Search for Charm, Charm-Strange and Bottom and Bottom-Strange Pentaquark Baryons and 4-Quark Mesons in P-Pbar Collisions at CDF

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I. ABSTRACT

We search for exotic multiquark states using the high statistics charm samples taken with the CDF RunII detector using the Silicon Vertex Trigger, and final state particle ID including time of flight. We investigate the following final states: $Proton$ (or π or K) plus D_s^- (charge 0); $Proton$(or π or K) plus D_s^+ (charge 2) mass spectra (and corresponding antiparticles); $Proton$ (or π or K) plus D^- (charge 0); $Proton$(or π or K) plus D^+ (charge 2) mass spectra (and corresponding antiparticles) We look at states in both the short lived (Lxy less than 100 or 700 micron) and long lived categories (Lxy greater than 700 micron).

II. SUMMARY

In order to search for exotic Pentaquark and four-quark states with massive quarks, we need to discover the mass range, lifetime and decay modes. In this note, we outline the motivation and the procedure for a search for Pentaquarks and exotic mesons. We first search for states in the charm sector. If such states are found, the observed masses and decay modes can be used to predict the masses in the b sector. (We then plan to search for Pentquarks in the b sector).

In the charm sector we first focus on the following final states (both prompt short lived and also long lived):

(a) $\Sigma_c^0 = P_{\overline{c}s}^0 = \overline{c}suud$ (if short lived) decays to $(Proton\ D_s^-)$ and $(Anti-Proton\ D_s^+)$. (In models which predict that Pentaquarks with both s and c quarks are long lived, it is called the T_s^0 and does not decay to those channels)

(b) $P_{\overline{s}c}^{++} = \overline{s}cuud$ (if short lived) decays to $(Proton\ D_s^+)$ and $(Anti-Proton\ D_s^-)$. (In models which predict that Pentaquarks with both s and c quarks are long lived, it is called the F^{++})

(c) $\Theta_c^0 = P_{\overline{c}d}^0 = \overline{c}duud$ (if short lived) decays to $(Proton\ D^-)$ and $(Anti-Proton$ plus $D^+)$. (in models which predict that Pentaquarks with both s and c quarks are long lived, this state is not stable since it does not include strange quarks)

(d) $P_{\overline{d}c}^{++} = \overline{d}cuud$ (if short lived) decays to $(Proton\ D^+)$ and $(Anti-Proton$ plus $D^-)$. (in models which predict that Pentaquarks with both s and c quarks are long lived, this state is not stable since it does not include strange quarks)

(e) We also plan to look for the corresponding states in the b-quark sector.

As a control sample, we use the above channels (with a proton replaced with a pion or a kaon). This allows us to check our procedure to to make sure that we observed the known states D^{0*} (2460) (a short lived state decaying to $\pi^+\ D^-$ and $\pi^-\ D^+$) as well as the B^0 and B_s^0 mesons (long lived states decaying to $\pi\ D$ or $\pi\ D_s$). In addition, this di-meson sample can be used to look for exotic four-quark states. For example exotic states with charm and strangeness in the channels π^+ or K^+ plus D_s^- (charge 0) and π^- or K^- plus D_s^+ (charge 2).

As shown in Table 1, early chiral models predicted that Pentaquarks are very massive and wide and difficult to see [15]. Some models predict that some are unstable, and a few are narrow long-lived and very much below threshold [13]. Other models predict that the are narrow short-lived (20 MeV width) and with masses just above threshold [12,6,7]. For example The $\Sigma_c^0 == P^0_{\overline{c}s}$ $=\overline{c}sudd$ is estimated to be 3545 MeV in old Chiral [15] models and therefore very wide. Another state with the same quark composition is called the T_s^0 and is estimated to be 2580 MeV and stable in the model of Stewart, Wessling and Wise [13]. In this model, since the mass of 2580 MeV is much below *proton* D_s threshold of 2907 MeV, this state is long lived.

Within the diquark model of Shuryak [12] Σ_c^0 was estimated to be just below threshold at 2880 MeV (where it was looked for and not found [4] by E791). This same state is estimated by in Lipkin's model [12] to be around 3165 MeV and therefore 20 MeV wide and above threshold.

Even within those specific models, the uncertainty on the predicted mass is about 100 MeV. In addition, some models predict positive parity, and some negative parity, and some both [14]. If Pentaquarks exist, some models predict various higher mass excitations [14] of different angular momentum states (so each Pentaquark is a series of states). Some models predict that only a certain combination of quarks is stable (e.g. diquarks are not bound if there are two quarks of the same kind). All models predict that there could be multiple closely spaced states above threshold.

Blind searches (like E791) are very good in setting good limits on particles within a specific model (or looking for rare decay mode where we know where to look). However, no new particle has ever been discovered using a blind search. Therefore, we first do a general search using cuts which are based on general physics arguments and are not dependent on the parity, spin and mass within any specific model. We plan to look at each of the regions in sequence since each mass region implies different width/lifetime and different final state decay modes.

We start with a search for narrow states (20 MeV wide states) just above threshold, as well as wider states at higher masses (which would occur as higher angular momentum spin or radial excitations). This mas region region is favored by the the constituent diquark-triquark model. Within the Lipkin diquark-triquark Pentaquark model we estimate the mass region that is of interest by assuming that the newly reported state $\Theta_s^{\pm}(1540)$ is the $\overline{s}uudd$ Pentaquark state. Using this we estimate the following masses for Charm Pentaquarks:

(a) We use Huang estimate using Likpkin's model of 3165 MeV for Σ_c^0. (We then correct it since it overestimates the Θ_c (1540) to be 1592 MeV). Therefore, we estimate that the $\Sigma_c^0 = P^0_{\overline{c}s}$ $=\overline{c}sudd$ should is around 3120 MeV and decay to Proton plus D_s^- (and the corresponding antiparticle);

(b) We estimate that (if it exists) the $P^{++}_{\overline{s}c}$ $=\overline{s}cudd$ may be around 3200 MeV and decay to Proton plus D_s^+ (and the corresponding antiparticle);

(c) Using Huang and Cheung we estimate that the $\Theta_c^0 = P^0_{\overline{c}d}$ $=\overline{c}duud$ should be around 2980 MeV and decay to Proton plus D^- (and the corresponding antiparticle);

(d) We estimate that if it exists, that the $P^{++}_{\overline{d}c}$ $=\overline{d}cuud$ should be around 3060 MeV and decay to Proton plus D^+ (and the corresponding antiparticle).

We investigate states in both the short lived and long lived categories.

If the above indication is confirmed in the Charm sector, then one could estimate the following masses for the corresponding Pentaquark states in the b sector:

(a) The $\Theta_b^+ = P^+_{\overline{b}}$ $=\overline{b}uudd$ (and the corresponding antiparticle) is estimated by Lipkin to be be around 6400 MeV ;

(b) The $\Sigma_b^+ = P^+_{\overline{b}s}$ $=\overline{b}sudd$ (and the corresponding antiparticle) is estimated by Lipkin to be at 6570 MeV (this is close to our estimate in the appendix that it should be around 6535 MeV).

Since these particular two body final state decay channels and mass regions appear to be promising, we are doing detailed analysis including both a side band analysis, and several decay modes of charm mesons.

compos.	*Mass1*	*Mass2*	*Mass3*	*Mass4*	*Mass5*	*Mass6*	*mass7*	*thresh*
names	1*chiral*97	2*cheung*	3*Lipkin*	4*Jaffe*	5*Shuryak*	6*stable*	7*lattice*	*Decay*
charge	*Genovese*	*diquark*04	*Huang*04	*Huang*04	*Huang*04	*steward*04	*Sasasi*03	*mode*
uudd$\bar{\mathbf{s}}$(+)	*NA*	1562−	1592			1540	1760	1433.2
$\mathbf{\Theta^+ 1540}$	$P^+_{\bar{s}}$	−1481	$-42 = 1540$				$-200 = 1540$	nK^+
uudd$\bar{\mathbf{c}}$(0)	3607	2997−	2990	2710	2700	*unstable*	3576	2807
Θ^0_c	$P^0_{\bar{c}}$	2938	$-42 = 2950$			*Look*−>	$-200 = 3376$	$P\ D^-$
$uudd\bar{b}(+)$	6889	6422−	6400	6050	6040	*unstable*		6219
Θ^+_b	$P^+_{\bar{b}}$	−6370	*Lipkin*	*Jaffe*	*Shuryak*	*Stewart*	*Sasasi*	$P\ B^0$
uusd$\bar{\mathbf{c}}$(0)	3545		3165	2870	2880	2580		2907
$\mathbf{\Sigma}$	$P^0_{\bar{c}s}$		$-42 = 3123$			T^0_s	*Look*−>	$P\ D^-_s$
$uusd\bar{b}(+)$	6827		6570	6210	6220	5920		6349
Σ^+_b	$P^+_{\bar{b}s}$	*Cheung*	*Lipkin*	*Jaffe*	*Shuryak*	*Stewart*	*Sasasi*	$P\ B^0_s$
$udsd\bar{c}$(-)	3545		3165	2870	2880	2580		3057
Σ^-_c	$P^-_{\bar{c}s}$		$-42 = 3123$			T^0_s		$N\ D^-_s$
$udsd\bar{b}(0)$	6827		6570	6210	6220	5920		6309
Σ^0_b	$P^0_{\bar{b}s}$	*Cheung*	*Lipkin*	*Jaffe*	*Shuryak*	*Stewart*	*Sasasi*	$N\ B^0_s$
$udss\bar{c}$(-)	3630		3340	3135	3060	2770		3084
Ξ^-_c	$P^-_{\bar{c}ss}$		$-42 = 3298$			T^-_{ss}		$\Lambda^0_s\ D^-_s$
$udss\bar{b}(0)$	6911		6740	6475	6400	6100		6485
Ξ^+_b	$P^+_{\bar{b}s}$					R^0_{ss}		$\Lambda^0_s\ B^0_s$
$uuss\bar{c}(0)$			3340			*unstable*		
Ξ^0_c	$P^0_{\bar{c}ss}$		$-42 = 3298$					
$uuss\bar{b}(0)$			6740			*unstable*		
Ξ^+_b	$P^+_{\bar{b}ss}$	*Cheung*	*Lipkin*	*Jaffe*	*Shuryak*	*Stewart*	*Sasasi*	
$ddss\bar{c}(-)$			3340			*unstable*		
Ξ^{--}_c	$P^{--}_{\bar{c}ss}$		$-42 = 3298$					$\Sigma^-_s\ D^-_s$
$ddss\bar{b}$(-)			6740			*unstable*		6559
Ξ^-_b	$P^-_{\bar{b}ss}$							$\Sigma^+_s\ B^0_s$
$usss\bar{c}$(-)	3940					*unstable*		
	$P^-_{\bar{c}ss}$							$\Xi\ D^-_s$
$usss\bar{b}(+)$	7223					*unstable*		
	$P^+_{\bar{b}sss}$	*Cheung*	*Lipkin*	*Jaffe*	*Shuryak*	*Stewart*	*Sasasi*	$\Xi\ B^0_s$
$dscd\bar{u}$(-)						*stable?*		
	$P^-_{\bar{u}cs}$					F^-_s		
$sucu\bar{d}(++)$		3460, 3541	*v.narrow*	$\Lambda^+_c K^- \pi^+ \pi^+$	*maybe*(*ccu*)	*stable?*		
SELEX?	$P^{++}_{\bar{d}cs}$	3780	26*MeV wide*	*seen?*	*maybe*(*ccu*∗)	F^{++}_s		$\Sigma^+_s\ D^+$
$dscs\bar{u}$(-)						*stable?*		
	$P^-_{\bar{u}css}$					F^-_{ss}		
$uscs\bar{u}(+)$						*stable?*		
	$P^+_{\bar{u}css}$					F^+_{ss}		
udcu$\bar{\mathbf{s}}$(++)			3200			*stable?*		2906
	$P^{++}_{\bar{s}c}$		*Bodek*			F^{++}	*Look*−>	$P\ D^+_s$
$udcd\bar{s}(+)$						*stable?*		2906
	$P^+_{\bar{s}c}$					F^+		$N\ D^+_s$
udcu$\bar{\mathbf{d}}$(++)			3060			*unstable*	*non* − *exotic*	2807
ucu(*also*)	$P^{++}_{\bar{d}c}$		*Bodek*				*Look*−>	$P\ D^+$
$sucd\bar{d}(+)$		3443, 3520	*v.narrow*	$\Lambda^+_c K^- \pi^+$	*maybe*(*ccd*)	*unstable?*		
SELEX?	$P^+_{\bar{d}cs}$			*seen?*	*maybe*(*ccd*)			$\Lambda^0_s\ D^+$

TABLE I. Pentaquark states in various theoretical models.

