H. A. TANAKA

PHYSICS 489/1489

INTRODUCTION TO HIGH ENERGY PHYSICS

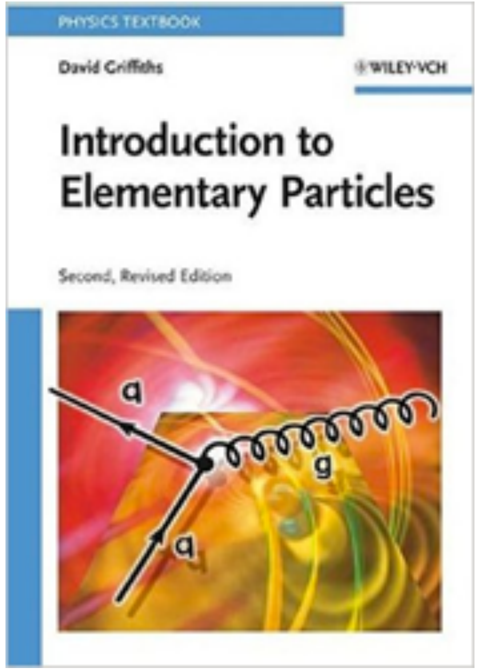
SOME LOGISTICS

- 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
  - Lagrangian Mechanics
  - quantum mechanics
    - Dirac Notation, perturbation theory, commutators, spin/angular momentum
  - multivariate calculus, matrix/linear algebra

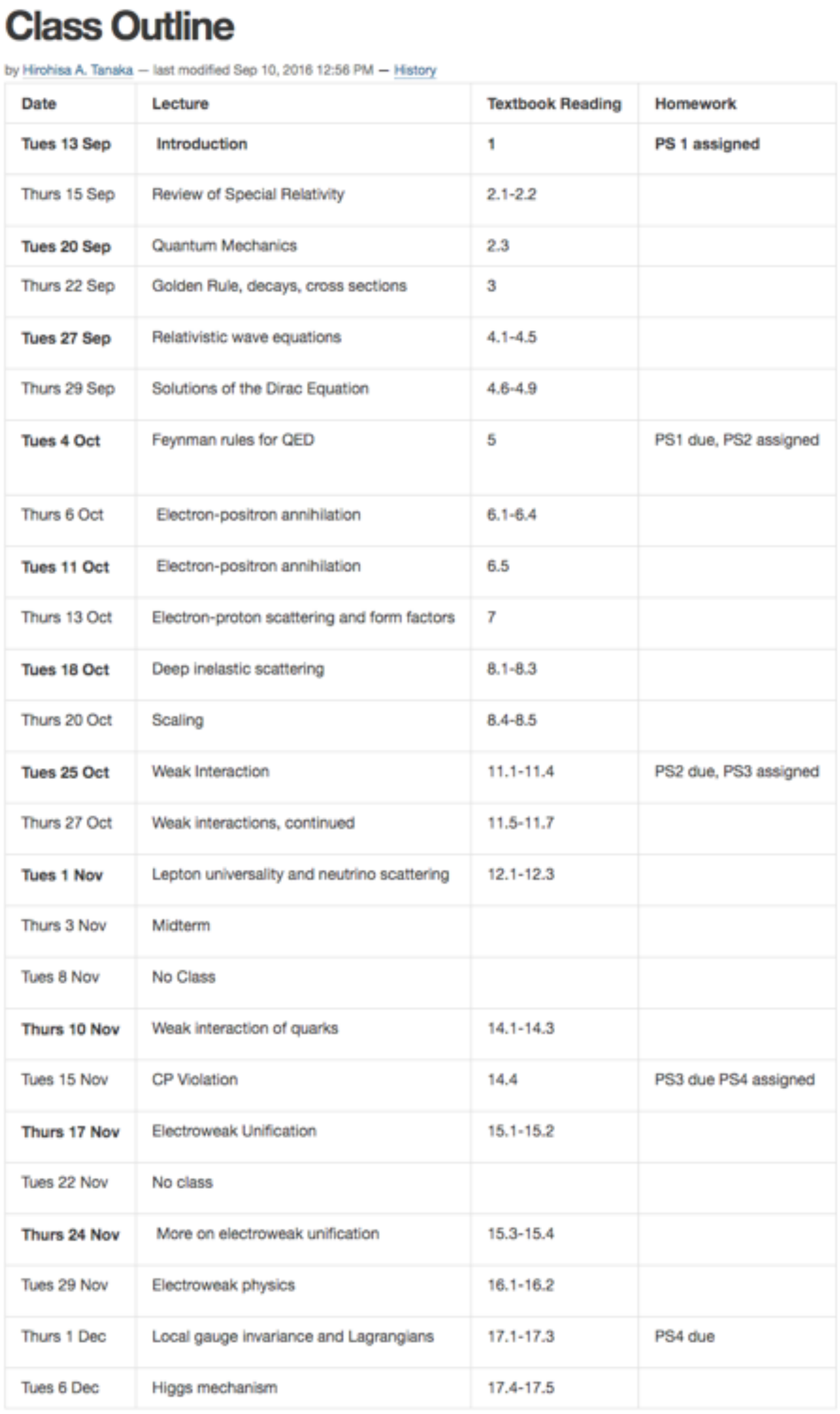
SOME MORE LOGISTICS

- Course website:
  - https://sites.physics.utoronto.ca/tanaka/physics-489-1489-2016
  - 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 3 November (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



- D. J. Griffiths:
  - "Introduction to Elementary Particles"
- Good alternative reference for class



Class Outline

by Hirohisa A. Tanaka — last modified Sep 10, 2016 12:56 PM — History

Date	Lecture	Textbook Reading	Homework
Tues 13 Sep	**Introduction**	**1**	**PS 1 assigned**
Thurs 15 Sep	Review of Special Relativity	2.1-2.2	
Tues 20 Sep	Quantum Mechanics	2.3	
Thurs 22 Sep	Golden Rule, decays, cross sections	3	
Tues 27 Sep	Relativistic wave equations	4.1-4.5	
Thurs 29 Sep	Solutions of the Dirac Equation	4.6-4.9	
Tues 4 Oct	Feynman rules for QED	5	PS1 due, PS2 assigned
Thurs 6 Oct	Electron-positron annihilation	6.1-6.4	
Tues 11 Oct	Electron-positron annihilation	6.5	
Thurs 13 Oct	Electron-proton scattering and form factors	7	
Tues 18 Oct	Deep inelastic scattering	8.1-8.3	
Thurs 20 Oct	Scaling	8.4-8.5	
Tues 25 Oct	Weak Interaction	11.1-11.4	PS2 due, PS3 assigned
Thurs 27 Oct	Weak interactions, continued	11.5-11.7	
Tues 1 Nov	Lepton universality and neutrino scattering	12.1-12.3	
Thurs 3 Nov	Midterm		
Tues 8 Nov	No Class		
Thurs 10 Nov	Weak interaction of quarks	14.1-14.3	
Tues 15 Nov	CP Violation	14.4	PS3 due PS4 assigned
Thurs 17 Nov	Electroweak Unification	15.1-15.2	
Tues 22 Nov	No class		
Thurs 24 Nov	More on electroweak unification	15.3-15.4	
Tues 29 Nov	Electroweak physics	16.1-16.2	
Thurs 1 Dec	Local gauge invariance and Lagrangians	17.1-17.3	PS4 due
Tues 6 Dec	Higgs mechanism	17.4-17.5	

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

STUDY GROUP

- I’ve entered this class for a “Registered Study Group”

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HIGH ENERGY PHYSICS

- “Particle physics”
    - “Elementary particles”
    - “fundamental interactions/particles”
- What does “high energy” have to do with fundamental particles/interactions?

THE STANDARD MODEL

particles

ν_e ν_μ ν_τ no charge, no color

e^- μ^- τ^- -1 charge, no color

u c t +2/3 charge, color

d s b -1/3 charge, color

antiparticles

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

Z $W^\pm$ Mediators of EM interaction

γ Mediator of EM interaction

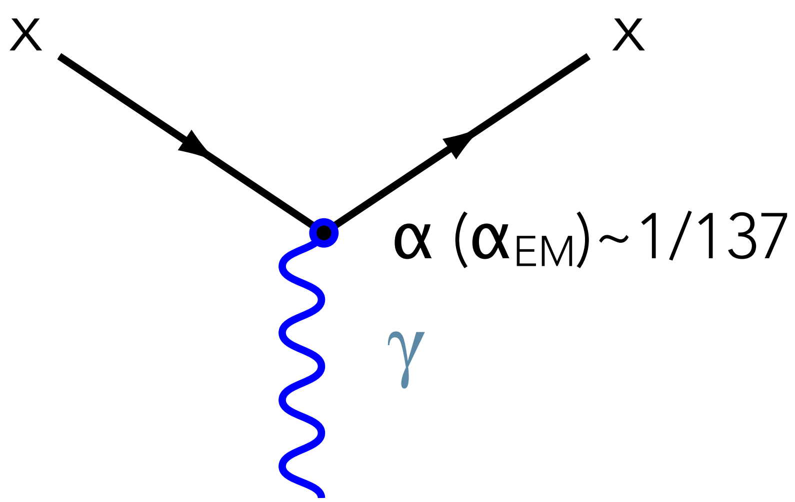
g Mediator of strong interaction

H agent of spontaneous symmetry breaking

INTERACTIONS

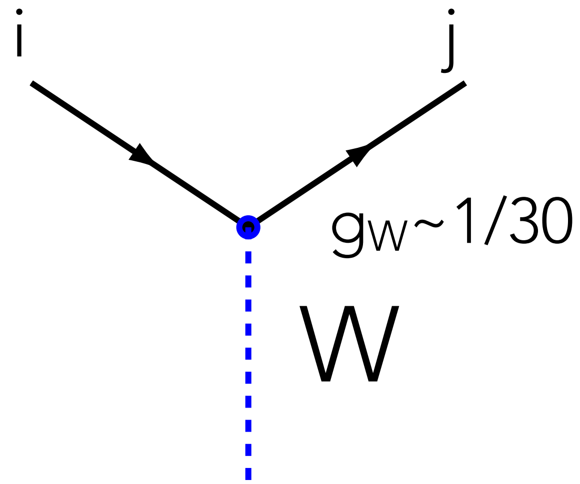
- Fundamental building block of an interaction is the “vertex”

electromagnetism
“quantum electrodynamics”



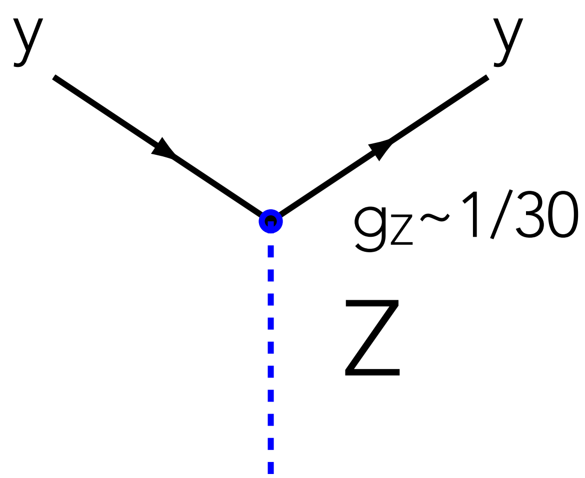
x is any charged particle

weak charged current



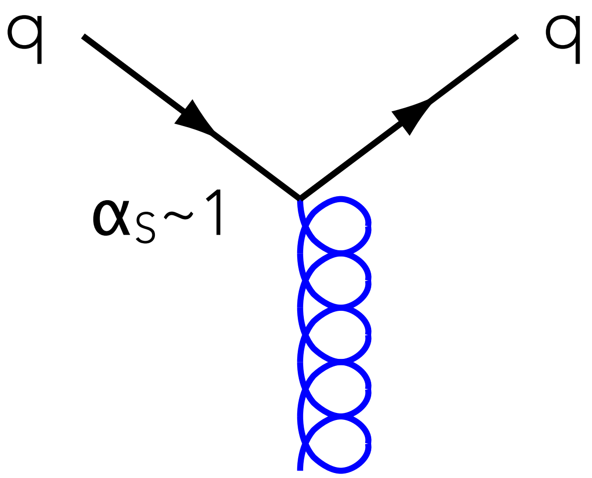
i:+2/3 quark, j: -1/3 quark
or
i: ν_l, j: l^-

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”
  - 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

