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Some recent developments in hadron spectroscopy

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SPIN 2004, Trieste

Outline

1. Introduction
2. $\mathbf{N} = \mathbf{2}$ Charmonium
3. $\mathbf{N} = \mathbf{3}$ Double Charm baryons
4. $\mathbf{N} = \mathbf{4}$ X(3.872) , $D_{s,J}$??
5. $\mathbf{N} = \mathbf{5}$ Pentaquarks
6. $\mathbf{N} \geq \mathbf{6}$ Hexaquarks and beyond
7. **Multiquarks in various models**
8. **Charmonium hybrids**
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1. Introduction

Several recent developments in hadron spectroscopy.
Pentaquark among them, but not only pentaquark.

Some universally expected states seen, at last, or tentatively seen.
For instance $Q\overline{Q}$, QQq
Happy feeling of better control.

Other states were expected by a minority:
pentaquarks, molecules and other multiquarks, hybrids, chiral partners, etc.

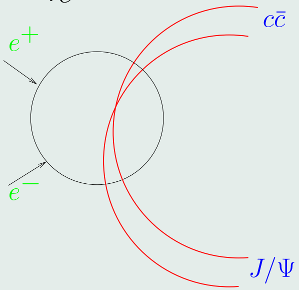
No single, simple explanation of all new states. Hence everybody embarrassed in the event they all survive.

2. Charmonium

$Q\overline{Q}$: New states in $(c\bar{c})$, $(b\bar{b})$, $b\bar{c}$.

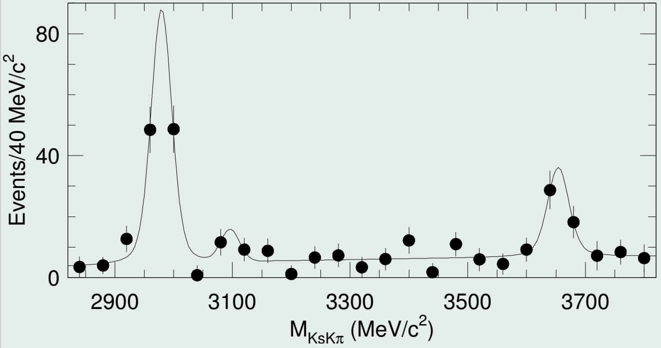
For instance η'_c

Already searched for in $\psi' \to \gamma\eta'_c,\ \gamma\gamma \to \eta'_c,\ p\bar{p} \to \eta'_c$.

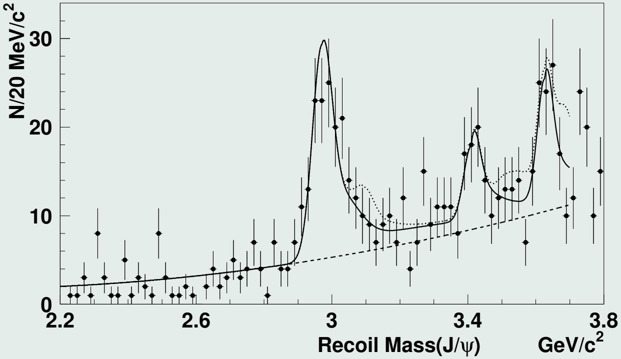


New means: B decay and double charm prod.

B decay



$J/\Psi + X$



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$$\boxed{\boldsymbol{\psi'(2S) - \eta_c(2S) = 32 \pm 6 \pm 8\ \mathrm{MeV}}}$$

Smaller than expected in potential models
Smaller than expected by $p\bar{p}$ scanners

Due to coupling to $D\overline{D}$, $D^*\overline{D} + c.c.$ and $D^*\overline{D}^*$
In particular , the nearby $D\overline{D}$ pushes ψ' down without coupling ot η_c'
(Eichten et al., Martin et al.)

$$\boxed{h_c \text{ (spin singlet state with } \ell = 1)}$$

not yet firmly seen. It is crucial to test the short-range character of spin-spin forces.

3. Double-charm baryons -Exp.-1

Ξ_{cc}^+ seen in two different decay modes:

$\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

$\Xi_{cc}^+ \rightarrow p D^+ K^-$

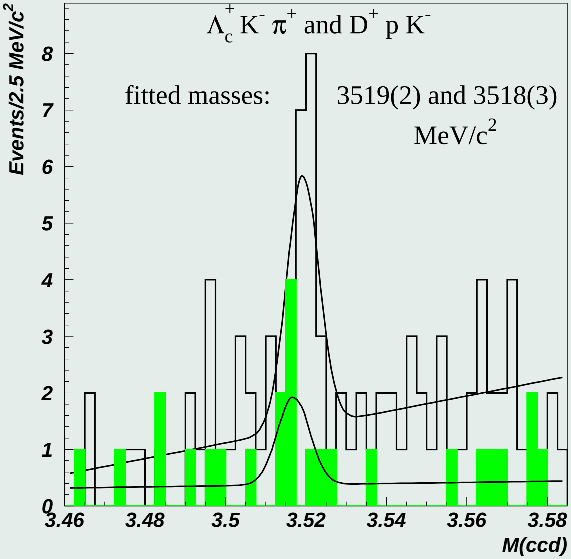

FIG. 3: Gaussian fits for $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ (unshaded) $\Xi_{cc}^+ \rightarrow p D^+ K^-$ (shaded) on same plot

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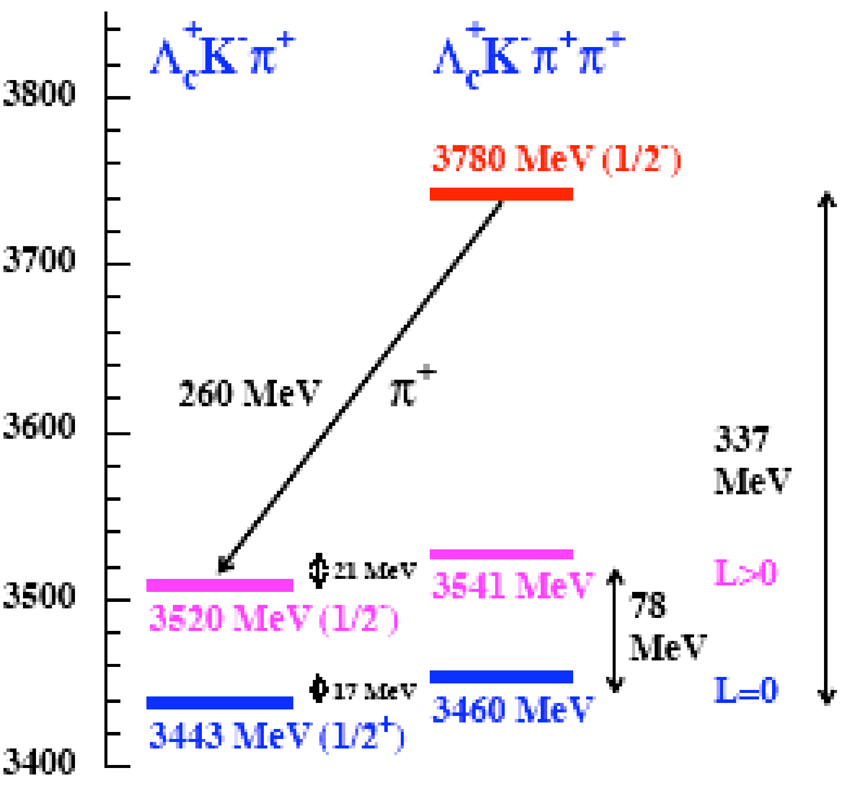
Double-charm baryons. Exp.-2

1. other dedicated experiments, e.g., FOCUS, do not see (ccq)
2. Isospin partners, excitations, seen by SELEX, need confirmation.



Double-charm baryons, Th.-1

Perhaps the most interesting of ordinary hadrons.
Combine in a single object two extreme regime:

1. Slow motion of two heavy quarks, as in quarkonium
2. Relativistic motion of a light quark in the field of a static coloured source

The large M/m ratio in (QQq) indicates a quark–diquark structure. and suggests a two-step calculation

1. Solve QQ with QQ direct interaction, to estimate the diquark
2. Solve $[QQ]-q$ to estimate the baryon

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Double-charm baryons, Th.-2

Instead, a Born–Oppenheimer approach is perhaps better suited.

1. For a given QQ separation, estimate the light quark energy in the field of two colour sources
2. Add the direct QQ interaction, to build the effective QQ potential
3. Solve the QQ problem.

Tests in simple NR models show that the Born–Oppenheimer approximation is better than accurate (Fleck, R.)

The method could be applied with a better treatment of the light quark. One could also estimate directly the effective QQ potential on the lattice.

Double-charm baryons, Weak decays-1

$D^0(c\bar u)$ and $D^+(c\bar d)$ have different lifetimes.

c quark, when decaying, does not ignore its surrounding.

Besides simple W^+ emission (followed by lepton-pair or quark–antiquark creation), and by hadronization), there is a contribution of W exchange.

Also interferences in the final state.

Applied to single-charm baryons, with qualitative success, but the spread of lifetimes larger than predicted.

$\exists$ predictions for double-charm baryons. Again: simple W^+ emission, W-exchange, interferences

In ccq (and in $b\bar c$), the c quark is deeply bound,

discussions on the influence on lifetime.

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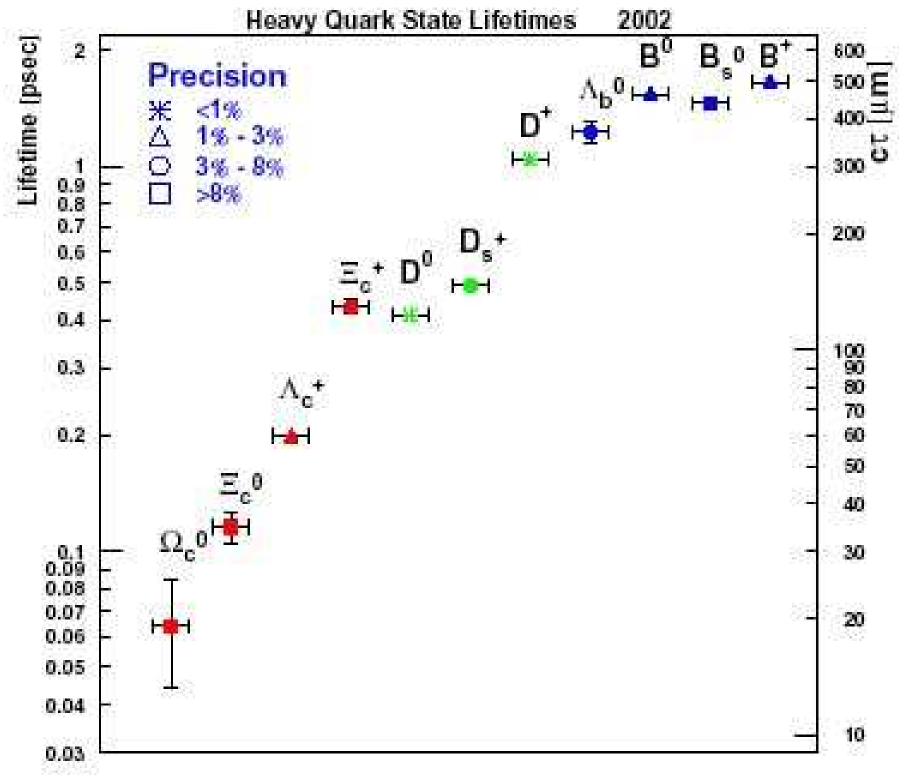
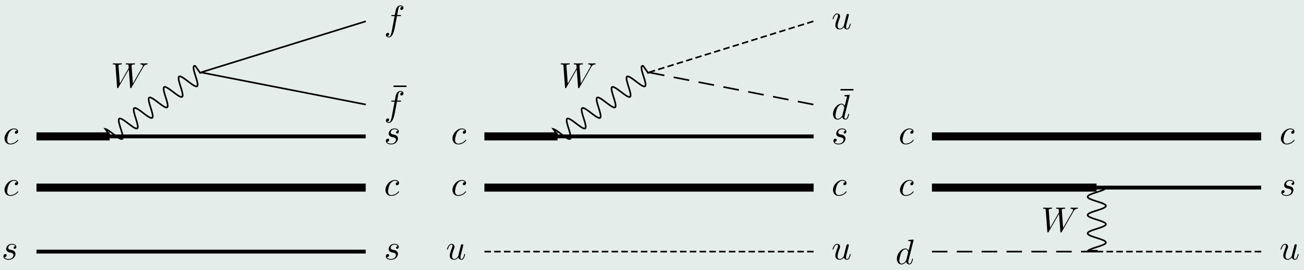
Double-charm baryons, Weak decays-2

Comparison of heavy hadron lifetimes (from Cooper)



Some contributions to the weak decay of double-charm baryons



Typical prediction: $\tau(\Xi_{cc}^{+}) < \tau(\Omega_{cc}^{+}) < \tau(\Xi_{cc}^{++})$

(Guberina, Kiselev, Fleck, etc.) Interest also in BR (e.g., Semi-lept. vs. hadronic)

Beyond double charm: triple charm

The ultimate goal of baryon spectroscopy (Bjorken)
To study the (QQQ) dynamics

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4. Tetraquarks, Exotic Mesons

Speculations on $(qq\bar{q}\bar{q})$ for many years. Also gluonium, hybrids, etc.

