Q

FINNEGANS WAKE

James Joyce

New York: The Viking Press

1939

riverrun, past Eve and Adam's, from swerve of shore to bend of bay, brings us by a commodius vicus of recirculation back to Howth Castle and Environs.

Sir Tristram, violer d'amores, fr'over the short sea, had passen-core rearrived from North Armorica on this side the scraggy isthmus of Europe Minor to wielderfight his penisolate war: nor had topsawyer's rocks by the stream Oconee exaggerated themselse to Laurens County's gorgios while they went doublin their mumper all the time: nor avoice from afire bellowsed mishe mishe to tauftauf thuartpeatrick: not yet, though venissoon after, had a kidscad buttended a bland old isaac: not yet, though all's fair in vanessy, were sosie sesthers wroth with twone nathandjoe. Rot a peck of pa's malt had Jhem or Shen brewed by arclight and rory end to the regginbrow was to be seen ringsome on the aquaface.

The fall (bababadalgharaghtakamminarronnkonnbronntonner-ronntuonnthunntrovarrhounawnskawntoohoohoordenenthur-nuk!) of a once wallstrait oldparr is retaled early in bed and later on life down through all christian minstrelsy. The great fall of the offwall entailed at such short notice the pftjschute of Finnegan, erse solid man, that the humptyhillhead of humself prumptly sends an unquiring one well to the west in quest of his tumptytumtoes: and their upturnpikepointandplace is at the knock out in the park where oranges have been laid to rust upon the green since dev-linsfirst loved livvy.

sad and weary I go back to you, my cold father, my cold mad father, my cold mad feary father, till the near sight of the mere size of him, the moyles and moyles of it, moananoaning, makes me seasilt saltsick and I rush, my only, into your arms. I see them rising! Save me from those therrble prongs! Two more. Onetwo moremens more. So. Avelaval. My leaves have drifted from me. All. But one clings still. I'll bear it on me. To remind me of. Lff! So soft this morning ours. Yes. Carry me along, taddy, like you done through the toy fair. If I seen him bearing down on me now under whitespread wings like he'd come from Arkangels, I sink I'd die down over his feet, humbly dumbly, only to washup. Yes, tid. There's where. First. We pass through gràss behush the bush to. Whish! A gull. Gulls. Far calls. Coming, far! End here. Us then. Finn, again! Take. Bussoftlhee, mememormee! Till thousendsthee. Lps. The keys to. Given! A way a lone a last a loved a long the

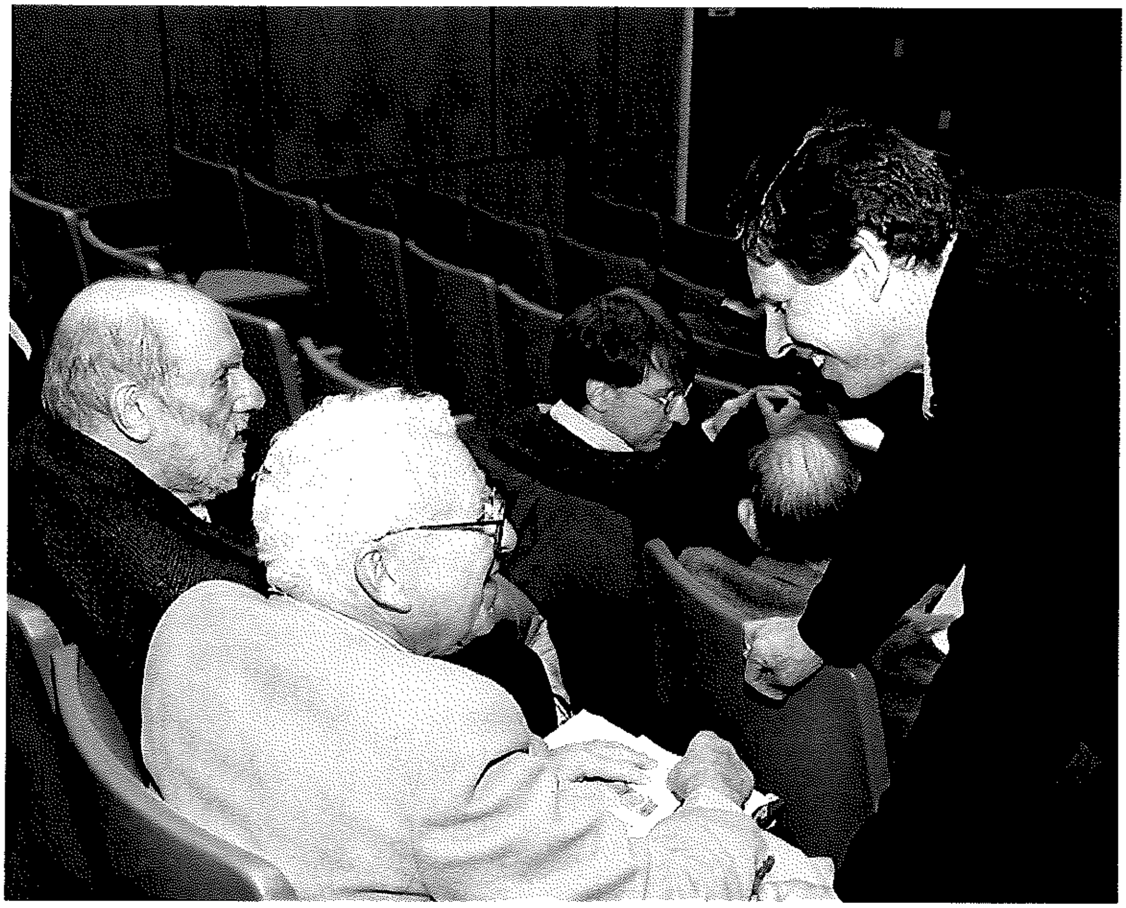
PARIS,
1922-1939.

— Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.
But O, Wreneagle Almighty, wouldn't un be a sky of a lark
To see that old buzzard whooping about for uns shirt in the dark
And he hunting round for uns speckled trousers around by Palmerstown Park?
Hohohoho, moulty Mark!
You're the rummest old rooster ever flopped out of a Noah's ark
And you think you're cock of the wark.
Fowls, up! Tristy's the spry young spark
That'll tread her and wed her and bed her and red her
Without ever winking the tail of a feather
And that's how that chap's going to make his money and mark!