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

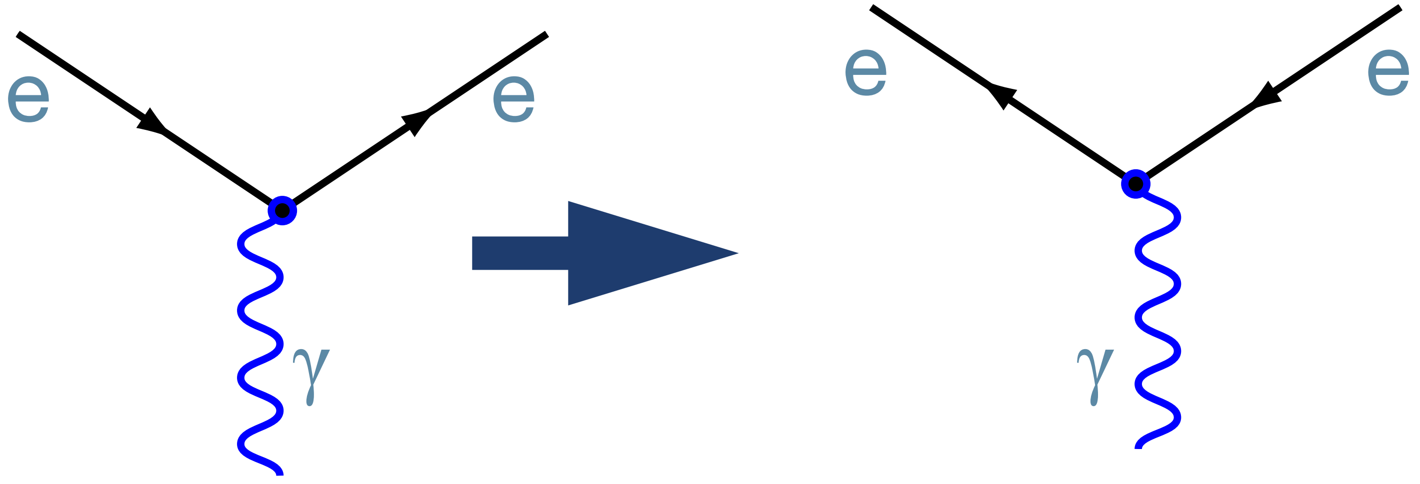
γ Mediator of EM interaction

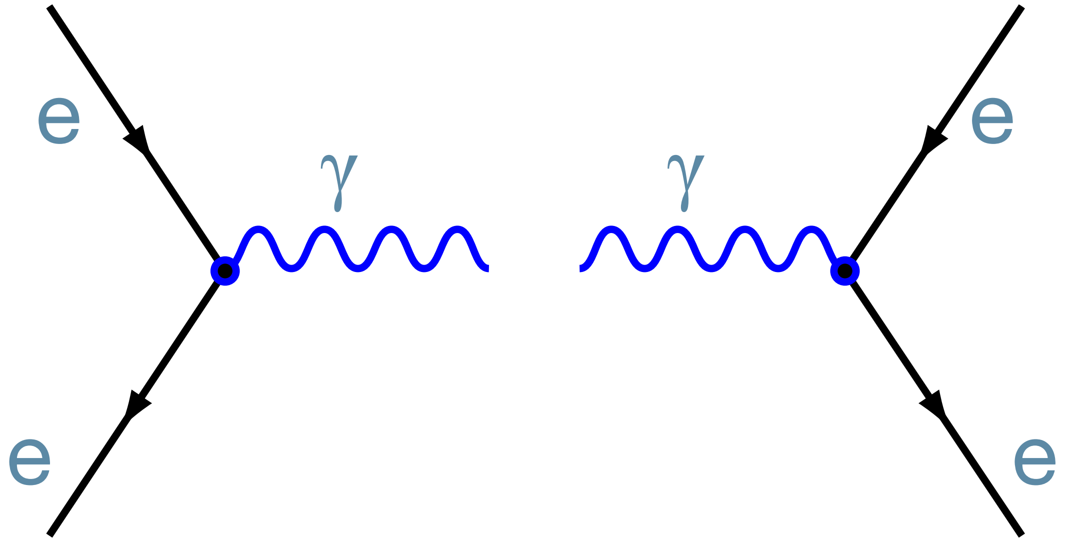
g Mediator of strong interaction

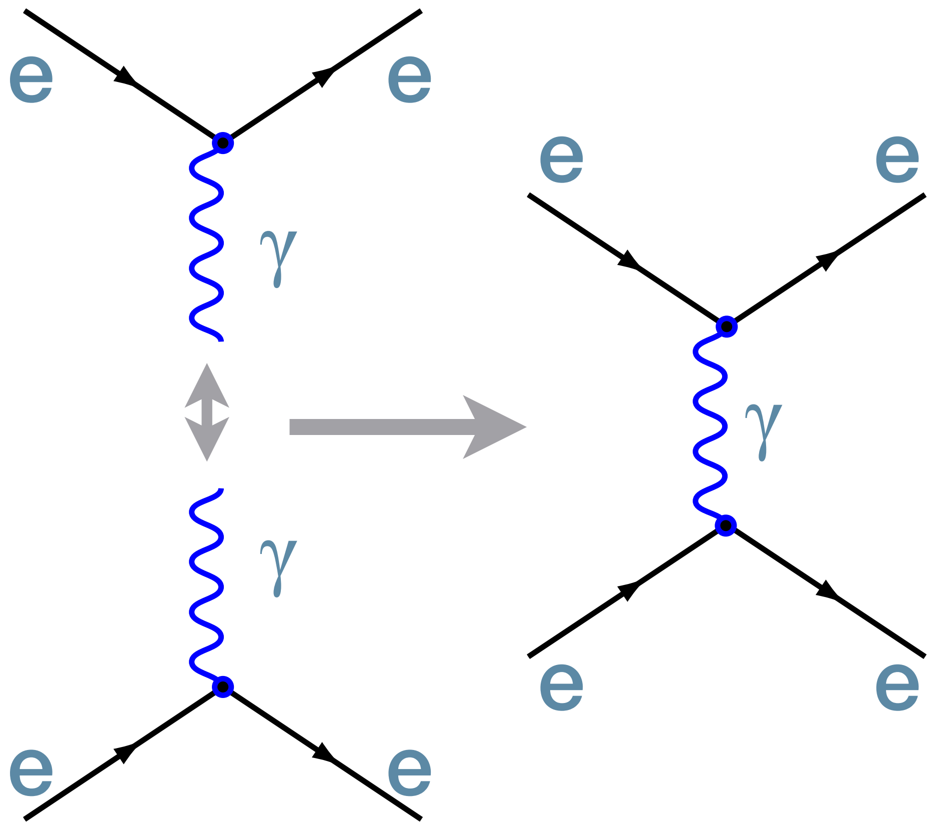
H agent of spontaneous
symmetry breaking

BUILDING UP INTERACTIONS

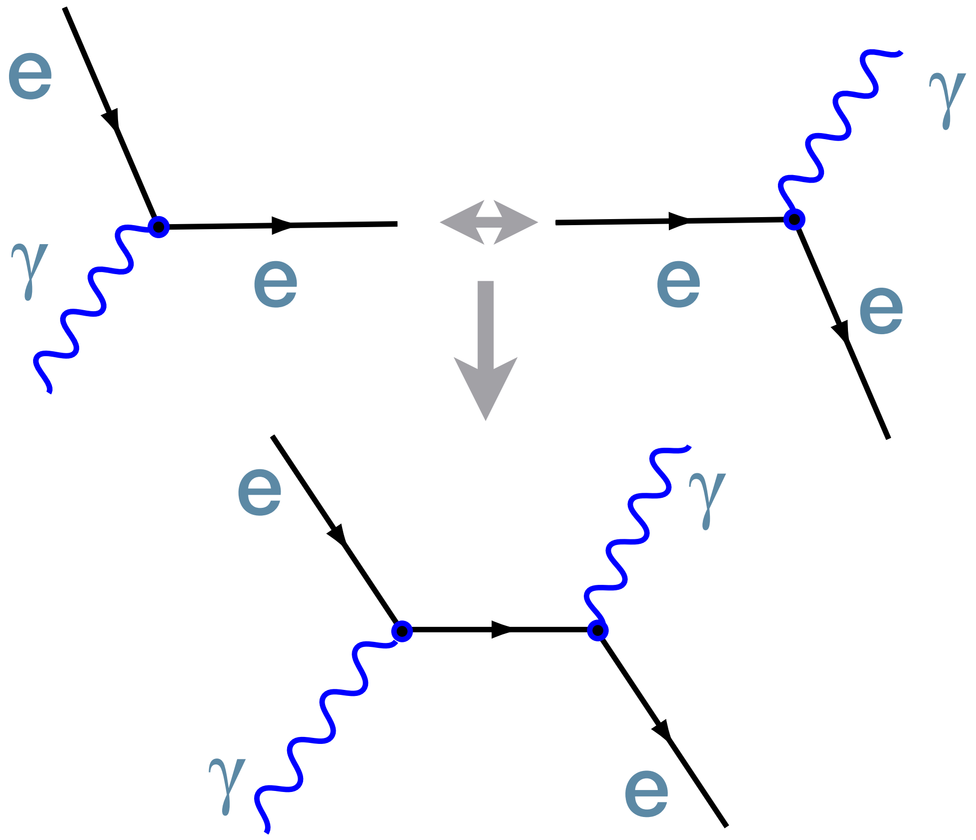
- Vertices can be rotated and connected by common particles ("propagator")







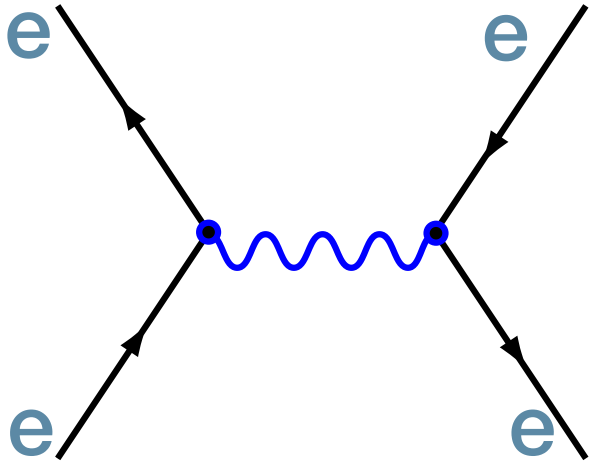
$e^- + e^- \rightarrow e^- + e^-$

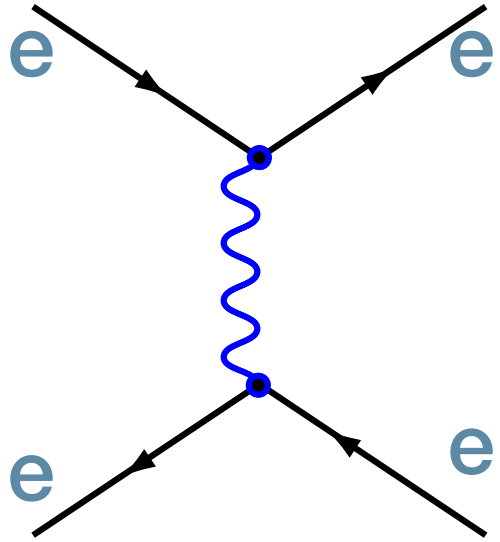


$e^- + \gamma \rightarrow e^- + \gamma$

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

MULTIPLE DIAGRAMS:



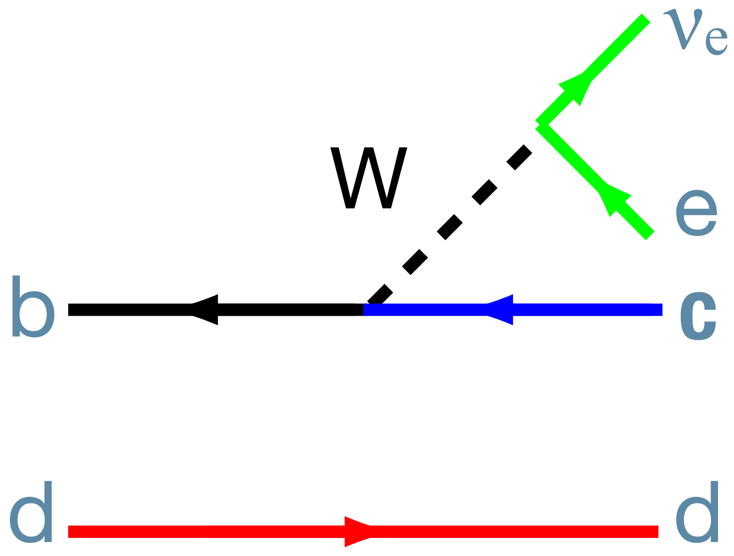


- In fact, any allowed process has an infinite number of possible diagrams
- Recall the coupling constant:
  - diagrams with more vertices have vertex factors
  - if this is small, diagrams with more vertices contribute less
  - we do calculation at “order N” where N is the number of vertices.
    -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

