{3}} - \frac{4049}{1080}g_1^6 g_1^6\pi^4 + \frac{90514741}{54432000}\pi^6 \\
&\quad - \frac{95624828289}{2050048}f_7^6 - \frac{29295}{512}g_1^6 f_2^6 f_4^6 + \frac{107919}{512}g_1^6 f_3^6 f_3^6 + \frac{337365}{256}f_3^6 g_1^6 f_3^6 \\
&\quad - \frac{55618247}{409600}f_5^6\pi^2 - \frac{1055}{256}g_1^6 f_2^6 f_2^6\pi^2 + \frac{26}{3}f_1^4 f_2^4 f_2^4\pi^2 + \frac{553}{4}g_1^6 f_3^6 g_1^6\pi^2 \\
&\quad - \frac{35189}{1024}f_3^6 g_1^6 g_1^6\pi^2 + \frac{79147091}{2211840}f_3^6\pi^4 - \frac{3678803}{4354560}g_1^6\pi^6 \\
&\quad \left. + \sqrt{3}(E_{4a} + E_{5a} + E_{6a} + E_{7a}) + E_{6b} + E_{7b} + U\right)\left(\frac{\alpha}{\pi}\right)^4 .
\end{aligned}
$$

Cyclotomic polylogarithms at unity, with weights that are 4th or 6th roots of unity

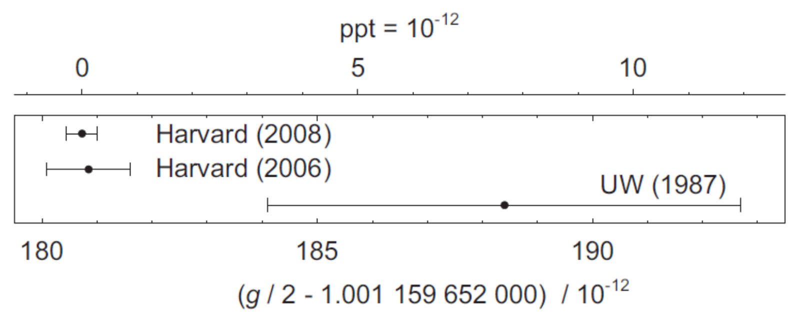
Elliptic and "Unknown"

All needed to match incredible improvements in experimental precision



Rich, Wesley 1972

Van Dyck, Schwinberg, Dehmelt, 1977-1987



Hanneke, Hoogerheide, Gabrielse, 2006-2010

$$\boxed{g/2 = 1.001\ 159\ 652\ 180\ 73\ (28) \quad [0.28\ \text{ppt}]}$$

Magnetic anomaly anomalies?

- New measurement of fine structure constant in cesium:

$$\alpha^{-1}(\text{Cs}) = 137.035999046(27).$$

- Leads to 2.4σ discrepancy for electron

Davoudiasl, Marciano
arXiv:1806.10252

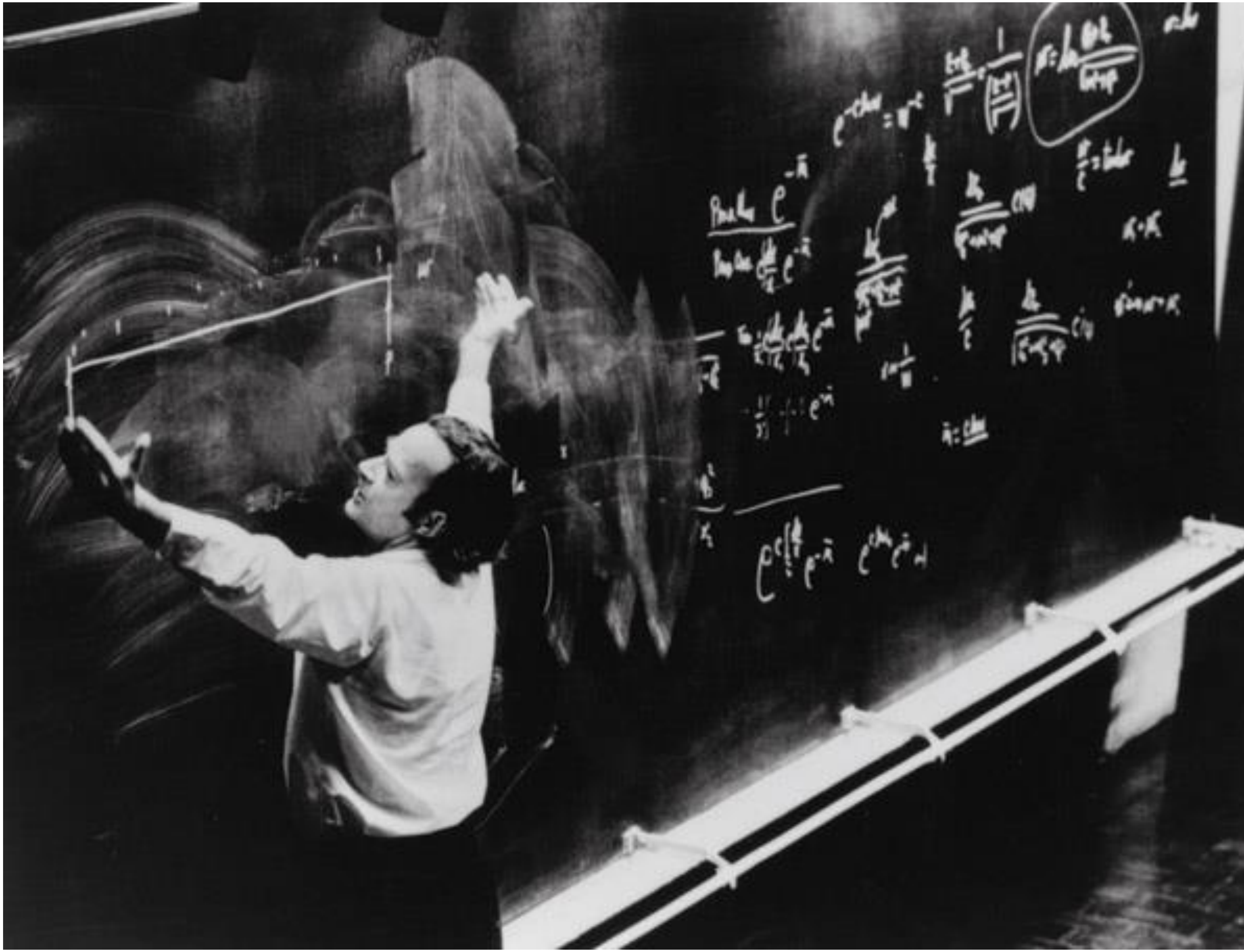
$$\begin{aligned}\Delta a_e &\equiv a_e^{\text{exp}} - a_e^{\text{SM}} \\ &= [-87 \pm 28\,(\text{exp}) \pm 23\,(\alpha) \pm 2\,(\text{theory})] \\ &\times\ 10^{-14},\end{aligned}$$