- Low-lying scalar mesons (Jaffe, etc.)
- Excess of scalar mesons (L. Montanet, etc.)
- Long-range meson-meson interaction (see below)
- Favourable mass assymmetry in $(QQ\bar{q}\bar{q})$, etc.

Possible candidates ?

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$c\bar{s}$

$D^*_{s,J}$ states at Belle, Babar, Cleo, Selex, etc.

Scalar excitation close to ground state. Too large a spin-orbit force for potential models. Chiral partner of the ground-state? Or 4-quark state $(c\bar{s}q\bar{q})$?

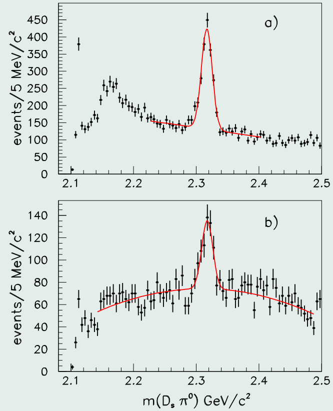
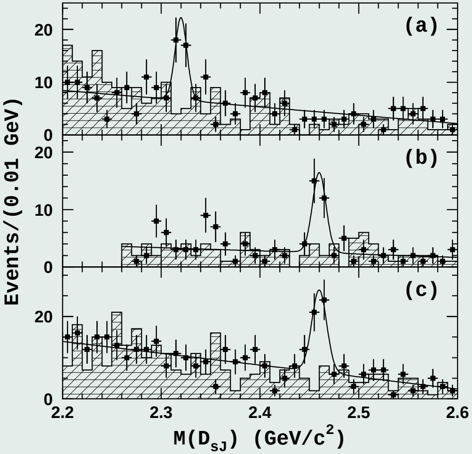


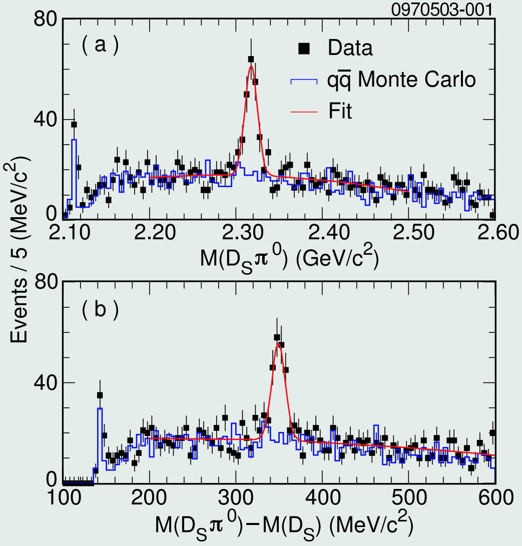
FIG. 2: The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$. The fits to the mass distributions as described in the text are indicated by the curves.

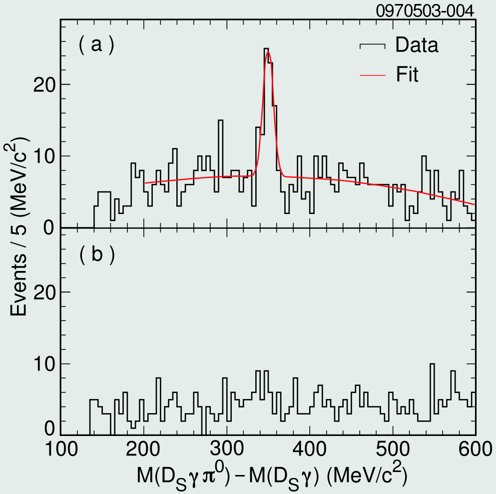
4



BABAR (B decay)

BELLE (B decay)


0970503-001
(a)
Data
$q\bar{q}$ Monte Carlo
Fit
80
40
0
2.10
2.20
2.30
2.40
2.50
2.60
$M(D_S\pi^0)$ (GeV/c^2)
Events / 5 (MeV/c^2)
(b)
80
40
0
100
200
300
400
500
600
$M(D_S\pi^0) - M(D_S)$ (MeV/c^2)


0970503-004
(a)
Data
Fit
20
10
0
Events / 5 (MeV/c^2)
(b)
20
10
0
100
200
300
400
500
600
$M(D_S\gamma\pi^0) - M(D_S\gamma)$ (MeV/c^2)

CLEO

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Another intriguing D_s^* reported

Fig.	state	events	ΔM MeV/c^2	Mass MeV/c^2	Significance $(S-B)/\sqrt{B}$	σ MeV/c^2	Γ MeV/c^2	χ^2/n_d
1	$\eta(548) \to \gamma\gamma$	5087 ± 863		544.8 ± 2.9	$13.9\ \sigma$	27.8 ± 4.3		1.17
2	$D_s^+(2632) \to D_s^+\eta$	45 ± 9.3	667.4 ± 2.9	2635.9 ± 2.9	$7.2\ \sigma$	10.7		0.95
3	$D_s^+(2573) \to D^0K^+$	25 ± 9	705.4 ± 4.3	2569.9 ± 4.3	$5.4\ \sigma$	4.9	14^{+9}_{-6}	0.77
3	$D_s^+(2632) \to D^0K^+$	14 ± 4.5	767.0 ± 1.9	2631.5 ± 1.9	$5.3\ \sigma$	4.9	$< 17(90\%CL)$	

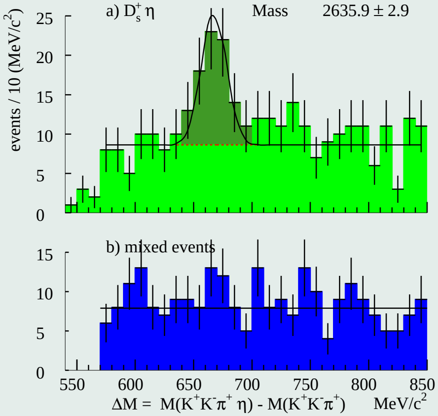
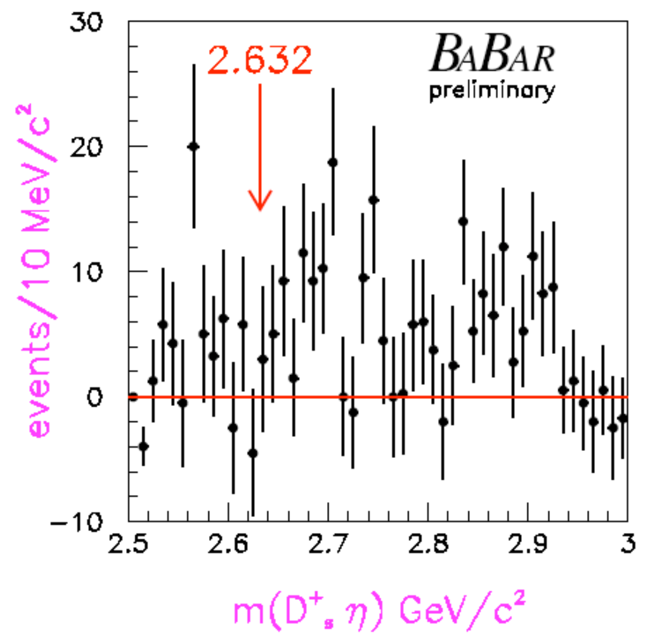


FIG. 2: (a) M(KK$\pi^\pm$ η) - M(KK$\pi^\pm$) mass difference distribution. Charged conjugates are included. The shaded region is the event excess used in the estimation of signal significance. Results for the fit shown are in Table I. (b) Mass difference distribution for mixed events as described in the text.

But


2.632
BABAR
preliminary
events/10 MeV/c^2
30
20
10
0
−10
2.5
2.6
2.7
2.8
2.9
3
m(D^+_s, η) GeV/c^2

Another intriguing state in the $(\boldsymbol{c\bar{c}})$ sector:

$$X(3.872)$$

$(\boldsymbol{c\bar{c}})$? or $(\boldsymbol{c\bar{q}} - \boldsymbol{\bar{c}q})$?

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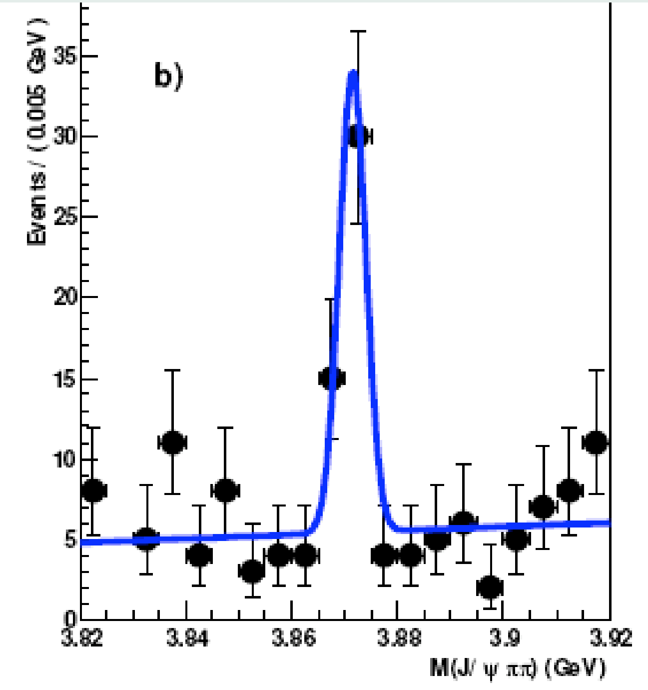
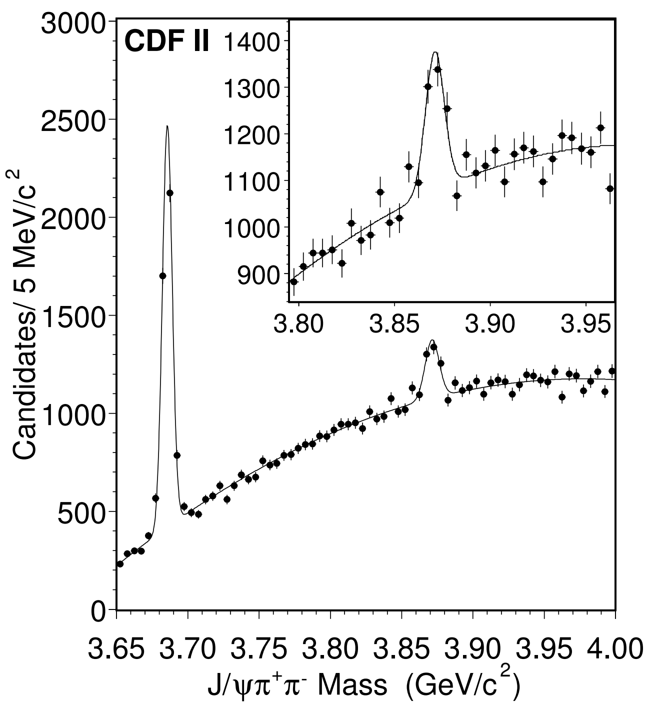
Belle (KEK) $X(3.872)$ CDF (Fermilab)





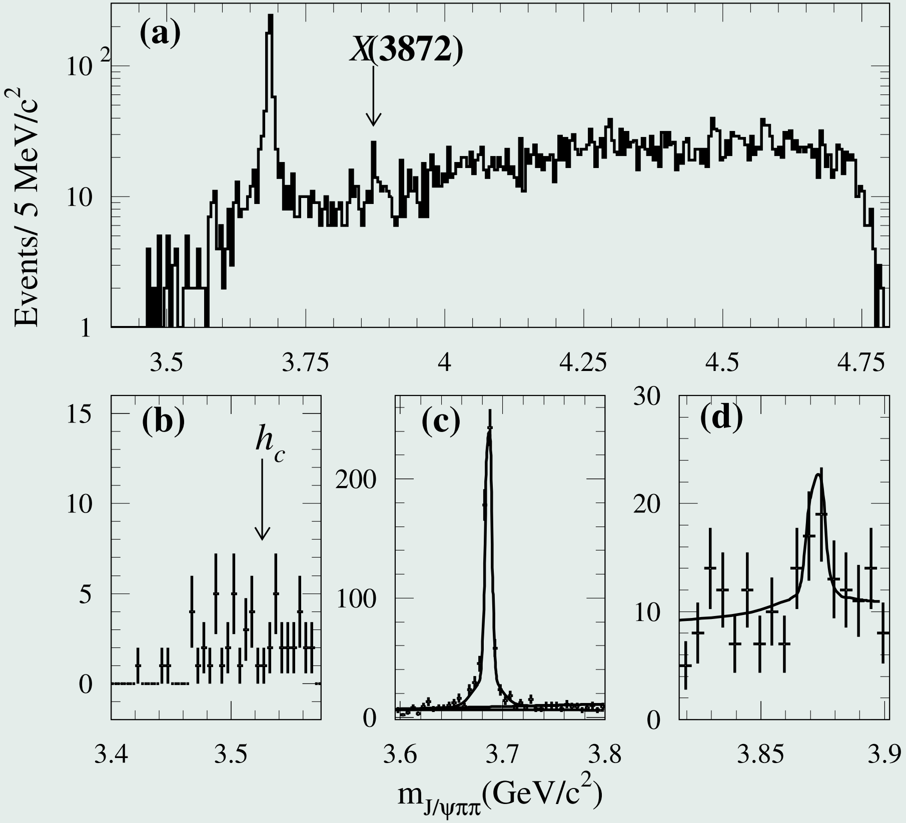
M = 3872.0 +– 0.6 +– 0.5 MeV

M($D^o + \underline{D}^{*o}$) = 3871.5 +– 0.5 MeV

n.b. M($D^+ + \underline{D}^{*-}$) = 3879.5 +– 0.7 MeV

Accidental agreement?
X = $c\underline{c}$ (2^{-+} or 2^{--} or . . .),
or a molecular (**multiquark**) state?

