2014 Summer School on Elementary Particle Physics
Petnica Summer Institute

Particle Physics

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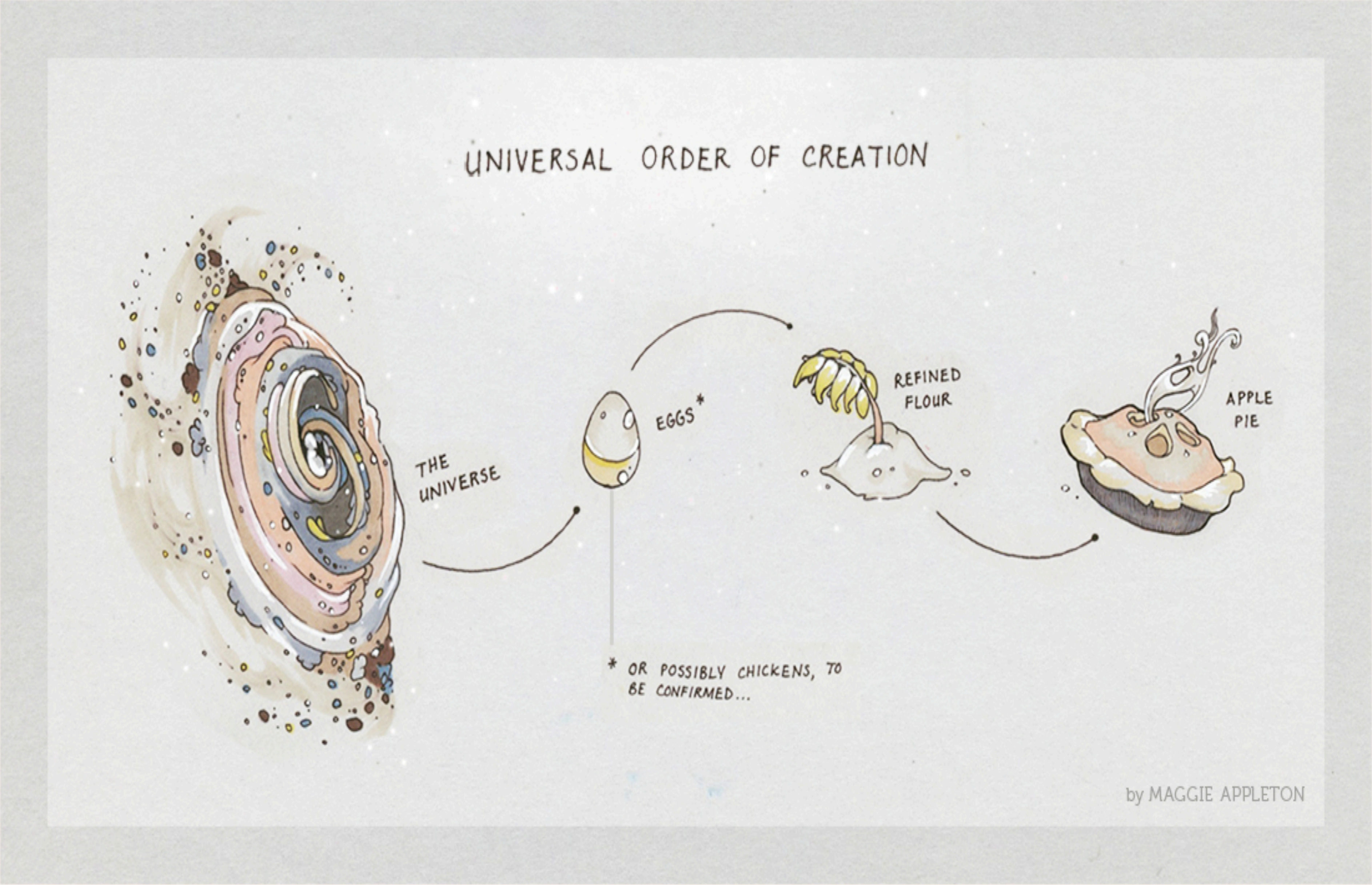


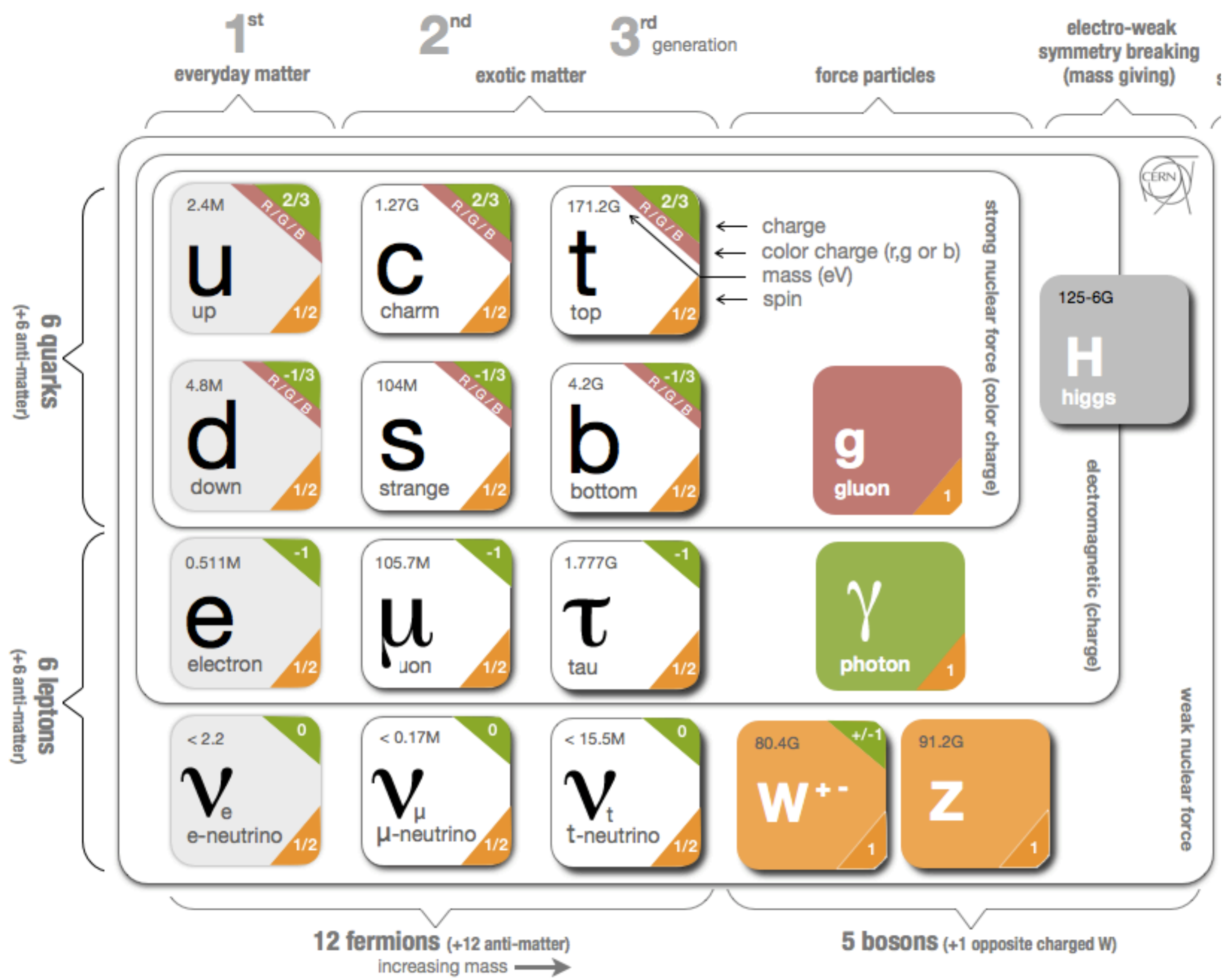
"If you want to make an apple pie from scratch, you must first create the universe."

CARL SAGAN

Ingredients of the Universe

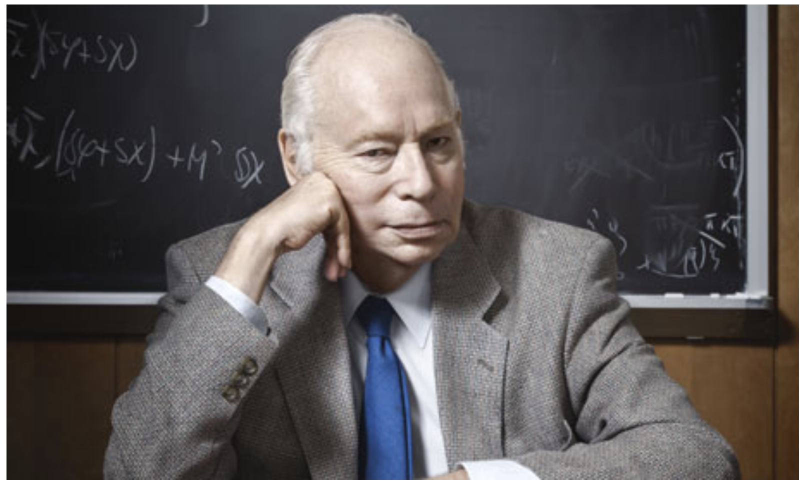
Group→1 ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

New Improved Ingredients



+ 95%
Secret sauce

4 Golden Lessons



- No one knows everything, and you don’t have to.
- Go for the messes – that’s where the action is.
- Forgive yourself for wasting time.
- Learn the history of science.

Steven Weinberg (2003)

Structure of the lectures

- Lecture 1: An overview of particle physics
    - General Motivation
    - Folk-history of Particle Physics
        - » e, p, n
        - » photons
        - » Positron, …
        - » from hadrons and mesons to quarks
        - » neutrinos, …
        - » W/Z bosons, Higgs
    - Present-day understanding of the Universe
    - What may lie ahead

Structure of the lectures

- Lecture 2: Basic tools and techniques
  - Preliminaries
  - Basic observables
  - Experiments
    - » sources: why high-energy, high-luminosity, high-weirdness
    - » detectors: calorimetry, particle-id, …
    - » software: triggers, cuts, statistics
  - Theory
    - » Representing particle, interactions, and processes
    - » Scattering and decay
    - » Some examples

Structure of the lectures

- Lecture 3: Guided by Symmetry
    - Energy : Neutrinos
    - Charge : Global/Local symmetry
    - Spin : Neutrinos
    - Isospin : Flavor
    - Pauli-antisymmetry: Color
    - Asymptotic freedom and Confinement : Color
    - Parity, CP : Weak interaction phenomena
    - Gauge symmetry : Z boson
    - Gauge symmetry: Higgs boson

Units

We will often make use of *natural units*. This means that we work in a system where the action is expressed in units of Planck's constant:

$$\hbar \approx 1.055 \times 10^{-34}\mathrm{Js}$$

and velocity is expressed in units of the light speed in vacuum:

$$c = 2.998 \times 10^{8}\mathrm{m/s}.$$

In other words we often use $\hbar = c = 1$.

