Tetraquarks, pentaquarks and the like
Old and new views

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Outline of the talk

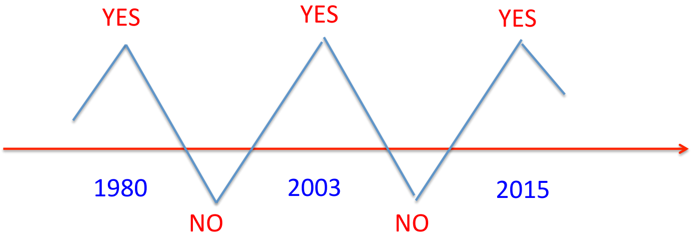
Pre-history (from 1968 to 2003: hints for tetra- & penta-quarks)

- Motivation & Background
  - Duality (Rosner, 1968)
    - $MM \to MM$, $MB \to MB$, $B\bar{B} \to B\bar{B}$
  - Large N-expansions
    - $1/N_c$ @ $g^2 N_c = const$ ('t Hooft, 1973)
    - $1/N_f$ @ $g^2 N_c = const$ and $N_f/N_c = const$ (Veneziano, 1975)
  - Experiments (1975 -1980 & around 2003)
    - LEAR - S [$M \sim 1936, \Gamma \sim 4 - 8$ MeV] & other candidates
- A theoretical picture emerged from QCD predicting
  - "hidden baryon" states → Baryonium
    (Rossi, Veneziano, 1977)

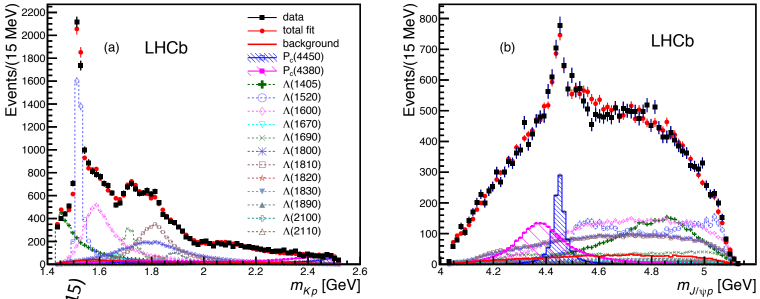
History (2003 - today)

- More "stable" experimental data (after 2011)
- A better understanding of Baryonium (Rossi, Veneziano, 2015)
- Phenomenology of tetra-quarks, penta-quarks, . . .
  (Yaffe, 1977 - Guerrieri, Maiani, Polosa, Riquer, . . . 2004 - 2015)

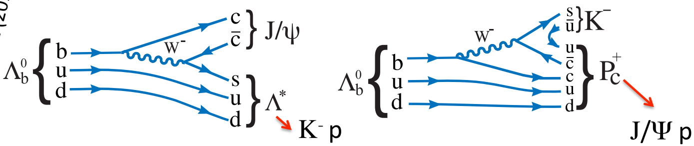
The multi-quark saga



4q's & 5q's discovery history



Phys. Rev. Lett. 115, 072001 (2015)



Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

$M(P_{Ic}^+) = 4450$ $\quad J^P = 5/2^+$ $\quad \Gamma = 39$ MeV

$M(P_{IIc}^+) = 4380$ $\quad J^P = 3/2^-$ $\quad \Gamma = 205$ MeV

The evidence of 4q's states - Experiments

G.T. Bodwin, E. Braaten, E. Eichten, S.L. Olsen, T.K. Pedlar, J. Russ
arXiv:1307.7425v3 [hep-ph]

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment ($\#\sigma$)	1st observation
$X(3823)$	3823.1±1.9	< 24	$?^{?-}$	$B \to K + (\chi_{c1}\gamma)$	Belle [4] (3.8)	Belle 2013
$\boldsymbol{X(3872)}$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [5, 6] (12.8), *BABAR* [7] (8.6)	Belle 2003
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [8–10] (np), DØ [11] (5.2)	
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [12][a] (4.3), *BABAR* [13][a] (4.0)	
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9)	
				$B \to K + (J/\psi\,\gamma)$	Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6)	
				$B \to K + (\psi(2S)\,\gamma)$	*BABAR* [19][a] (3.5), Belle [17][a] (0.4)	
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [20] (np)	
$\boldsymbol{X(3915)}$	3917.5 ± 1.9	20±5	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [21] (8.1), *BABAR* [22] (19)	Belle 2004
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [23] (7.7), *BABAR* [13, 24](7.6)	
$\boldsymbol{\chi_{c2}(2P)}$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [25] (5.3), *BABAR* [26] (5.8)	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27] (6.0)	Belle 2007
				$e^+e^- \to J/\psi + (...)$	Belle [28] (5.0)	
$\boldsymbol{G(3900)}$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	*BABAR* [29] (np), Belle [30] (np)	*BABAR* 2007
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [31] (7.4)	Belle 2007
$\boldsymbol{Y(4140)}$	4144.5 ± 2.6	15^{+11}_{-7}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [32, 33] (5.0), CMS [34] (>5)	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D}^*)$	Belle [27] (5.5)	Belle 2007

Narrow states are below the $B\bar{B}$ threshold

The evidence of 4q's states - Experiments

G.T. Bodwin, E. Braaten, E. Eichten, S.L. Olsen, T.K. Pedlar, J. Russ

arXiv:1307.7425v3 [hep-ph]

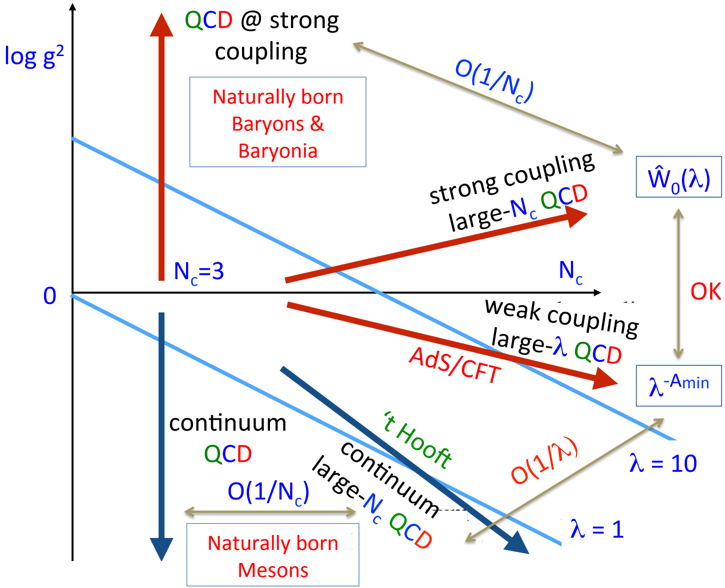
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$\boldsymbol{Y(4260)}$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	*BABAR* [35, 36] (8.0), CLEO [37] (5.4)	*BABAR* 2005
					Belle [31] (15)	
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [38] (11)	
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [38] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$??^{+}$	$B \to K + (J/\psi\,\phi)$	CDF [33] (3.1)	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [39] (3.2)	Belle 2009
$\boldsymbol{Y(4360)}$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	*BABAR* [40] (np), Belle [41] (8.0)	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [42] (8.2)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	Belle [41] (5.8)	Belle 2007
$\boldsymbol{Z_c^+(3900)}$	3898 ± 5	51 ± 19	$1^{?-}$	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [43] (np), Belle [44] (5.2)	BESIII 2013
				$e^+e^- \to \pi^- + (J/\psi\,\pi^+)$	Xiao *et al.* [45][a] (6.1)	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (1.1)	Belle 2008
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (2.0)	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K + (\psi(2S)\,\pi^+)$	Belle [48, 49] (6.4), *BABAR* [50] (2.4)	Belle 2007
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [51, 52] (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [53, 54] (16)	
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [53, 54] (16)	

Narrow states are below the $B\bar{B}$ threshold

The emergence of Baryonium interpretation - Theory

- The physically interesting limit of QCD is g^2 & $\lambda = g^2 N_c$ small
- We have a (more or less) good control of the theory
  - in perturbation theory: $g^2 \to 0$ @ N_c fixed
  - in the 't Hooft limit: $1/N_c \to \infty$ @ $\lambda = g^2 N_c$ fixed
  - in the strong coupling limit: $1/g^2 \to 0$ @ N_c fixed (possibly large)
  - in the AdS/CFT limit: $1/N_c \to 0$ @ λ fixed and large
- The overall situation is pictorially illustrated in the next figure
- As we shall see, "naturally"
  - mesons appear in the 't Hooft and strong coupling limit
  - baryons & baryonia in the strong coupling limit
- The key question is: can we walk clockwise to real physics?
- With some optimism we shall argue that this is, indeed, the case

