H. A. TANAKA

PHYSICS 489/1489

INTRODUCTION TO HIGH ENERGY PHYSICS

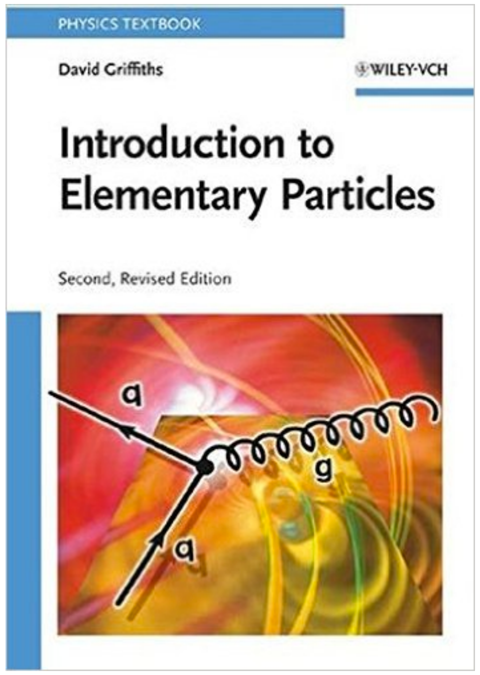
SOME LOGISTICS

- Instructor: Hirohisa Tanaka
  - “Hiro”
  - htanaka@physics.utoronto.ca
- Office Hours (MP801A)
  - TBA: we’ll do a doodle poll
- TA: Randy Conklin
  - MP920
  - rconklin@physics.utoronto.ca
- Pre-requisites: PHY354, PHY356
  - special relativity, relativistic kinematics
  - Lagrangian Mechanics
  - quantum mechanics
    - Dirac Notation, perturbation theory, commutators, spin/angular momentum
  - multivariate calculus, matrix/linear algebra
  - if you are unsure, please talk to me

SOME MORE LOGISTICS

- Course website:
  - https://sites.physics.utoronto.ca/tanaka/physics-489-1489-2017/
  - under construction!
  - lectures, problem sets, solutions, posted here.
- Textbook: "**Modern Particle Physics**", M. Thomson
  - lectures generally follow the text, but not exhaustively
  - it is essential to read the textbook . . . it may not have been covered in lecture!
- Grading:
  - 4 problem sets (40%)
  - 1 midterm examination on 12 October (20%)
  - 1 final examination (40%)
- For homework:
  - it is fine and encouraged to work together, but each person must fully show their work
  - submit in drop box in basement before 1700 on due day
  - solutions will be posted at that time
    - late assignments will not accepted after solutions are posted
    - if you anticipate any issues with turning in the assignment, **please tell me in advance**

CLASS OUTLINE



PHYSICS TEXTBOOK

David Griffiths

WILEY-VCH

Introduction to Elementary Particles

Second, Revised Edition

- D. J. Griffiths:
    - "Introduction to Elementary Particles"
    - Good alternative reference for class
- PDG: http://pdg.lbl.gov
    - encyclopedia on particle properties and other relevant information

Thu 7 Sep	**Introduction**		**PS 1 assigned**
Tue 12 Sep	Review of Special Relativity	1, 2.1-2.2	
Thu 14 Sep	Quantum Mechanics	2.3	
Tue 19 Sep	Golden Rule, decays, cross sections	3	
Thu 21 Sep	Relativistic wave equations	4.1-4.5	
Tue 26 Sep	Review	4.6-4.9	
Thu 28 Sep	The Dirac Equation	5	PS1 due, PS2 assigned
Tue 3 Oct	Feynman Rules for QED	6.1-6.4	
Thu 5 Oct	Electron-positron annihilation	6.5	
Tue 10 Oct	QED experiments		
Thu 12 Oct	midterm		
Tue 17 Oct	Electron-proton scattering and form factors	7.1-7.2	
Thu 19 Oct	Form Factors	7.3-7.4	
Tue 24 Oct	Symmetries and local gauge invariance	9.1, 10.1	PS2 due, PS3 assigned
Thu 26 Oct	Strong Interactions	10.2-10.6	
Tue 31 Oct	Weak interactions	11	
Thu 2 Nov	Weak interaction of leptons	12.1, 12.2	
Tue 14 Nov	Weak interaction of quarks	14.1-14.3, 14.4.1,14.4.2, 14.7	
Thu 16 Nov	No class		
Tue 21 Nov	Electroweak Mixing	15.1-15.2	
Thu 23 Nov	Neutrino oscillations	13	
Tue 28 Nov	Electroweak physics	16.1-16.2	
Thu 30 Nov	Lagrangians and spontaneous symmetry breaking	17.1-17.3	
Tue 5 Dec	Higgs mechanism	17.4-17.5	PS 4 Due

CLASS OBJECTIVES:

- Learn the “taxonomy” of the elementary particles/interactions
  - what are the fundamental constituents and their interactions?
  - what are the basic properties and rules which govern them? (what is allowed/forbidden)?
  - depict basic processes through Feynman diagrams
- Understand the basic principles of how we produce/detect elementary particles and study their properties
- Kinematics of particle interactions
  - Use special relativity, conservation laws
- Calculate the amplitude of an elementary processes using the Feynman diagrams/rules, and calculate cross sections/decay rates

HIGH ENERGY PHYSICS

- “Particle physics”
  - “Elementary particles”
  - “fundamental interactions/particles”
- What does “high energy” have to do with fundamental particles/interactions?
- Rest of today:
  - whirlwind tour across what we know about particle physics
  - fill in the details later

THE STANDARD MODEL

ν_e ν_μ ν_τ no charge, no color

e^- μ^- τ^- -1 charge, no color

particles

u c t +2/3 charge, color

d s b -1/3 charge, color

ν_e ν_μ ν_τ no charge, no color

e^+ μ^+ τ^+ +1 charge, no color

$\bar{u}$ $\bar{c}$ $\bar{t}$ -2/3 charge, color

$\bar{d}$ $\bar{s}$ $\bar{b}$ +1/3 charge, color

antiparticles

Z $W^\pm$ Mediators of EM interaction

γ Mediator of EM interaction

g Mediator of strong interaction

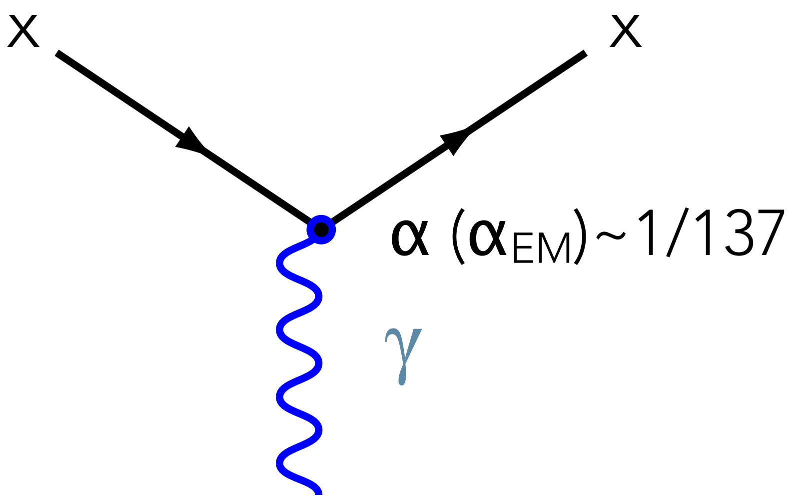
H agent of spontaneous symmetry breaking

INTERACTIONS

(Problem 1.1)

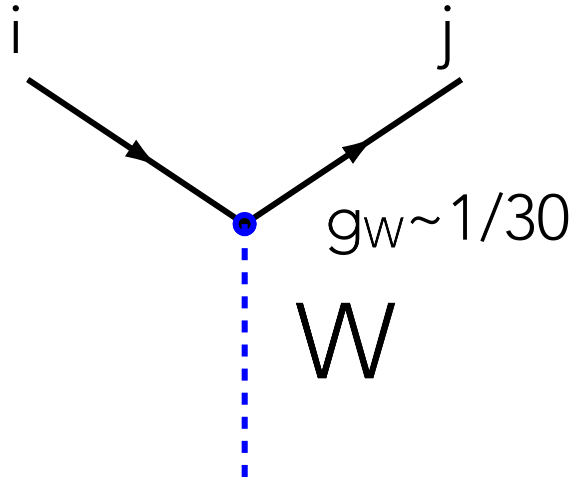
- Fundamental building block of an interaction is the “vertex”

electromagnetism
“quantum electrodynamics”



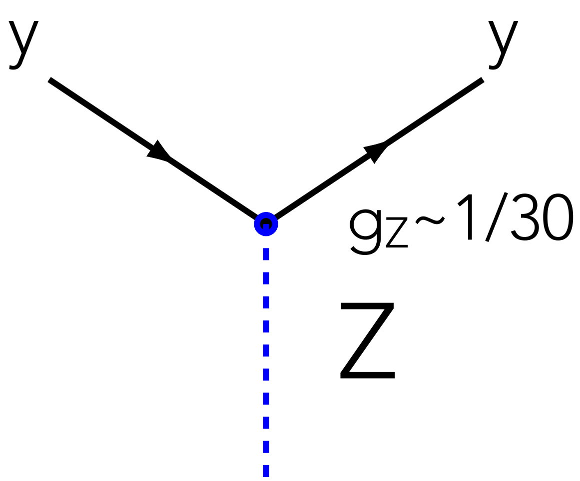
x is any charged particle

weak charged current



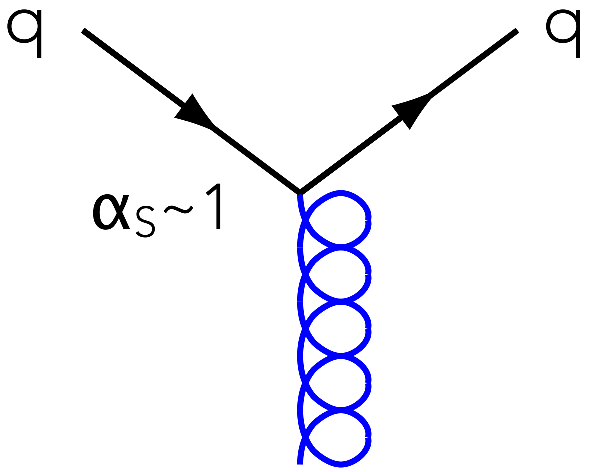
i:+2/3 quark, j: -1/3 quark
or
i: ν_l, j: l^-

weak neutral current



y is quark or lepton

strong interaction
“quantum chromodynamics”



q is any quark (colored object)

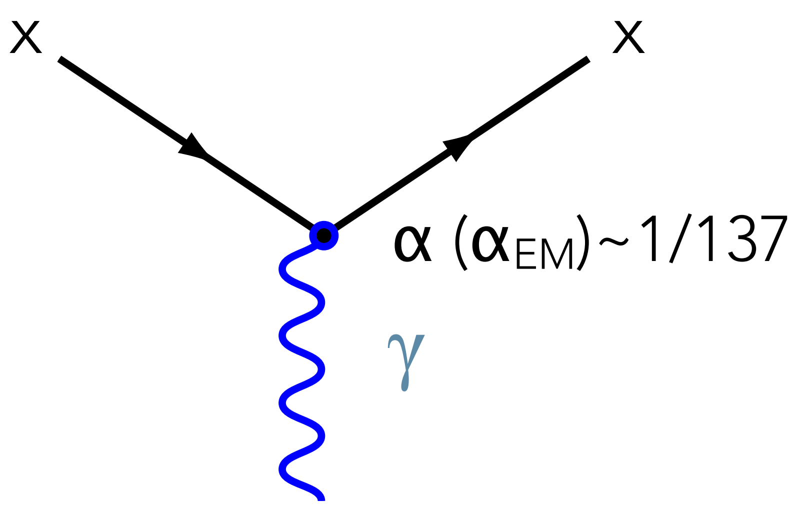
- arrows: direction matters!
  - backward arrow means “antiparticle” (opposite charges)
  - don’t mix up arrow and label
- same letter means same particle
- vertex factor “coupling constant”
  - not part of diagram but indicates “strength” of interaction

CONSERVATION LAWS

(Problem 1.3)

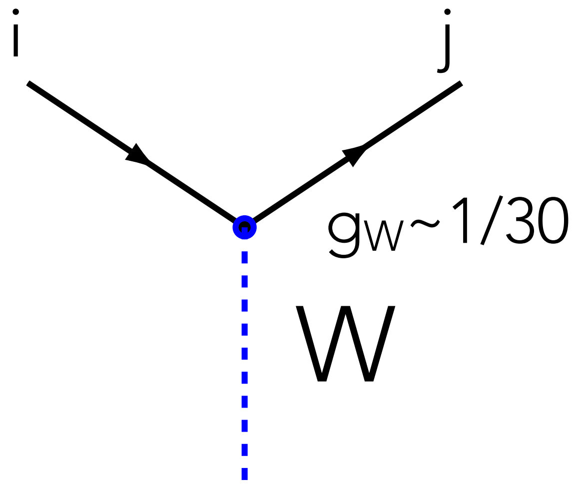
- Fundamental building block of an interaction is the “vertex”

electromagnetism
“quantum electrodynamics”



x is any charged particle

weak charged current



i:+2/3 quark, j: -1/3 quark

or

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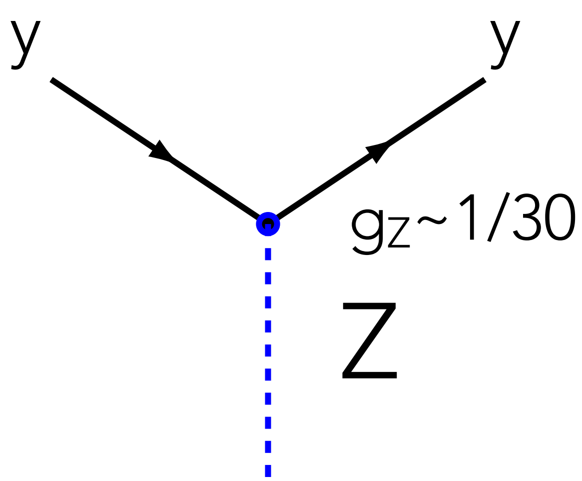