Measuring Earth-Moon distance to width of human hair: 10^{-13}

- Opposite in sign to better known 3.7σ discrepancy for muon

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (2.74 \pm 0.73) \times 10^{-9}$$

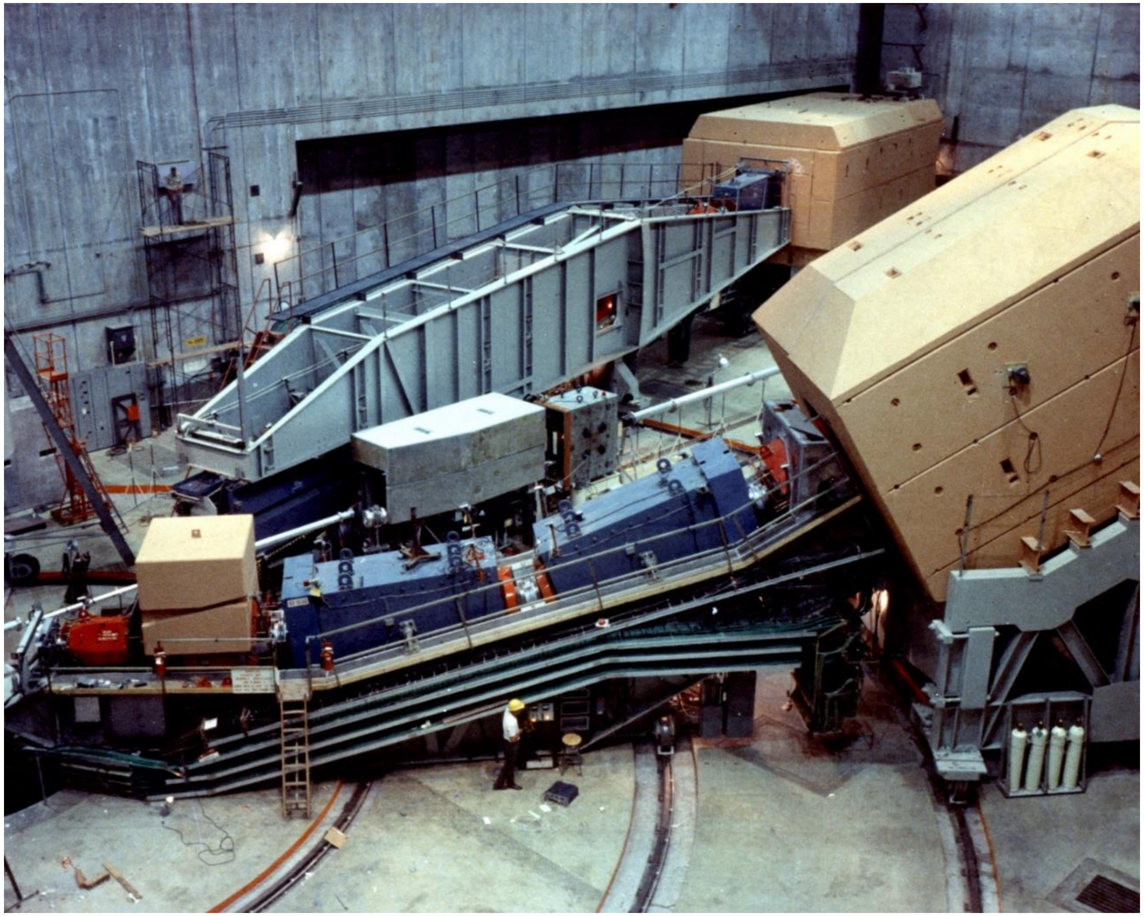
- Could one or both of these be harbingers of new physics?
- Or statistical fluctuations or other issues?



On to real (hard) particle scattering

- Feynman's role in understanding structure of matter: the proton as a bound state of more fundamental objects, quarks and gluons.
- Gell-Mann and Zweig proposed quarks in early 1960s, but were they real, or a mathematical tool to represent symmetries?
- SLAC, a lab built in the 1960s to scatter electrons off protons at record energies, could answer question directly