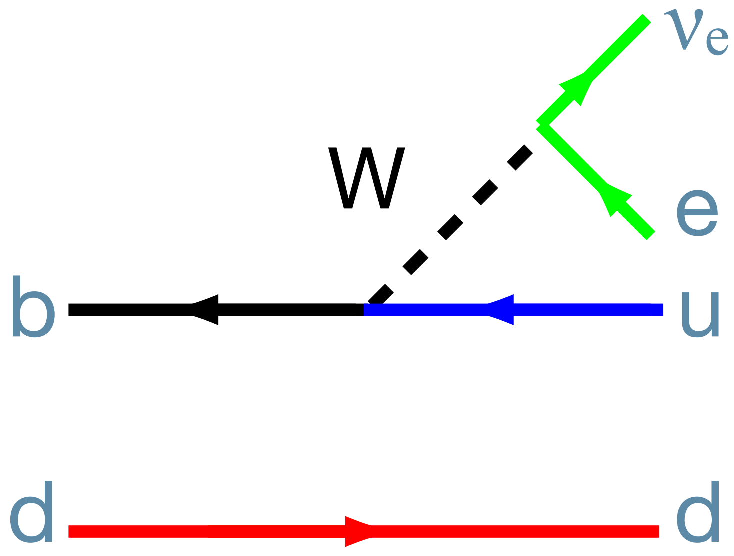
HADRONS

- 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

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

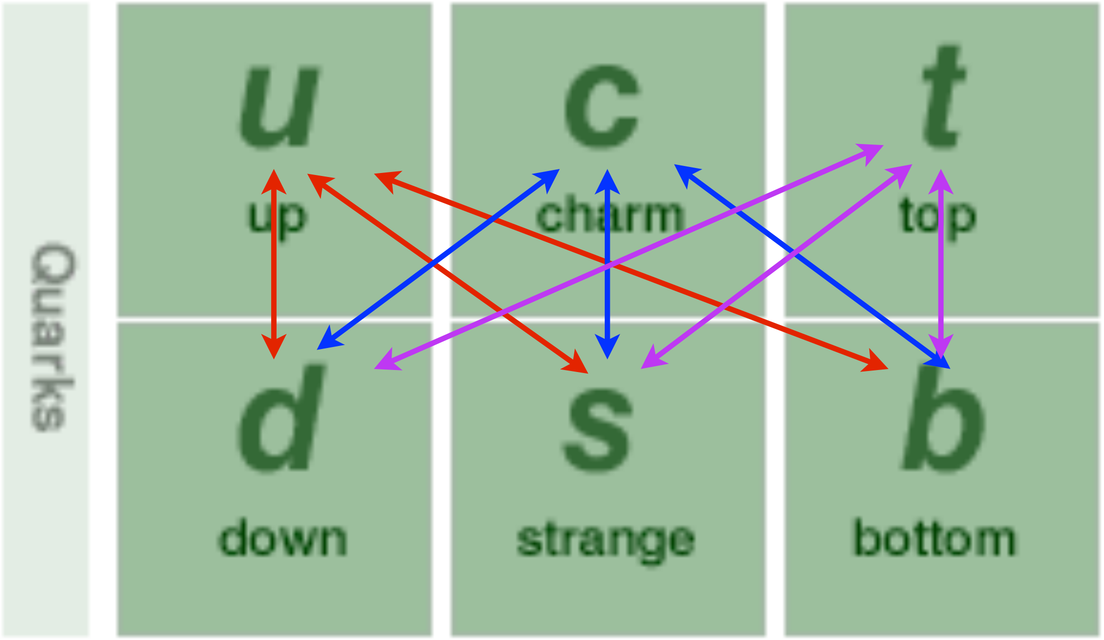


$$B^0 \to \rho^- + e^+ + \nu_e$$

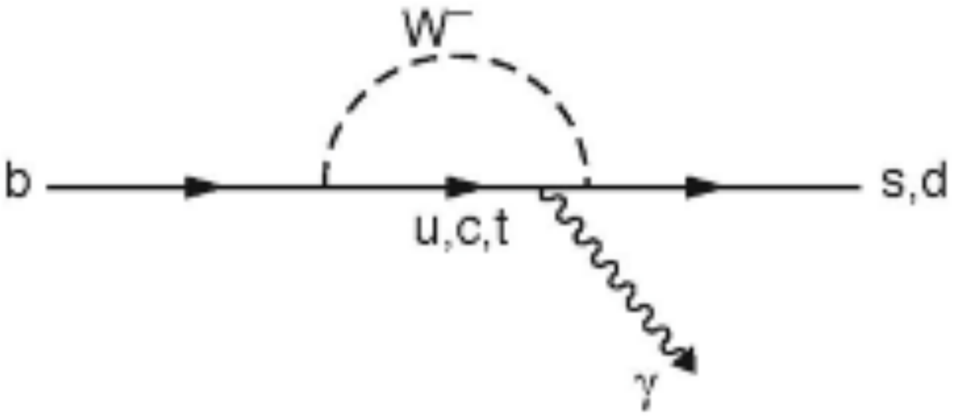


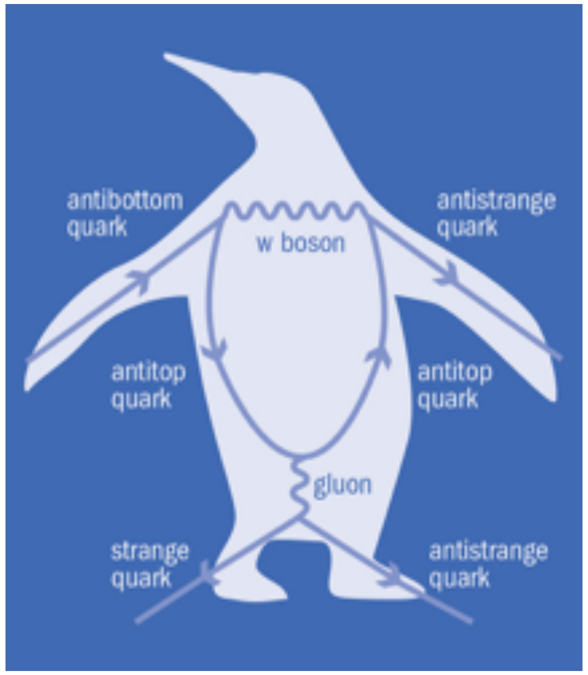
WEAK CHARGED CURRENT

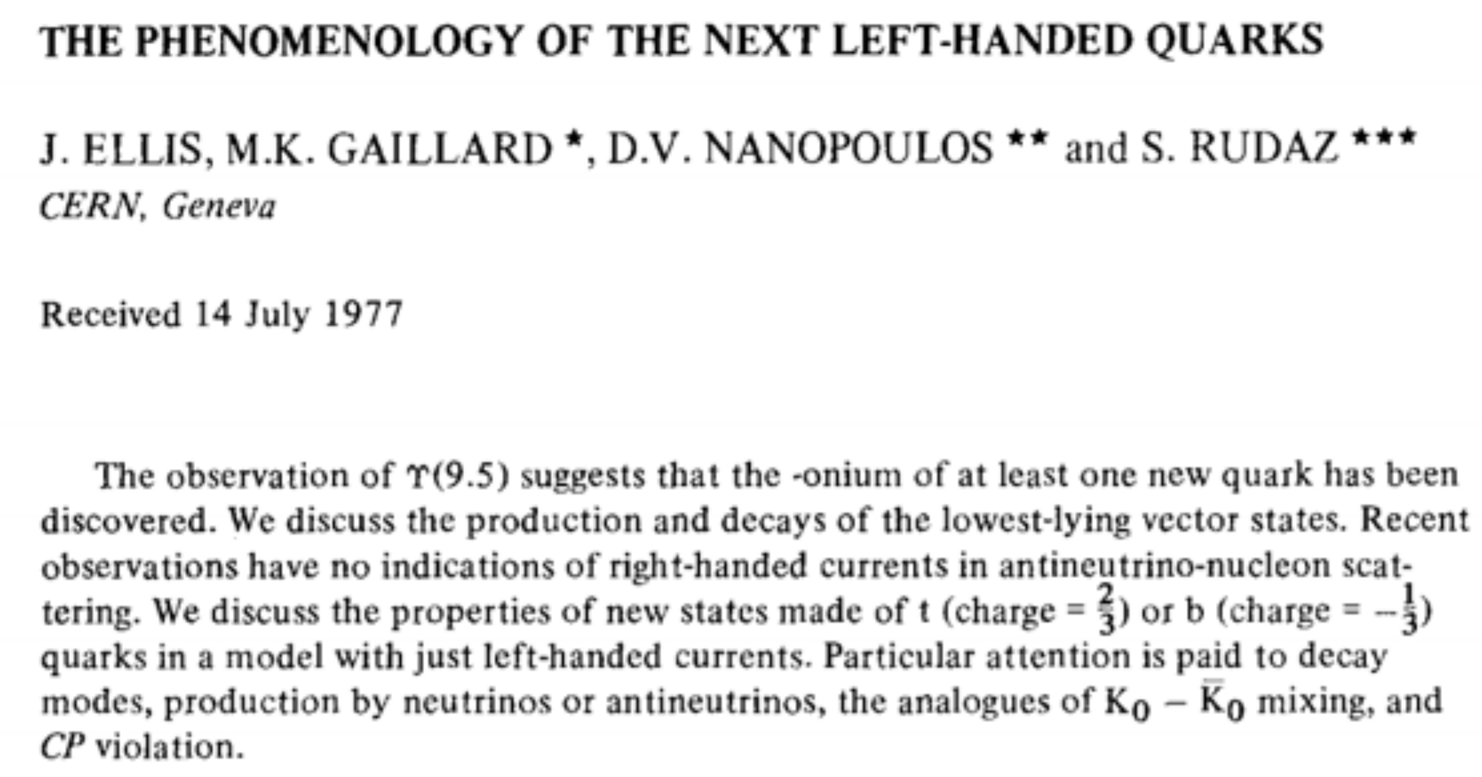
- This is probably the most complicated process
  - it is the only one that can change the identity of a particle
- For leptons (neutrinos) it is relatively easy:
  - change a neutrino into its corresponding lepton
  - $\nu_l \Leftrightarrow l^-$
- For quarks, any transition from “top” to bottom row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



THE PENGUIN DIAGRAM





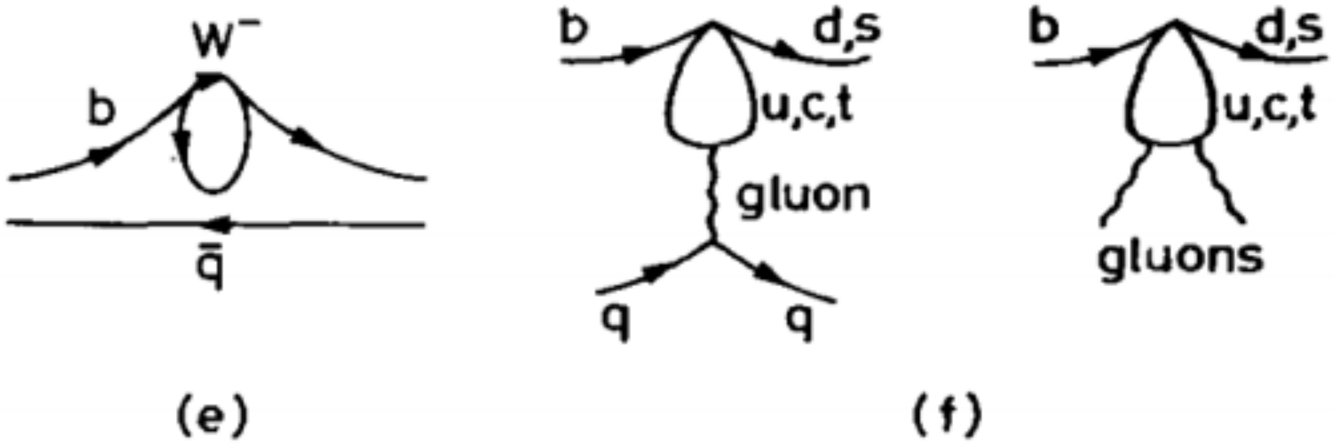


THE PHENOMENOLOGY OF THE NEXT LEFT-HANDED QUARKS

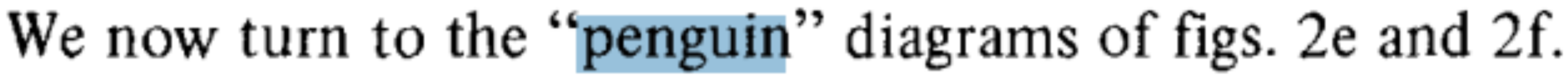
J. ELLIS, M.K. GAILLARD *, D.V. NANOPOULOS ** and S. RUDAZ ***
CERN, Geneva

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.