Overhoved, shrillgleescreaming. That song sang seaswans. The winging ones. Seahawk, seagull, curlew and plover, kestrel and capercallzie. All the birds of the sea they trolled out rightbold when they smacked the big kuss of Trustan with Usolde.

And there they were too, when it was dark, whilest the wild-caps was circling, as slow their ship, the winds aslight, upborne the fates, the wardorse moved, by courtesy of Mr Deaubaleau Downbellow Kaempersally, listening in, as hard as they could, in Dubbeldorp, the donker, by the tourneyold of the wattarfalls, with their vuoxens and they kemin in so hattajocky (only a

Charles Sommerfield, Murray Gell-Mann and Barton Zwiebach



Quark model

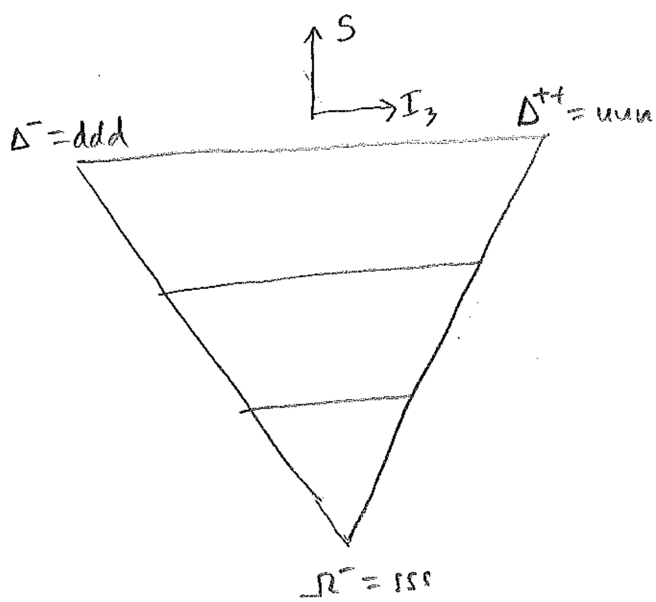
To explain the patterns of mesons and baryons,

Murray Gell-Mann and George Zweig independently proposed that hadrons are constituted of 3 types ("flavors") of more fundamental particles, called u, d, s.

Zweig called them "aces"

Gell-Mann called them "quarks"

[Finnegan's Wake]



	I_3	S	A	q
Δ^{++}	$\frac{3}{2}$	0	1	2
Δ^-	$-\frac{3}{2}$	0	1	-1
Ω^-	0	-3	1	-1
u	$\frac{1}{2}$	0	$\frac{1}{3}$	$\frac{2}{3}$
d	$-\frac{1}{2}$	0	$\frac{1}{3}$	$-\frac{1}{3}$
s	0	-1	$\frac{1}{3}$	$-\frac{1}{3}$

Quarks are fractionally charged!

Fractionally charged particles have never been observed (in isolation)

1960's deep skepticism about the physical reality of quarks (incl. by Gell-Mann)

Deep inelastic scattering expts at SLAC in late 1960's showed ~~that~~ hadrons had substructure

Quarks are believed to be permanently confined.

Strange particles are those containing 1 or more s quarks

Mass of the strange quark about 150 MeV more than u + d accounts for breaking of degeneracy of supermultiplets

---

Quarks have $A = \frac{1}{3}$, antiquarks $A = -\frac{1}{3}$

Baryons (qqq) have $A = 1$, mesons ($q\bar{q}$) have $A = 0$

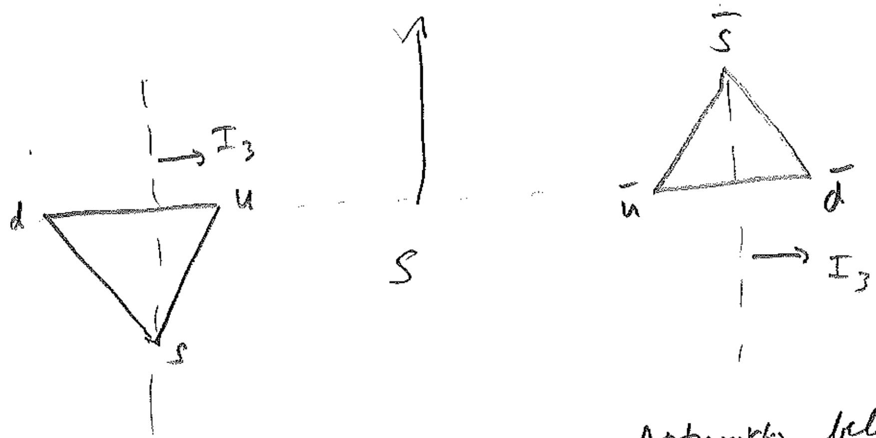
Baryon # conservation is really quark # conservation

Standard model conserves both quark + lepton #

GUTs allow quarks → leptons, violating both (proton decay)

Q3

Quarks belong to the fundamental representation of $SU(3)_{flavor}$



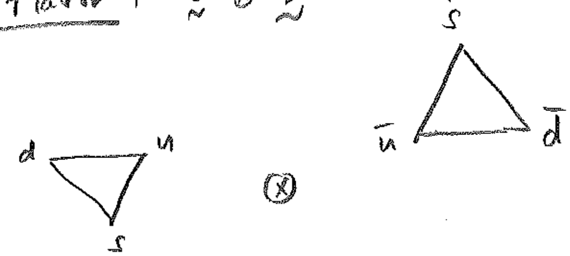
Antiquarks belong to $\bar{\underset{\sim}{3}}$

Quarks belong to $\underset{\sim}{3}$ of $SU(3)_{flavor}$

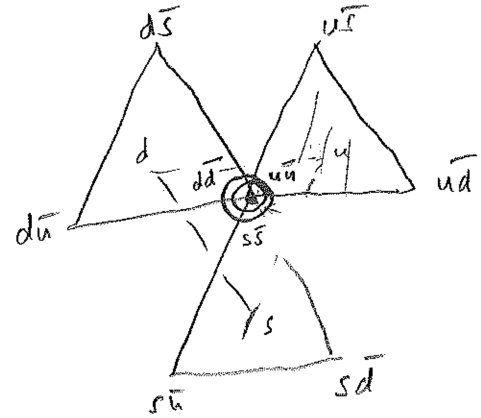
u, d belong to $\underset{\sim}{2}$ of $SU(2)$ isospin
s belong to $\underset{\sim}{1}$ of $SU(2)$ isospin

