NOTE: FOR ALL GRADING ISSUES, PLEASE CONTACT FLIP TANEDO AT flipt@stanford.edu

1. GRIFFITHS 1.2

$$m = \frac{\hbar}{r_0 c}$$

$$\approx 3.5 \times 10^{-28}\ \text{kg}$$

$$\simeq \boxed{386\ m_e} \simeq \boxed{197\ \text{MeV}}$$

$m_e \simeq 9.11 \times 10^{-31}$ kg

$m_\pi \simeq \boxed{140\ \text{MeV}}$ from 2004 PARTICLE PHYSICS BOOKLET

"Not too bad," AS ONE OF YOUR COLLEAGUES PUT IT.

2. GRIFFITHS 1.10 (TABLE IIB OF REFERENCE: M. ROOS RMP 35, 314 (1963).)

See attached copy of table IIb.

ALSO ATTACHED: J. EXPTL. THEORET. PHYS. (USSR) 43, 1543 (1962)

↳ this is reference 52 of M. Roos' paper, it was cited in many of the mesons in his table IIb that did not "stand the test of time."

In case you were curious why so many of the table IIb mesons turned out to be false, consider fig 1 & 2 in the Anutdinov paper. (EXPERIMENTALISTS MAY BE SLIGHTLY MORE INCENSED THAN THEORISTS...)

Table IIb. Mesonic Resonant States, March 1963.

Symbol	Charge	Isospin	Spin	Parity G-parity	S	Mass (MeV)	Mass ($m_{\pi\pm}$)	Full width Γ (MeV)	Lifetime Γ^{-1} ($1/m_{\pi\pm}$)	Production Process	Production k_{lab} (MeV)	Decay Modes	Decay Branching ratio (%)	Decay Q (MeV)	References
K_3^*	−	$\geq \frac{3}{2}$			1	1630 ± 100	11.7			$\pi^- p$	3534	$(K_1^*\pi\pi)^-$ $(K_1^*\rho)^-$ $(K\pi\rho)^-$ others		470 $\lessdot$ 100 225	55
K_3^*	+				1							same, charge +		same	55
χ_3	0				0	1340 ± 70	9.6			$\pi^- p$	2287	$(\rho\pi\pi)^0$ others		290	55
κ_3	0				0	1275 ± 25	9.1			$\pi^- p$	2125	$K^0\bar{K}^0$ K^+K^-		279 287	24
K^{**}					1	1260	9.0			$\pi^- N$		$K(n\pi)$			55
f	0	0	2	++	0	1253 ± 20	9.0	100 ± 50	1.4	$\pi^- p$	2070	$\pi^-\pi^+$	100	970	33
K_5^* K_5^*	−− ++	$\frac{5}{2}$			1 1	1150 ± 50	8.2			$\pi^- p$	2250	$K^0\pi^+\pi^+$ $K^0\pi^-\pi^-$		373 373	55 55
χ_1 χ_1	− 0	1			0 0	1050 1040	7.5 7.4			$\pi^- p$	1620	$\pi^-\pi^-\pi^+\pi^0$ $\pi^+\pi^-(\pi\pi)^0$		496 481–491	51 53
κ_2	0	0	even	++	0	1040 ± 40	7.4			$K^- p$	1780	$K_1^0K_1^0$ even number π's		44	58
κ_1	0	0	odd	−−	0	1020	7.3	< 3	>47	$K^- p$	1760	$K_1^0K_2^0$ odd number π's		24	59
ψ_6	−−	2			0	990	7.2			$\pi^- p$	1490	$\pi^-\pi^-$	100	711	52
ψ_6	0				0							$\pi^-\pi^+$		711	52
ψ_6	++				0							$\pi^+\pi^+$	100	711	52
K_1^*	−	$\frac{1}{2}$	1	−	−1	888 ± 3	6.4	50 ± 10	2.8	$K^- p$	1074	$\bar{K}^0\pi^-$ $K^-\pi^0$	60 ± 16 40 ± 16	252 261	34
$\bar{K}_1^*$	0				−1					$K^- p$	1078	$K^-\pi^+$ $\bar{K}^0\pi^0$		256 257	34
K_1^*	+				1					$\pi^- p$	1834	$K^0\pi^+$ $K^+\pi^0$	67 33	252 261	34
K_1^*	0				1					$\pi^- p$	1657	$K^+\pi^-$ $K^0\pi^0$		256 257	35, 34
φ_3	0				0	885 ± 10	6.3			$\pi^- p$	1284	$\pi^+\pi^-$		606	36
ω	0	0	1	− −	0	781.1 ± 0.8	5.6	<12	>12	$\bar{p}p$		$\frac{\text{neutr.}}{\pi^+\pi^-\pi^0}$ = $\pi^+\pi^-\gamma^0$ $\pi^+\pi^-\pi^0\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-$	0.12 ± 0.03 < 2 <12 < 5 4	373 503 232 223 503	37 53 53
ρ	−	1	1	− +	0	757 ± 5	5.4	120 ± 10	1.2	$\pi^- p$	1029	$\pi^-\pi^0$ $\pi^-\pi^0\pi^0$ $\pi^-\pi^0\pi^0\pi^0$ $\pi^-\pi^+\pi^-\pi^0$	>91 < 3 ≤ 4 < 2	475 340 205 196	38, 33, 39 53 54 53
ρ	0				0	751 ± 6	5.4	110 ± 10	1.3	πN	1029	$\pi^-\pi^+$ neutrals $\pi^+\pi^-\pi^+\pi^-$	94 (+6/−40) 6 (+40/−6) < 2	470 191	40, 33, 36, 39 53
ρ_2	0				0	780	5.6	60	2.3	πN	1085	$\pi^-\pi^+$ neutrals		500	41
ρ_1	0				0	720	5.2	20	7	πN	975	$\pi^-\pi^+$ neutrals		440	40
ρ	+				0					$\pi^+ p$	1066	$\pi^+\pi^0$		495	39
ψ_4	−−	2			0	760	5.4			$\pi^- p$	1310	$\pi^-\pi^-$	100	481	52
ψ_4	0				0						1055	$\pi^-\pi^+$		481	52
ψ_4	++				0						1590	$\pi^+\pi^+$	100	481	52
K_1^{**}	0	$\frac{1}{2}$	≥1		1	730 ± 10	5.2	≤20	≥7	$\pi^- p$	1485	$K^+\pi^-$ $K^0\pi^0$		96 97	50, 56
K_1^{**}	+				1							$(K\pi)^+$		92–101	50, 56
δ δ δ	− 0 +	1 or 2			0 0 0	645 ± 25	4.5			$\pi^- p$	810	$\pi^-\pi^0$ $\pi^+\pi^-$ $\pi^+\pi^0$		350 345 350	43 43 43
α α	0 +	1 or 2			0 0	625	4.5	<80	>1.7	pp		$\pi^+\pi^-\pi^0$ $\pi^+\pi^+\pi^-$		225 220	42 42
ψ_2 ψ_2 ψ_2	−− 0 ++	2	0 or 2		0 0 0	605 ± 25 580	4.3 4.2	75	1.9	$\pi^- p$	1025 733 1235	$\pi^-\pi^-$ $\pi^-\pi^+$ $\pi^+\pi^+$	100 100	326 301 326	45, 52 52 52, 45
ζ ζ ζ	− 0 +	1			0 0 0	564 ± 9 541 ± 18	4.0 3.9	<43	>3.2	$\pi^- p$ $\pi^- p$ $\pi^+ p$	707 672	$\pi^-\pi^0$ $\pi^+\pi^-$ $\pi^+\pi^0$		289 262 289	44 44 44

