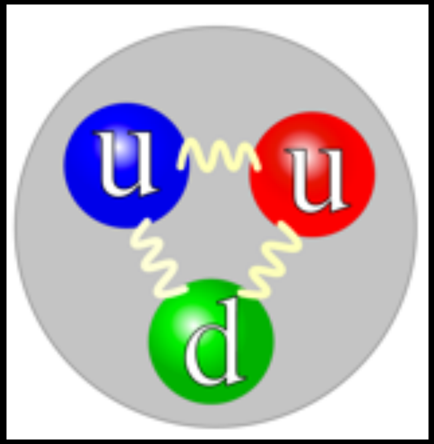
Quarks have fractional charge and spin 1/2

proton(J=1/2) = (even spatial ground state) u↑ u↓ d↑

anti-symmetric spin



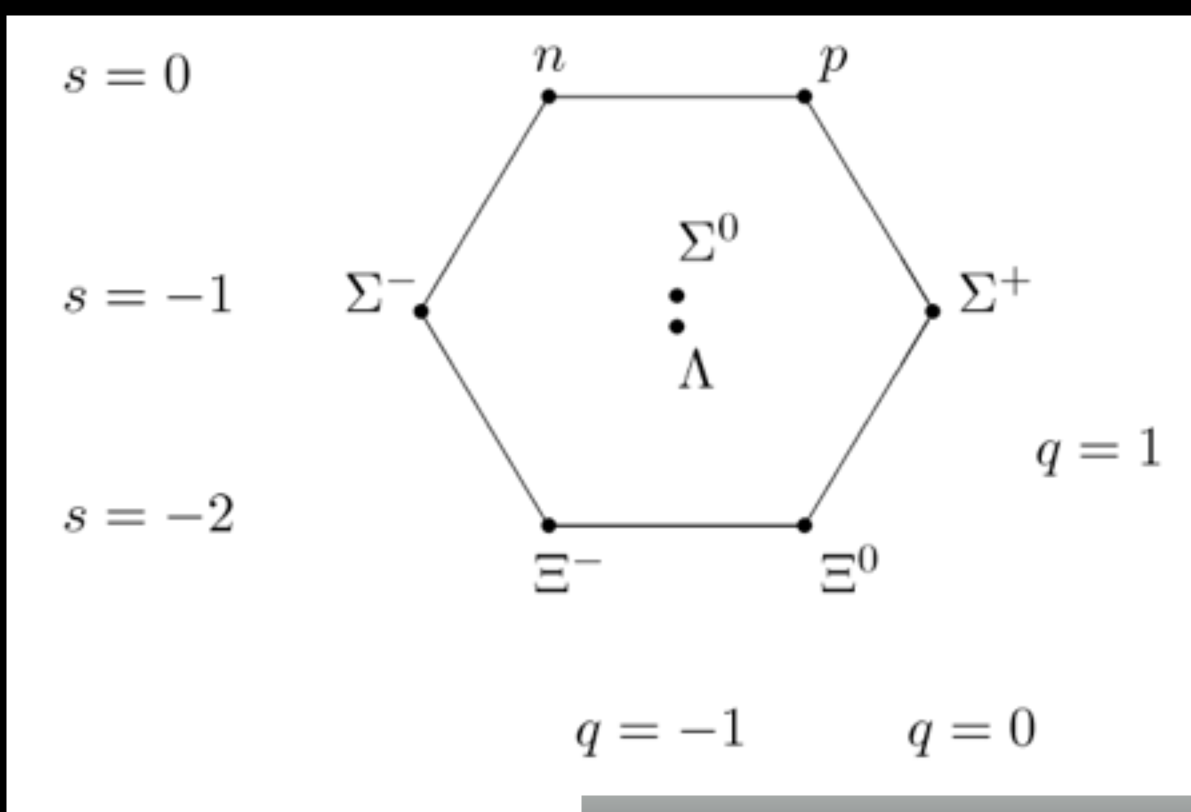
$q_u = +2/3\ e$

$q_d = -1/3\ e$

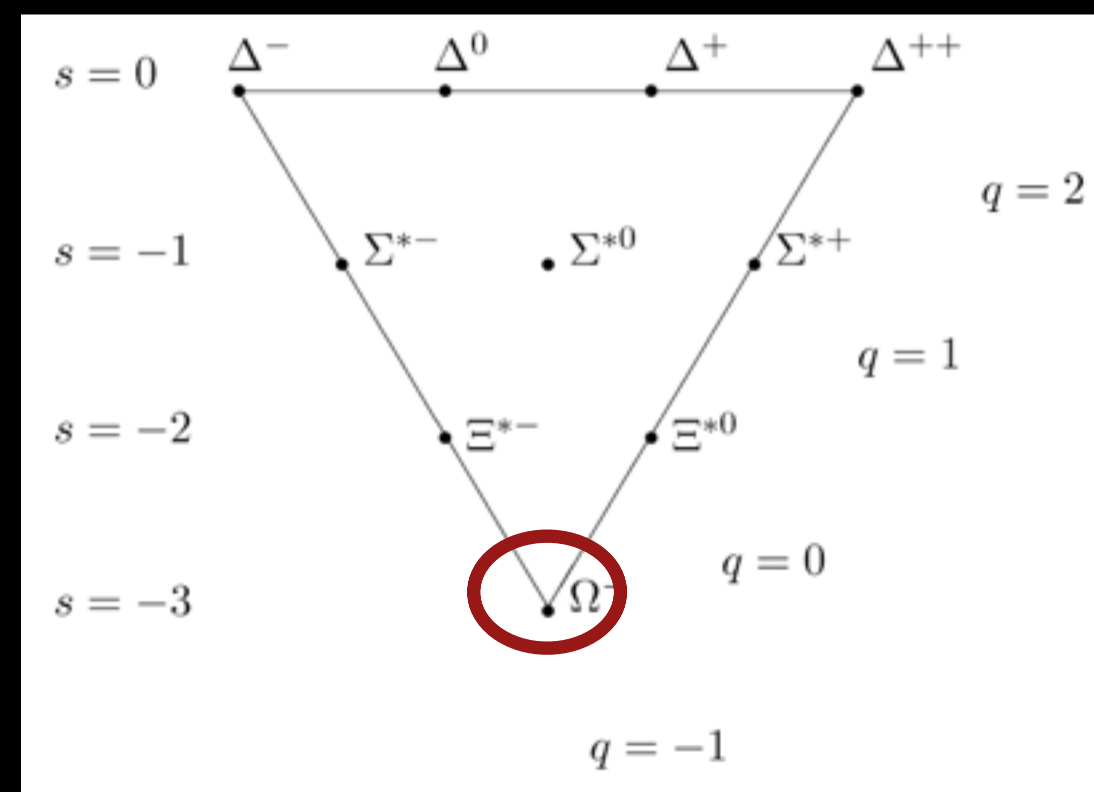
Proliferation of baryons explained by by Gell-Mann: 3 quarks: u,d,s