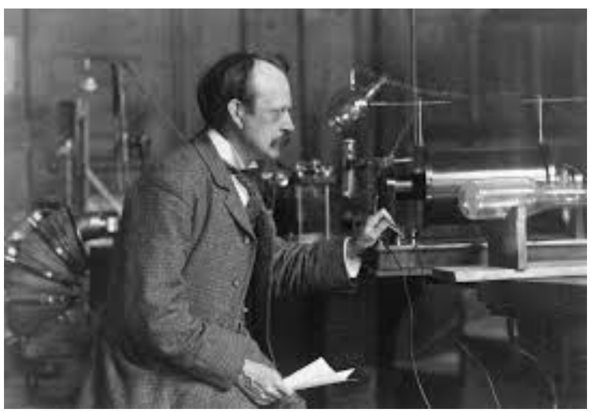
This implies, however, that the results of calculations must be translated back to measureable quantities in the end. Conversion factors are the following:

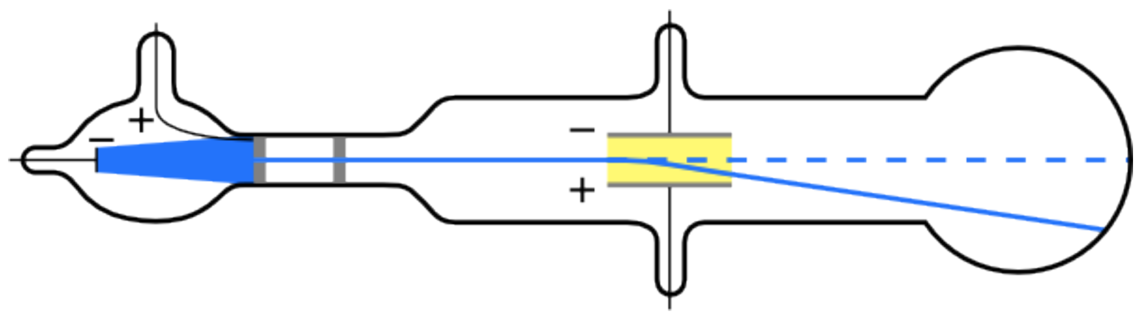
quantity	conversion factor	natural unit	normal unit
mass	$1\ \mathrm{kg} = 5.61 \times 10^{26}\,\mathrm{GeV}$	GeV	GeV/c^2
length	$1\ \mathrm{m} = 5.07 \times 10^{15}\,\mathrm{GeV}^{-1}$	GeV^{-1}	$\hbar c/\,\mathrm{GeV}$
time	$1\ \mathrm{s} = 1.52 \times 10^{24}\,\mathrm{GeV}^{-1}$	GeV^{-1}	$\hbar/\,\mathrm{GeV}$
unit charge	$\mathrm{e} = \sqrt{4\pi\alpha}$	1	$\sqrt{\hbar c}$

A Folk History of Particles

Electrons

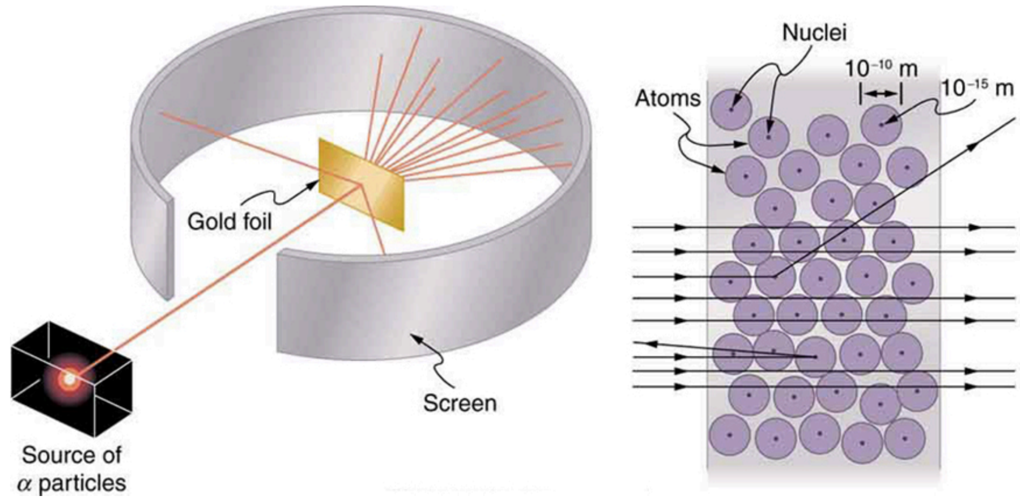
- 1700s to 1900: Many experiments with ionized gases. Some kind of "rays" that were deflected by E and B fields
- 1897-1903: JJ Thomson after many years of experiments on different gases concludes that mass/charge was constant, small, and the rays were produced by most substances.





- 1906: Millikan confirms that charge is indeed quantized

Nucleus



1910: Geiger, Marsden, Rutherford discover that the positive charge in the atom is concentrated

Protons

1919: The “H” particles that are emitted by all substances when bombarded by alpha particles, must be a common constituent of all elements, and must be the protons

Rutherford

Neutron

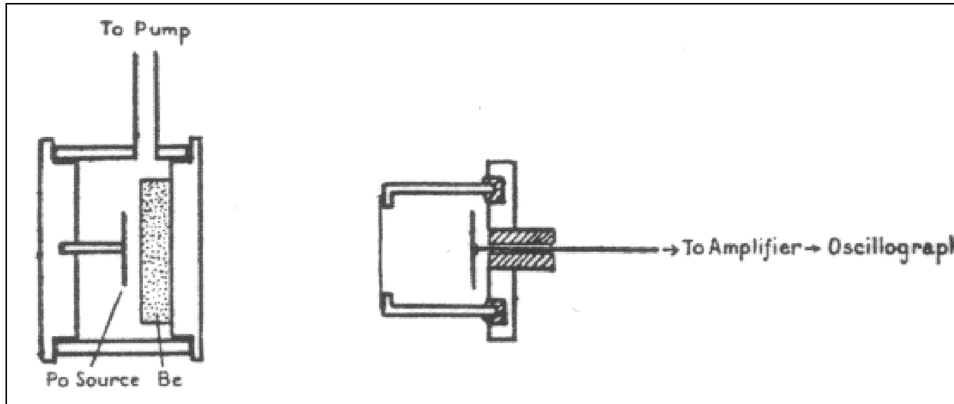


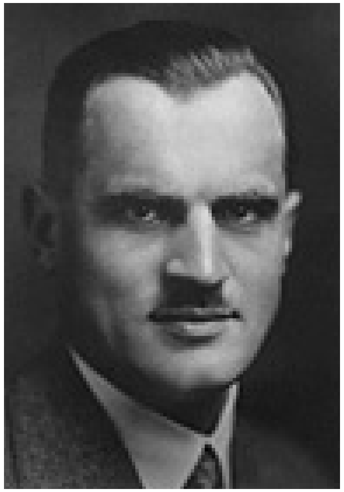
FIG. 1.

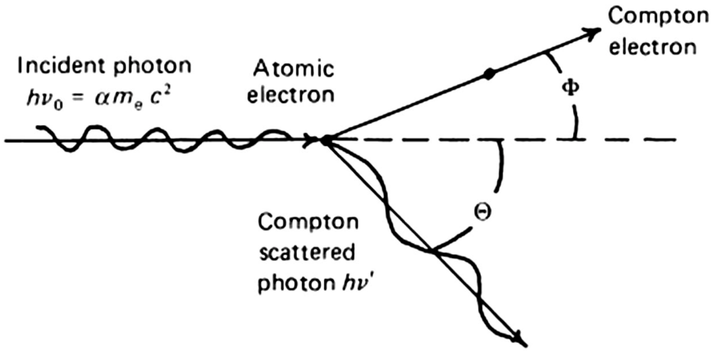
1932: Bombarding Beryllium with alpha particles produces invisible rays that however can knock-off protons from wax. These rays have a lot of energy, and must be carried by a particle as massive as the proton. This is the neutron.

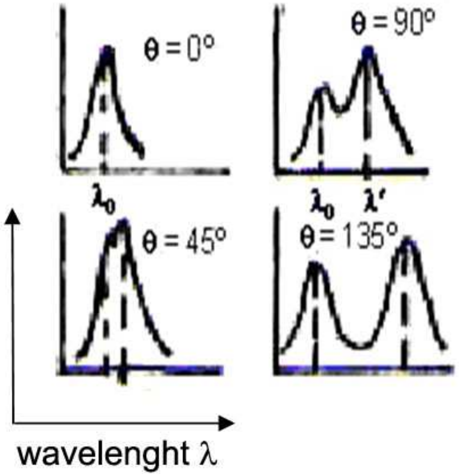
Chadwick

Photon

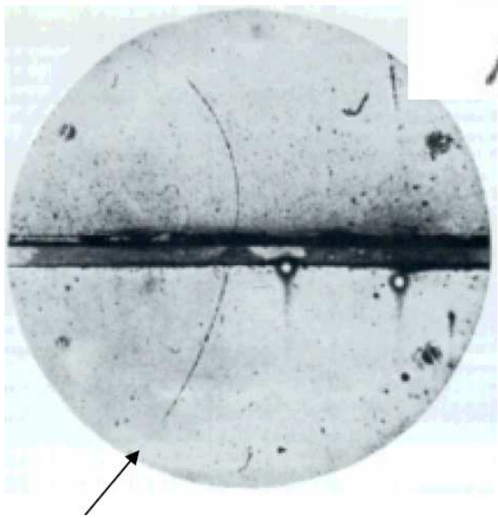
- 1900: Planck's Law E=hv
- 1905: Einstein's Photoelectric effect E = hv - W
- 1923: Compton Scattering