TABLE IIb. Mesonic Resonant States, March 1963. (*Continued*)

Symbol	Charge	Isospin	Spin	Parity G-parity	S	Mass (MeV)	Mass ($m_{\pi\pm}$)	Full width Γ (MeV)	Life-time Γ^{-1} ($1/m_{\pi\pm}$)	Production: Process	Production: k_{lab} (MeV)	Decay: Modes	Decay: Branching ratio (%)	Decay: Q (MeV)	References
η	0	0	0	− +	0	548.5 ± 0.6	3.93	≤ 7	⩾20	πp	685	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-\gamma$ $3\pi^0$ $\pi^0\gamma$ 2γ others	25 ± 10 7 ± 2 68 ± 10 (for $3\pi^0$, $\pi^0\gamma$, 2γ, others)	135 270 144 414 549	46
φ_2	0	0			0	520 ± 20	3.7	70 ± 30	2.0	$\pi^- p$	639	$\pi^+\pi^-$		240	47
ψ_2	−−	2			0	440	3.1			$\pi^- p$	735	$\pi^-\pi^-$	100	160	52
ψ_2	0				0	420–440	3.1				515	$\pi^-\pi^+$		160	52
ψ_2	++				0	440	3.1				975	$\pi^+\pi^+$	100	160	52
φ_1	0	0			0	395 ± 10	2.8	50 ± 20	2.8	$\pi^- p$	446	$\pi^+\pi^-$		115	47
ψ_1	−−	2			0	330	2.4			$\pi^- p$	557	$\pi^-\pi^-$	100	50	52
ψ_1	0				0	330	2.4				340	$\pi^-\pi^+$		50	52
ψ_1	++				0	330	2.4				790	$\pi^+\pi^+$	100	50	52
ω_{ABC}	0	0			0	317 ± 6	2.3	≤16	⩾9	pd		$\pi^+\pi^-$		38	49

and DuMond, Nuovo Cimento **5**, 541 (1957) and *Fundamental Constants of Physics* (Interscience Publishers, Inc., New York, 1957).

8. The neutron mean life is based on the value 11.7 ± 0.3 min for the half life, by A. N. Sosnovskij, P. E. Spivak, Y. A. Prokoviev, I. E. Kutikov, and Y. P. Dobrynin, Nucl. Phys. **10**, 395 (1959).

9. $m(K^+)$ is from the compilation of E. O. Okonov, Fortschr. Physik **8**, 42 (1960), who also gives the K^- mass as 493.9 ± 0.4 MeV.

$\tau(K^+)$ is a weighted average of the following results in 10^{-8}sec: 1.224 ± 0.013, compilation of Barkas & Rosenfeld (cf. reference 3), 1.231 ± 0.011, A. M. Boyarski, E. C. Loh, L. Q. Niemela, D. M. Ritson, R. Weinstein and S. Ozaki, Phys. Rev. **128**, 2398 (1962).

The K^+ branching ratios are from B. P. Roe, D. Sinclair, J. L. Brown, D. A. Glaser, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Letters **7**, 346 (1961); and G. Giacomelli, D. Monti, G. Quareni, A. Quareni-Vignudelli, W. Püschel, and J. Tietge, Phys. Letters **3**, 346 (1963). Note that these branching ratios (except for τ) disagree with the weighted averages obtained from emulsion experiments, as quoted by Crawford (cf. reference 6):

$$\mu 2 = 57.4 \pm 2.0\,,$$
$$\pi 2 = 25.6 \pm 1.5\,,$$
$$\mu 3 + e3 + \tau = 11.0 \pm 1.0\,,$$
$$\tau = 5.7 \pm 0.2\,.$$

10. J. Button and B. C. Maglic, Phys. Rev. **127**, 1297 (1962).

11. $m(K^0)$ is from A. H. Rosenfeld, F. T. Solmitz and R. D. Tripp, Phys. Rev. Letters **2**, 110 (1959). $\mu(K^0)$ is from E. O. Okonov, J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 1554 (1962).

$\tau(K_1^0)$ is a weighted average, based on the following recent results only (in 10^{-10}sec), all quoted by Crawford (cf. reference 6):

0.94 ± 0.05, Crawford *et al.* (cf. below),

0.90 ± 0.05, A. F. Garfinkel, Report Nevis 104 (1962). [Thesis, Columbia University, Physics Department (unpublished).]

0.885 ± 0.025, R. L. Golden, G. Alexander, J. A. Anderson, F. S. and B. B. Crawford, L. J. Lloyd, G. W. Meisner, and L. Price (to be published).