Proton has spin 1/2
gluons (like photons) have spin 1
only way to get half-integer spin
is to have half-integer spin constituents

spin-1/2 Baryons



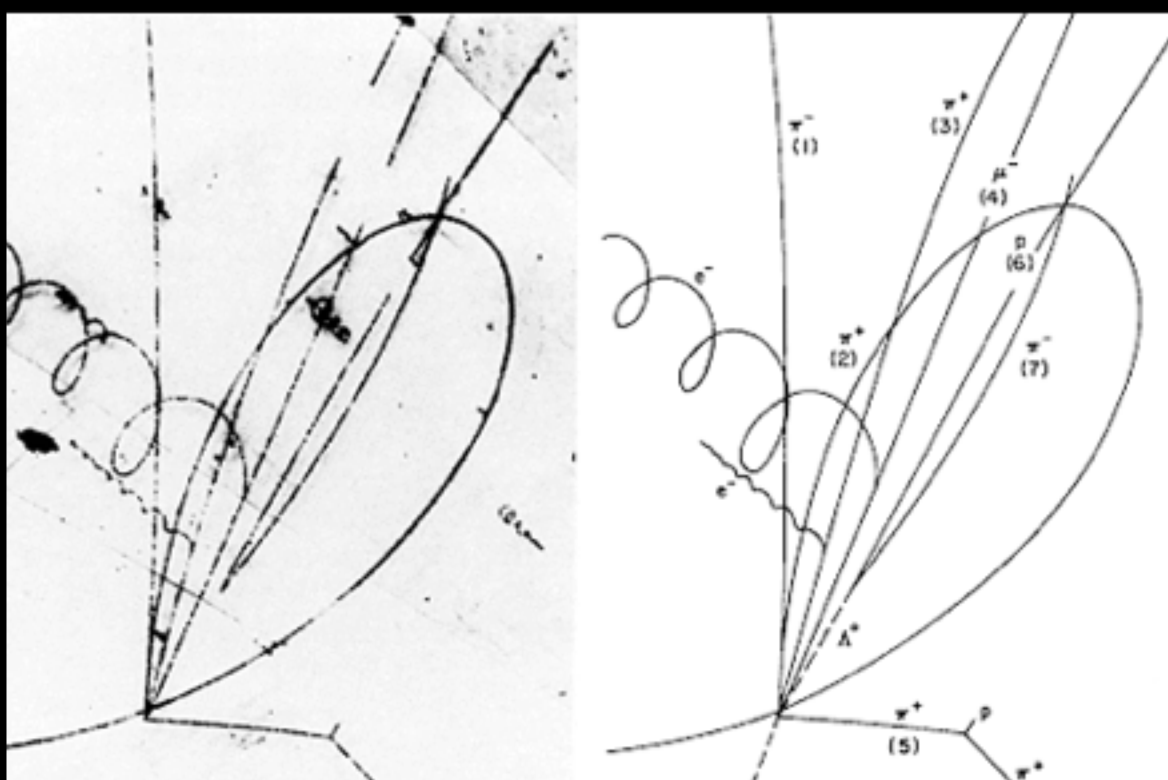
spin-3/2 Baryons



$SU(3)_F$ flavor (u,d,s) symmetry

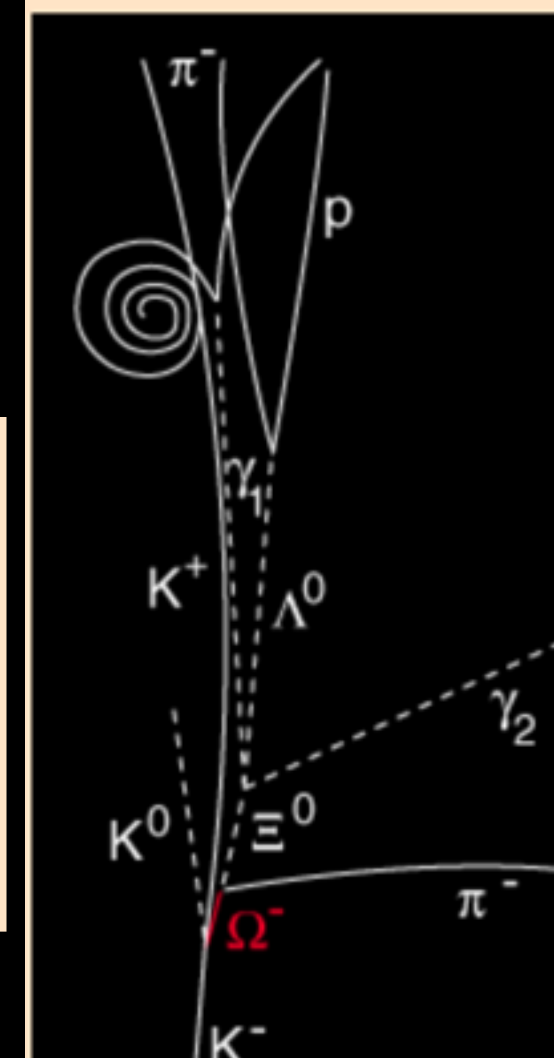
Bottom corner of the spin-3/2 decuplet had not yet observed. Gell-Mann predicted "Ω^-" in 1962 — $J=3/2$, $s=-3$, $q=-1$ and $m \approx 1680$ MeV/c^2 (from strange quark mass scaling)