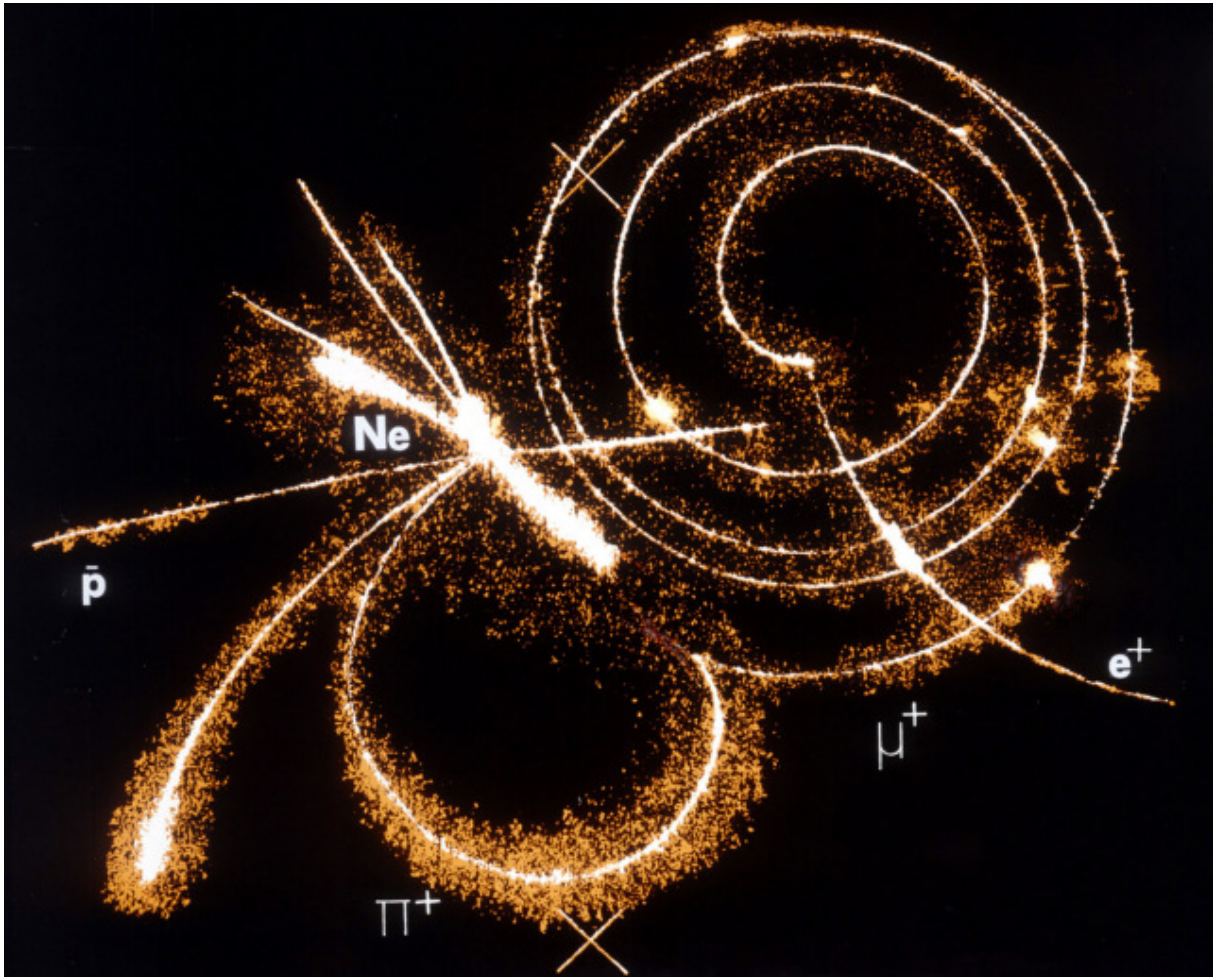
(e) (f)

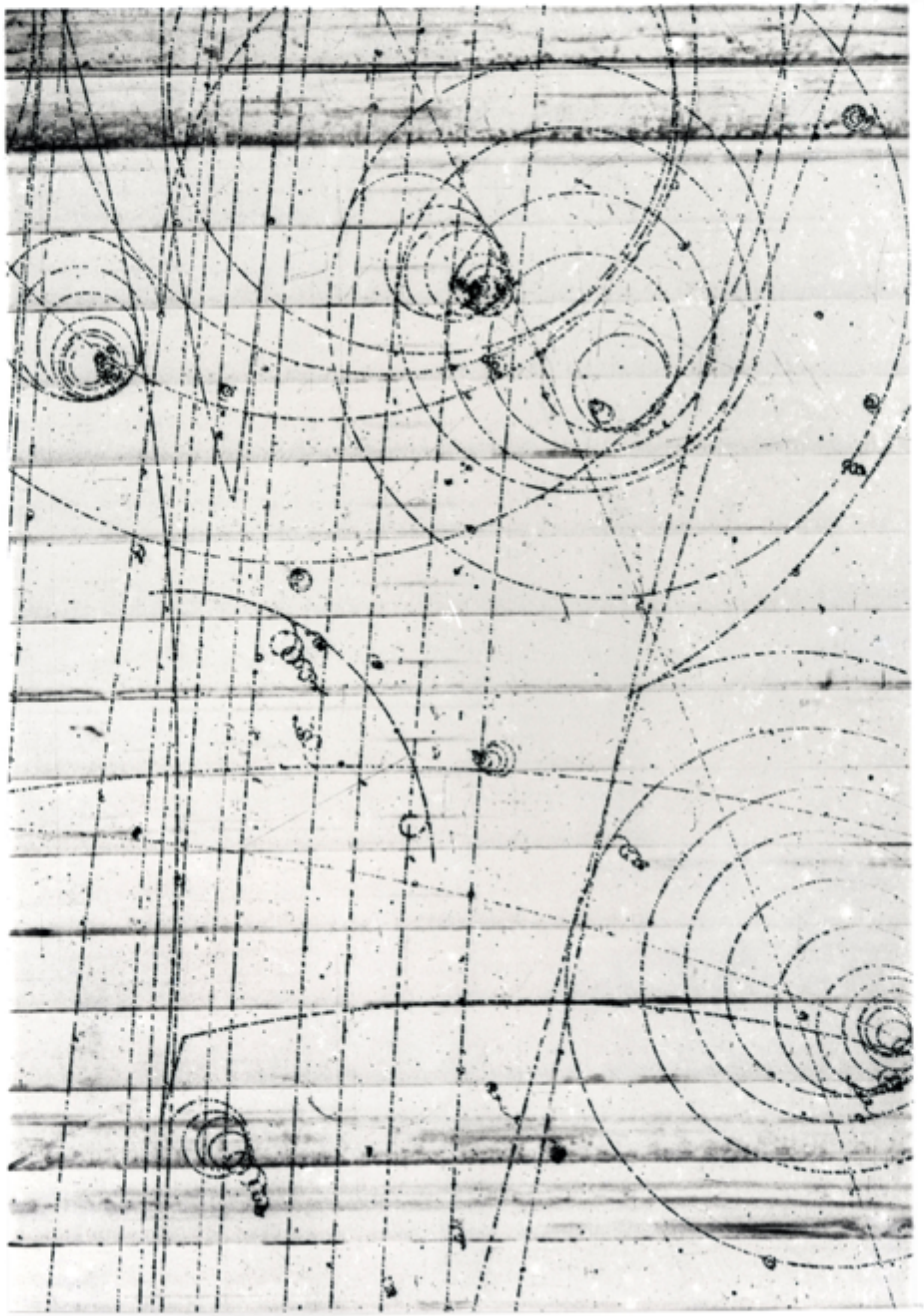


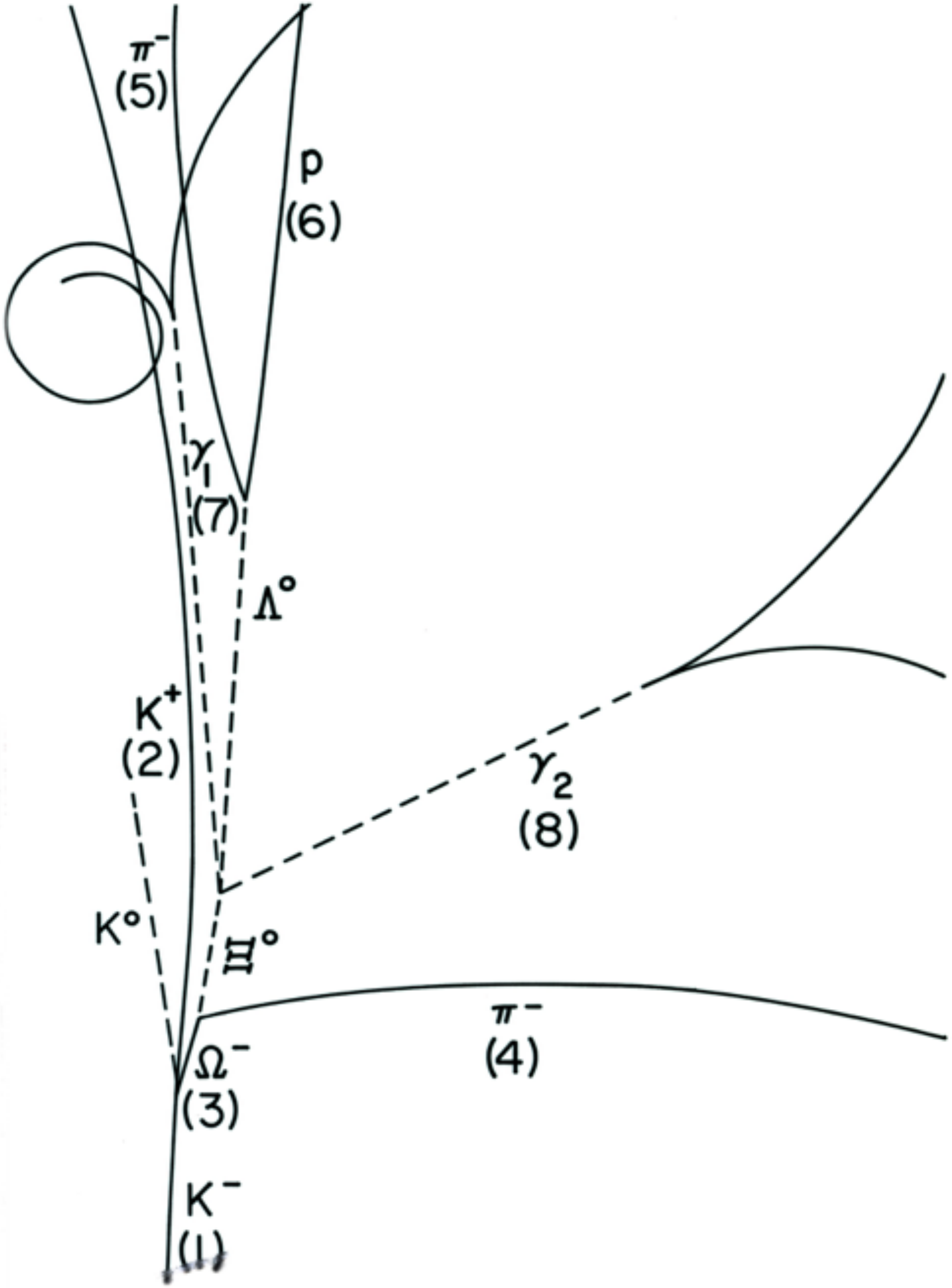
We now turn to the "penguin" diagrams of figs. 2e and 2f.