The $K_1^0 \to \pi^0\pi^0$ branching ratio is a weighted average of the following results in percent:

28.5 ± 3.6 by F. S. Crawford, M. Cresti, R. Douglass, M. Good, G. Kalbfleisch, M. L. Stevenson, and H. Ticho, Phys. Rev. Letters **2**, 266 (1959),

29.4 ± 2.1, M. Chretien, V. Fisher, H. R. Crouch, R. E. Lanou, J. T. Massimo, A. M. Shapiro, J. P. Averell, A. E. Brenner, D. R. Firth, L. G. Hyman, M. E. Law, R. H. Milburn, E. E. Ronat, K. Strauch, J. C. Street, J. J. Szymanski, L. Guerriero, I. A. Pless, L. Roesenson, and G. A. Saladin (to be published), quoted by Crawford (cf. reference 6),

33.5 ± 1.4, J. L. Brown, J. A. Kadyk, G. H. Trilling, B. P. Roe, D. Sinclair, and J. C. Vander Welde, Phys. Rev. (to be published),

26.0 ± 2.4, Anderson *et al.* (cf. reference 6),

29 ± 3, weighted average of earlier results, reported at the 1960 Rochester Conference.

12. $\tau(K_2^0)$ is a weighted average of the following results in 10^{-8}sec

6.8 (+2.6/−1.5), Crawford (cf. reference 6),

8.1 (+3.3/−2.4), M. Bardon, K. Lande, L. M. Lederman, and W. Chinowsky, Ann. Phys. **5**, 156 (1958).

5.1 (+2.4/−1.3), S. E. Darmon, A. Rousset and W. Six, Phys. Letters **3**, 57 (1962).

The branching ratios have been obtained from the following results:

$R_1 = \dfrac{K_2^0 \to 3\pi^0}{K_2^0 \to \text{all charged}} = 0.38 \pm 0.07$, M. H. Anikina, M. S. Zhuravleva, D. M. Kotliarevsky, Z. S. Mandyavidze, A. M. Mestvirishvili, D. Neagu, E. O. Okonov, N. S. Petrov, A. M. Rosanova, V. A. Rusakov, G. G. Tachtamishev, and L. V. Chekhaidze, *Proceedings of the 1962 Annual International Conference on High-Energy Physics at Geneva* (CERN, Geneva, Switzerland, 1962), p. 452.

$R_2 = \dfrac{K_2^0 \to \pi^+\pi^-\pi^0}{K_2^0 \to \text{all charged}} = 0.127 \pm 0.020$, D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, *Proceedings of the Aix-en-Provence International Conference on Elementary Particles in 1961* (CEN Saclay, Seine et Oise, France, 1962), Vol. I, 241 (1961).

$R_2 = 0.134 \pm 0.018$, Anikina, *et al.*

$R_3 = \dfrac{K_2^0 \to \pi e \nu_e}{K_2^0 \to \text{all charged}} = 0.458 \pm 0.048$, Luers, *et al.*

$R_3 = 0.415 \pm 0.120$, A. Astier, L. Blaskovic, M. M. de Courreges, B. Equer, A. Lloret, P. Rivet, and J. Siaud, *Proceedings of the Aix-en-Provence International Conference on Elementary Particles in 1961* (CEN Saclay, Seine et Oise, France, 1962), Vol. I, 227 (1961). A value on $R_3 = (0.185^{+0.038}_{-0.034})$ by Astier *et al.* has not been used.

13. $\tau(\pi^0)$ is from G. von Dardel, D. Dekkers, R. Mermod, J. D. van Putten, M. Vivargent, G. Weber, and K. Winter, Phys. Letters **4**, 51 (1963).

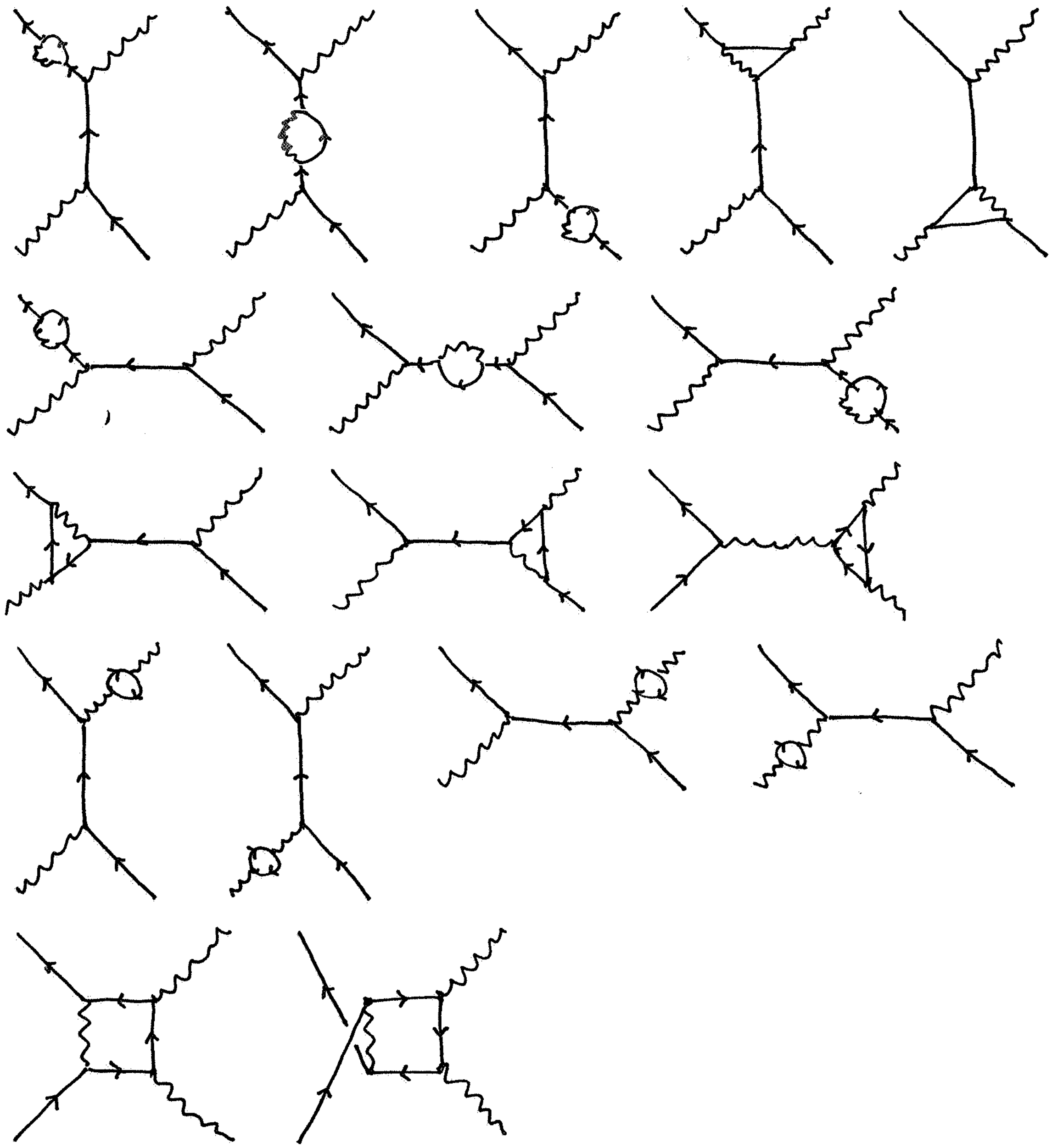
The relative frequency for γe^+e^--decay is from J. Tietge and W. Püschel, Phys. Rev. **127**, 1324 (1962).