Discovered at Brookhaven in bubble chamber (1964).



$$\underset{\bar{u}s}{K^-} + \underset{uud}{p} \rightarrow \underset{sss}{\Omega^-} + \underset{u\bar{s}}{K^+} + \underset{d\bar{s}}{K^0}$$

	Lifetime
$\underset{sss}{\Omega^-} \rightarrow \underset{uss}{\Xi^0} + \underset{\bar{u}d}{\pi^-}$	$.8 \times 10^{-10}$ s
$\underset{uss}{\Xi^0} \rightarrow \underset{uds}{\Lambda^0} + 2\gamma$	2.9×10^{-10} s
$\underset{uds}{\Lambda^0} \rightarrow \underset{uud}{p} + \underset{\bar{u}d}{\pi^-}$	2.6×10^{-10} s



V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964)

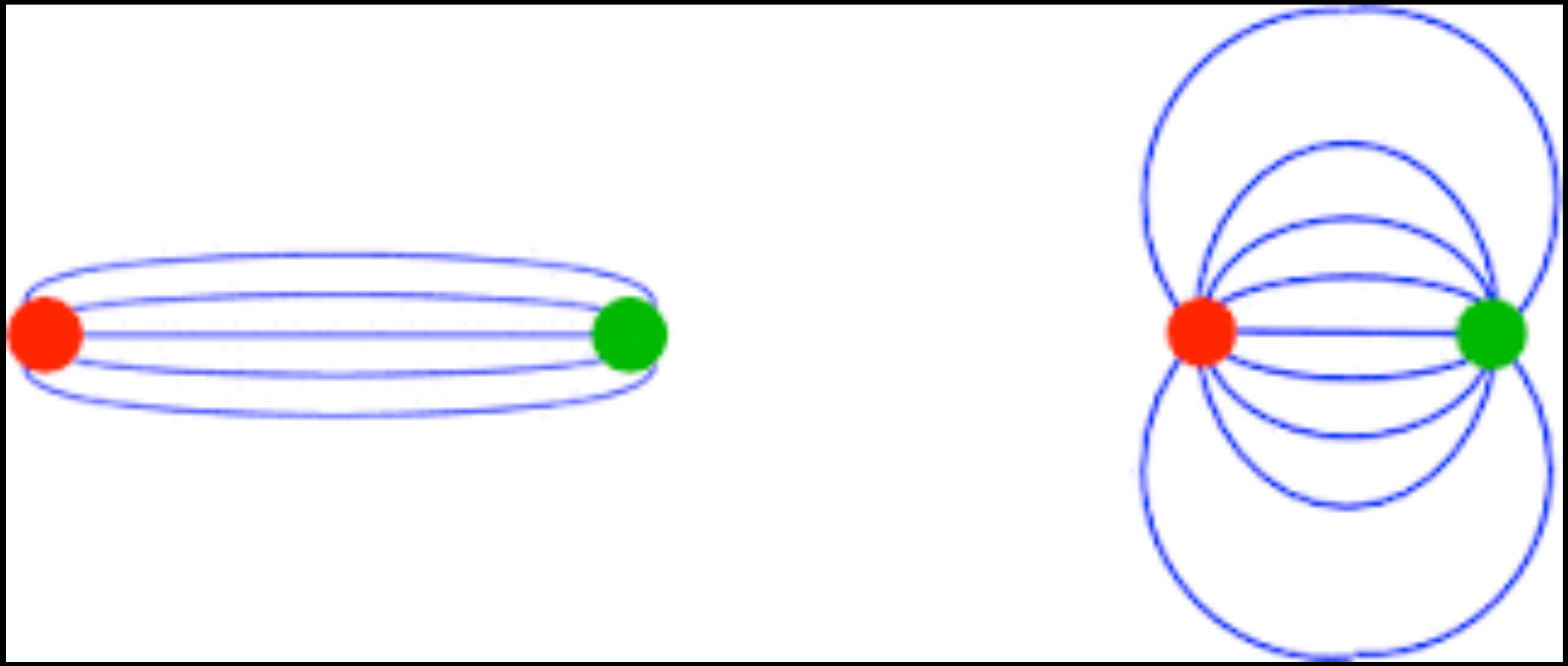
Color: $\Omega^-(J=3/2)$ = (even spatial ground state) $s_r\uparrow$ $s_b\uparrow$ $s_g\uparrow$