$X(3872)$, cont.



Babar evidence for $X(3872)$

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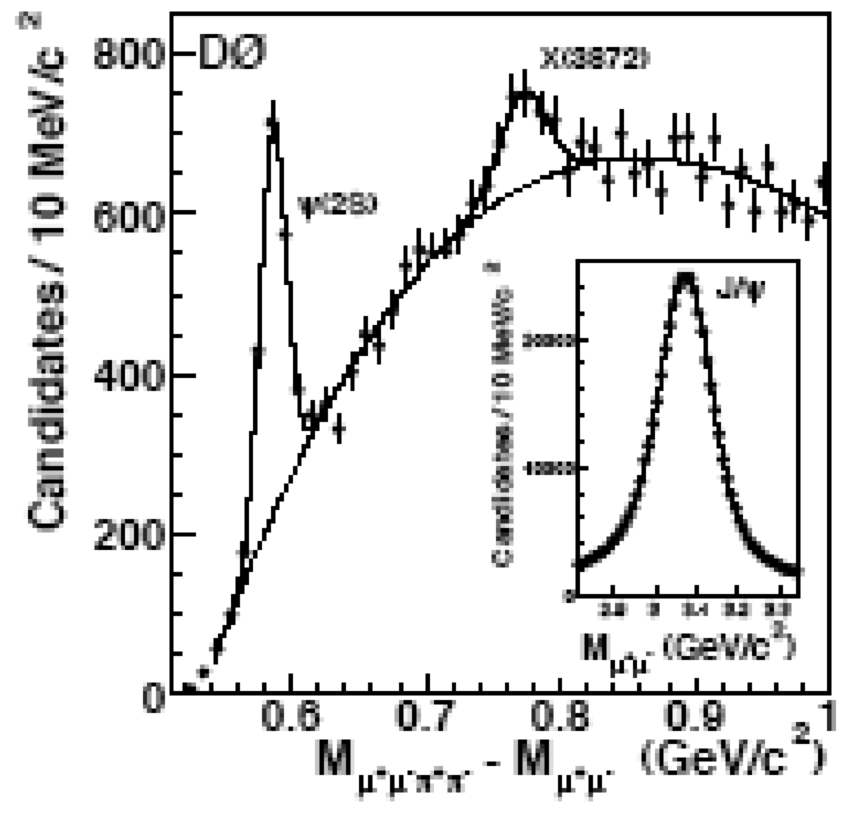
$X(3872)$, cont.



$D0$ evidence for $X(3872)$

$X(3872)$ not seen at CLEO ($e^+e^- \longrightarrow e^+e^- + X$), i.e., not coupled to $\gamma\gamma$, this setting restrictions on its quantum numbers.

Spectroscopy: A molecular interpretation favoured.
Production: Some patterns are similar to those of ordinary charmonium. ($D0$ collbaroration)

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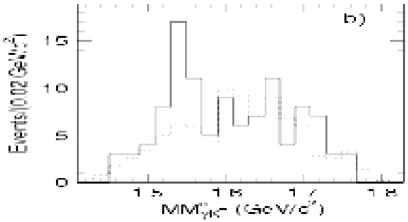
5. Pentaquarks

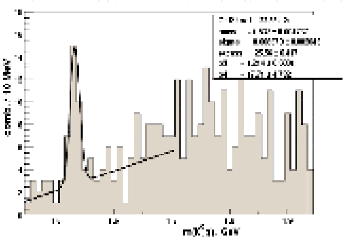
5.1. Light pentaquark

Positive results

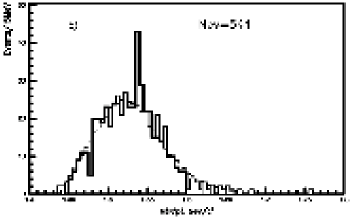
LEPS@SPring8



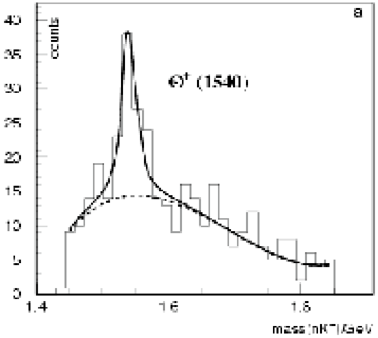
ITEP



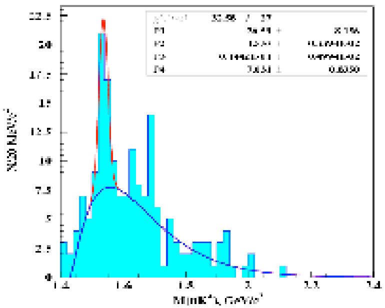
DIANA@ITEP



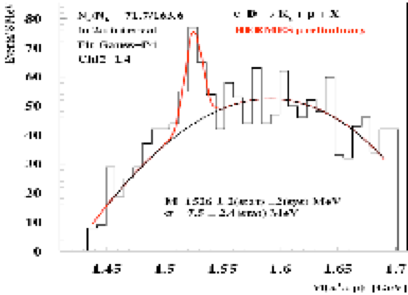
SAPHIR @ ELSA



CLAS@JLAB



HERMES@DESY



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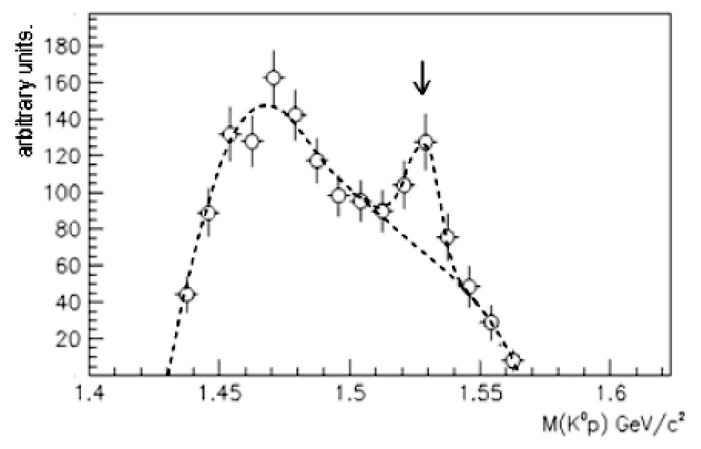
COSY-TOF results



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Experimental signals for pentaquarks(Zhao and Close).

Experiments	bf Mass (MeV)	**Width (MeV)**	bf Observation
SPring-8 [1]	1540 ± 10	< 25	nK^+
SAPHIR [3]	$1540 \pm 4 \pm 2$	< 25	nK^+
CLAS-1 [2]	1542 ± 5	< 21	nK^+
CLAS-2 [4]	1555 ± 10	< 26	nK^+
DIANA [5]	1539 ± 2	< 9	$K^+n \to K^0_S p$
HERMES [6]	$1528 \pm 2.6 \pm 2.1$	$17 \pm 9 \pm 3$	pK^0_S
SVD [8]	$1526 \pm 3 \pm 3$	< 24	pK^0_S
ITEP ν [7]	1533 ± 5	< 20	pK^0_S
ZEUS [9]	$1521.5 \pm 1.5 \begin{array}{l} +2.8 \\ -1.7 \end{array}$	$6.1 \pm 1.6 \begin{array}{l} +2.0 \\ -1.4 \end{array}$	$pK^0_S, \bar{p}K^0_S$
COSY-TOF [10]	1530 ± 5	$< 18 \pm 4$	$pp \to \Sigma^+ pK^0_S$

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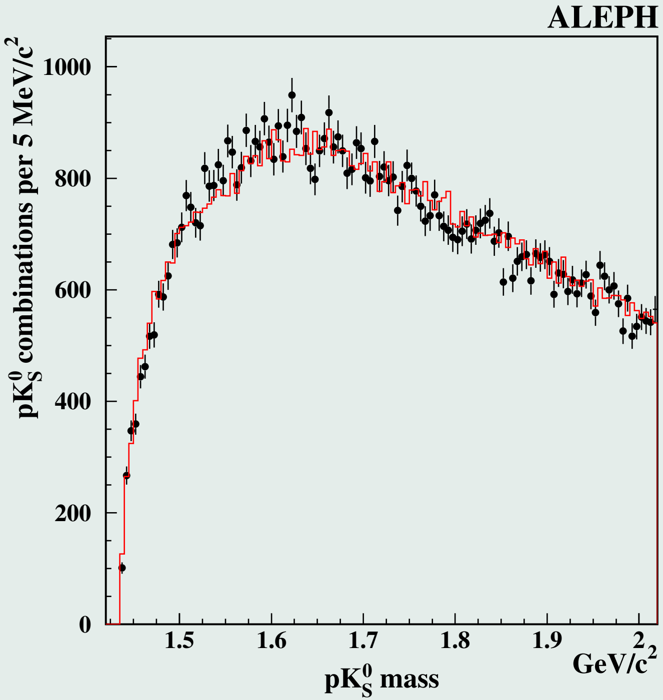
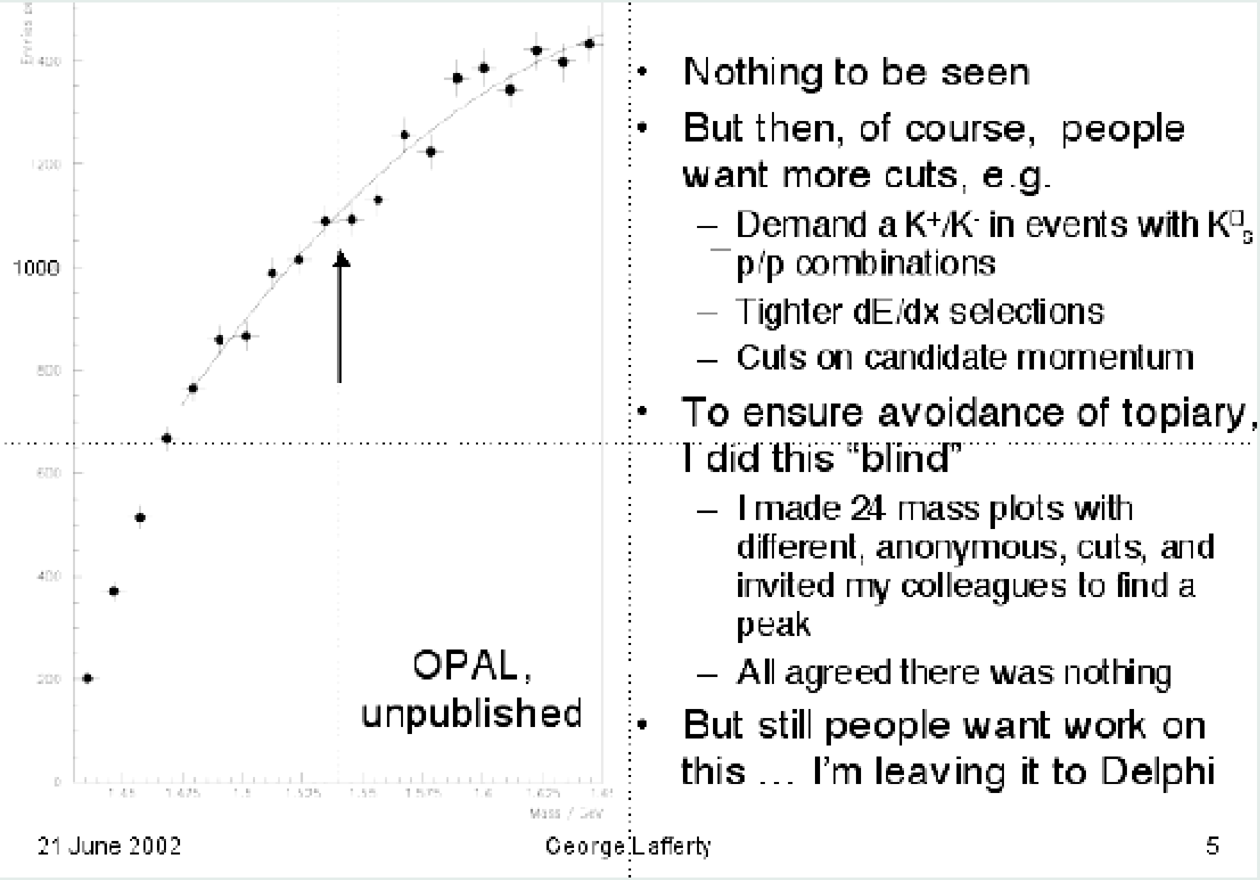
Negative results by ALEPH, HERA-b, CDF, BES, PHENIX, STAR, OPAL, DELPHI, HyperCP, etc. Other negative results not published.