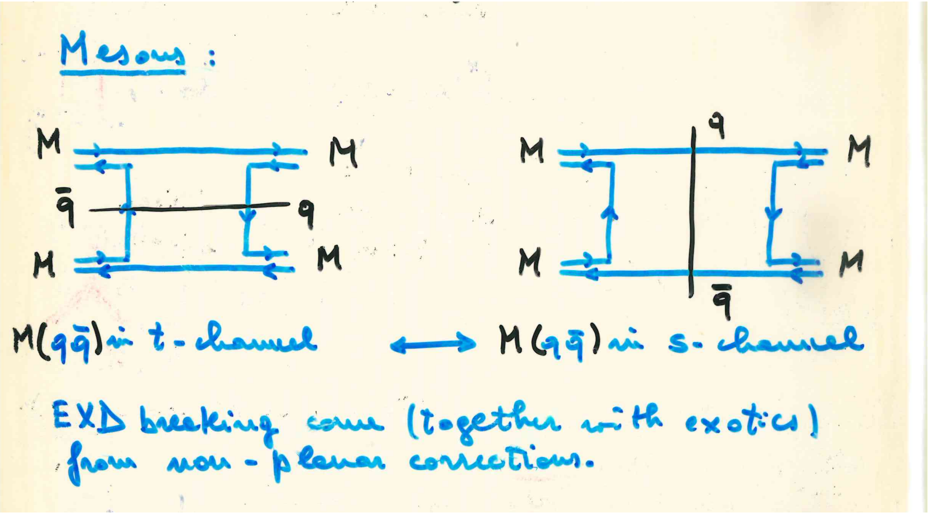
The interesting limits of QCD



Duality in *MM* $\rightarrow$ *MM* amplitudes

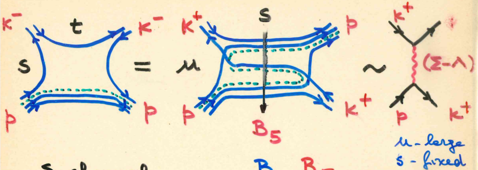
From my 1977 CERN seminar

From my 1977 CERN seminar



Duality in $MB \to MB$ amplitudes

1) (s,t) term

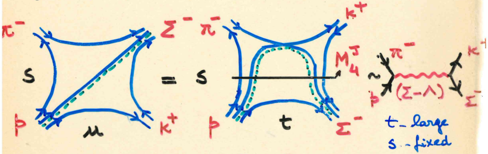


s-channel ~ B, B_5, ...

t-channel ~ M, M^J, ...

u-channel ~ B_5, ...

2) (s, u) term



s-channel ~ B, B_5, ...

t-channel ~ M^J_4, ...

u-channel ~ B, B_5, ...

15 III

EXD for baryons is being studied in T.E. (Konishi, Rosenzweig).

As in QCD, M_4^J and B_5 are on the same footing. Consider

$K^- p \to K^- p$ — (s,t) term only; u-exotic : no B_5

$\pi^- p \to K^+ \Sigma^-$ — (s,u) term only; t-exotic : no M_4^J

- Both give EXD for strange trajectories.
- If EXD is broken

$\mathrm{Disc}_u (K^- p \to K^- p) \neq 0$ — B_5 couples

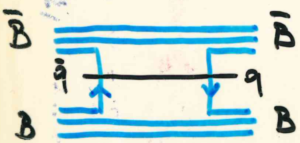
duality

$\mathrm{Disc}_t (\pi^- p \to K^+ \Sigma^-) \neq 0$ — M_4^J couples.

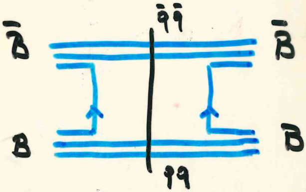
Properties abstracted from QCD appear to be more generally true.

Duality in $B\bar{B} \to B\bar{B}$ amplitudes

Baryons (Rosner '68)

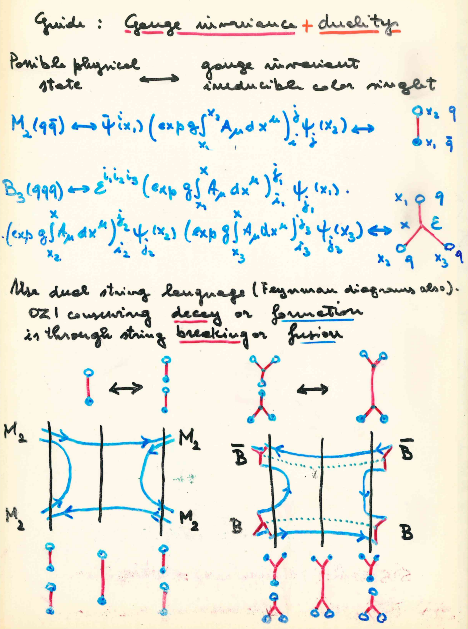


$M(q\bar{q})$ in t-channel

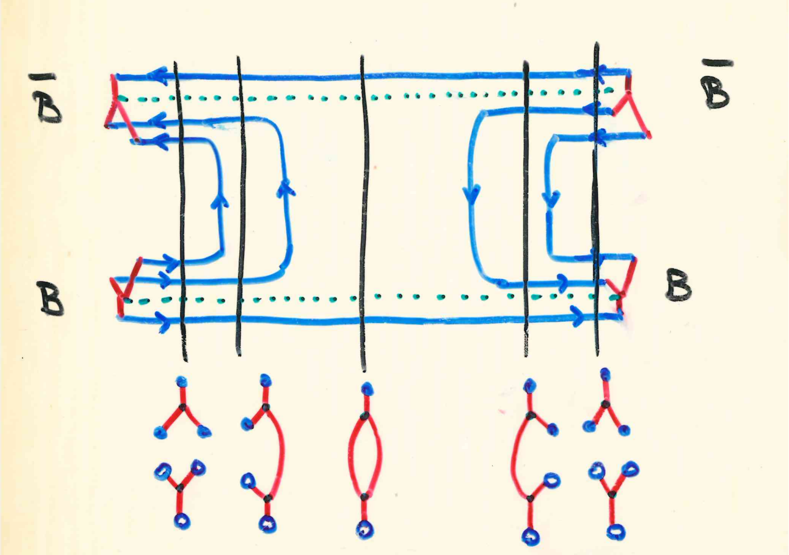


$qq\bar{q}\bar{q}$ in s-channel

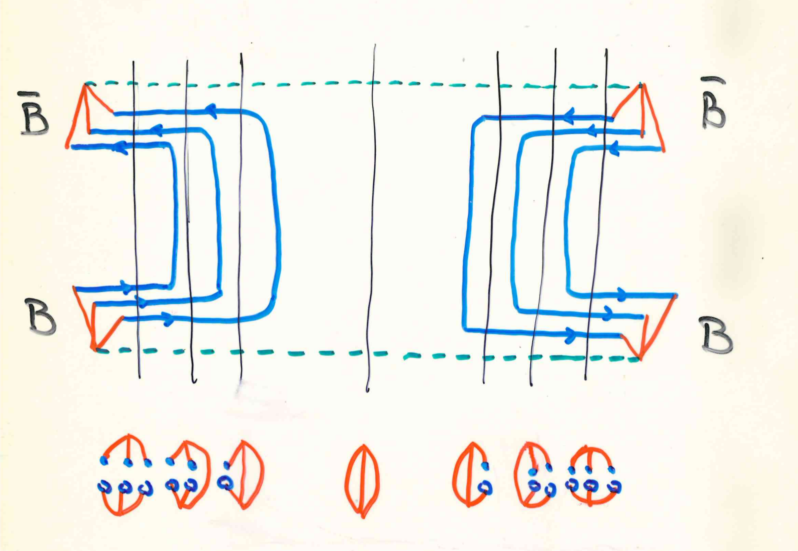
$qq\bar{q}\bar{q}$ $\begin{cases} 2\ M(q\bar{q}) \text{ continuum} \\ \text{new resonance} \end{cases}$



QCD string breaking & fusion



QCD string breaking & fusion

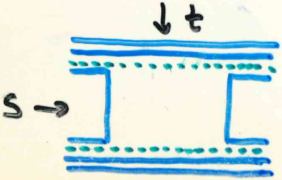


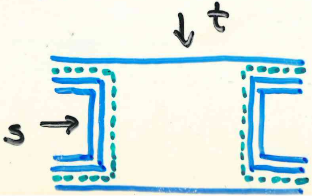
QCD string breaking & fusion

i) Solve Rosner' paradox : baryonium.

ii) Baryonium $\not\to$ ordinary mesons.

iii) Duality is between annihilation and scattering diagrams.