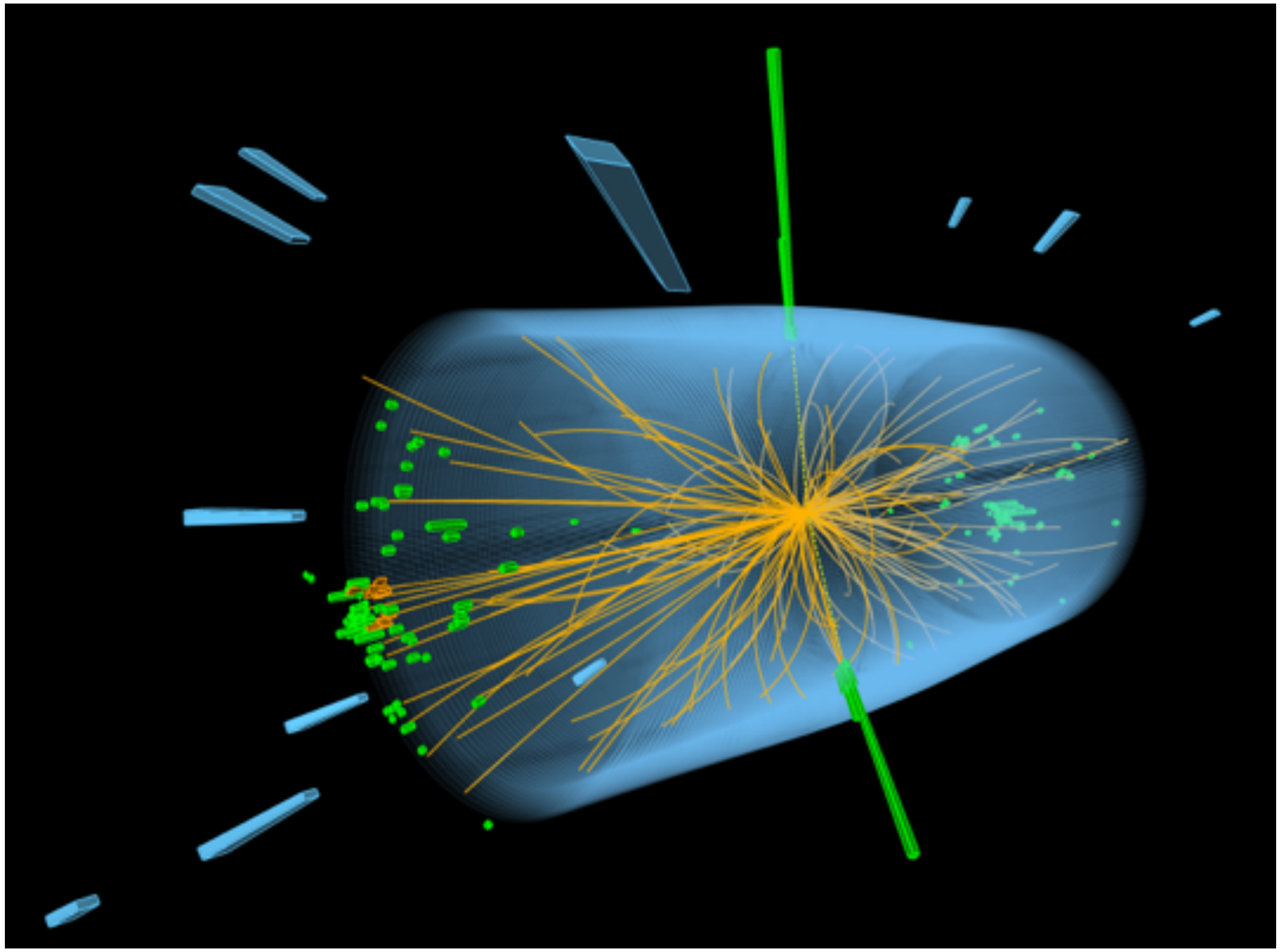
STUDYING PARTICLES

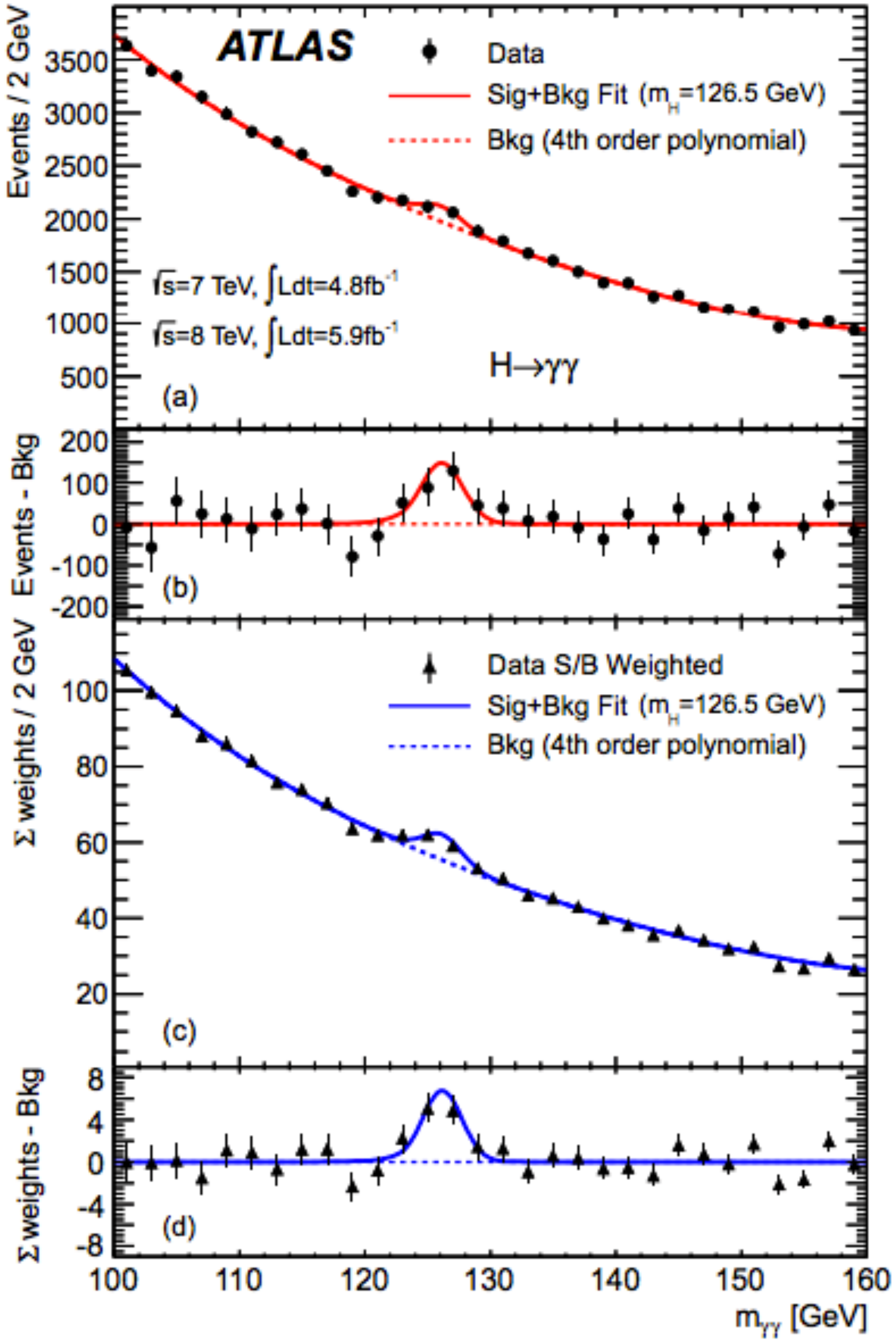
- Decays:
  - disintegration of particles into other particles
  - rate of decay, type of particles emitted, and kinematics of decay can tell us about underlying mechanism.
  - energy/momentum conservation can tell us its mass
- Scattering
  - collision of particles
  - outgoing particles may or may 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

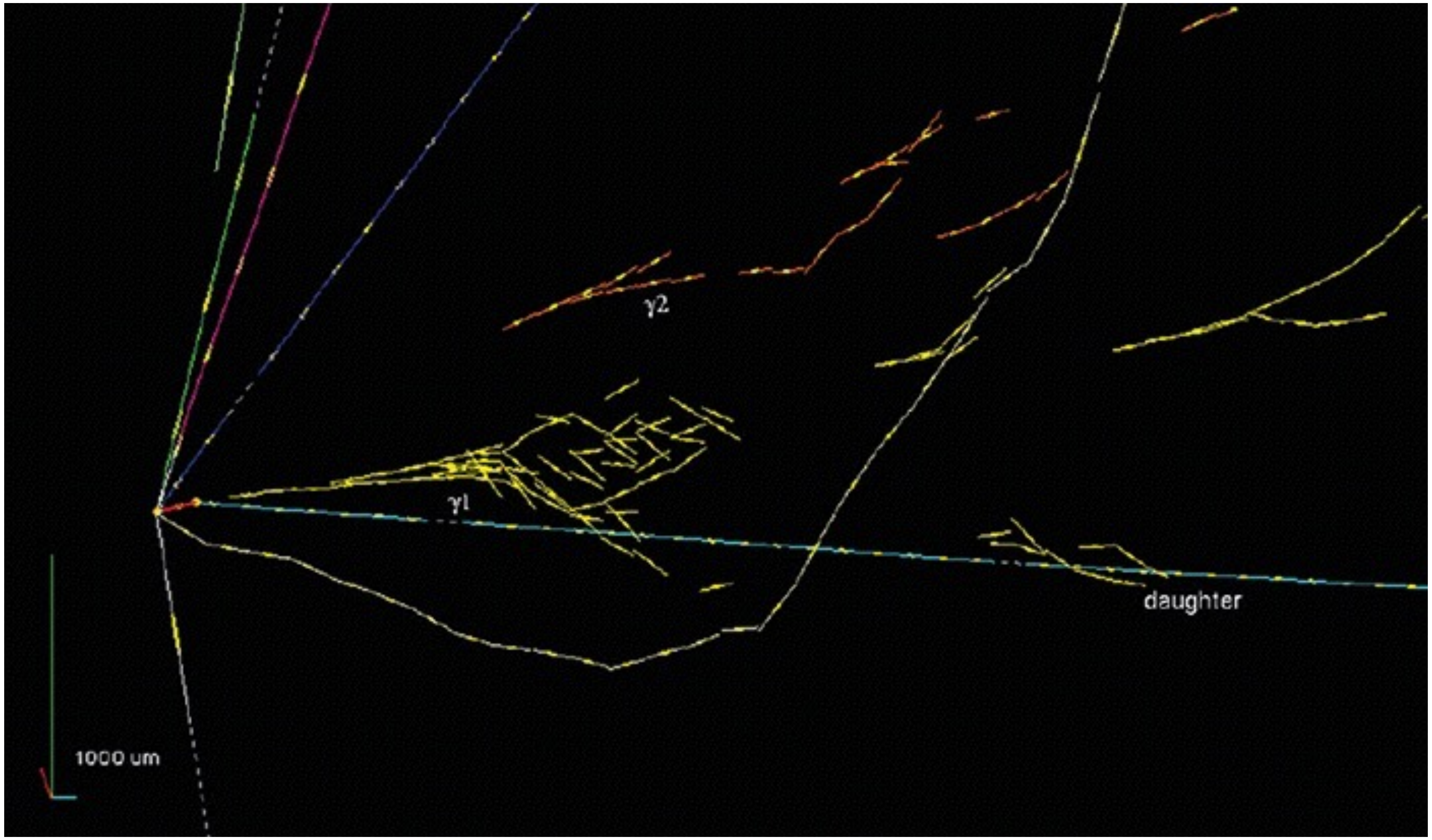

Ne
p̄
e+
μ+
π+

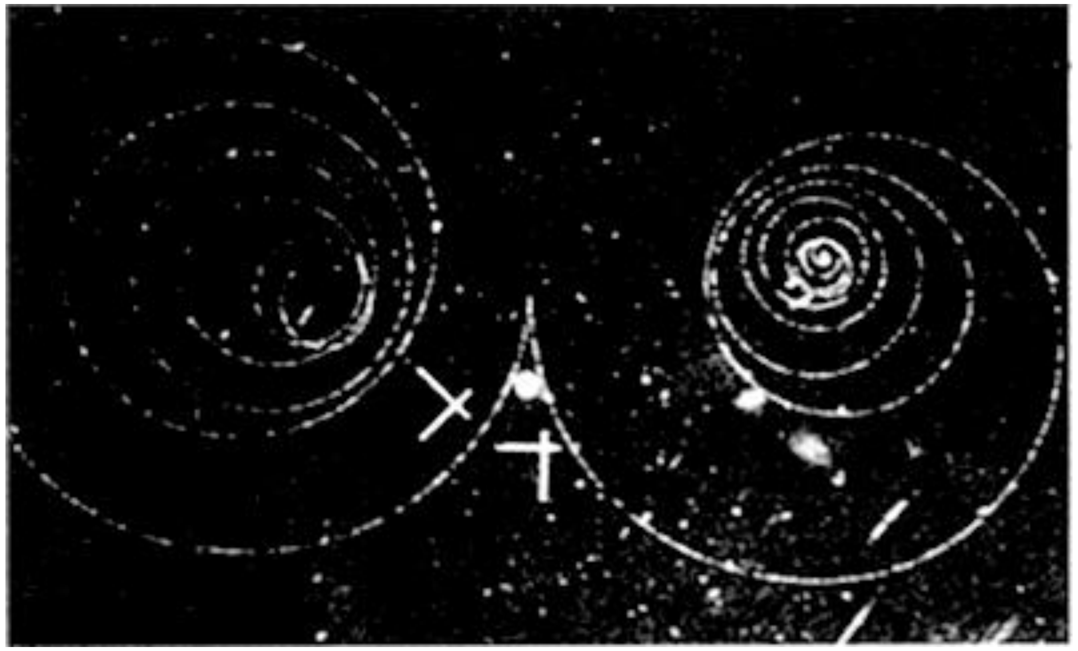



π⁻
(5)
p
(6)
γ₁
(7)
Λ°
K⁺
(2)
γ₂
(8)
K°
Ξ°
π⁻
(4)
Ω⁻
(3)
K⁻
(1)