14. $\mu(\mu^+)$ is from G. Charpak, F. Farley, R. L. Garwin, T. Muller, J. C. Sens, and A. Zichichi, Phys. Letters **1**, 16 (1962).

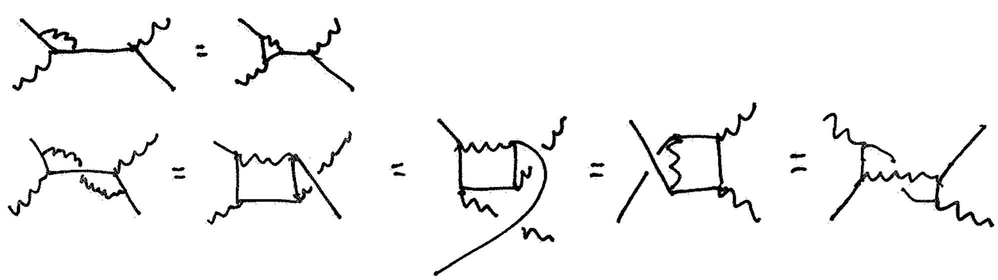
$m(\mu^+)$ is a combined value of the latest measurements, as given by G. McD. Bingham, Nuovo Cimento **27**, 1352 (1963).

$\tau(\mu^+)$ is a weighted average from R. A. Lundy, Phys. Rev. **125**, 1686 (1962).

3. GRIFFITHS 2.3, I WILL FOLLOW GRIFFITHS AND HAVE TIME FLOW UPWARDS



NOTES



9. GRIFFITHS 2.5

(a) $\Xi^- \rightarrow \Lambda + \pi^-$
$(dss) \rightarrow (uds) + (d\bar{u})$ } $\Delta S = -1$

$\Xi^- \rightarrow n + \pi^-$
$(dss) \rightarrow (udd) + (d\bar{u})$ } $\Delta S = -2$

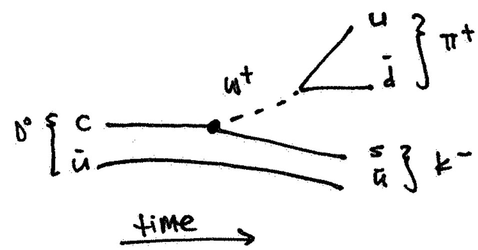
WE EXPECT PREFERENTIAL DECAY TO $\Lambda + \pi^-$ TO MINIMIZE STRANGENESS VIOLATION.

INDEED, THE 2004 PARTICLE PHYSICS BOOKLET LISTS

$$\left(\Gamma_{\Xi^- \rightarrow \Lambda + \pi^-} / \Gamma_{TOT}\right) = 99.9\%$$

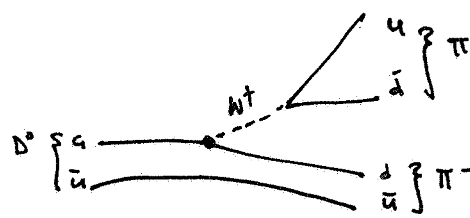
(b) $D^0 \rightarrow K^- + \pi^+$
$(c\bar{u}) \rightarrow (s\bar{u}) + (u\bar{d})$

AMPLITUDE $\propto V_{cs}$
PDG 2004: $\Gamma / \Gamma_{tot} = 3.8\%$



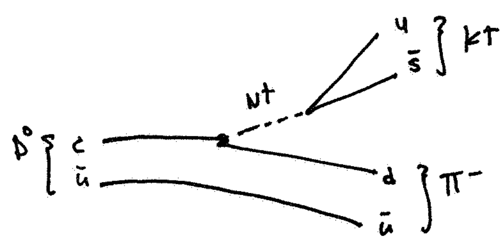
$D^0 \rightarrow \pi^- + \pi^+$
$(c\bar{u}) \rightarrow (d\bar{u}) + (u\bar{d})$

AMPLITUDE $\propto V_{cD}$
PDG 2004: $1.38 \times 10^{-3}\%$



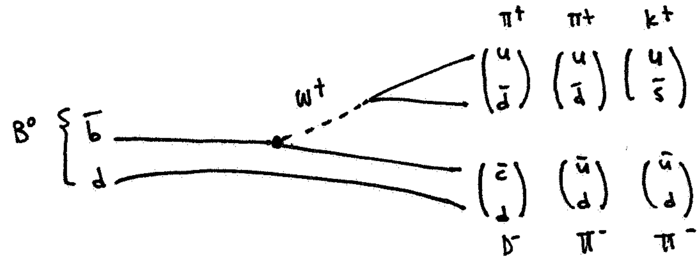
$D^0 \rightarrow K^+ + \pi^-$
$(c\bar{u}) \rightarrow (u\bar{s}) + (d\bar{u})$

AMPLITUDE $\propto V_{cD} V_{us}$
PDG 2004: $1.4 \times 10^{-4}\%$



SINCE $V_{cs} > V_{cD}$, WE EXPECT THE $K^- \pi^+$ MODE TO OCCUR MORE THAN THE OTHER TWO

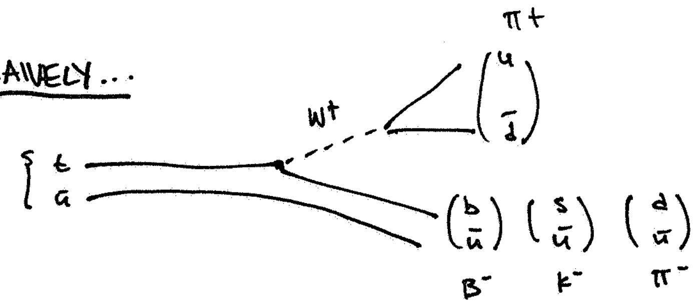
(c)