Pre-historical phenomenology

- Birth
- Rise
- Evaporation

of Baryonium states

MASS (MeV)	WIDTH (MeV)	STATIST. EVIDENCE	REACTION
1455 1660 1695		99% C.L. 97.5% C.L. 98±2% C.L.	$\bar{p}p \to \gamma X$, $\hookrightarrow E_\gamma = \begin{cases} 420 \pm 17 \\ 216 \pm 9 \\ 183 \pm 7 \end{cases}$ SUM OF THE TW
1794.5±1.4	<8	95% C.L.	$\bar{p}d \to p_{VIS}(\bar{p}n) \to p_{VIS}(2m)\pi$
1897±1	25±6		$\bar{p}d \to p_{VIS}(\bar{p}n) \to p_{VIS} X^-$
1936±4	4÷8		$\begin{cases} p\bar{p} \to p\bar{p} \\ \sigma^T(p\bar{p}) \\ p\bar{p} \to (2m) \text{ PRONGS} \end{cases}$
2020±3	24±12	7.6 S.D.	$\pi^- p \to p_{FAST}\, \pi^-(p\bar{p})$
2204±5	16^{+20}_{-16}	5.5 S.D.	SAME
2600±10	<19	5.5 S.D.	$\bar{p}p \to (K_0\pi\pi\pi)^\pm \pi\pi\pi X^0$
2460±10	≤10	5 S.D.	$K^+p \to (\bar{\Lambda}p\pi^+)$
2850±5	<39	5.1 S.D.	$\bar{p}d \to p_{SPECT.} \begin{pmatrix} N\bar{N} \\ N\bar{N}\pi \end{pmatrix}^0 \pi^-$
2950±10	<15	6 S.D.	$\pi^- p \to p_{SLOW}\, (p\bar{p}\pi^-)_F X$
3050±10	<20	3.1 S.D.	$\bar{p}d \to p_{SPECT.}\, \pi^- \begin{pmatrix} N\bar{N} \\ N\bar{N}\pi \end{pmatrix}^0$

$\Gamma/M \leq 10^{-2}$

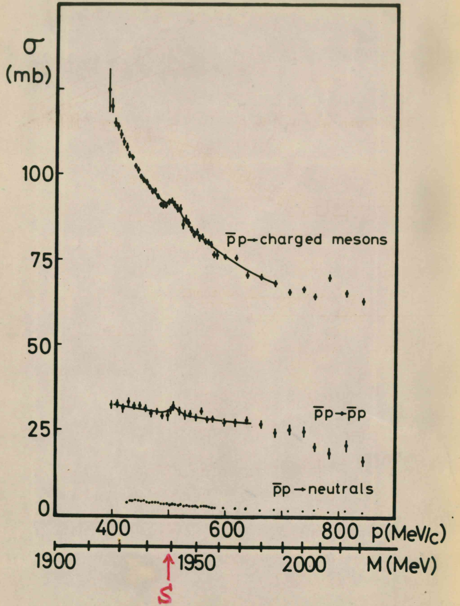
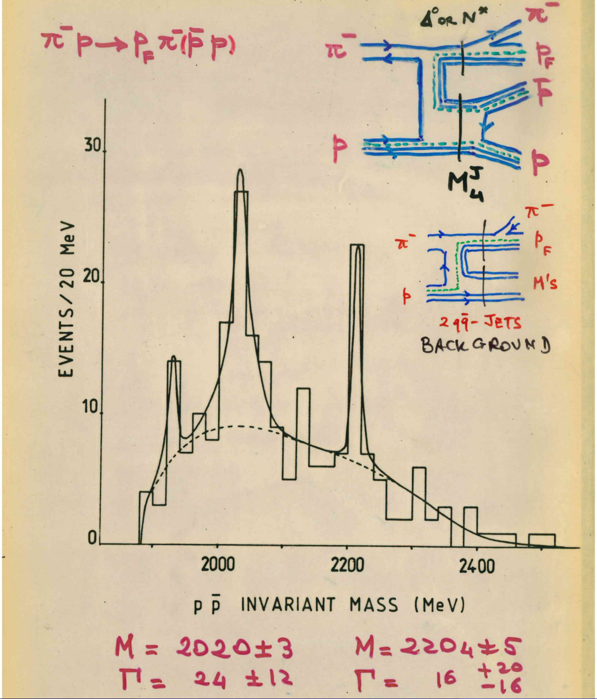
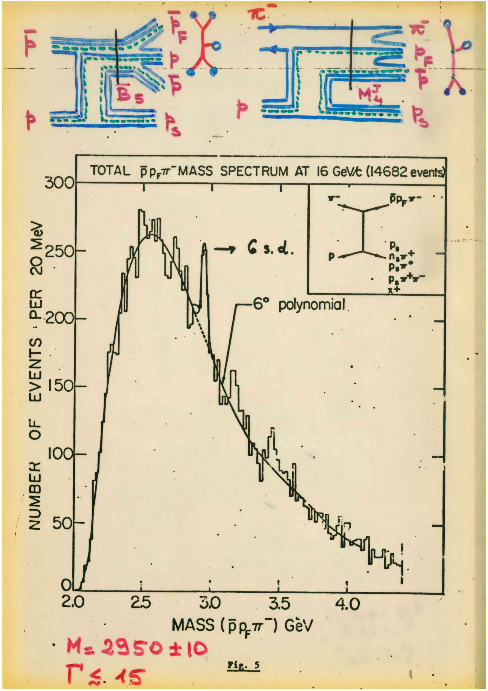


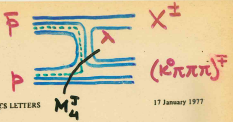
Fig. 2

M = 1936 ± 1
Γ = 8 ÷ 4


π⁻p → p_F π⁻(p̄ p)
Δ° OR N*
π⁻
π⁻
p_F
p̄
p
p
M₄^J
π⁻
π⁻
p_F
M's
p
2 qq̄- JETS
BACKGROUND
EVENTS / 20 MeV
30
20
10
0
2000
2200
2400
p p̄ INVARIANT MASS (MeV)
M = 2020 ± 3
Γ = 24 ± 12
M = 2204 ± 5
Γ = 16 +20 −16


TOTAL $\bar{p}p_F\pi^-$ MASS SPECTRUM AT 16 GeV/c (14682 events)
NUMBER OF EVENTS PER 20 MeV
MASS ($\bar{p}p_F\pi^-$) GeV
6 s.d.
6° polynomial
M = 2950 ± 10
Γ ≤ 15
Fig. 5

$\bar{p}p \to (K^0\pi\pi\pi)^{\mp} X^{\pm}$



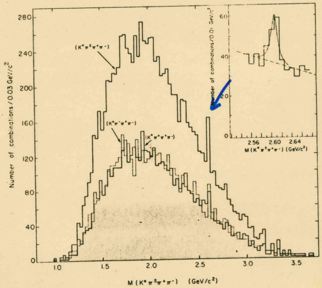


Fig. 1. Effective mass distribution for the $(K^0\pi^{\pm}\pi^{+}\pi^{-})$ combinations from the 6-prong-V^0 events: for the total sample, and for positive and negative charges. The insert shows the estimate of the background and of the experimental resolution.

is 108 ± 10 combinations. It would require a fluctuation of the background of 5.5 standard deviations to reach the signal.

An estimate of the product of the production cross section σ_I for the I peak times its branching ratio BR into the observed final state, integrated over our experimental resolution, gives $\sigma_I \cdot \mathrm{Br} \approx 20$ μbarn (corrected for the neutral decay mode of K^0_s) ‡1. The I appears equally in the positive and negative electric charges as shown by fig. 1.

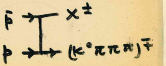
BEBC was filled with hydrogen and photographed by 4 cameras. The exposure yielded approximately 250000 pictures, with an average number of 5.2 incident antiprotons of 12 GeV/c per picture. The momentum of each incident track, which varies slowly according to the point of entry into the chamber, is known with $|\Delta p| = 0.060$ GeV/c. The π^- contamination of the 3-stages RF separated beam is 5 ± 3%. The scanning of the film yielded ~3000 events of the 6-prong and ⩾ 1 V^0 topology, in a selected fiducial volume, with a scanning efficiency of 80%.

The high magnetic field (35 kG) and long tracks observed in a large chamber (ϕ 3.7 m) enable us to reach a high resolution, requiring also a high accuracy in measurement and event reconstruction. The events were measured in the different participating laboratories, on the automatic devices Erasme and Polly,

‡1 The inclusive cross sections and charged multiplicities are given in ref. [2].

$M = 2600 \pm 10$

$\Gamma \leq 18$



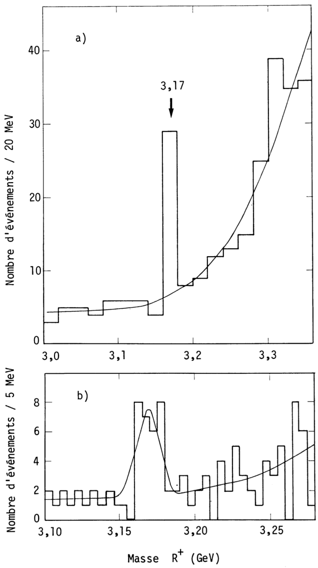


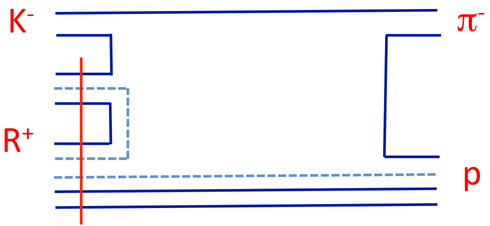
Figure 4 — a) Spectre de masse du système hypéronique R^+ pour des événements dans lesquels le π^- provenant de la réaction $K^-p \to \pi^-R^+$ se situe dans l'hémisphère arrière du système du centre de masse. La courbe en trait plein représente l'ajustement du fond avec une probabilité maximale. L'impulsion du K^- incident était de 8,25 GeV/c.
b) Spectre de masse du R^+ pour les mêmes événements que dans la figure 4a, par intervalles de 5 MeV.