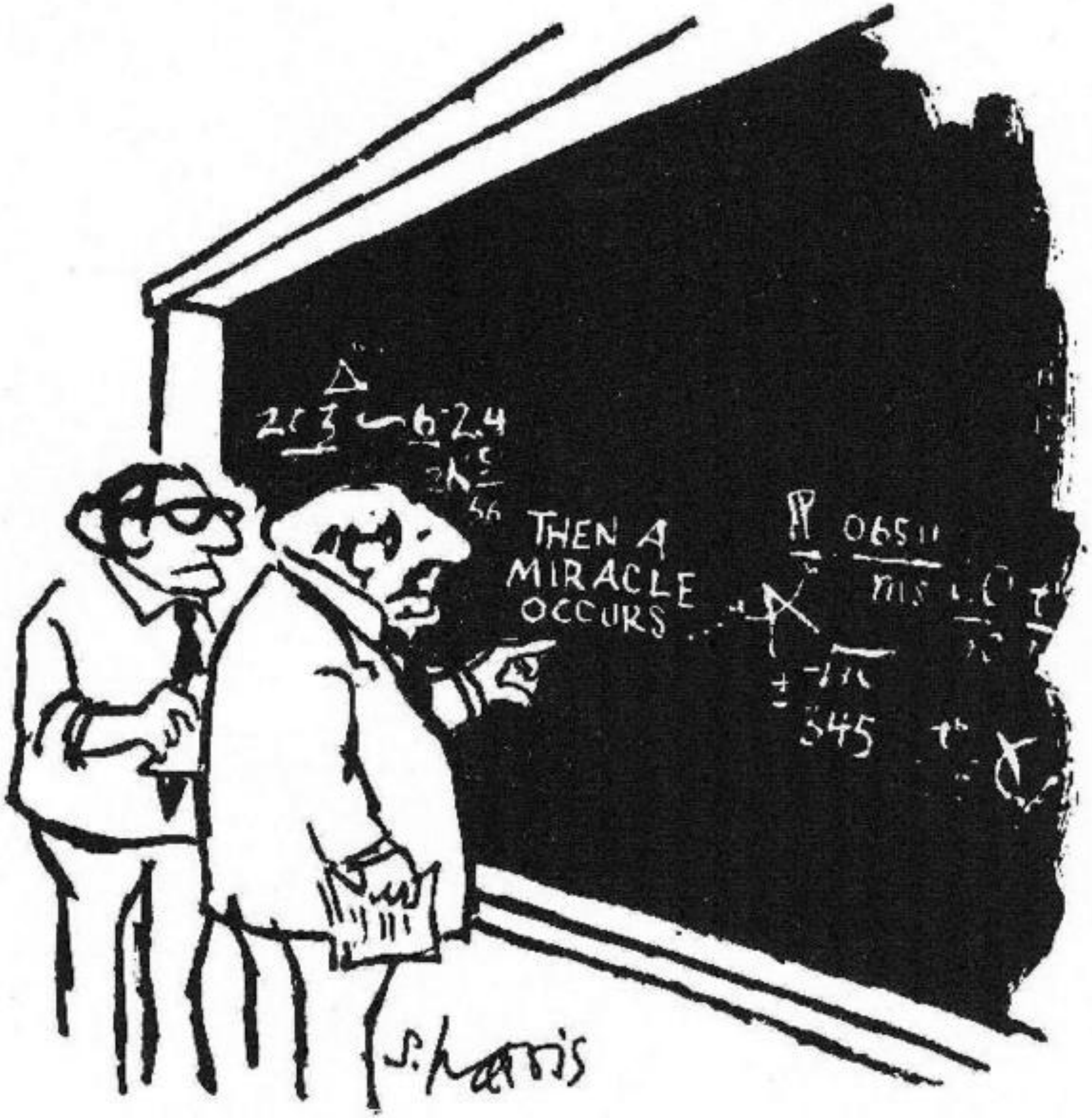

ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
$H\rightarrow\gamma\gamma$
Events / 2 GeV
500
1000
1500
2000
2500
3000
3500
(a)
Events - Bkg
200
100
0
-100
-200
(b)
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Σ weights / 2 GeV
20
40
60
80
100
(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."

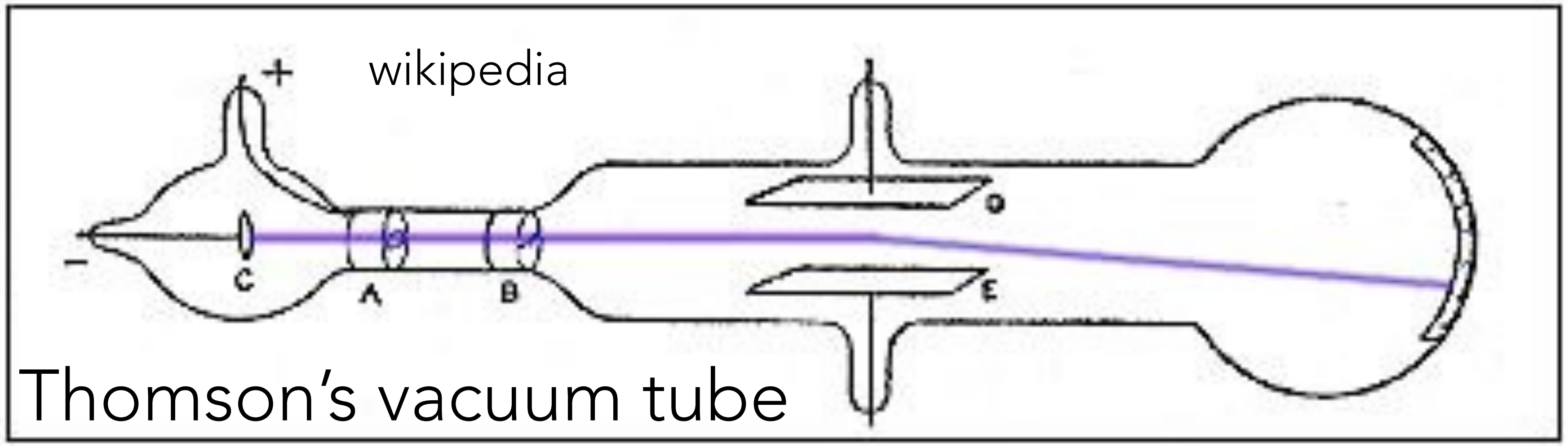
NOTE ON UNITS

- 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

"First" elementary particle



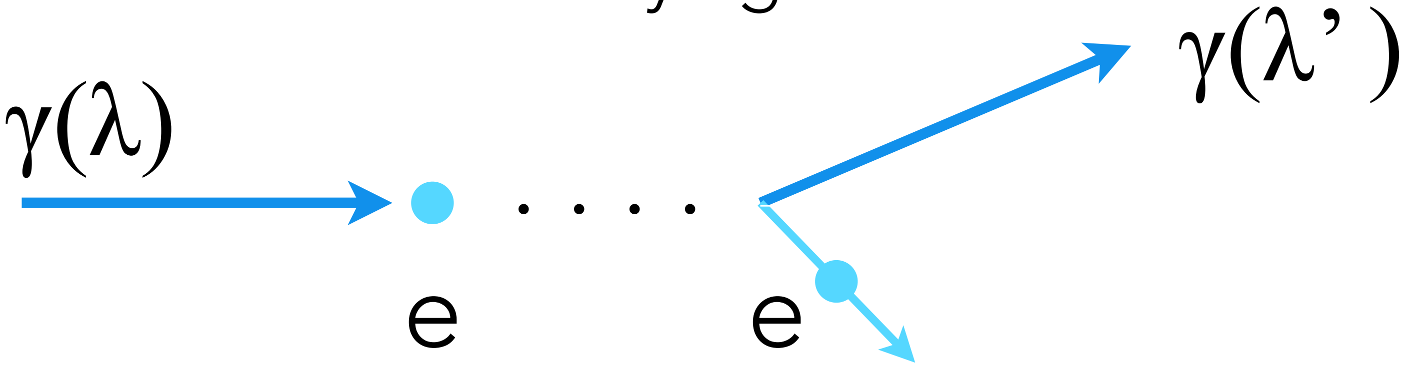
wikipedia

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

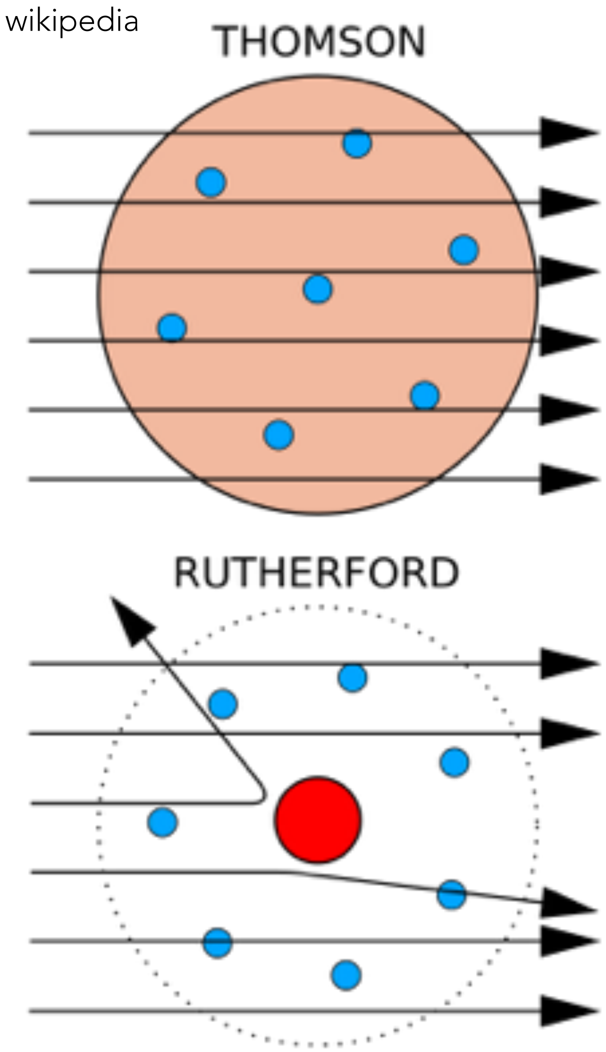
PARTICLE VERSUS WAVE

- 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



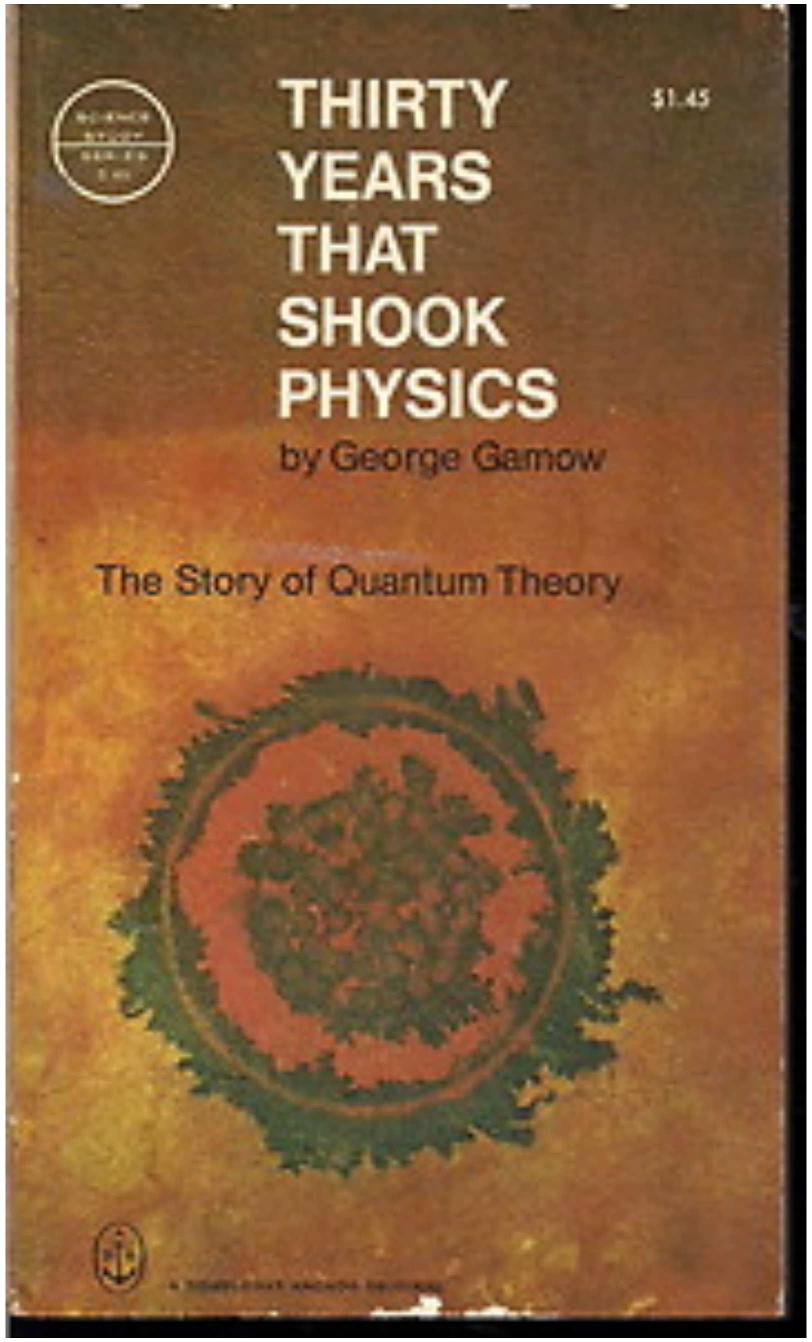
  - Relation between λ, λ' and θ is precisely that of a particle with mass = 0 and energy hc/λ (hc/λ') striking the electron

INTO THE ATOM



- "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:
  - $\alpha + {}^{12}N \rightarrow {}^{17}O + {}^{1}H$ (=p)
  - first indication that protons are contained within the nucleus (and = hydrogen nuclei)
  - Rutherford also postulated neutrons . . .