$B^0 \longrightarrow \pi^+ + D^- \quad \propto V_{cb}$
$B^0 \longrightarrow \pi^+ + \pi^- \quad \propto V_{ub}$
$B^0 \longrightarrow K^+ + \pi^- \quad \propto V_{ub}$

$V_{cb} > V_{ub}$, SO WE EXPECT $B^0 \to \pi^+ + D^-$ TO DOMINATE

<u>NAIVELY...</u>



$\propto V_{tb}$ $\propto V_{ts}$ $\propto V_{td}$

$V_{tb} > V_{ts} > V_{td}$

SO $(t\bar{u}) \to \pi^+ + B^-$ DOMINATES AMONG THESE

<u>HOWEVER</u>: GRIFFITHS WAS WRITTEN BEFORE THE MASS OF THE TOP QUARK WAS DETERMINED; IT TURNS OUT THAT THE TOP IS SO MASSIVE THAT IT DOES NOT FORM MESONS!

5. GRIFFITHS 2.7

(a) $p + \bar{p} \rightarrow \pi^+ + \pi^0$
(b) $\eta \rightarrow \gamma + \gamma$
(c) $\Sigma^0 \rightarrow \Lambda + \pi^0$
(d) $\Sigma^- \rightarrow n + \pi^-$
(e) $e^+ + e^- \rightarrow \mu^+ + \mu^-$
(f) $\mu^- \rightarrow e^- + \bar{\nu}_e$
(g) $\Delta^+ \rightarrow p + \pi^0$
(h) $\bar{\nu}_e + p \rightarrow n + e^+$
(i) $e + p \rightarrow \nu_e + \pi^0$
(j) $p + p \rightarrow \Sigma^+ + n + K^0 + \pi^+ + \pi^0$
(k) $p \rightarrow e^+ + \gamma$
(l) $p + p \rightarrow p + p + p + \bar{p}$
(m) $n + \bar{n} \rightarrow \pi^+ + \pi^- + \pi^0$
(n) $\pi^+ + n \rightarrow \pi^- + p$
(o) $K^- \rightarrow \pi^- + \pi^0$
(p) $\Sigma^+ + n \rightarrow \Sigma^- + p$
(q) $\Sigma^0 \rightarrow \Lambda + \gamma$
(r) $\Xi^- \rightarrow \Lambda + \pi^-$
(s) $\Xi^0 \rightarrow p + \pi^-$
(t) $\pi^- + p \rightarrow \Lambda + K^0$
(u) $\pi^0 \rightarrow \gamma + \gamma$
(v) $\Sigma^- \rightarrow n + e + \bar{\nu}_e$

a) NO - CHARGE CONSERVATION
b) YES - EM
c) NO - ENERGY CONSERVATION
d) YES - WEAK
e) YES - EM
f) NO - LEPTON #
g) YES - STRONG
h) YES - WEAK
i) NO - BARYON #
j) YES - STRONG
k) NO - BARYON #
l) YES - STRONG
m) YES - STRONG
n) NO - CHARGE CONSERVATION
o) YES - WEAK
p) NO - CHARGE CONSERVATION
q) YES - EM
r) YES - WEAK
s) NO - $\Delta S = 2$
t) YES - STRONG
u) YES - EM
v) YES - WEAK

6. GRIFFITHS 3.18

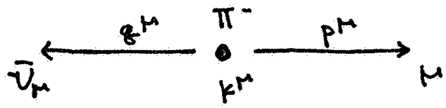
(a) $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

<u>WORK IN THE CM FRAME</u>

LET k^μ = INITIAL 4-MOMENTUM OF π^-

q^μ = FINAL 4-MOMENTUM OF $\bar{\nu}_\mu$

p^μ = FINAL 4-MOMENTUM OF μ^-



ASSUME $\bar{\nu}_\mu$ MASSLESS $\Rightarrow q^0 = |\vec{q}|$ $\quad$ $\hat{q} = \vec{q}/|\vec{q}|$

$\Rightarrow q^\mu = (E_{(\nu)}, E_{(\nu)}\hat{q})$

CM FRAME IS π^- REST FRAME $\Rightarrow k^\mu = (m_{(\pi)}, \vec{0})$

CONSERVATION OF 4-MOMENTUM : $k^\mu = q^\mu + p^\mu$ $\quad (*)$

$$(*) \Rightarrow p^\mu = (\underbrace{(m_{(\pi)} - E_{(\nu)})}_{E_{(\mu)}}, \underbrace{-E_{(\nu)}\hat{q}}_{\vec{p}})$$

$$(*) \Rightarrow q^\mu = k^\mu - p^\mu$$

$$q^2 = k^2 - 2k^\mu p_\mu + p^2$$

$$0 = m_{(\pi)}^2 - 2m_{(\pi)}E_{(\mu)} + m_{(\mu)}^2 \qquad = m_{(\pi)}^2 - 2m_{(\pi)}(m_{(\pi)} - E_{(\nu)}) + m_{(\mu)}^2$$

$$\Rightarrow E_{(\mu)} = \frac{m_{(\pi)}^2 + m_{(\mu)}^2}{2m_{(\pi)}} \qquad \Rightarrow E_{(\nu)} = \frac{m_{(\mu)}^2 - m_{(\pi)}^2}{2m_{(\pi)}}$$