ALEPH results, for instance



OPAL results



OPAL,
unpublished

- Nothing to be seen
- But then, of course, people want more cuts, e.g.
  - Demand a K^+/K^- in events with K^0_S $\bar{p}/p$ combinations
  - Tighter dE/dx selections
  - Cuts on candidate momentum
- To ensure avoidance of topiary, I did this “blind”
  - I made 24 mass plots with different, anonymous, cuts, and invited my colleagues to find a peak
  - All agreed there was nothing
- But still people want work on this … I'm leaving it to Delphi

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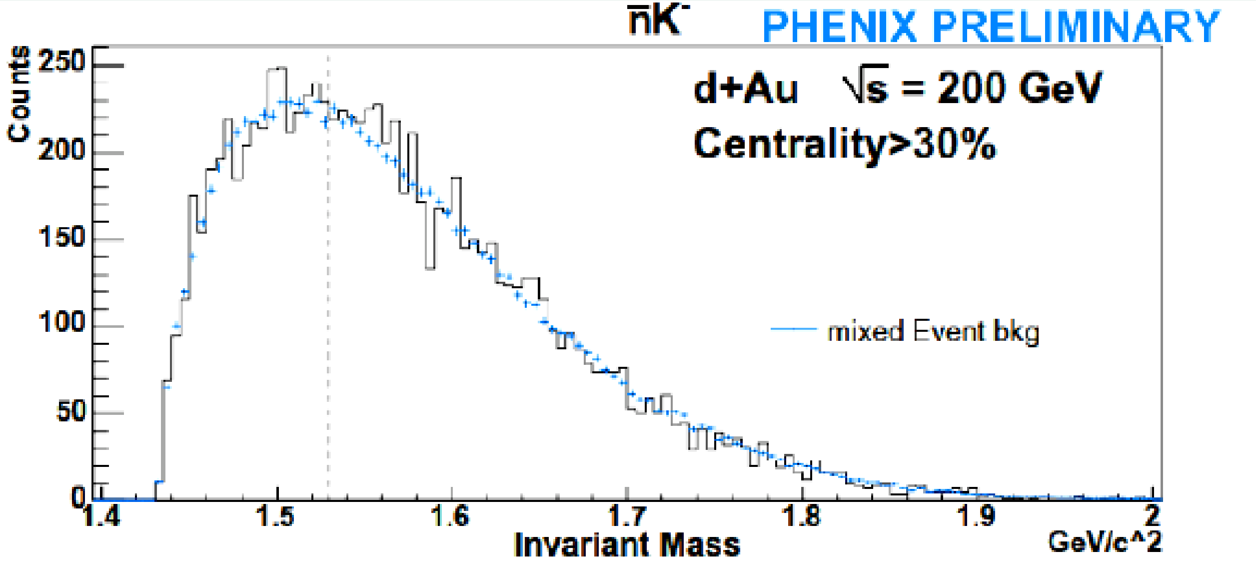
PHENIX results



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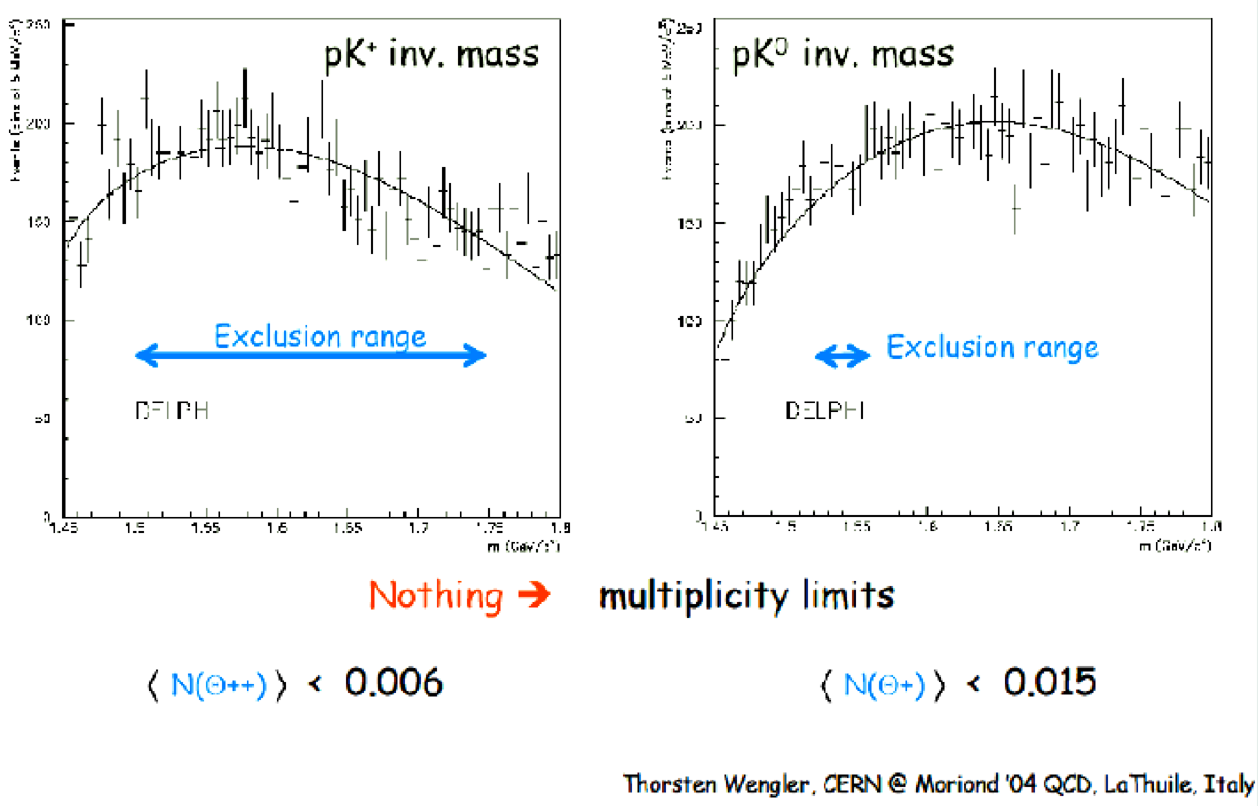
DELPHI results



Nothing → multiplicity limits

$\langle N(\Theta^{++}) \rangle < 0.006$ $\langle N(\Theta^{+}) \rangle < 0.015$

Thorsten Wengler, CERN @ Moriond '04 QCD, LaThuile, Italy

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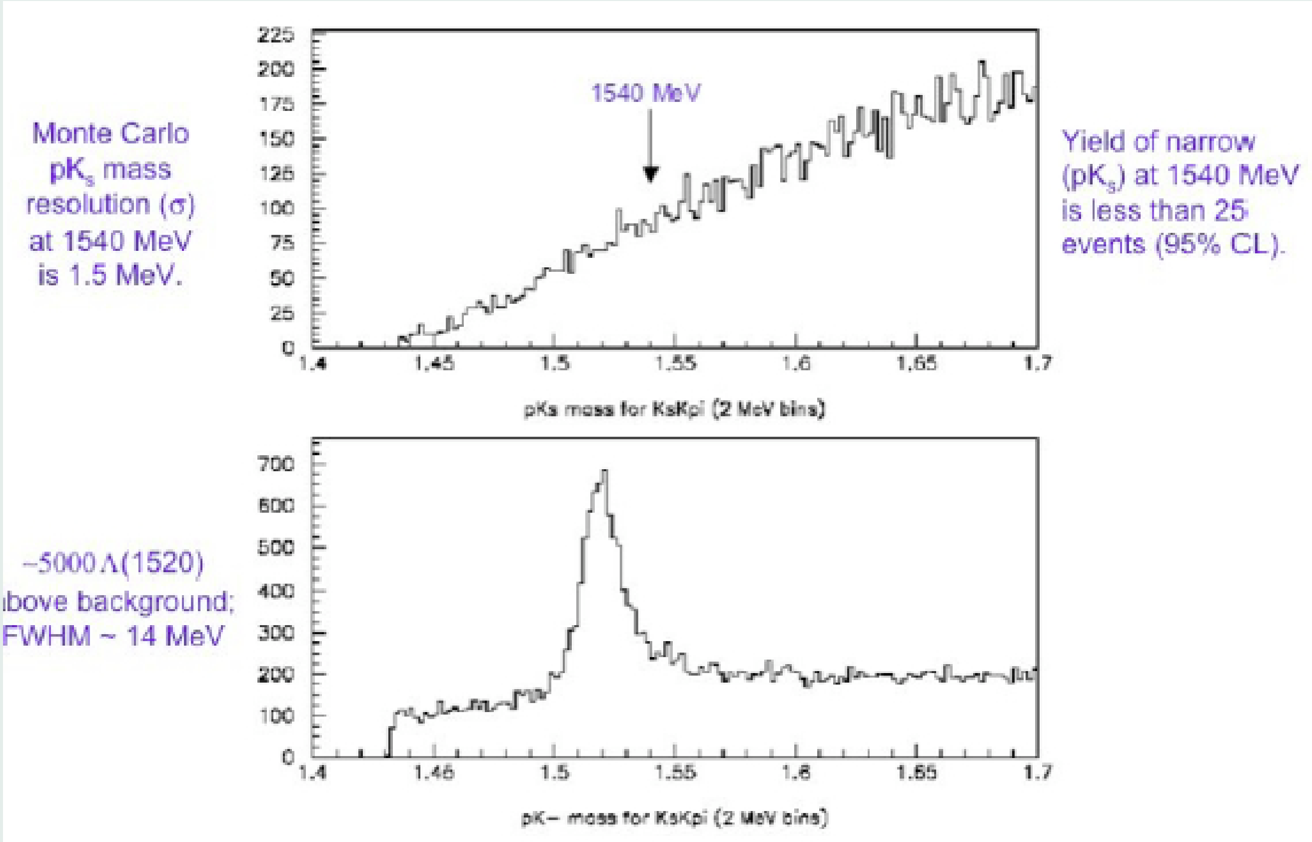
E690 by D. Christian at QNP 2004



Monte Carlo pK_s mass resolution (σ) at 1540 MeV is 1.5 MeV.

Yield of narrow (pK_s) at 1540 MeV is less than 25 events (95% CL).

~5000 $\Lambda(1520)$ bove background; FWHM ~ 14 MeV

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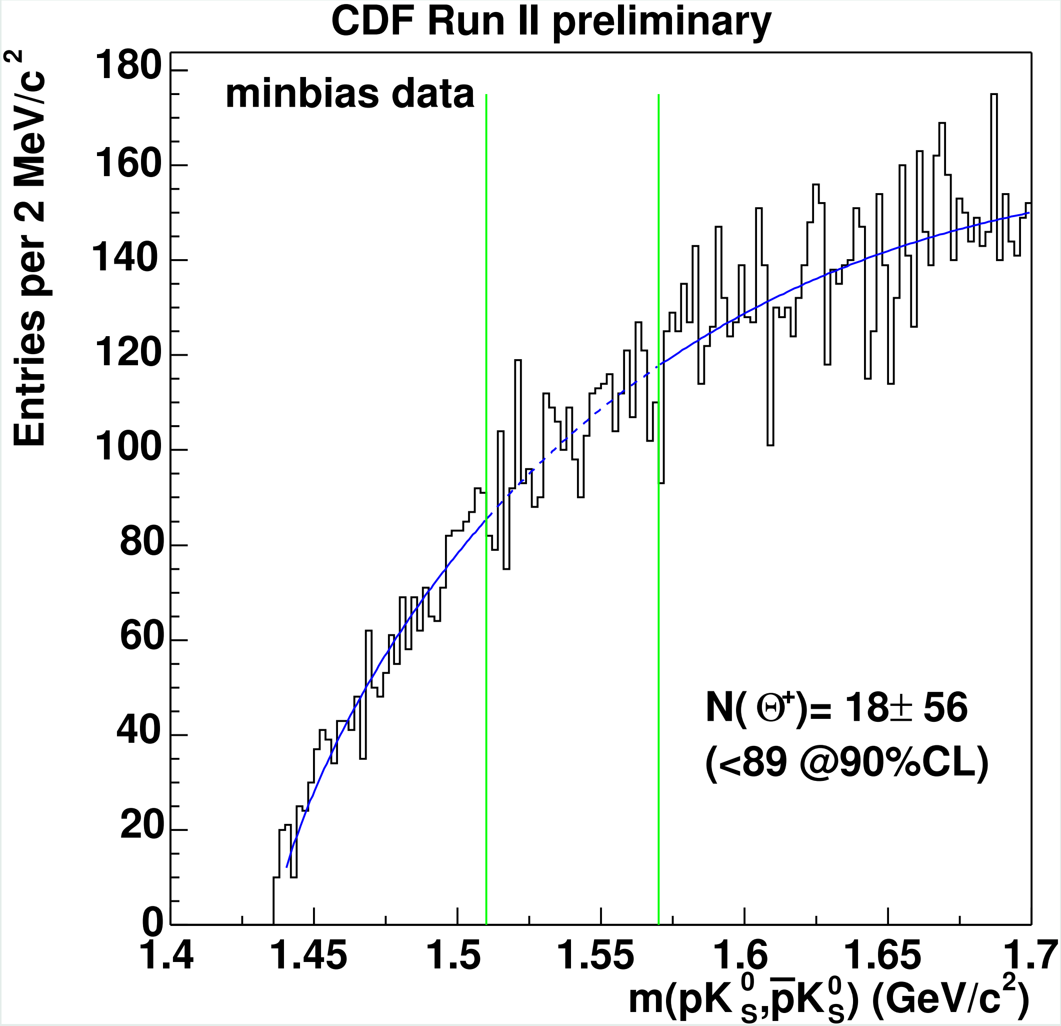
CDF Summer 2004