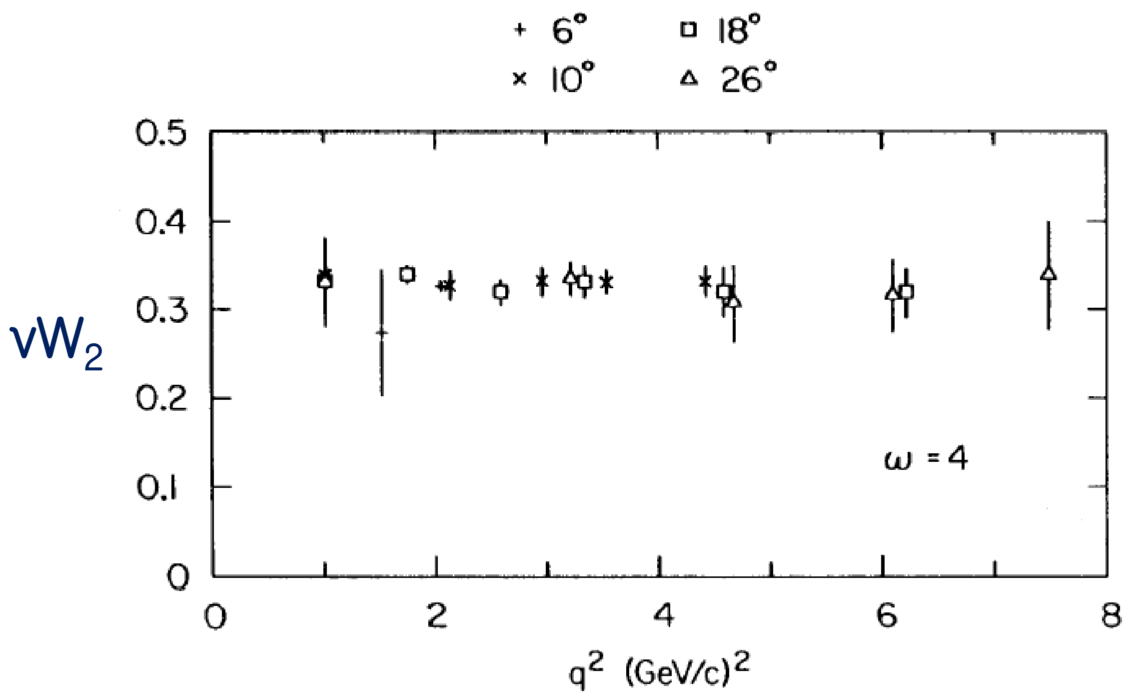
Where quarks were found

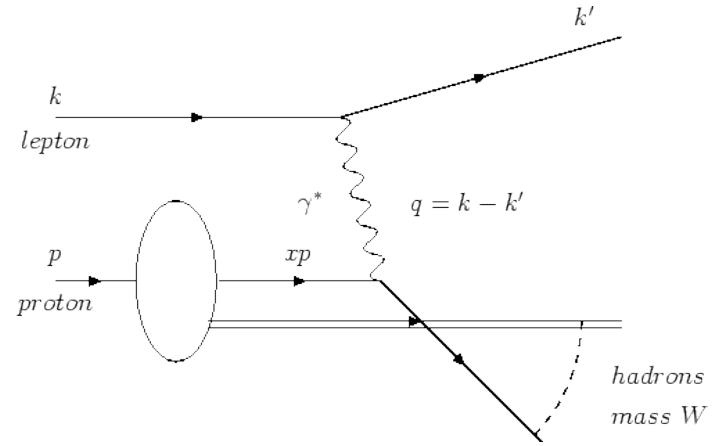


End Station A at SLAC, where "deep inelastic" scattering experiments were performed that revealed "Bjorken Scaling"

Talk by Marty Breidenbach
at SLAC Summer Institute 2018,
"50 years of the Standard Model"

Scaling: νW_2 for fixed ω vs q^2

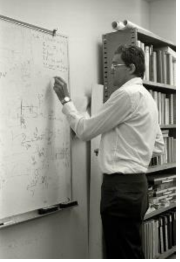




$$q^2 = \text{photon virtuality}$$

$$\omega = \frac{2p \cdot q}{q^2} = \frac{2M_p \nu}{q^2} = \frac{1}{x}$$

M. Breidenbach, SSI 2018



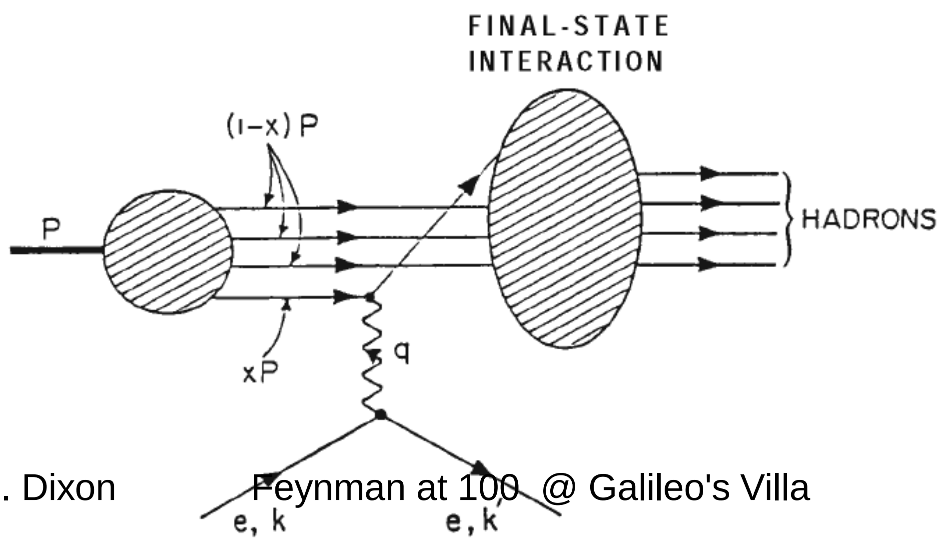
Bj Bjorken

M. Breidenbach, SSI 2018

Partons

[Joan Feynman worked at NASA Ames near SLAC around 1968]

- Many of us did not understand bj's current algebra motivation for scaling
- Feynman visited SLAC in August 1968. He had been working on hadron-hadron interactions with point like constituents called partons. We showed him the early data on the weak q^2 dependence and scaling – and he (instantly!) explained the data with his parton model.
- In an infinite momentum frame, the point like partons were slowed, and the virtual photon simply elastically scatters from one parton without interactions with the other partons – the impulse approximation.
- This was a wonderful, understandable model for us.



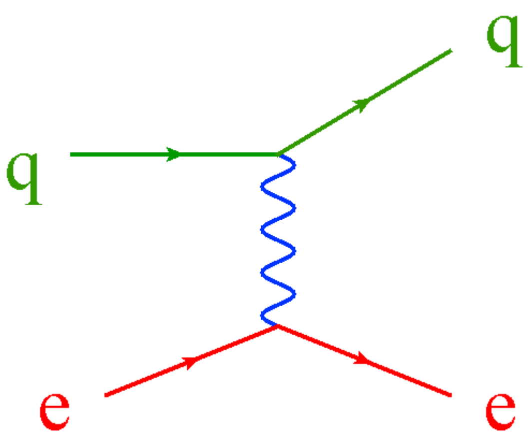
$$W_2^{(i)}(\nu,q^2)=Q_i^2\delta(\nu-q^2/2MX_i)$$
$$=Q_i^2 x_i/\nu\ \delta(x_i-q^2/2M\nu)$$

$$\nu W_2(\nu,q^2) = \sum_N \mathcal{P}(N)\left\{\sum_{i=1}^{N} Q_i^2\right\} x f_N(x)=F_2(x)$$

$$x = \frac{q^2}{2M\nu} = \frac{1}{\omega}$$

"pdf"

Same iconic Feynman diagram, now with quarks



Two deep inelastic structure functions, F_1 and F_2
But this diagram depends on spin of partons, and for spin ½, get Callan-Gross relation, $F_2 = 2xF_1$

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x,Q^2)$$

Confirmed experimentally early on
(at large x where gluon can be neglected)

Scaling → asymptotic freedom
→ nonabelian gauge theories
→ QuantumChromoDynamics, QCD (SU(3) color)

Gross, Wilczek; Politzer 1973

Fritzsch, Gell-Mann 1972;
Weinberg 1973

Feynman and the weak interaction

V – A left-handed structure

also Sudarshan, Marshak

PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

Theory of the Fermi Interaction

R. P. Feynman and M. Gell-Mann
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

A "shotgun" wedding!