USING $|\vec{p}| = -E_{(\nu)}$

AND $V_{(\mu)} = \frac{|\vec{p}|}{E_{(\mu)}} \Rightarrow -\frac{E_{(\nu)}}{E_{(\mu)}} = \frac{m_{(\pi)}^2 - m_{(\mu)}^2}{m_{(\pi)}^2 + m_{(\mu)}^2}$

$$\gamma = \frac{1}{\sqrt{1 - v^2}} = \frac{m_{(\pi)}^2 + m_{(\mu)}^2}{\sqrt{(m_{(\pi)}^2 + m_{(\mu)}^2)^2 - (m_{(\pi)}^2 - m_{(\mu)}^2)^2}}$$

$$= \frac{m_{(\pi)}^2 + m_{(\mu)}^2}{\sqrt{4m_{(\pi)}^2 m_{(\mu)}^2}}$$

$$= \frac{m_{(\pi)}^2 + m_{(\mu)}^2}{2m_{(\pi)}m_{(\mu)}}$$

(CONTINUED) $\Rightarrow$

μ LIFETIME IN LAB (CM) FRAME $= \gamma \tau$

$\Rightarrow$ DISTANCE TRAVELLED $d = v_{(\mu)} \gamma \tau$

PLUG IN
$m_{(\pi)} = 140$ MeV
$m_{(\mu)} = 106$ MeV
$\tau_{(\mu)} = 2.20 \times 10^{-6}$ s

$\boxed{d = 186 \text{ m.}}$

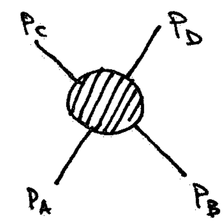
(b) TRICK QUESTION! (Yeah, I know, that's awful, isn't it?)

THE HINT IS IN THE CAPTION OF FIG. 1.7 - THE IMAGE COMES FROM A BOOK TITLED "THE STUDY OF ELEMENTARY PARTICLES BY THE PHOTOGRAPHIC METHOD."

THE VALUE FOR d WE CALCULATED IS FOR VACUUM. IN ORDER FOR THIS PHOTOGRAPH TO BE TAKEN, THE INTERACTION OCCURED IN A MEDIUM (ILFORD EMULSION), WHICH ACCOUNTS FOR THE DISCREPANCY.

NO POINTS WERE DEDUCTED FOR MISSING PART (b).

7. GRIFFITHS 3.22, a & d ONLY



SET $c = 1$ LIKE ANY REASONABLE PARTICLE PHYSICIST.

$$s = (p_A + p_B)^2 = (p_C + p_D)^2$$
$$t = (p_A - p_C)^2$$
$$u = (p_A - p_D)^2$$

(a)
$$
\begin{aligned}
s + t + u = {} & p_A^2 + 2p_A \cdot p_B + p_B^2 \\
& + p_A^2 - 2p_A \cdot p_C + p_C^2 \\
& + p_A^2 - 2p_A \cdot p_D + p_D^2
\end{aligned}
$$

$p_i^2 = m_i^2 \;;\; i = A, B, C, D$

$$= 3m_A^2 + m_B^2 + m_C^2 + m_D^2 - 2p_A \cdot (p_B - (p_C + p_D))$$

$\leftarrow$ $p_C + p_D = p_A + p_B$ (CONS. OF 4 MOMENTUM)

$$= 3m_A^2 + m_B^2 + m_C^2 + m_D^2 - 2p_A \cdot (p_B - (p_A + p_B))$$

$$-2p_A \cdot (p_B - (p_A + p_B)) = -2m_A^2$$

$$= \boxed{m_A^2 + m_B^2 + m_C^2 + m_D^2}$$

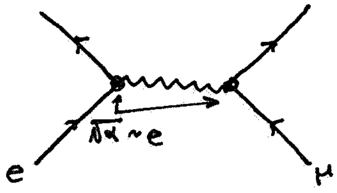
(d) IN THE CM FRAME, $\vec{p}_A = -\vec{p}_B$

$$\Rightarrow p_A + p_B = (E_A + E_B, 0, 0, 0)$$

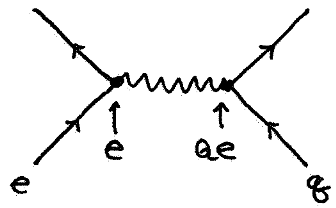
$$s = (p_A + p_B)^2 = (E_A + E_B)^2 = E_{CM}^2$$

$$\boxed{E_{CM} = \sqrt{s}}$$

8.



$$\sigma \sim |\mathcal{M}|^2 \sim \frac{\alpha^2}{s} \sim \frac{e^4}{s}$$



$$\sigma \sim |\mathcal{M}|^2 \sim \sum_{\substack{q \text{ s.t.} \\ 2m_q < \sqrt{s}}} \frac{3Q^2 e^4}{s}$$

SUM RUNS OVER KINEMATICALLY ALLOWED QUARK SPECIES, i.e. q SUCH THAT $2m_q < \sqrt{s}$

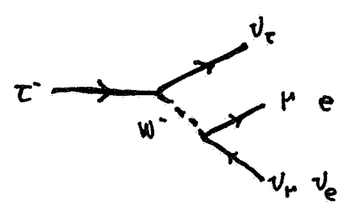
Q = CHARGE OF QUARK q IN UNITS OF e

$= \begin{cases} 2/3 & \text{FOR } q: u, c, t \\ -1/3 & \text{FOR } q: d, s, b \end{cases}$

FACTOR OF 3 COMES FROM SUMMING THE (IDENTICAL) CONTRIBUTION FROM 3 POSSIBLE QUARK COLORS.

$$\Rightarrow \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_{\substack{q \text{ s.t.} \\ 2m_q < \sqrt{s}}} 3Q^2$$

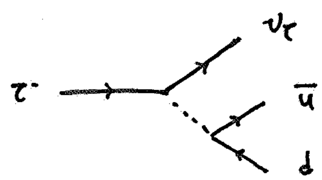
9. ALL DECAYS OF τ^- INVOLVE THE WEAK FORCE (in particular, the W^- boson). CONSIDER ONLY THE LOWEST ORDER TREE LEVEL DIAGRAMS.



LEPTONIC DECAYS

$\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$

$\to \nu_\tau e^- \bar{\nu}_e$



SEMILEPTONIC DECAYS

$\tau^- \to \nu_\tau d \bar{u}$ (× 3 COLORS)

DO NOT CONSIDER...

→ top/bottom modes (VIOLATES ENERGY CONS.)

→ strange modes } (VIOLATES STRANGENESS OR OTHERWISE

→ charm modes } REQUIRES OFF DIAGONAL ELEMENTS OF V_{CKM} → HIGHER ORDER)

ASSUME THESE DECAYS ARE ROUGHLY ON THE SAME SCALE

THEN, TO THIS ORDER, $\mathcal{B}(\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu) \sim 1/5 \approx 20\%$.