$K^- p \to \pi^- R^+$

$R^+ \to \Sigma K\bar{K} / \Lambda K\bar{K} / \Xi K$

T. Amirzadeh *et al.*
CERN/EP 79-101
September 18, 1979

A narrow pentaquark?
$M \approx 3.17$ GeV



The systematics of hadronic states and amplitudes

Table IIa

Simplest mesons and baryons : colour structure and string picture

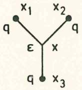
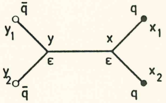
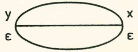
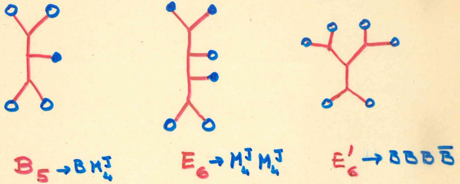
HADRON	GAUGE INVARIANT OPERATOR	STRING PICTURE
$M_2 = q\bar q$ meson	$\bar q^{j_2}(x_2)\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu\, dx^\mu\right)\right]_{j_2}^{j_1} q_{j_1}(x_1)$	
M_o = quarkless meson	$Tr\left[P\exp\left(ig\oint A_\mu\, dx^\mu\right)\right]$	
$B_3 = qqq$ baryon	$\varepsilon^{j_1j_2j_3}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu\, dx^\mu\right) q(x_1)\right]_{j_1}$ $\left[P\exp\left(ig\int_{x_2}^{x} A_\mu\, dx^\mu\right) q(x_2)\right]_{j_2}\left[P\exp\left(ig\int_{x_3}^{x} A_\mu\, dx^\mu\right) q(x_3)\right]_{j_3}$	

Table IIb

The three ($N_c = 3$) baryonium families : colour structure and string picture ;
The symbol $\exp \int_x^y$ is a shorthand for the path ordered exponential used in Table IIa.

HADRON	GAUGE INVARIANT OPERATOR	STRING PICTURE
M_4^J = baryonium with $qq\bar q\bar q$ quantum numbers	$\varepsilon_{j_1j_2j_3}\,\varepsilon^{k_1k_2k_3}\left[\bar q(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\bar q(y_2)\exp\int_y^{y_2}\right]^{j_2}\left[\exp\int_x^{y}\right]^{j_3}_{k_1}\left[\exp\int_{x_1}^{x} q(x_1)\right]_{k_2}\left[\exp\int_{x_2}^{x} q(x_2)\right]_{k_3}$	
M_2^J = baryonium with $q\bar q$ quantum numbers	$\varepsilon_{j_1j_2j_3}\,\varepsilon^{k_1k_2k_3}\left[\bar q(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\exp\int_x^{y}\right]^{j_2}_{k_1}\left[\exp\int_x^{y}\right]^{j_3}_{k_2}\left[\exp\int_{x_1}^{x} q(x_1)\right]_{k_3}$	
M_0^J = quarkless baryonium	$\varepsilon_{j_1j_2j_3}\,\varepsilon^{k_1k_2k_3}\left[\exp\int_x^{y}\right]^{j_1}_{k_1}\left[\exp\int_x^{y}\right]^{j_2}_{k_2}\left[\exp\int_x^{y}\right]^{j_3}_{k_3}$	

According to our rules one can formally construct other exotic states beside $M^J_{0,2,4}$:



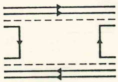
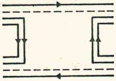
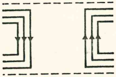
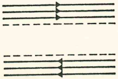
Important for duality in 2 body reactions.

For instance: existence of M^J_4 and B_5 modifies the pattern of EXD for baryon trajectories, as obtained from the absence of exotics in $B\bar{B} \to MM$ and $MB \to BM$.

This is very welcome, because such a pattern is in conflict with experimental evidence.

Table IIIa

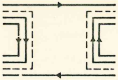
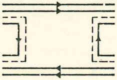
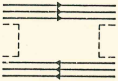
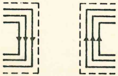
Contributions to $B\bar{B}$ scattering $(N_c=3)$

$B\bar{B} \to B\bar{B}$ JUNCTION DUALITY DIAGRAMS SCATTERING	S-CHANNEL FORMATION	MULTIPLICITY a)	t-CHANNEL b) EXCHANGE	SLOPE
1 	M_4^J 	$\bar{n}(s') \simeq \bar{n}_{e^+e^-}(s')$	$s^{\alpha_R - 1} \sim s^{-1/2}$ Regge pole	α'_R
2 	M_2^J 	$\bar{n}(s') \simeq 2\bar{n}_{e^+e^-}(s'/4)$	$s^{2\alpha_R - 2} \sim s^{-1}$ 2-Reggeon cut	$\frac{1}{2}\alpha'_R$
3 	M_0^J 	$\bar{n}(s') \simeq 3\bar{n}_{e^+e^-}(s'/9)$	$s^{3\alpha_R - 3} \sim s^{-3/2}$ 3-Reggeon cut	$\frac{1}{3}\alpha'_R$
4 	Non-resonant two jet background	$\bar{n}(s') \simeq 2\bar{n}_{e^+e^-}(s'/4)$	$s^{\alpha_P - 1} \sim s^0$ Pomeron	$\frac{1}{2}\alpha'_R$

a) s' is the invariant mass of the final state excluding the leading baryons
b) to estimate the s-behavior we have taken $\alpha_R = 0.5$

Table IIIb

Contributions to $B\bar{B}$ annihilation ($N_c=3$)

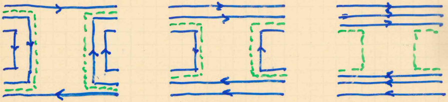
$B\bar{B} \to B\bar{B}$ JUNCTION DUALITY DIAGRAMS ANNIHILATION	s-CHANNEL FORMATION	MULTIPLICITY	t-CHANNEL EXCHANGE a)	SLOPE
1 	$1q\bar{q}$ - jet	$\bar{n}(s) \simeq \bar{n}_{e^+e^-}(s)$	$s^{\alpha(M_4^J)-1} \sim s^{-3/2}$ Regge pole	$\alpha'(M_4^J) \sim \alpha'_R$
2 	$2q\bar{q}$ - jets	$\bar{n}(s) \simeq 2\bar{n}_{e^+e^-}(s/4)$	$s^{\alpha(M_2^J)-1} \sim s^{-1}$ Regge pole	$\alpha'(M_2^J) \sim \frac{1}{2}\alpha'_R$
3 	$3q\bar{q}$ - jets	$\bar{n}(s) \simeq 3\bar{n}_{e^+e^-}(s/9)$	$s^{\alpha(M_0^J)-1} \sim s^{-1/2}$ Regge pole	$\alpha'(M_0^J) \sim \frac{1}{3}\alpha'_R$
4 	M_0 	$\bar{n}(s) \simeq 2\bar{n}_{e^+e^-}(s/4)$	$s^{2\alpha_B-2} \sim s^{-2}$ 2 - Reggeon cut (baryon)	$\frac{1}{2}\alpha'_R$

a) To estimate the s-behaviour we have taken $\alpha_B \simeq 0$.