	I	Y	I_z	q
$\{4\}\bar{s}$	2	2		
$uuuu\bar{s}$			2	+3
$uuud\bar{s}$			1	+2
$uudd\bar{s}$			2	+1
$uddd\bar{s}$			−1	0
$dddd\bar{s}$			−2	−1
$\{31\}\bar{s}$	1	2		
$uuud\bar{s}$			1	+2
$uudd\bar{s}$			0	+1
$uddd\bar{s}$			−1	0
$\{2^2\}\bar{s}$	0	2		
$uudd\bar{s}$			0	+1

FIG. 1. Quantum numbers of strangeness +1 (anti-strange) Pentaquarks (Brian G. Wybourne hep-ph/0307170, note that there is mistake in this table and the $uudd\bar{s}$ state has I_z of zero (and not 2 as shown))

penta	I_z	Y	q	$\mathcal{S}$
uudd$\bar{u}$	$-\frac{1}{2}$	1	0	0
uudd$\bar{d}$	$\frac{1}{2}$	1	1	0
uudd$\bar{s}$	0	2	1	+1
uuds$\bar{u}$	0	0	0	−1
uuds$\bar{d}$	1	0	1	−1
uuds$\bar{s}$	$\frac{1}{2}$	1	1	0
uuss$\bar{u}$	$\frac{1}{2}$	−1	0	−2
uuss$\bar{d}$	$\frac{3}{2}$	−1	1	−2
uuss$\bar{s}$	1	0	1	−1
udss$\bar{u}$	$-\frac{1}{2}$	−1	−1	−2
udss$\bar{d}$	$\frac{1}{2}$	−1	0	−2
udss$\bar{s}$	0	0	0	−1
udds$\bar{u}$	−1	0	−1	−1
udds$\bar{d}$	0	0	0	−1
udds$\bar{s}$	$-\frac{1}{2}$	1	0	0
ddss$\bar{u}$	$-\frac{3}{2}$	−1	−2	−2
ddss$\bar{d}$	$-\frac{1}{2}$	−1	−1	−2
ddss$\bar{s}$	−1	0	−1	−1

FIG. 2. Quantum numbers of lowest lying Pentaquark states (from Brian G. Wybourne hep-ph/0307170)

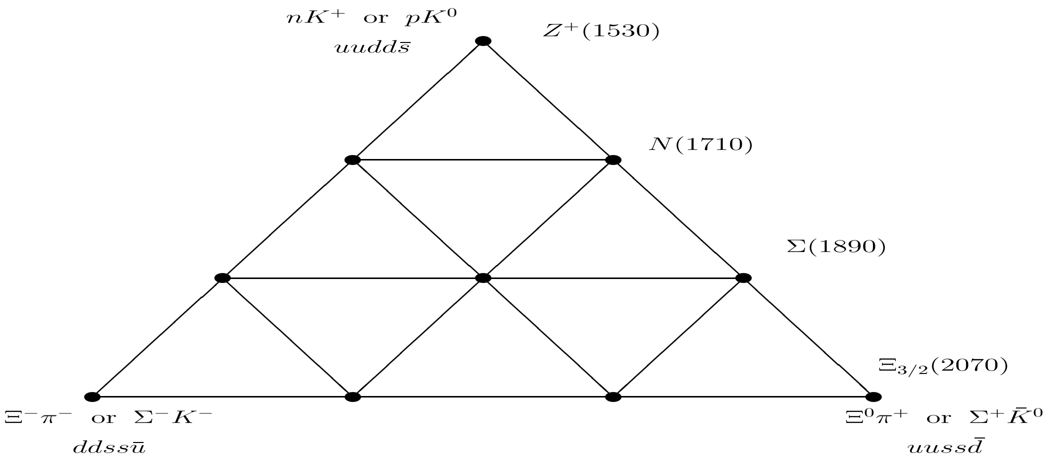


FIG. 3. Diagram of Pentaquark low lying Pentaquark states as proposed originally by Polyakov hep-ph/9703372. Only the three states in the corner are exotic. Note that the best estimate of these masses in 2004 is that the Z(1530) is at 1540 MeV, the N(1710) is at 1650 MeV, the Σ (1890) is at 1750 MeV and the Ξ (2070) is either at 1780 or 1869 MeV. The state with one anti-strange quark (top corner)is exotic. The two states in the bottom corners are exotic.

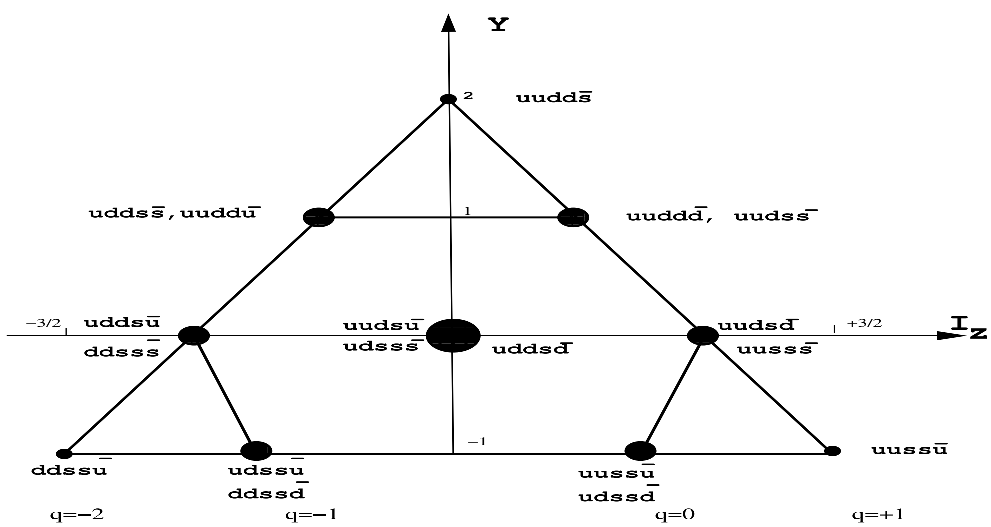


FIG. 4. Quark assignments of lowest lying Pentaquark multiplet. Note that there is mistake in this figure and the bottom right hand corner should be a $uuss\bar{d}$ state (not $uuss\bar{u}$). (from Brian G. Wybourne hep-ph/0307170) The state with one anti-strange quark (top corner)is exotic. The two states in the bottom corners are exotic.

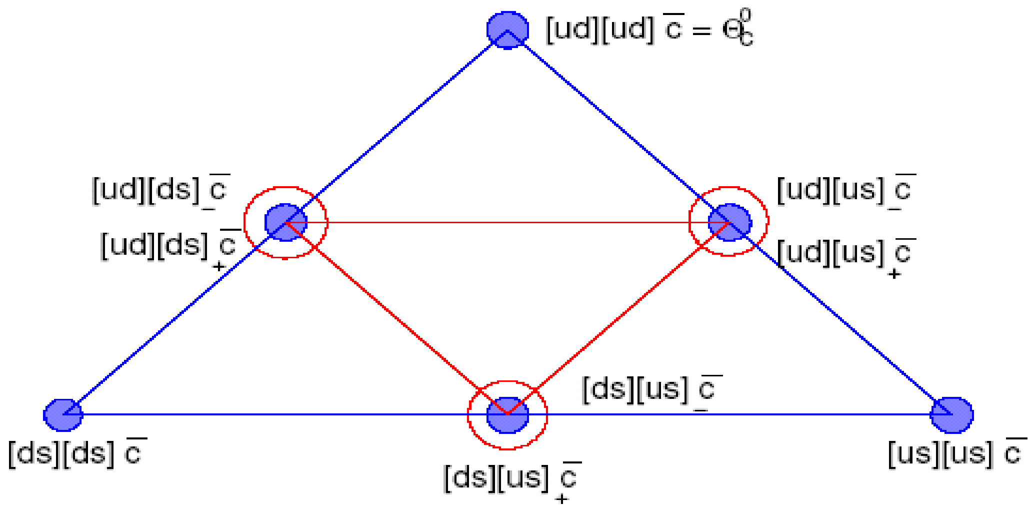


FIG. 5. Diagram of Pentaquark states with one anticharm quark. Not shown are states with a bottom quark (e.g. instead of a strange quark) which may also be possible; or states with an antibottom antiquark instead of anticharm. Figure from Cheung, hep-ph/0308176)

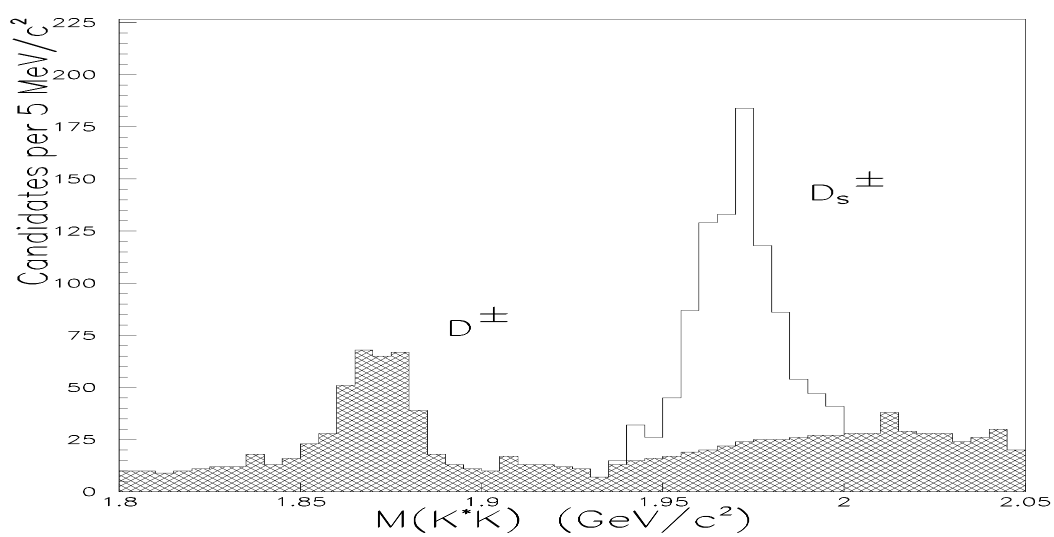


Fig. 2. The $K^-K^+\pi^-$ invariant mass distribution for events which satisfy the final $K^{*0}K^-$ selection criteria described in the text. The D_s^- normalization signal is seen clearly. The level of the background under the D_s^- signal was determined from the background levels observed above and below the signal region and from studies of $D^- \to K^+\pi^-\pi^-$ reflections, as discussed in the text. The part of the shaded area in the D_s signal region indicates the overall level of the background there.

FIG. 6. E791 Ds mass peak used for their search for Pentaquarks

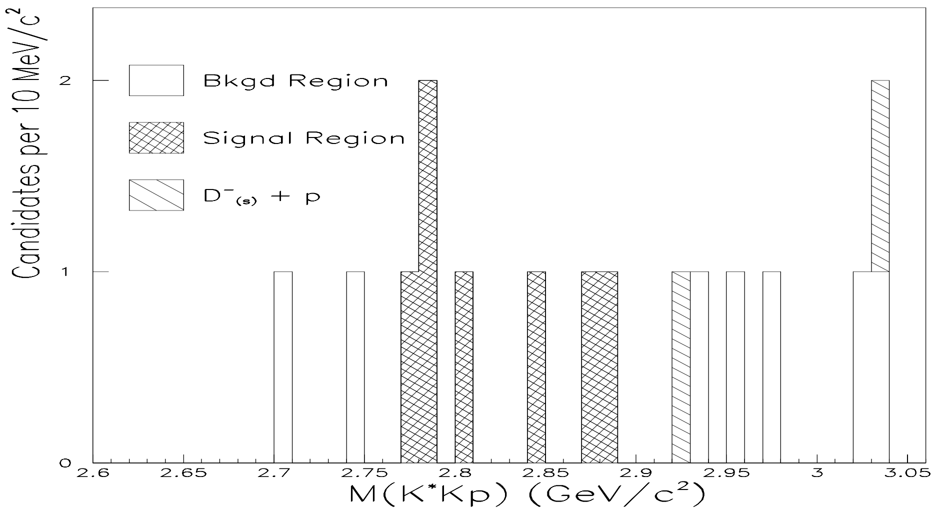


Fig. 1. The $K^-K^+\pi^-p$ invariant mass distribution for the events which satisfy the final $P^0_{\bar{c}s} \rightarrow K^{*0}K^-p$ selection criteria described in the text. To avoid bias, the signal region from 2.75 GeV/c^2 to 2.91 GeV/c^2 (in which the events have been cross-hatched) was masked until the selection criteria were determined. The events denoted with slanted lines are kinematically consistent with either the D_s^-p hypothesis or the D^-p hypothesis.