PHYSICS IN THE 1930S



$1.45

THIRTY YEARS THAT SHOOK PHYSICS

by George Gamow

The Story of Quantum Theory

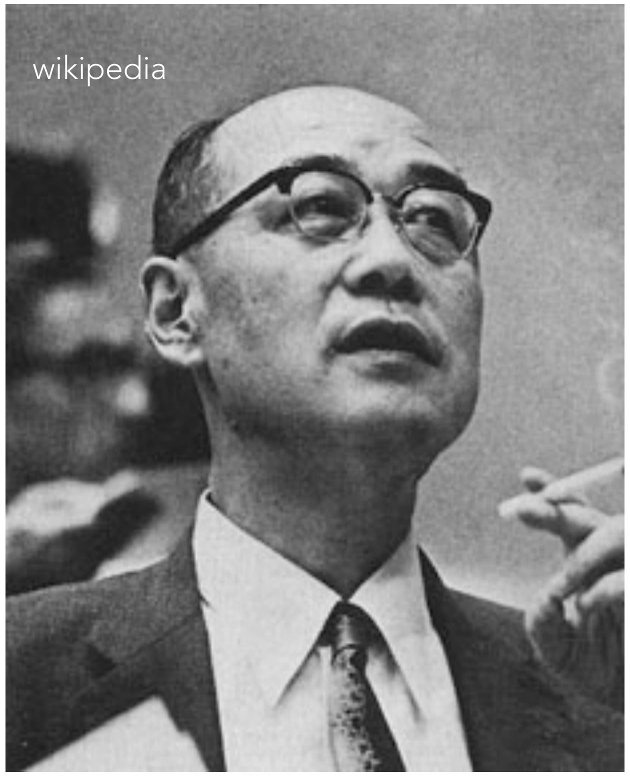
- In the tumultuous era that gave birth to:
  - special/general relativity
  - quantum mechanics

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

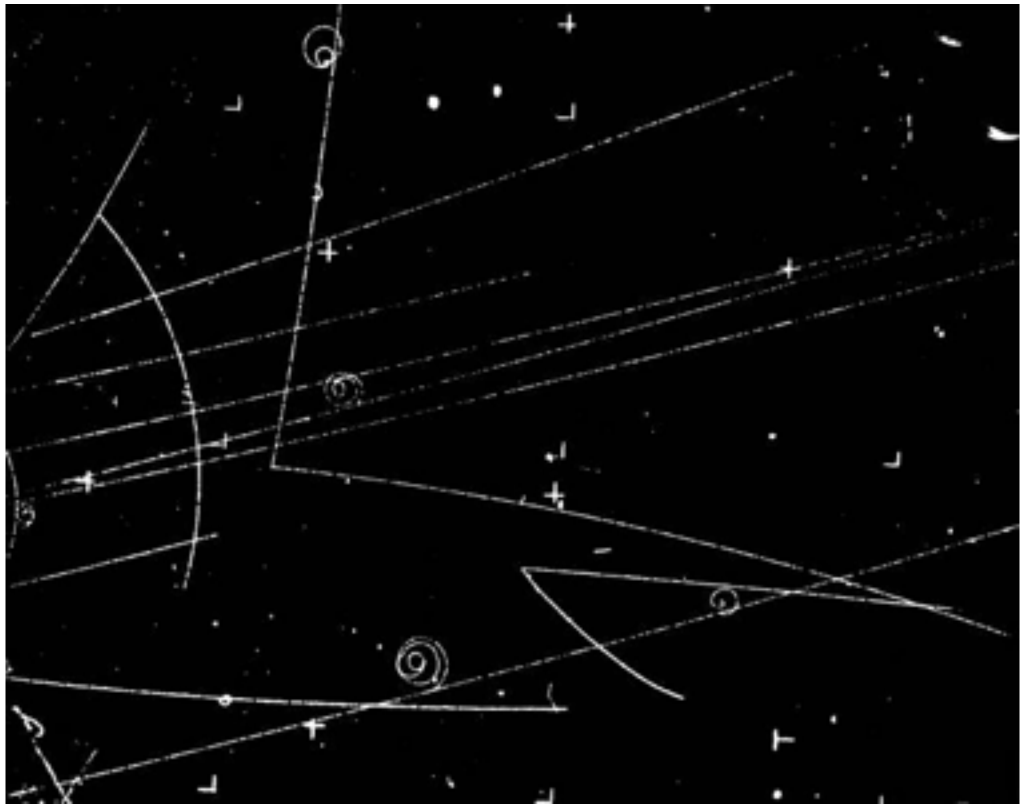
$\boxed{p}$ $\boxed{e^-}$ $\boxed{\gamma}$

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

The Yukawa Hypothesis


wikipedia

- 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

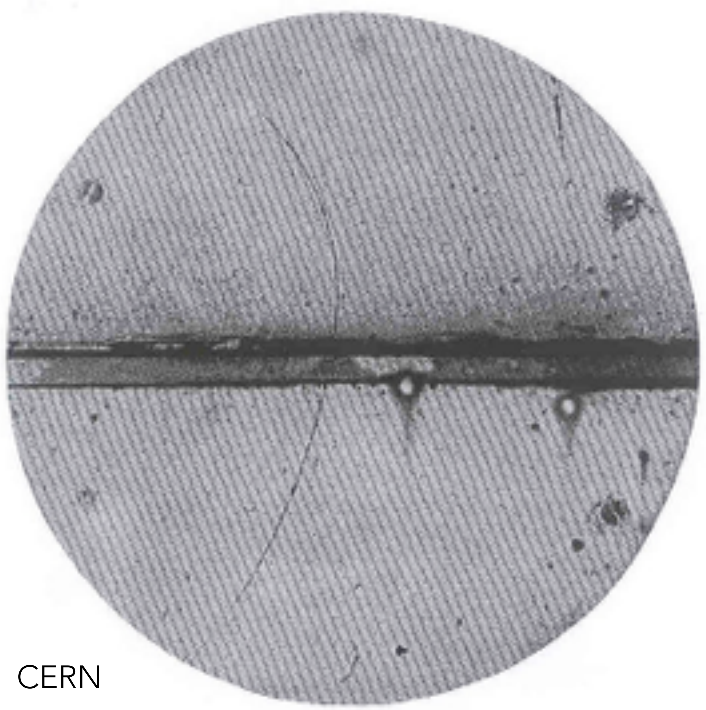

wikipedia

- 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

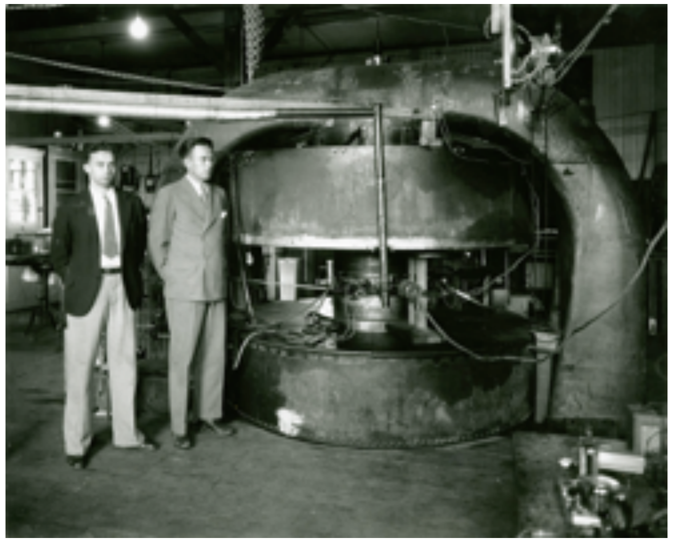
Such a particle is actually observed

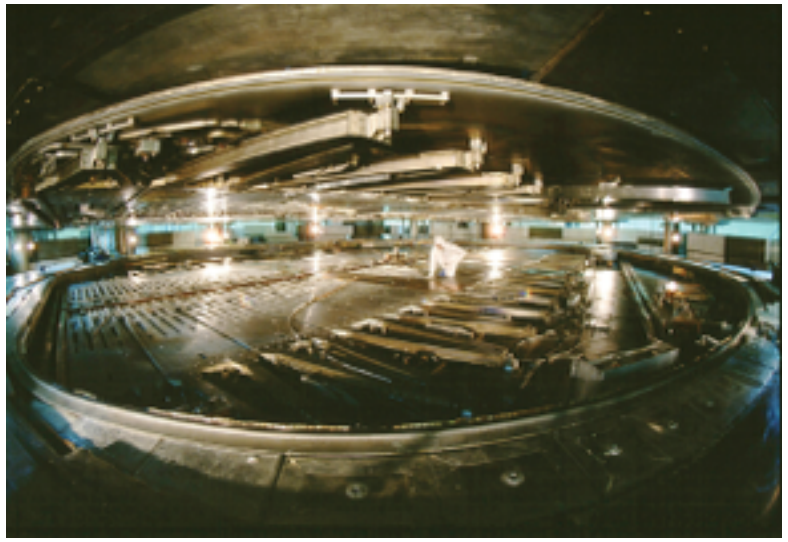
- just like the electron, but positively charged
- in due course, find every particle has an antiparticle
- (In some cases, e.g. γ, it is itself)

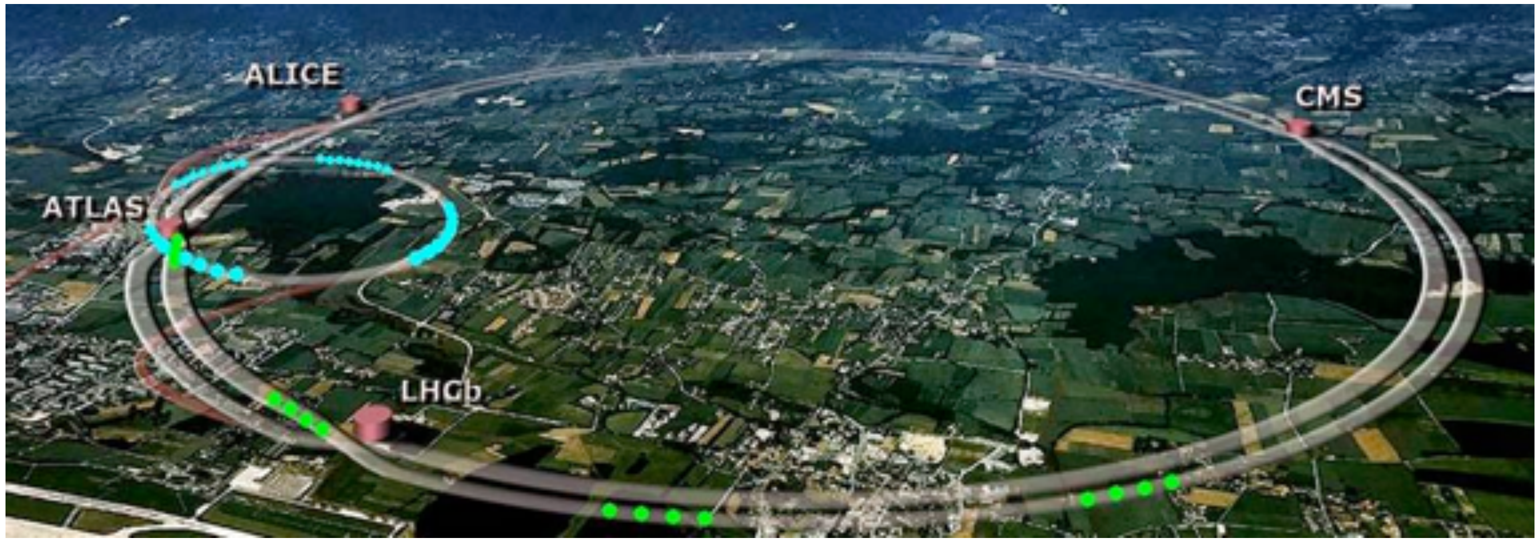
antiparticles are denoted by a "bar"


CERN

ACCELERATORS







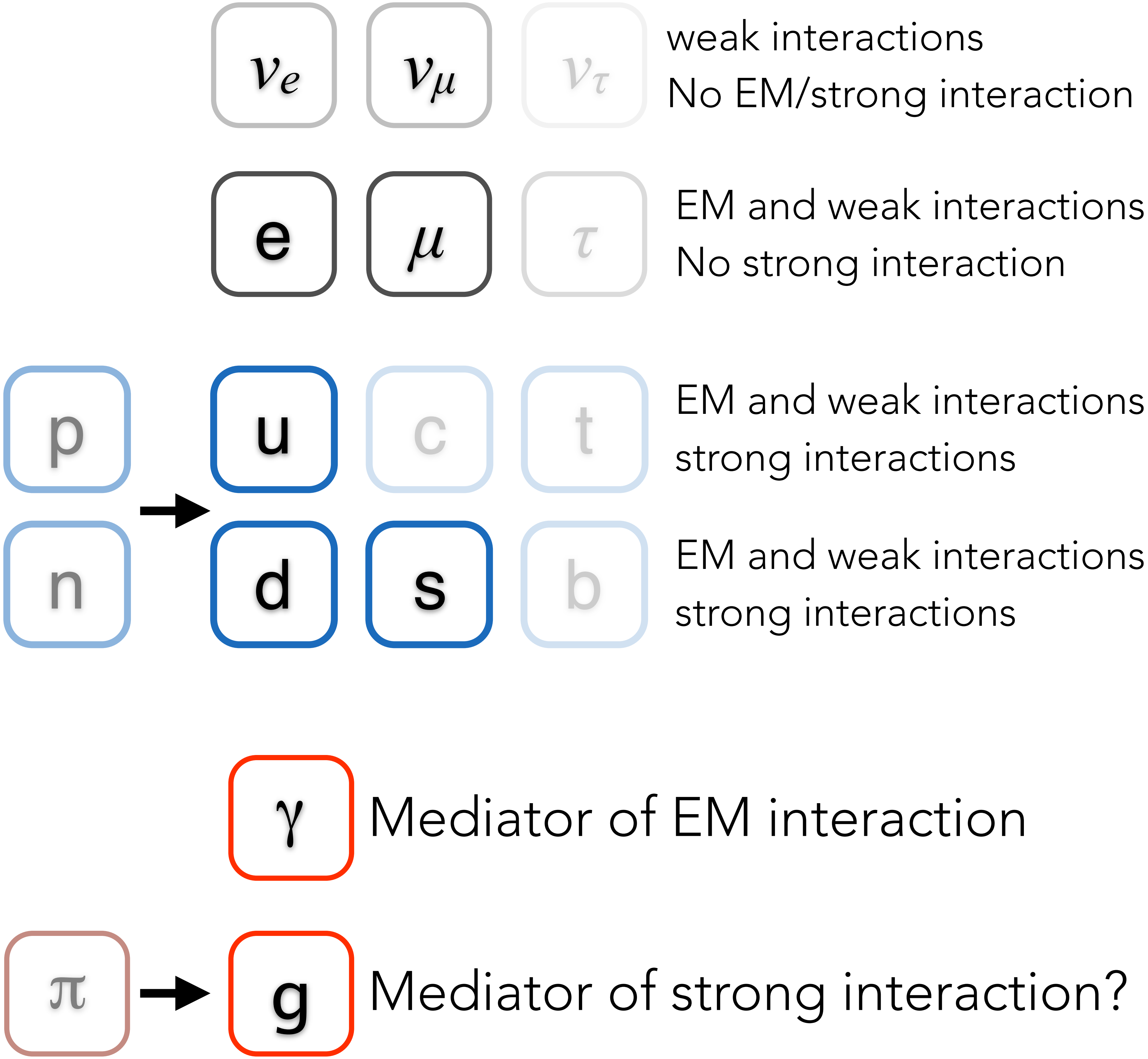
HADRON ZOO

- 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^-
    - 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