Regge trajectories

BARYONIUM REGGE TRAJECTORIES

ANNIHILATION DIAGRAMS : $s^{\alpha^J(0)-1}$ LARGE s, FIXED t



M_4^J M_2^J M_0^J t-CHANNEL

$$\begin{cases} \alpha_4^J(0) = 2\alpha_B(0) - 1 + (1-\alpha_R(0)) \sim -1/2 \\ \alpha_2^J(0) = 2\alpha_B(0) - 1 + 2(1-\alpha_R(0)) \sim 0 \\ \alpha_0^J(0) = 2\alpha_B(0) - 1 + 3(1-\alpha_R(0)) \sim 1/2 \end{cases}$$

$(\alpha_B(0) \sim 0)$

NUMBER OF (MULTIPERIPHERAL) JETS

- $\alpha^{n_J}_{n_q}(0) = 1 - \frac{1}{4}(n_q + n_J)$ (1/4 AFTER FITTING ρ, K^*, B TRAJECTORIES)

$\alpha_R(0) = 1 - \frac{2}{4} = 1$ $\alpha'_R(0) \sim 1$

$\alpha_B(0) = 1 - \frac{1}{4}(3+1) = 0$ $\alpha'_B(0) \sim \alpha'_R(0)$

$\alpha_4^J(0) = 1 - \frac{1}{4}(4+2) = -1/2$ $\alpha_4^{J\prime}(0) \sim \alpha'_R(0)$

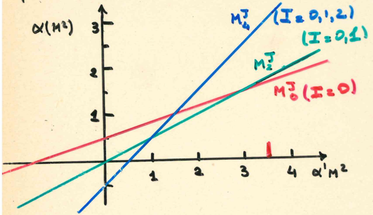
$\alpha_2^J(0) = 1 - \frac{1}{4}(2+2) = 0$ $\alpha_2^{J\prime}(0) \sim \alpha'_R(0)/2$

$\alpha_0^J(0) = 1 - \frac{1}{4}(0+2) = \frac{1}{2}$ $\alpha_0^J(0) \sim \alpha'_R(0)/3$

$\alpha_P(0) = 1 - \frac{1}{4}(0+0) = 1$ $\alpha'_P(0) \sim \alpha'_R(0)/2$

BARYONIUM

+ Using their dual relation to meson jet production, one obtains estimates for $\alpha^J(0), \alpha'^J(0)$



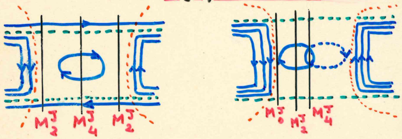
$M^2 > 0 \rightarrow M_4^J$

$M^2 < 0 \rightarrow M_0^J$

Mixing effects will modify this picture.

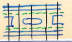
(I) Mixing between baryonium states VOZ R

It is induced by planar quark loops.

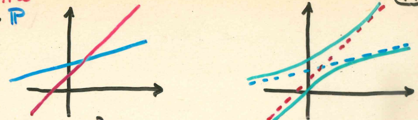


Mixing in the I = 0,1 sectors

Mixing in the I = 0 sector.

(I = 2 is unmixed )

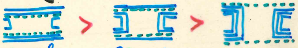
Plane f, ω
cylinder ℙ



(17)

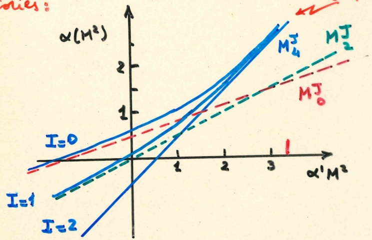
+ For large $M^2 > 0$ mixing is small

(non mixing diagrams dominate at high energy:



)

Leading baryonium trajectories:

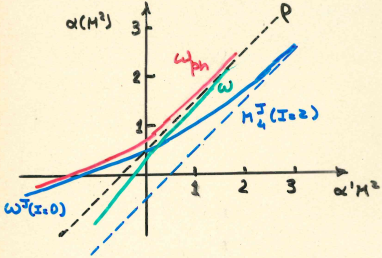


- At this level still an exact selection rule NZR

$M^J \not\to q\bar{q}$ mesons.

Narrow states in $N\bar{N}$?

Mixing between ω and $M^J(I=0, C=-1) \equiv \omega^J$.



After mixing with $C=-1$ cylinder, ω is lowered, but it mixes with ω^J, giving an output leading trajectory ω_{ph}, which

for $M^2>0$ is near the ω

for $M^2<0$ tend to the flatter ω^J

Approaching today's phenomenology

- Birth
- Rise
- Evaporation

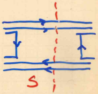
of pentaquarks

PENTAQUARK STATES

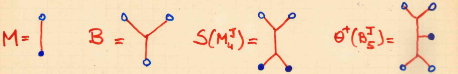
* OLD TIMES (1974 – 1980)

$$S \begin{cases} M \simeq 1936 \\ \Gamma \lesssim 20 \\ J^{PC} = 3^{--} \end{cases}$$

$p\bar{p}$ – ELASTIC / TOTAL



• BARYONIUM PICTURE G.C. ROSSI G. VENEZIANO



* PRESENT DAYS (JULY 8th, 2003 – ...)

$$\Theta^+ \begin{cases} M \simeq 1526 \\ \Gamma \lesssim 20 \\ S = 1 \quad P = + \end{cases}$$

$\gamma n \to K^- \Theta^+$, $\hookrightarrow K^+ n$

$pp \to \Theta^+ X$, $\hookrightarrow K^0 p$

$\Xi^{--}, \Xi^-, \Xi^0, \Xi^+ \begin{cases} M \simeq 1860 \\ \Gamma \lesssim 20 \end{cases}$ $pp \to \Xi + X$, $\hookrightarrow (\Xi / \Xi^*)\pi$

• DIQUARK PICTURE R. JAFFE F. WILCZEK

$(\bar{3}_c \bar{3}_f)_{S=0}^{I}$ (oo) $\to (\bar{6}_f, S=1)_{II}$

$(\bar{3}_c \bar{3}_f)_{S=1/2}$

$(\bar{3}_c \bar{3}_f)_{S=0}^{I}$ (oo)

$[I + I] \Rightarrow \underbrace{\bar{3}_f \times \bar{3}_f}_{dq \times dq} = 3_f \times \bar{6}_f$ $\underbrace{\bar{6}_f \times \bar{3}_f}_{dqdq \times \bar{q}} = 8_f + \overline{10}_f$

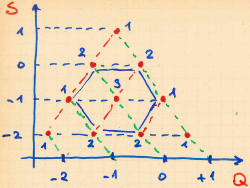
$\ell = 1$

$[I + I] \Rightarrow \underbrace{6_f}_{dq} \times \underbrace{\bar{3}_f}_{dq} \times \underbrace{3_f}_{\bar{q}} = \underbrace{6_f}_{dq} \times (\underbrace{3_f + 6_f}_{dq \times \bar{q}}) = 8 + 10 + 1 + 8 + 27$

• UNCORRELATED QUARK MODEL

$(3 \times 3 \times 3 \times 3)_f \times \bar{3}_f = (3, \bar{6}, 15, 15')_f \times \bar{3}_f = (1, 8, \overline{10}, 27, \overline{35})_f$

$(P = -)$



$\bar{6}_f = \begin{Bmatrix} [ud]^2 & [ud][us]_+ & [us]^2 \\ [us][ds]_+ & [ds]^2 & [ds][ud]_+ \end{Bmatrix}$

BOSONS

Θ^+ $[ud][ud]\bar{s}$ $S=1$

N^+ $[ud][ud]\bar{d}$
N_s^+ $[ud][us]\bar{s}$ } $S=0$ ROPER (1440)?

Q=+1

Σ^+ $[ud][us]\bar{d}$
Σ_s^+ $[us][us]\bar{s}$ } $S=-1$

Ξ^+ $[us][us]\bar{d}$ $S=-2$

N_s^0 $[ud][ds]\bar{s}$
N^0 $[ud][ud]\bar{u}$ } $S=0$

Λ $[ud][ds]\bar{d}$
Σ^0 $[ud][us]\bar{u}$ } $S=-1$ **Q=0**
Σ_s^0 $[us][ds]\bar{s}$

Ξ_{uu} $[us][us]\bar{u}$
Ξ^0_{ud} $[us][ds]\bar{d}$ } $S=2$

Ξ^{--} $[ds][ds]\bar{u}$ $S=-2$ **Q=-2**

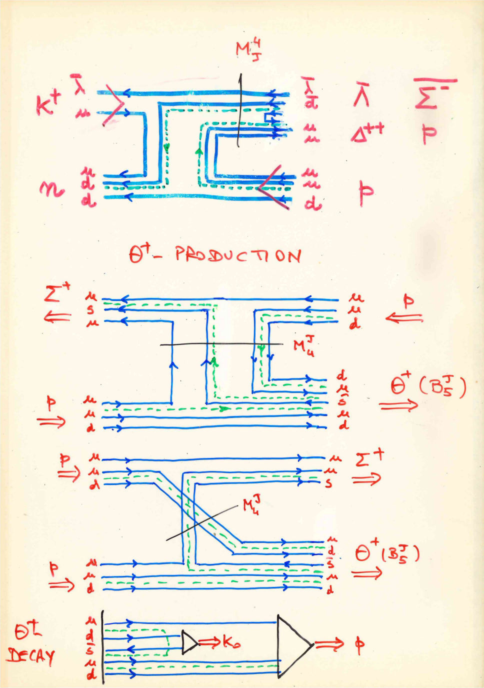
Σ^- $[ud][ds]\bar{u}$
Σ_s^- $[ds][ds]\bar{s}$ } $S=-1$ **Q=-1**

