The Standard Model

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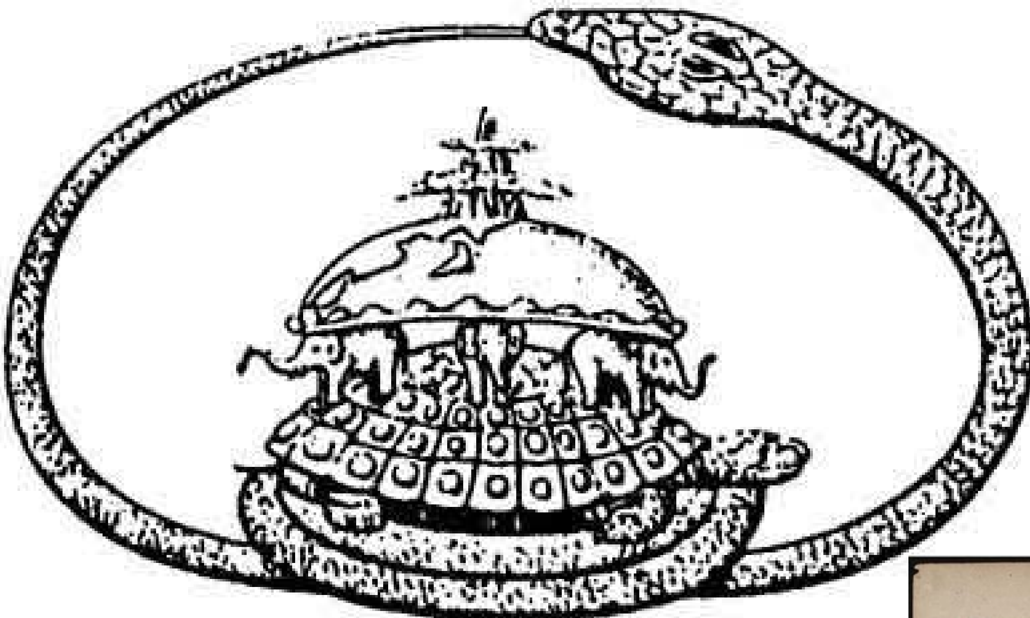
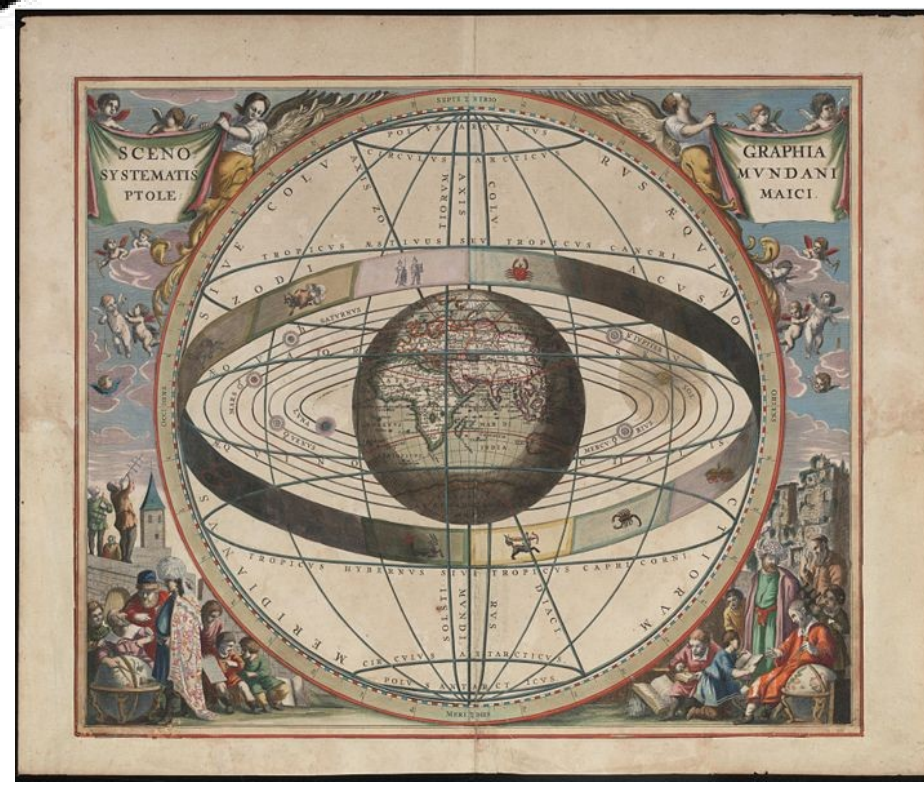
1. Overview of the standard mode

3. Tests of the Electroweak
4. standard model




SCENO
SYSTEMATIS
PTOLE:
GRAPHIA
MVNDANI
MAICI.

Periodic Table of the Elements

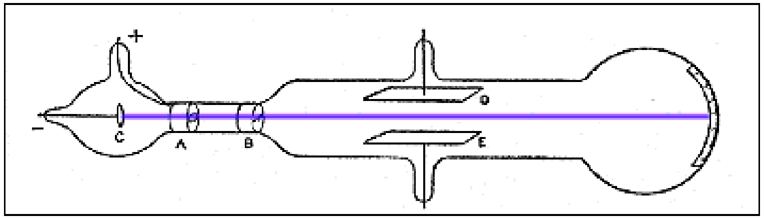
- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