Q4

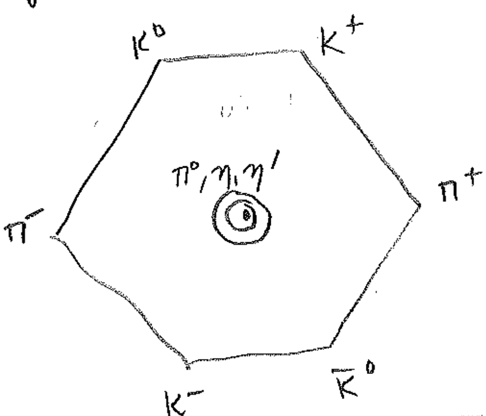
Meson flavor: $\underset{\sim}{3} \otimes \underset{\sim}{\bar{3}}$



Center the △ on each vertex of ▽



This is just the meson nonet!



π^0, η, η' are linear combinations of $u\bar{u}, d\bar{d}, s\bar{s}$

$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

$$\eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

$$\left[\begin{aligned} \rho^0 &= \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \\ \omega &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \\ \phi &= s\bar{s} \end{aligned}\right]$$

In actuality $\underset{\sim}{3} \times \underset{\sim}{\bar{3}} = \underset{\sim}{8} \oplus \underset{\sim}{1}$ $\left\{ \begin{array}{l} \eta' \text{ belongs to } \underset{\sim}{1} \\ \text{Rest belongs to } \underset{\sim}{8} \end{array} \right.$

symmetric combination $\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$

Don't present this!

[C 13]

Isospin of quarks: $|\tfrac{1}{2}\rangle = u$

$|-\tfrac{1}{2}\rangle = d$

antiquarks $|\tfrac{1}{2}\rangle = -\bar{d}$ (minus for technical reasons)

$|-\tfrac{1}{2}\rangle = \bar{u}$

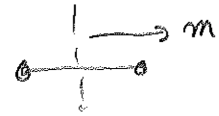
mesons $|1,1\rangle = |\tfrac{1}{2}; \tfrac{1}{2}\rangle = -u\bar{d} = \pi^+$

$|1,0\rangle = \frac{1}{\sqrt{2}}\left(|\tfrac{1}{2}; -\tfrac{1}{2}\rangle + |-\tfrac{1}{2}; \tfrac{1}{2}\rangle\right) = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) = \pi^0$

$|1,-1\rangle = |-\tfrac{1}{2}; -\tfrac{1}{2}\rangle = d\bar{u} = \pi^-$

Quarks + antiquarks have spin $\frac{1}{2}$

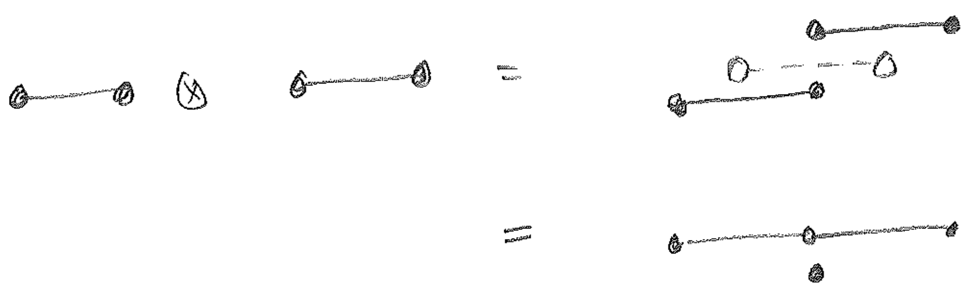
$\Rightarrow$ belong to $\underset{\sim}{2}$ of $SU(2)_{spin}$



<u>meson spin</u>: $\underset{\sim}{2} \otimes \underset{\sim}{2} = \underset{\sim}{3} \oplus \underset{\sim}{1}$

spin 1 = vector meson

spin 0 = scalar meson



3

1

Baryons = 3 quarks

Recall Baryon decuplet has $J = \frac{3}{2}$

Consider the $J_z = \frac{3}{2}$ state of $\Delta^{++} = uuu$

$$(u\uparrow)(u\uparrow)(u\uparrow)$$

Problem: this state is totally symmetric under exchange of quarks but quarks are fermions, so must be totally antisymmetric (TA) under exchange of identical particles.

Solution: the quarks are not identical; they are distinguished by an attribute called color which comes in 3 distinct varieties: R, G, B

[O.W. Greenberg 1964] $(u\uparrow R)(u\uparrow G)(u\uparrow B)$

More precisely, to make the state TA, define

$$\underset{\sim}{1}_{TA} = \frac{1}{\sqrt{6}}(RGB + GBR + BRG - RBG - BGR - GRB)$$

We say that baryons belong to the $\underset{\sim}{1}_{TA}$ of color (a.k.a. color singlet state)

Baryon spin

$$\underset{\sim}{2} \otimes \underset{\sim}{2} \otimes \underset{\sim}{2} = \underset{\sim}{4}_{TS} \oplus \underbrace{\underset{\sim}{2}_S \oplus \underset{\sim}{2}_A}$$

spin $\frac{3}{2}$ (decuplet) spin $\frac{1}{2}$ (octet) [do on side board]