invent additional quantum number : color (rbg)
to satisfy exclusion principle

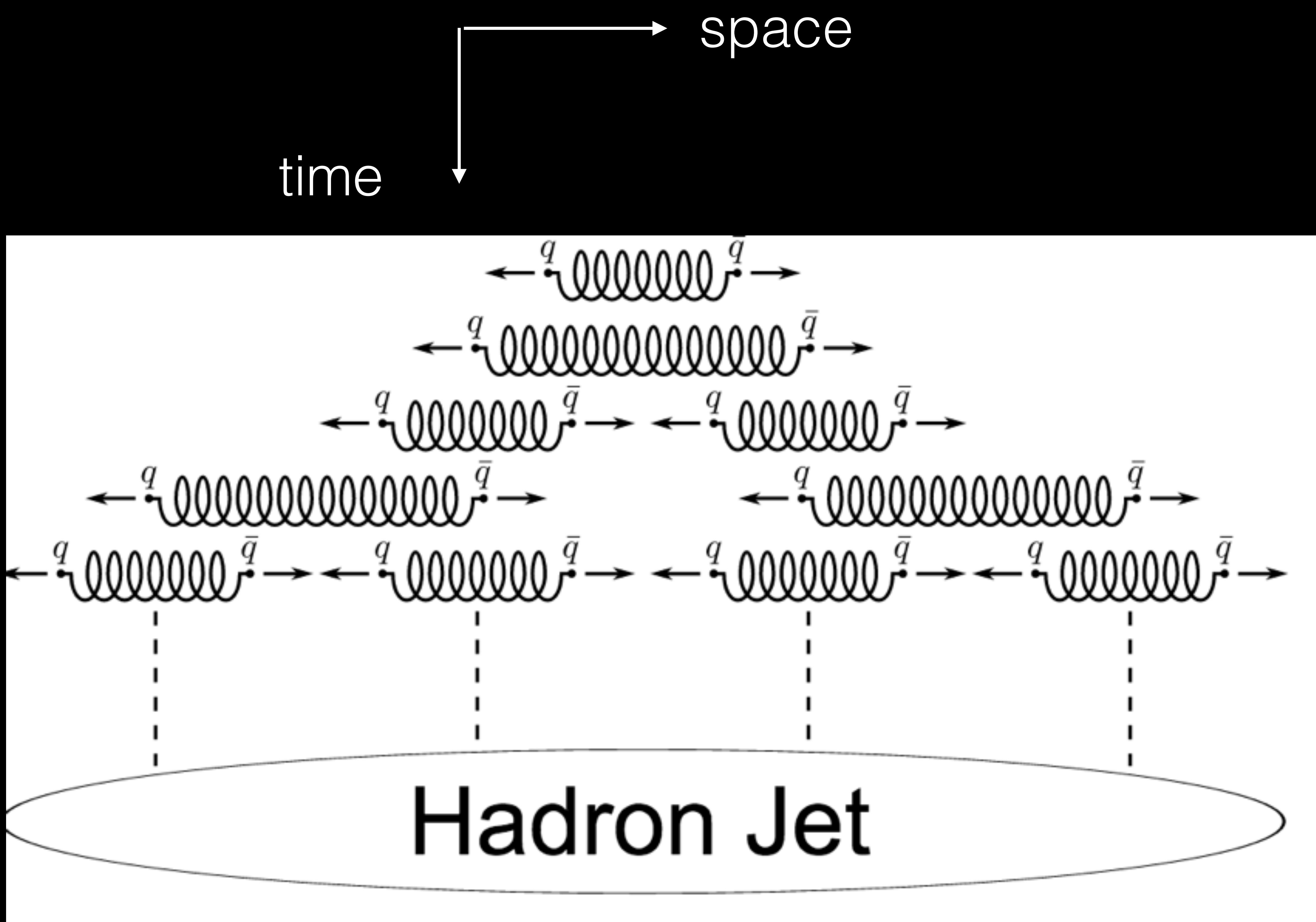
$SU(3)_c$ color (r,b,g) symmetry

QCD force based on this symmetry has properties asymptotic freedom and confinement