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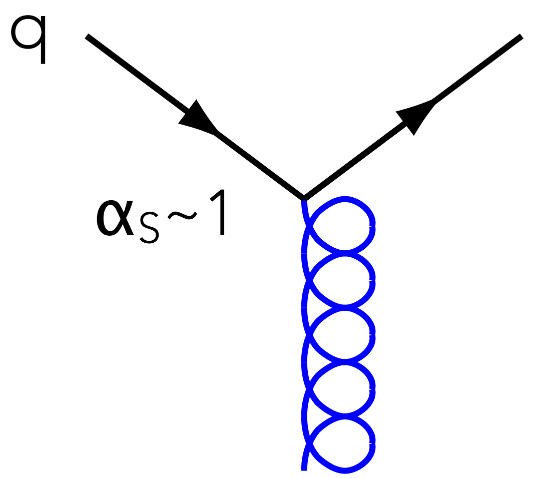


q is any quark (colored object)

- Some “laws” are automatically built into the diagrams
- Conservation of electric charge
- Conservation of lepton number
    - “e”, "μ" “τ”
- Baryon number
    - number of quarks

THE STANDARD MODEL

ν_e ν_μ ν_τ weak interactions
No EM/strong interaction

e μ τ EM and weak interactions
No strong interaction

u c t EM and weak interactions
strong interactions

d s b EM and weak interactions
strong interactions

Z $W^\pm$ Mediators of EM interaction

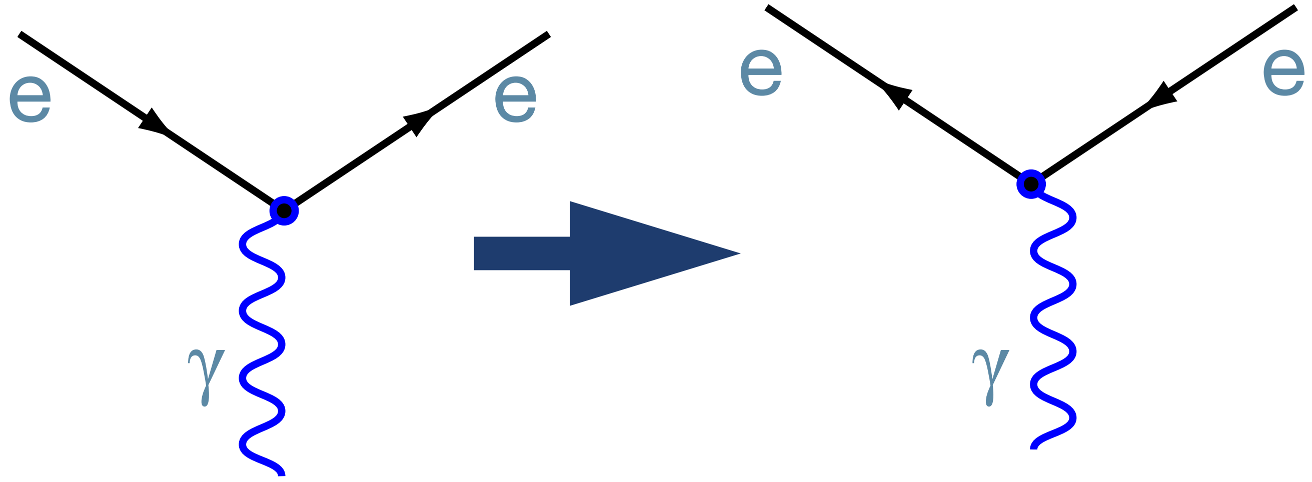
γ Mediator of EM interaction

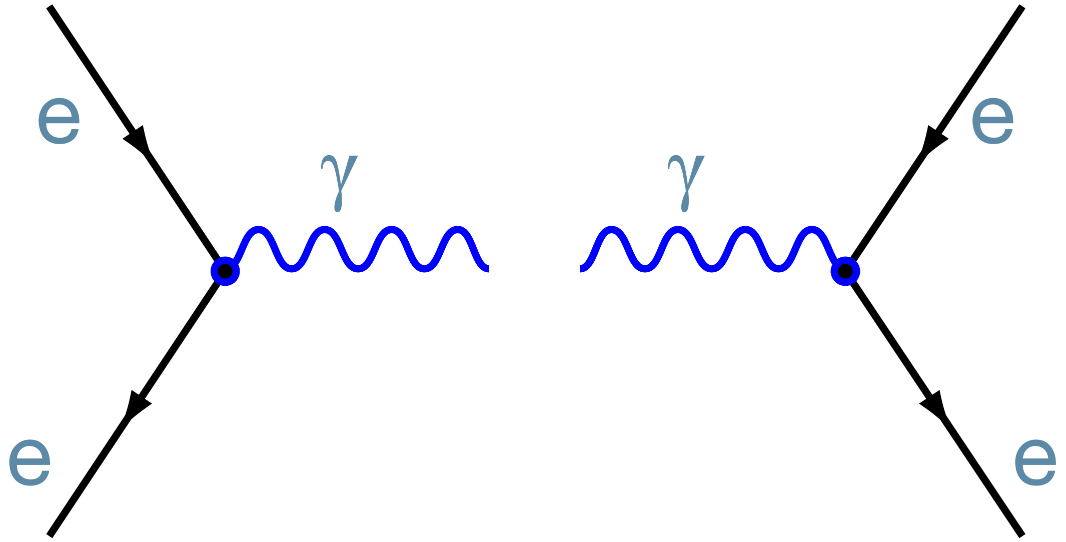
g Mediator of strong interaction

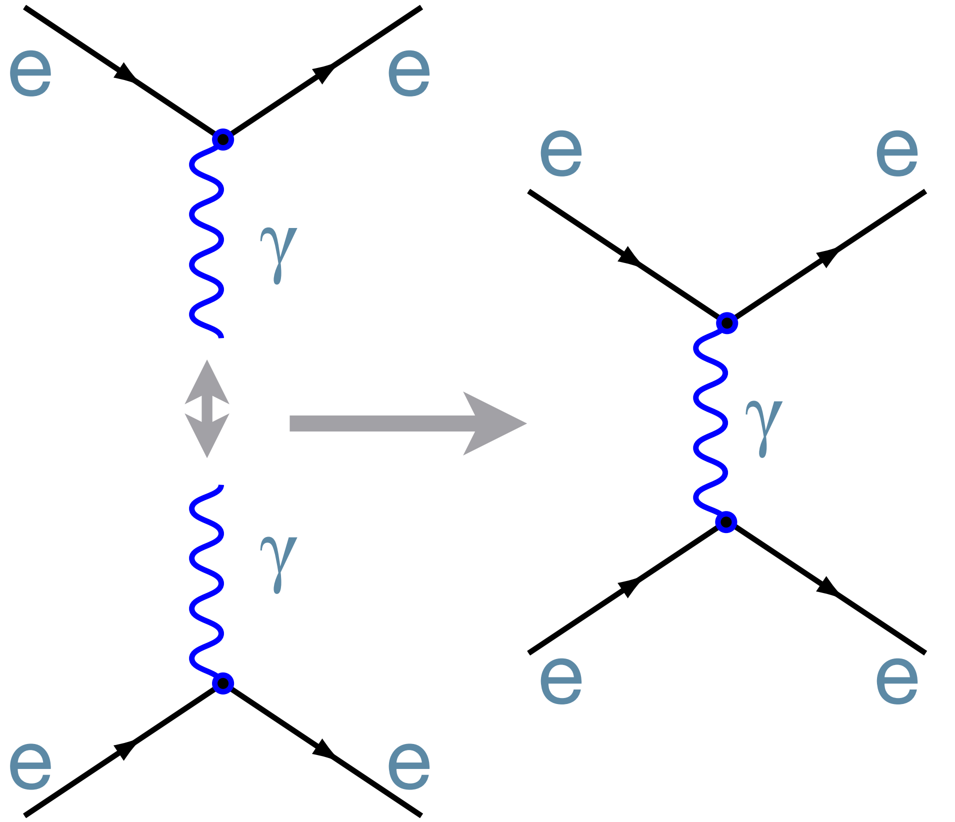
H agent of spontaneous
symmetry breaking

BUILDING UP INTERACTIONS

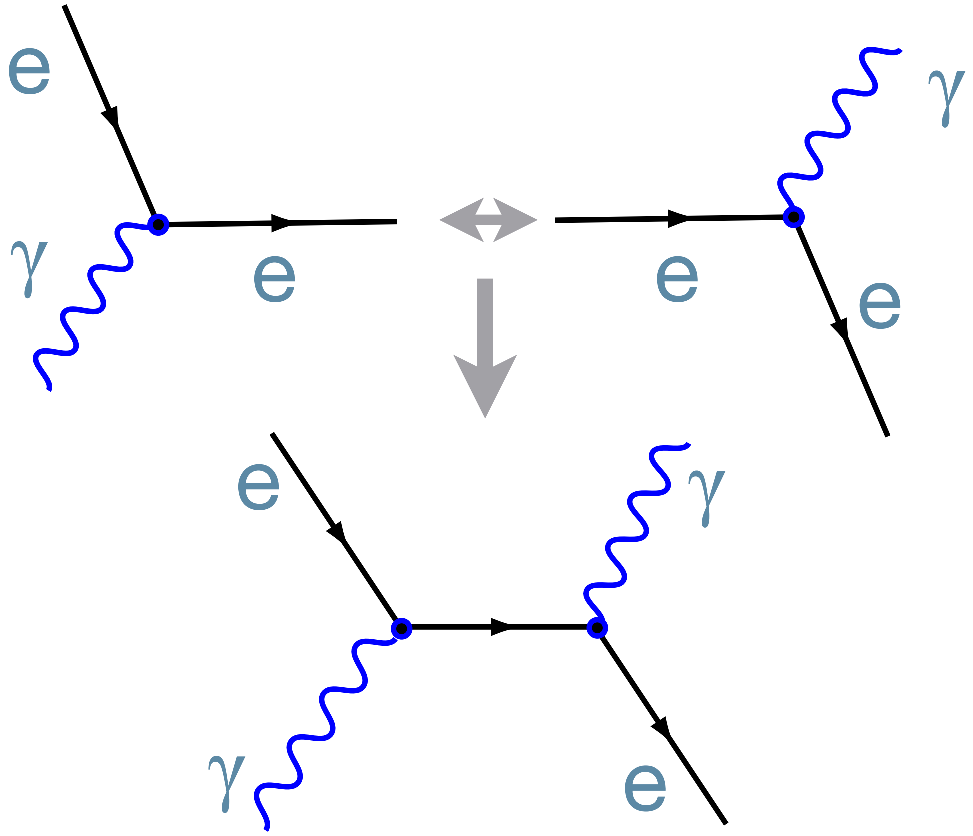
- Vertices can be rotated and connected by common particles ("propagator")







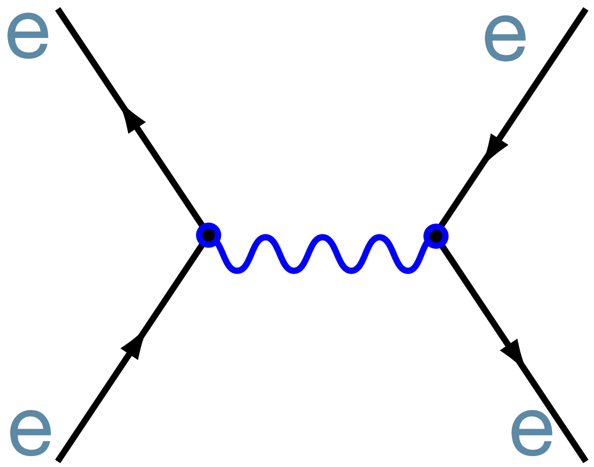
$$e^- + e^- \rightarrow e^- + e^-$$

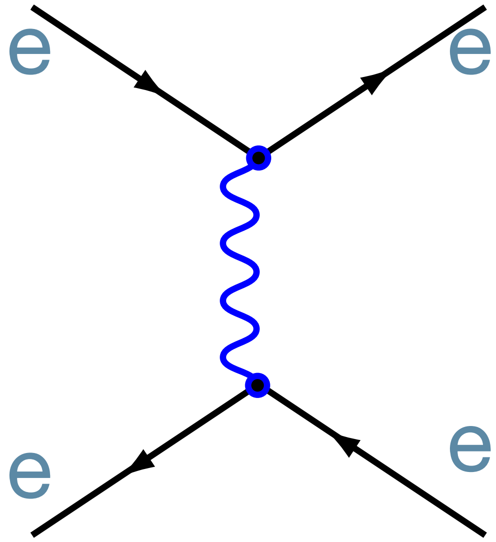


$$e^- + \gamma \rightarrow e^- + \gamma$$

Person: Why does your van have Feynman diagrams on it?
Feynman: Because I AM Richard Feynman!