Recall

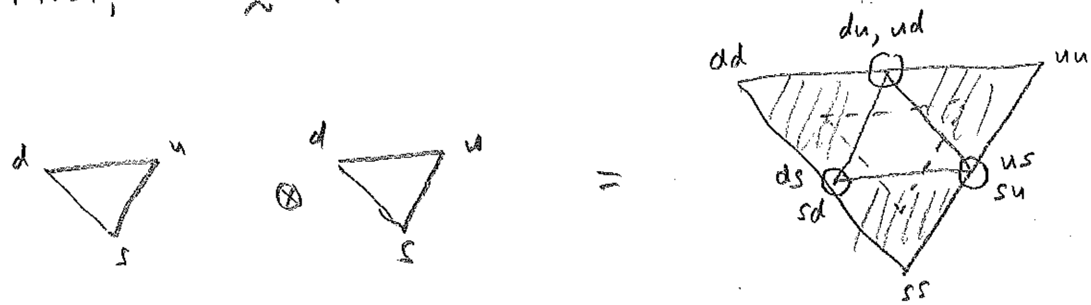
$$\underset{\sim}{4}_{TS} \text{ states are } \begin{cases} \uparrow\uparrow\uparrow \\ \frac{1}{\sqrt{3}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow) \\ \frac{1}{\sqrt{3}}(\uparrow\downarrow\downarrow + \downarrow\uparrow\downarrow + \downarrow\downarrow\uparrow) \quad] \text{ omit} \\ \downarrow\downarrow\downarrow \end{cases}$$

$$\underset{\sim}{2}_S \text{ states are } \begin{cases} \frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \\ \frac{1}{\sqrt{6}}(\uparrow\downarrow\downarrow + \downarrow\uparrow\downarrow - 2\downarrow\downarrow\uparrow) \quad] \text{ omit} \end{cases}$$

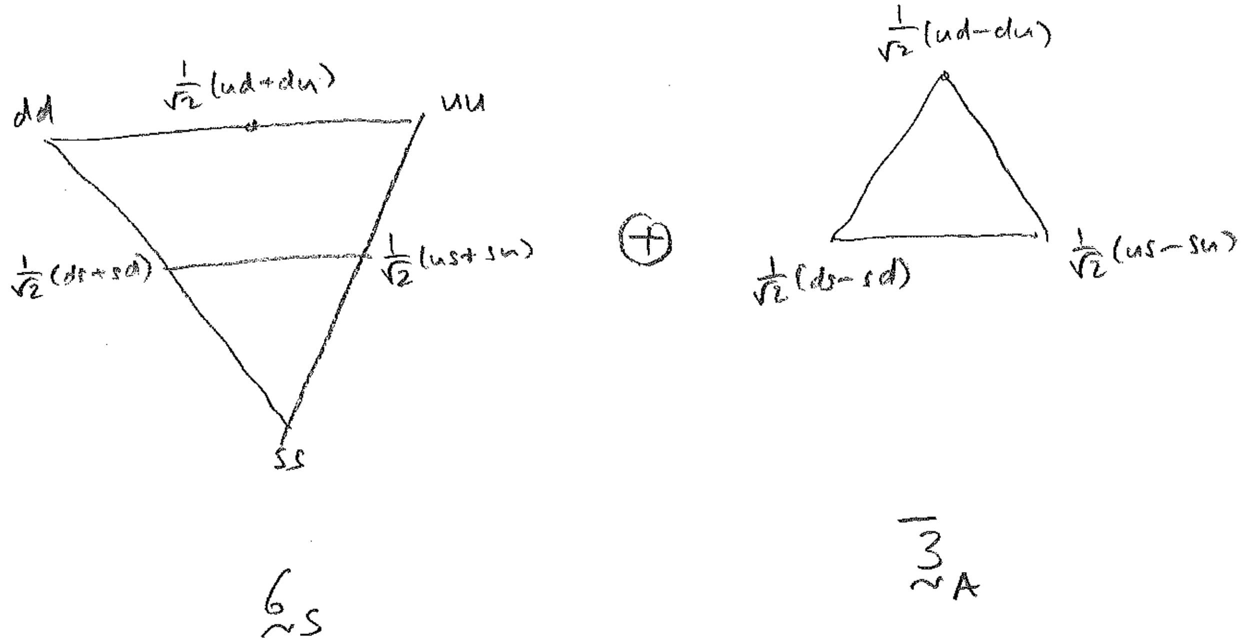
$$\underset{\sim}{2}_A \text{ states are } \begin{cases} \frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \\ \frac{1}{\sqrt{2}}(\uparrow\downarrow\downarrow - \downarrow\uparrow\downarrow) \quad] \text{ omit} \end{cases}$$

<u>Baryon flavor</u> $\underset{\sim}{3} \otimes \underset{\sim}{3} \otimes \underset{\sim}{3}$

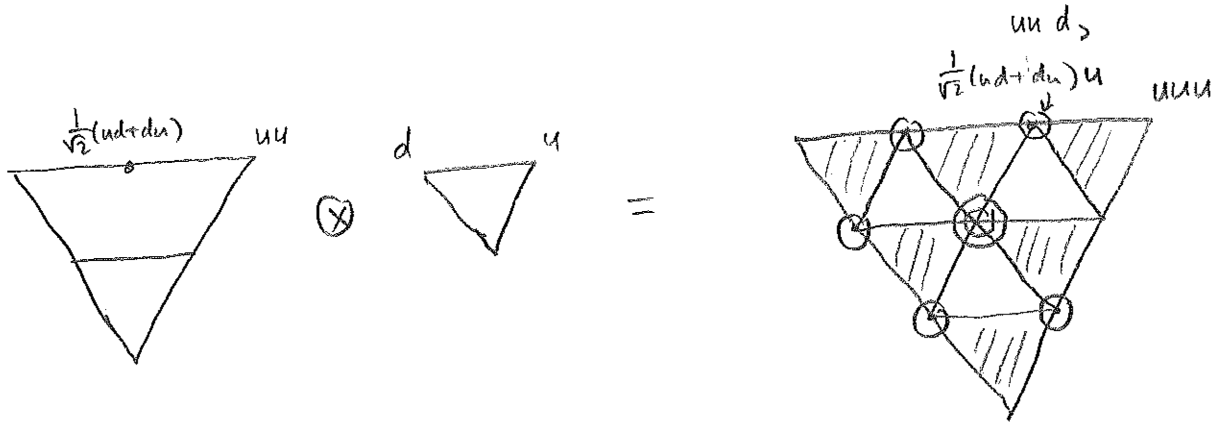
First, do $\underset{\sim}{3} \otimes \underset{\sim}{3}$