FIG. 7. E791 Blind analysis for long lived Pentaquarks with a mass of 2.8 GeV

III. INTRODUCTION

Recently, there have been number of reports of exotic 5-quark baryons [1] (Pentaquarks) and four-quark mesons [2,3]. The first Pentaquark that was reported reported consists of four light quarks and one anti-strange quark. This $\Theta^+_{\bar{s}}(1540)$ state has been identified with $\bar{s}uudd$ 5-quark combination as shown in the top corner of Fig. 3

The anti-strangeness is what makes this particular Pentaquark an exotic state. It is possible that there are other anti-stange Pentaquarks that include an $\bar{s}$ with the four-quark combinations (uuuu, uuud, uudd, uddd and dddd). If such states exist, then one expects corresponding states in the anticharm, anticharm-strange, and charm-antistrange sectors and similarly in the bottom quark sector. For example in the anticharm sector one could have a $\bar{c}$ with a (uuuu, uuud, uudd, uddd and dddd) as shown in Fig. 5. In the antistrange-charm sector one expects a $\bar{s}c$ pair with a (uuu, uud, udd and ddd) combinations. We therefore begin our search with the D_s sample, as described below. If there are any Baryons with either antistrange or anticharm quantum numbers, they would be considered exotic.

In addition, there have been two recent reports of four-quark states [2,3]. One of them is the exotic $D_s^+(2317)$ reported by the BaBar collaboration (a narrow state decaying into a D_s^+ and a π^0). If this state is a $c\bar{s}(u\bar{u}d\bar{d})(+)$ four quark exotic state, then there could be analogous states $c\bar{s}d\bar{u}(0)$ (2325 ??) decaying to $D_s^+\pi^-$ or $c\bar{s}u\bar{d}(++)$(2325 ??) decaying to $D_s^+\pi^+$. We therefore also search for these charged analogue states decaying into D_s mesons in combination with charged pions and kaons.

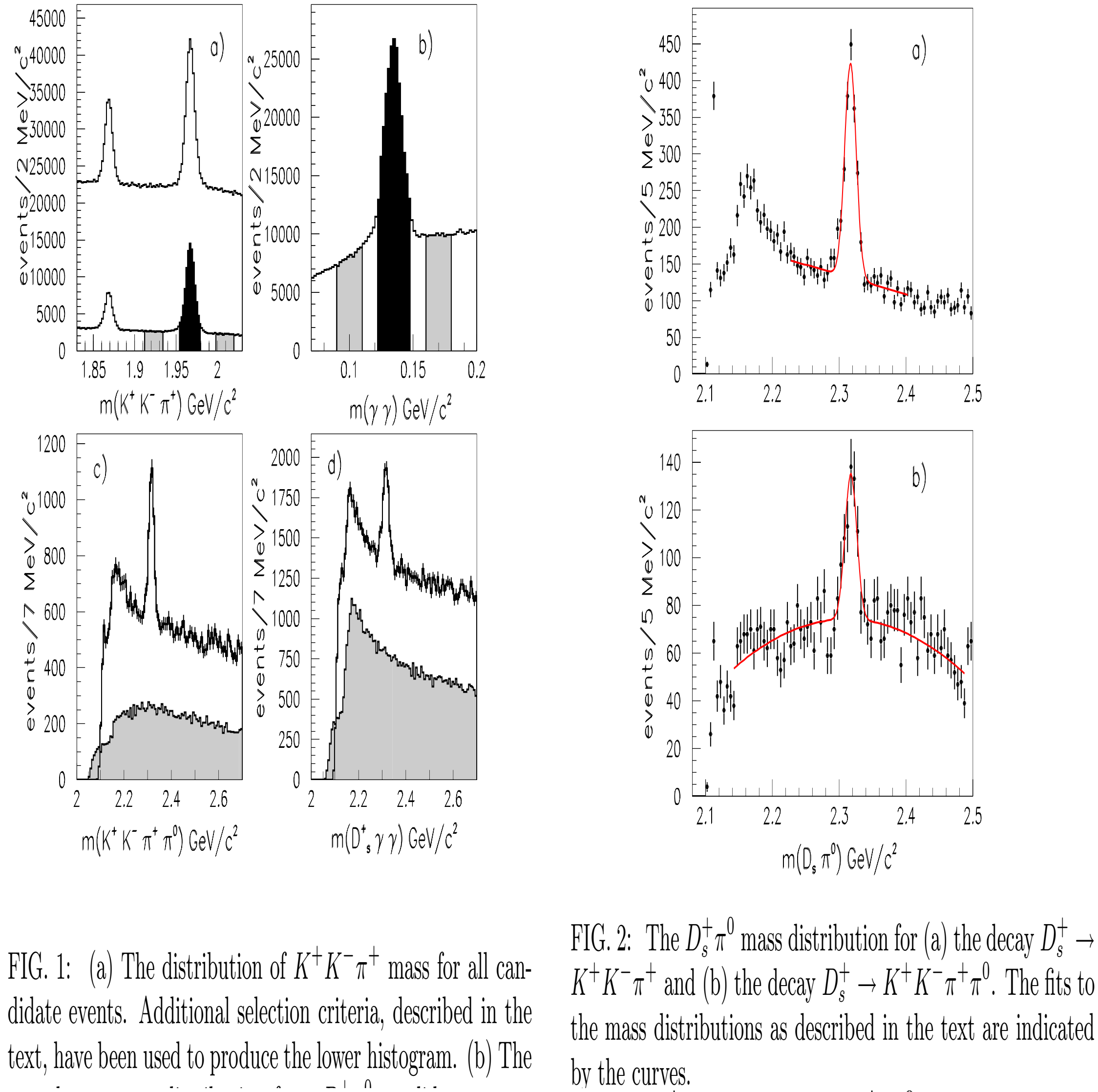


FIG. 8. This figure taken from the BaBar paper on the $D_s^+(2317)$ in the $(D_s^+\ \pi^0)$ final state. If this state is a $c\overline{s}(u\overline{u}d\overline{d})(+)$ four-quark exotic state, then there could be analogous states $c\overline{s}d\overline{u}(0)$ (2325 ??) decaying to $D_s^+\pi^-$ or $c\overline{s}u\overline{d}(++)$(2325 ??) decaying to $D_s^+\pi^+$. We therefore also search for these charged analogue states decaying int D_s mesons in combination with charged pions and kaons.

Since the D_s sample contains also Cabbibo suppressed charged D decays, we also use the D meson Cabbibo suppressed events to check our procedure and normalize to known decay modes of B^0 (long lived), and $D^{0*}(2460)$ (short lived) mesons which decay to D^+ plus a π^-. In addition, we also check that our samples show the known D_s^+ plus π^- decays of the both the B^0 and B_s long lived mesons.

Therefore, the di-meson samples should have both short-lived known states and well as known long lived states to provide checks on the search procedure, and a normalzation sample.

A. Recent Limits and models

It is expected that in bound hadrons (including Pentaquarks), the constituent mass of the light quarks (e.g. up, down, strange) is reduced in the presence of heavyier quarks (e.g. strange, charm, bottom). Therefore, the initial predictions for Pentaquark states stated that Pentaquarks were long lived (because the mass could be below threshold for a strong decay). Based on the prediction of severalsuch models, the E791 collaboration [4] searched for a long lived $\Sigma_c^0 = P_{\bar{c}s}^0 = \bar{c}sudd$ in the interactions of 500 GeV negative pions with nuclear targets. No such Pentaquarks were found (assuming a lifetime of 0.4 ps and masses between 2.75 and 2.91 GeV). The decay mode that was assumed was a proton and a virtual (below threshold) D_s (i.e. a K^{*0} K^- *proton* final state). This was a blind search that masked this region and looked for long lived (stable) Pentaquarks predicted to be 2.88 GeV (by Shuryak and Zahed), 2.87 GeV by Jaffe and Wilcek. The E791 results are shown in the Fig. 6 and Fig. 7.

In contrast, the recently observed Pentaquark state in the antistrange sector is above threshold for hadronic decays is short lived with a width of 20 MeV (e.g. the $\Theta_{\bar{s}}^{+}(1540)$ resonance). Such a narrow width can be explained by an isopspin-violating hadronic decay (for states above threshold).

Therefore, now that the $\Theta_{\bar{s}}^{+}(1540)$ mass is known, a recent calculation using a model by Lipkin (see hep-ph/040119) indicates that the Pentaquark state which includes both strange and charm quarks $\Sigma_c^0 = P_{\bar{c}s}^0 = \bar{c}sudd$ should be short lived (with a width of 20 MeV) and at a mass of 3.165 GeV (i.e. above threshold for strong decays) (Since this same model also predicts that the state found at 1540 should be at 1592, we think that the Σ_c^0 may be about 3123 Mev). In addition, the same model predicts that there should be also charm Pentaquark without strangeness at a mass of 2990 MeV.

On the other hand Stewart, Wessling and Wise (hep-ph/0402076) assert that although the $\Theta_{\bar{s}}^{+}(1540)$ resonance is above threshold and wide, the situation is much different when a charm quark is in the picture. This paper claims that , E791 did a blind analysis in the wrong mass region (2800). Using the mass of the $\Theta_{\bar{s}}^{+}(1540)$ they predict that the $\Sigma_c^0 = P_{\bar{c}s}^0 = \bar{c}sudd$ state should be long lived and stable with a mass of 2580 MeV. In their model, only state which have BOTH charm and strangeness are stable. Therefore, a charm Pentaquark without strangeness is not stable in this particular model.

In contrast to the stable model, a lattice QCD calculation by Sasaki (hep-lat/0310014) gets a mass of 1760 for the $\Theta_{\bar{s}}^{+}(1540)$ if it is negative parity and 2620 if it is positive parity. The same lattice calculation for the $\Theta_{\bar{c}}^{0}$ (negative parity) yields a mass of 3578. More refined lattice calculations which first agree with the measurement of 1540 are needed.

To date, we have not found any published searches (in journals or conference proceedings) for above threshold narrow short lived (20 MeV width) Pentaquark states in the charm, charm-strange and bottom sectors. We have been told that some there were some low statistics unpublished searches by experiments E400 [10] and SELEX [11] at Fermilab. However, SELEX [11] has reported some states that could be interpreted as a Pentaquark. First they see two narrow(++) states and one wider (++) state in the $\Lambda_c K^- \pi^+ \pi^+$ which have the quantum numbers of a $\bar{d}cusu(++)$ Pentaquark. The charge 2 baryon states that were observed by Selex are at 3460 MeV and 3541 MeV (narrow) and at 3780 MeV (with a width of 26 MeV). If not identified as exotics, then these states may be related to $ccu++$ and $ccu*++$ baryons. Secondly, they also see two narrow states states in the $\Lambda_c K^- \pi^+$ which have the quantum numbers of a $\bar{d}cdsu(+)$ Pentaquark. The charge 1 baryon states that were observed by Selex are at 3443 MeV and 3520 MeV. If not identified as exotics, then these states may be related to $ccd+$ and $ccd*+$ baryons.