The representation of Fermi particles by two-component Pauli spinors satisfying a second order differential equation and the suggestion that in β decay these spinors act without gradient couplings leads to an essentially unique weak four-fermion coupling. It is equivalent to equal amounts of vector and axial vector coupling with two-component neutrinos and conservation of leptons. (The relative sign is not determined theoretically.) It is taken to be "universal"; the lifetime of the μ agrees to within the experimental errors of 2%. The vector part of the coupling is, by analogy with electric charge, assumed to be not renormalized by virtual mesons. This requires, for example, that pions are also "charged" in the sense that there is a direct interaction in which, say, a π^0 goes to π^- and an electron goes to a neutrino. The weak decays of strange particles will result qualitatively if the universality is extended to include a coupling involving a Λ or Σ fermion. Parity is then not conserved even for those decays like $K \to 2\pi$ or 3π which involve no neutrinos. The theory is at variance with the measured angular correlation of electron and neutrino in He^6, and with the fact that fewer than 10^{-4} pion decay into electron and neutrino.

Later completed to $SU(2)_L$ x U(1)
with neutral currents
and a Higgs mechanism

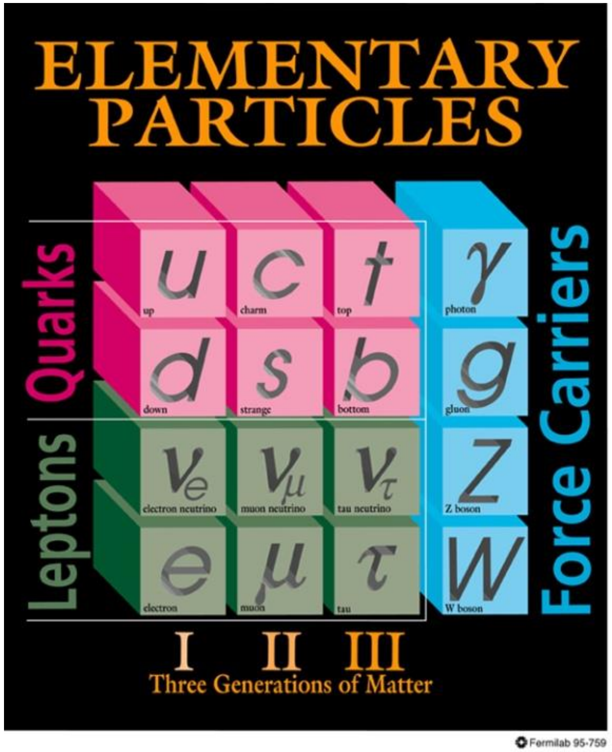
Glashow, Weinberg, Salam 1961-1968

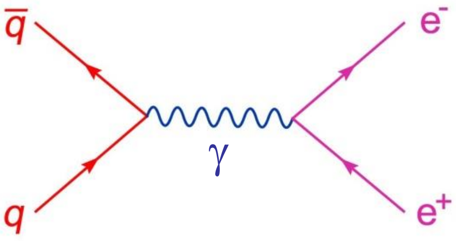
Brout, Englert; Higgs;
Guralnik, Hagen, Kibble 1964

Standard Model

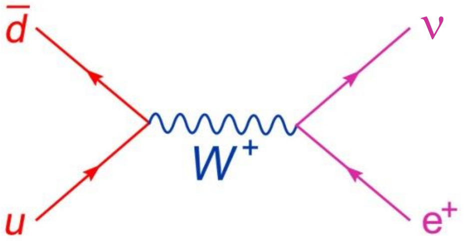
- All elementary forces except gravity in same basic framework
- Matter made of spin ½ fermions
- Forces carried by spin 1 vector bosons: γ W^+ W^- Z^0 g
- Add a spin 0 Higgs boson H to explain masses of W^+ W^- Z^0

  → finite, testable predictions for all quantities
- Solidly in place by the early 1980s

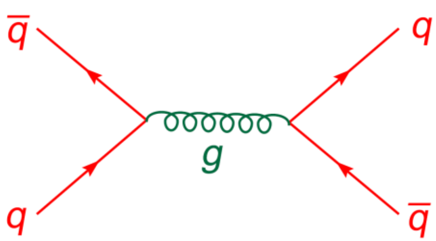




electromagnetism (QED)



weak



strong (QCD)

Feynman and quantum gravity

- Transcript of talk at *Conference on Relativistic Theories of Gravitation*, Jablonna,1962, *Acta Physica Polonica* 24 (1963) 697.

"There's a certain irrationality to any work in gravitation… for example, as far as quantum effects are concerned let us consider the effect of the gravitational attraction between an electron and a proton in the hydrogen atom; it changes the energy [and hence the phase of the wave function] a little bit. The effect of gravitation on the hydrogen atom is to shift the phase by 43 seconds of phase in every hundred times the lifetime of the universe!"

Feynman and quantum gravity

"An atom made purely by gravitation, let us say two neutrons held together by gravitation, has a Bohr orbit of 10^8 light years. The energy of this system is 10^{-70} rydbergs. I wish to discuss here the possibility of calculating the Lamb correction to this thing, an energy of the order of 10^{-120}. The irrationality is shown also in the strange gadgets of Prof. Weber, in the absurd creations of Prof. Wheeler and other such things, because the dimensions are so peculiar...

I am investigating this subject despite the real difficulty than there are no experiments… so I made believe that there were experiments."

Gravitational Compton scattering

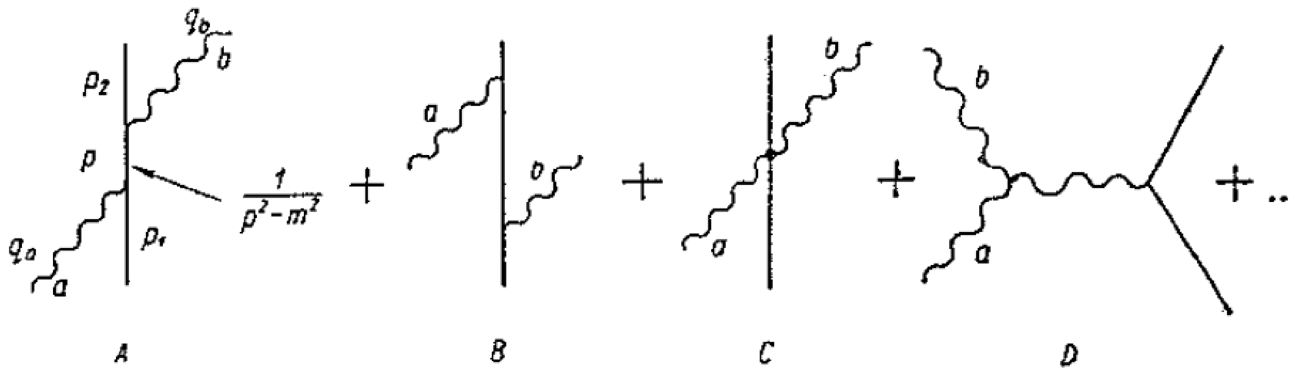


Fig. 2

The third one comes in because there are terms with two h's and two φ's in the Lagrangian. One adds the four diagrams together and gets an answer for the Compton effect. It is rather simple, and quite interesting; that it is simple is what is interesting, because the labour is fantastic in all these things.