“strange particles”

- 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 u c t

EM and weak interactions
strong interactions

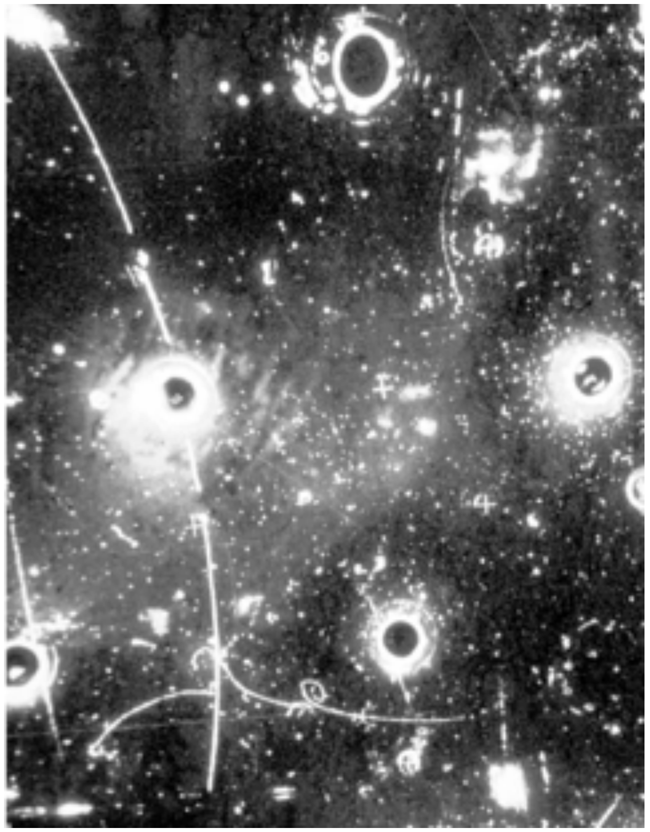
n → d s b

EM and weak interactions
strong interactions

γ Mediator of EM interaction

π → g Mediator of strong interaction?

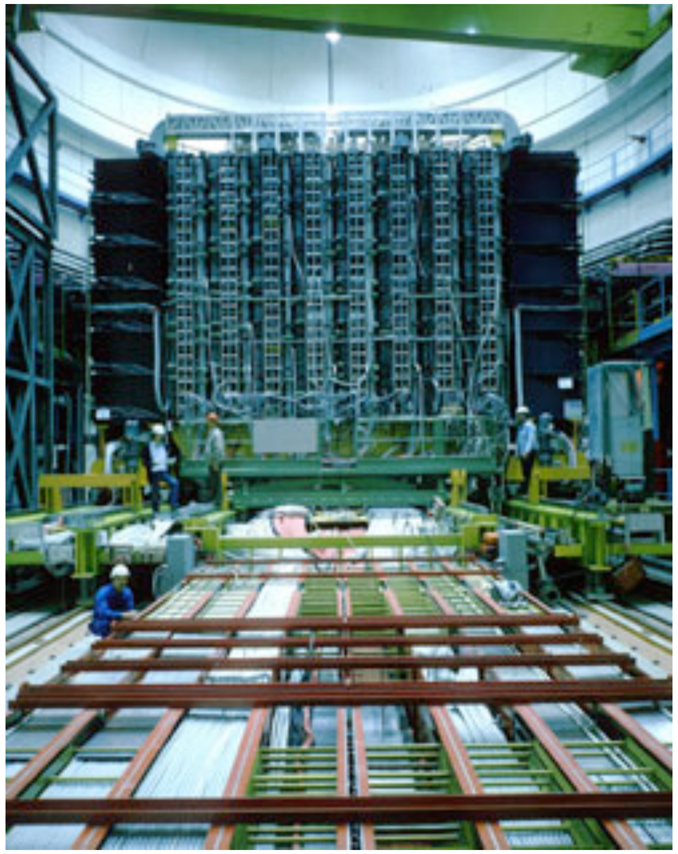
DISCOVERY OF NC, W, Z

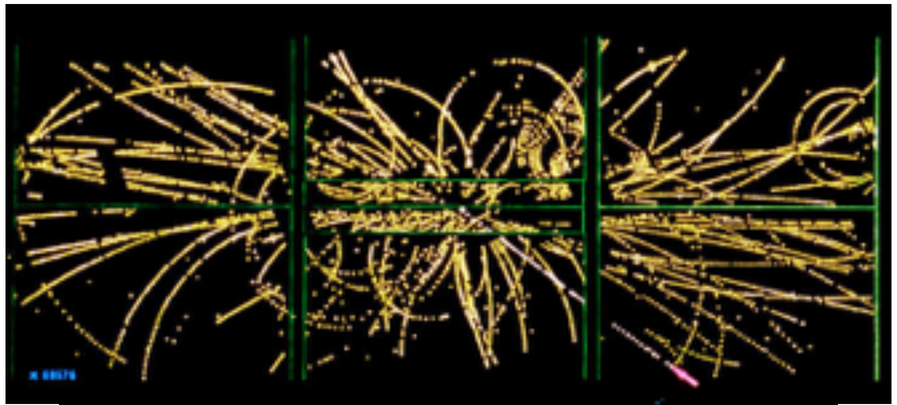


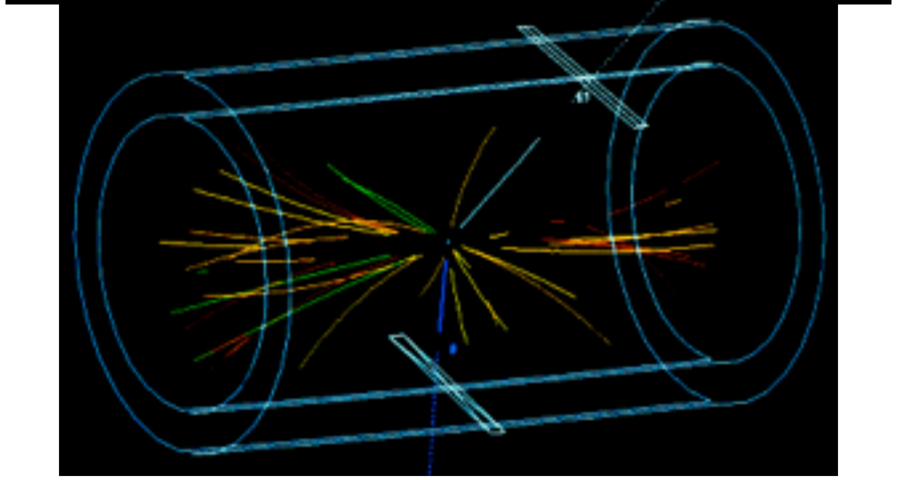
- NC reaction of neutrinos in bubble chamber

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

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





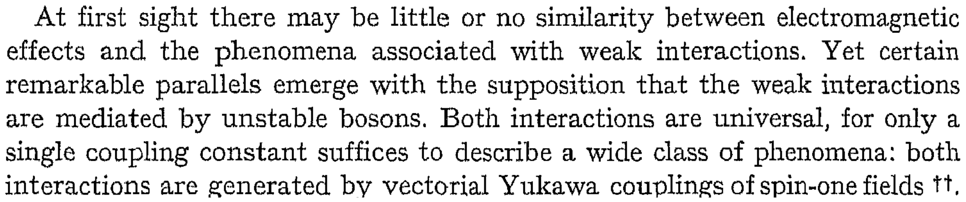


W, Z are extremely massive

W ~ 80 GeV/c^2

Z ~ 91 GeV/c^2

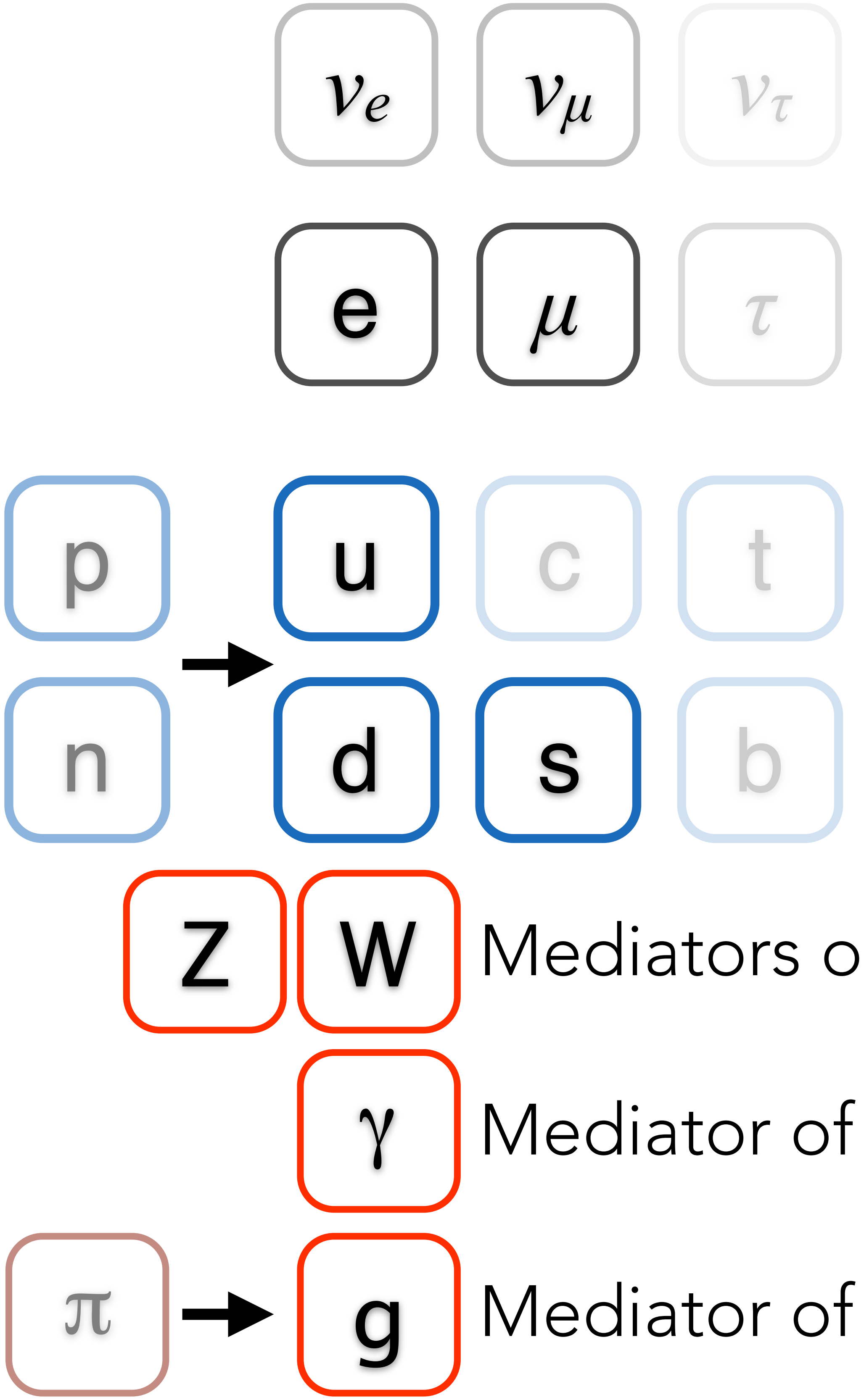
See later that this is responsible for the "weakness" of the weak interaction



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



weak interactions
No EM/strong interaction

EM and weak interactions
No strong interaction

EM and weak interactions
strong interactions

EM and weak interactions
strong interactions

Mediators of EM interaction

Mediator of EM interaction

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, $m_p = 938.272\ MeV/c^2 = 1.672 \times 10^{-27}$ 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

NEXT TIME

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