MULTIPLE DIAGRAMS:



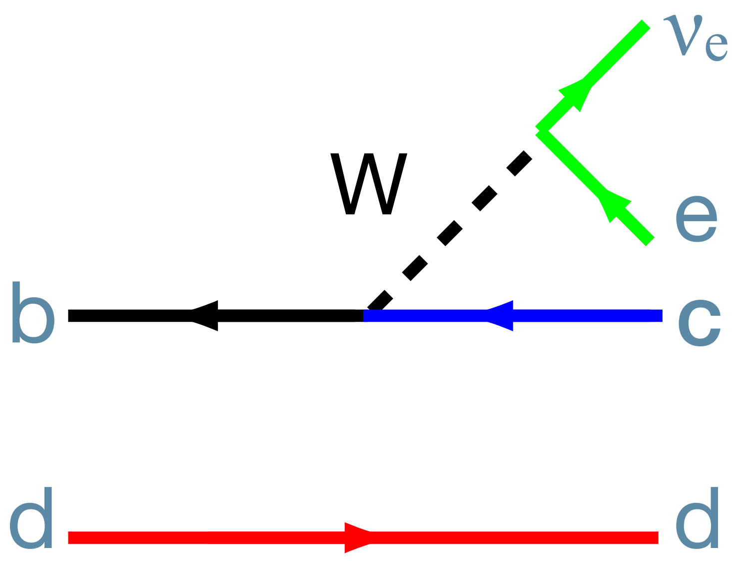


- In fact, any allowed process has an infinite number of possible diagrams
- The coupling constant:
  - diagrams with more vertices have vertex factors
  - if this is small, diagrams with more vertices contribute less
  - we do calculation at “order N” where N is the number of vertices.
    - must consider all diagrams of “order N”
    - if we want more precise calculation we go to higher order

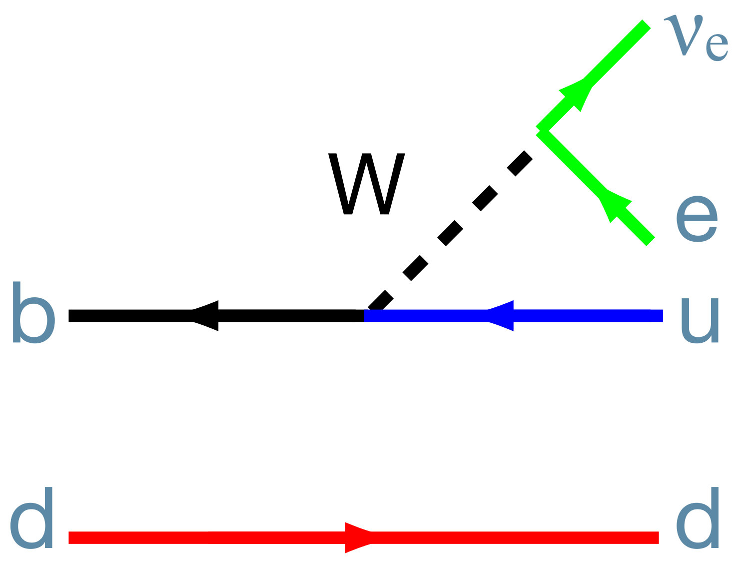
HADRONS

- In the laboratory, we never see “free quarks” but bound systems:
  - “mesons”: quark and antiquark pair
  - “baryons”: three quarks bound together
    - “antibaryons”: three antiquarks bound together
  - Collectively they are called “hadrons”
- To understand the underlying mechanism for a process involving hadrons, consider the constituent quarks (look it up, no need to memorize)
  - D^{*-} = bound state of anti-c quark and d quark
  - ρ^- = bound state of anti-u quark and d quark

$$B^0 \to D^{*-} + e^+ + \nu_e$$

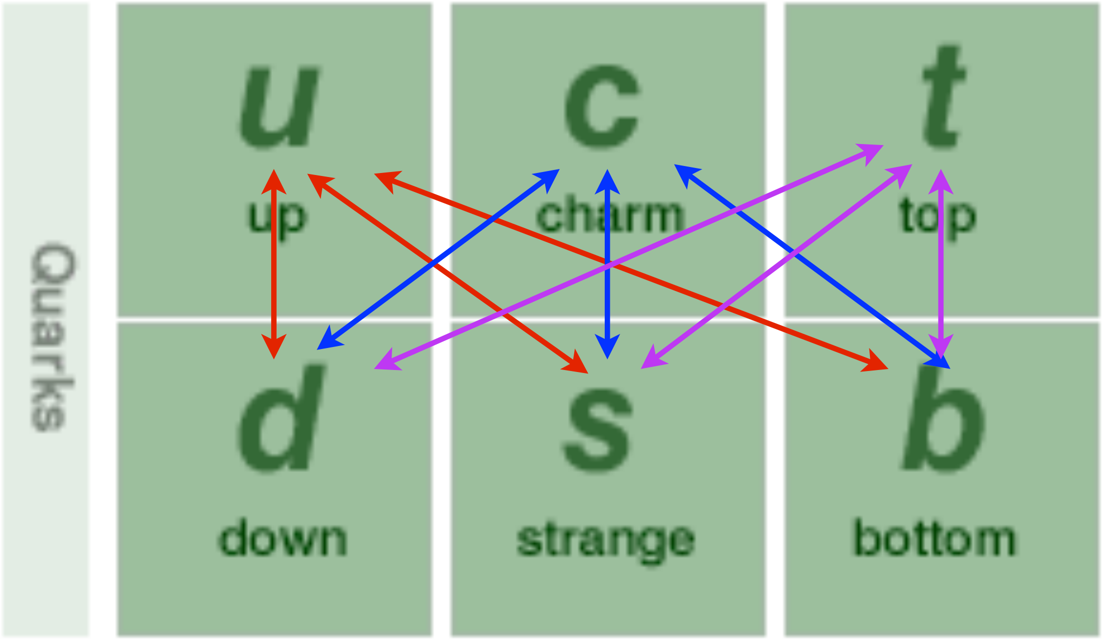


$$B^0 \to \rho^- + e^+ + \nu_e$$

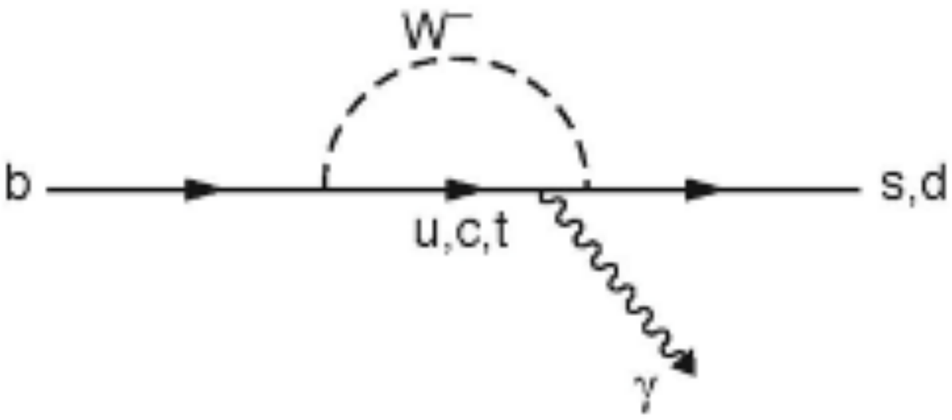


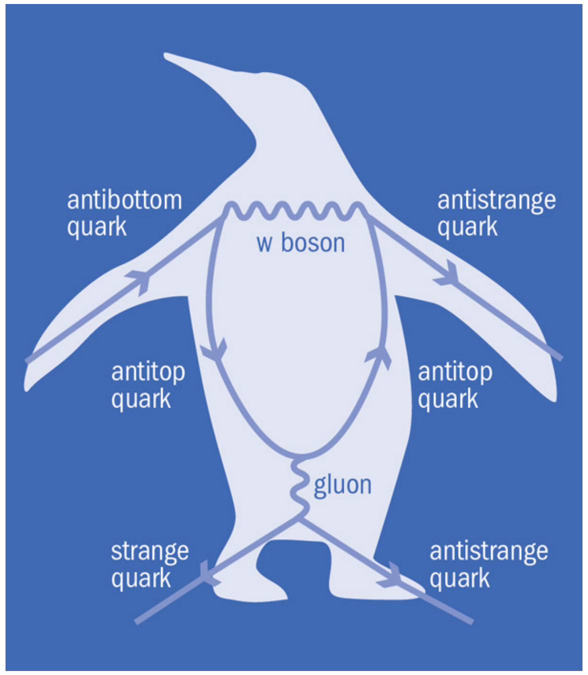
WEAK CHARGED CURRENT

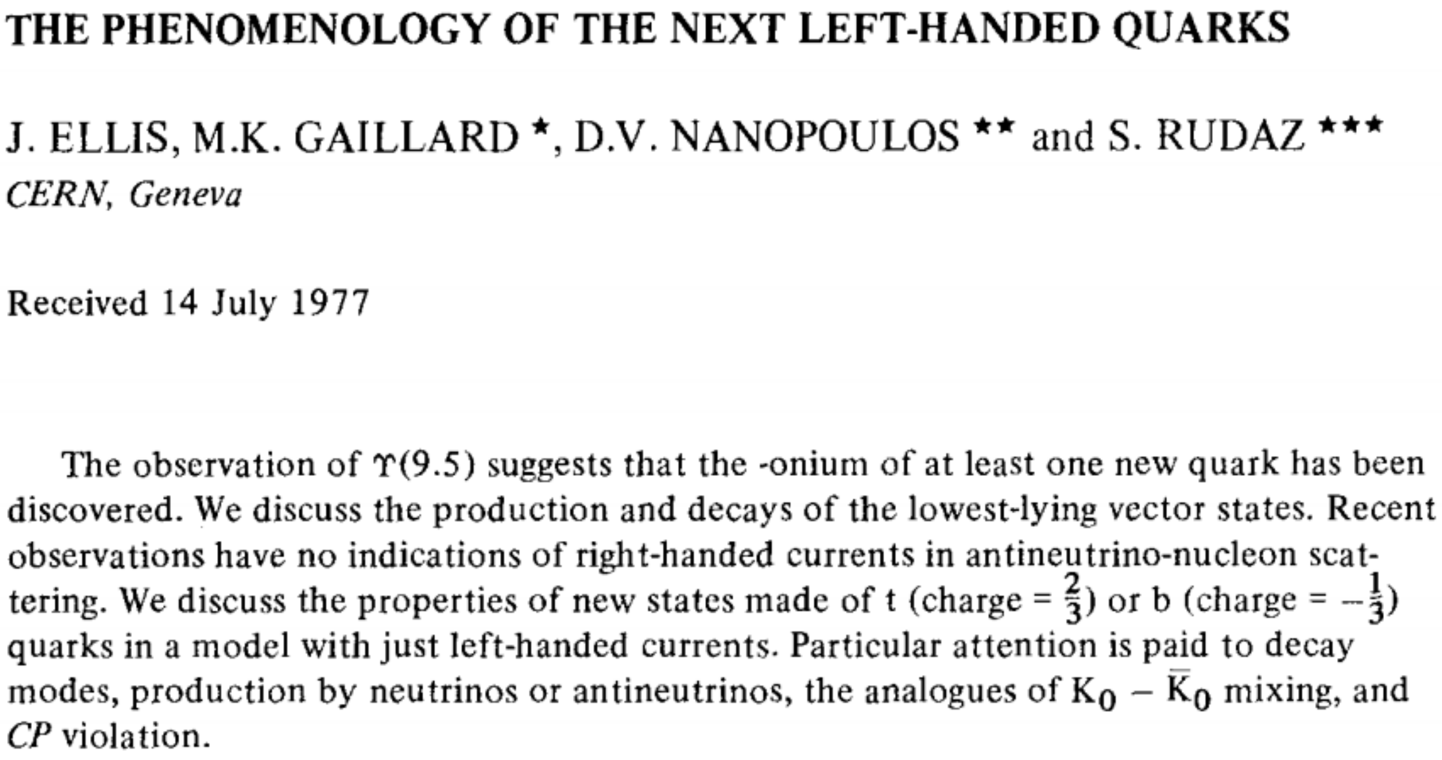
- This is probably the most complicated process
    - it is the only one that can change the identity of a particle
- For leptons (neutrinos) it is relatively easy:
    - change a neutrino into its corresponding lepton
    - $\nu_l \Leftrightarrow l^-$
- For quarks, any transition from "top" to bottom row is possible:
    - crossing columns ("generations" is disfavoured
    - "Cabibbo-suppressed"



THE PENGUIN DIAGRAM





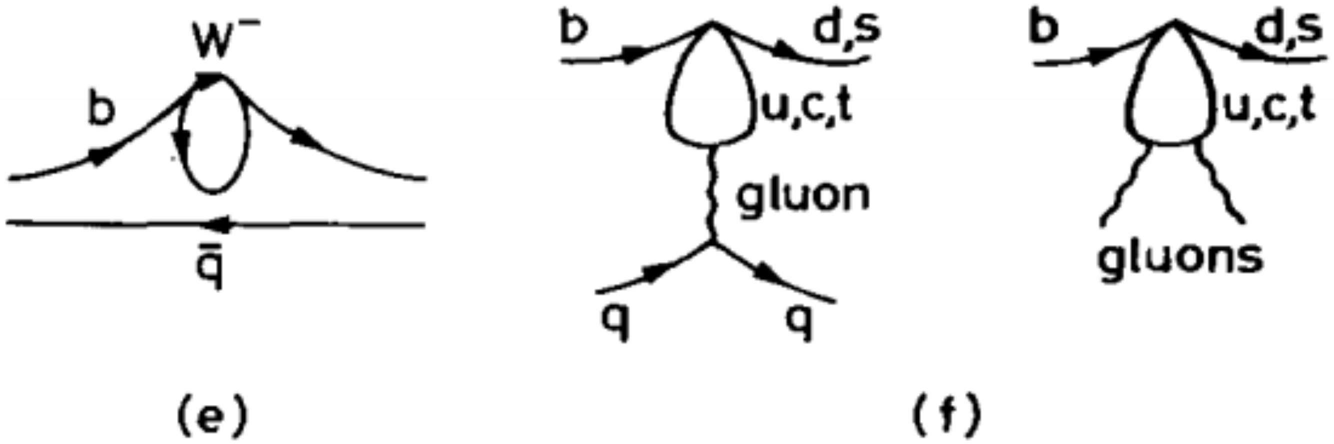


THE PHENOMENOLOGY OF THE NEXT LEFT-HANDED QUARKS

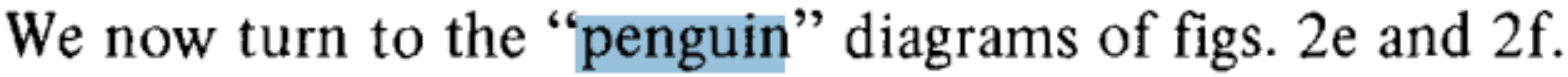
J. ELLIS, M.K. GAILLARD *, D.V. NANOPOULOS ** and S. RUDAZ ***
CERN, Geneva

Received 14 July 1977

The observation of $\Upsilon(9.5)$ suggests that the -onium of at least one new quark has been discovered. We discuss the production and decays of the lowest-lying vector states. Recent observations have no indications of right-handed currents in antineutrino-nucleon scattering. We discuss the properties of new states made of t (charge = $\frac{2}{3}$) or b (charge = $-\frac{1}{3}$) quarks in a model with just left-handed currents. Particular attention is paid to decay modes, production by neutrinos or antineutrinos, the analogues of $K_0 - \bar{K}_0$ mixing, and *CP* violation.