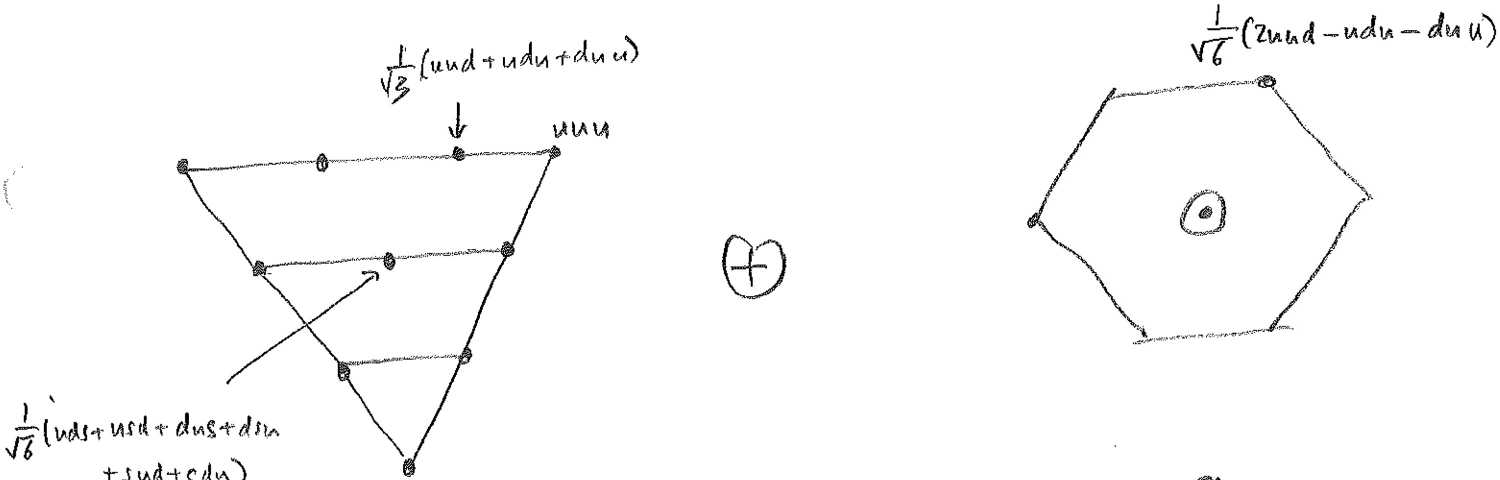
Decompose these 9 states into sym and anti combination



Next: $\underset{\sim}{6}_S \otimes \underset{\sim}{3}$

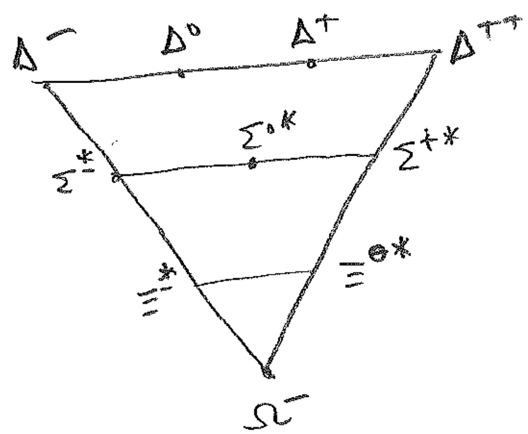


Decompose these 18 states into TS + S combinations



$\underset{\sim}{10}_{TS}$ $\qquad$ $\underset{\sim}{8}_S$

This is the baryon decuplet

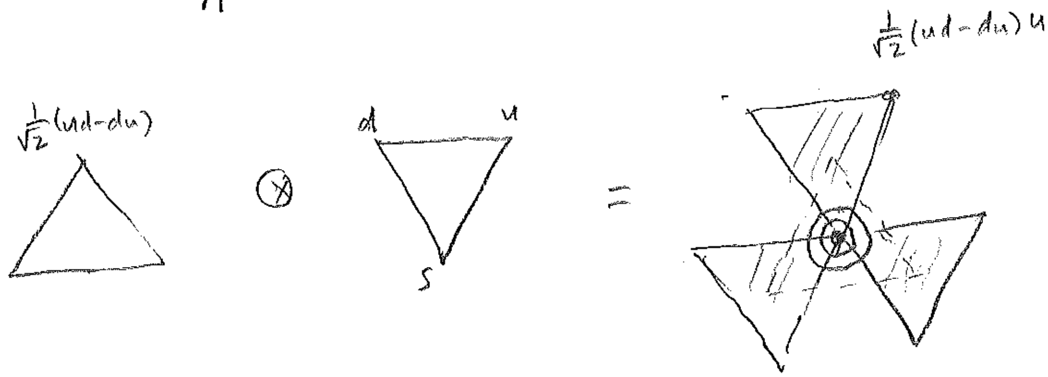


belongs to $(\underset{\sim}{4}_{TS}, \underset{\sim}{10}_{TS}, \underset{\sim}{1}_{TA})$

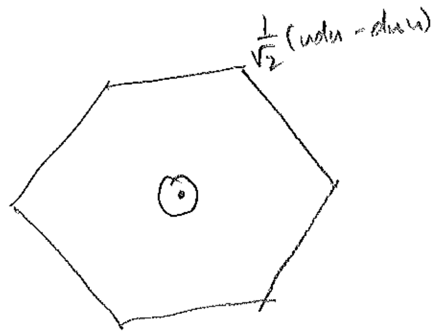
of (spin, flavor, color)

observe that it is overall TA

Next: $\bar{\underset{\sim}{3}}_A \otimes \underset{\sim}{3}$



Decompose these 9 states into



$\oplus$

$\frac{1}{\sqrt{6}}(uds-dus+dsu-sdu+sud-usd)$

$\underset{\sim}{8}_A$ $\qquad$ $\underset{\sim}{1}_A$

Altogether: $\underset{\sim}{3}\otimes\underset{\sim}{3}\otimes\underset{\sim}{3} = \underset{\sim}{10}_{TA} \oplus \underbrace{\underset{\sim}{8}_S \oplus \underset{\sim}{8}_A}_{} \oplus \underset{\sim}{1}_{TA}$

Baryon decuplet
$(\underset{\sim}{4}_{TS}, \underset{\sim}{10}_{TS}, \underset{\sim}{1}_{TA})$

no baryon corresponds to this flavor state. One would need a TA spin state, which does not exist

Baryon octet

$\underbrace{(\underset{\sim}{2}_S, \underset{\sim}{8}_S, \underset{\sim}{1}_{TA}) + (\underset{\sim}{2}_A, \underset{\sim}{8}_A, \underset{\sim}{1}_{TA})}_{}$ of (spin, flavor, color)

This linear combo is TA overall
(see handout)