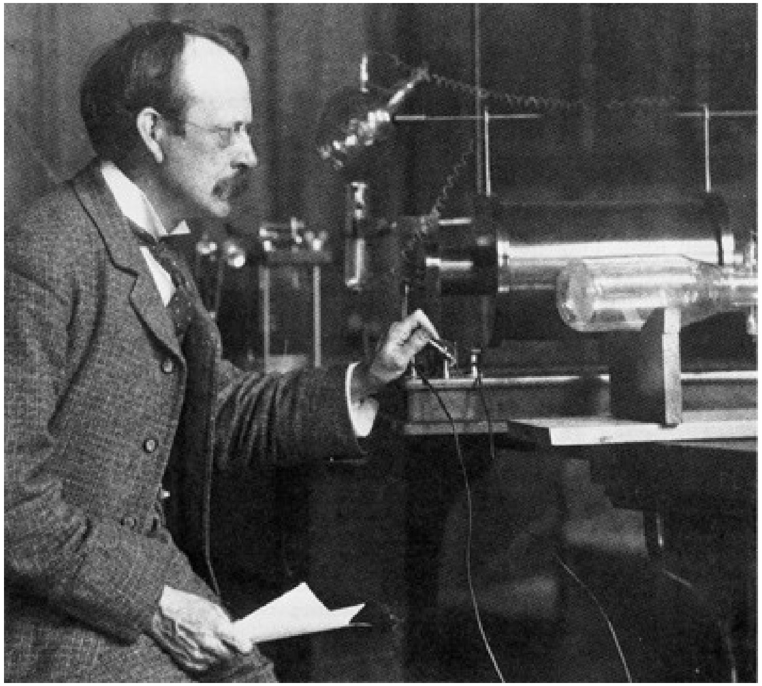
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

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
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

Discovery of electron : 1897

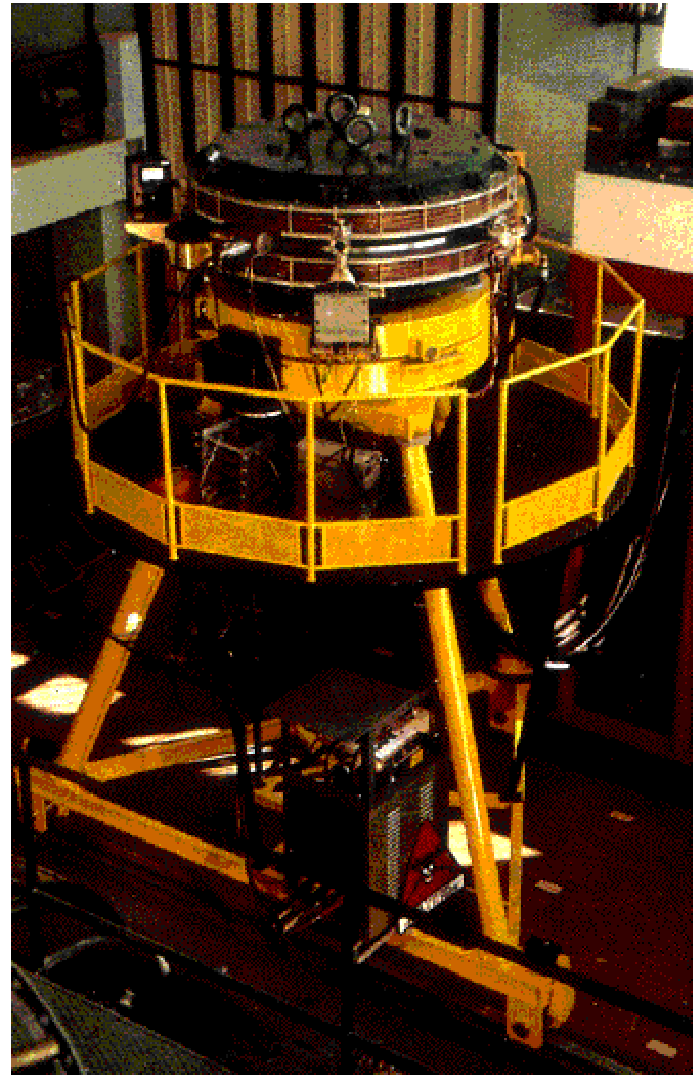
J.J.Thomson





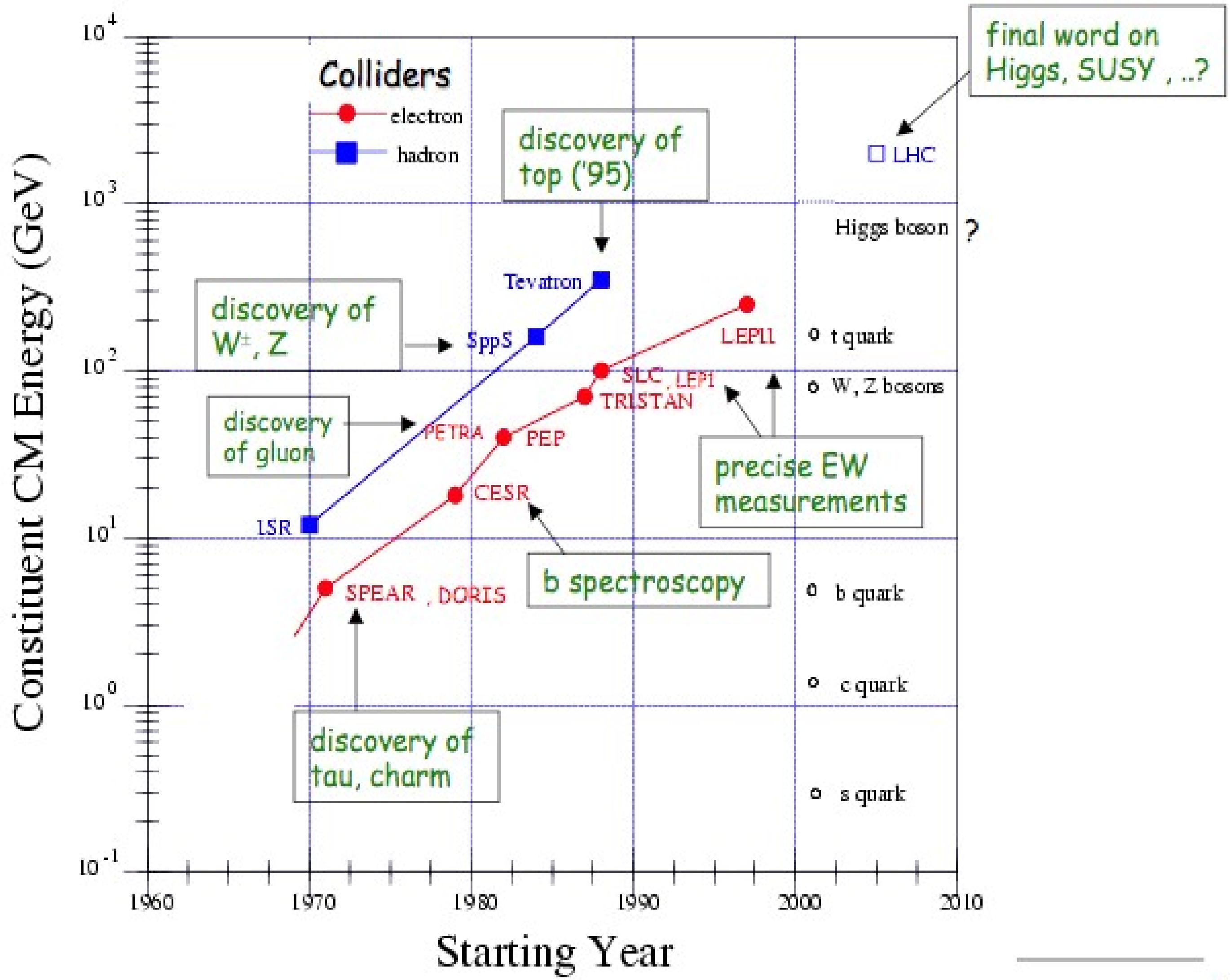
Toward higher energies : particle accelerators