Experimental Evidence - Wine and Cheese, May, 2002

Selex reported 3 significant high-mass peaks

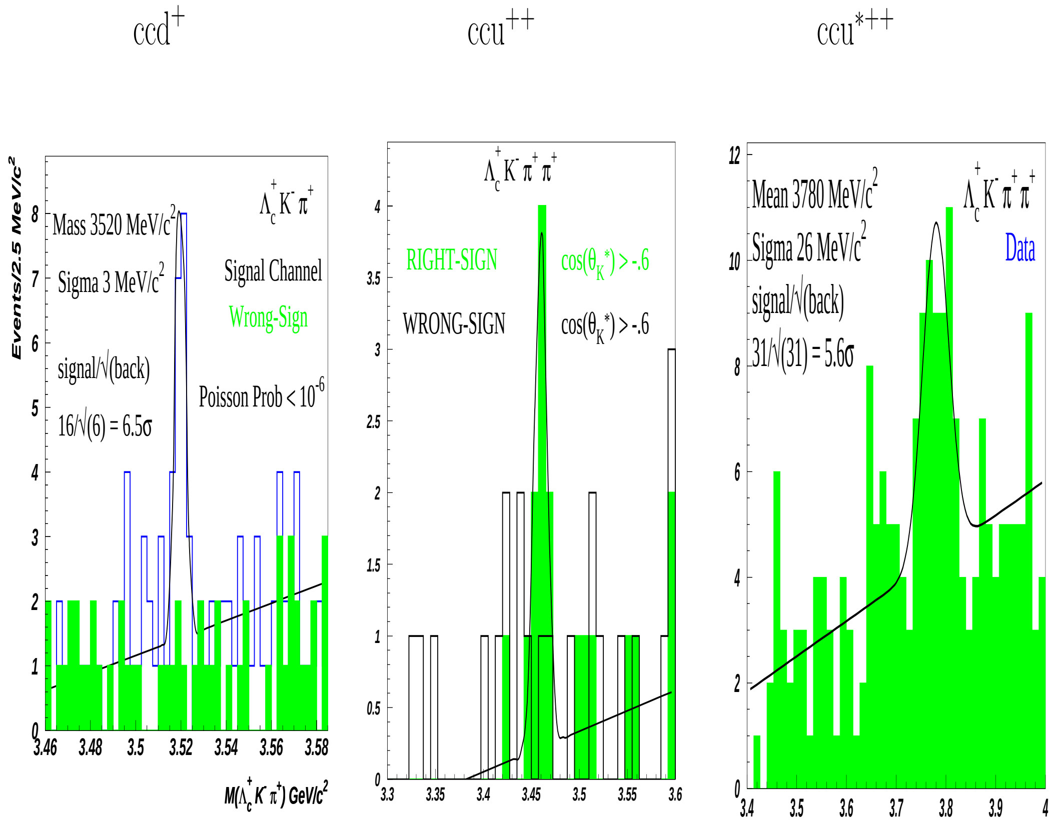


FIG. 9. Select 2002 Data and 2003 data (next figure): SELEX has reported some states that could be interpreted as a Pentaquark. First they see two narrow(++) states and one wider (++) state in the $\Lambda_c K^- \pi^+ \pi^+$ which have the quantum numbers of a $\overline{d}cusu(++)$ Pentaquark. The charge 2 baryon states that were observed by Selex are at 3460 MeV and 3541 MeV (narrow) and at 3780 MeV (with a width of 26 MeV). If not identified as exotics, then these states may be related to $ccu++$ and $ccu*++$ baryons. Secondly, they also see two narrow states states in the $\Lambda_c K^- \pi^+$ which have the quantum numbers of a $\overline{d}cdsu(+)$ Pentaquark. The charge 1 baryon states that were observed by Selex are at 3443 MeV and 3520 MeV. If not identified as exotics, then these states may be related to $ccd+$ and $ccd*+$ baryons.

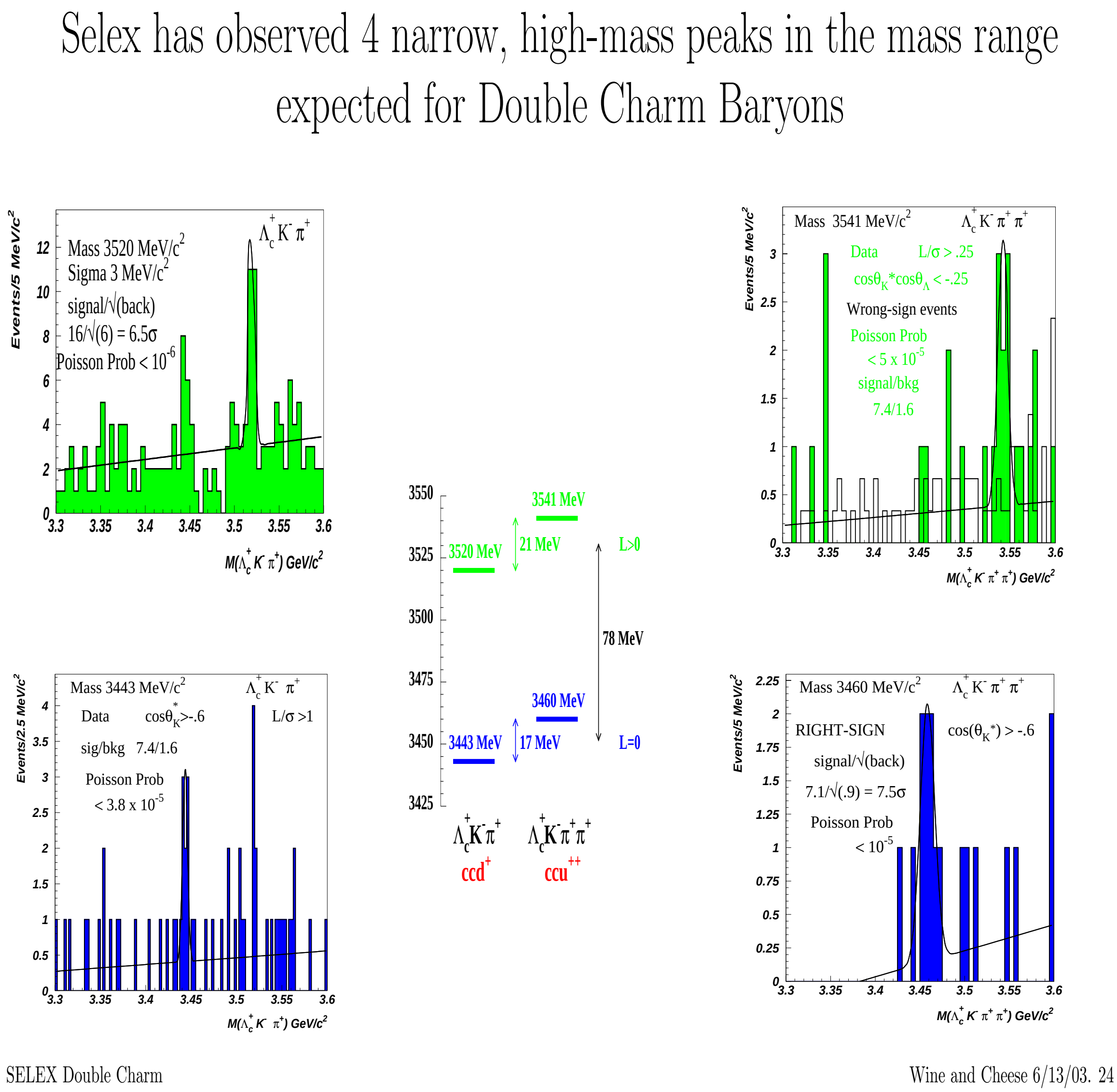


FIG. 10. Selex 2003 data (and 2002 data previous figure): SELEX [11] has reported some states that could be interpreted as a Pentaquark. First they see two narrow(++) states and one wider (++) state in the $\Lambda_c K^- \pi^+ \pi^+$ which have the quantum numbers of a $\overline{d}cusu(++)$ Pentaquark. The charge 2 baryon states that were observed by Selex are at 3460 MeV and 3541 MeV (narrow) and at 3780 MeV (with a width of 26 MeV). If not identified as exotics, then these states may be related to $ccu++$ and $ccu*++$ baryons. Secondly, they also see two narrow states states in the $\Lambda_c K^- \pi^+$ which have the quantum numbers of a $\overline{d}cdsu(+)$ Pentaquark. The charge 1 baryon states that were observed by Selex are at 3443 MeV and 3520 MeV. If not identified as exotics, then these states may be related to $ccd+$ and $ccd*+$ baryons.

Note that it is also expected (e.g. in the model of Stewart et al.) that bottom Pentaquark states should decay into charm Pentaquark states. Therefore, if by accident, the bottom pentaquarks are long lived and decay to short lived charm Pentaquarks, then one would have a state with a width of 20 MeV, but with a displaced vertex. Therefore, a-priori we need to look at all these options. OPbservation of one of these possible new states will greatly help narrow down the range of possible options.

Therefore, we take the approach that we do not know where Charm Petaquark states should exit. Table 1 below shows the range of predictions in various models. Therefore, to do a search one needs to look in a wide mass range, in different decay modes, and look for both short lived and long lived states. As a check on various biases, we make sure that in the sample, we optimize cuts on states which are known to exit. As a furtrher, if any state is observed we then search for it in different decay modes.

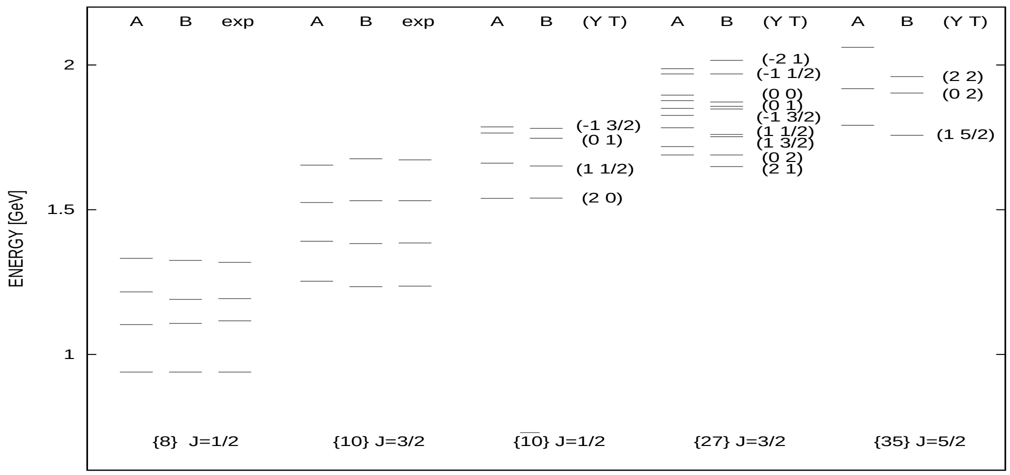


Figure 4: Lowest rotational states in the $SU(3)$ soliton model for fits A and B. The experimental masses of the {8} and {10} baryons are depicted for comparison. Not all states of the {35} are shown.

FIG. 11. Figure from rom hep/0304058 Walliser and Kopeliovich - Soliton states for lowest level strange pentaquarks for two different models assumptions. We use model B in our estimates of state mass splittigs.

Table 2: Rotational states of non-minimal multiplets with exotic quantum numbers below 2 GeV including all members of $\{\overline{10}\}$ and $\{27\}$. The experimental Z datum enters the fits. The lowest exotic $Y = \pm 3$ baryon states are also included.

		J	Y	T	decay modes	estimated energy [GeV] A	B
Z	$\{\overline{10}\}$	$\frac{1}{2}$	2	0	KN	1.54	1.54
Z^*	$\{27\}$	$\frac{3}{2}$	2	1	KN	1.69	1.65
	$\{27\}$	$\frac{3}{2}$	0	2	$\pi\Sigma$, $\pi\Sigma^*$, $\pi\pi\Lambda$	1.72	1.69
X	$\{35\}$	$\frac{5}{2}$	1	$\frac{5}{2}$	$\pi\Delta$, $\pi\pi N$	1.79	1.76
	$\{\overline{10}\}$	$\frac{1}{2}$	-1	$\frac{3}{2}$	$\pi\Xi$, $\pi\Xi^*$, $\bar{K}\Sigma$	1.79	1.78
	$\{27\}$	$\frac{3}{2}$	-1	$\frac{3}{2}$	$\pi\Xi$, $\pi\Xi^*$, $\bar{K}\Sigma$	1.85	1.85
	$\{35\}$	$\frac{5}{2}$	0	2	$\pi\Sigma$, $\pi\Sigma^*$	1.92	1.90
	$\{35\}$	$\frac{5}{2}$	2	2	$K\Delta$, $K\pi N$	2.06	1.96
	$\{27\}$	$\frac{3}{2}$	-2	1	$\pi\Omega$, $\bar{K}\Xi$, $\bar{K}\Xi^*$	1.99	2.02
	$\{35\}$	$\frac{5}{2}$	-3	$\frac{1}{2}$	$\bar{K}\Omega$, $\bar{K}\bar{K}\Xi$	2.31	2.36
Z^{**}	$\{\overline{35}\}$	$\frac{3}{2}$	3	$\frac{1}{2}$	KKN, $KK\Delta$	2.41	2.38

FIG. 12. Table from hep/0304058 Walliser and Kopeliovich - Soliton states for lowest level strange pentaquarks for two different models assumptions. We use model B in our estimates of state mass splittigs.