Feynman discovers ghosts

(and Feynman tree theorem)

The amplitude to remain in the same state for a time T in general is of the form

$$e^{-i\left(E_0 - i\frac{\gamma}{2}\right)T}$$

you see that the imaginary part of the phase goes as $e^{-\frac{\gamma}{2}T}$; which means that the probability of being in a state must decrease with time. Why does the probability decrease in time? Because there's another possibility, namely, these two objects could come together, annihilate, and produce a real pair of gravitons. Therefore, it is necessary that this decay rate of the closed loop diagrams in Fig. 4 that I obtain by directly finding the imaginary part of the sum agrees with another thing I can calculate independently, without looking at the closed loop diagrams. Namely, what is the rate at which a particle and antiparticle annihilate into two gravitons? And this is very easy to calculate (same set of diagrams as Fig. 2, only turned on its side). I calculated this rate from Fig. 2, checked whether this rate agrees with the rate at which the probability of the two particles staying the same decreases (imaginary part of Fig. 4), and it does not check. Somethin'gs the matter.

Gravity, YM and ghosts

But this disease which I discovered here is a disease which exist in other theories. So at least there is one good thing: gravity isn't alone in this difficulty. This observation that Yang-Mills was also in trouble was of very great advantage to me; it made everything much easier in trying to straighten out the troubles of the preceding paragraph, for several reasons. The main reason is if you have two examples of the same disease, then there are many things you don't worry about. You see, if there is something different in the two theories it is not caused by that. For example, for gravity, in front of the second derivatives of $g_{\mu\nu}$ in the Lagrangian there are other g's, the field itself. I kept worrying something was going to happen from that. In the Yang-Mills theory this is not so, that's not the cause of the trouble, and so on. That's one advantage — it limits the number of possibilities. And the second great advantage was that the Yang-Mills theory is enormously easier to compute with than the gravity theory, and therefore I continued most of my investigations on the Yang-Mills theory, with the idea, if I ever cure that one, I'll turn around and cure the other.

...

But then secondly, you must subtract from the answer, the result that you get by imagining that in the ring which involves only a graviton going around, instead you calculate with a different particle going around, an artificial, dopey particle is coupled to it. It's a vector particle. artificiallv coupled to the external field, so designed as to correct the error in this one.

What if?

- What if Feynman had known about or invented the helicity method in 1962? He might well have discovered

$$\text{Gravity} = \text{YM}^2$$

- What if Napoleon had had a B-52 at the battle of Waterloo? [Monty Python]

Feynman's Adventures in Biology: A Timeline

C. Callan, Feynman@100, Singapore

- Grad school at Princeton: Curiosity about biology led him to take a few courses and adopt a skeptical view of the practice of professional biology.
- The 50s: Golden age of the new biology at Caltech. Feynman exercises his curiosity by "hanging out" in Delbruck's lab. He meets, interacts with, and impresses current and future leaders of the new field of molecular biology.
- '59: "Plenty of Room at the Bottom" talk challenges physics to go to work at molecular scales, imitating life. It foresaw the miniaturization revolution in computing, and espoused a physics-inspired view of the core issues of biology.
- '61-'62: A sabbatical in place, working at the bench in Delbruck's lab. Study of reverting mutants of bacteriophages led to a serious Genetics paper. Further work with Meselson and Lamson on ribosomes targeted core issues of the new biology, but didn't quite gel.
- '62-'64: The Feynman Lectures on Physics had one biological chapter (on color vision). In an aside, he showed that the insect eye optimizes function subject to constraints of physics … foreshadowing a major future trend in biophysics
- '69: The Hughes Aerospace lectures on biology and chemistry were pedagogical, but they contain Feynman's evolved view of the core problems of biology and some thoughts about how physics and biology should interact.

What did Feynman actually do in the Delbruck lab, and what was its significance?