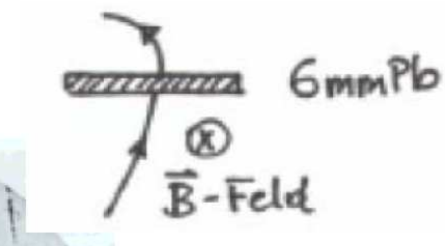




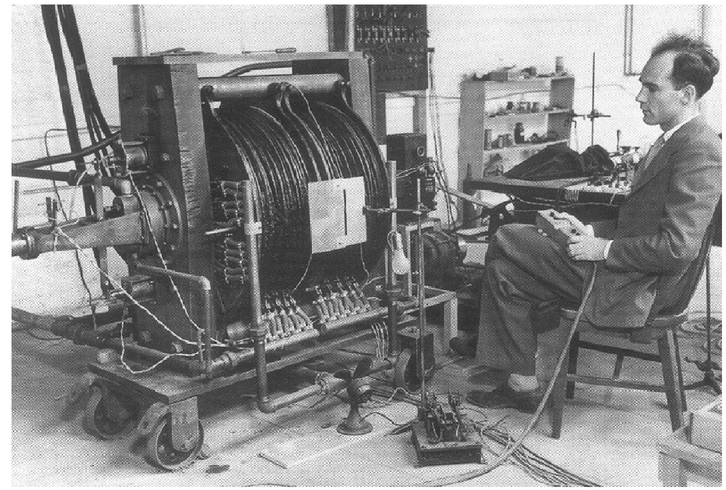


Positron





$$\vec{F} = q\vec{v} \times \vec{B}$$

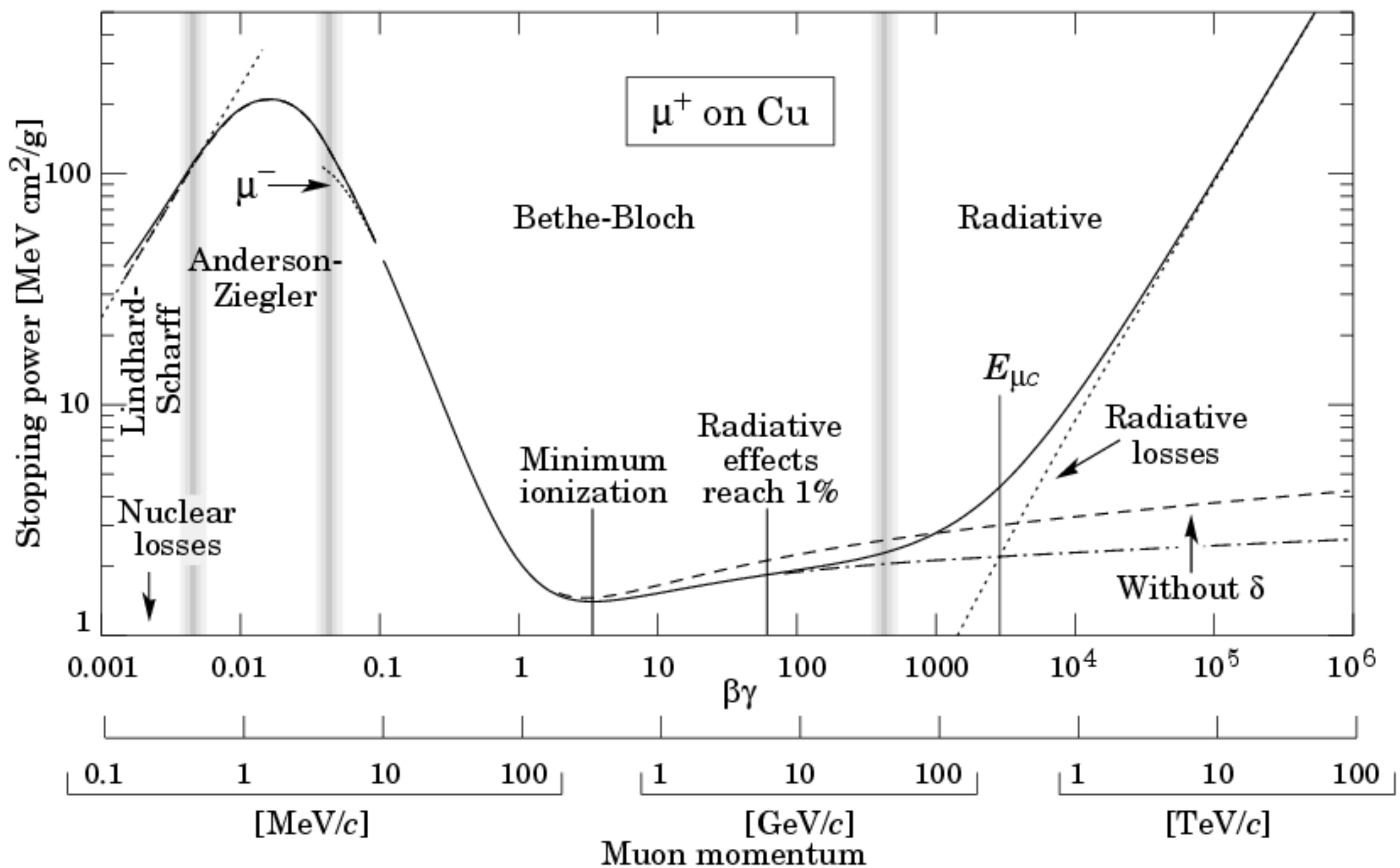


Curvature in B field tells
momentum and charge

The particle had mass = electron, but positive charge!
Anderson (1932), just as predicted by Dirac (1930)

Antiproton discovered by Segre and Chamberlain (1955)

Energy Loss Rate



What holds the nucleus?

If there is a new force that holds the protons in the nucleus, it must be stronger than the electromagnetic force and be limited to the size of the nucleus.

From this, a new particle of mass ~200 MeV was predicted.

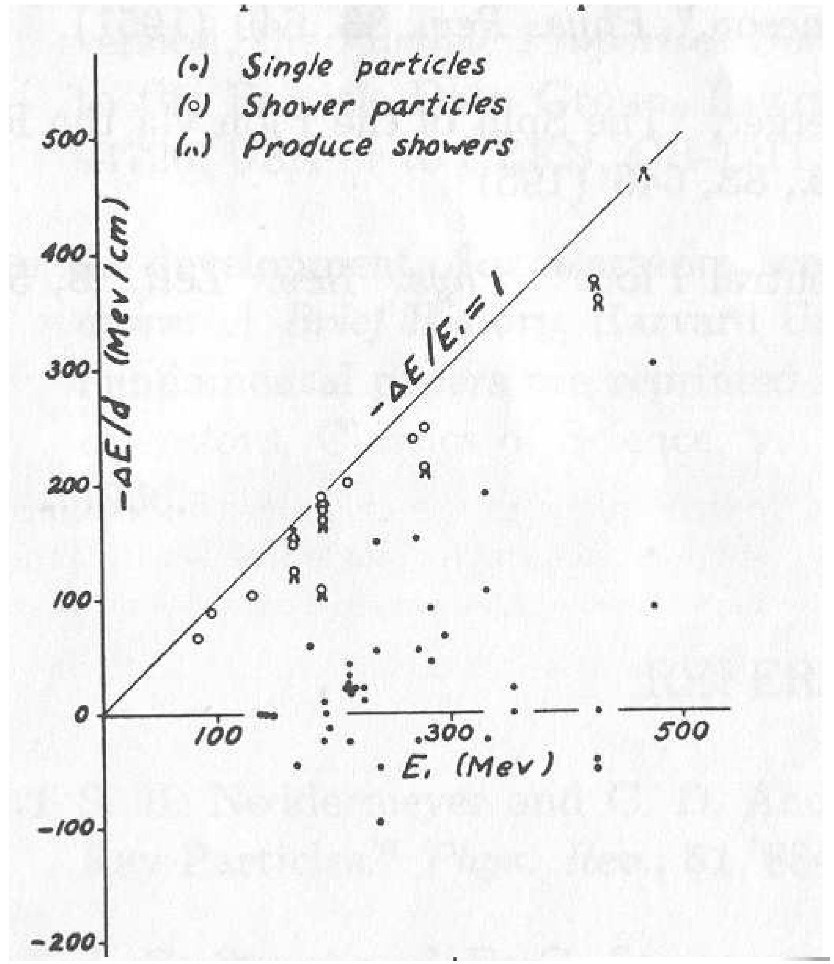
Yukawa (1935)

Discovering the muon

Measure energy loss rate, and seen that there are particles of mass ~100 MeV that do not lose much energy

These were initially thought to be pions, but are muons.

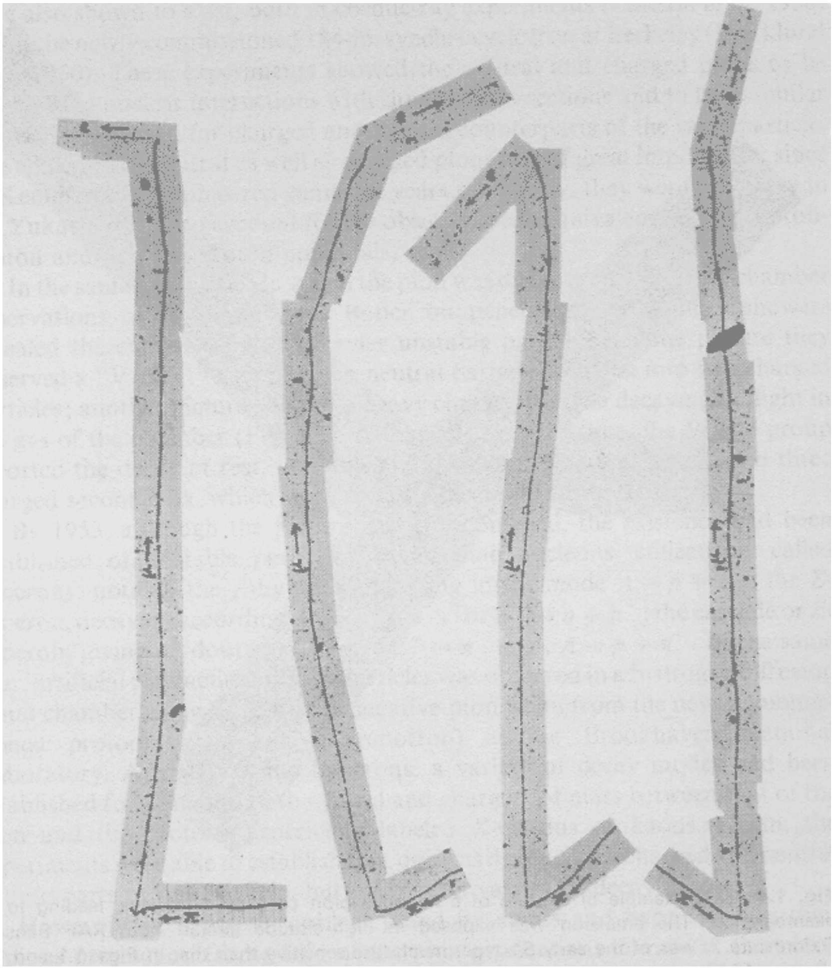
Who ordered that?