Q11

The spin and flavor wavefunctions

$$2_S = \frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \qquad \text{of } \mathrm{SU}(2)_{\text{spin}}$$

$$8_S = \frac{1}{\sqrt{6}}(2uud - udu - duu) \qquad \text{of } \mathrm{SU}(3)_{\text{flavor}}$$

are both symmetric under exchange of the first two entries. Therefore,

$$\begin{aligned}(2_S, 8_S) = \frac{1}{6}(&4u\uparrow u\uparrow d\downarrow -2u\uparrow d\uparrow u\downarrow -2d\uparrow u\uparrow u\downarrow \\ &-2u\uparrow u\downarrow d\uparrow + u\uparrow d\downarrow u\uparrow + d\uparrow u\downarrow u\uparrow \\ &-2u\downarrow u\uparrow d\uparrow + u\downarrow d\uparrow u\uparrow + d\downarrow u\uparrow u\uparrow)\end{aligned}$$

is symmetric under exchange of the first two entries. The flavor and spin wavefunctions

$$2_A = \frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \qquad \text{of } \mathrm{SU}(2)_{\text{spin}}$$

$$8_A = \frac{1}{\sqrt{2}}(udu - duu) \qquad \text{of } \mathrm{SU}(3)_{\text{flavor}}$$

are both antisymmetric under exchange of the first two entries. Therefore,

$$(2_A, 8_A) = \frac{1}{2}(u\uparrow d\downarrow u\uparrow -d\uparrow u\downarrow u\uparrow -u\downarrow d\uparrow u\uparrow +d\downarrow u\uparrow u\uparrow)$$

is symmetric under exchange of the first two entries. The linear combination

$$\begin{aligned}\frac{1}{\sqrt{2}}\left[(2_S, 8_S) + (2_A, 8_A)\right] &= \frac{1}{6\sqrt{2}}(4u\uparrow u\uparrow d\downarrow -2u\uparrow d\uparrow u\downarrow -2d\uparrow u\uparrow u\downarrow \\ &\qquad -2u\uparrow u\downarrow d\uparrow +4u\uparrow d\downarrow u\uparrow -2d\uparrow u\downarrow u\uparrow \\ &\qquad -2u\downarrow u\uparrow d\uparrow -2u\downarrow d\uparrow u\uparrow +4d\downarrow u\uparrow u\uparrow) \\ &= \frac{\sqrt{2}}{3}(u\uparrow u\uparrow d\downarrow +\text{cyclic permutations}) \\ &\quad -\frac{1}{3\sqrt{2}}(d\uparrow u\uparrow u\downarrow +\text{all permutations})\end{aligned}$$

is totally symmetric, i.e. symmetric under exchange of *any* two entries. Finally,

$$1_{TA} = \frac{1}{\sqrt{6}}(RGB - GRB + GBR - BGR + BRG - RBG) \qquad \text{of } \mathrm{SU}(3)_{\text{color}}$$

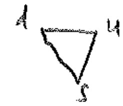
is totally antisymmetric, i.e. antisymmetric under exchange of any two entries. Consequently, the complete wavefunction

$$\frac{1}{\sqrt{2}}\left[(2_S, 8_S, 1_{TA}) + (2_A, 8_A, 1_{TA})\right] \qquad \text{of } \mathrm{SU}(2)_{\text{spin}} \times \mathrm{SU}(3)_{\text{flavor}} \times \mathrm{SU}(3)_{\text{color}}$$

is totally antisymmetric, thus obeying the Pauli exclusion principle for fermions.

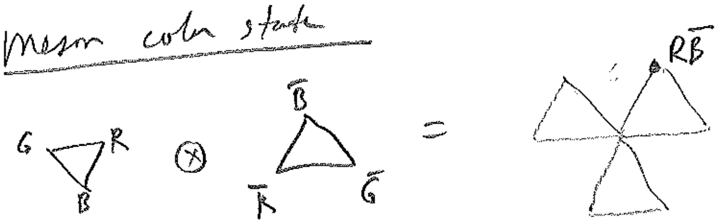
Observe that the $\underset{\sim}{1}_{TA}$ flavor state: $\frac{1}{\sqrt{6}}(uds + dsu + sud - usd - sdu - dus)$

looks analogous to the $\underset{\sim}{1}_{TA}$ color state: $\frac{1}{\sqrt{6}}(RGB + GBR + BRG - \dots \quad)$

This suggests that just as  belong to $\underset{\sim}{3}$ of $SU(3)_{flavor}$

the colors  belong to the $\underset{\sim}{3}$ of a new group $SU(3)_{color}$

<u>Meson color state</u>



$\oplus \quad \frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B})$

$$\underset{\sim}{3} \otimes \underset{\sim}{\bar{3}} = \underset{\sim}{8} \oplus \underset{\sim}{1}$$

color singlet (colorless)

<u>Baryon color state</u>

$$\underset{\sim}{3} \otimes \underset{\sim}{3} \otimes \underset{\sim}{3} = \underset{\sim}{10}_{TS} \oplus \underset{\sim}{8}_{S} \oplus \underset{\sim}{8}_{A} \oplus \underbrace{\underset{\sim}{1}_{TA}}$$

$$\frac{1}{\sqrt{6}}(RGB + GBR + BRG - RBG - BGR - GRB)$$

color singlet (colorless)

All observed hadrons belong to color singlet states.
(color confinement) ie color neutral

Summary

Q13

Mesons

Quarks belong to $(\underset{\sim}{2}, \underset{\sim}{3}, \underset{\sim}{3})$ of (spin, flavor, color)

Antiquarks belong to $(\underset{\sim}{2}, \underset{\sim}{\bar{3}}, \underset{\sim}{\bar{3}})$

$\Rightarrow$ mesons belong to $(\underset{\sim}{2}, \underset{\sim}{3}, \underset{\sim}{3}) \otimes (\underset{\sim}{2}, \underset{\sim}{\bar{3}}, \underset{\sim}{\bar{3}})$

$= (\underset{\sim}{2} \otimes \underset{\sim}{2},\ \underset{\sim}{3} \otimes \underset{\sim}{\bar{3}},\ \underset{\sim}{3} \otimes \underset{\sim}{\bar{3}})$