C. Callan, Feynman@100, Singapore

182 R. S. EDGAR, R. P. FEYNMAN, S. KLEIN, I. LIELAUSIS, AND C. M. STEINBERG

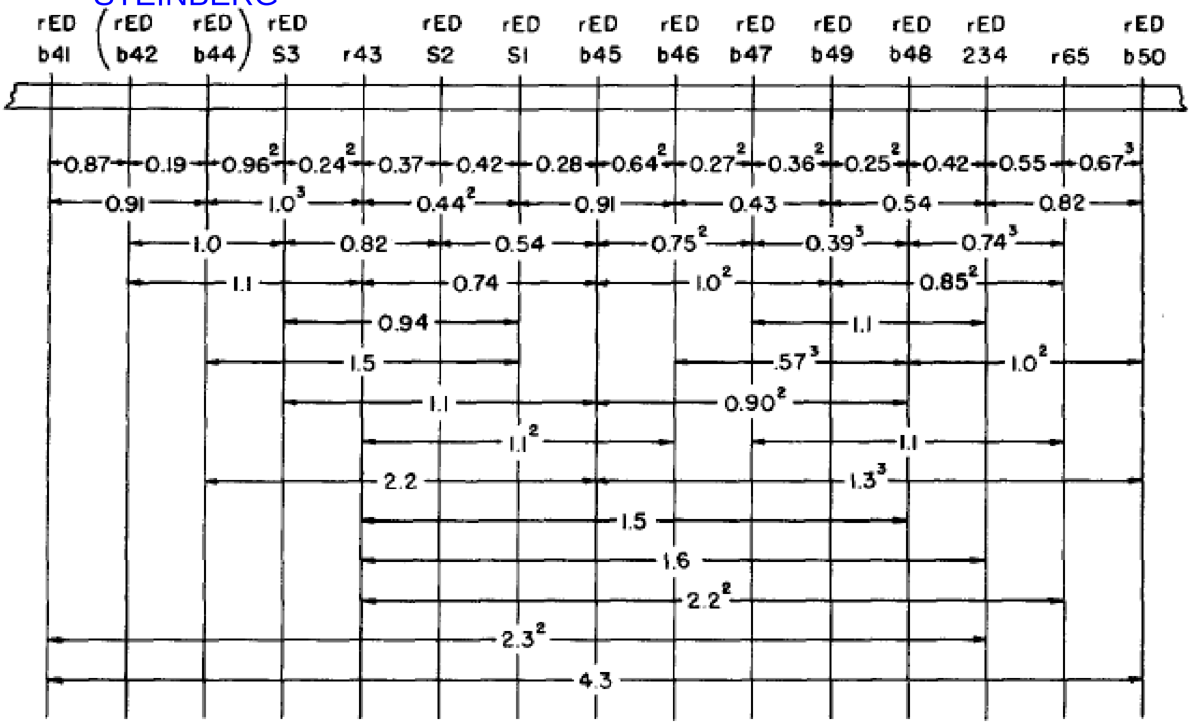


FIGURE 2.—Map of the *r*II B cistron of T4D. Average recombination values (in %) are shown; the superscript is the number of crosses upon which the average is based. Markers enclosed in brackets are too close together to be ordered with certainty. All of the markers are capable of spontaneous reversion.

Genetics 47: 179-186 February 1962.

The goal was to map out mutations in phage strain T4D. The mutation hunt was tedious but fruitful. A paper resulted.

Mutants could (rarely) revert to normal-ish. By undoing the first mutation .. or what? RPF's specific concern was to figure out how this reversion worked.

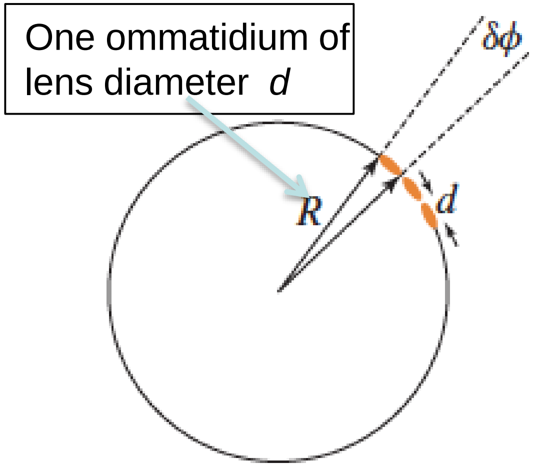
He found three mutants (s1, s2, s3) whose reversion came from a second mutation very near the original one, but not right AT it.

Two years later it was realized that this is a piece of evidence for the 3 base genetic code.

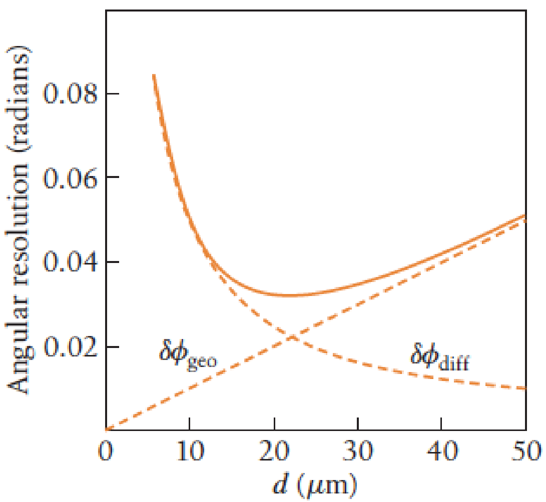
Feynman's demonstration that the insect eye design is optimized within the limits set by physics

C. Callan, Feynman@100, Singapore

Insect eye is a spherical bundle of cone-like cells. Each cone looks at angle range $\delta\phi = d/R$. Limits detailed seeing …. Why not make d (hence $\delta\phi$) smaller?



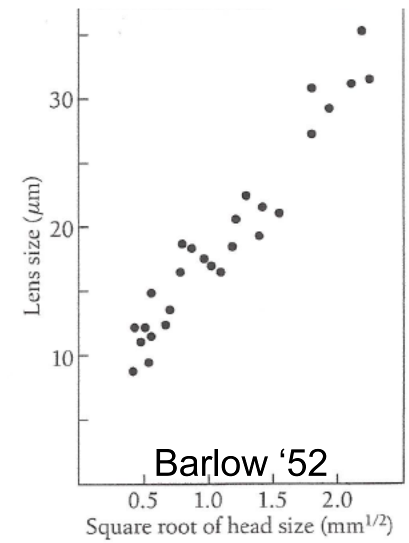
Not so fast! Light has a finite wavelength λ and diffraction fuzzes the angular resolution of aperture d by $\delta\phi = \lambda/d$.



The true angular resolution of the ommatidium is the sum

$$\delta\phi = d/R + \lambda/d$$

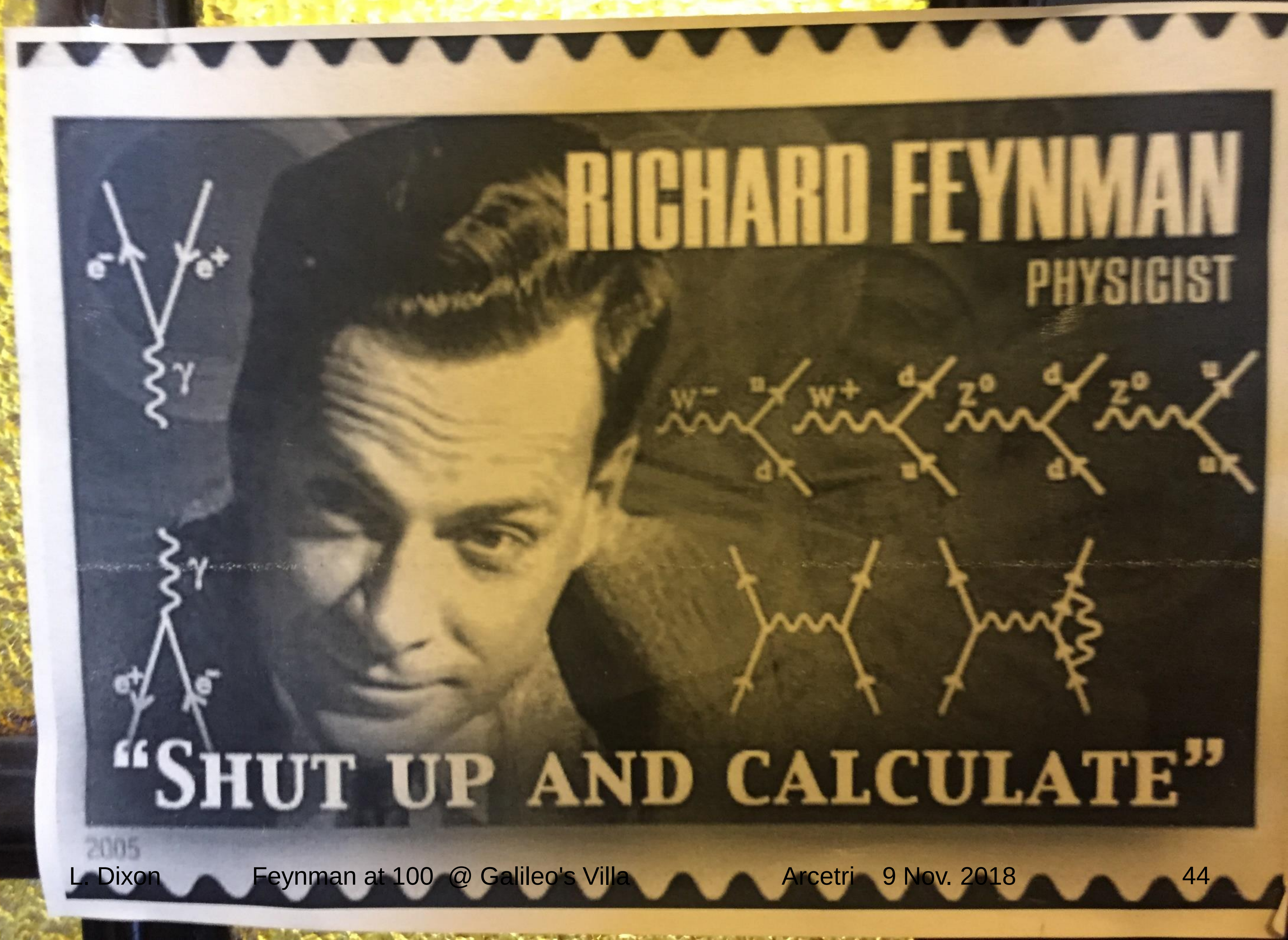
This is smallest for $d_{best} = \sqrt{\lambda R}$