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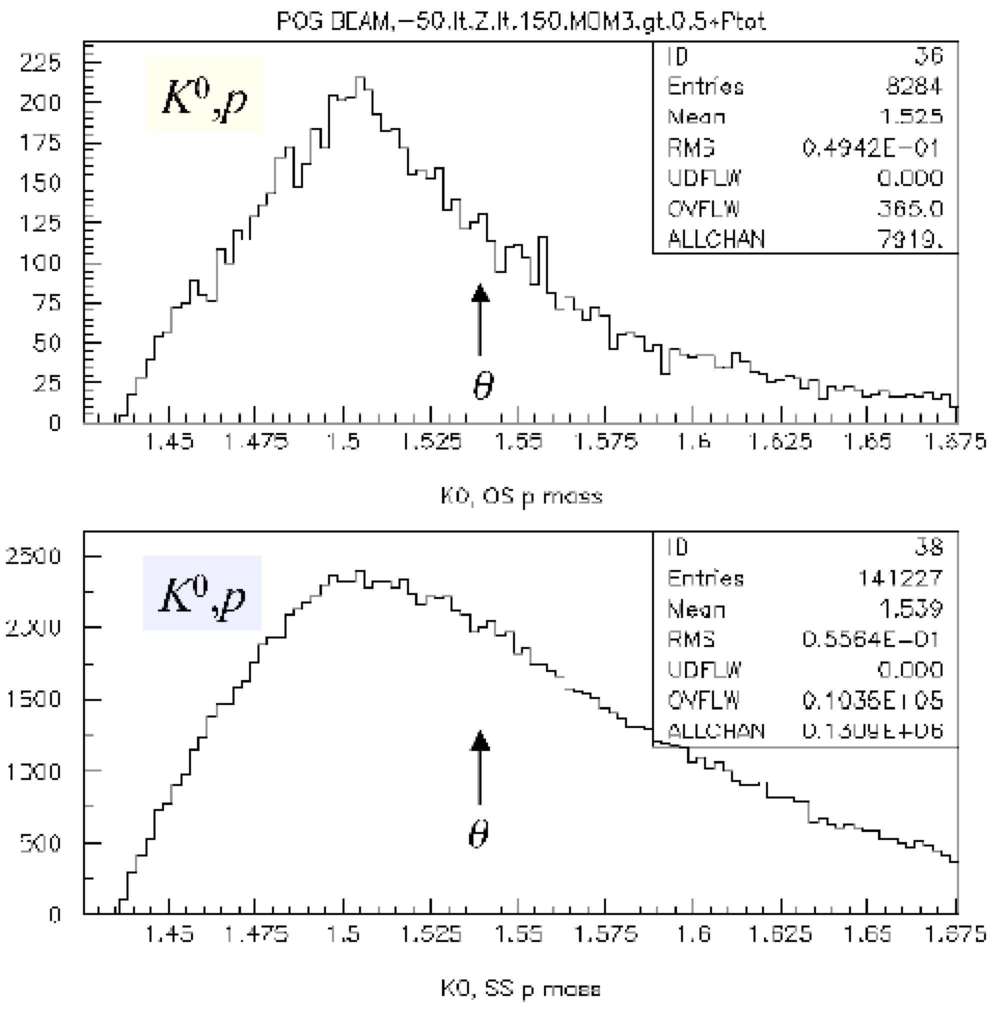
E871/HyperCP by M. Longo at QNP 2004



DATA

Reconstructed
K^0, p mass,
positive beam,
events from
thin window.

Babar

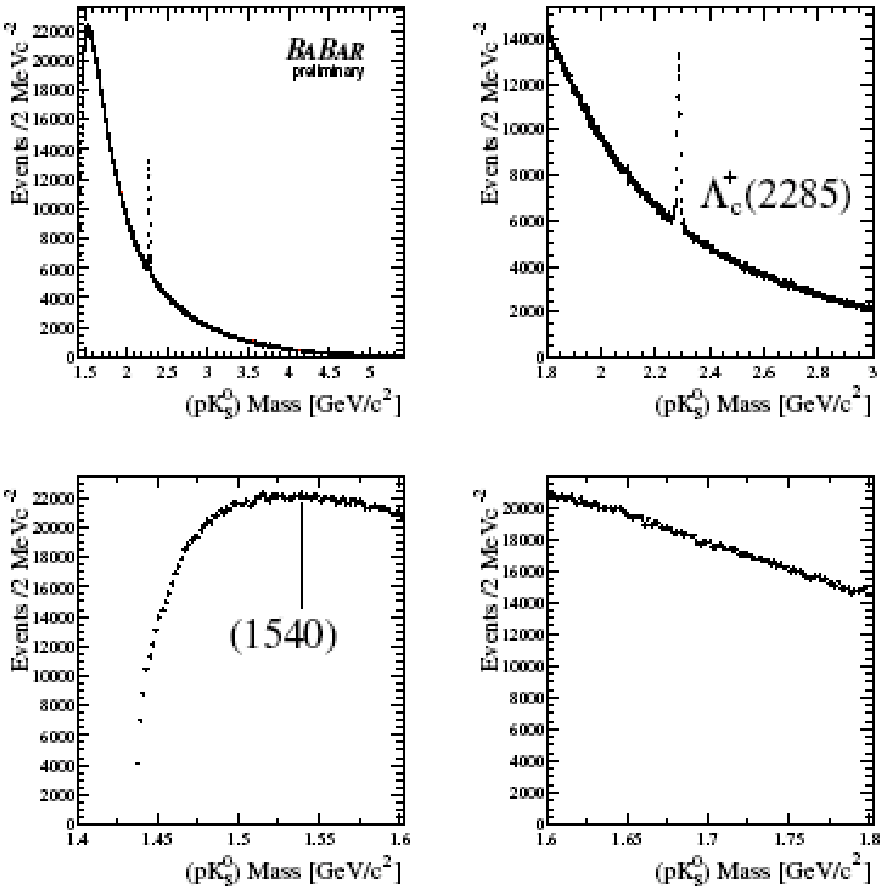


Figure 2: Distribution of the pK^0_S invariant mass for combinations satisfying all the criteria described in the text. The same data are plotted four times in different pK^0_S mass regions.

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Pentaquark and KN scattering

See Cahn and Trilling,
Sibirtsev et al., hep-ph/0405099;
Nussinov, hep-ph/0307357;
R.A. Arndt et al., nucl-th/0311030;
Haidenbauer & Krein,Phys.Rev. C68, 05221(2003).

A small width is required for this state have escape detection in early or recent analyses of KN data.

Alternatively, the state is perhaps seen (DIANA, Gibbs, nucl-th/0405024) but again, with a small width

But a small width is hard to understand.

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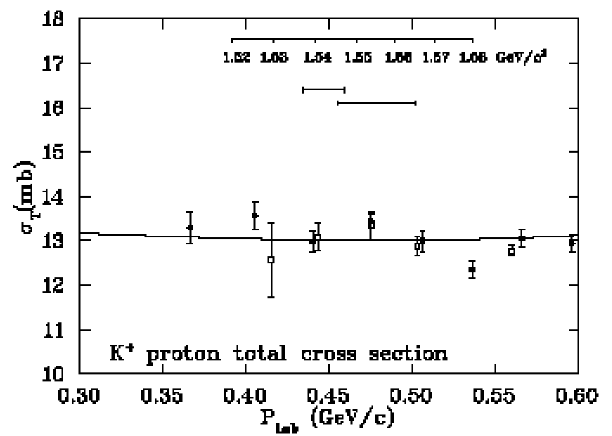

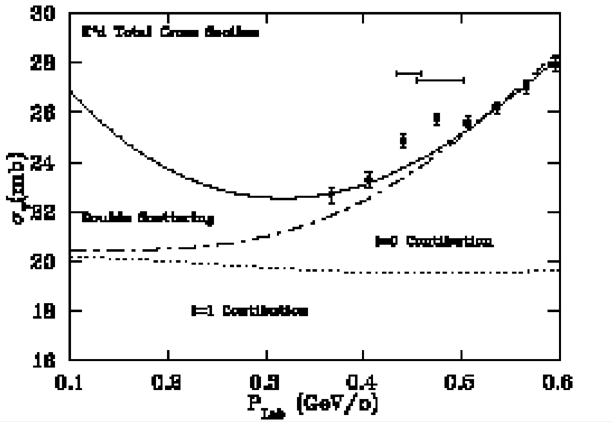

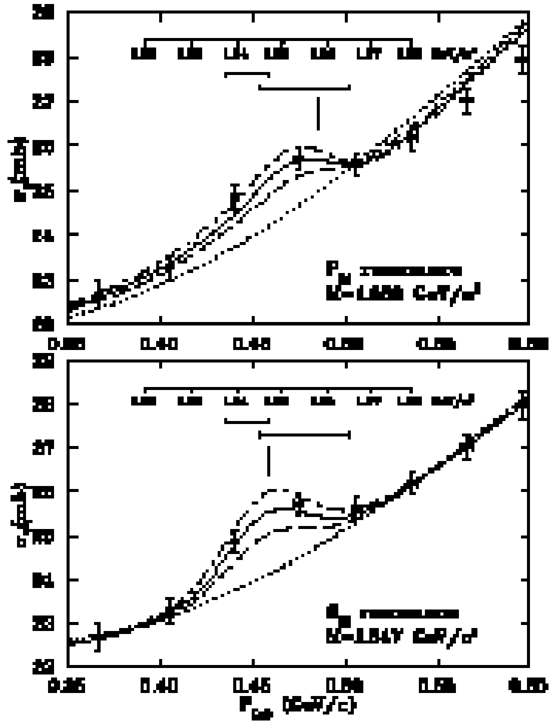

From Meissmer et al.

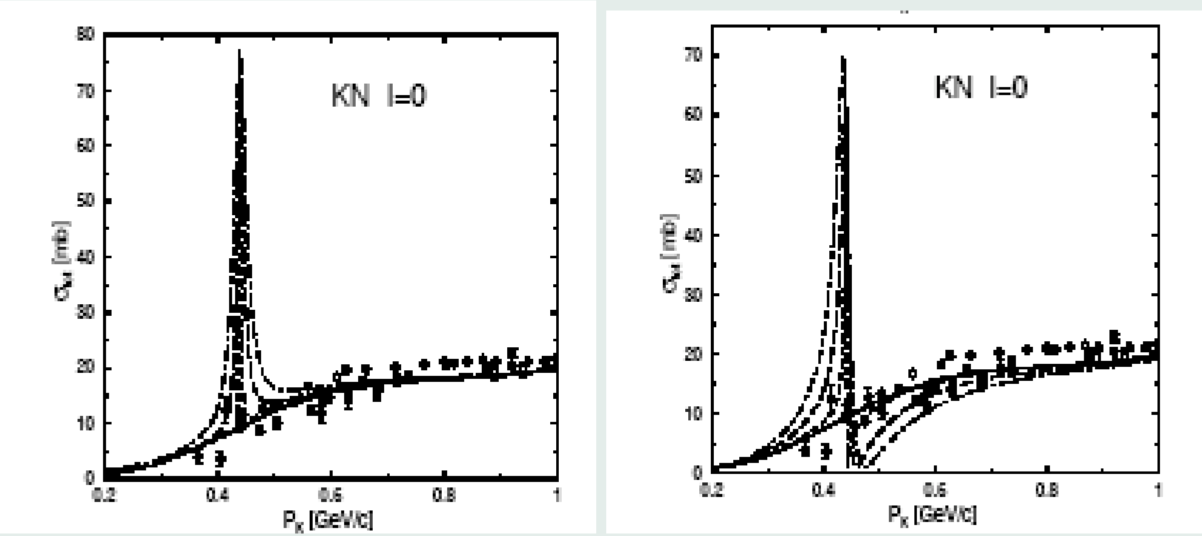

Fig. 2. The KN reaction cross section for the $I=0$ channel as a function of the kaon momentum. Results are shown for negative (top) and positive (bottom) parity of the Θ^+ resonance. The various curves correspond to different Θ^+ widths, $\Gamma_{\Theta^+}=1$ MeV (short dashed), 5 MeV (long dashed), and 10 MeV (dash-dotted), while the solid line is the prediction without a Θ^+ contribution. Data are taken from Refs. [9] (filled circles), [10] (squares), [11] (open circles), and [12] (crosses).