$= (\underset{\sim}{3} \oplus \underset{\sim}{1},\ \underbrace{\underset{\sim}{8} \oplus \underset{\sim}{1}}_{\text{nonet}},\ \cancel{\underset{\sim}{8}} \oplus \underset{\sim}{1})$

color neutral

spin 1 (vector mesons)

spin 0 (scalar mesons)

Summary

$\Rightarrow$ Baryons belong to $(\underset{\sim}{2}, \underset{\sim}{3}, \underset{\sim}{3}) \otimes (\underset{\sim}{2}, \underset{\sim}{3}, \underset{\sim}{3}) \otimes (\underset{\sim}{2}, \underset{\sim}{3}, \underset{\sim}{3})$

$= (\underset{\sim}{2} \otimes \underset{\sim}{2} \otimes \underset{\sim}{2},\ \underset{\sim}{3} \otimes \underset{\sim}{3} \otimes \underset{\sim}{3},\ \underset{\sim}{3} \otimes \underset{\sim}{3} \otimes \underset{\sim}{3})$

$= (\underset{\sim}{4}_{TS} \oplus \underset{\sim}{2}_S \oplus \underset{\sim}{2}_A,\ \underset{\sim}{10}_{TS} \oplus \underset{\sim}{8}_S \oplus \underset{\sim}{8}_A \oplus \underset{\sim}{1}_{TA},\ \underbrace{\underset{\sim}{10}_{TS} \oplus \underset{\sim}{8}_S \oplus \underset{\sim}{8}_A}_{\text{not color neutral}} \oplus \underset{\sim}{1}_{TA})$

Need TA combinations of these

Baryon decuplet: $(\underset{\sim}{4}_{TS}, \underset{\sim}{10}_{TS}, \underset{\sim}{1}_{TA}) \rightarrow J = \frac{3}{2}$

Baryon octet: $(\underset{\sim}{2}_S, \underset{\sim}{8}_S, \underset{\sim}{1}_{TA}) + (\underset{\sim}{2}_A, \underset{\sim}{8}_A, \underset{\sim}{1}_{TA}) \rightarrow J = \frac{1}{2}$

There is <u>no</u> baryon flavor singlet $(\ \ , \underset{\sim}{1}_{TA}, \underset{\sim}{1}_{TA})$

spin state would need to be TA which would require 3 orientations of spin but only have ↑ and ↓

Magnetic moments of baryons

Recall $\vec{\mu} = g \frac{q}{2m} \vec{J}$

Magnetic moment of baryon = vector sum of moments of constituent quarks

Proton $J_z = \frac{1}{2}$ state:

$$\frac{\sqrt{2}}{3}(\underbrace{u\uparrow u\uparrow d\downarrow}_{2\mu_u - \mu_d} + \text{cyc perms}) - \frac{1}{3\sqrt{2}}(\underbrace{d\uparrow u\uparrow u\downarrow}_{\mu_d} + \text{all perms})$$

$$\Rightarrow \mu_p = \underset{\text{probability}}{\left(\frac{2}{9}\right)}(2\mu_u - \mu_d)\cdot 3 + \frac{1}{18}(\mu_d \cdot 6) = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d$$

see Griffiths table

Neutron $J_z = \frac{1}{2}$ state $\Rightarrow \mu_n = \frac{4}{3}\mu_d - \frac{1}{3}\mu_u$

Quarks are fundamental spin-$\frac{1}{2}$ particles $\Rightarrow$ Dirac eqn predicts $g = 2$

$$\begin{cases} \mu_u = 2 \cdot \frac{(2/3 e)}{2m_u}\left(\frac{\hbar}{2}\right) = \frac{e\hbar}{3m_u} \\ \mu_d = -\frac{e\hbar}{6m_d} \end{cases}$$

$J_z = \frac{1}{2}$ state

$$\Rightarrow \begin{cases} \mu_p = \frac{4e\hbar}{9m_u} + \frac{e\hbar}{18m_d} \\ \mu_n = -\frac{e\hbar}{9m_u} - \frac{2e\hbar}{9m_d} \end{cases}$$

Table 5.5 Magnetic dipole moments of octet baryons

Baryon	Moment	Prediction	Experiment
p	$(\frac{4}{3})\mu_u - (\frac{1}{3})\mu_d$	2.79	2.793
n	$(\frac{4}{3})\mu_d - (\frac{1}{3})\mu_u$	−1.86	−1.913
Λ	μ_s	−0.58	−0.613
Σ^+	$(\frac{4}{3})\mu_u - (\frac{1}{3})\mu_s$	2.68	2.458
Σ^0	$(\frac{2}{3})(\mu_u + \mu_d) - (\frac{1}{3})\mu_s$	0.82	?
Σ^-	$(\frac{4}{3})\mu_d - (\frac{1}{3})\mu_s$	−1.05	−1.160
Ξ^0	$(\frac{4}{3})\mu_s - (\frac{1}{3})\mu_u$	−1.40	−1.250
Ξ^-	$(\frac{4}{3})\mu_s - (\frac{1}{3})\mu_d$	−0.47	−0.651

The numerical values are given as multiples of the nuclear magneton, $e\hbar/2m_pc$. *Source: Particle Physics Booklet* (2006).

What are the masses of quarks?

Ambiguous, because not observed

PPB gives the "current quark masses", best fit values in the fundamental Lagrangian

$m_u \sim 2.2\,\text{MeV}$
$m_d \sim 4.7\,\text{MeV}$
$m_s \sim 95\,\text{MeV}$

Here we'll use the "effective (or constituent) masses" which take into account strong force interactions

$m_u \sim m_d \sim \frac{1}{3} m_p$

$m_s \sim \frac{1}{3} m_\Omega$

nuclear magneton

Then $\mu_p = \frac{4}{3}\frac{e\hbar}{m_p} + \frac{e\hbar}{6m_p} = \frac{3e\hbar}{2m_p} = 3\mu_N$

$\mu_n = -\frac{e\hbar}{3m_p} - \frac{2e\hbar}{3m_p} = -\frac{e\hbar}{m_p} = -2\mu_N$

Not bad, compared w/ expt. $\mu_p = 2.79\,\mu_N$
$\mu_n = -1.91\,\mu_N$

[HW: calc. Ω^- mag moment]

Table 4.4 Quark masses (MeV/c^2)

Quark flavor	Bare mass	Effective mass
u	2	336
d	5	340
s	95	486
c	1300	1550
b	4200	4730
t	174 000	177 000

Warning: These numbers are somewhat speculative and model dependent [12].