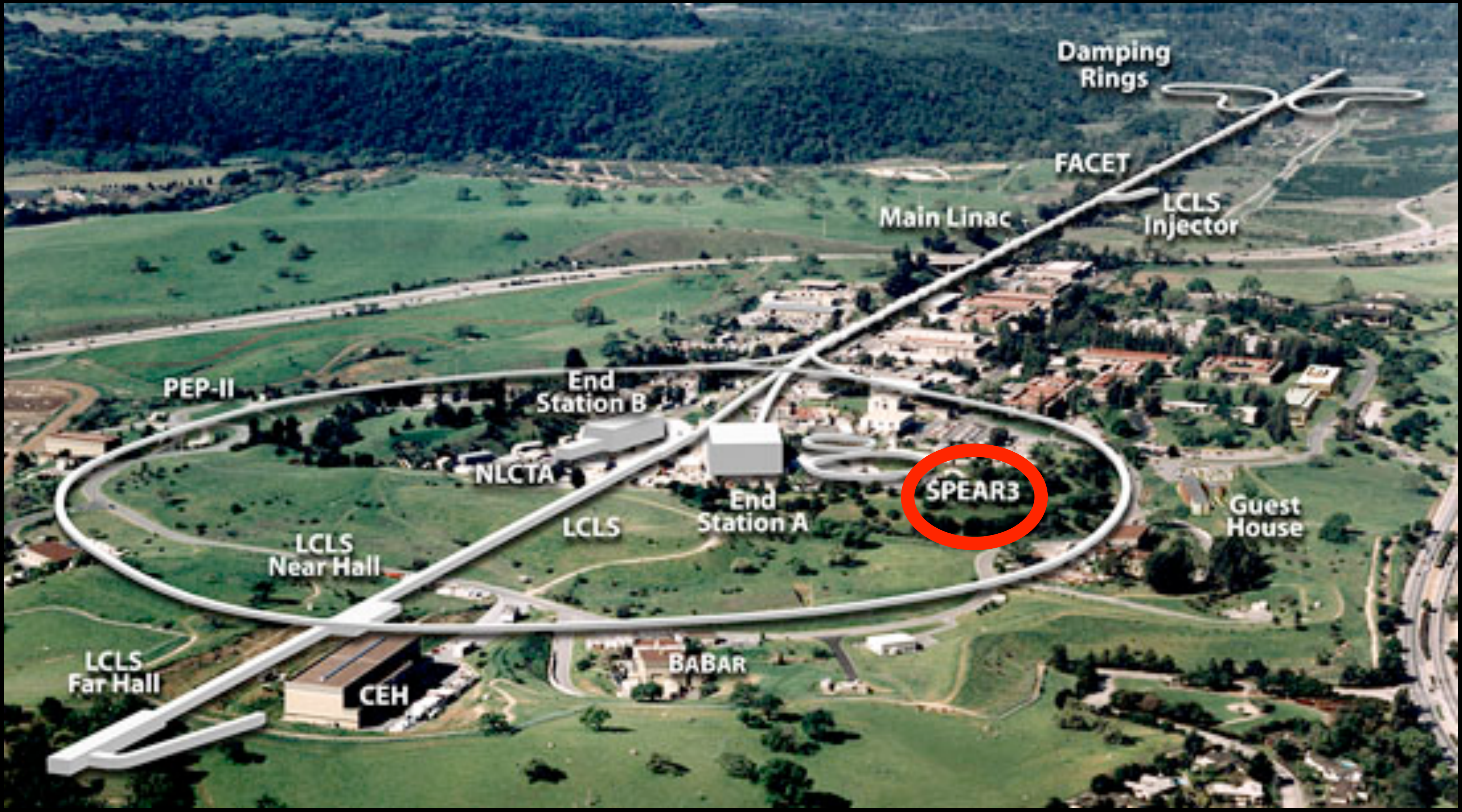
QED: photons have q=0



QCD: gluons have color charge

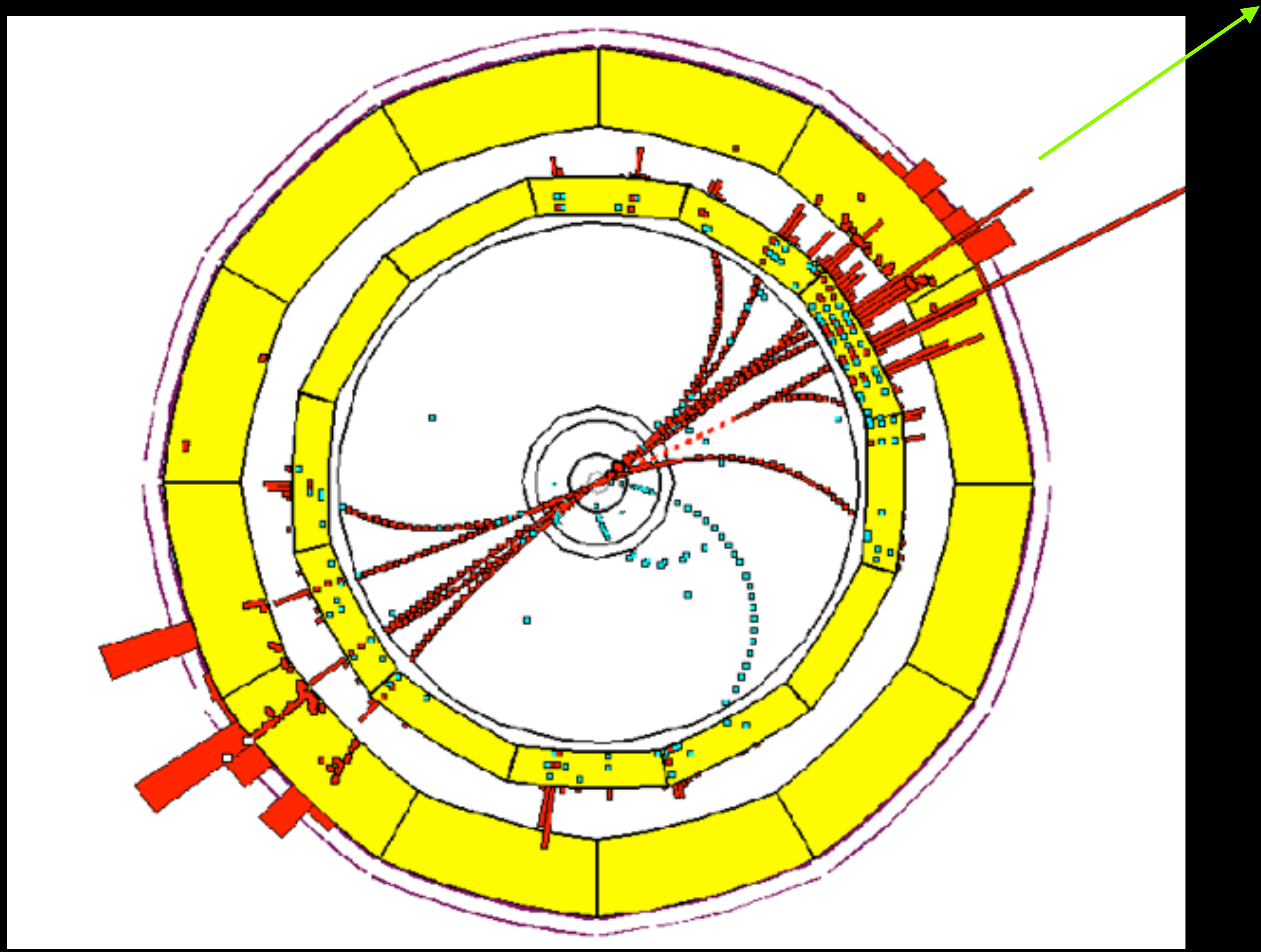

space
time
q
q̄
Hadron Jet