Ξ^-_{dd} $[ds][ds]\bar{d}$
Ξ^-_{ud} $[us][ds]\bar{u}$ } $S=-2$

MASS SPECTRUM

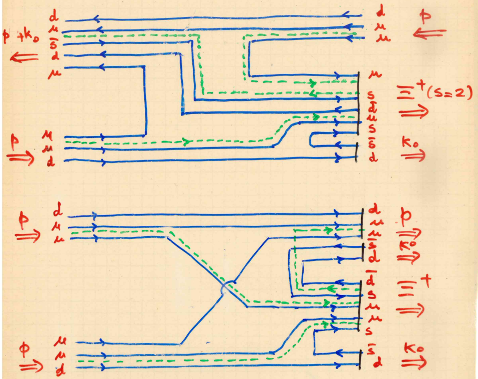
DIQUARK JW:
Σ_s
Ξ
N_s
$\Lambda\Sigma$
Θ
N

SOLITON MIT-BAG:
Ξ
Σ
N
Θ



M_J^4
K^+
$\bar{\lambda}$
u
n
u
d
d
$\bar{\lambda}$
$\bar{d}$
$\bar{\Lambda}$
$\bar{\Sigma}^-$
u
u
Δ^{++}
p
u
u
d
p
Θ^+- PRODUCTION
Σ^+
u
s
u
u
u
d
p
M_4^J
p
u
u
d
d
u
$\bar{s}$
u
d
$\Theta^+ (B_5^J)$
p
u
u
d
u
u
s
Σ^+
M_4^J
p
u
u
d
u
d
$\bar{s}$
u
d
$\Theta^+ (B_5^J)$
Θ^+
DECAY
u
d
$\bar{s}$
u
d
K_0
p

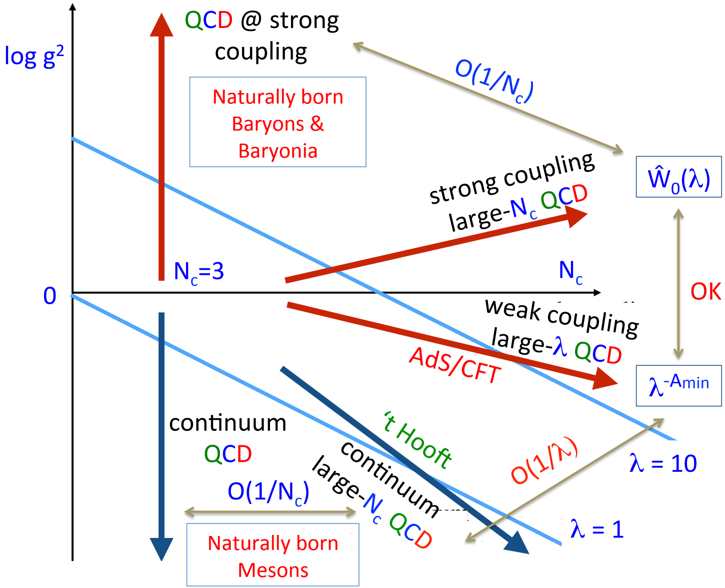
Ξ^+ - PRODUCTION



Back to theory!

- The limits of QCD
- from large g^2 & fixed N_c ...
  - Meson propagator and amplitudes
  - Baryon propagator and amplitudes
- ... to small g^2 & N_c continuum QCD

Recall ... the interesting limits of QCD



Strong coupling

$$\langle P\exp\left(ig\int_{\mathcal{C}} A_\mu dx^\mu\right)\rangle =$$

$$= \frac{\int \mathcal{D}A_\mu \, P e^{ig\int_{\mathcal{C}} A_\mu dx^\mu} \, e^{S}}{\int \mathcal{D}A_\mu \, e^{S}} \equiv W(\mathcal{C})$$

$$W(\mathcal{C}) \xrightarrow[\text{lattice}]{} \langle \frac{1}{N} \mathrm{Tr}\left(\prod_{\mathcal{C}} U\right)_P \rangle =$$

$$= \frac{\int \prod_i dU_i \, \frac{1}{N} \mathrm{Tr}\left(\prod_{\mathcal{C}} U\right) e^{-\frac{1}{g^2} S_w(U)}}{\int \prod_i dU_i \, e^{-\frac{1}{g^2} S_w(U)}}$$

$$\int_{SU(N)} d(U_{m\mu})\,(U_{m,\mu})_{ij}\,(U^{+}_{m\mu})_{k\ell} = \frac{1}{N}\,\delta_{i\ell}\,\delta_{jk}$$

but

$$\int dU \; U = 0 \qquad \Big(\int_{SU(N)} dU = 1 \Big)$$

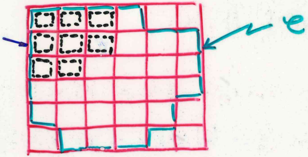
$$\int dU \; UU = 0$$

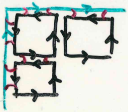
$$\vdots$$

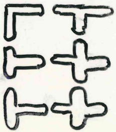
$$\int dU \; \underbrace{UU\ldots U}_{N-1} = 0$$

$$\int dU \; U_{i_1 j_1} U_{i_2 j_2} \cdots U_{i_N j_N} = \frac{1}{N!}\, \varepsilon_{i_1 \ldots i_N}\, \varepsilon_{j_1 \ldots j_N}$$

There exist other non-zero contractions: $\int UUU^{+}U^{+} \neq 0$







For any surface S bounded by $\mathcal{C}$

$$W(\mathcal{C}) \sim \frac{1}{N}\left(\frac{1}{g^2}\right)^P \left(\frac{1}{N}\right)^L N^V = \left(\frac{1}{g^2 N}\right)^P N^{P-L+V}$$

$$P-L+V = 2-2h-b = 1 \quad \begin{pmatrix} h=0 \\ b=1 \end{pmatrix}$$

$$W(\mathcal{C}) = \left(\frac{1}{g^2 N}\right)^{A/a^2} = e^{-KA}$$

$$K = \frac{1}{a^2}\log(g^2 N)$$

P = no of plaquettes paving S. $P = A/a^2$

V = no of vertices

L = no of links

In the strong coupling limit $1/g^2 \to 0$

$$K \to \infty \Rightarrow W(\mathcal{C}) \sim \exp(-K A_{min})$$

Meson propagator and amplitudes

$q\bar{q}$ mesons are intermediate states in the gauge invariant correlator

$$G_{\mathcal{M}}(\mathcal{C}_{t'},\mathcal{C}_t) = \langle \mathcal{M}(\mathcal{C}_{t'})\mathcal{M}^\dagger(\mathcal{C}_t)\rangle$$

where

$$\mathcal{M}(\mathcal{C}_t) = \frac{1}{\sqrt{N_c}}\bar{q}(\vec{r},t)U[\mathcal{C}_t]q(\vec{s},t)\,, \quad U[\mathcal{C}_t] = \mathcal{P}\exp\left[ig\int_{\vec{r}}^{\vec{s}} d\vec{x}\,\vec{A}(\vec{x},t)\right]$$

$\mathcal{C}_t$ is a line joining the point $(\vec{r},t)$ with $(\vec{s},t)$

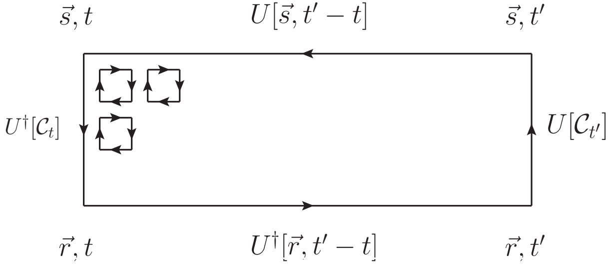
Contracting the quark fields, one finds

$$G_{\mathcal{M}}(\mathcal{C}_{t'},\mathcal{C}_t) = \frac{1}{N_c}\frac{\int\prod_i dU_i\,\mathrm{Tr}\Big(U^\dagger[\mathcal{C}_t]S_F(\vec{r},t;\vec{r},t')U[\mathcal{C}_{t'}]S_F(\vec{s},t';\vec{s},t)\Big)e^{-\frac{1}{g^2}S_{LYM}(U)}}{\int\prod_j dU_j e^{-\frac{1}{g^2}S_{LYM}(U)}}$$

In the static limit we replace the quark propagator with

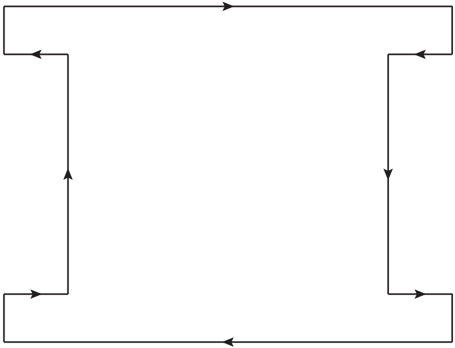
$$S_F(\vec{s},t';\vec{s},t) \to U[\vec{s},t'-t] = \prod_{\tau\in[t,t']} U[\vec{s},\tau]$$

$$G_{\mathcal{M}}(\mathcal{C}_{t'},\mathcal{C}_t) = \frac{1}{N_c}\frac{\int \prod_i dU_i \,\mathrm{Tr}\Big(U^\dagger[\mathcal{C}_t]U^\dagger[\vec{r},t-t']U[\mathcal{C}_{t'}]U[\vec{s},t'-t]\Big)e^{-\frac{1}{g^2}S_{LYM}(U)}}{\int \prod_j dU_j e^{-\frac{1}{g^2}S_{LYM}(U)}}$$