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5.2. Ξ^{--} candidate

NA49 claim (part of the collaboration)

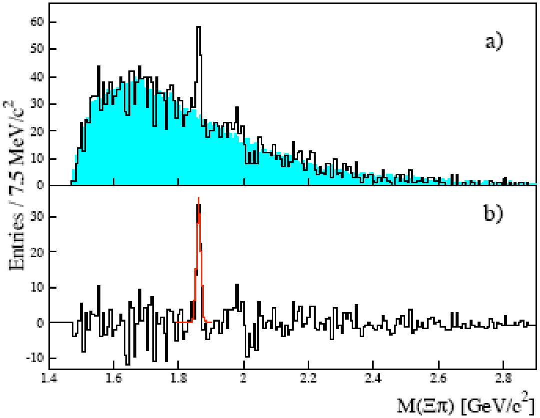
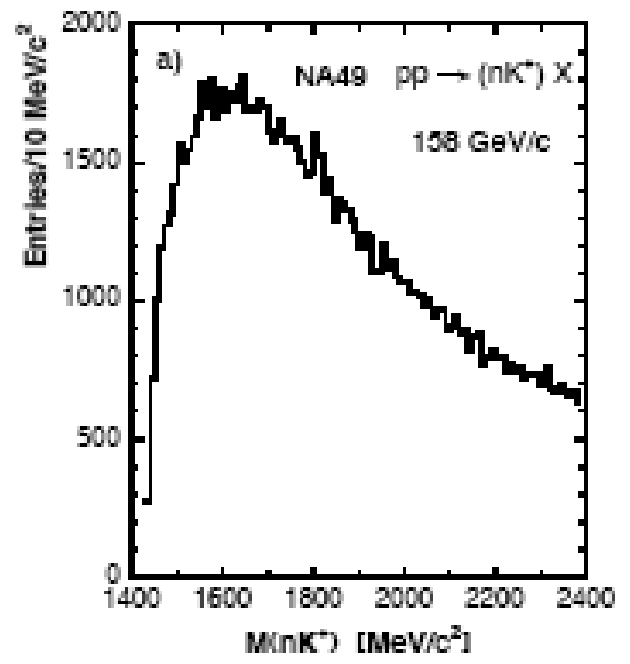
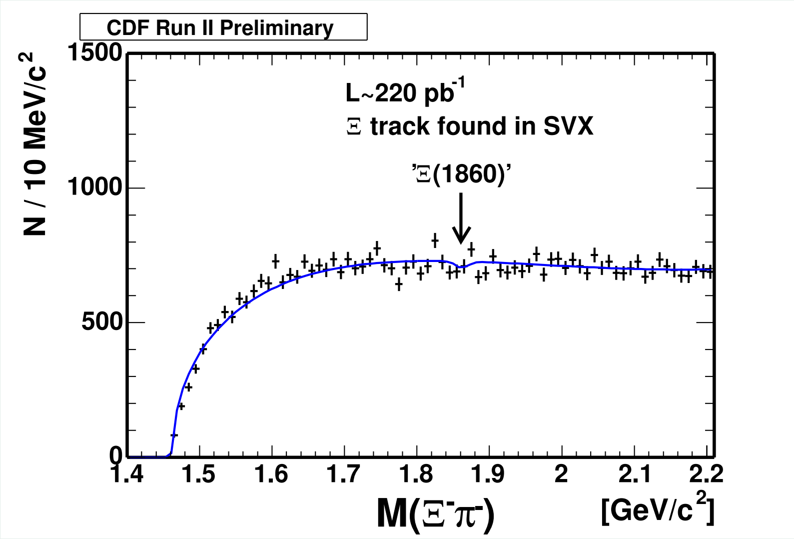


FIG. 3: (Color online) (a) The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$ and $\overline{\Xi}^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalised mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.

NA49 result (rest of the collaboration)



CDF search for Ξ^{--}, Summer 2004



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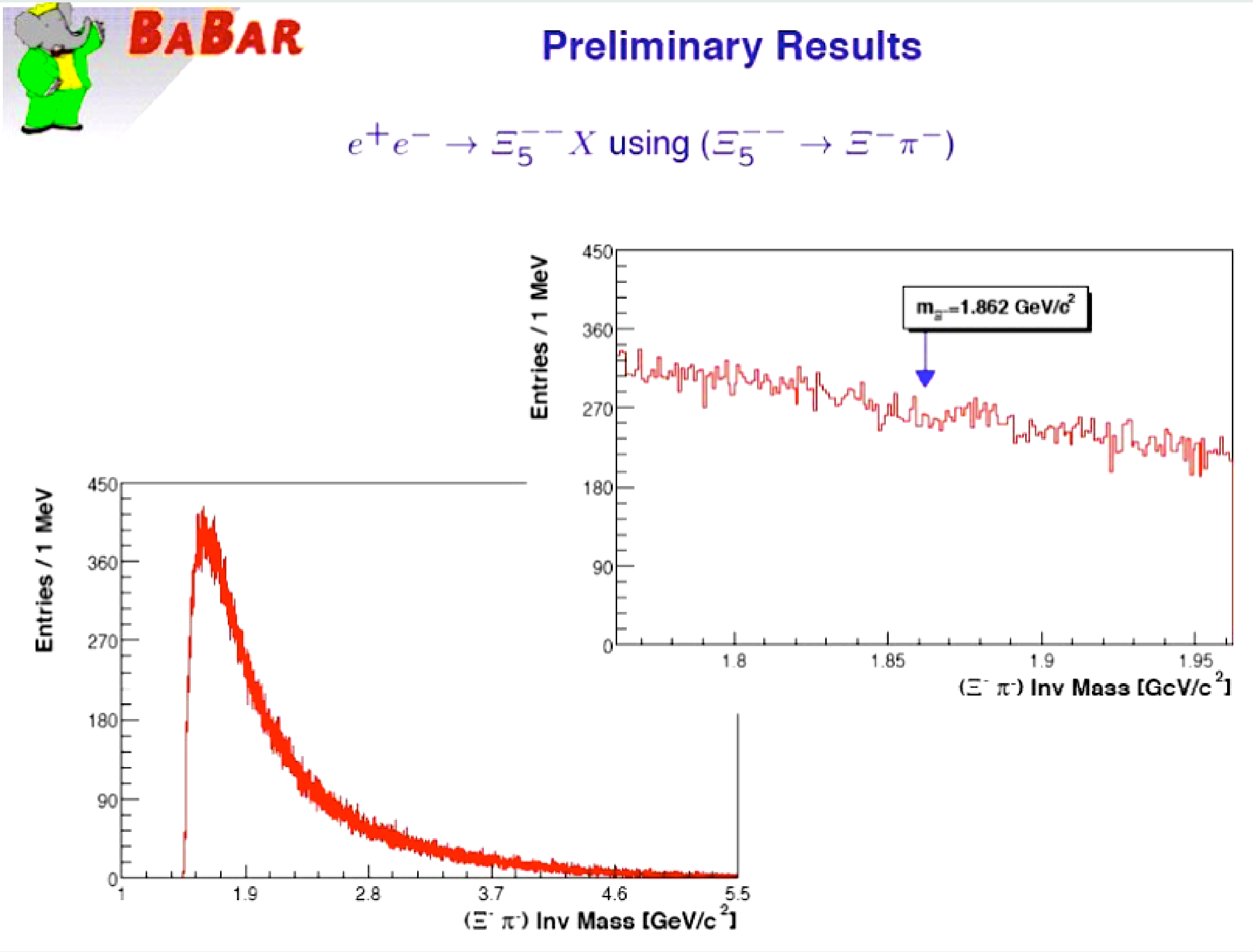
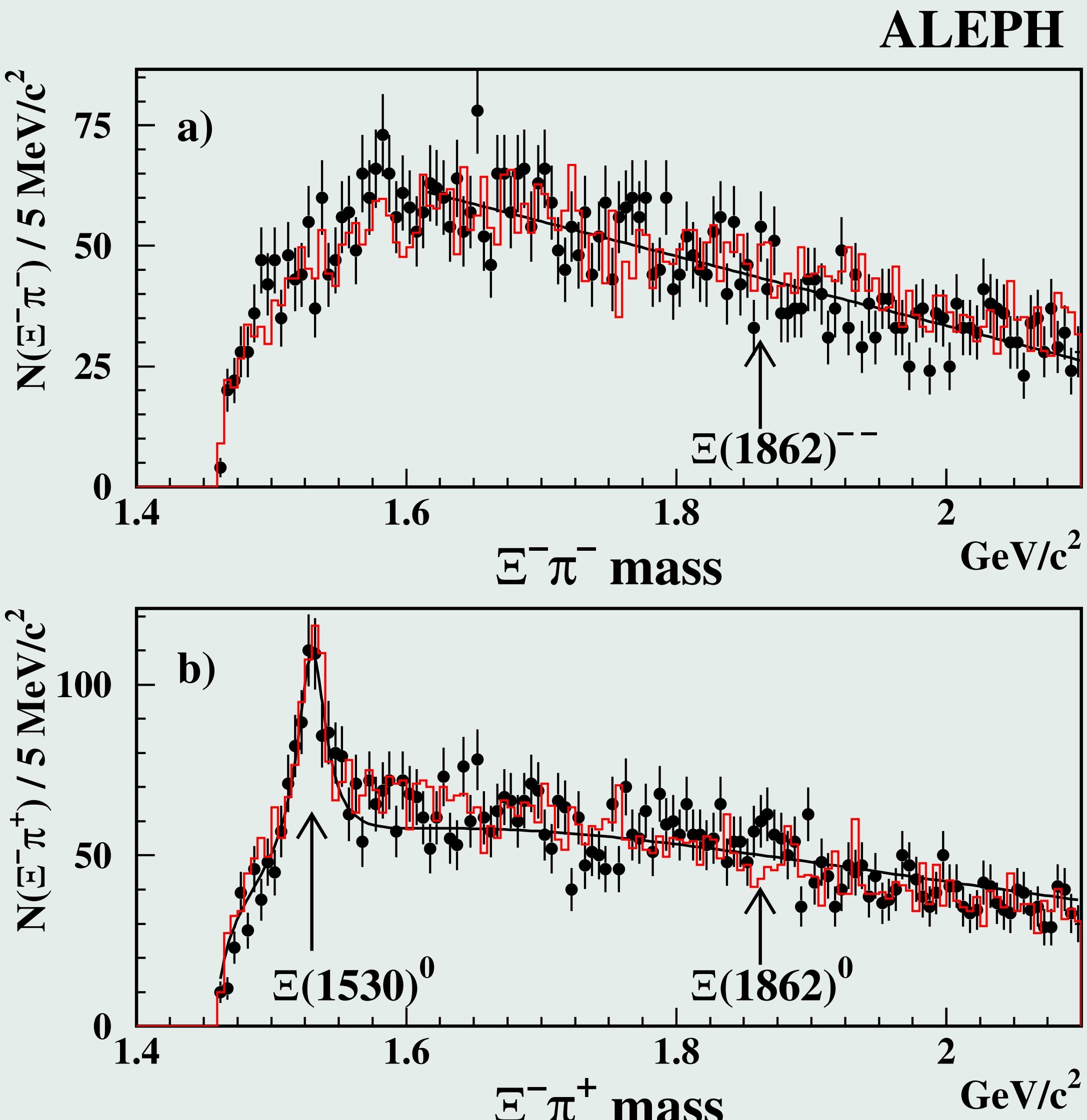
BaBar search for Ξ^{--}



Preliminary Results

$e^+e^- \to \Xi_5^{--} X$ using ($\Xi_5^{--} \to \Xi^- \pi^-$)


ALEPH
a)
N(Ξ⁻π⁻) / 5 MeV/c²
0
25
50
75
1.4
1.6
1.8
2
Ξ(1862)⁻⁻
Ξ⁻π⁻ mass
GeV/c²
b)
N(Ξ⁻π⁺) / 5 MeV/c²
0
50
100
Ξ(1530)⁰
Ξ(1862)⁰
1.4
1.6
1.8
2
Ξ⁻π⁺ mass
GeV/c²