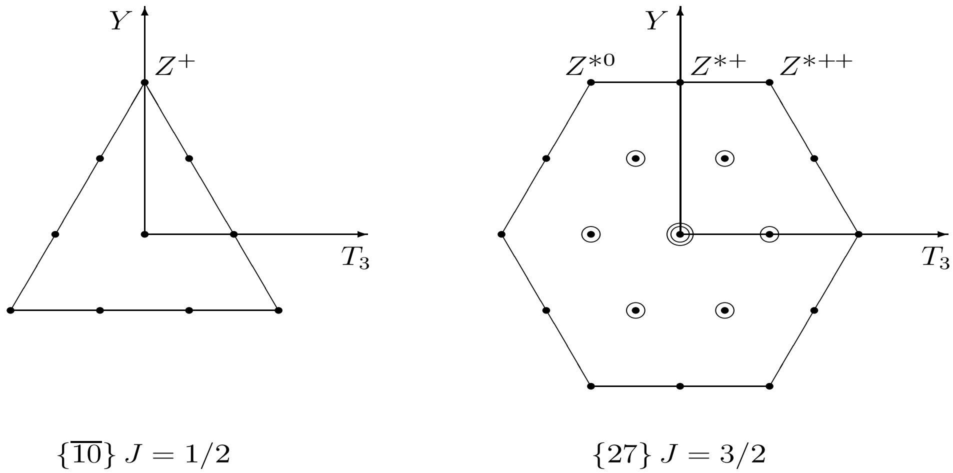


Figure 2: The $T_3 - Y$ diagrams for the baryon multiplets $\{\overline{10}\}$ and $\{27\}$ which include the lowest $S = +1$ states.

FIG. 13. Figure from hep/0304058 Walliser and Kopeliovich - Soliton multiplets for lowest level strange pentaquarks.

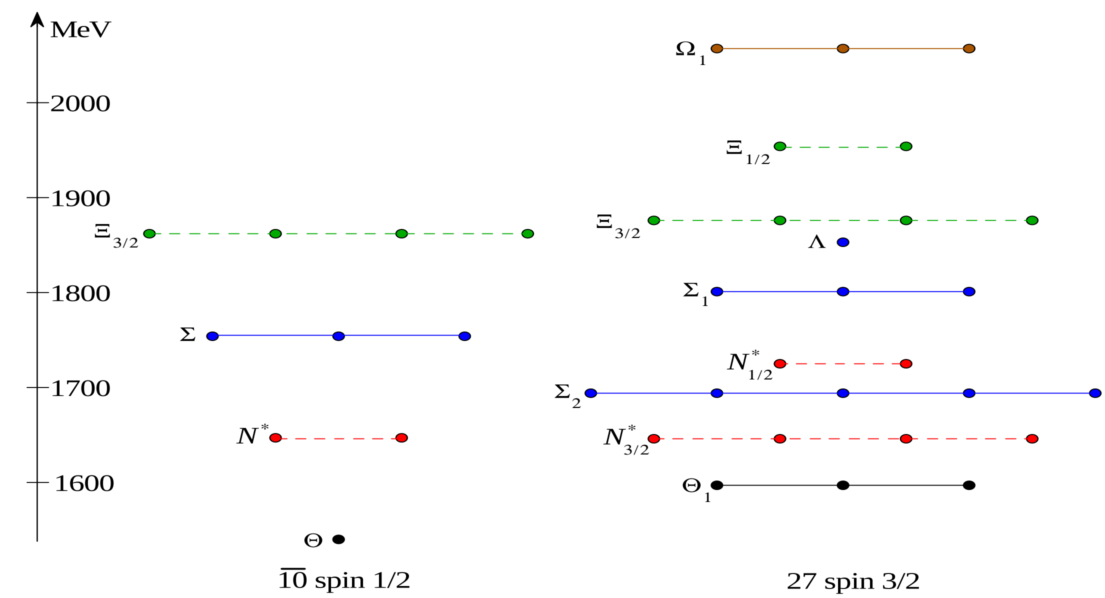
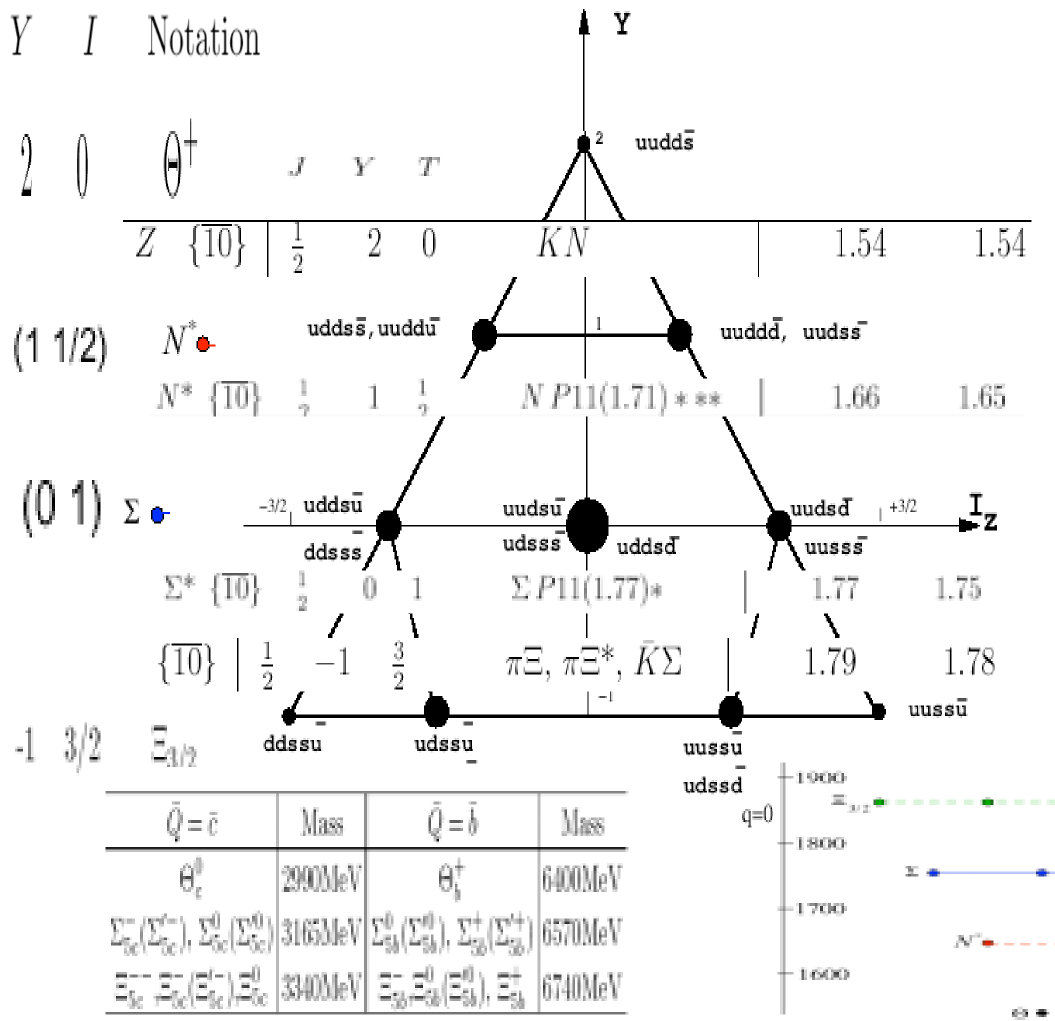


Fig. 4. *The spectra of exotic baryons found at first order in SU(3) symmetry breaking, using parameters fitted from the* Θ^+ *and* $\Xi_{\overline{10}}$ *masses. The* $(\overline{10}, \frac{1}{2}^+)$ *spectrum is shown on the left, and the* $(27, \frac{3}{2}^+)$ *spectrum on the right.*

FIG. 14. Mass levels from the soliton model of Ellis. for lowest level strange pentaquarks. It is similar to model B of hep/0304058 Walliser and Kopeliovich, except that Ellis constrains the double strange state at 1750 Mev at the Walliser model to be at 1860 MeV, under the assumption that the NA49 state is a pentaquark



$\bar{Q}=\bar{c}$	Mass	$\bar{Q}=\bar{b}$	Mass
Θ_c^0	2900MeV	Θ_b^+	6400MeV
$\Sigma_{5c}^-(\Sigma_{5c}'^-)$, $\Sigma_{5c}^0(\Sigma_{5c}'^0)$	3165MeV	$\Sigma_{5b}^0(\Sigma_{5b}'^0)$, $\Sigma_{5b}^+(\Sigma_{5b}'^+)$	6570MeV
Ξ_{5c}^{--}, $\Xi_{5c}^-(\Xi_{5c}'^-)$, Ξ_{5c}^0	3340MeV	Ξ_{5b}^-, $\Xi_{5b}^0(\Xi_{5b}'^0)$, Ξ_{5b}^+	6740MeV

FIG. 15. Mass values of the lowest lying pentaquark multiplet with strange quarks within the soliton model. We use the second number which is model B of hep/0304058 Walliser and Kopeliovich. The model of Ellis gets similar results except that Ellis constrains the double strange state at 1750 Mev at the Walliser model to be at 1860 MeV, under the assumption that the NA49 state is a pentaquark

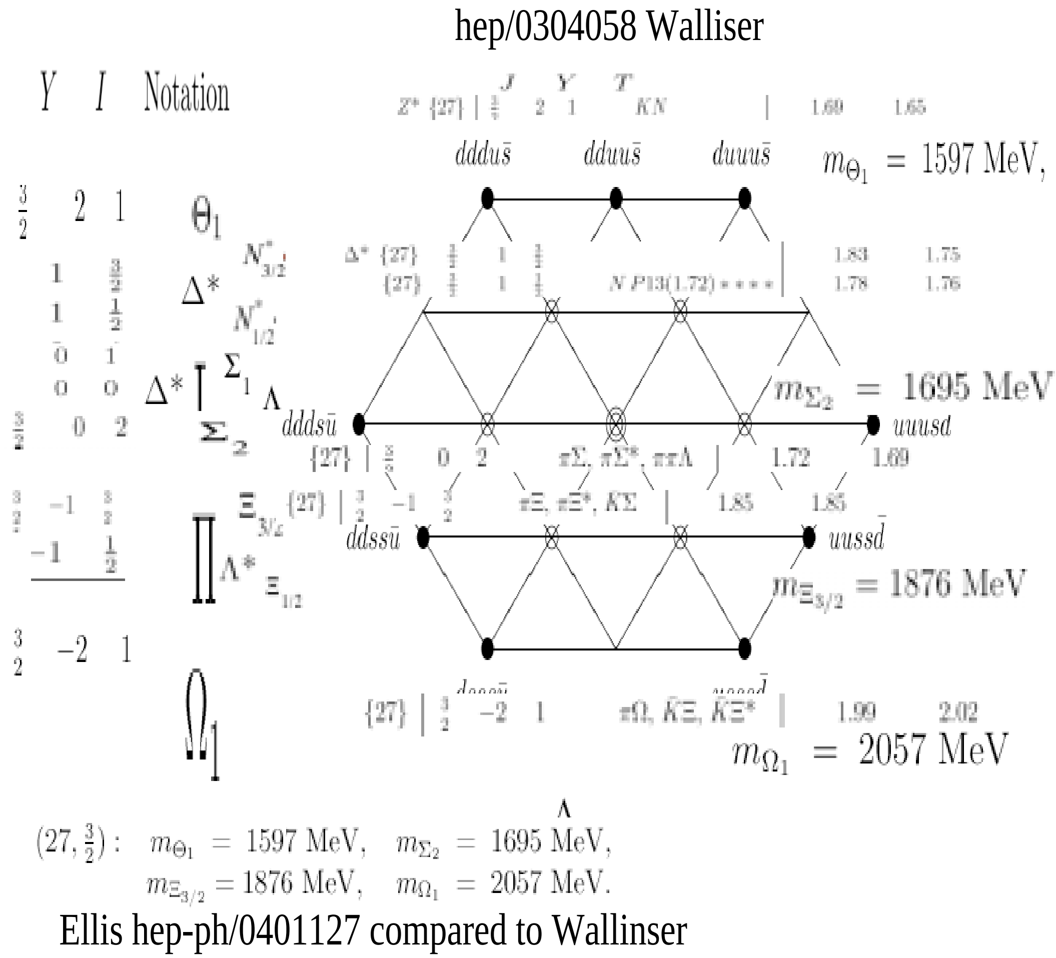


FIG. 16. Mass value of the second lowest lying pentaquark multiplet with strange quarks within the soliton model. We use the second number which is model B of hep/0304058 Walliser and Kopeliovich and compare it to the values from the soliton model of Ellis