$G_M(\mathcal{C}_{t'},\mathcal{C}_t) = \langle$ Wilson loop with sides $|\vec{s}-\vec{r}| \times |t'-t| \rangle$

$MM \to MM$ amplitude



$$\mathcal{M}_{MM \to MM}(\lambda) \propto \lambda^{-A_{min}}$$

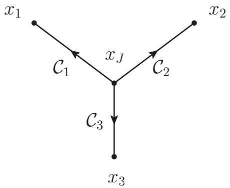
Baryon propagator and amplitudes

In SU(N_c) QCD the (normalized) wave-function of the baryon reads

$$B(\mathcal{C}_1,\mathcal{C}_2,\ldots,\mathcal{C}_{N_c})=\frac{1}{\sqrt{N_c!}}\epsilon_{i_1 i_2\ldots i_{N_c}}U[\mathcal{C}_1]^{i_1}_{j_1}q(x_1)^{j_1}\,U[\mathcal{C}_2]^{i_2}_{j_2}q(x_2)^{j_2}\ldots U[\mathcal{C}_{N_c}]^{i_{N_c}}_{j_{N_c}}q(x_{N_c})^{j_{N_c}}$$

$$U[\mathcal{C}_k]^{i_k}_{j_k}=\mathcal{P}\exp\left[ig\int_{\mathcal{C}(x_J,x_k)}dy^\mu A_\mu(y)\right]^{i_k}_{j_k},\quad k=1,2,\ldots,N_c$$

with $\mathcal{C}(x_J,x_k)$ a curve joining the point x_J to x_k.



We want to compute in the strong coupling limit the correlator

$$G_B(\{\vec{r}_k,k=1,2,\ldots,N_c\},\vec{r}_J;t'-t)=\langle B(\mathcal{C}_1,\mathcal{C}_2,\ldots,\mathcal{C}_{N_c})B^\dagger(\mathcal{C}'_1,\mathcal{C}'_2,\ldots,\mathcal{C}'_{N_c})\rangle$$

The computational strategy outlined for the meson propagator leads to a kind of book with pages sewed by a Levi-Civita symbol

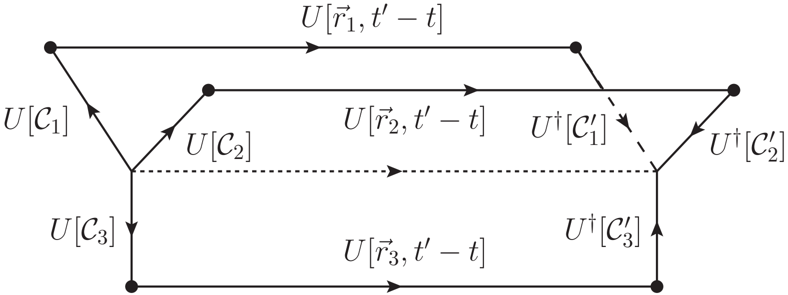


Figure : The $N_c = 3$ baryon propagator.

Tiling the pages of the book with plaquettes from the action

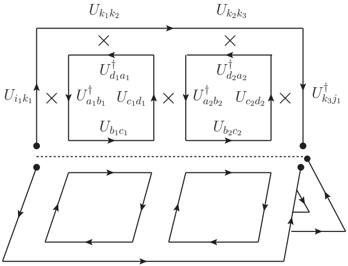


Figure : Tiling each of the the $N_c = 3$ pages with two plaquettes.

The group integral on the links along the dotted lines gives

$$\sum_{\ell_k} \int dUU_{i_1\ell_1} U_{i_2\ell_2} \dots U_{i_{N_c}\ell_{N_c}} \int dUU_{j_1\ell_1} U_{j_2\ell_2} \dots U_{j_{N_c}\ell_{N_c}} =$$

$$= \frac{1}{N_c!^2} \epsilon_{i_1 i_2 \dots i_{N_c}} \epsilon_{j_1 j_2 \dots j_{N_c}} N_c \sum_{\ell_k} \epsilon_{\ell_1 \ell_2 \dots \ell_{N_c}} \epsilon_{\ell_1 \ell_2 \dots \ell_{N_c}} = \frac{1}{N_c!} \epsilon_{i_1 i_2 \dots i_{N_c}} \epsilon_{j_1 j_2 \dots j_{N_c}}$$

$B\bar{B} \to B\bar{B}$ amplitude

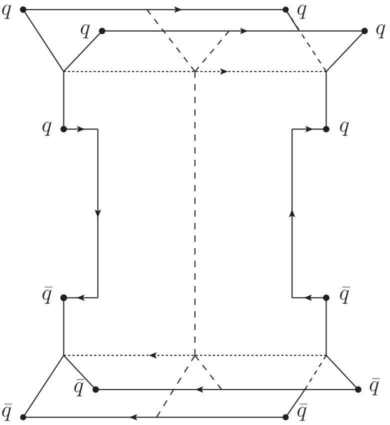
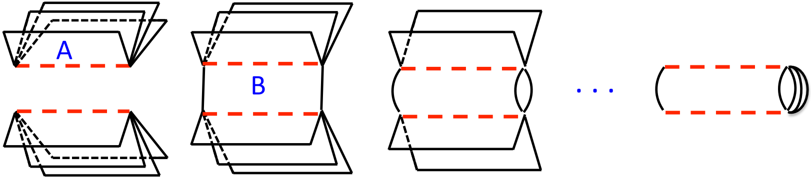


Figure : Baryon-antibaryon scattering amplitude with M_4^J intermediate states

A hierarchical classification

$\lambda = g^2 N$



Pomeron	One-sheet	Two-sheets		N-sheets
$\frac{\lambda^{-2NA}}{N^2}$	$\frac{\lambda^{-[2(N-1)A+B]}}{N}$	$\frac{\lambda^{-[2(N-2)A+2B]}}{N^2}$	. . .	$\frac{\lambda^{-NB}}{N^N}$
glueball	$M^J_{2(N-1)}$	$M^J_{2(N-2)}$		M^J_0

From strong coupling to AdS/CFT

- $W(g^2, N_c) \to W(\lambda, N_c)$
- Large λ & N_c expansion O' Brien Zuber

$$W(\lambda, N_c) = W_0(\lambda)\Big[1 + O(1/N_c)\Big]$$

$$W_0(\lambda) = \sum_{A=A_{min}} \lambda^{-A} F^{(A)} = \lambda^{-A_{min}}\Big[1 + O(1/\lambda)\Big]$$

- Large g^2 & N_c expansion

$$W(\lambda, N_c) = W_0(\lambda, N_c)\Big[1 + \Delta\Big], \quad \Delta = O(1/g^2) = O(N_c/\lambda)$$

$$W_0(\lambda, N_c) = \widehat{W}_0(\lambda)\Big[1 + O(1/N_c)\Big]$$

- If we can say $\Delta = O(1/\lambda)$ O' Brien Zuber, then

$$W(\lambda, N_c) = \widehat{W}_0(\lambda)\Big[1 + O(1/N_c) + O(1/\lambda)\Big]$$

- Thus in the large λ & N_c limit $\to \widehat{W}_0(\lambda) \propto \lambda^{-A_{min}}$

Conclusions and Summary

(I)

Conclusions and Summary of the results

) We define a kind of T.E. for baryons in QCD. A new type of duality in $B\bar{B}$ emerges between ann. and scatt., i.e. between ann. in 1, 2 and 3 $q\bar{q}$-jets and creation of new (in leading order zero width) resonances (baryonium) with $qq\bar{q}\bar{q}$, $q\bar{q}$ and no quark content, respectively. Duality diagrams, showing flavour flow, must be augmented by junction lines, showing colour flow. EXD is modified

) Adding quark loops, baryonium decays in $\bar{B}$+M's, but not just into M's: a selection rule (NZR)? Breaking of usual ZR may be comparable with e.m. mixing: M_4^J tend to be a pure quark state, not an eigenstate of I-spin.

(II)

III) When junction or baryon loops are added baryonium mixes with ordinary M's: Violation of NZR. It may well be that few states survive annihilation.

Look for (possibly) narrow states near $N\bar{N}$-threshold in σ_T, σ_{el} and in missing mass experiments (virtual annihilation)

IV) Baryonium trajectories, which control annihilation, can be estimated. $B\bar{B}$ Annihilation is dominated by a $I=0$ flat trajectory, is central and consists asymptotically of three $q\bar{q}$-jets.

$$\bar{n}^{(p\bar{p})}_{ann.} / \bar{n}^{(pp)}_{scatt.} \simeq 3/2$$

Thanks for your attention

Back-up slides

E.m. mixing

(17 I)

+ Absence of S(1936) signal in $p\bar{p} \to n\bar{n}$ may be an indication of a rather amusing property of baryonium.