2004 PARTICLE PHYSICS BOOKLET SAYS $\mathcal{B}(\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu) \sim 17\%$.
(NOT BAD AT ALL!)

10. (a)

$q^\mu = (m, \vec{0})$

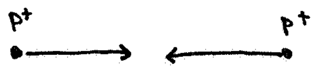
$k^\mu = (E, \sqrt{E^2 - m^2}\,\hat{k})$

$\hat{k} = \vec{k}/|\vec{k}|$

$$
\begin{aligned}
s &= (k^\mu + q^\mu)^2 \\
&= (E + m, \sqrt{E^2 - m^2}\,\hat{k})^2 \\
&= (E+m)^2 - (E^2 - m^2) \\
&= 2Em + 2m^2
\end{aligned}
$$

$$\boxed{\sqrt{s} = \sqrt{2m(E+m)}}$$

(b)



$q^\mu = (E, -\sqrt{E^2 - m^2}\,\hat{k})$

$k^\mu = (E, \sqrt{E^2 - m^2}\,\hat{k})$

$$
\begin{aligned}
s &= (2E, 0)^2 \\
&= 4E^2
\end{aligned}
$$

$$\boxed{\sqrt{s} = 2E}$$

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$\pi\pi$ INTERACTIONS IN THE MULTIPLE PRODUCTION OF PIONS IN πp COLLISIONS

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Resonance states were found for two π-mesons of the same charge and the mass values of 0.33; 0.44; 0.58; 0.76; and 0.99 BeV in an investigation of $\pi\pi$ interactions in π^-p collisions at an energy of 7.2 BeV. Similar resonances were found for the $\pi^+\pi^-$ and $\pi^-\pi^0$ systems at the same mass values. An assumption is put forward of the possibility of isotopic and mechanical spin degeneracy in strong interactions.

WE investigated the $\pi\pi$ interaction in multiple pion production in π^-p collisions. The energy of the primary negative pions was 7.2 BeV. The energy spread of the negative pions in the primary beam is satisfactorily described by a Gaussian distribution with half width 0.8 BeV. Measurements were made with the aid of a liquid-hydrogen bubble chamber 25 cm in diameter, placed in a 13.5-kG magnetic field.

Altogether 13,000 photographs were obtained. The reactions investigated were

$$\pi^- + p \rightarrow 2\pi^- + 2\pi^+ + n + k\pi^0, \quad (1)$$

$$\pi^- + p \rightarrow 3\pi^- + 3\pi^+ + n + k\pi^0, \quad (2)$$

where k is the unknown number of π^0 mesons. The reactions

$$\pi^- + p \rightarrow 2\pi^- + \pi^+ + p + k\pi^0, \quad (3)$$

$$\pi^- + p \rightarrow 3\pi^- + 2\pi^+ + p + k\pi^0 \quad (4)$$

were eliminated by identifying the protons by measuring the momenta and estimating the ionization. In the reactions (1) and (2) segregated in this manner there may be a small admixture of reactions (3) and (4), when the proton momentum exceeds 1.5 BeV/c. For reactions (1) and (2), distributions over the effective masses were plotted (the total energy of two pions in their own c.m.s.) for all possible combinations of two pions. All three possible charge states were investigated (the $\pi^-\pi^-$, $\pi^+\pi^+$, and $\pi^+\pi^-$ meson combinations).

Ideograms corresponding to the distributions over the effective masses for reaction (1) are shown in Fig. 1. The determination of the effective masses was carried out over the measurements of the momenta and angles of emission of the pions. The mean square value of the error in the determination of the effective mass was ±25 MeV.

As follows from Fig. 1, sharp maxima are observed in the constructed ideograms at mass values 0.33, 0.44, 0.58, 0.76, and 0.99 BeV. Maxima were observed in all three charge states within the limits of errors at the same values of the masses. It must be noted that the first two maxima in the ideogram for the $\pi^+\pi^-$ combinations were not resolved.

The results obtained point to the possibility of realizing resonances in the two-pion system with the mass values indicated above.

To check whether the same pion participates simultaneously in several maxima, the following processing was carried out: two-charge combinations contained in each maximum on the curves of Fig. 1a and b were picked out. For these pions, a distribution was plotted over the effective masses of the $\pi^+\pi^-$ combinations. The distributions obtained turn out to be smooth, within the limits of statistical errors. From the smoothness of the distributions it follows that the same pion does not participate in two maxima.

The distribution over the effective masses for reaction (2) is shown in Fig. 2. What is striking is the presence of almost all maxima observed in the analysis of four-prong events. The relative intensity of the maxima in the case of six-prong stars, however, is appreciably different from the intensity of the maxima in four-prong stars and the maxima at high values of the masses are partially suppressed.

The table lists the values of the masses of the resonances (in BeV) for three charge states of four- and six-prong stars. From the analysis of