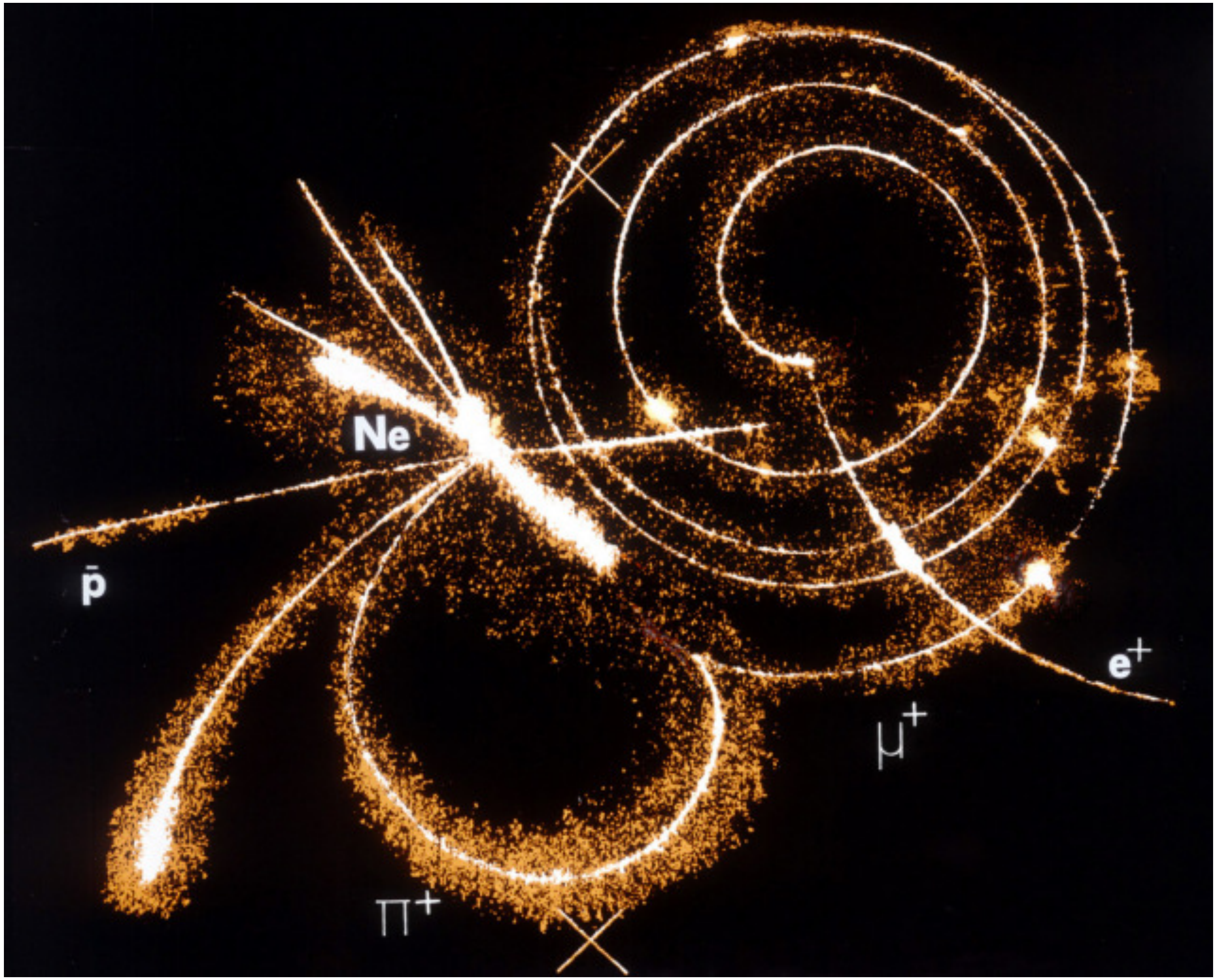
(e) (f)

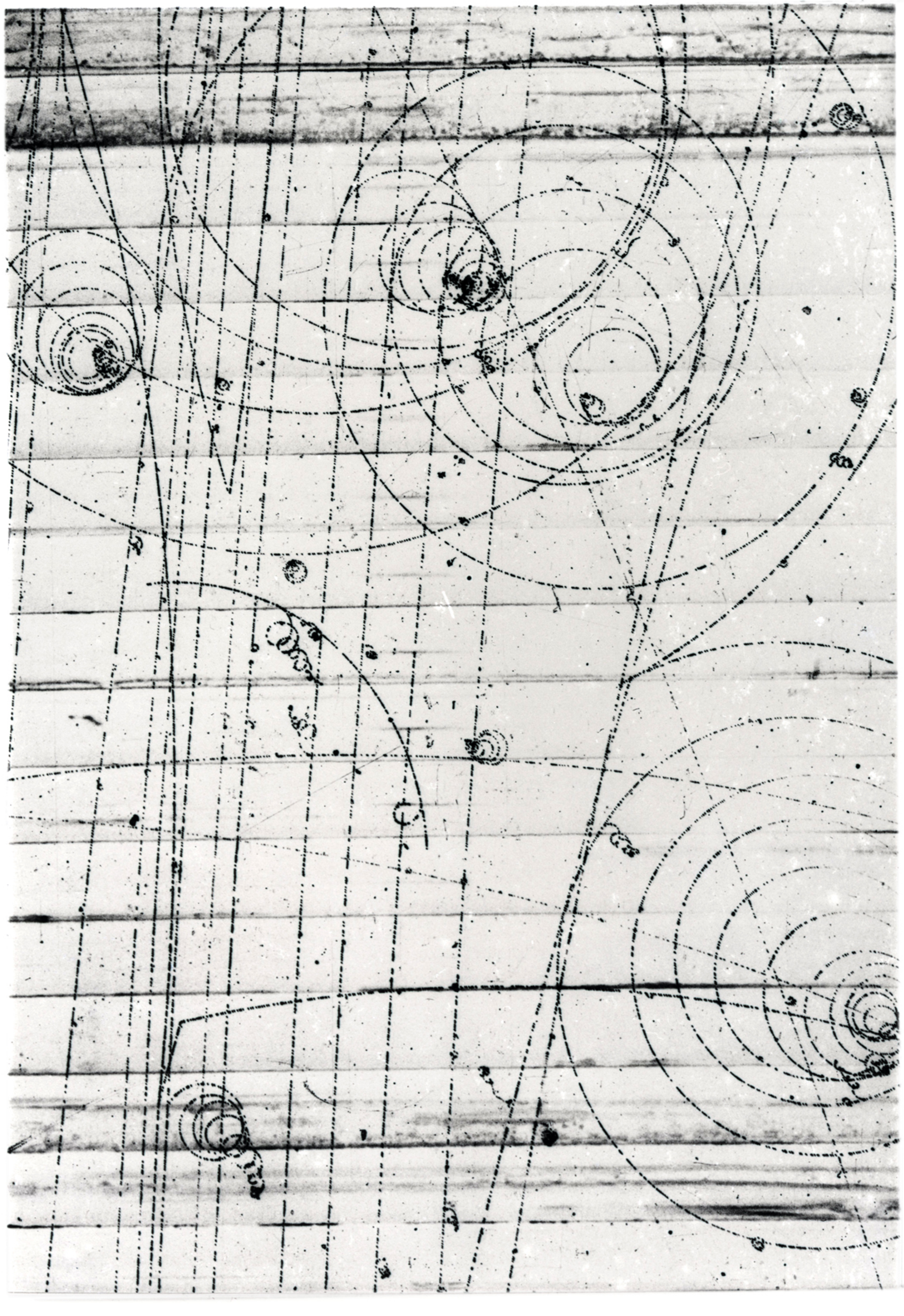


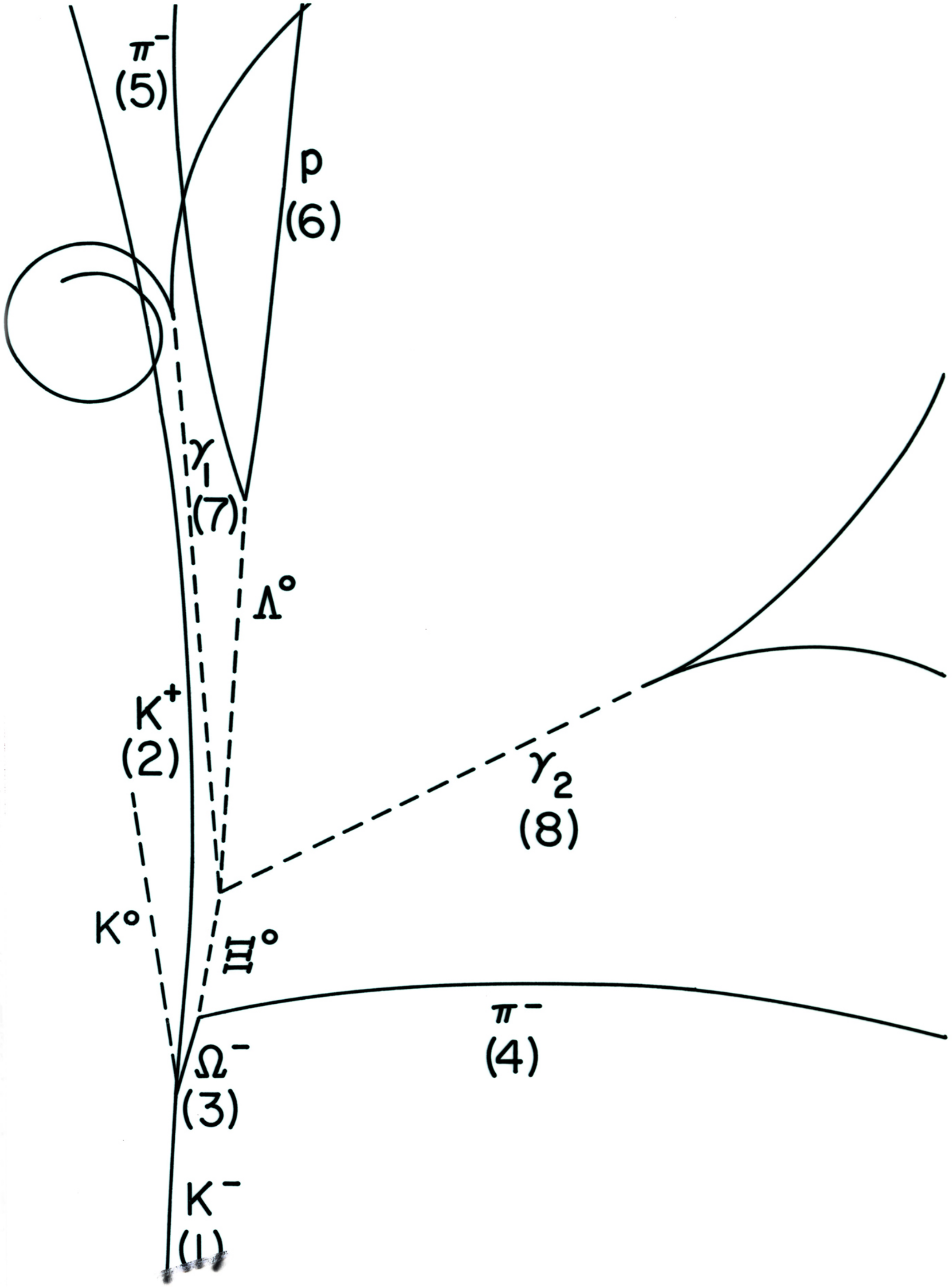
We now turn to the "penguin" diagrams of figs. 2e and 2f.

STUDYING PARTICLES

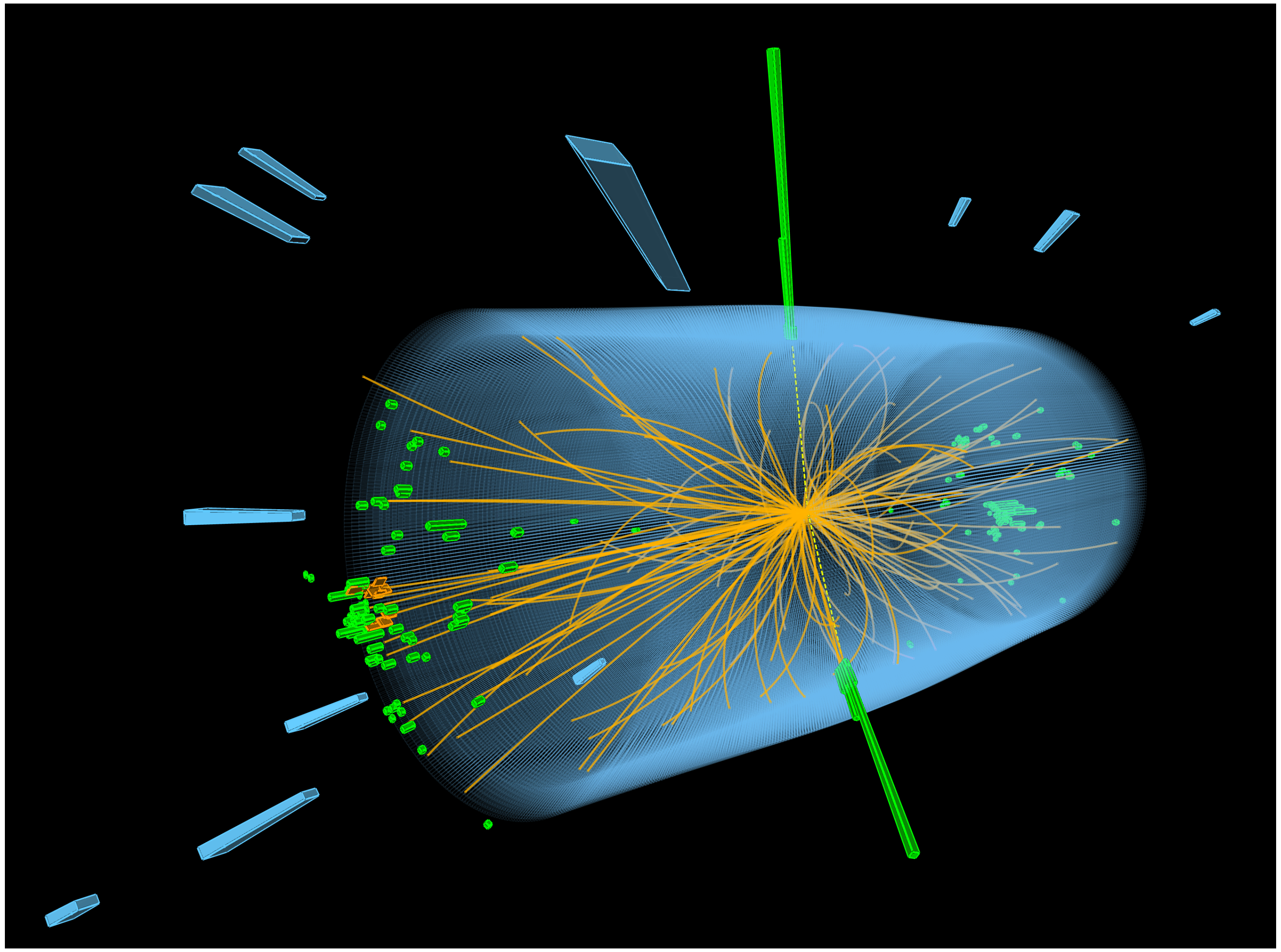
- Decays:
  - disintegration of particles into other particles
  - rate of decay, type of particles emitted, and kinematics of decay can tell us about underlying mechanism.
  - energy/momentum conservation can tell us its mass
- Scattering
  - collision of particles
  - outgoing particles may or may not be the same
  - cross section ("probability") of interaction and outgoing particles can tell us about underlying mechanism
- Decay vs. Scattering:
  - in some cases, decays are "scattering" of constituent particles
  - many particles of short lived; they can one (Problem 1.5)