First Cyclotron (1931)
10 cm diameter



ADA (frascatti, Italy)
e+e- collider (1961)

Simplified and non-exhaustive summary of SM tests at Colliders



Making of the Standard Model

Simplified (and not quite consistent) history

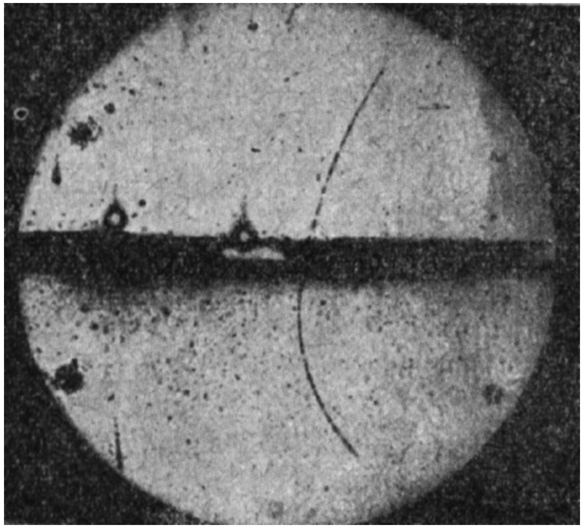
Back in 1930s-1940s :

- Elementary particles = e, p, n   (and antiparticles, e.g. e+)
- 4 interactions known
-     - Gravity
-     - electromagnetic
-     - weak
-     - strong

Not relevant, too weak
QED : quantum field theory
β decay,
Bind p,n to form nucleus

Precise nature was not understood

Antiparticles



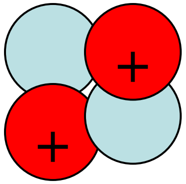
C.D. Anderson (1928)

Discovery of e+
in cosmic rays in cloud chamber

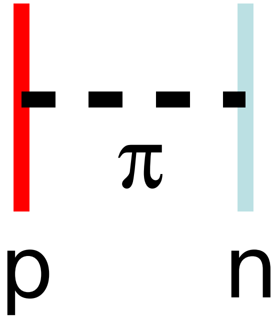
A few years before, it was postulated
in the Dirac theory.

Yukawa theory (1935)

Nuclear force : something much stronger than e.m force



Exchange of intermediate boson



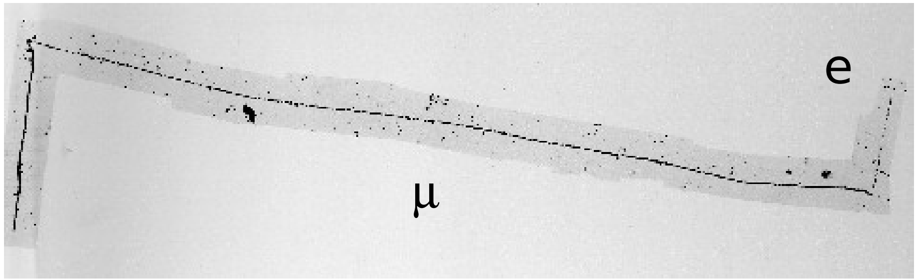
Short range force (size of nucleus) → mass of π

1 fm ⇔ 1/ 200 MeV

Searched for π ˋ and discovered μ

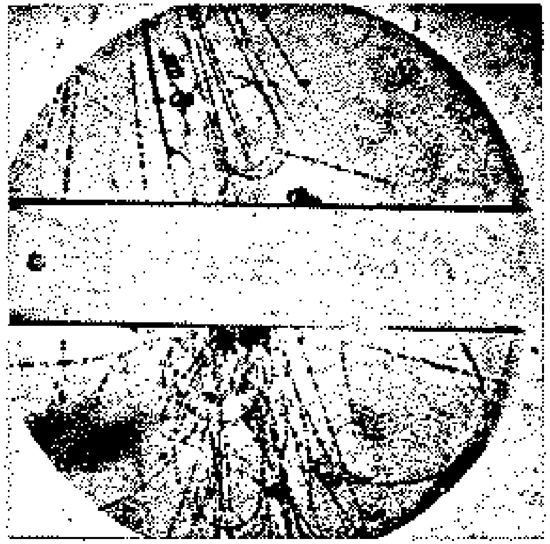
Long lived, penetrating particle in cosmic ray
Anderson et al (1936)
→ μ : another lepton

The meson was finally found in cosmic ray
Powell et al (1947)

π


$$\pi \rightarrow \mu\nu\mu, \quad \mu \rightarrow e\nu\mu\nu e$$

“Strange” particles



Rochester, Butler (1947)

Cloud chamber photo

Long lived neutral particle,
decaying into 2 charged particles

$$K0 \rightarrow \pi+\pi-$$

$$\Lambda \rightarrow p\pi-$$

.....