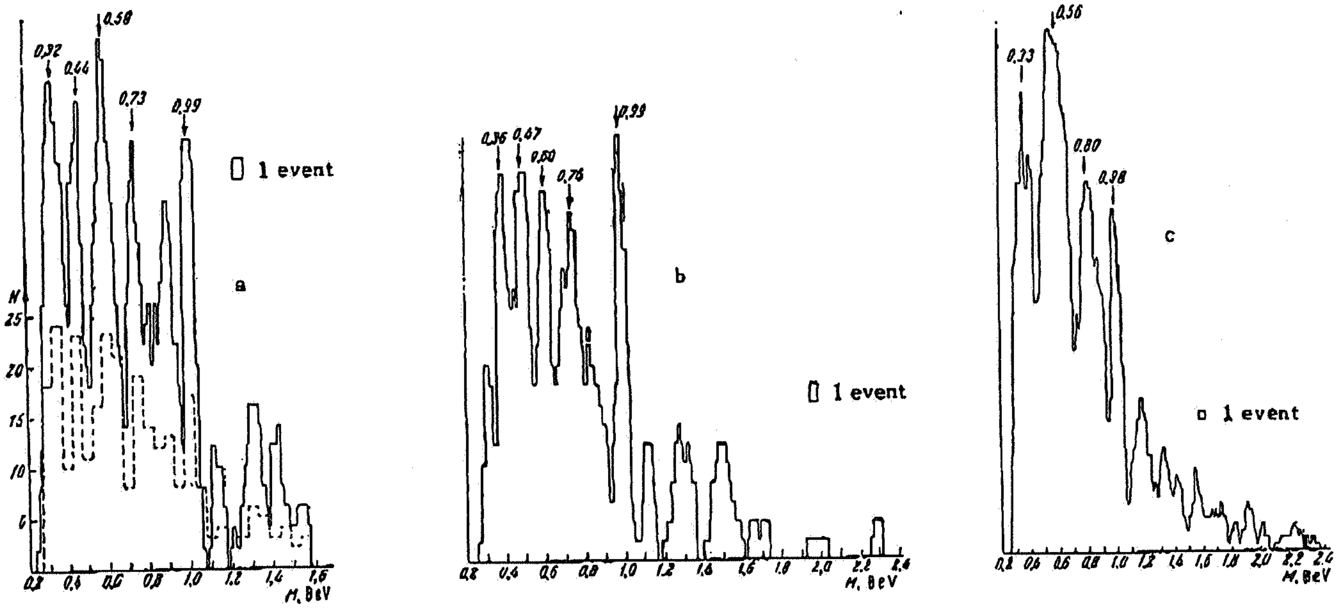

FIG. 1. Distribution over the effective masses for combinations in four-prong stars: a – $\pi^-\pi^-$ combinations, 280 combinations, 280 stars (the dashed line is the histogram); b – $\pi^+\pi^+$ combinations, 247 combinations, 247 stars; c – $\pi^+\pi^-$ combinations, 916 combinations, 229 stars.

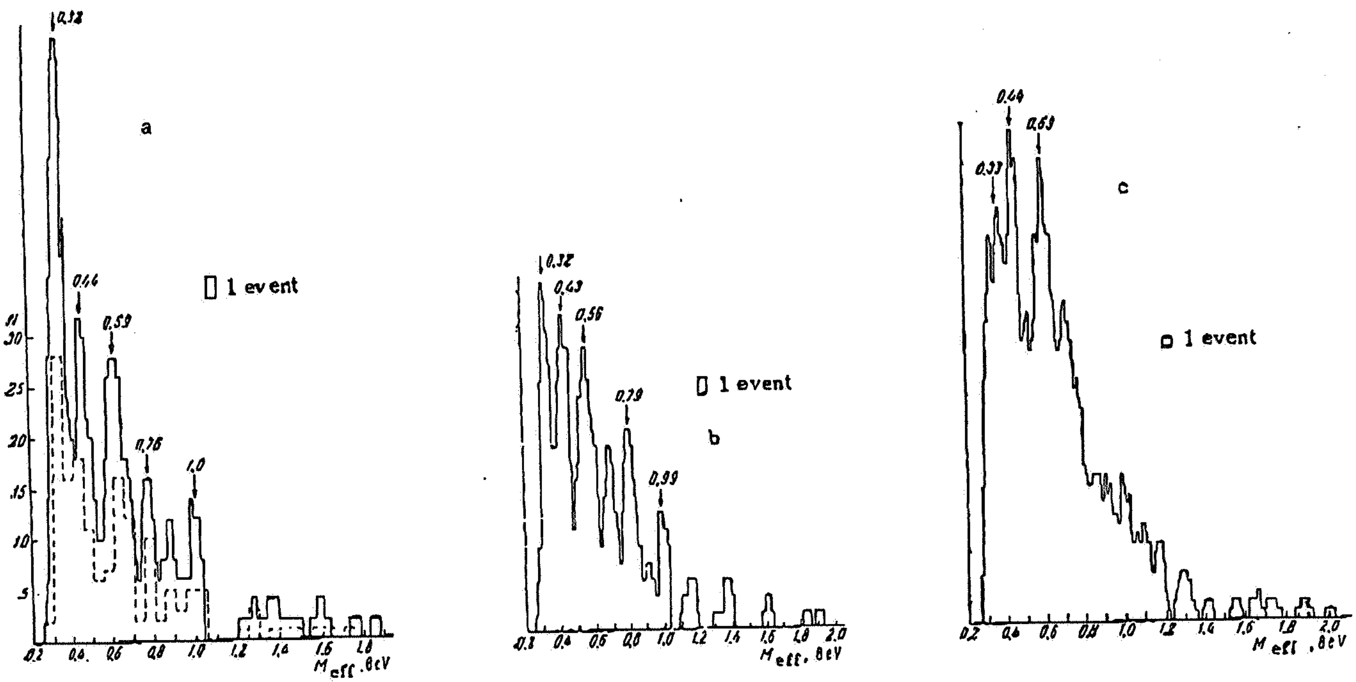

FIG. 2. Distribution over the effective masses for combinations in six-prong stars: a – $\pi^-\pi^-$ combinations (the dashed line is the histogram), 156 combinations, 52 stars; b – $\pi^+\pi^+$ combinations, 156 combinations, 52 stars; c – $\pi^+\pi^-$ combinations, 468 combinations, 52 stars.

the systematic errors it follows that the true value of the masses of the resonances can differ from those listed in the table by not more than 30 MeV.

Resonance maxima are observed at mass values 0.33, 0.44, 0.58, 0.76, and 0.99 BeV. Of these, the three resonances at values of M_{eff} equal to 0.58, 0.76, and 0.99 BeV were observed earlier in the charge states 0 and 1[1-3]. The maxima at M_{eff} = 0.33 and 0.44 BeV call for an additional analysis aimed at determining whether they are due to resonances in the system.

Four-prong stars			Six-prong stars			$M_{eff, av.}$
Charge states			Charge states			
(− −)	(+ +)	(+ −)	(− −)	(+ +)	(+ −)	
0.32	0.36	0.33	0.32	0.32	0.33	0.33
0.44	0.47	—	0.44	0.43	0.44	0.44
0.58	0.59	0.56	0.59	0.56	0.59	0.58
0.73	0.74	0.79	0.77	0.79	—	0.76
0.99	0.99	0.98	1.0	0.99	—	0.99

The existence of resonant states in doubly-charged systems of two pions at close values of the masses was also recently observed in πn collisions at 2.8 BeV by Shalamov and Grashin[4].

The available experimental data evidently indicate that there exist two systems of resonances in systems with identical mass values, but with different values of isotopic and mechanical spins, that is, in strong interactions one observes degeneracy in the isotopic and mechanical spins.

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