Discovering the charged pions

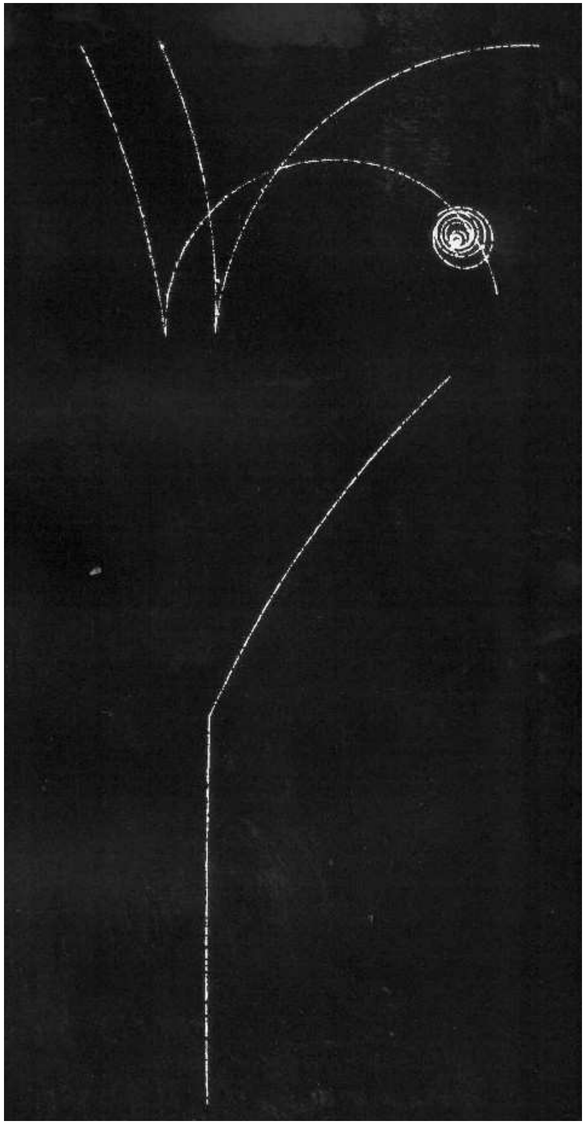
Pions decayed into a muon, and so thus were slightly more massive (140 MeV)

Usually not seen at sea level

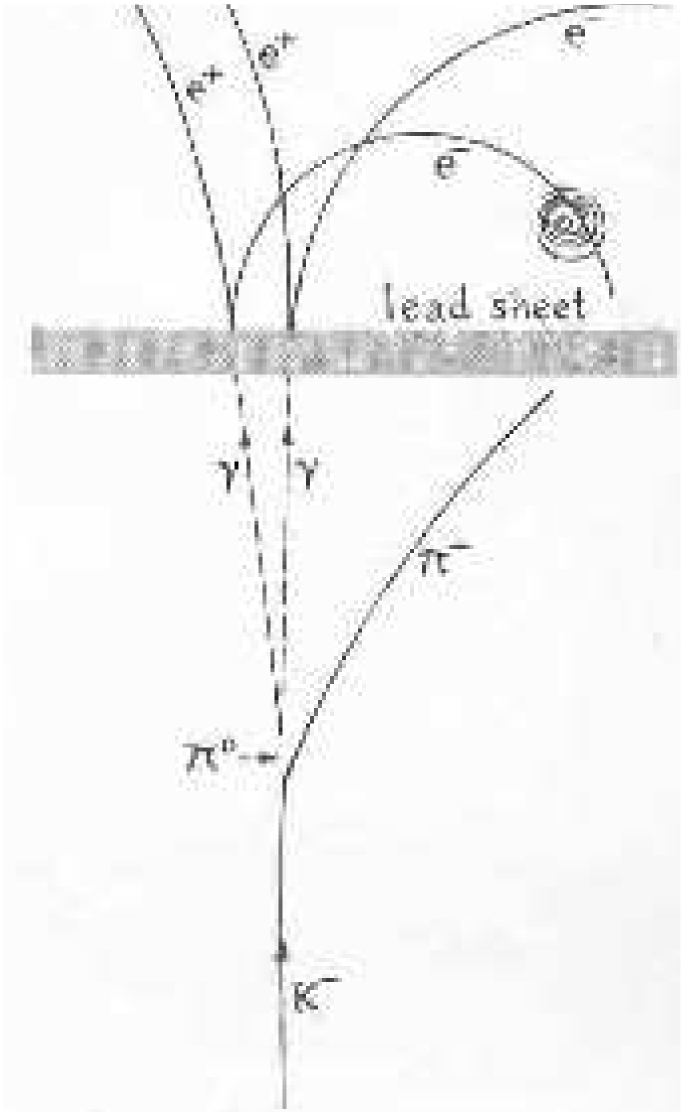


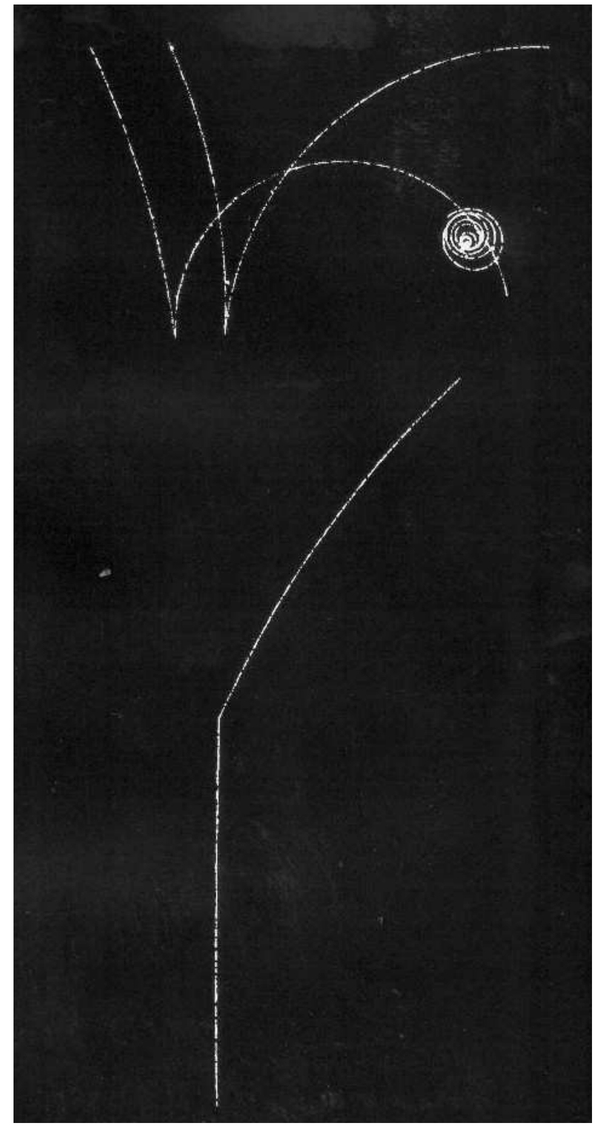
Neutral Pions

Can you guess what's happening here?



Neutral Pions



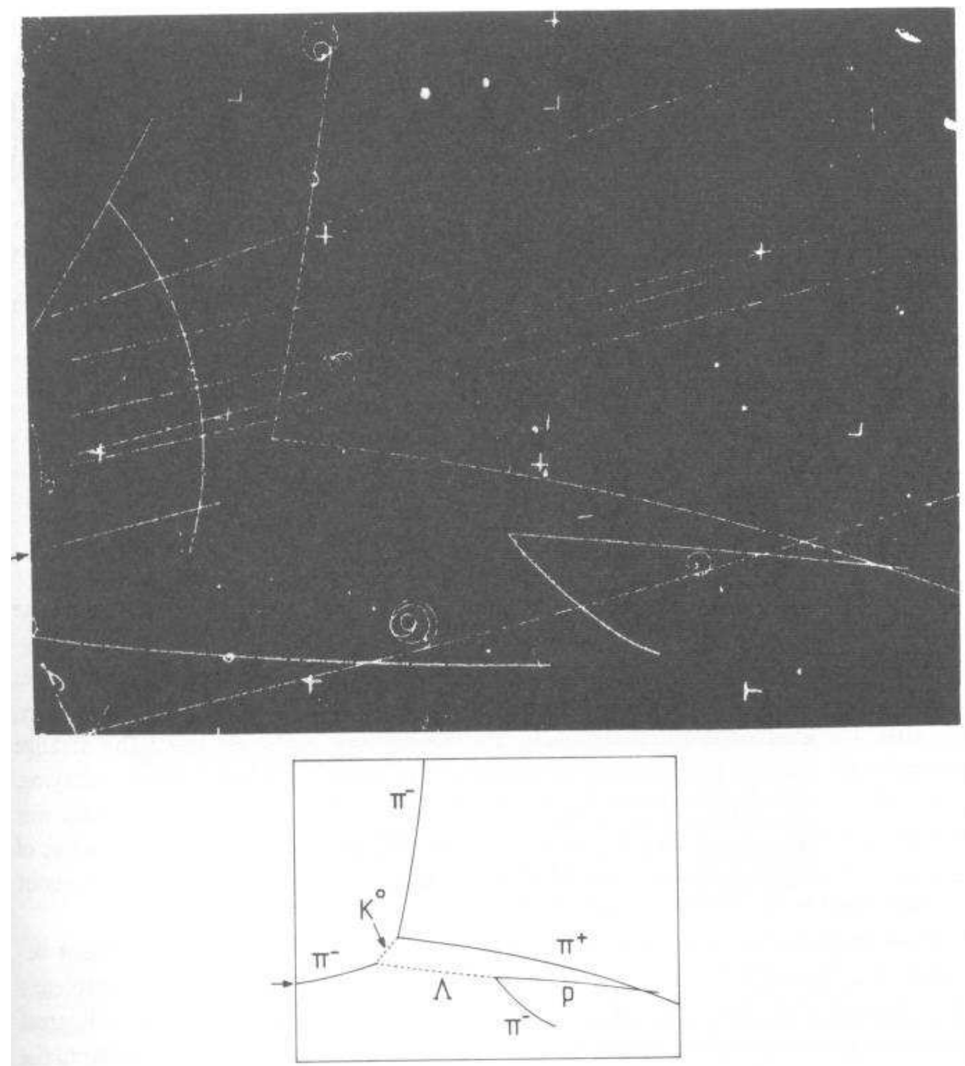


Strangeness

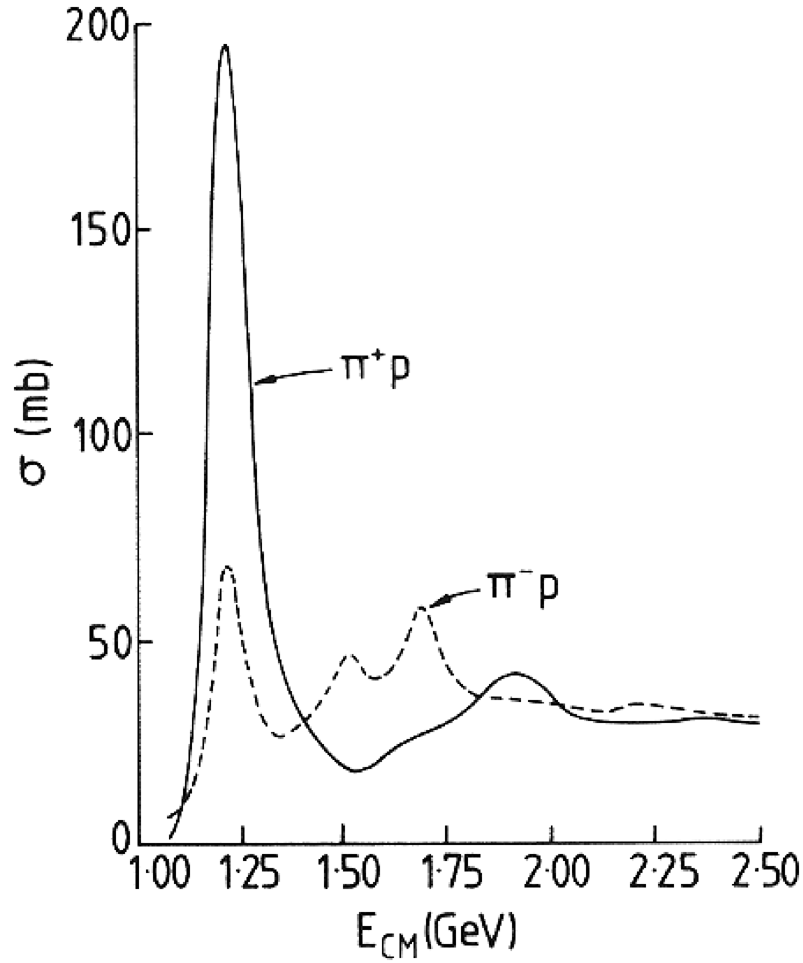
Some particles are always produced in pairs, and by strong interactions.