back in the day (1970's) , SLAC, Menlo Park, California



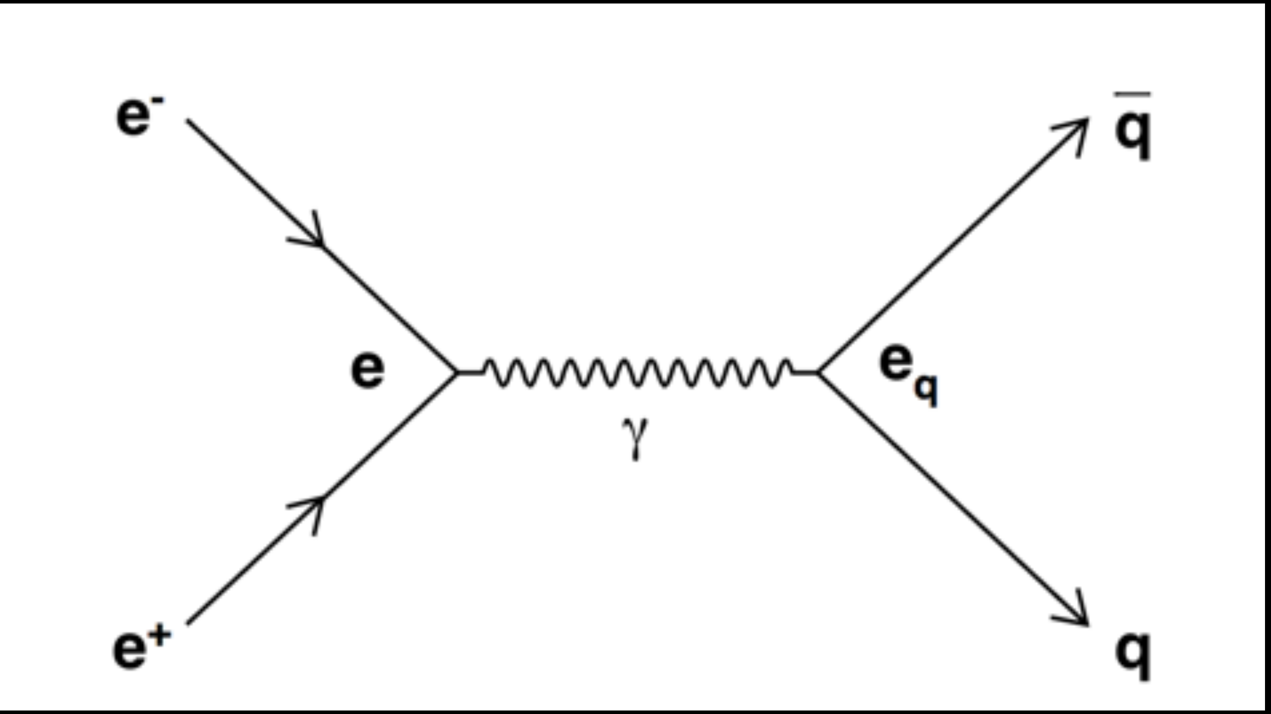
jets in e^+e^- annihilation

jet axis



“jets” of hadrons = pions, etc.