Interference:

(1) with background suitably choosen

(2) bt. I=0, I=1 resonances very degenerate in mass

In case (2) $\Delta M < \Gamma/2 \simeq 2 \div 4$ MeV: less or equal than em split. whithin an isospin multiplet!

- Reexamin pattern of mixing, including em isospin breaking, which may not be negligible

- Simple and well known case of mesons

$$f = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \qquad A_2 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$I=0 \qquad\qquad I=1$$

$$
\begin{array}{c|cc} & u & d \\ \hline u & m+\delta & -\delta \\ d & -\delta & m+\delta+\gamma \end{array}
\;\rightarrow\;
\begin{array}{c|cc} & 0 & 1 \\ \hline 0 & m+\frac{\gamma}{2} & -\frac{\gamma}{2} \\ 1 & -\frac{\gamma}{2} & m+2\delta+\frac{\gamma}{2} \end{array}
$$

quark basis → Isospin basis

m : unperturbed mass, diagonal

plan.

2δ : I=0 shift due to s.i., diagonal in I-basis

non plan.

γ : em shift, diagonal in q-basis

1) $\delta \gg \gamma/2$ - usual case

Mass matrix diag in I-basis $\Rightarrow$ physical states have well defined I and G

2) $\delta \ll \gamma/2$ - exceptional case

mass matrix diag in q-basis $\Rightarrow$ physical states have not well defined I and G

Is it possible to have $\gamma/2 \simeq \delta$ or even $\gamma/2 \gg \delta$?

17_{III}

Necessary conditions:

1) Large masses to have small OZI violations.
(δ small?)

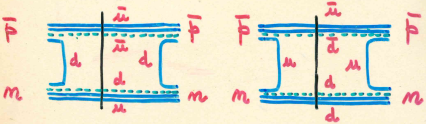
2) u and/or d quarks (or better, heavier doublets). (q- or I- basis?)

3) Small widths (i.e. a selection rule against decaying into light mesons).
(distance in complex mass plane).

A candidate: Baryonium

Consider $\bar{p}n \to \bar{p}n$ (or $\bar{\pi}p \to \bar{\pi}p$)

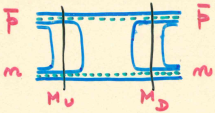
Two $Q=-1$ intermediate states in



$|M_u\rangle = |\bar{u}\bar{u}\,ud\rangle$ $\quad$ $|M_d\rangle = |\bar{u}\bar{d}\,dd\rangle$

$|I=1\rangle \pm |I=2\rangle$

Isospin degeneracy breaking comes from



which mixes M_U and M_D.

Including electromagnetism, mass matrix becomes

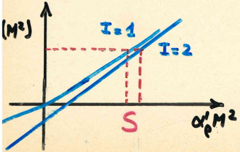
$$\mathcal{M}^{Q=-1} = \left(M - \frac{7}{2}\varepsilon\right)\underset{\sim}{1} + \begin{pmatrix} \gamma - \delta_{12}/2 & \delta_{12}/2 \\ \delta_{12}/2 & 3\gamma - \delta_{12}/2 \end{pmatrix}$$

M = mass before mixing $\quad \gamma = m_d - m_u + \frac{3}{2}\varepsilon$

$$\varepsilon \simeq \left(\frac{1}{3}\right)^2 \alpha \left\langle \frac{1}{r} \right\rangle \simeq .5\,\text{MeV} \qquad m_d - m_u \simeq 5\,\text{MeV}$$

$$\gamma \simeq 5 \div 8\ \text{MeV}.$$

Value of δ_{12} :



$$\Delta\alpha_{12} = \tfrac{1}{2}\, e^{-\alpha'_P M^2}$$

$$\Rightarrow \delta_{12} \simeq 4\,\text{MeV}$$

With these values physical states are more than 90 % $|M_U\rangle$ and $|M_D\rangle$

Phenomenological consequences

1) In $\bar{p}n \to \bar{p}n$ $(\bar{n}p \to \bar{n}p)$ 2 peaks with $\Delta m \simeq 2\gamma \simeq 10 \div 15$ MeV

2) Maximal violation of G - parity:

$$\Gamma(M_{U,D} \to \pi\rho) = \Gamma(M_{U,D} \to \pi\omega)$$

3) $$\Gamma(M_U \to \pi \ell^+\ell^-) = 4\,\Gamma(M_D \to \pi \ell^+\ell^-)$$

(In Drell-Yan the factor of 4 in
$$\sigma(\pi^- C \to \ell^+\ell^- X) = 4\,\sigma(\pi^+ C \to \ell^+\ell^- X)$$
is expected in the continuum.)

Experimental situation

1) No evidence of two peaks (no good data).

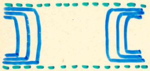
2) However the ratio:

$$\frac{\sigma_{el}(\bar{p}p)}{\sigma_{el}(\bar{p}p)+\sigma_{el}(\bar{p}n)} = \frac{\sigma(I=0)+\sigma(I=1)}{\sigma(I=0)+3\sigma(I=1)} = \begin{cases} \xrightarrow{I=0} 1 \\ \xrightarrow{I=1} 1/3 \end{cases}$$

is experimentally $\simeq 1/2$, as we would predict.

Similar analysis for the $Q=0$ states coupled to $p\bar{p} \to p\bar{p}$ and $p\bar{p} \to n\bar{n}$.

$$|M_{UU}\rangle = |\bar{u}\bar{u}uu\rangle$$
$$|M_{UD}\rangle = |\bar{u}\bar{d}ud\rangle$$
$$|M_{DD}\rangle = |\bar{d}\bar{d}dd\rangle$$



shifts $I=0$

We must diagonalize a 3x3 matrix, depending on two parameters:

$$\delta_{12}/\delta_{02} \text{ and } \gamma/\delta_{02}$$

From a numerical exploration by computer:

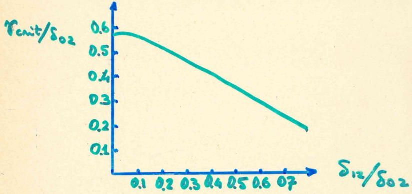
1) for a wide range of them, the lowest state (to be identified with $S(1936)$) couples to $p\bar{p} \to p\bar{p}$ 1 or 2 order of magnitude more than the others.
 It also couples more to $p\bar{p} \to n\bar{n}$.

2) it is possible to solve the problem of the absence of S-signal in $p\bar{p} \to n\bar{n}$.

Define $\lambda = \left.\dfrac{\sigma(p\bar{p} \to n\bar{n})}{\sigma(p\bar{p} \to p\bar{p})}\right|_{S\text{-peak}}$

plot $\gamma_{crit}/\delta_{02}$ for which $\lambda < 1/15$, as a function of δ_{12}/δ_{02}

↳ exp. bound



Estimates of δ_{12}/δ_{02} lie between $\sim .14$ and $2/3$. Correspondingly, taking, as before, $\delta_{12} = 4$ MeV

$$\gamma_{crit} \simeq 2 \div 14 \text{ MeV}$$

For $\gamma > \gamma_{crit}$, $S(1936) = |\bar{u}\bar{u}uu\rangle$ (90%) and does not couple to $n\bar{n}$.

3) at the S-peak maximal I and G violation:

$\Gamma(S\to\rho\rho) = \Gamma(S\to\rho\omega) = \Gamma(S\to\omega\omega)$

Note: $S \to \pi^0\pi^0$, but $S \not\to \pi^+\pi^-$

Ξ - MIXING

Ξ^{--} $[ds][ds]\bar{u}$ 1860

Ξ^{-} $\begin{cases} [ds][ds]\bar{d} & 1865 \text{ (PURE QUARK)} \not\to \Xi^{*0}\pi^{-} \; (ssu)\;(d\bar{u}) \\ [ds][us]\bar{u} & 1855 \end{cases}$

Ξ^{0} $\begin{cases} [us][us]\bar{u} & 1850 \text{ (PURE QUARK)} \not\to \Xi^{*-}\pi^{+} \; (ssd)\;(u\bar{d}) \\ [us][ds]\bar{d} & 1860 \end{cases}$

Ξ^{+} $[us][us]\bar{d}$ 1855

- CONSIDER Ξ^{-}: ONE WOULD SEE
  1 BUMP IN THE $\Xi^{*0}\pi^{-}$ CHANNEL
  2 BUMPS IN THE $\Xi^{*-}\pi^{0}$ CHANNEL
- THE KEY ARGUMENT IN FAVOUR OF THE JW DIQUARK MODEL IS THE EXISTENCE OF

$\Xi^{+} \longrightarrow \Xi^{*0}\pi^{+}$ BUT $\overline{10}_f \to \overline{10}_f + 8_f$ BY $SU(3)_f$

$\Rightarrow$ BESIDES A $\overline{10}_f$ THERE MUST BE AN 8_f

PROBLEM: WHY THEIR WIDTH IS SO SMALL