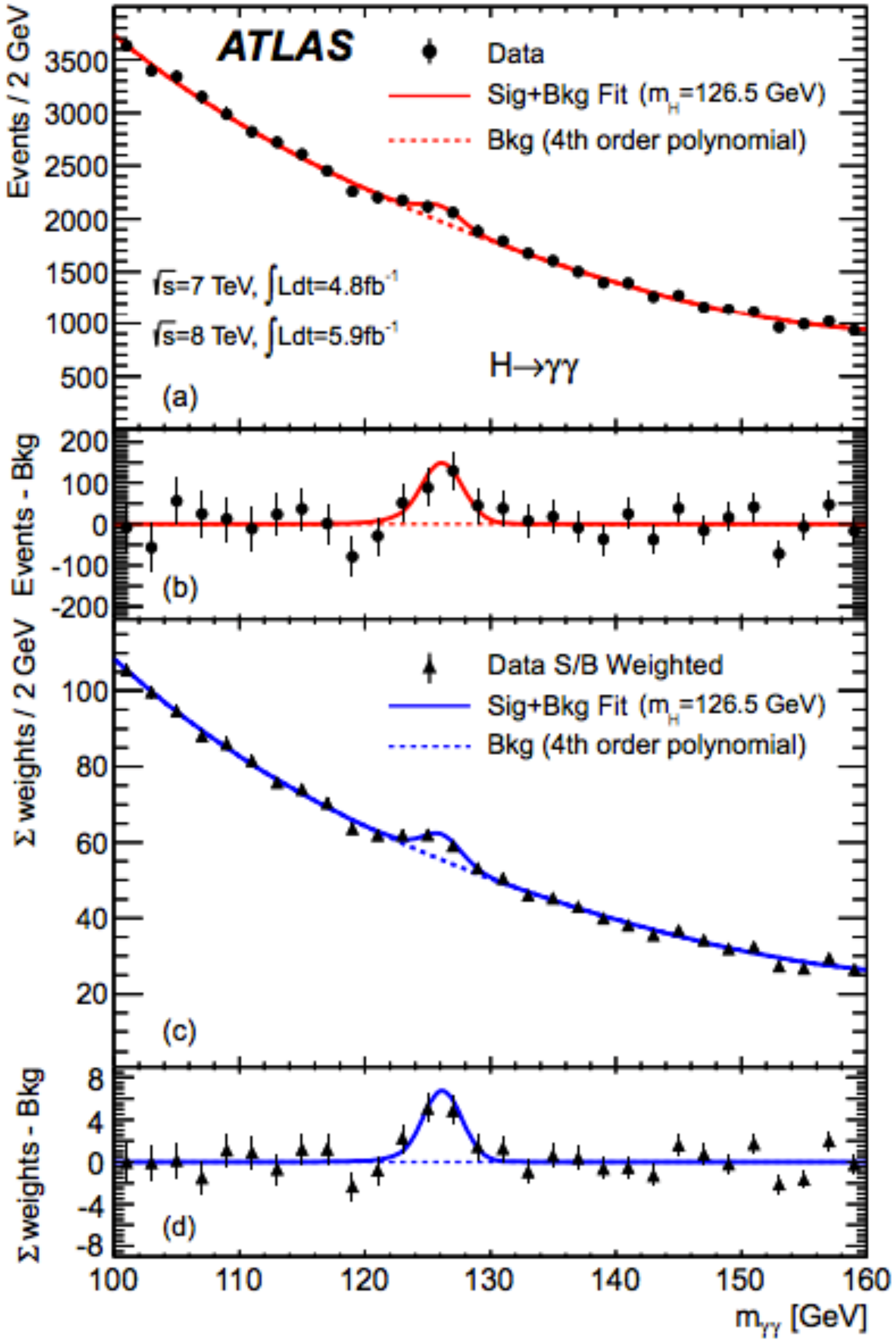

Ne
p̄
e⁺
μ⁺
π⁺

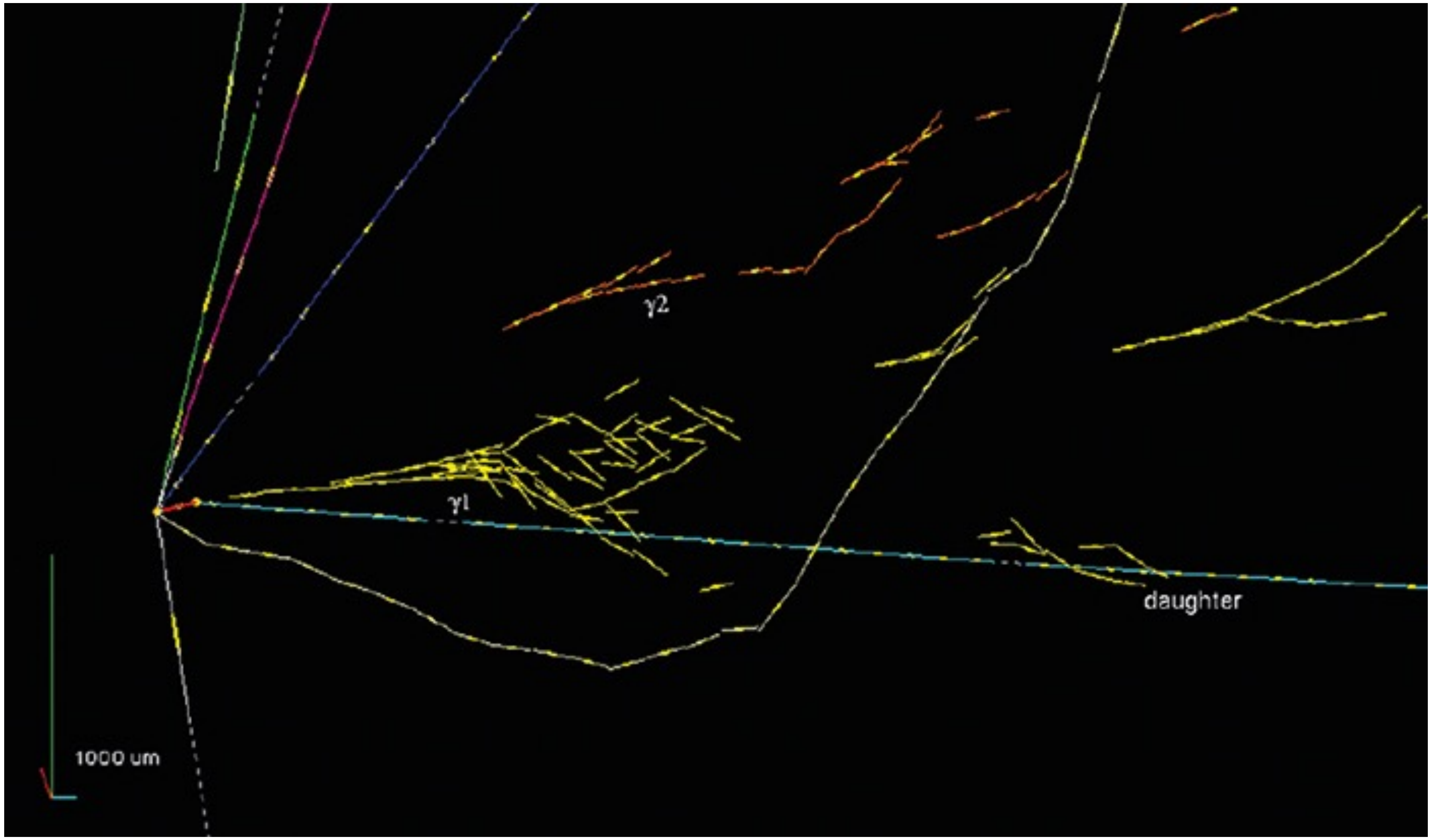


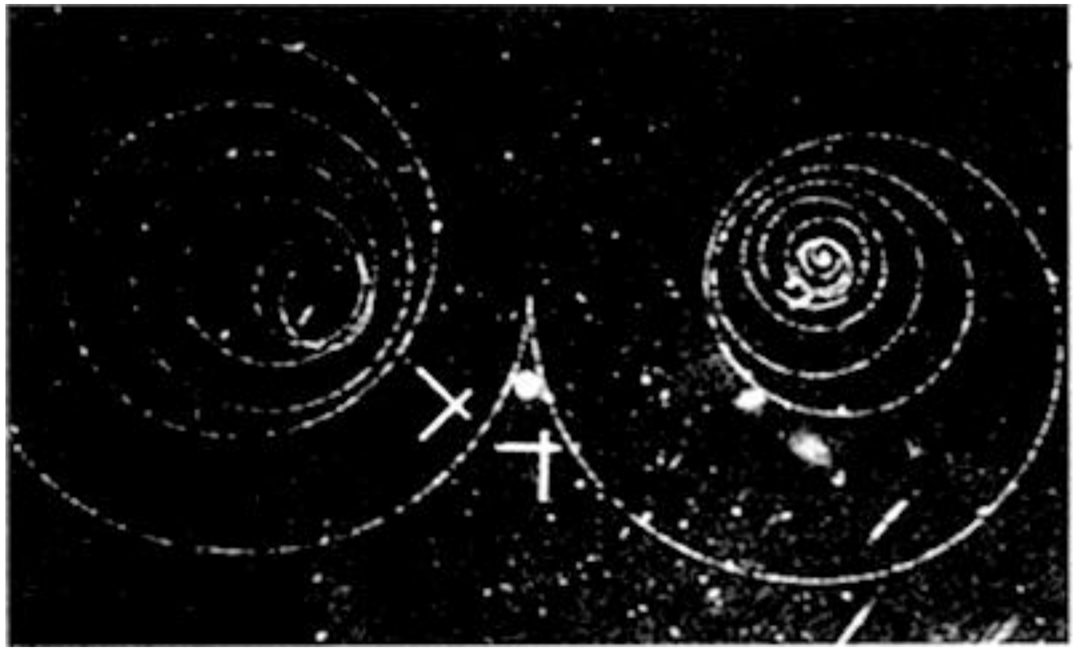


π^-
(5)
p
(6)
γ_1
(7)
Λ°
K^+
(2)
γ_2
(8)
K°
Ξ°
π^-
(4)
Ω^-
(3)
K^-
(1)



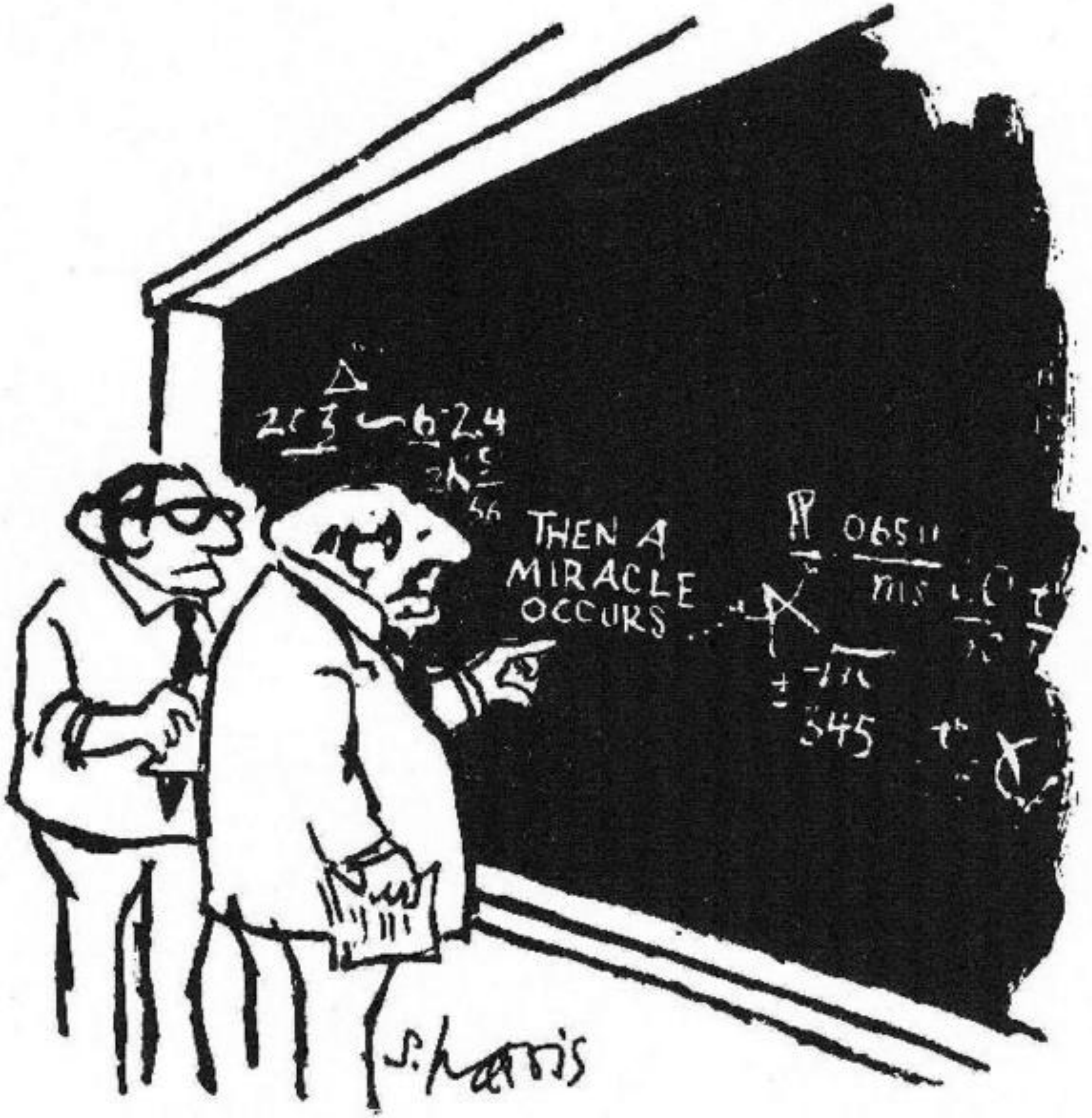

ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
H→γγ
Events / 2 GeV
3500
3000
2500
2000
1500
1000
500
(a)
Events - Bkg
200
100
0
-100
-200
(b)
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Σ weights / 2 GeV
100
80
60
40
20
(c)
Σ weights - Bkg
8
4
0
-4
-8
(d)
100
110
120
130
140
150
160
$m_{\gamma\gamma}$ [GeV]


γ2
γ1
daughter
1000 um



WHAT WE WILL NOT COVER

- In some sense, this class is pedagogically misplaced
- A more logical approach might be to study the fundamental framework of "quantum field theory" first
    - consistent quantum mechanical framework for treating relativistic particles
    - beyonds the scope of this class . . . . .
- We have other fundamental principles (conservation laws, symmetry, etc.) to work with.
- But a large part of the class will come out of nowhere without a full explanation
    - Feynman rules for calculating the amplitude of a process



"I think you should be more explicit here in step two."