Ratio of total cross sections: hadrons to muons



$$R = \frac{\sigma_{q\bar{q}}}{\sigma_{\mu^+\mu^-}} = 3\Sigma q^2$$

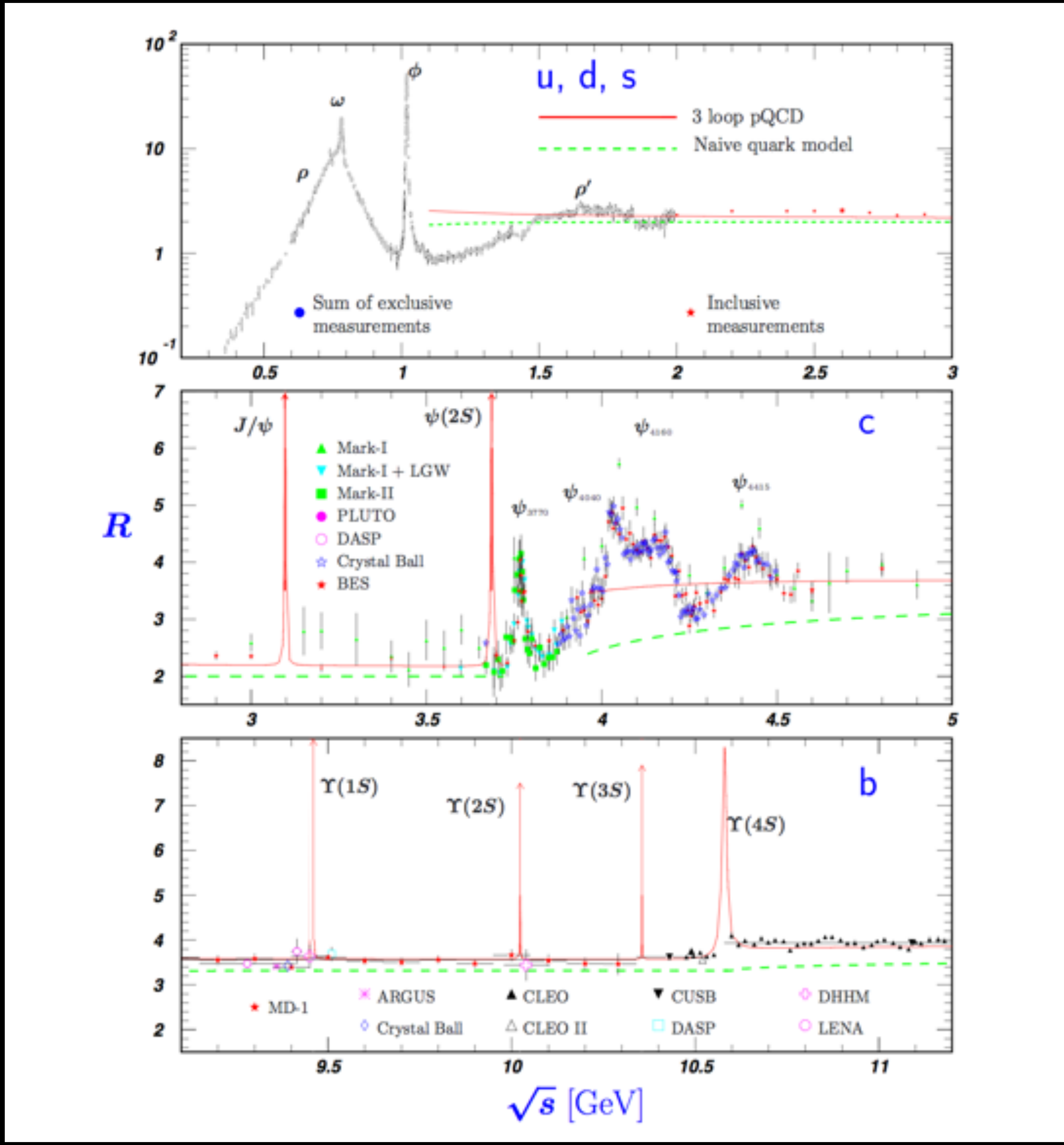
3 for color!