‘Strangeness’ Nishijima, Gell-mann
a new quantum number

And, many more particles(hadrons) (1950s - 1960s)

Higher energy accelerators

$\pi+$, $\pi-$, $\pi 0$, K+, K-, K0, K0, $\rho+$, $\rho-$, $\rho 0$, ω, …….

p, n, Λ, $\Sigma+$, $\Sigma-$, $\Sigma 0$, $\Xi+$, $\Xi-$, $\Xi 0$, …..

Something must be wrong!

Composite model of hadrons

Classification of hadrons ~ periodic table

Sakata (1959) (p,n,Λ) as fundamental particles

Gell-mann, Zweig (1964) Quark model

The quark model (of 1960s)

flavour	charge
u	+2/3
d	- 1/3
s	- 1/3

p = u u d

n = u d d

Λ = u d s

$\pi^+ = u\,\bar{d}$

$K^+ = u\,\bar{s}$

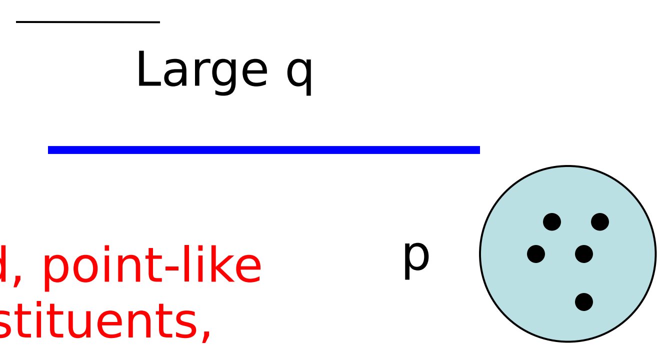
.....

- Successful classification of (known, and unknown) hadrons

  but is it a reality ?

- Test with e-p deep inelastic scattering

e



Hard, point-like
Constituents,
behaving as if they are free particles

Neutrinos and weak interaction

- idea of neutrino : Pauli (1930)
- in order to account for the missing energy in β-decays

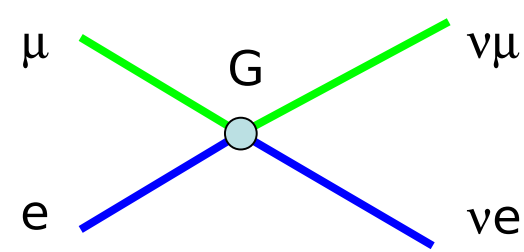
- Discovery of neutrino : Reines and Cowan (1956)
  νe from nuclear reactor

- 2 neutrinos νe, νμ : lepton number conservation

- Parity non-conservation in weak interaction
  Lee and Yang : the “τ–θ puzzle” (1956)
  Wu, Lederman : experimental tests,
  60Co β-decay, μ-decay (1957)

- V-A theory of weak interaction

Left handed ν, assumed to be massless

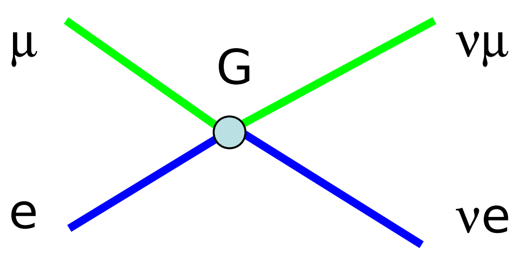


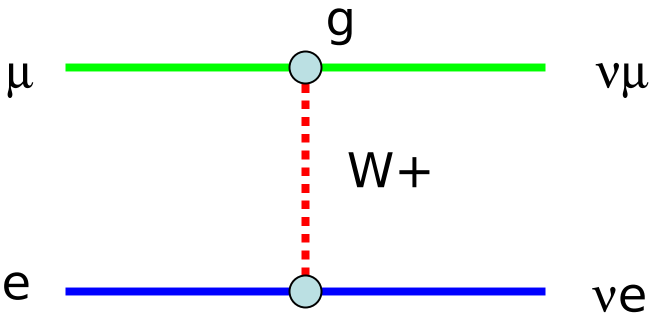
In 1960s

- e.m. interaction is already under control
- QED : first successful Quantum Field Theory.

- There are three quarks (u,d,s) perhaps, inside hadrons.
  but what is the force to tie them together?
  no free quarks, very strong, yet quarks look free at high Q

- V-A theory incorporates parity violation and allows
- calculation of weak decays,
- but it has problems (weak interaction diverges at
- high energy), and why it is weak?