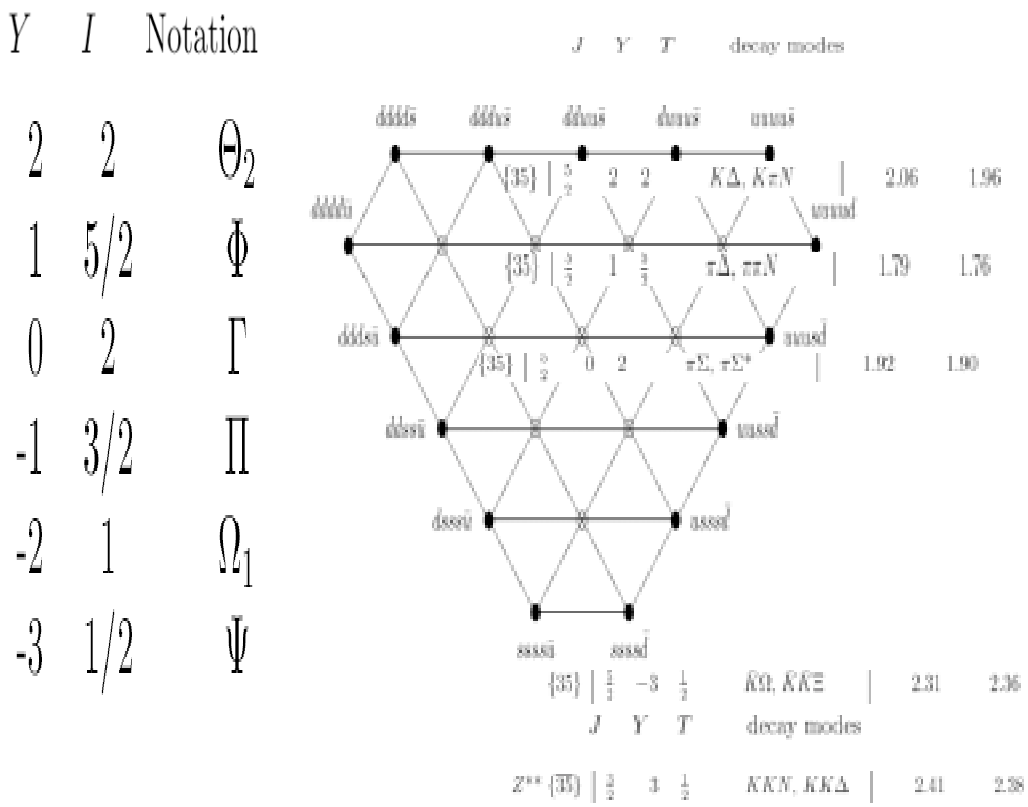


FIG. 17. Mass value of the third lowest lying pentaquark multiplet with strange quarks within the soliton model. We use the second number which is model B of hep/0304058 Walliser and Kopeliovich

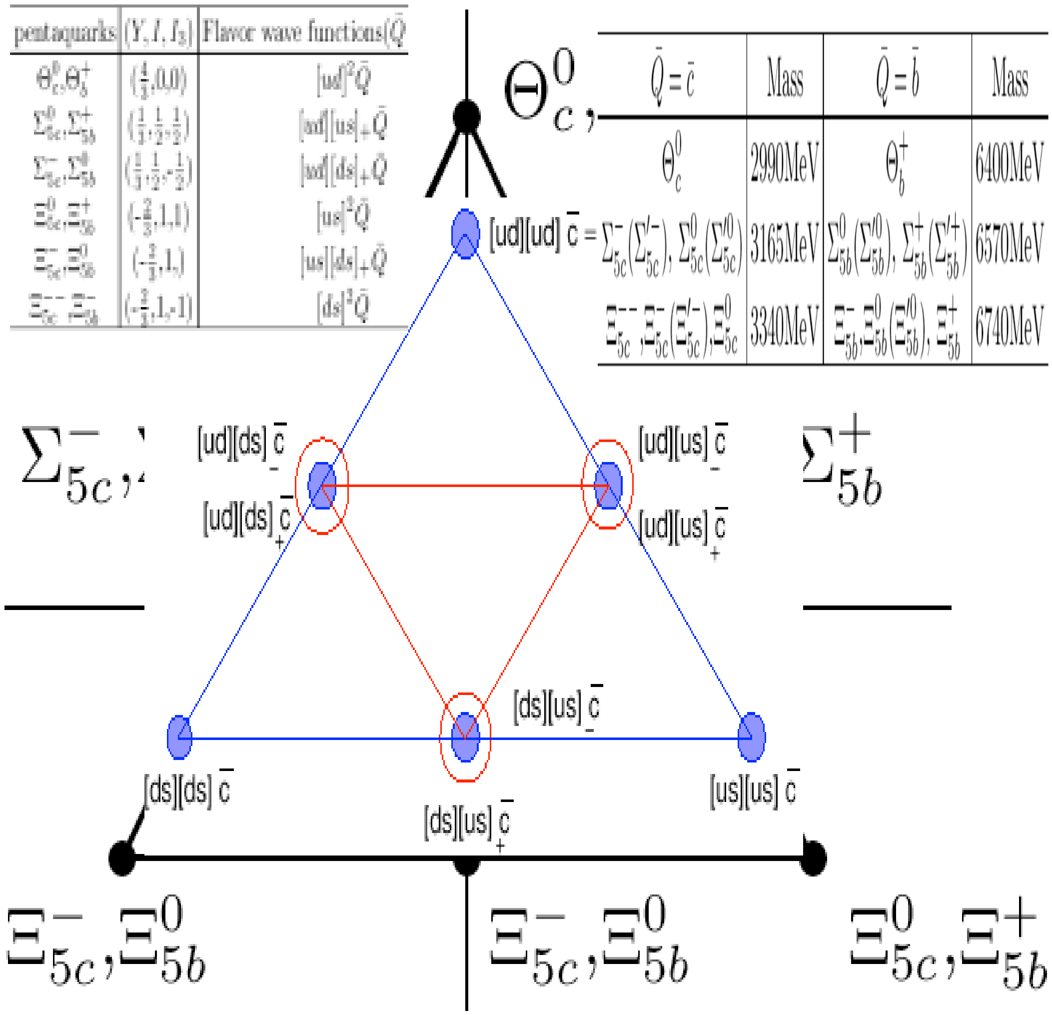


FIG. 18. Predictions of the model of Lipkin for the lowest lying multiplet of pentaquarks which include one heavy (charm or bottom) antiquark.

					uudd-sbar		second multipl	3rd multiplet	
					1540		1597	1960	
			cbar-sbar	1410	4810	dbar-sbar			
				2950	**6350**	*2950*	*3007*	*3370*	*charm*
				uudd-cbar	**uudd-bbar**	*6350*	*6407*	*6770*	*bottom*
			uudd-ubar				uudd-dbar		
			udds-sbar				**uuds-sbar**		
			1650				**1650**		
	cbar-ubar	1475	4880			1475	4880	bbar-ubar	
		3125	**6530**			**3125**	**6530**		
		udds-cbar	**udds-bbar**			**uuds-cbar**	**uuds-bbar**		
					uuds-dbar				
			udds-ubar		**uuds-ubar**		**uuds-dbar**	**2nd multip**	**3rd multiplet**
			ddss-sbar		udss-sbar		udss-sbar		
			1750		**1750**		**1750**	**1695**	**1900**
	cbar-ubar	1375	4780	1375	4780	1375	4780	bbar-ubar	
		3125	**6530**	**3125**	**6530**	**3125**	**6530**	3070	3275
		udds-cbar	**udss-bbar**	**uuds-cbar**	**uuds-bbar**	**uuds-cbar**	**uuds-bbar**	6475	6680
							3125	*3070*	*3275*
							6530	*6475*	*6680*
			udss-ubar			uuss-ubar			
	ddss-ubar		ddss-dbar			udss-dbar		uuss-dbar	
	1860		**1860**			**1860**		**1860**	
1440	4840	1440	4840		1440	4840	1440	4840	bbar-dbar
3300	**6700**	**3300**	**6700**		**3300**	**6700**	**3300**	**6700**	
ddss-cbar	**ddss-bbar**	**udss-cbar**	**udss-bbar**	**+**	**udss-cbar**	**udss-bbar**	**uuss-cbar**	**uuss-bbar**	
				Xsi	*strange*	*1860*	*1876*	*2060*	
					charm	*3300*	*3316*	*3500*	
					bottom	*6700*	*6716*	*6900*	

FIG. 19. Combining the predictions of the model of Lipkin for the lowest lying multiplet of pentaquarks which include one heavy (charm or bottom) antiquark, with the spectrum of the strange-antiquark pentaquarks to get a mass estimate of higher level exitation of pentaquark states which contain at least one heavy antiquark.

IV. MULTIPLE STATES ARE EXPECTED

We now show that multiple pentaquarks are expected for every quark combination. Therefore, even if there are stable long lived pentaquarks, it is expected that there are higher level excitation, and there can be some which are very close to each other in mass, and others which are not.

Fig. 11 and Fig. 12 shows the predicted states for the lowet lying strange Pentaquark states within the soliton model of Walliser and Kopeliovich (hep/0304058) for the first three multiplets. As shown in Fig. 13 the states are similar to those of the constituent quark model. Fig. 14 shows how the masses change within the soliton model of Ellis (hep-ph/0401127) for which the $\Xi_{3/2}$ is constrained to be at a mass of 1860 Mev (which assumes that the state published by NA49, but not confirmed by CDF is a pentaquark). Fig. 15 shows the masses within the soliton model for the first multiplet. Figure Fig. 16 shows the masses for the second multiplet and Fig. 17 shows the masses for the third multiplet.

Fig. 18 show the lowest lying multiplet within the model of Lipkin for Pentaquarks with charm and bottom quarks. Figure Fig. 19 shows a spreadsheet which assumes that the level spacing for the Pentaquarks in the strange quark multiplets are similar to the level spacing in the charm and bottom sector. We also assume that the $\Theta_{s,0,1,2}$ Pentaquarks occur at 1540, 1597 (spin 3/2 second multiplet) and 1960 MeV. We assume that the lowest level Θ_c and Θ_b Pentaquarks are at 2950 and 6350 MeV, respectively (we lower all values by 50 MeV from Lipkins predictions since his model predicts 1590 instead of 1540 for the Θ_s). Similarly, we assume that the Σ_{5c} and Σ_{5b} Pentaquarks are at 3125 and 6530 MeV, respectively, and the Ξ_{5c} and Ξ_{5b} are at 3310 and 6700, respectively.

Using the above information one expects $\Theta_{c,0,1,2}$ Pentaquarks at 2950, 3007 and 3370 MeV and $\Theta_{b,0,1,2}$ states at 6350, 6407 and 6770 MeV. Similarly if the Σ_{5s} states are at 1750, 1695 and 1900 MeV in the strange sector, then one expects the charm-strange $\Sigma_{5c,0,1,2}$ pentaquarks to be at 3125, 3070 and 3275 MeV and the bottom-strange $\Sigma_{5b,0,1,2}$ Pentaquarks to be at 6530, 6475 abd 6680 MeV.