Table 5.3 Pseudoscalar and vector meson masses. (MeV/c^2)

Meson	Calculated	Observed
π	139	138
K	487	496
η	561	548
ρ	775	776
ω	775	783
K^*	892	894
ϕ	1031	1020

Table 5.6 Baryon octet and decuplet masses. (MeV/c^2)

Baryon	Calculated	Observed
N	939	939
Λ	1114	1116
Σ	1179	1193
Ξ	1327	1318
Δ	1239	1232
Σ^*	1381	1385
Ξ^*	1529	1533
Ω	1682	1672

Rewrite

skip in 2019

rewrite??

Direct Experimental evidence for color

Inelastic electron-positron scattering

$e^+e^- \longrightarrow$ (all possible charged pairs of particles + antiparticles)

$\longrightarrow \mu^+\mu^-$ if $E_{cm} > 2 m_\mu c^2 \approx 210$ MeV

$\longrightarrow \tau^+\tau^-$ if $E_{cm} > 2 m_\tau c^2$

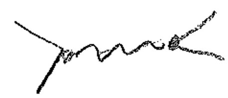
$\longrightarrow u\bar{u},\ d\bar{d}$

$\longrightarrow s\bar{s}$ if $E_{cm} > 2 m_s c^2 \approx$ ~~300 MeV~~

$\longrightarrow c\bar{c}$ if $E_{cm} > 2 m_c c^2 \approx 3$ GeV

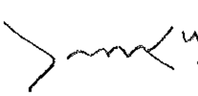
quark pairs then convert to mesons ("hadronization")

Amplitude: $e^+e^- \to \mu^+\mu^-$

 $\sim e^2$

Let $q_u =$

$e^+e^- \longrightarrow u\bar{u}$

 $\sim e\left(\frac{2}{3}e\right)$

$d\bar{d}$

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(\quad)} = \sum q^2$$

$$\frac{\sigma(e^+e^- \to u\bar{u})}{\sigma(e^+e^- \to \mu^+\mu^-)} \sim \left(\frac{q_u}{q}\right)^2$$

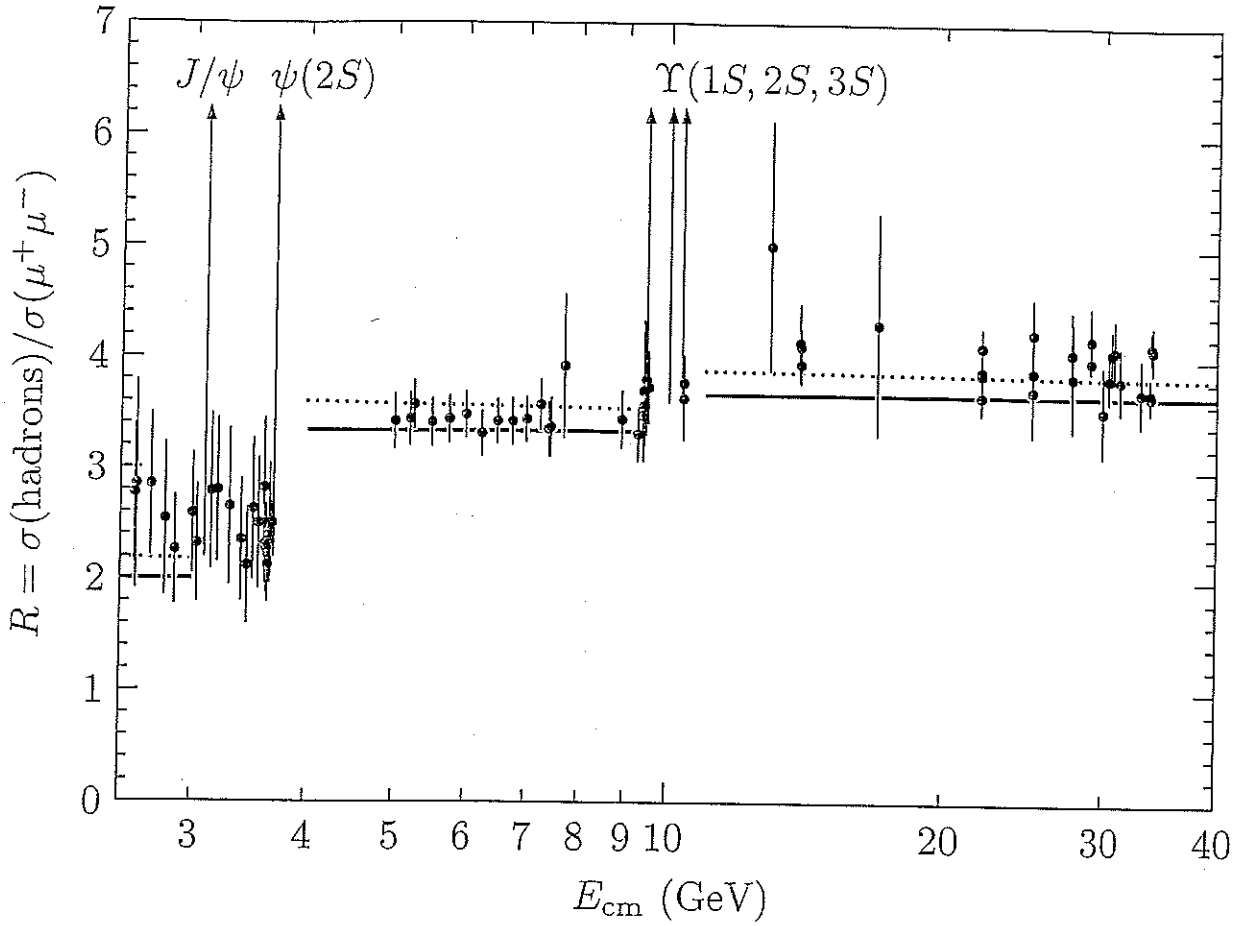


Figure 5.3. Experimental measurements of the total cross section for the reaction $e^+e^- \to$ hadrons, from the data compilation of M. Swartz, *Phys. Rev.* D (to appear). Complete references to the various experiments are given there. The measurements are compared to theoretical predictions from Quantum Chromodynamics, as explained in the text. The solid line is the simple prediction (5.16).

Peskin

cf 2nd ed of Griffiths