On the other hand, they appear to decay weakly.

This is strange.



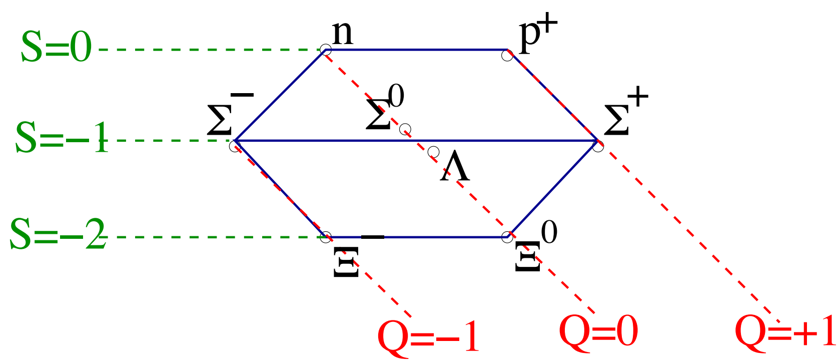
Resonances

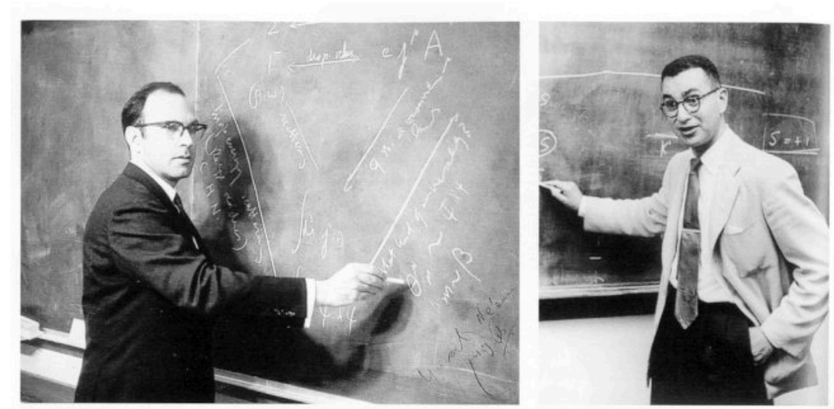


The Particle Zoo

First seen in	Reported events	Current interpretation
	Mesons	
1943 (1946)	Charged particle with M~500 MeV	K^+
1947	$\theta^0 \rightarrow \pi^+ \pi^-$, $V^0{}_2 \rightarrow \pi^+ \pi^-$	$K^0 \rightarrow \pi^+ \pi^-$
1947	$\theta^+ \rightarrow \pi^+$ (neutral), $\chi^+ \rightarrow \pi^+$ (neutral)	$K^+ \rightarrow \pi^+ \pi^0$
1949	$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$	$K^+ \rightarrow \pi^+ \pi^+ \pi^-$
1951	$\kappa^+ \rightarrow \mu^+$ (neutrals)	$K^+ \rightarrow \mu^+ \nu$
	Baryons	
1950	$V^0{}_1 \rightarrow p\ \pi^-$	$\Lambda \rightarrow p\ \pi^-$
1953	$V^+{}_1 \rightarrow p$ (neutrals)	$\Sigma^+ \rightarrow p\ \pi^0$
?	$\Lambda^+ \rightarrow n\ \pi^+$	$\Sigma^+ \rightarrow n\ \pi^+$
(1953)	$X^- \rightarrow V^0{}_1\ \pi^-$	$\Xi^- \rightarrow \Lambda\ \pi^-$