Since all of these multiple states have different spins and parity, one expects to see different peaks at different masses for different decay channels for Pentaquark states which have the same quark composition. The above scenario shows that there could be states which are very close to each other in mass.

V. PROCEDURE

A first look at the following Data Set:

We use the Two Track Trigger with: dataset-hbot1i; stripping-4.8.4; alignment is with ofotl-prd-read 100040 1 good. The run range is 152598168889 with about 162 pb (good runs only).

D_s cuts: Use D_s to $\phi\pi$ decy mode with ϕ to KK. The $K^-\pi^+$ form a trigger pair. We require a KK mass between 1.0 and 1.04 GeV. The transverse momentum of the D_s is required to be greater than 6.0 GeV. The Lxy of the D_s is greater than 500 micron. The DeltaZ0 between the two tracks is required to be less than 5 cm. The $d0_{track}$ is required to be greater than 0.012 cm and less than 0.1 cm. The PT of the offline tracks is required to be greater than 0.5 GeV. the PT(SVT Matched Tracks) is required to be greater than 2.0 GeV. The Chi-squared is less than 30 for the three vertex fit. (later we plan to remove events with a cosine of the angle between the D_s and the Kaon in the Φ rest frame less than 0.4 as done in the D_s Phys. Rev. D article to lower the background, but have not done this yet).

Proton (and Antiproton) selection: The PT of the proton is required to be greater than 3 GeV. The SVX phi side hits is required to be greater than 2. The COT (axial and stereo hits) are required to be more than 25. The PId (TOF and dEdX) is require to be Proton versus pion. The Cos($\theta*$) is required to be less than 0.9 (where $\theta*$ is the angle between the momentum of the Pentaquarks and the Proton track at the Pentaquark rest frame. The $P_{balance}$ = (p(Ds)-p(proton)/p(Ds+proton) is required to be less than 0.8.

In parallel we are re-processing the first 200 pb-1 of data to do the following: (a) Side band subtractions, (b) Additional Ds decay mode to (K K+*(892). (c) reduce PT cuts on D_s and Proton to increase statistics. (d) Remove events with a cosine of the angle between the D_s and the Kaon in the Φ rest frame less than 0.4 as done in the D_s Phys. Rev. D article. (e) Look the other Pentaquark channels (e.g. in the Proton D^+, Proton D^-,Proton D^0).

In addition, we are also doing the 4-quark exotic search described above (which is also to check on our efficiency by making sure that we observe the known decays of $D*$ and neutral B mesons. We look for exotic four-quark states with charm and strangeness in the channels $meson+$ plus D_s^- (charge 0) and $meson-0$ plus D_s^+ (charge 2).

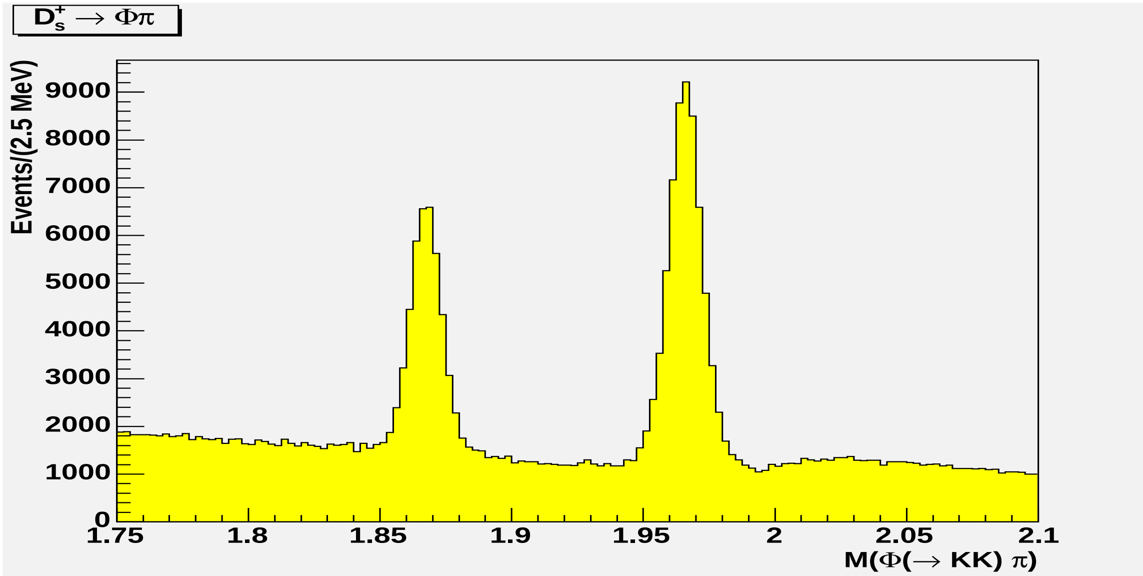


FIG. 20. $\phi\pi$ mass plot showing both D_s^+ and D^+ (Cabbibo suppressed mass peaks.
)

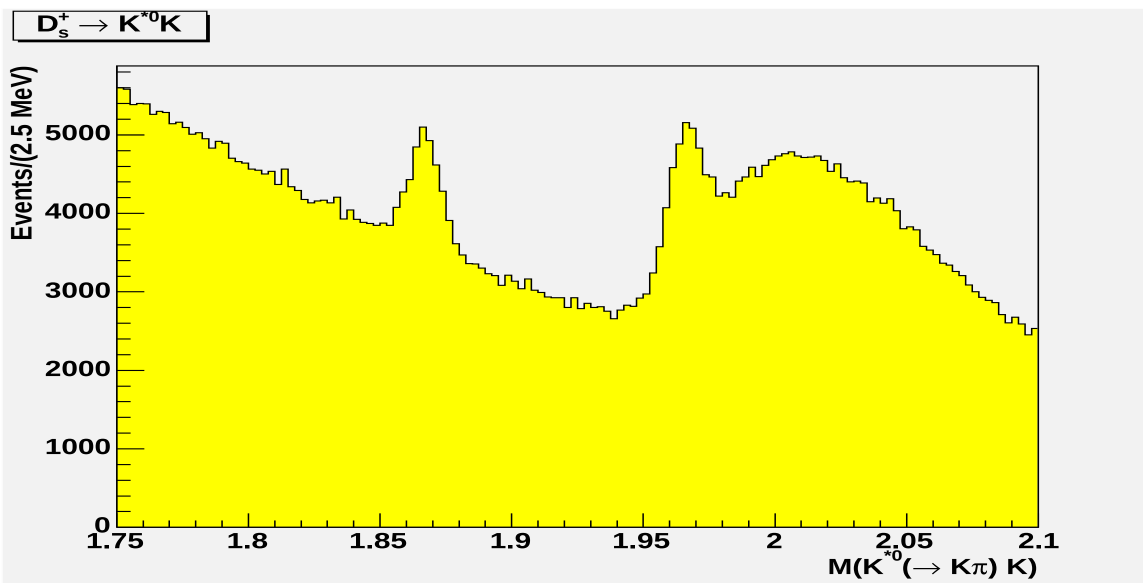


FIG. 21. KK^* mass plot showing both D_s^+ and D^+ (Cabbibo suppressed mass peaks.
)

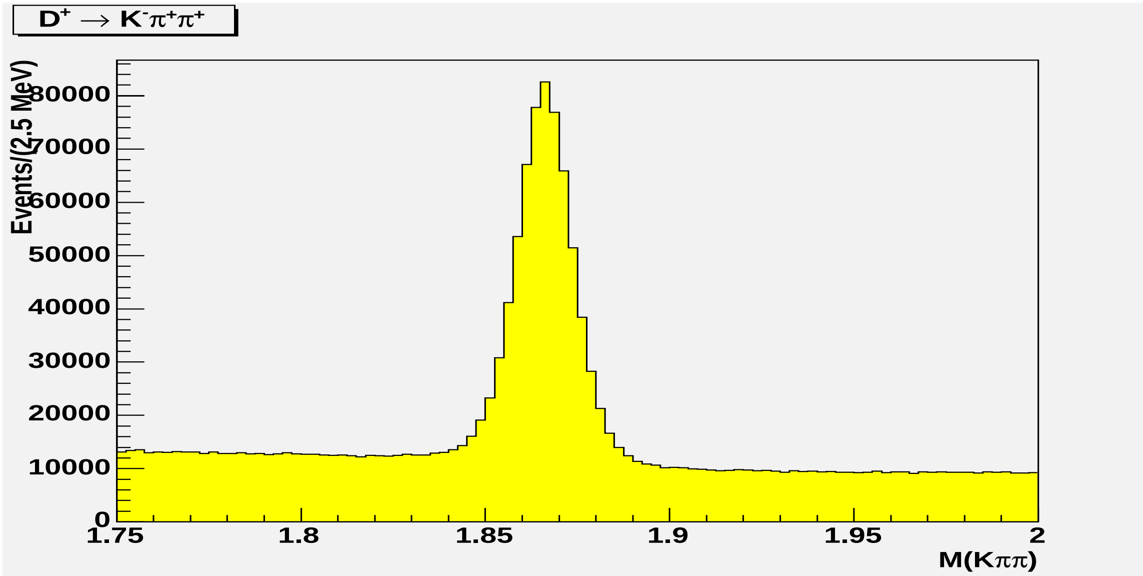


FIG. 22. $K\pi\pi$ mass plot showing the D^+ peak

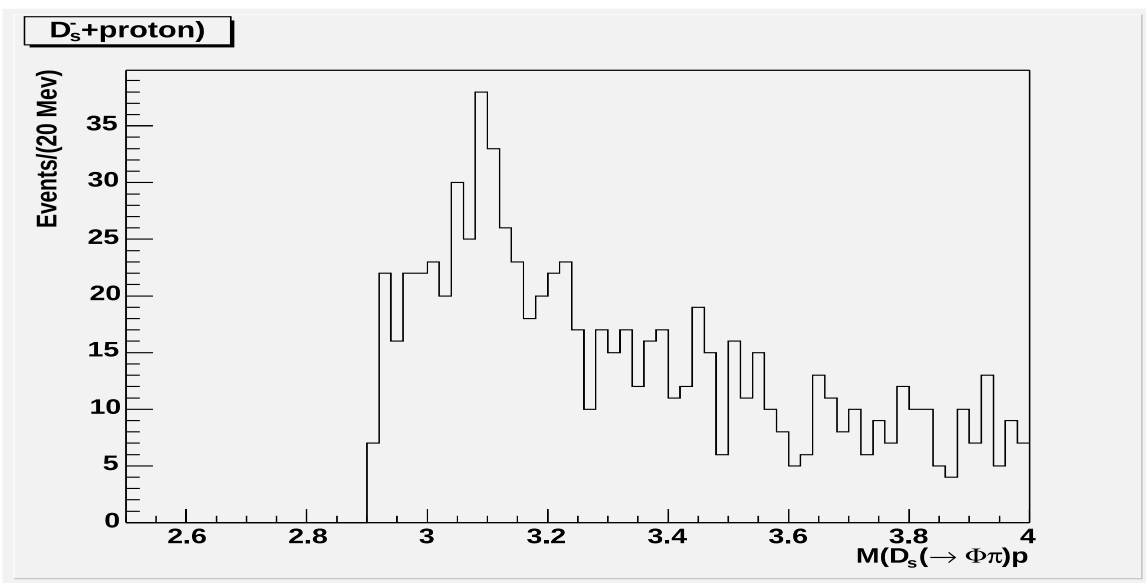


FIG. 23. Short Lived (Lxy less than 500 micron) Charge 0 Baryon Pentaquark Search: *proton* plus D_s^- (and *antiproton* plus D_s^+) mass plot using the D_s to $\phi\pi$ decay mode only. Here we are looking for a $P^0_{\bar{c}s} = \bar{c}sudd$ Pentaquark at an expected mass of 3100 MeV. There is an indication of a peak around this mass value which we are investigating. We are currently also running the $KK*$ spectrum as an independent sample.