The numbers come out pretty close for many species! Evolution must know about physical law.

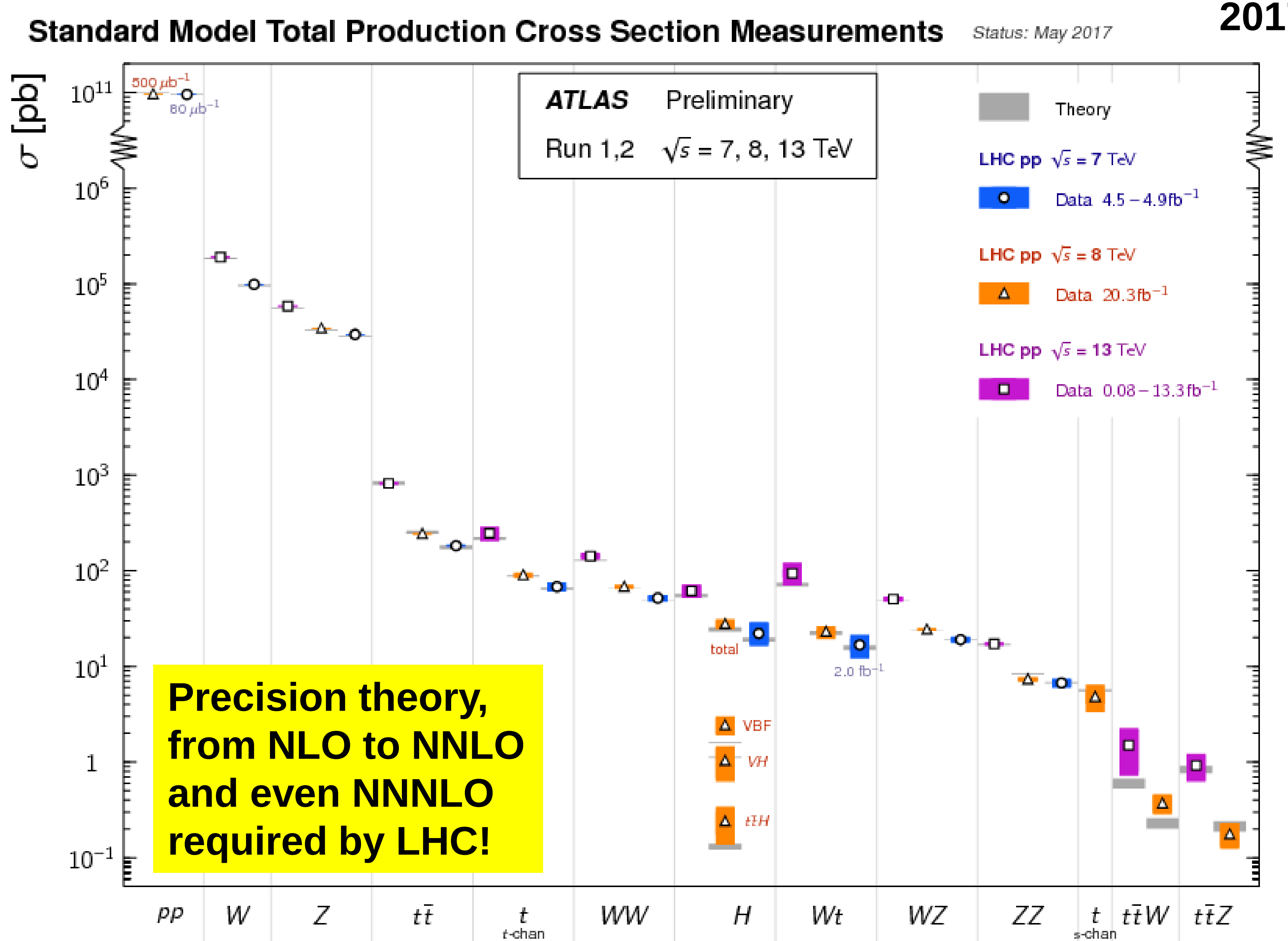
70 years of particle scattering…

- Feynman's insights in making perturbation theory in QED covariant meant "anyone could compute" perturbative scattering – later on, including computers
- Feynman diagrams at the heart of almost all quantitative comparisons between theory and experiment since 1947
- LHC demands for theory → reorganize Feynman diagrams to incorporate unitarity (as well as many other advances in loop and phase space integration). Still $i\varepsilon$!
- Spawned many other novel "amplitudes" developments
- But Feynman was a polymath, worked on many different areas of physics – and even biology!