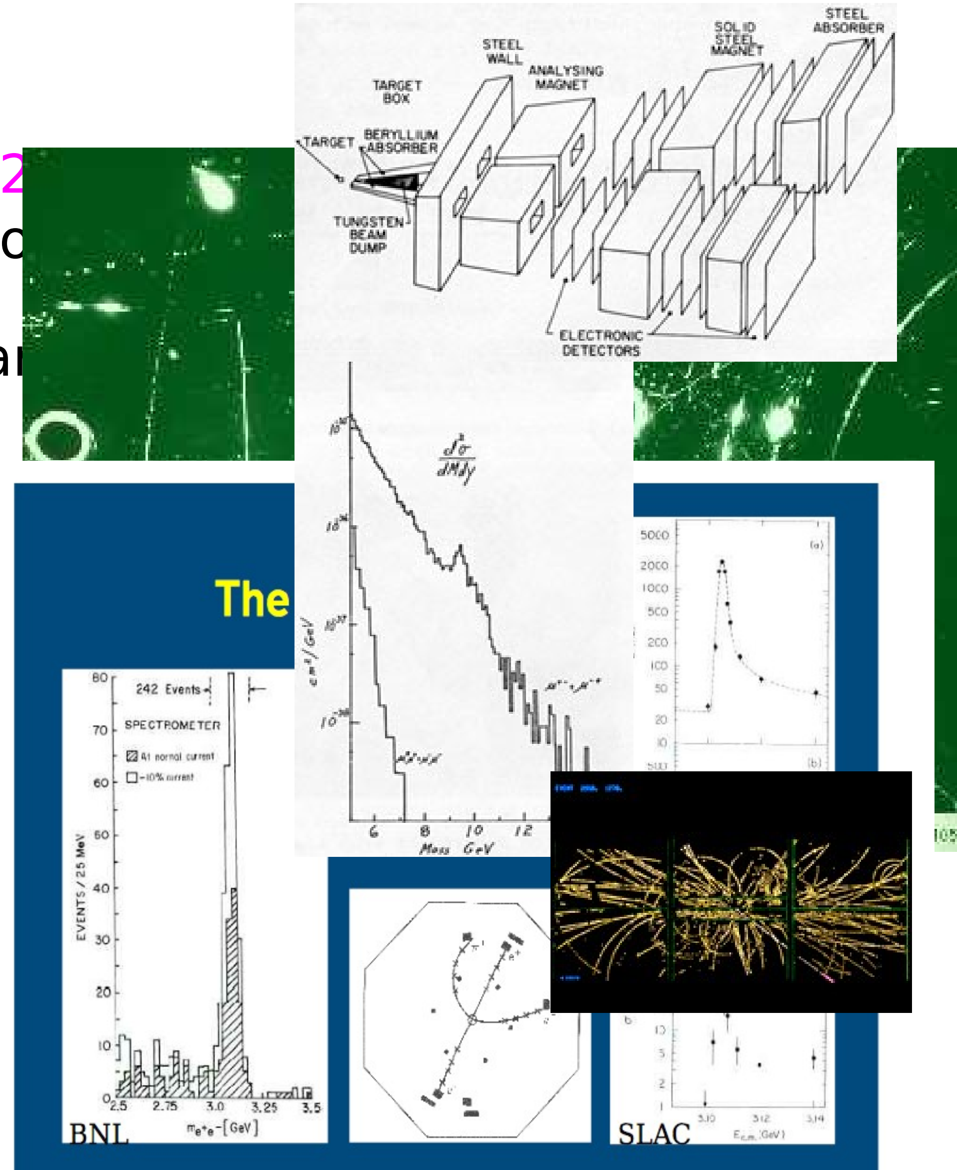
Such model (naïve) was considered, but didn't quite work

Further experimental results

- νN, νe scattering   1970s
  - Discovery of neutral current
  - (rough) determination of sin2
  - consistency with universal co

- Discovery of the 4th quark (char

- Discovery of τ lepton (3rd ge
- Discovery of bottom-quark (3
- Discovery of W and Z bosons
- High precision studies of Z bo
- Discovery of top-quark (3rd g
- High precision studies of W bo



The Standard Model, developed in 1960s-70s

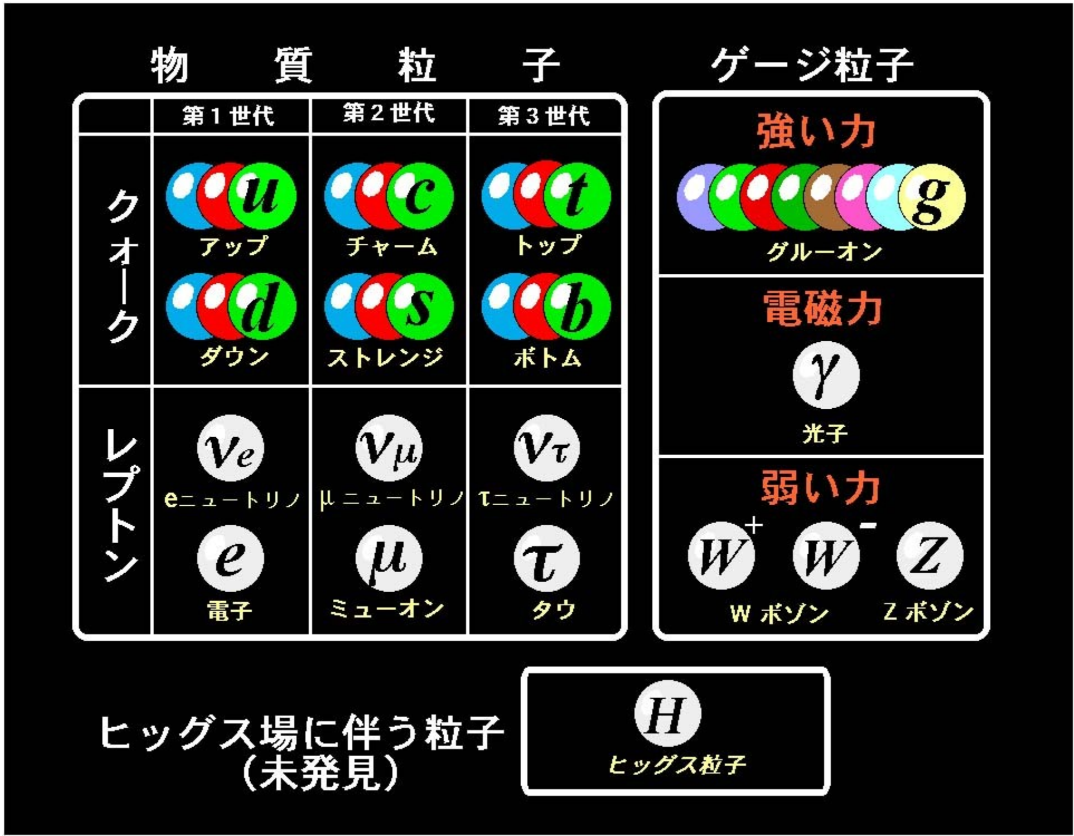
Ingredients:

Special relativity + quantum mechanics
⇒ Quantum field theory

Principle of gauge symmetry

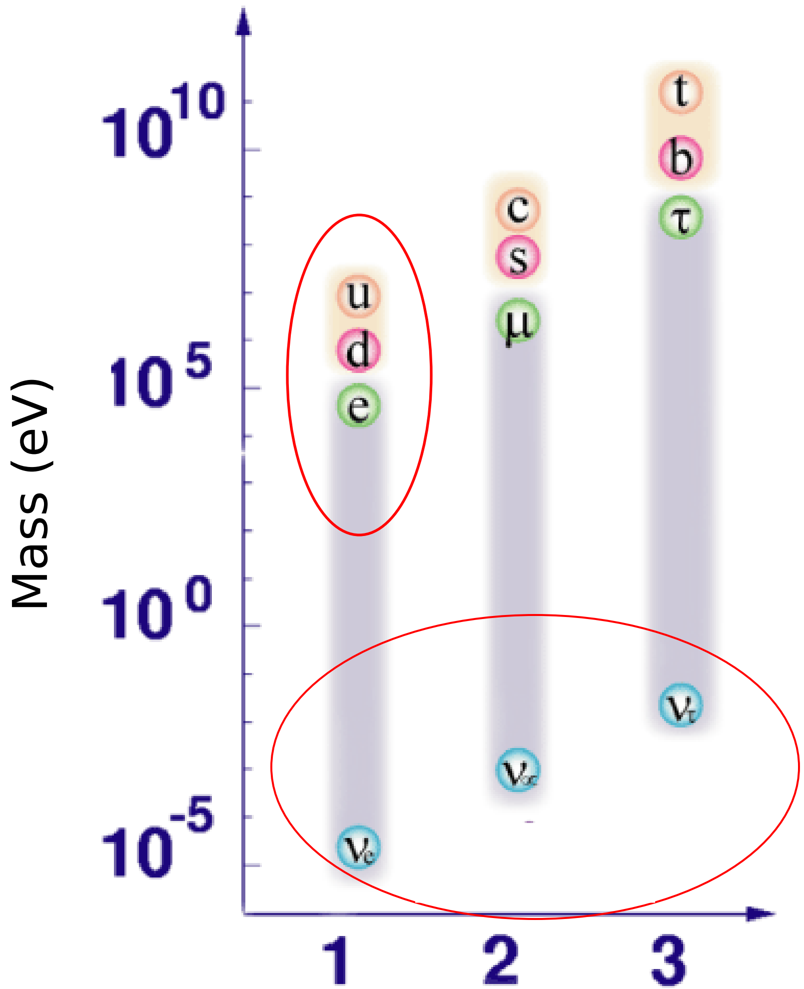
Spontaneously broken gauge symmetry : Higgs

Electroweak theory
QCD



Qaurk and lepton

The basic building blocks



The lightest members

The universe is made of these

But there are many other Members : generation

But, why these copies, and how many generations?

Strong interaction

QCD

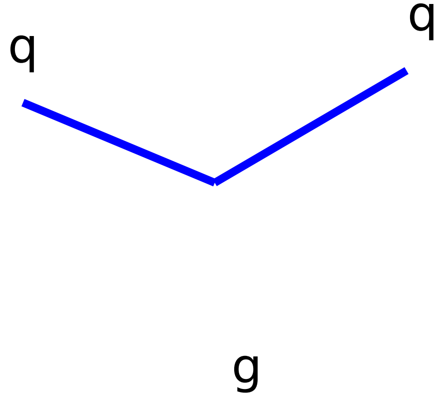
SU(3) symmetry
Color charge

Massless gauge boson : gluon “g”

Single coupling constant : $\alpha s(Q)$

- Very strong at low energy
  - Neither quark nor gluon can be a free particle
  - Always confined in hadrons

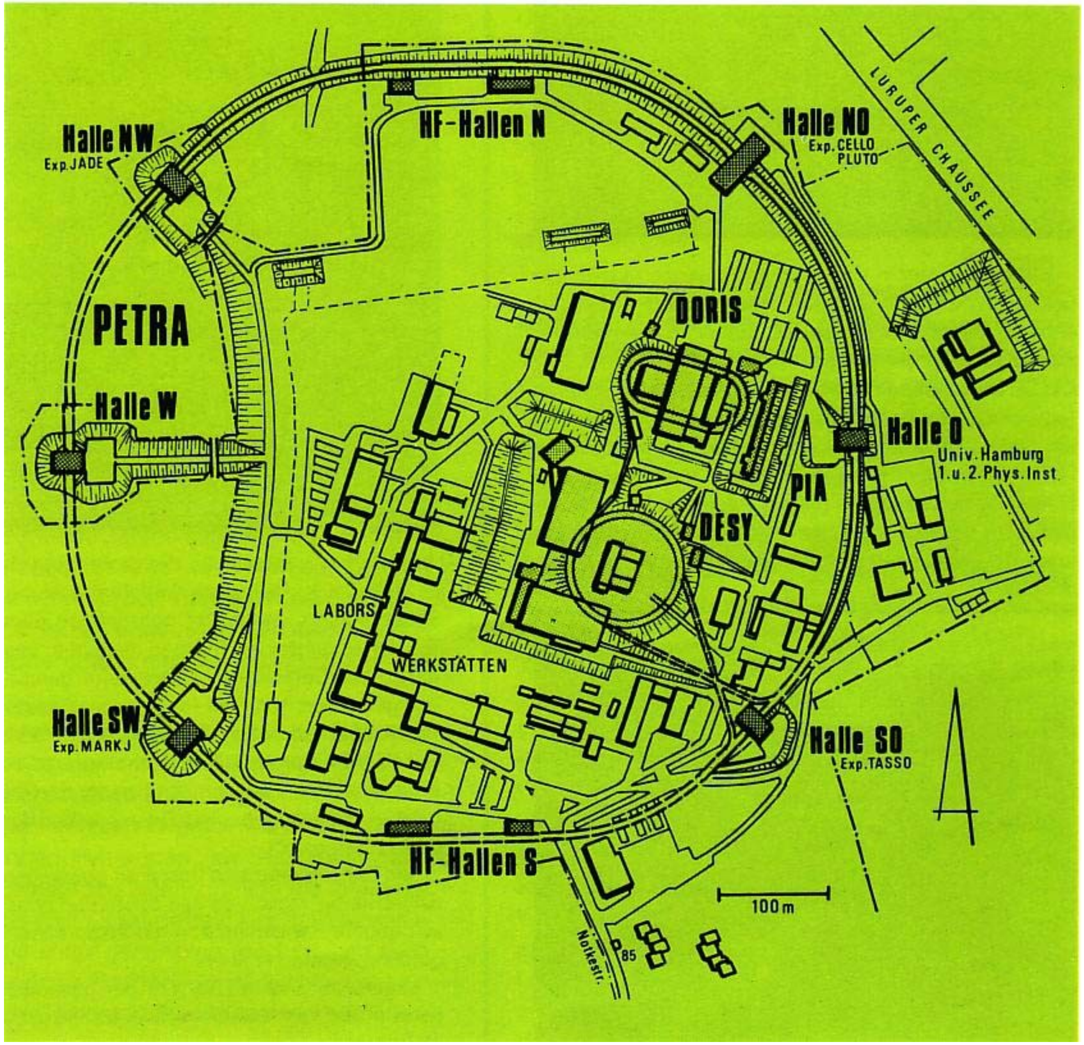
- Become weak at high energy
  - Gluon radiation can be observed