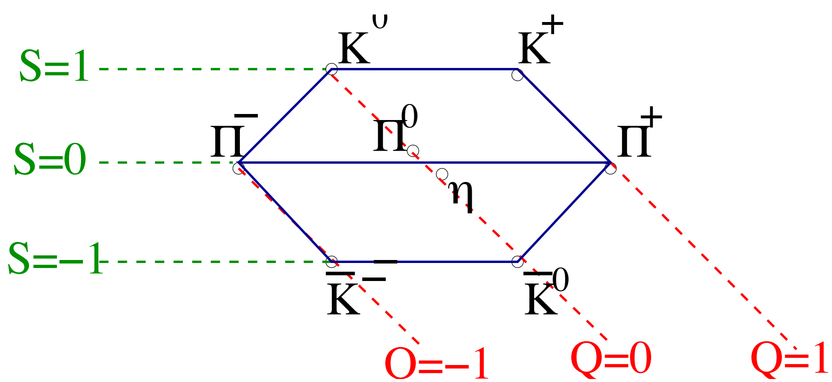
8-fold way





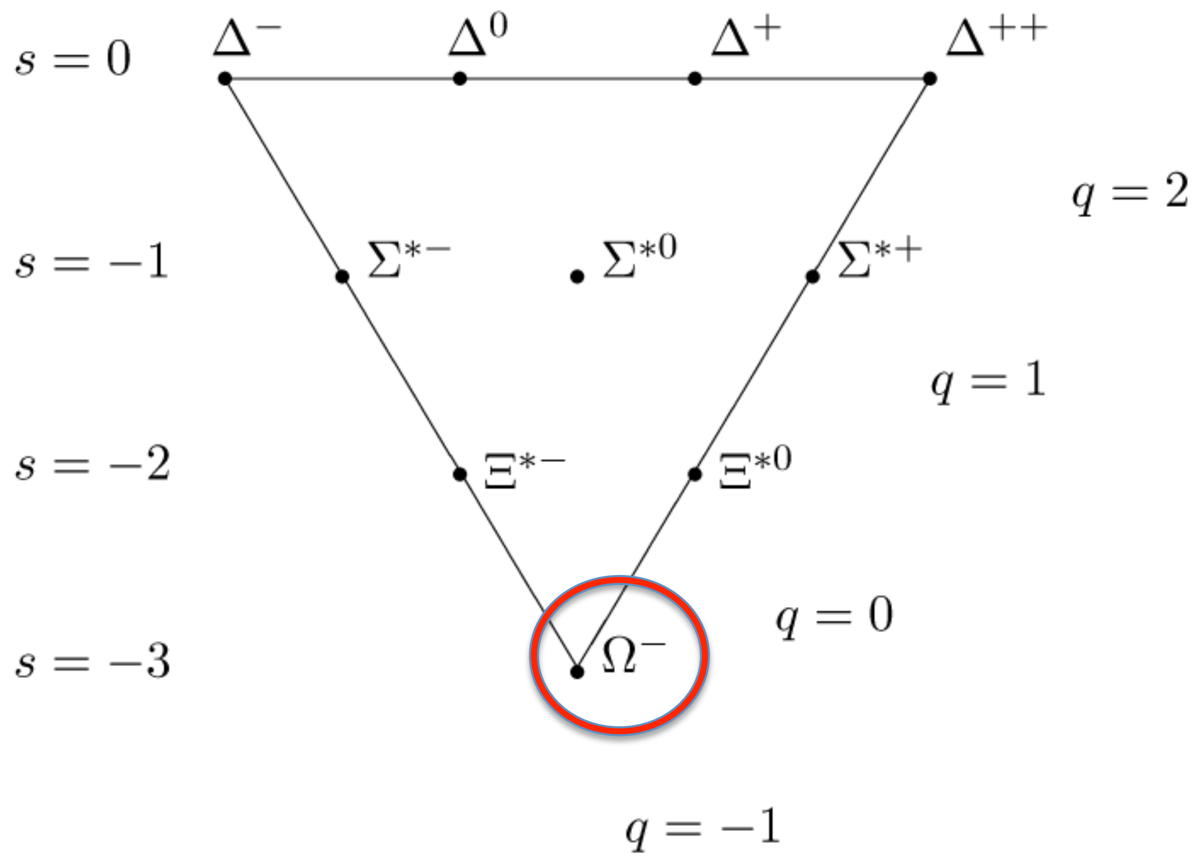
Yuval Ne'eman

Murray Gell-Mann

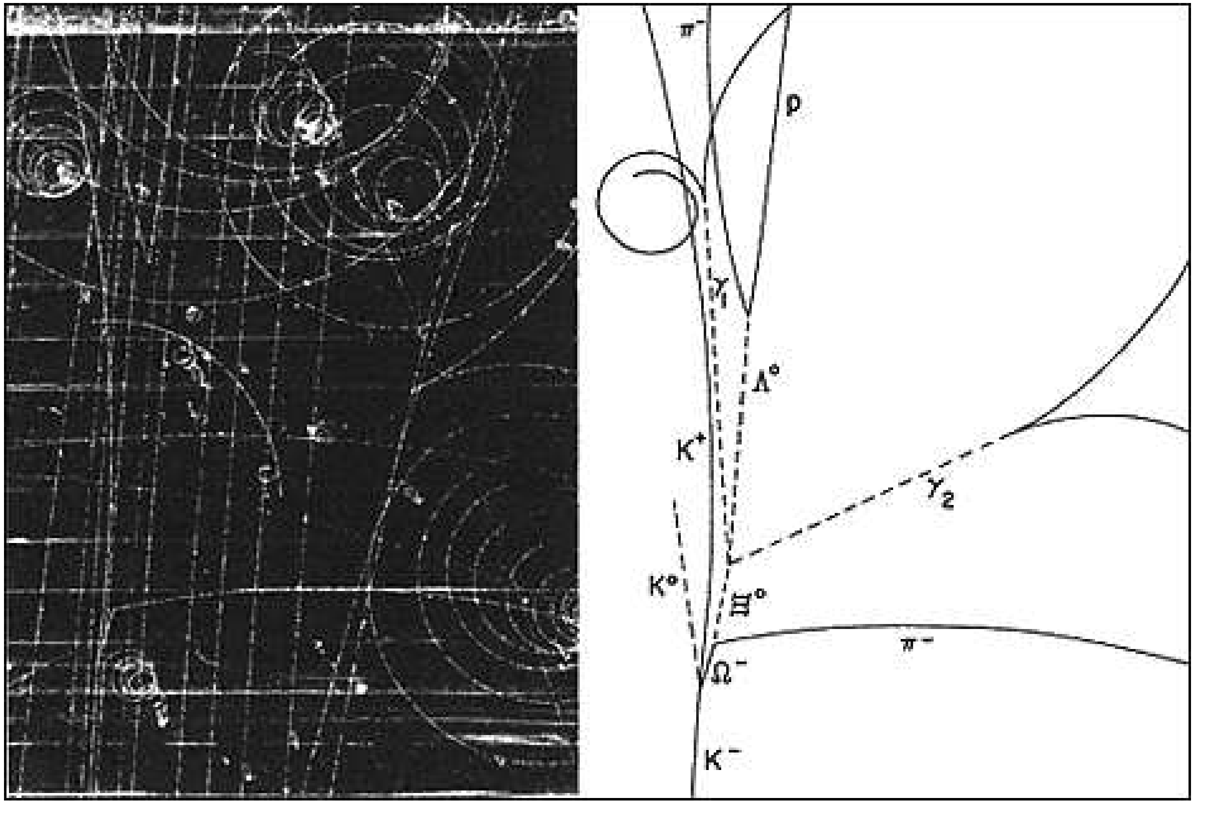


There are patterns in mesons and baryons

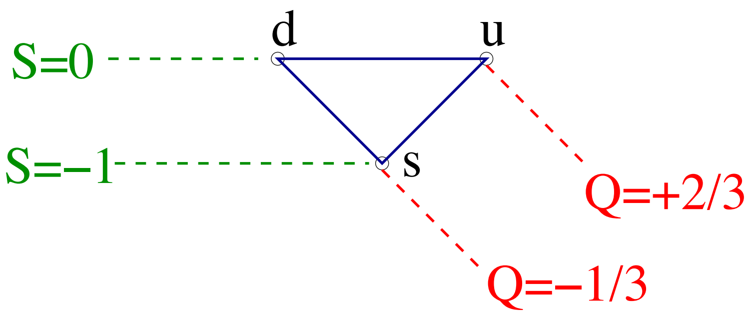
A Bold Prediction

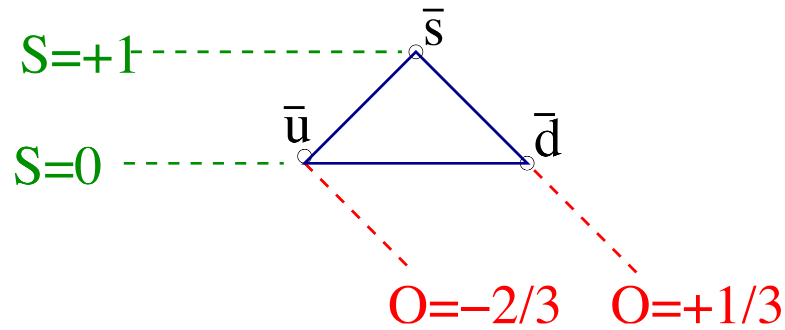


The Omega-Minus



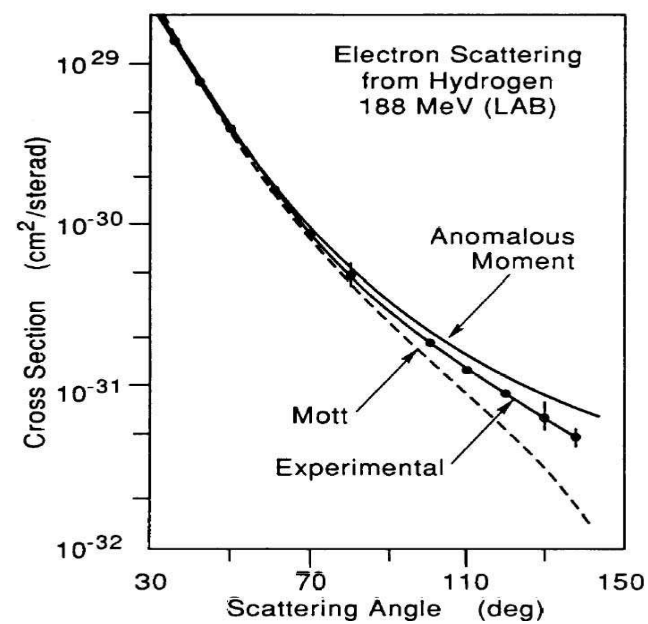
Quarks





All meson/baryon multiplets can be made using these basic “triangles”

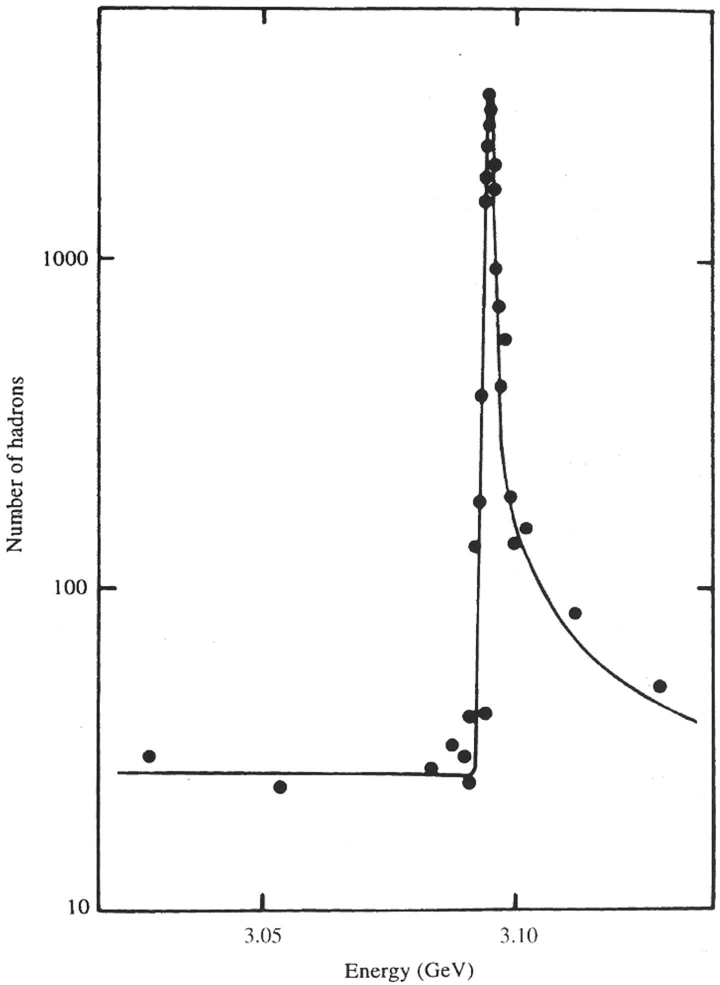
Neutron/Proton has substructure!



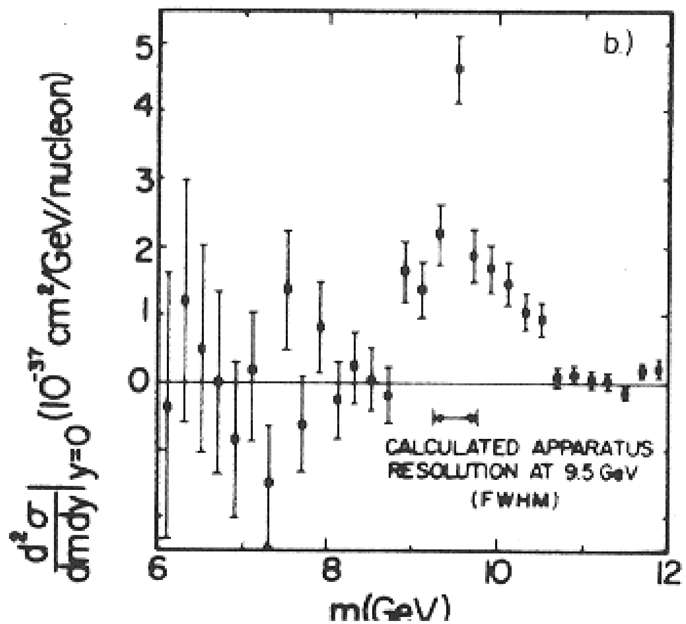
Charmonium

Extremely narrow peak at ~3 GeV

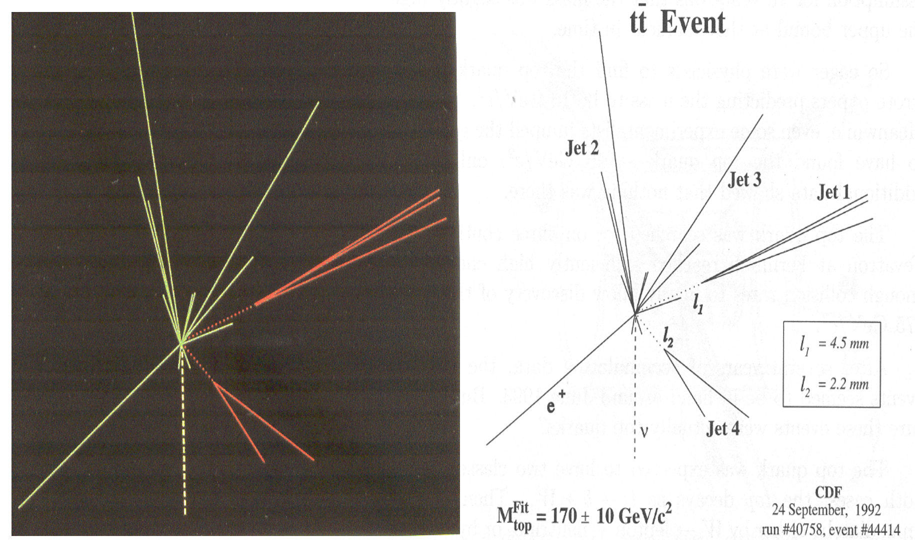
Seen by Sam Ting and Richter's groups, independently in 1974