jump in R when $E_{cm} > 2m_q$

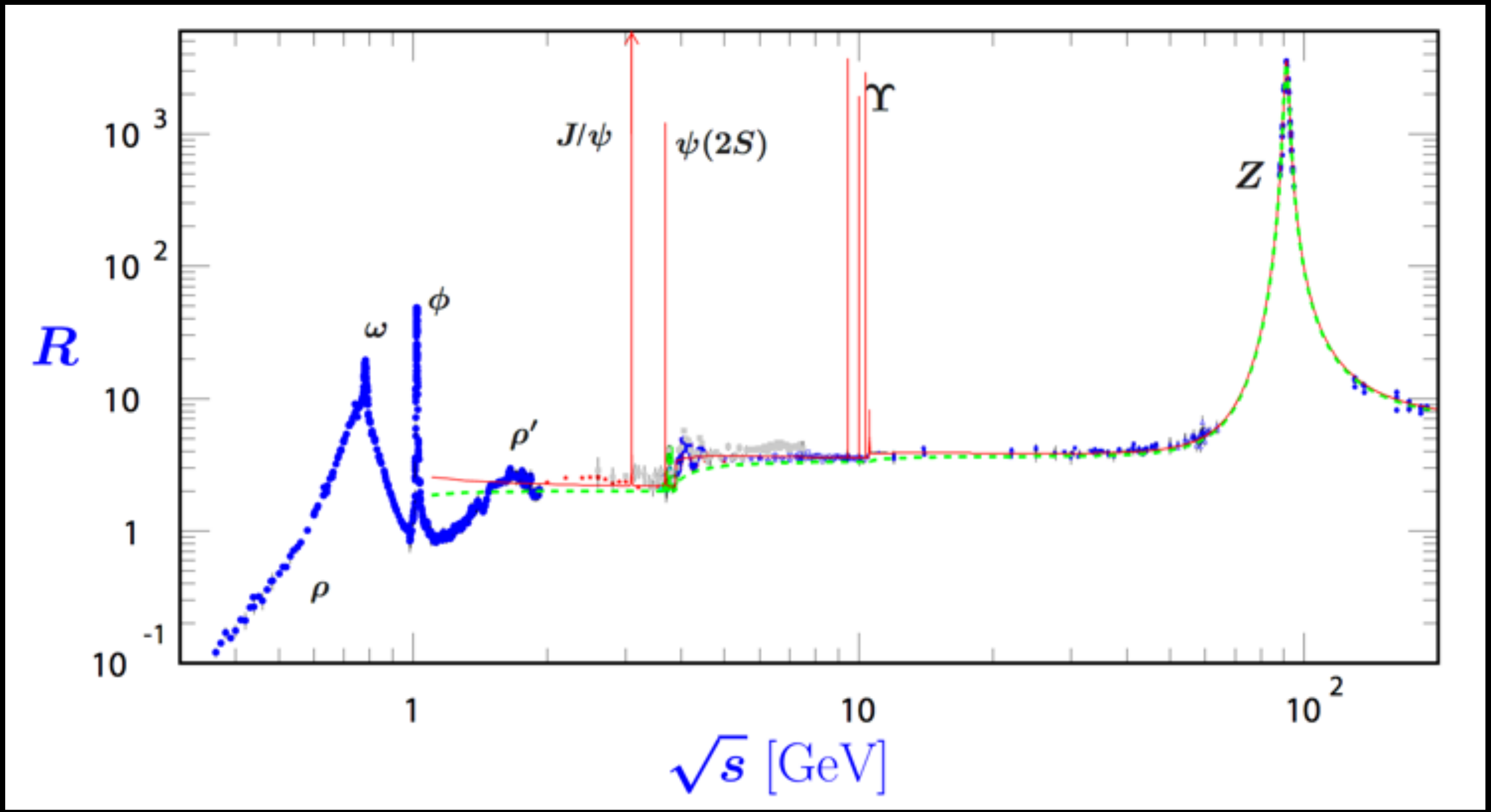
R(u+d+s) = 3(4+1+1)/9=2

R(u+d+s+c) =3(6+4)/9=10/3

R(u+d+s+c+b) =3(10+1)/9=11/3



also, q anti-q bound states appear as resonances



R
10^3
10^2
10
1
10^{-1}
1
10
10^2
$\sqrt{s}$ [GeV]
J/ψ
$\psi(2S)$
Υ
Z
ω
ϕ
ρ'
ρ

angular distribution of jet axis

beams polarized ⊥ plane of storage ring

$$d\sigma/d\Omega \propto 1 + \alpha \cos^2\theta + P^2\alpha \sin^2\theta \cos 2\phi,$$

α=1 for spin 1/2, -1 for spin 0

P is degree of polarization, azimuthal angle ϕ measured from plane of storage ring, polar angle Θ with respect to beam axis

G. Hanson *et al.*, "Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation." *Phys. Rev. Lett.*, **35**, 1609 (1975).

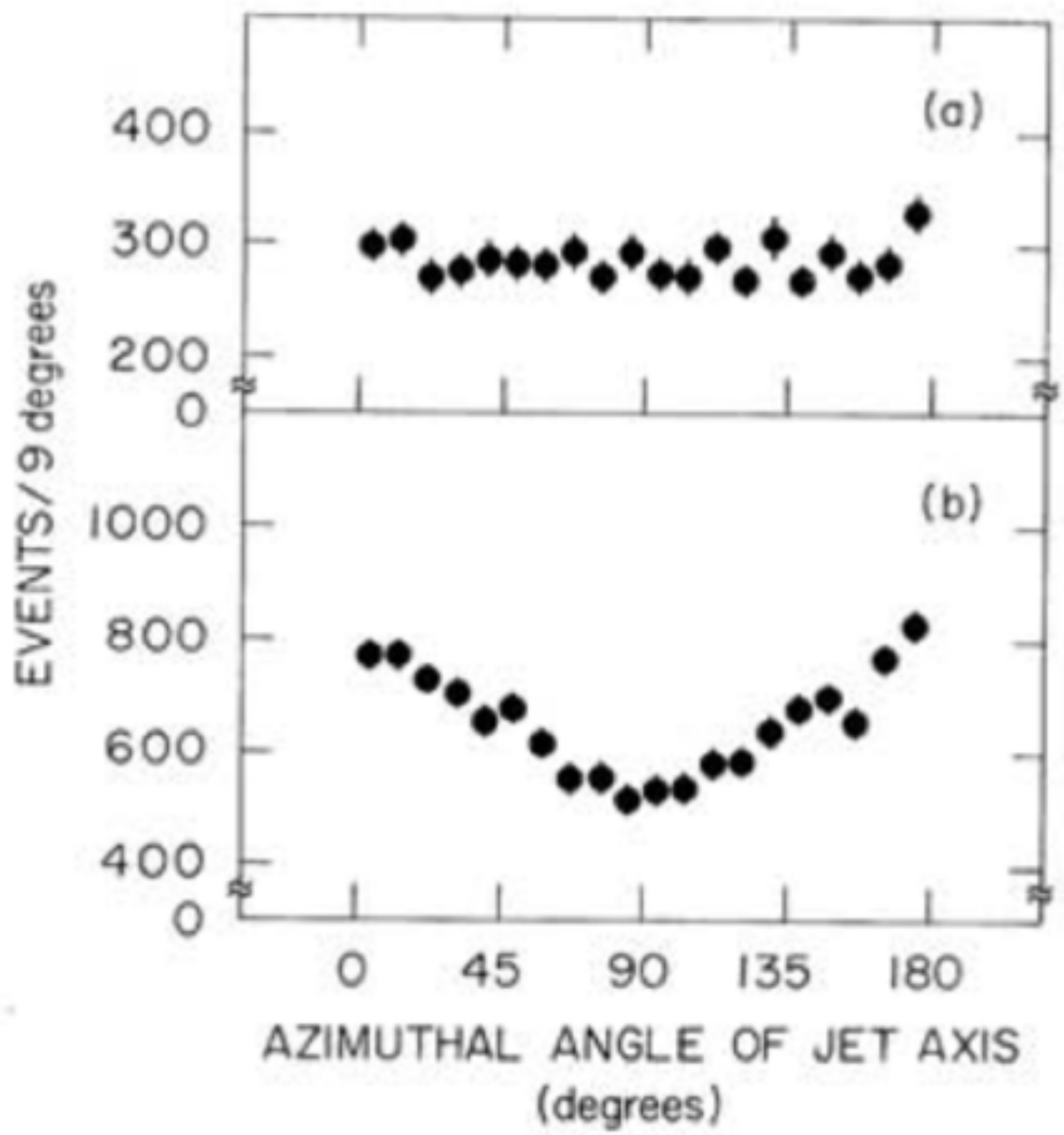


FIG. 3. Observed distributions of jet-axis azimuthal angles from the plane of the storage ring for jet axes with $|\cos\theta| \leq 0.6$ for (a) $E_{c.m.} = 6.2$ GeV and (b) $E_{c.m.} = 7.4$ GeV.

a) unpolarized P=0

b) polarized

quark charge and mass

quark	q	$\approx$ mass(MeV)
u	$2/3$	2.5
d	$-1/3$	5
s	$-1/3$	95
c	$2/3$	1250
b	$-1/3$	4200
t	$2/3$	173,000

quarks are "confined" inside hadrons
(proton, neutron, pion,…)