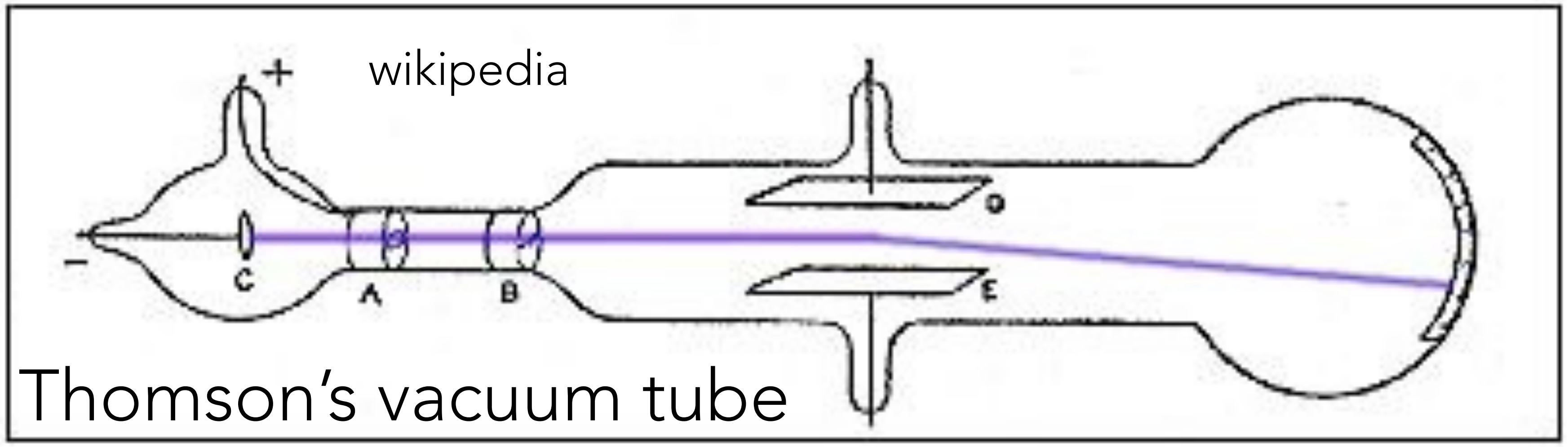
NOTE ON UNITS

- Standard unit of energy in particle physics is eV
  - keV, MeV, GeV, TeV, ...
  - 1 eV ~ 1.6 x 10^{-19} J
- Recall $E=mc^2$
  - Mass can be expressed in units of $[E]/c^2 \Rightarrow eV/c^2$
  - For reference, $m_p = 938.272\ MeV/c^2 = 1.672 \times 10^{-27}$ kg
- $\mathbf{p} = (\gamma)m\mathbf{v}$
  - momentum can be expressed in units of $[m]c \Rightarrow eV/c$
- Textbook generally uses $\hbar = c = 1$
  - Use eV as the units for mass, momentum, energy
  - I will often carry around units of c

NEXT TIME

- Please read Chapter 1, Chapter 2.1-2.2
- Problem set 1 is posted
- Doodle Poll for office hours:
  - https://doodle.com/poll/s2wk5hkc7scy3b6t
  - poll is dated for next week but will be used to set weekly times.

“FIRST” ELEMENTARY PARTICLE



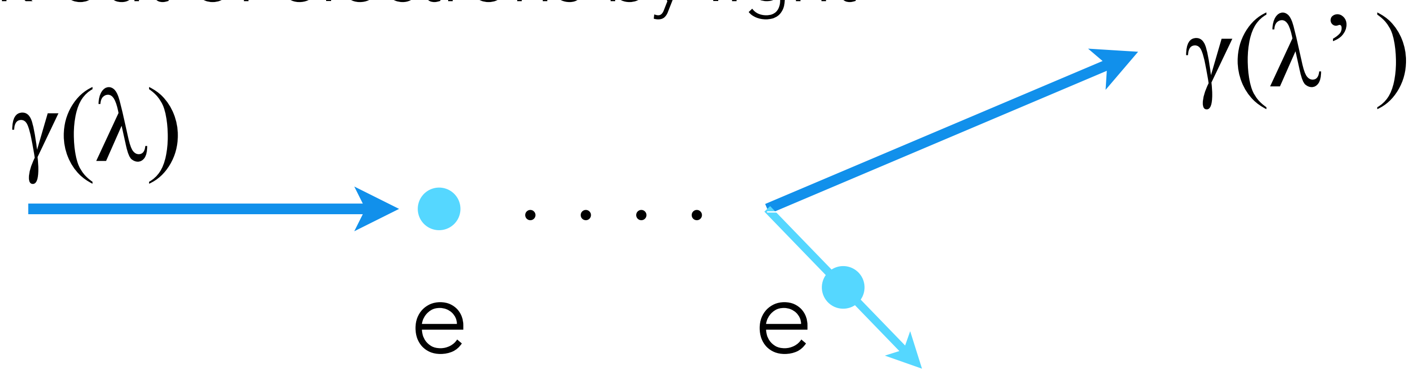
wikipedia

Thomson’s vacuum tube

- cathode ray studies:
  - What is a cathode ray? appears to be charged, but what is it?
- Series of experiments:
  - Demonstrated that electric charge follows the cathode ray
  - Deflected by electric field
  - Measured charge/mass ratio:
    - determine velocity by balancing E/B forces
    - Points to particle-nature of the electron

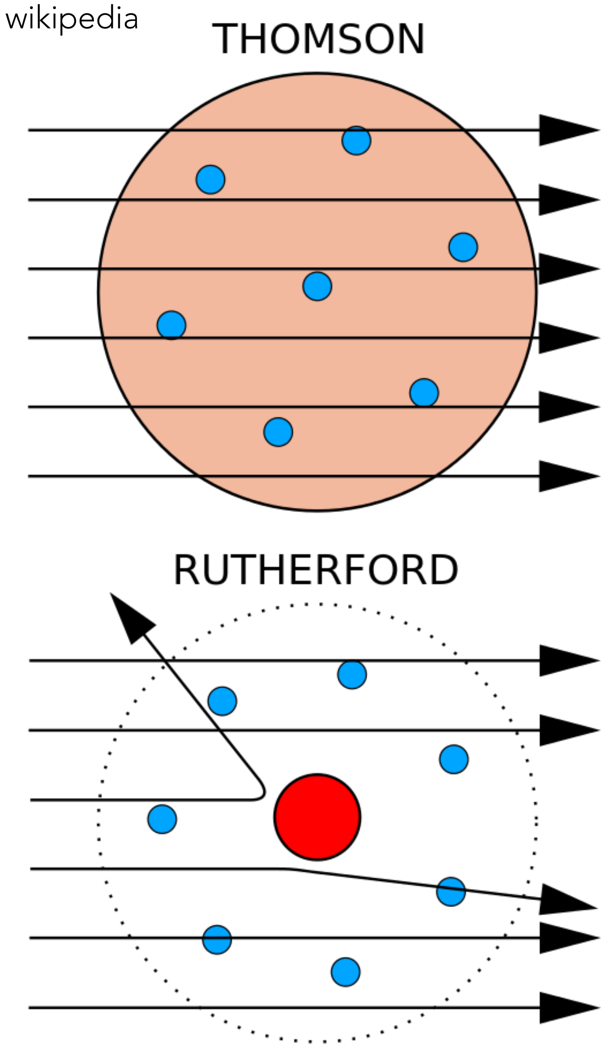
PARTICLE VERSUS WAVE

- Photon: firmly ingrained belief in wave nature
  - Planck's quantum hypothesis: first clue of particle nature.
  - Photoelectric effect: electrons from a material are liberated only when the wavelength of light is short
    - Einstein (1905): light is composed of particles, whose energy is proportional to frequency (Nobel Prize 1921)
- Compton scattering (1923):
  - Knock-out of electrons by light



  - Relation between λ, λ' and θ is precisely that of a particle with mass = 0 and energy hc/λ (hc/λ') striking the electron

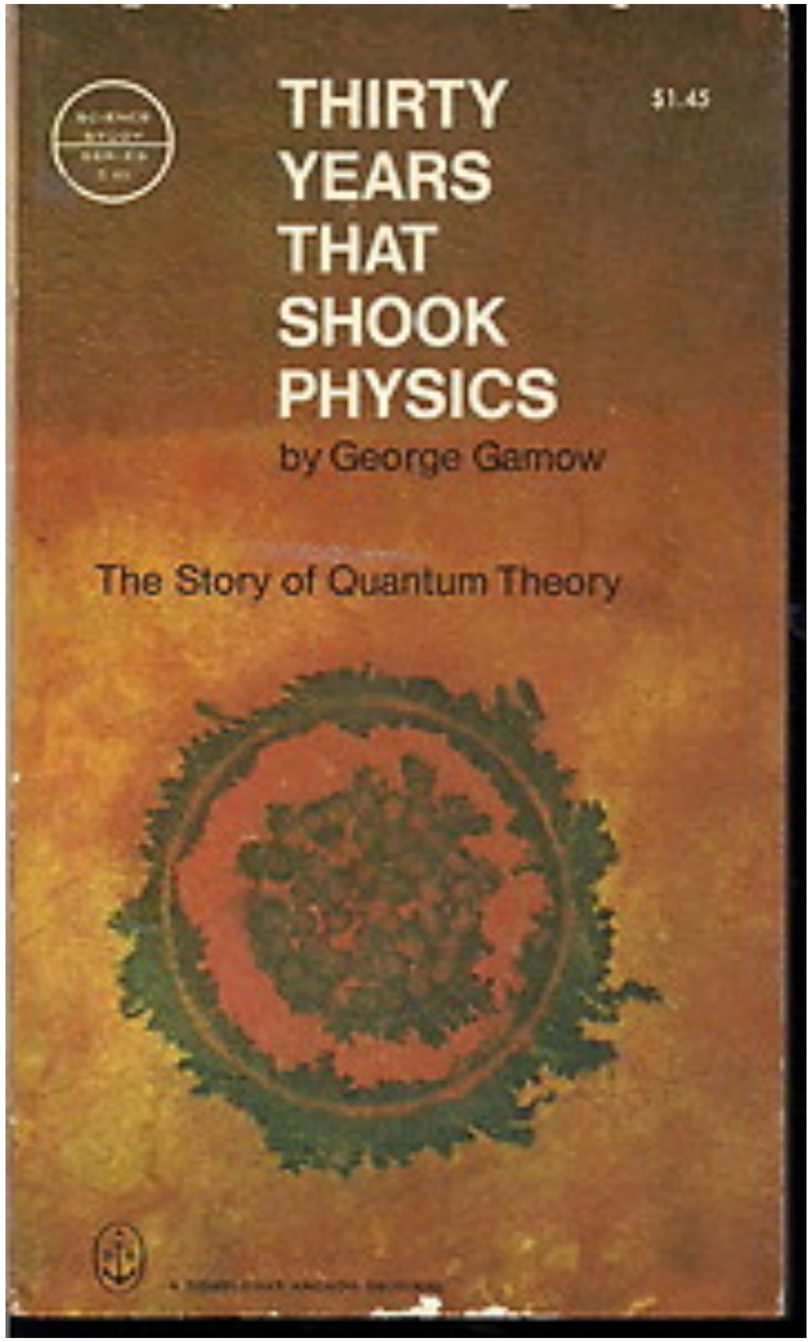
INTO THE ATOM



wikipedia

- “High energy physics” in the 1900-1920
- Radioactivity:
    - α (^{4}He nucleus)
    - β (electron)
    - γ (photon/light)
    - transmutation of elements into other elements!
- Discovery of the atomic nucleus:
    - very concentrated charged mass at the center of the atom scattering α particles
- Scattering experiments:
    - $\alpha + {}^{12}\mathrm{N} \rightarrow {}^{17}\mathrm{O} + {}^{1}\mathrm{H}$ (=p)
    - first indication that protons are contained within the nucleus (and = hydrogen nuclei)
    - Rutherford also postulated neutrons . . .

PHYSICS IN THE 1930S



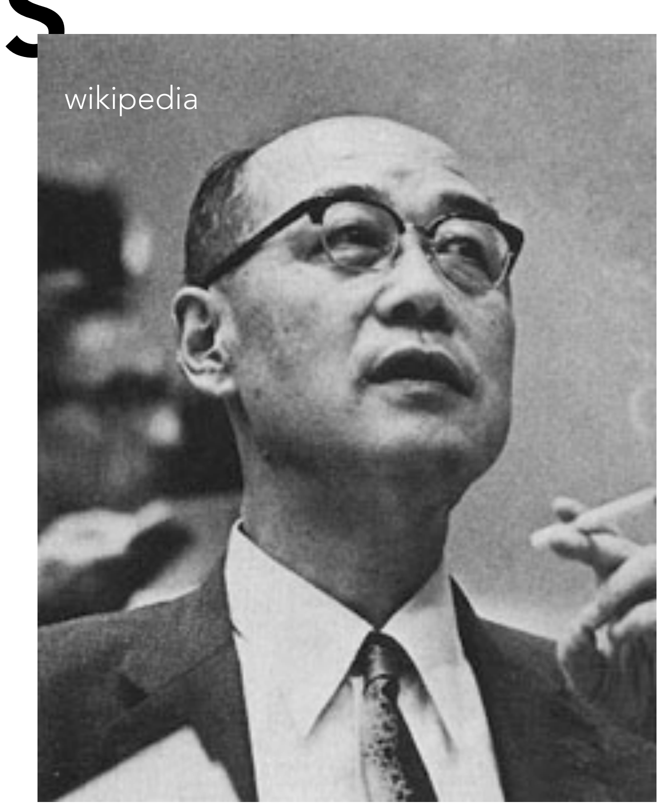
- In the tumultuous era that gave birth to:
    - special/general relativity
    - quantum mechanics

  within ~30 years, the basic building blocks of "ordinary matter" were identified.