Heavy quarks

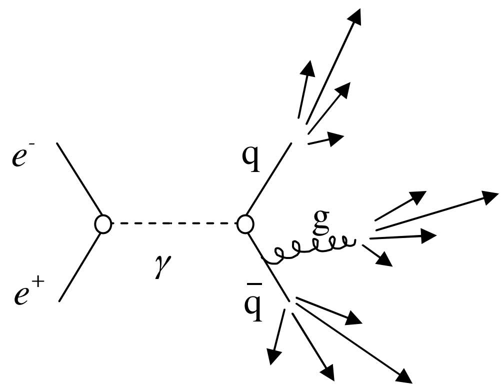


Bottomonium

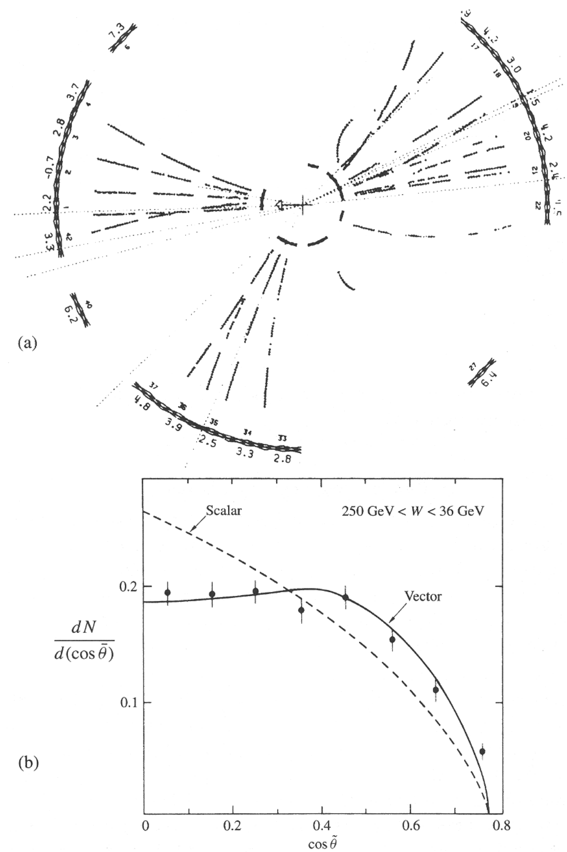


Top quarks

Gluons

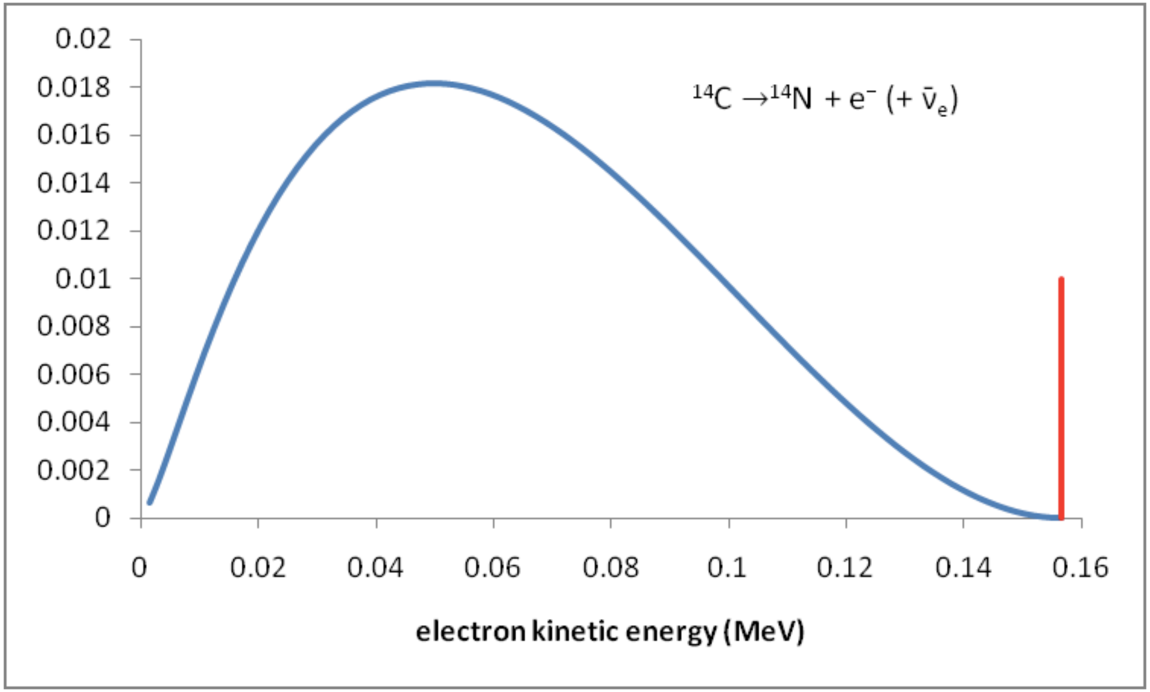


e^-
e^+
γ
q
g
$\bar{q}$



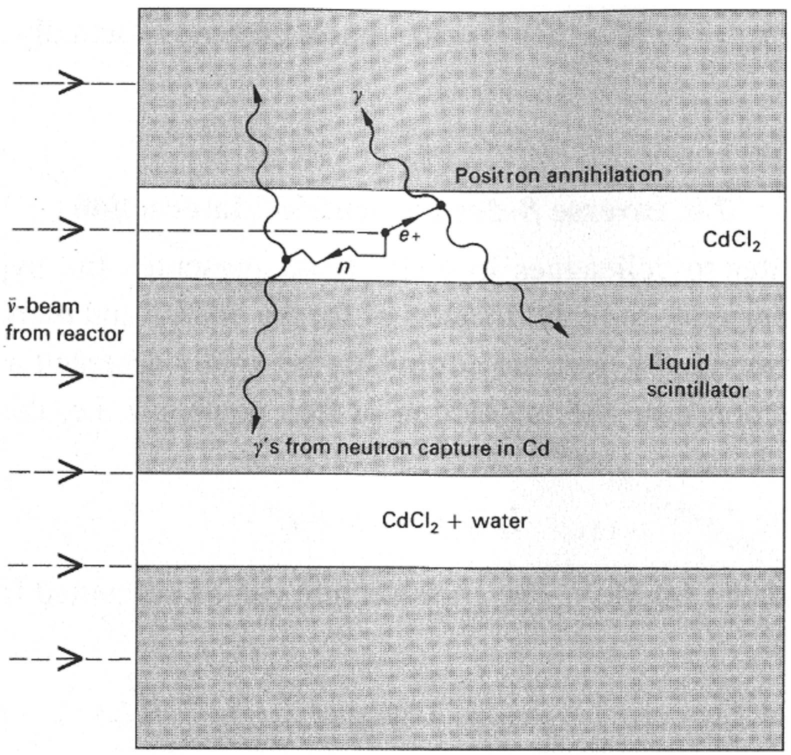
(a)
(b)
Scalar
250 GeV < W < 36 GeV
Vector
$\frac{dN}{d(\cos\tilde{\theta})}$
0.2
0.1
0
0.2
0.4
0.6
0.8
$\cos\tilde{\theta}$