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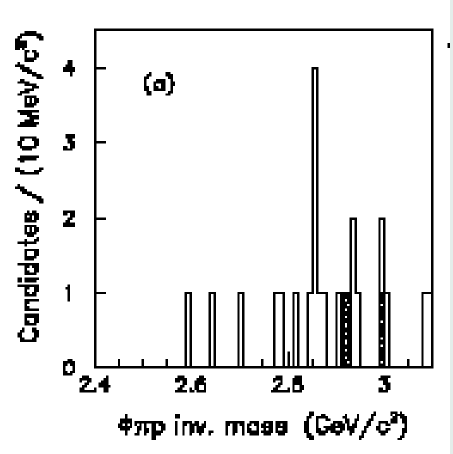
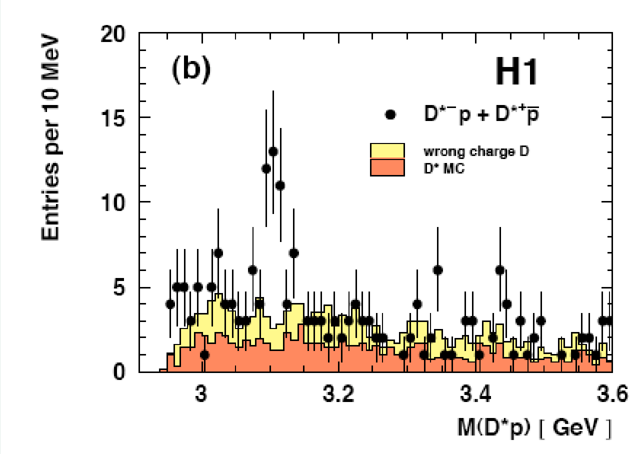
5.3. Heavy pentaquark

5.3.1. Experimental search

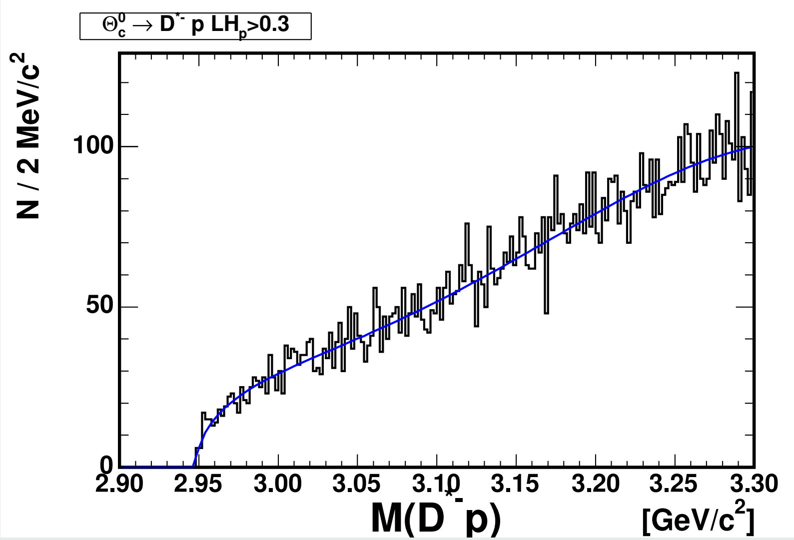
E791 (with strangeness)



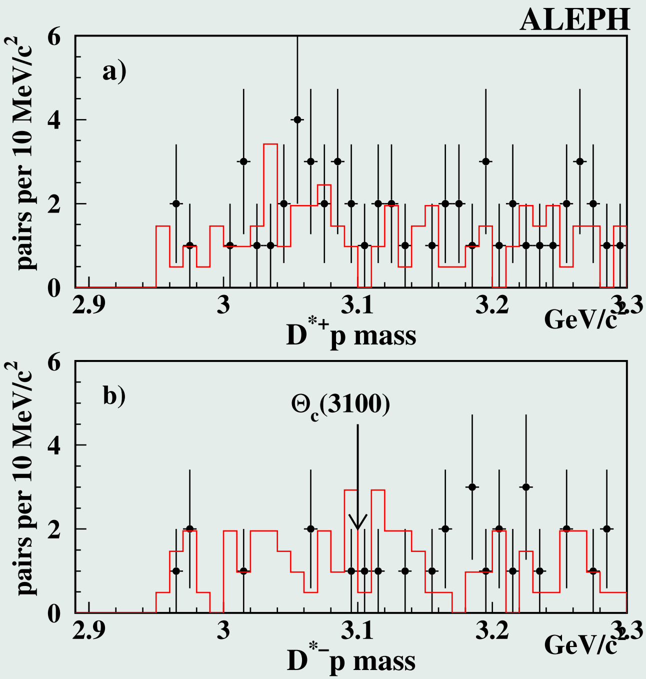
H1 (without strangeness)



CDF search for θ_c, Summer 2004



ALEPH search for θ_c



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6. Hexaquarks

6.1. Light hexaquarks

Various claims for non-strange dibaryons, never considered as confirmed.

The $H(uuddss)$ searched for in several experiments. Never seen. In particular, the hypernucleus ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ not seen decaying into $\alpha + H$.

6.2. Heavy hexaquarks

Speculations on dibaryons with charm $C = 2$ or higher. See, e.g., Julia-Diaz et al.
To be searched.

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7. Theoretical studies of multiquark spectroscopy

Usually little interest, except in simple constituent models.
Wave of works after the announcement of pentaquark candidates.

7.1. Lattice QCD

Sasaki, Czikor et al., Negele et al. found a possible signal close above KN threshold, with negative parity.

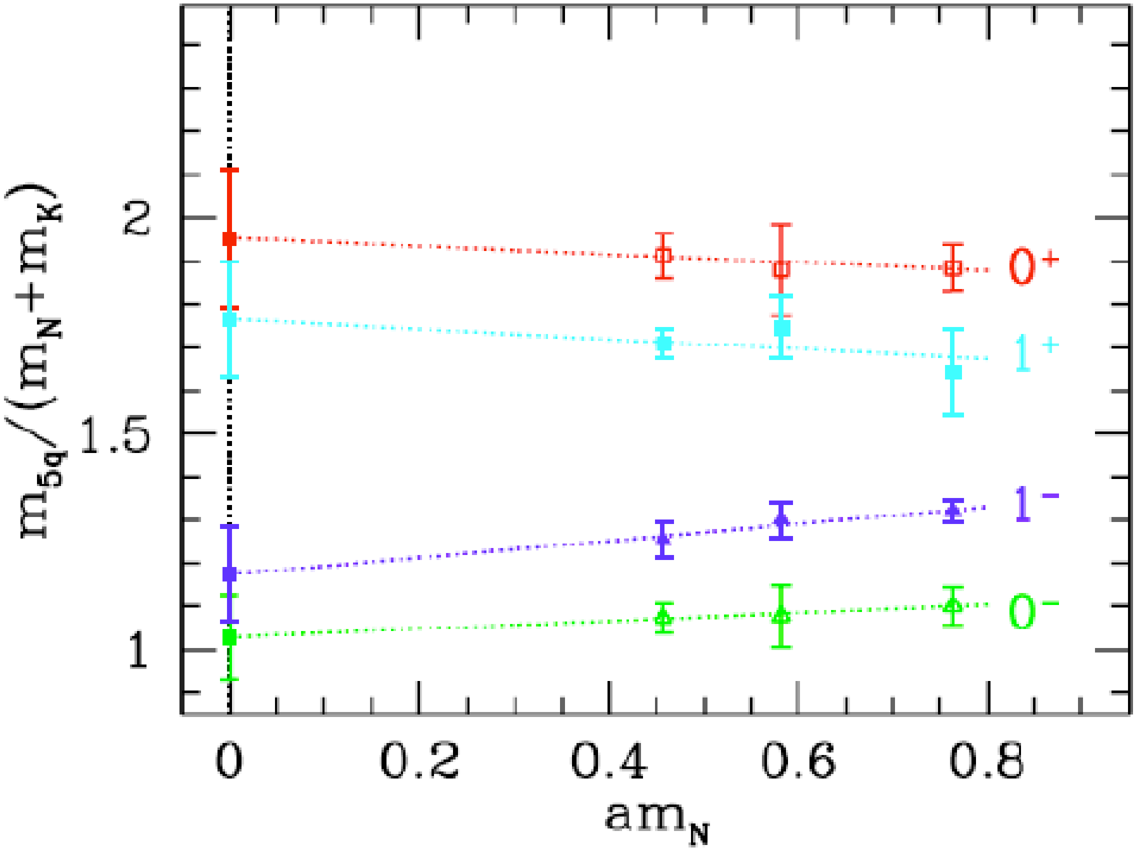
Ting-Wai Chiu and Tung-Hang Tsieh (hep-ph/0403020) assumes the Jaffe–Wilczek type of diquark clustering, and, not surprisingly, found something with positive parity near 1.5 GeV.

Mathur et al. found nothing, just the KN threshold.

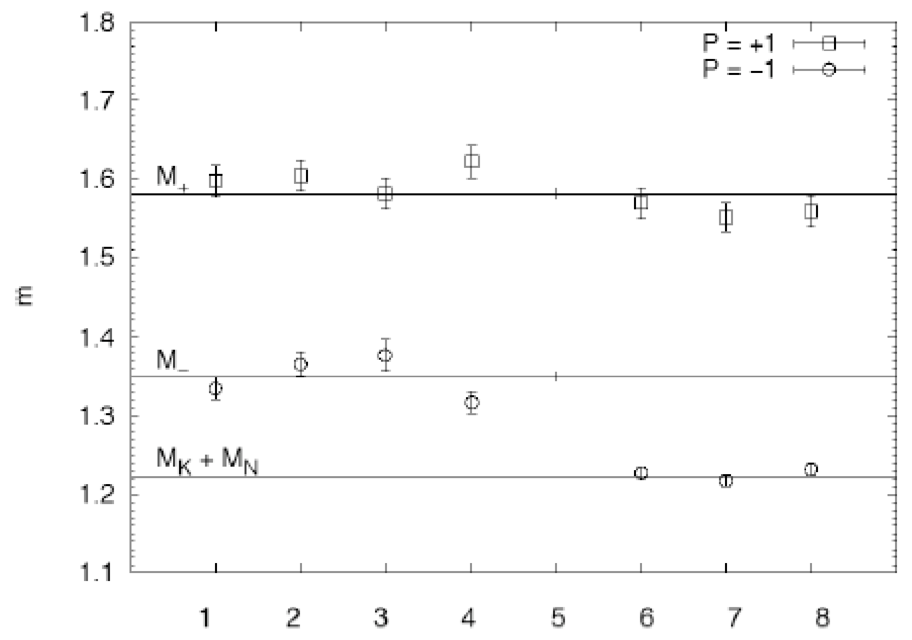
Etc., state far from being stabilised.

Quenched Wilson $20^3 \times 36$ lattice $\beta = 6$

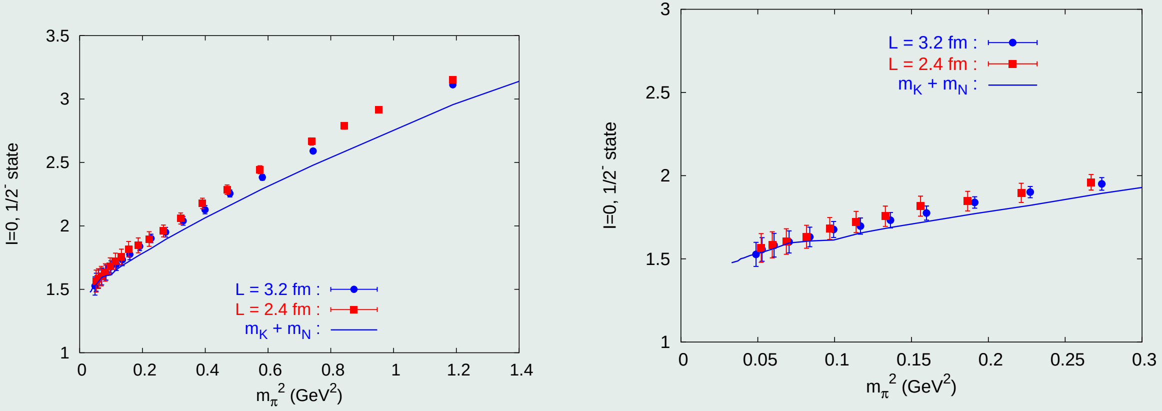
Range of m, L, β



MIT group @ QNP 2004



Mathur et al.


3.5
3
2.5
2
1.5
1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$I=0, 1/2^-$ state
m_π^2 (GeV^2)
L = 3.2 fm :
L = 2.4 fm :
$m_K + m_N$:
3
2.5
2
1.5
1
0
0.05
0.1
0.15
0.2
0.25
0.3
$I=0, 1/2^-$ state
m_π^2 (GeV^2)
L = 3.2 fm :
L = 2.4 fm :
$m_K + m_N$:

7.2. QCD sum rules

Powerful interpolation between perturbative and non-perturbative effects

But delicate

Some found states in all isospin states, so perhaps they have not yet removed the threshold.

Eidemüller assumes the same diquark clustering as Jaffe and Wilczek, gets $P = +1$.

Sugiyamma et al. found $P = -1$. Same for Zhu.

Too much dependence on the choice of operator. See, e.g., Kondo et al.

Same uncertainty for Ξ^{--}. See Matheus et al.

Cf. baryons in early days of QCD sum rules.

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7.3. Chiral soliton model

Dramatic prediction of something exotic beyond octet (N, Λ, etc.) and decuplet ($\Delta, \ldots \Omega^-$).