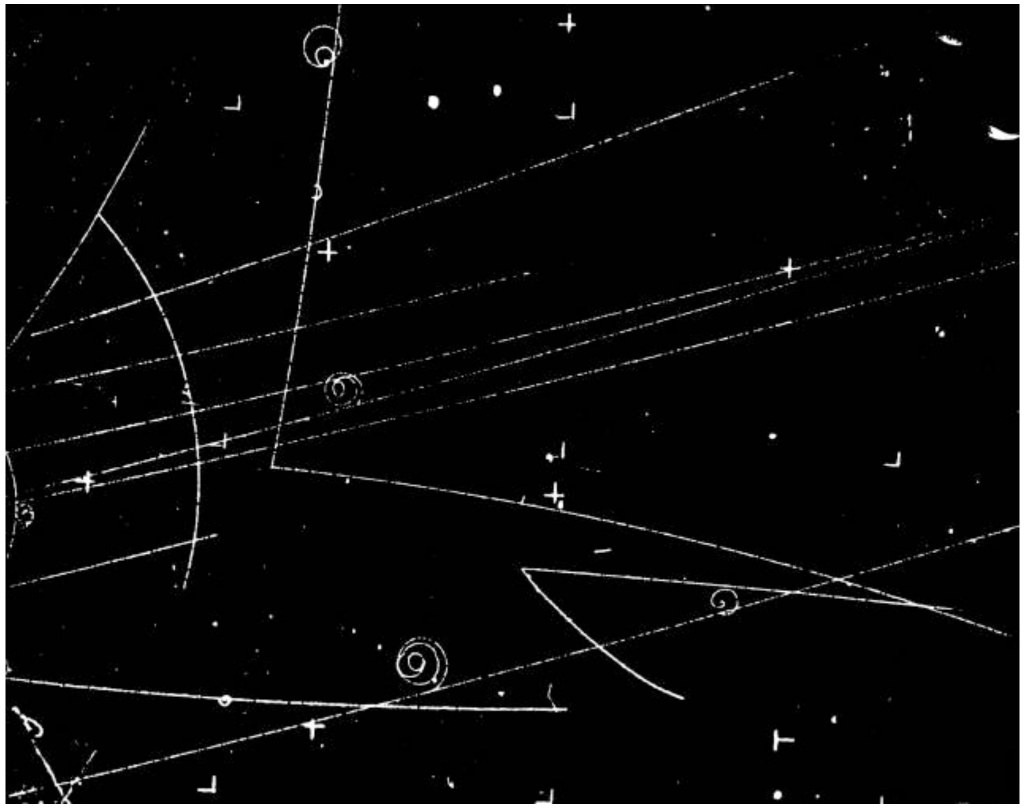
p e^- γ

- atoms are some number of protons bound together in the nucleus, with an equal number of electrons bound to them electromagnetically

THE YUKAWA HYPOTHESIS



- EM (photon) binds electron to nucleus
- Yukawa: some force (=particle) must bind the nucleus together
  - short range = massive
  - He called this the π particle (300 x m_e)



The π is sought in cosmic rays using photographic emulsions

Several things are discovered

- the μ “meson”
- the π meson
- “strange” particles K, Λ, Σ

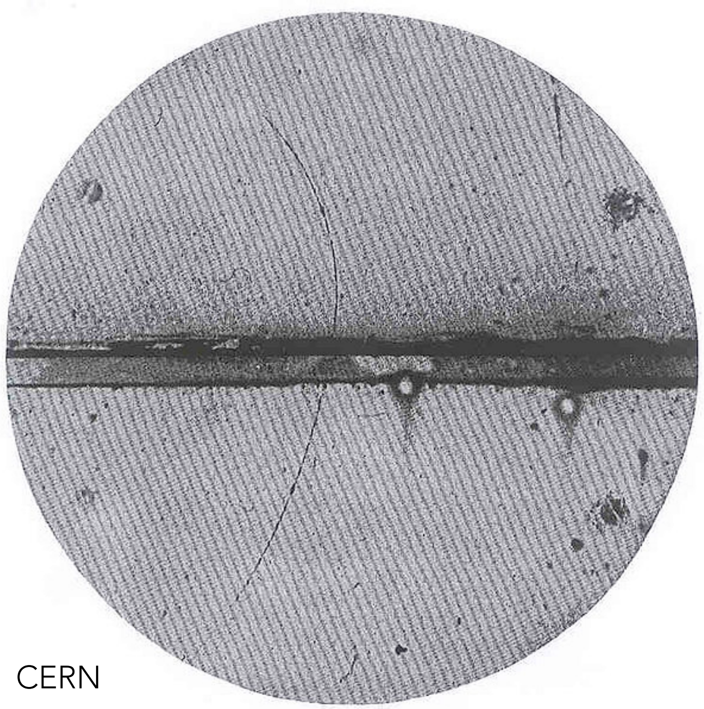
ANTIPARTICLES


wikipedia

- In the 1920's, physicists try to put together:
  - Quantum Mechanics
  - Special Relativity
- Dirac's attempt at this leads to the need for:
  - positively charged counterpart of the electron

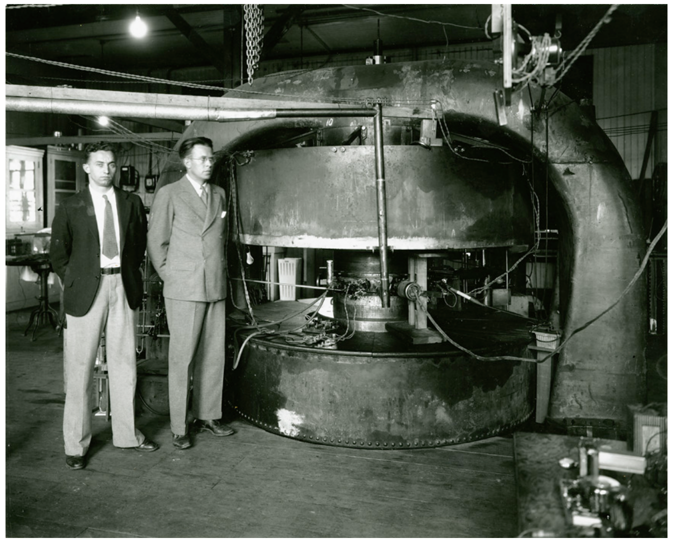
Such a particle is actually observed

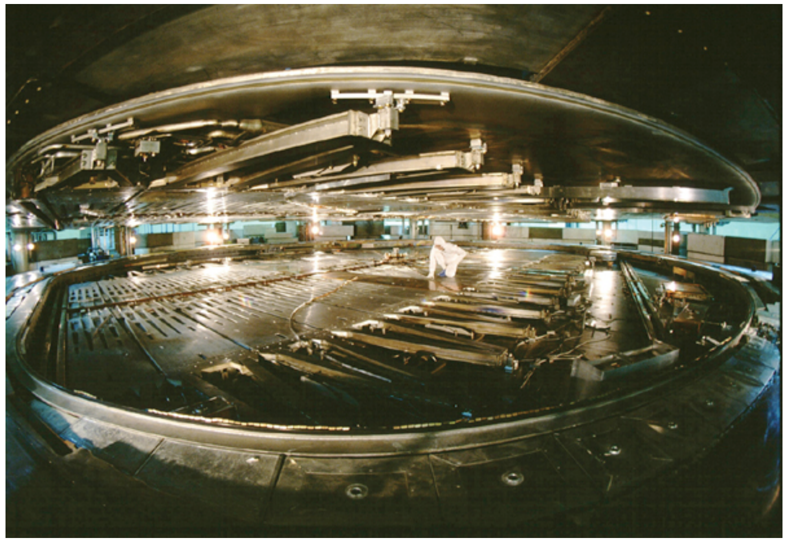
- just like the electron, but positively charged
- in due course, find every particle has an antiparticle
- (In some cases, e.g. γ, it is itself)

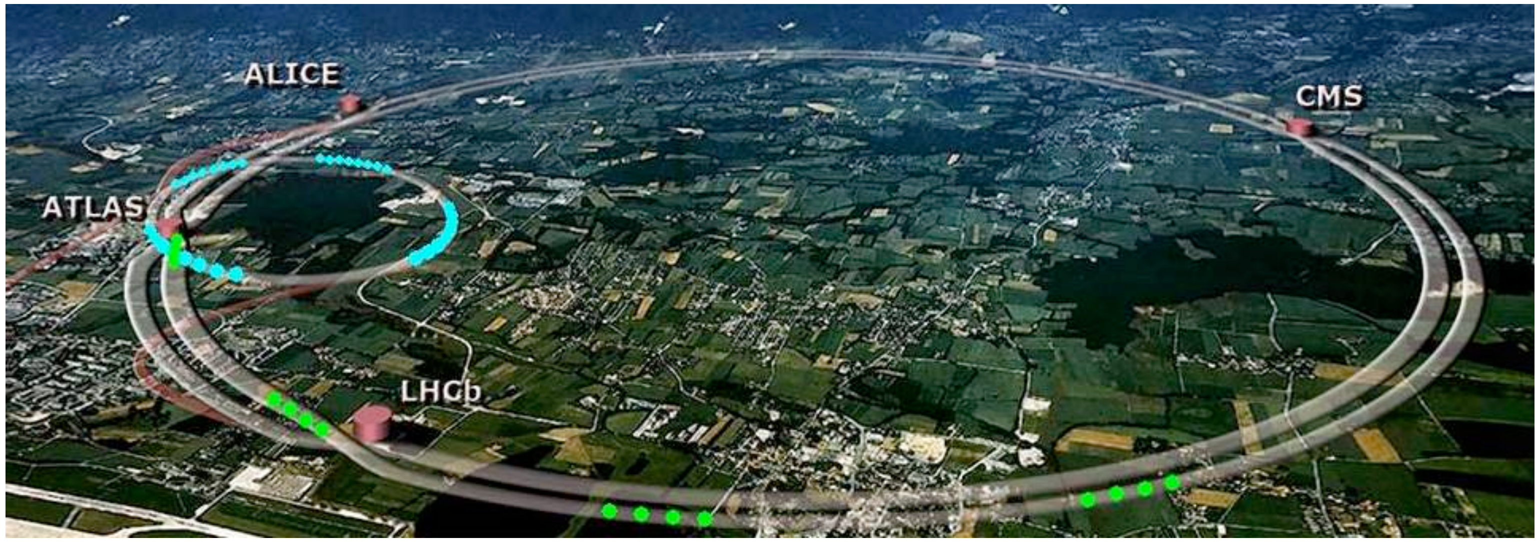

CERN

antiparticles are denoted by a "bar"

ACCELERATORS







HADRON ZOO

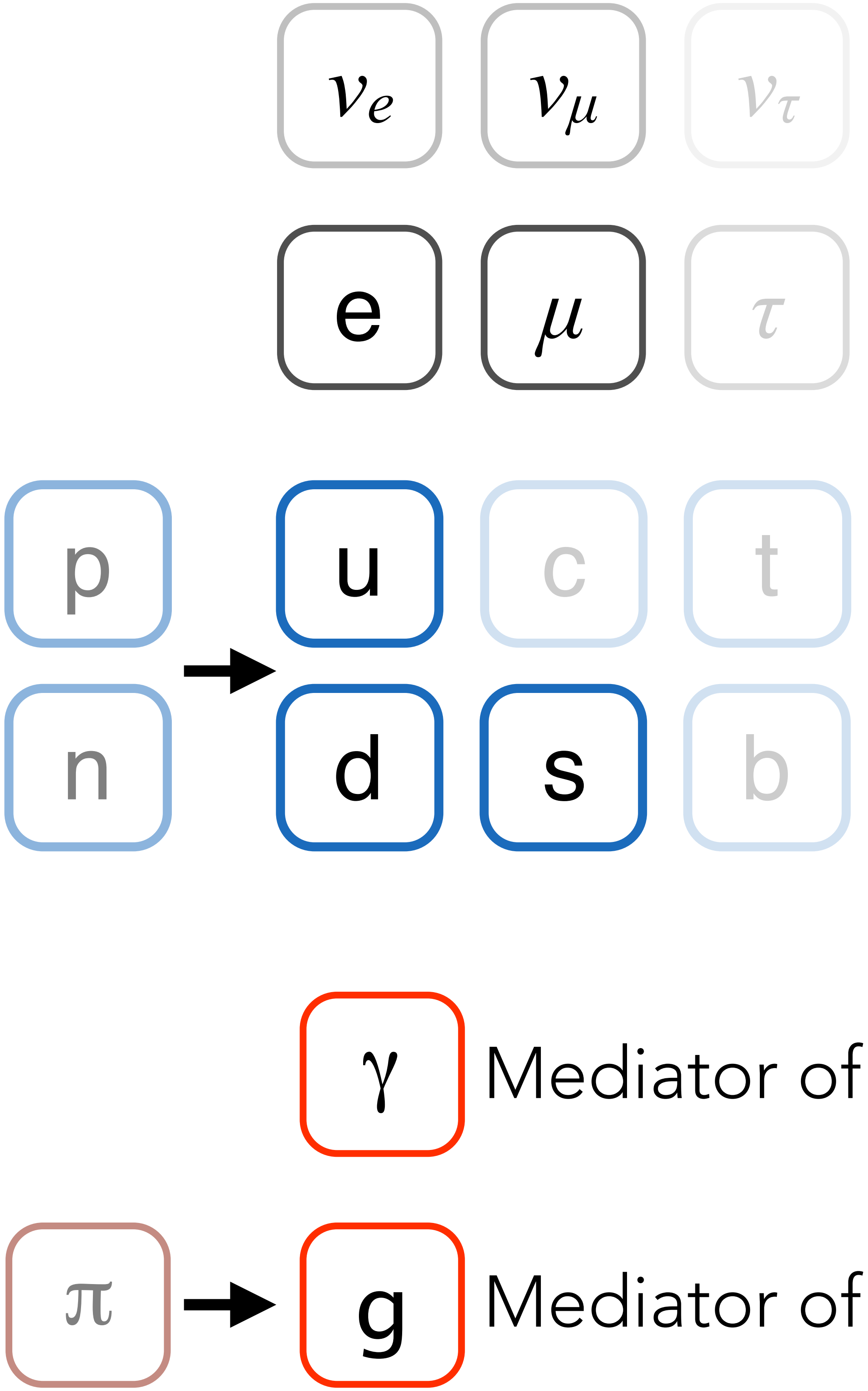
- As energies of accelerators increased, a proliferation of new particles (hadrons) were discovered:
    - Mesons:
        - “pseudoscalar” mesons: π^+, π^0, π^-, η, η', $\boxed{K^+, K^-, K^0, K^0}$
        - “vector” mesons: ρ^+, ρ^0, ρ^-, ω, φ, $\boxed{K^{*+}, K^{*-}, K^{*0}, K^{*0}}$
    - Baryons
        - p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^+, Ξ^0, Ξ^-