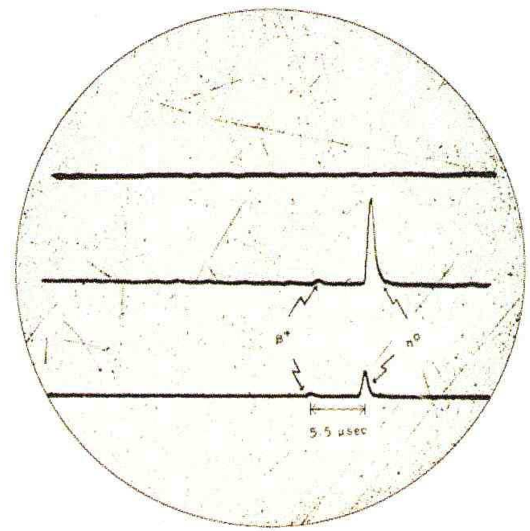
Neutrinos



Beta decays had already shown that there ought to be a new particle

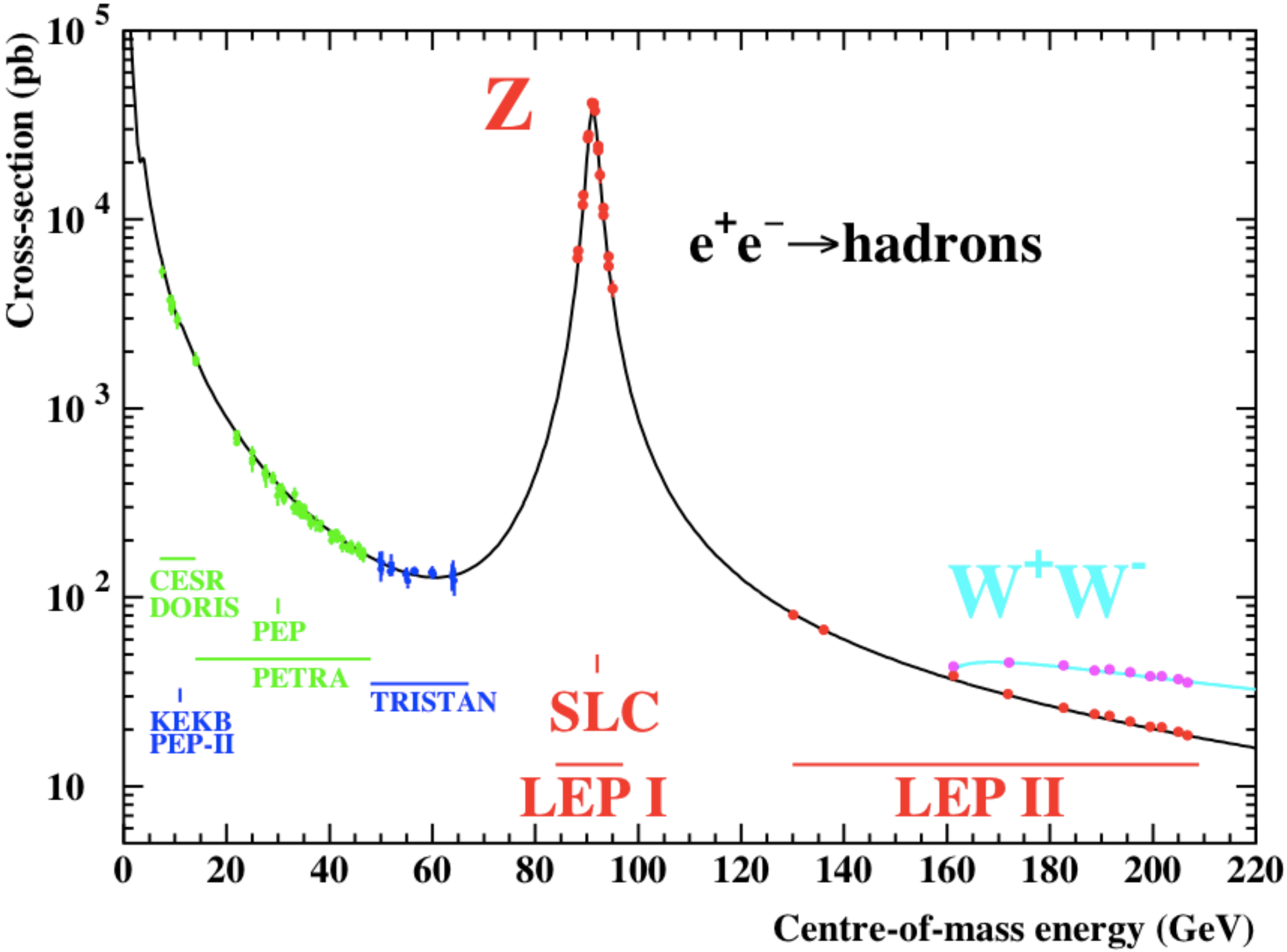
Neutrino Heartbeat





Followed by detection of all 3 flavors of neutrinos, leptons

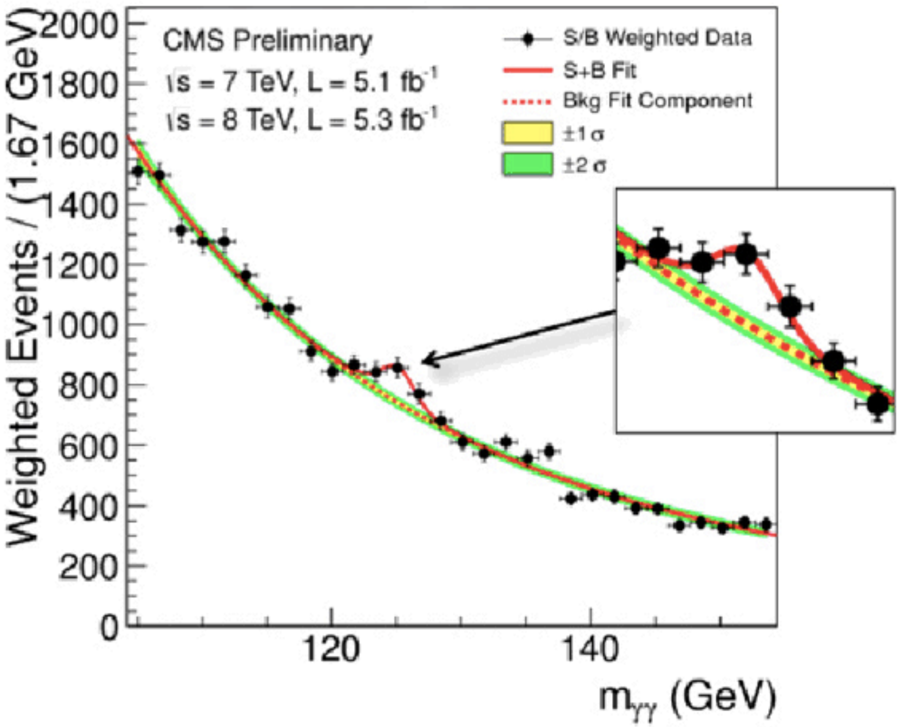
W, Z bosons



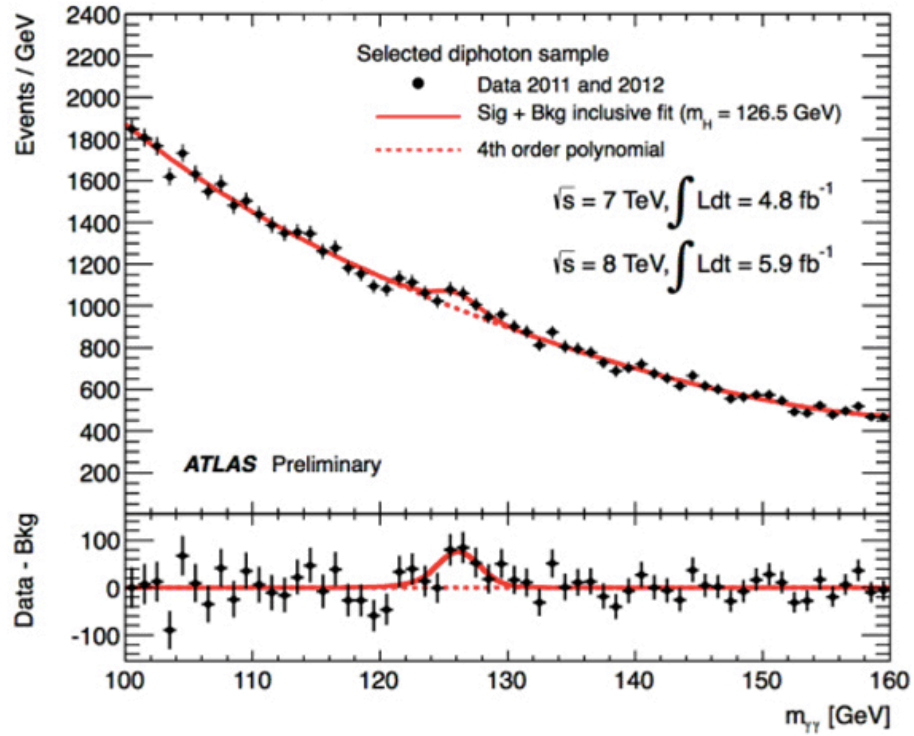
Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
$e^+e^- \rightarrow$hadrons
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
W^+W^-
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

Higgs Boson

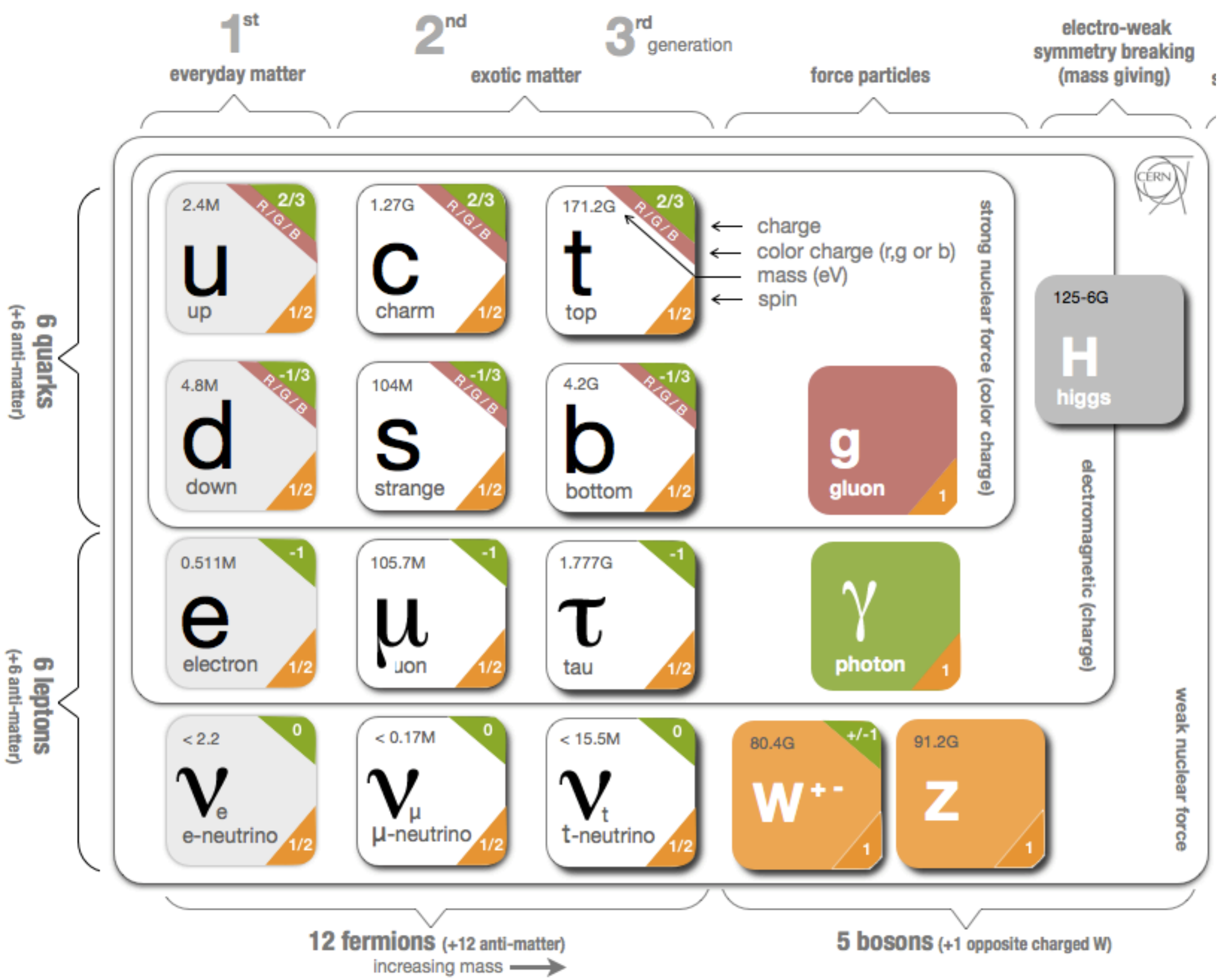
Experiment CMS



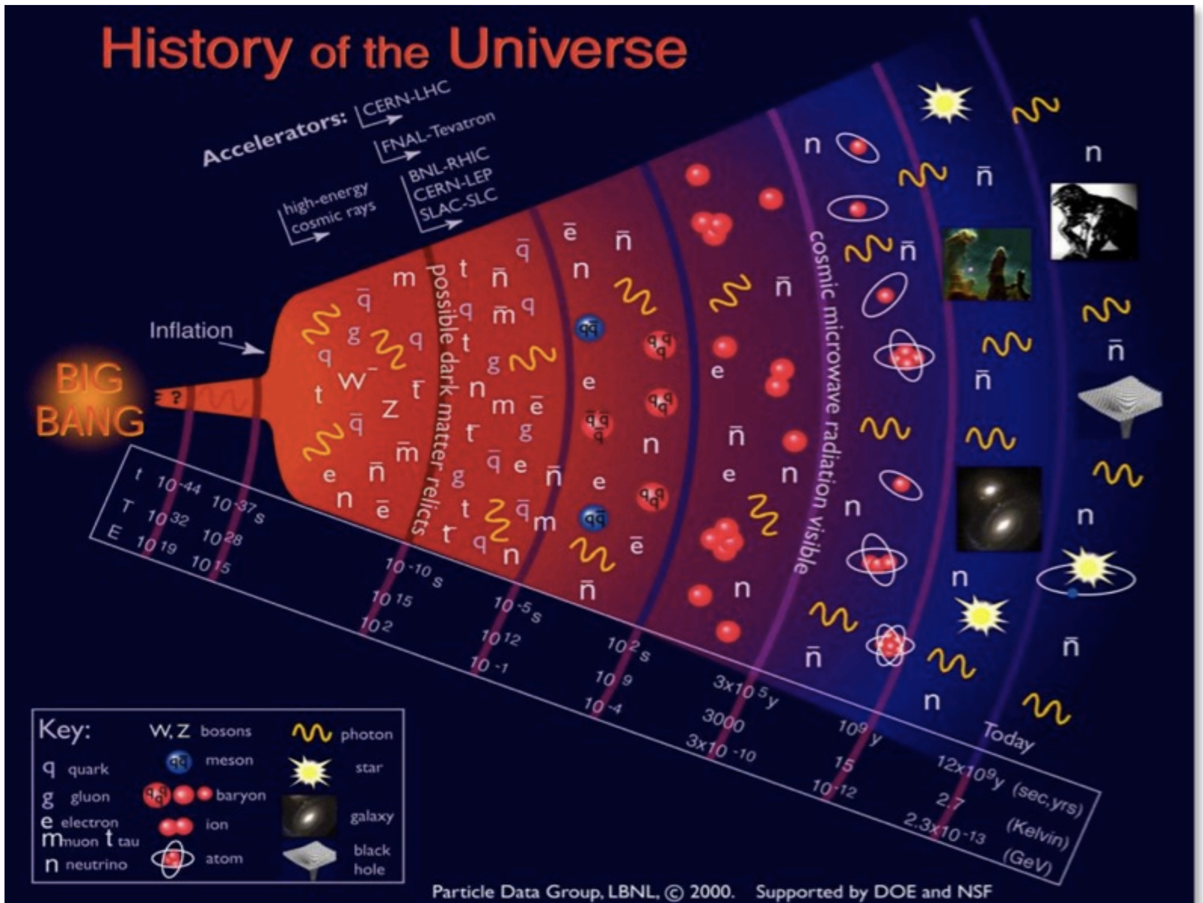
Experiment ATLAS



What we know today



Particle Physics in the Sky



We have reached a milestone…

- What are the fundamental building blocks?
- What are their interactions?
- Why are there 3 generations? Masses?
- Why matter > antimatter?
- What is Dark Matter/Energy?
- Why is the Standard Model, the way it is?
- …

but there is a long road ahead.

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    - Asymptotic freedom and Confinement : Color
    - Parity, CP : Weak interaction phenomena
    - Gauge symmetry : Z boson
    - Gauge symmetry: Higgs boson

References

- D.J Griffiths's, Elementary Particle Physics
- http://www.phys.ufl.edu/~korytov/phz6355/ (esp. for historical account)
- Halzen and Martin (for most of Lectures 2,3)
- http://www.nikhef.nl/~i93/Master/PP1/2011/Lectures/Lecture.pdf