But they soon convert into hadrons

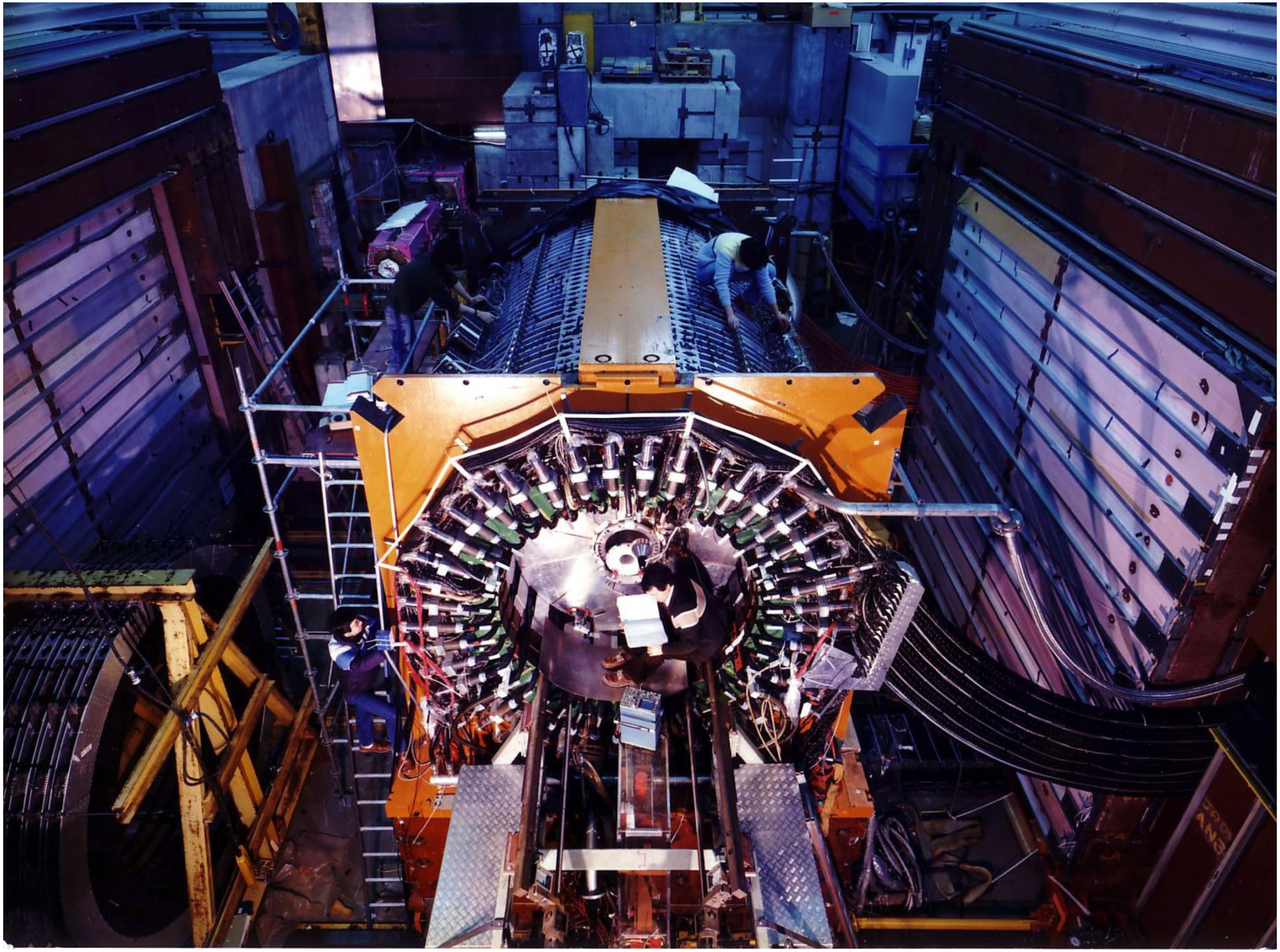
e+e- collider PETRA (1979-1986) DESY, Germany

2.3 km circumference, $\sqrt{s}$=12-47 GeV



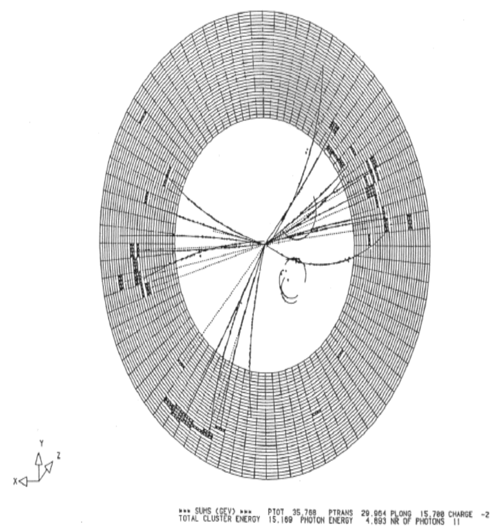
4 experiments
JADE
TASSO
PLUTO/CELLO
MART-J