RICHARD FEYNMAN
PHYSICIST
"SHUT UP AND CALCULATE"
2005

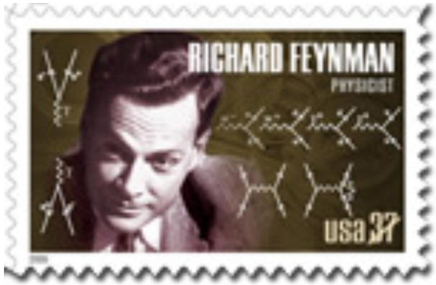
Extra Slides

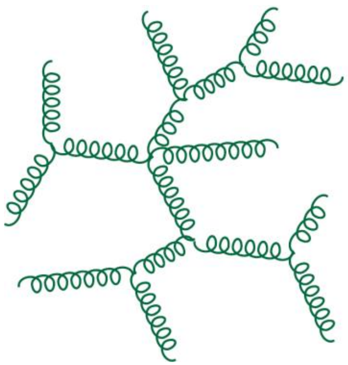
2017



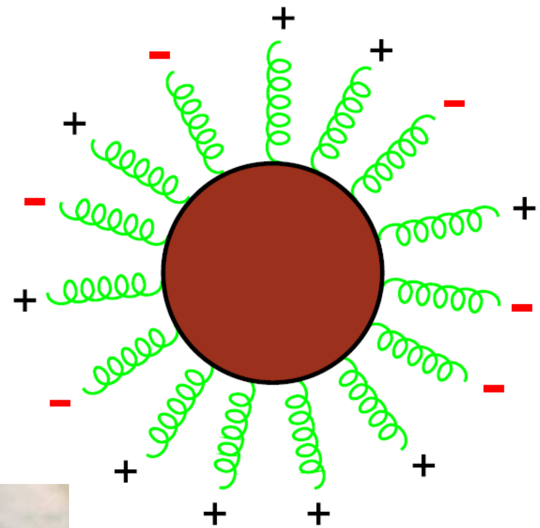
Precision theory, from NLO to NNLO and even NNNLO required by LHC!

Granularity vs. Fluidity





+ …



The tail of the mantis shrimp

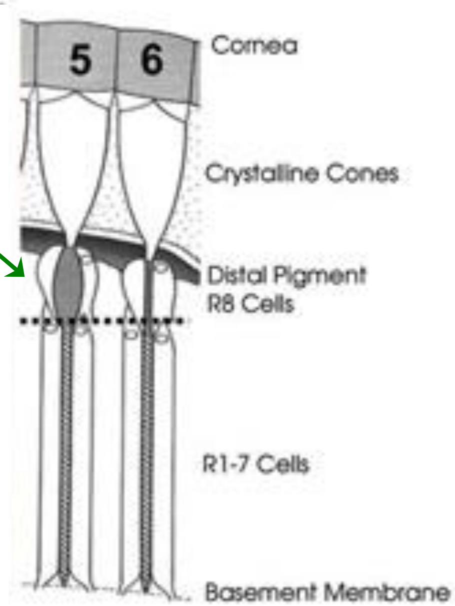
- Reflects left and right circularly polarized light differently

- Led biologists to discover that its eyes have differential sensitivity
- It communicates via the helicity formalism

"It's the most private communication system imaginable. No other animal can see it."

- Roy Caldwell (U.C. Berkeley)

$\lambda/4$ plate



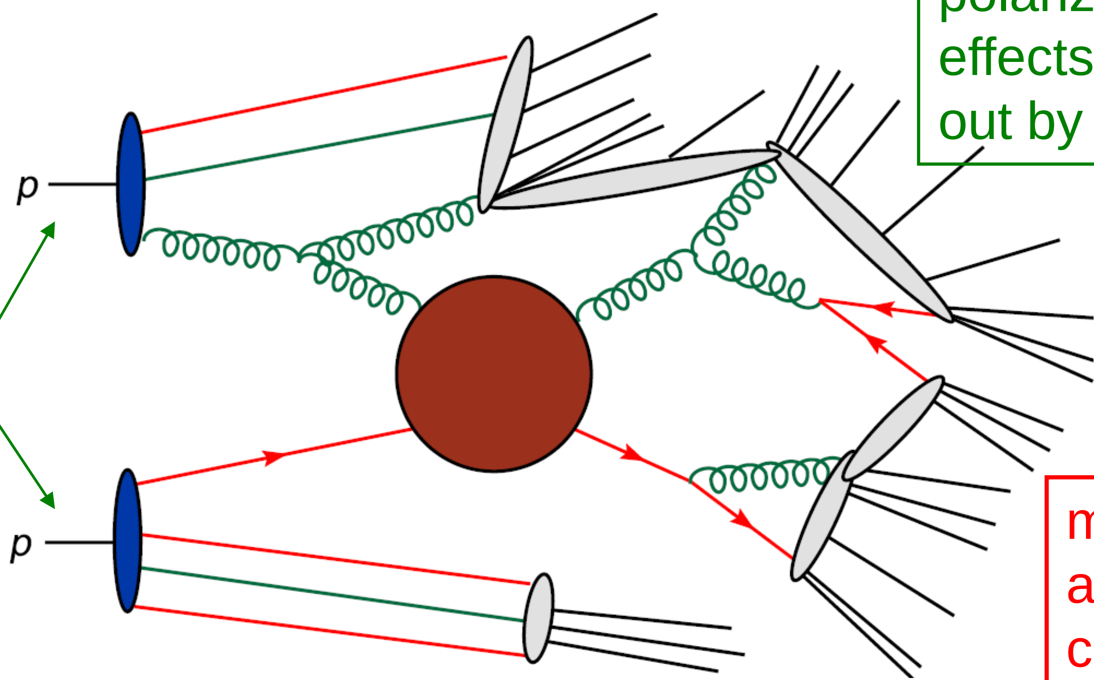
What the biologists didn’t know

Particle theorists have also evolved capability to communicate results via helicity formalism

LHC experimentalists are blind to it

any final-state polarization effects washed out by fragmentation

unpolarized



must sum over all helicity configurations

Biology in "The Feynman Lectures in Physics"

In the middle of the discussion of optics and electromagnetic waves we find two chapters on how the eye works and how we perceive color. Big change of pace!

Side note: the course TAs couldn't understand why the students had difficulty grasping Feynman's inspiring presentation of topics in physics … until the vision/seeing lectures. These were topics that were outside their expertise and for once they were blown away by the Feynman fire hose … just like the students!

Tucked away in the "Seeing" chapter was a little gem: a demonstration that the parameters of the insect eye were such as to give the best possible performance subject to the constraints of physics. Showing that evolution is a good engineer! The future would show that this approach illuminates many aspects of biology.