“strange particles”

-
    -
        - Δ^{++}, Δ^+, Δ^0, Δ^{--}, $\boxed{\Sigma^{*+}, \Sigma^{*0}, \Sigma^{*-}, \Xi^{*0}, \Xi^{*-}, \Omega^-}$
        - and many more . . . .
    - what are all these particles?
    - “Strange” = copiously produced, but long lifetime

- Willis Lamb (1955): “the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be **punished by a $10,000 fine.**”

PARTICLE PHYSICS IN THE 1970S



ν_e ν_μ ν_τ

weak interactions
No EM/strong interaction

e μ τ

EM and weak interactions
No strong interaction

p n → u d; c s; t b

u c t

EM and weak interactions
strong interactions

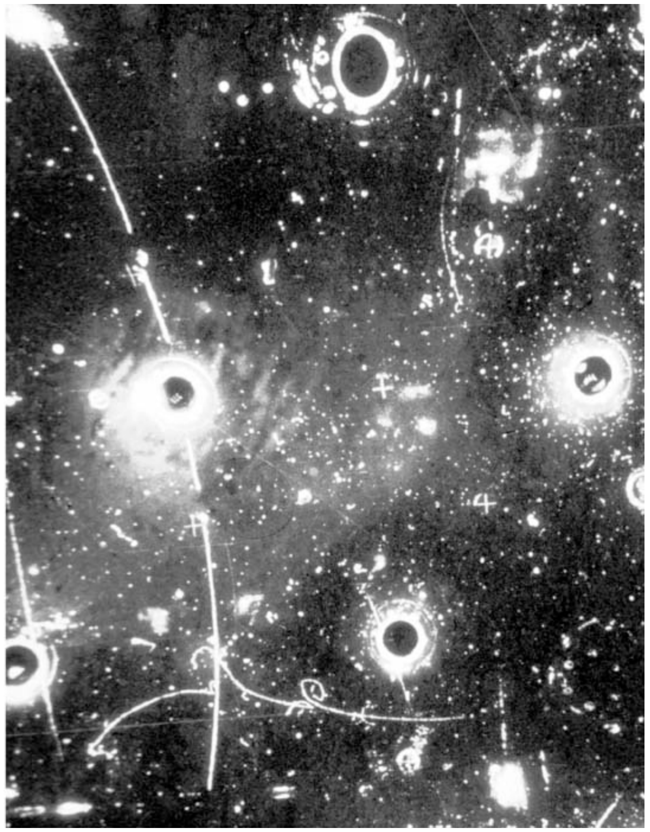
d s b

EM and weak interactions
strong interactions

γ Mediator of EM interaction

π → g Mediator of strong interaction?

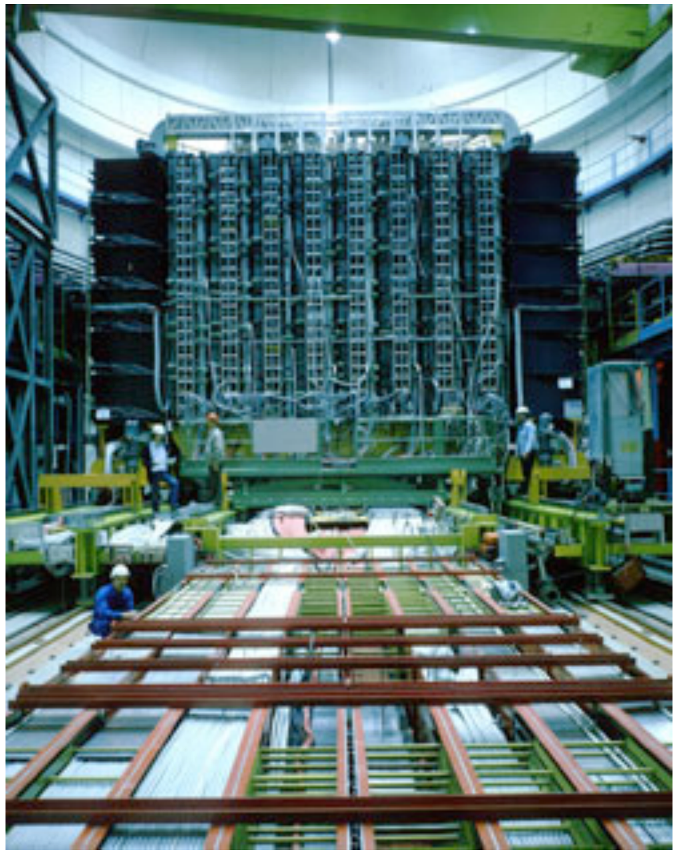
DISCOVERY OF NC, W, Z

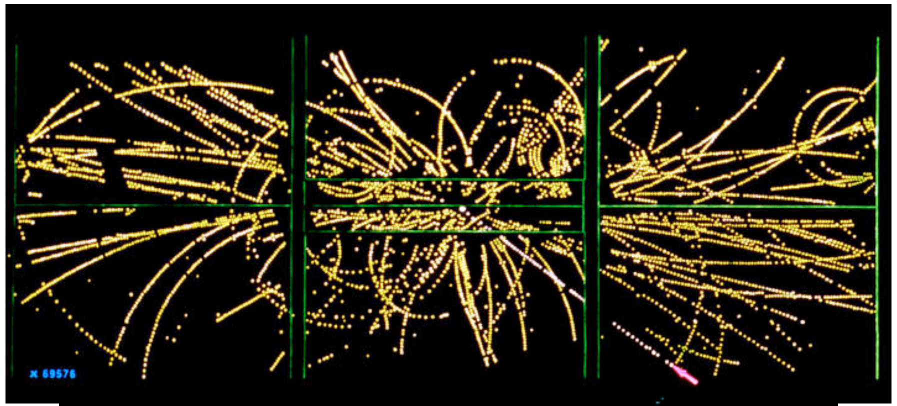


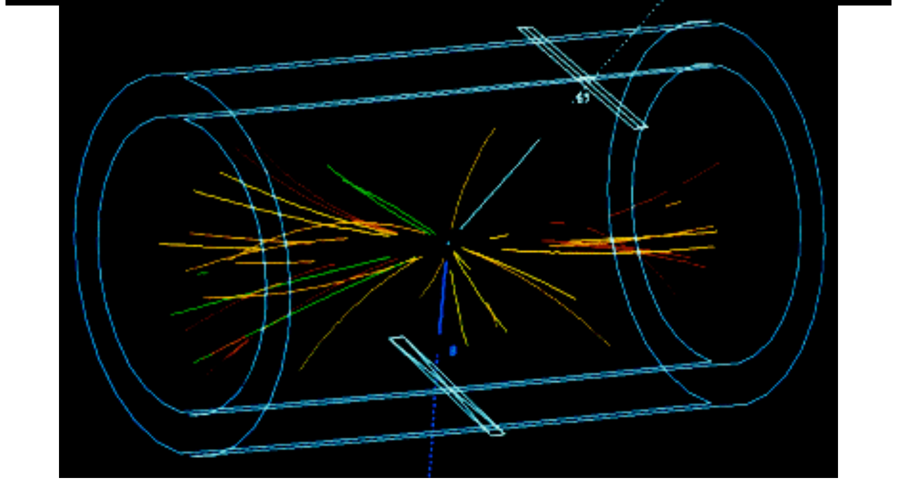
- NC reaction of neutrinos in bubble chamber

$$\nu_\mu + e \rightarrow \nu_\mu + e$$

- W production in pp collisions.
  - Observe W → e + ν_e
- Z particle by observing Z → e + e





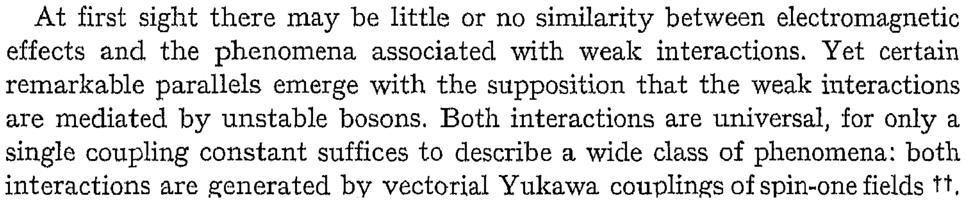


W, Z are extremely massive

W ~ 80 GeV/c^2

Z ~ 91 GeV/c^2

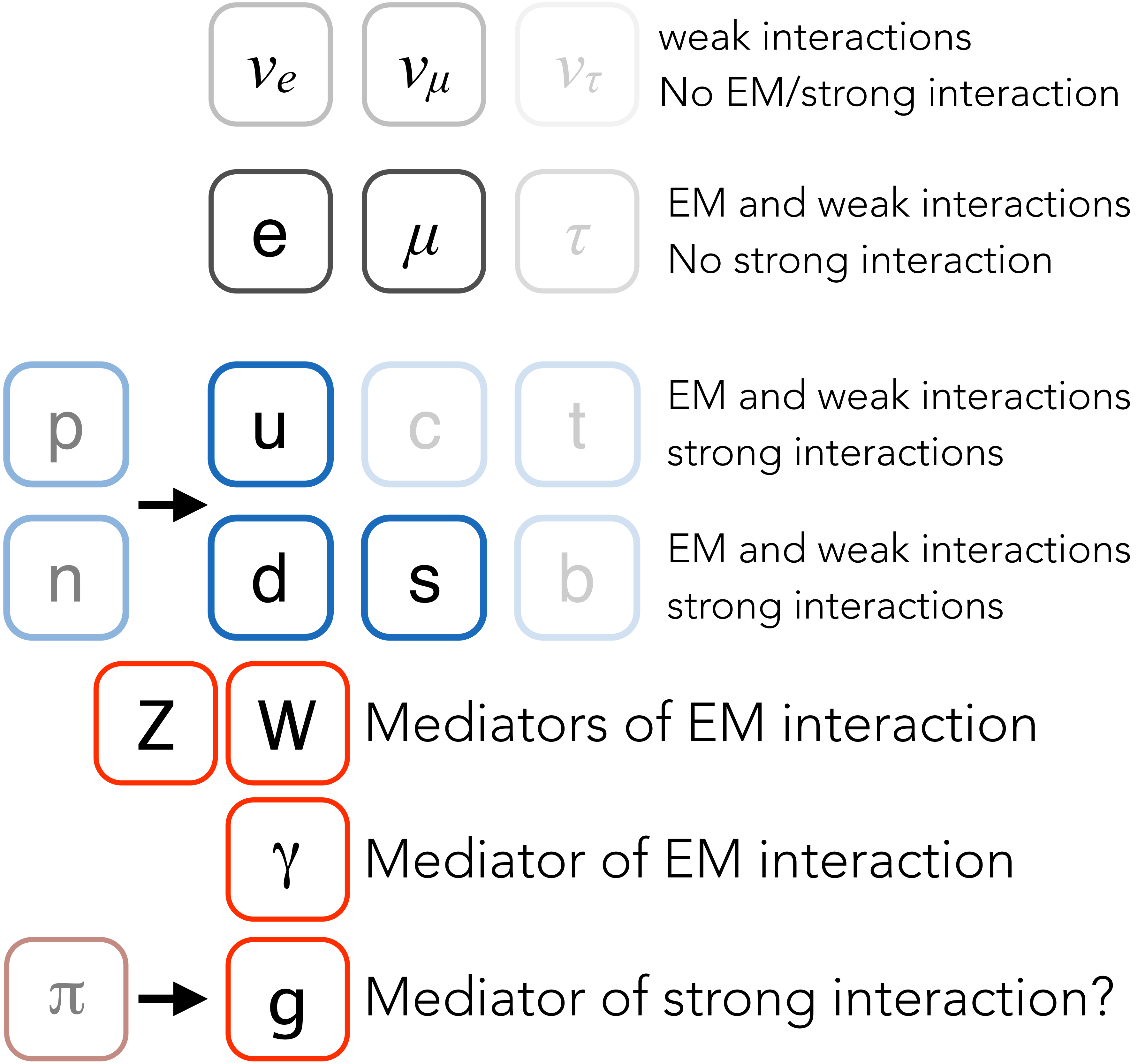
See later that this is responsible for the "weakness" of the weak interaction



At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields ††.

S.L. Glashow, 1960

PARTICLE PHYSICS IN THE 1970S



ν_e ν_μ ν_τ
weak interactions
No EM/strong interaction

e μ τ
EM and weak interactions
No strong interaction

p → u c t
EM and weak interactions
strong interactions

n → d s b
EM and weak interactions
strong interactions

Z W Mediators of EM interaction

γ Mediator of EM interaction

π → g Mediator of strong interaction?

NOTE ON UNITS

- Standard unit of energy in particle physics is eV
  - keV, MeV, GeV, TeV, ...
  - 1 eV ~ 1.6 x 10^{-19} J
- Recall $E=mc^2$
  - Mass can be expressed in units of $[E]/c^2 \Rightarrow eV/c^2$
  - For reference, m_p = 938.272 MeV/c^2 =1.672x10^{-27} kg
- $\mathbf{p} = (\gamma)m\mathbf{v}$
  - momentum can be expressed in units of $[m]c \Rightarrow eV/c$
- Textbook generally uses $\hbar = c = 1$
  - Use eV as the units for mass, momentum, energy

NEXT TIME

- Please read Chapter 1, Chapter 2.1-2.2
- Start looking at problem set.