$\overline{10}$ structure of the new multiplet, $P = +1$ unambiguous predictions of this approach (Chemtob, Praszalowicz, Manohar, Diakonov, Petrov and Polyakov, etc. remarkable pioneers)

Adjustment of mass, prediction of width: some uncertainty remains.
Still many features of this approach to be refined and clarified. See, e.g., Cohen

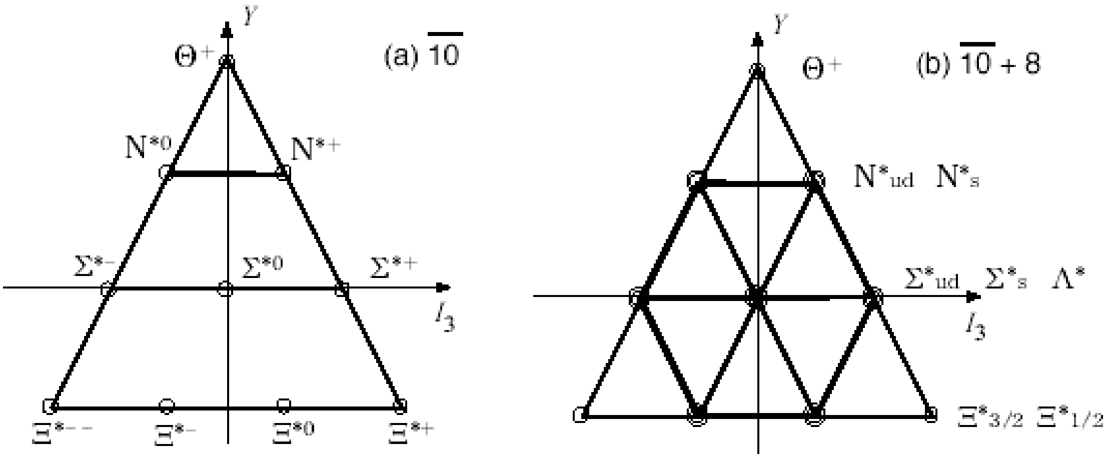

Fig. 1. (a) The $\overline{10}$ pentaquarks and (b) the mixing of the $\overline{10}$ plus 8 representations for the pentaquarks.

7.4. Constituent models

Main results

1. No multiquark for equal masses and confinement with usual colour dependence (The proliferation of multiquarks comes only in models with ad-hoc clustering hypothesis, not out of tedious few-body calculations.)

2. Mass asymmetry favours $(QQ\bar{q}\bar{q})$ as in atomic physics.

3. Spin-colour forces have interesting coherences. But . . .

4. Spin-flavour alternative also. Favour positive-parity pentaquarks. (Glozman,Stancu and Riska, Huang, Carlson et al., Hosada)

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Do not forget:

- Long-range forces. Good enough to bind pn. A Yukawa potential also expected between other particles containing light quarks.

  A weaker potential can still bind if experienced by heavier particles. $\rightarrow D\bar{D}^{*} + \mathrm{cc}$ model of $X(3.872)$.

  See, for instance, Törnqvist, Ericson and Karl, Manohar and Wise, Braaten, Swanson, etc.

  Charmed baryons might also form bound states. (Julia-Diaz + Riska)

- Borromean binding. If the potential is slightly too weak to bind two hadrons, it may well bind three hadrons.

  See, in particular, the refreshing appraoch to pentaquark by Bicudo: a borromean $KN\pi$ molecule, i.e., heptaquark. See, also, Felipe J. Llanes-Estrada (Madrid U.), E. Oset & V. Mateus.

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- ad-hoc clustering might work Diquark, for instance, advocated many many years ago to explain why mesons and baryons have the same Regge slope (M^2 vs. J). Same $3 - \bar{3}$ string tension.
  Diquark clustering in baryons at high J was proved much later.

- ad-hoc clustering might fail see, e.g., some of the speculations on baryonium in the late 70's.

  See, also, Frederiksson & Jändel. Phys.Rev.Lett.48:14,1982.
  And, more recently, Zhu, who remarks that a low lying $[ud][ud]\bar{s}$ might mean embarrassing low-lying dibaryons.

- Opening the Pandora's box

$$\underbrace{[ud]\,[ud]}_{\ell=1}\ \bar{s} = 1.54\ \mathrm{GeV} \overset{?}{\Longrightarrow} \underbrace{[ud]\,[ds]\,[sd]}_{\ell=0} \sim 2\ \mathrm{GeV}\,, \qquad \mathrm{H?}$$

$$\underbrace{[ud]\,[ud\bar{s}]}_{\ell=1} = 1.54\ \mathrm{GeV} \overset{?}{\Longrightarrow} \underbrace{[ud\bar{s}]\,[ud\bar{s}]\,[ud\bar{s}]}_{\ell=0} < \overline{\Omega^-}d\ \text{threshold}$$

etc.

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8. Hybrids of heavy quarkonia

Early speculation by Mandula and Horn (1978), and Hasenfratz, Horgan, Kuti and R. (1980).

The gluon, being coloured, is not only the vector of the interaction, it can also play a constituent role.

Ordinary quarkonium: governed by $V_{Q\overline{Q}}$, a kind of Born–Oppenheimer potential with the gluon field in its gournd-state.

Hybrid quarkonium: Next Born–Opppenheimer potential, with gluon field excited.

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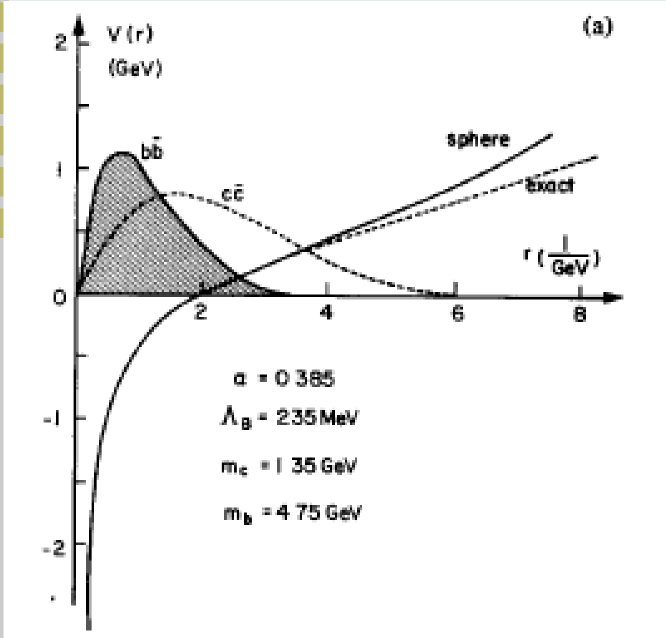

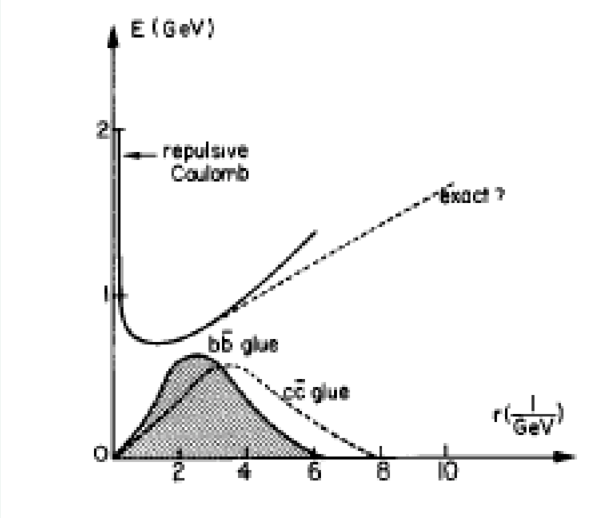

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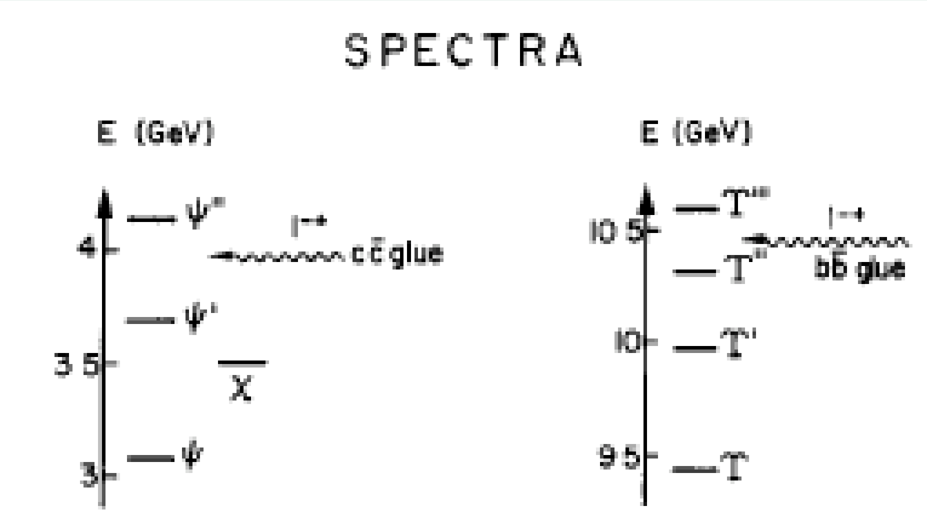
1980 predictions



$c\bar{c}g \sim 4$ GeV

$b\bar{b}g \sim 10.4$ GeV

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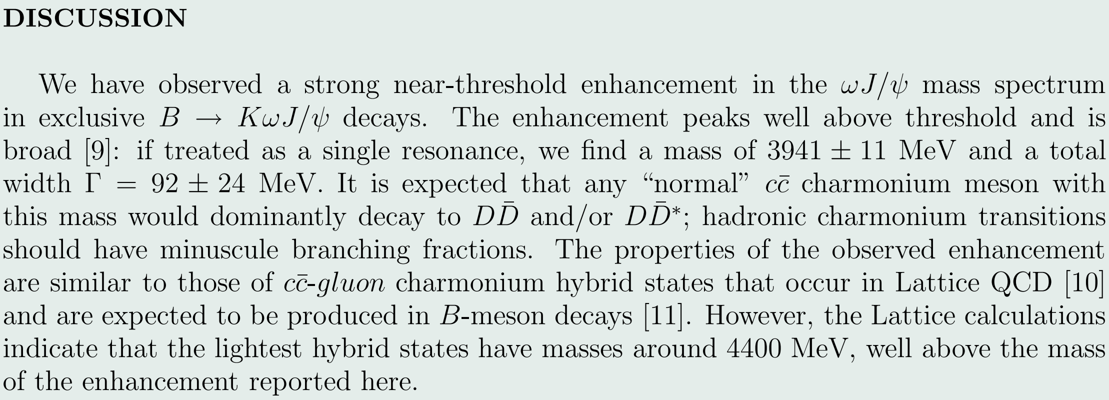
Further predictions

Flux-tube models, lattice QCD Usually masses a little higher.

Recently discovered state



DISCUSSION

We have observed a strong near-threshold enhancement in the $\omega J/\psi$ mass spectrum in exclusive $B \to K\omega J/\psi$ decays. The enhancement peaks well above threshold and is broad [9]: if treated as a single resonance, we find a mass of 3941 ± 11 MeV and a total width $\Gamma = 92 \pm 24$ MeV. It is expected that any "normal" $c\bar{c}$ charmonium meson with this mass would dominantly decay to $D\bar{D}$ and/or $D\bar{D}^*$; hadronic charmonium transitions should have minuscule branching fractions. The properties of the observed enhancement are similar to those of $c\bar{c}$-*gluon* charmonium hybrid states that occur in Lattice QCD [10] and are expected to be produced in B-meson decays [11]. However, the Lattice calculations indicate that the lightest hybrid states have masses around 4400 MeV, well above the mass of the enhancement reported here.

Belle, hep-ex/0408126

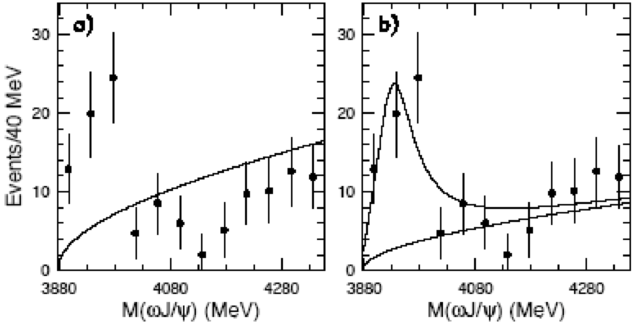


FIG. 6: $B \to K\omega J/\psi$ signal yields *vs* $M(\omega J/\psi)$. The curve in (a) indicates the result of a fit that includes only a phase-space-like threshold function. The curve in (b) shows the result of a fit that includes an S-wave Breit-Wigner resonance term.

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9. Conclusions

- Dramatic and welcome come-back of hadron spectroscopy.
- Some experiments have very convincing results, in particular in the heavy quark sector.
- Some claims obviously need confirmation, and better statistics.
- A straight hadron is usually seen in many experiments. A delicate structure might hardly survive brute-force production.
- Some theoretical models are very elegant but rely on ad-hoc hypotheses (clustering) that need to be checked.
- The small width of pentaquark is extremely puzzling.
- Intriguing possibility of candidates for $c\bar{c}g$ type of states.

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