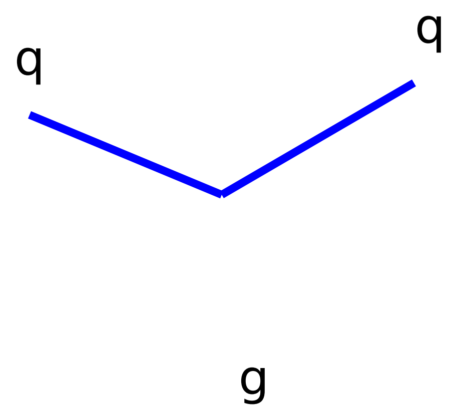
JADE detector at PETRA

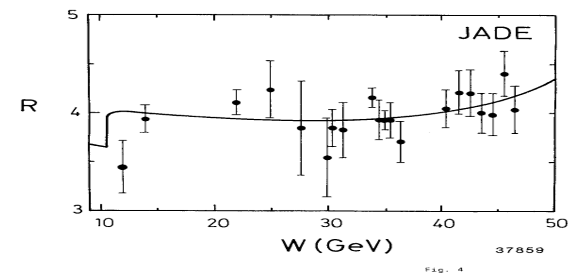


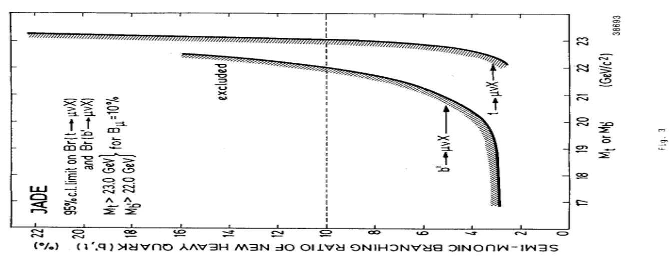
PETRA results

- Discovery of Gluon
- Tests of QCD
- Tests of electroweak theory
- New particle searches



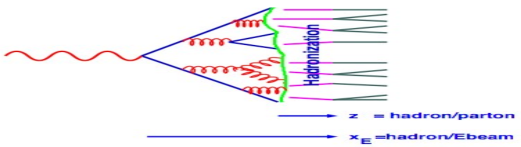




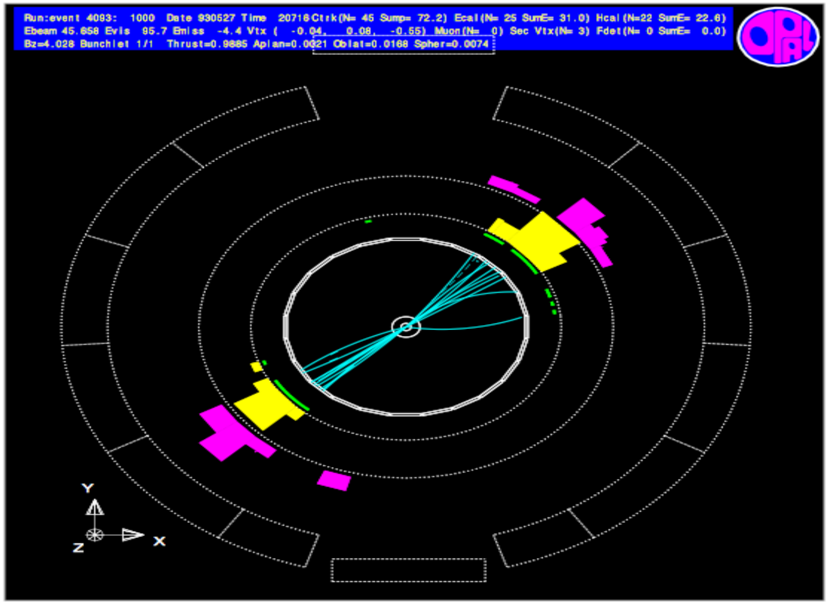


Cross-section for e+e- → qq

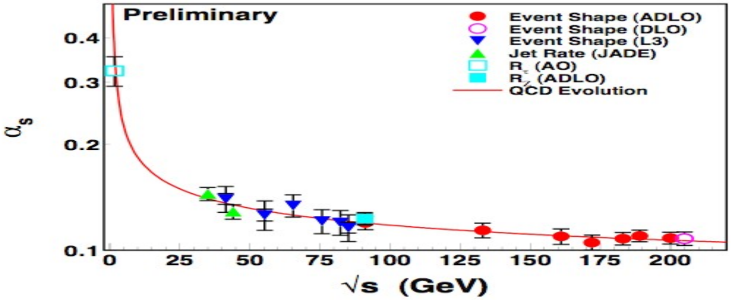
e+e- → qq



Hadronization
z = hadron/parton
x_E =hadron/Ebeam



Run:event 4093: 1000 Date 930527 Time 20716 Ctrk(N= 45 Sump= 72.2) Ecal(N= 25 SumE= 31.0) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis 95.7 Emiss -4.4 Vtx (-0.04, 0.08, -0.55) Muon(N= 0) Sec Vtx(N= 3) Fdet(N= 0 SumE= 0.0)
Bz=4.028 Bunchlet 1/1 Thrust=0.9885 Aplan=0.0021 Oblat=0.0168 Spher=0.0074
Y
X
Z



Preliminary
Event Shape (ADLO)
Event Shape (DLO)
Event Shape (L3)
Jet Rate (JADE)
R_τ (AO)
R_Z (ADLO)
QCD Evolution
α_s
0.4
0.3
0.2
0.1
0
25
50
75
100
125
150
175
200
√s (GeV)

Electromagnetic,
Weak and
Electroweak interaction

QED

Interaction of “electron” and photon

e

Higher order effects can be calculated correctly.

Renormalization