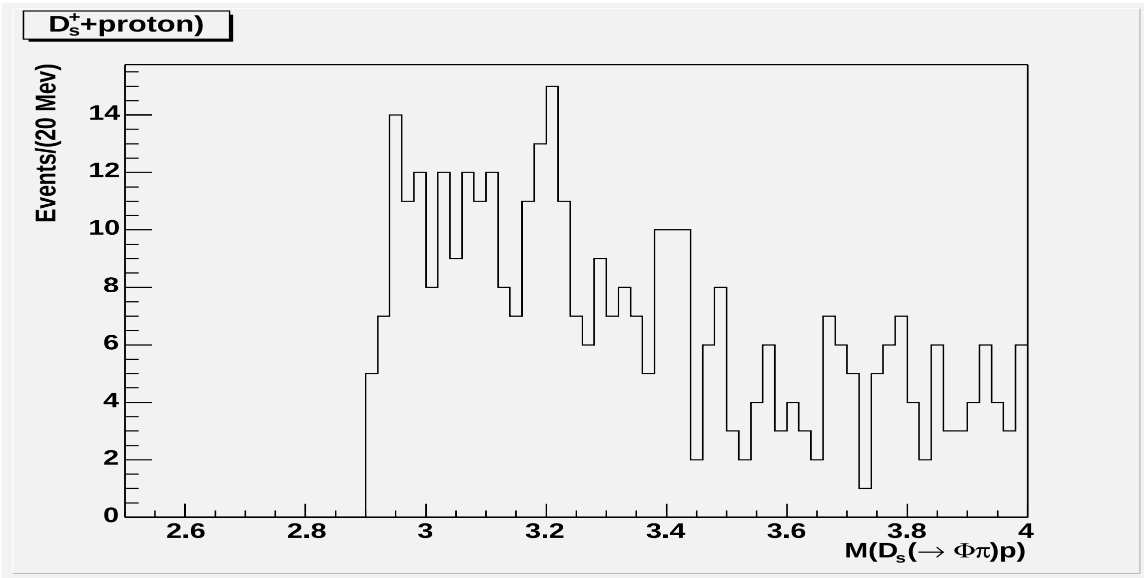


FIG. 24. Short Lived (Lxy less than 500 micron) Charge +2 and -2 Baryon Pentaquark Search: *proton* plus D_s^+ (and *antiproton* plus D_s^-) mass plot using the D_s to $\phi\pi$ decay mode only. Here we are looking for a $P_{\bar{s}c}^{++} = \bar{s}cudd$ Pentaquark at an expected mass of 3220. There is an indication of a peak around this mass value which we are investigating. We are currently also running the $KK*$ spectrum as an independent sample.

VI. INITIAL RESULTS AND FUTURE PLANS

We form the $\phi\pi$ invariant mass and the invariant mass plots that show the D_s peak and the Cabbibo suppressed D^+ peak (as shown in Fig. 20). We are currently also running the $KK*$ spectrum as an independent sample.

We look for both short lived (Lxy less than 500 microns) and long lived (Lxy greater than 500 microns) particles.

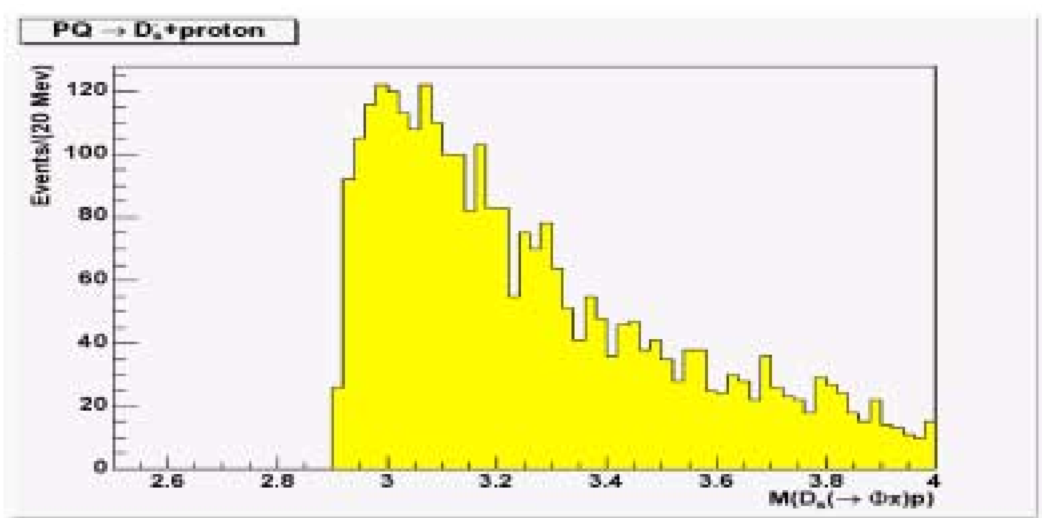


FIG. 25. Long Lived (Lxy greater than 500 micron) Charge 0 Baryon Pentaquark Search: *proton* plus D_s^- (and *antiproton* plus D_s^+) mass plot using the D_s to $\phi\pi$ decay mode only.

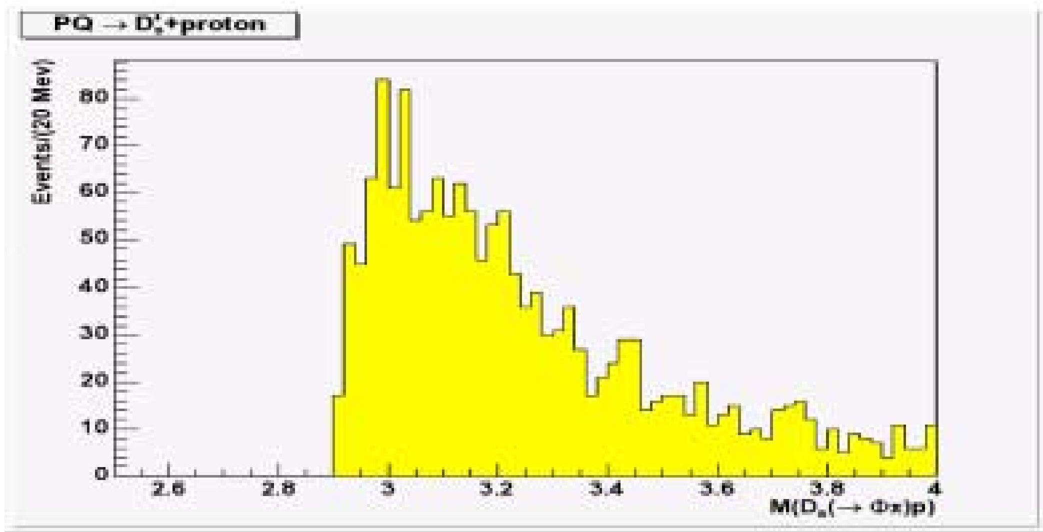


FIG. 26. Long Lived (Lxy less than 500 micron) Charge +2 and -2 Baryon Pentaquark Search: *proton* plus D_s^+ (and *antiproton* plus D_s^-) mass plot using the D_s to $\phi\pi$ decay mode only.

We now define the D_s mass peak as with a width of D we also define left and right side bands with the same width D. We plan to use side bands for background subtraction (we will leave a gap D between the side bands and the peak to make sure that we do not include any D_s mesons in the side bands. We also do the same for the Cabbibo suppressed D+ peak (and also for a higher sample D+ sample as well).

We form the invariant masses of the D_s with protons, Kaons and pions using particle ID criteria (with both charge 0 and charge 2 combinations) for the central, and left and right side band combinations for both the D_s^+ and D^+. By using the measured masses we can remove the measurement error in the D mass as follows.

Mx (Central) = (Measured mass of D meson and charged track combination) - MDmeson(measured) +MDmeson(PD)

Mx (left) = (Measured mass of D meson and charged track combination) - MDmeson(left) +MDmeson(PD)

Mx (right) = (Measured mass of D meson and charged track combination) - MDmeson(right) +MDmeson(PD)

The distribution of Mx(left) and Mx(right) are compared to make sure that the background distributions are the same. The average is taken and it is used as Mx(Backgroud)

X0 is calculated for (D_s^- *proton* and $D_s^+\overline{p}$ combination) X++ is calculated for (D_s^+ *proton* and $D_s^-\overline{p}$ combination)

And similarly with D_s^- replaced with a D^+, and with the proton replaced with a pion, and with a proton replaced with a Kaon.

The plot for short lived (Lxy less than 500 micron) charge 0 Pentaquark search in the D_s^- *proton* and D_s^+ *pbar* mass combination is shown in Fig. 23. For this figure, we only used the D_s^- and D_s^+ to $\phi\pi$ decay mode. A factor of 2 in statistics is expected when we add the other D_s decay mode. Here we are looking for a Pentaquark at an expected mass of 3100 MeV. There appears to be a hint of a signal in that region. We now plan to see if the same signal is there after side band subtraction, and if it is there in other decay modes of the Ds are included. Fig. 24 shows the same plot for the short lived charge 2 Pentaquarks. Here we are looking for a Pentaquark at an expected mass of 3220.

The following is the total number of events that contribute to the mass distribution. (D_s^- *Pbar* : 188 events (charge -2) D_s^+ *Proton* : 190 events (charge +2) D_s^- *Pbar* : 380 events (charge 0) D_s^- *proton* : 420 events (Charge 0).

Fig. 25 and Fig. 25 show the mass plot for long lived (Lxy greater than 500 microns) Pentaquarks with charge 0 and charge 2, respectively. Since we are looking above threshold, we do not expect to see any long lived pentquark states (except for the possibility that short lived charm pentaquark states could be produced in the decays of stable long lived bottom pentaquark states).

For the π D_s mass spectra we use some of the standard B-group cuts: The Mass of the D_s between 1.9585 and 1.9785 GeV, The Pt of the state we look for above 5 GeV. The Pt of the pion above 0.6 GeV. Chi2(X) less than 20. The mass of the ϕ between 1.016 and 1.023 GeV. We looked at charge zero (right sign) and charge 2 (wrong sign) with (Lxy greater than 700 micron and Lxy less than 700 micron. All these spectra have already been looked at by the B-group, so these are mostly to be used as checks of the analysis.

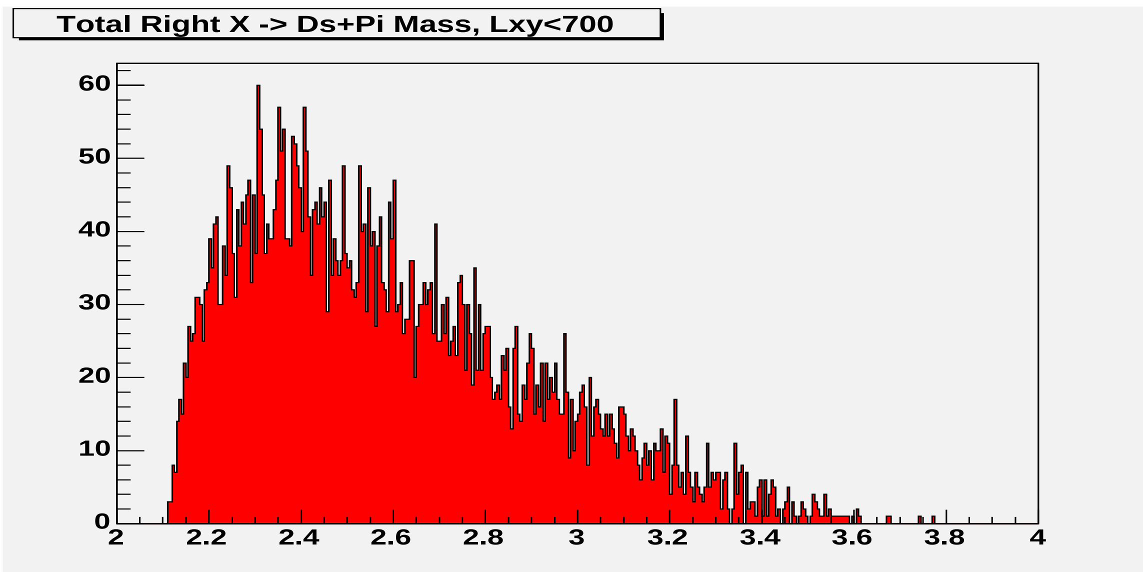


FIG. 27. Di-Mesons charge zero: $\pi^+ D_s^-$ (and $\pi^- D_s^+$) mass plot using the D_s to $\phi\pi$ decay mode only. Here we are looking for a exotic 4-quark state at a mass around 2325 MeV. Here Lxy is less than 700 microns.Unfortunately, we had a cut of a mass of 4 GeV. We expect to see the B0 and Bs peaks at mass of 5300 MeV for normalization.

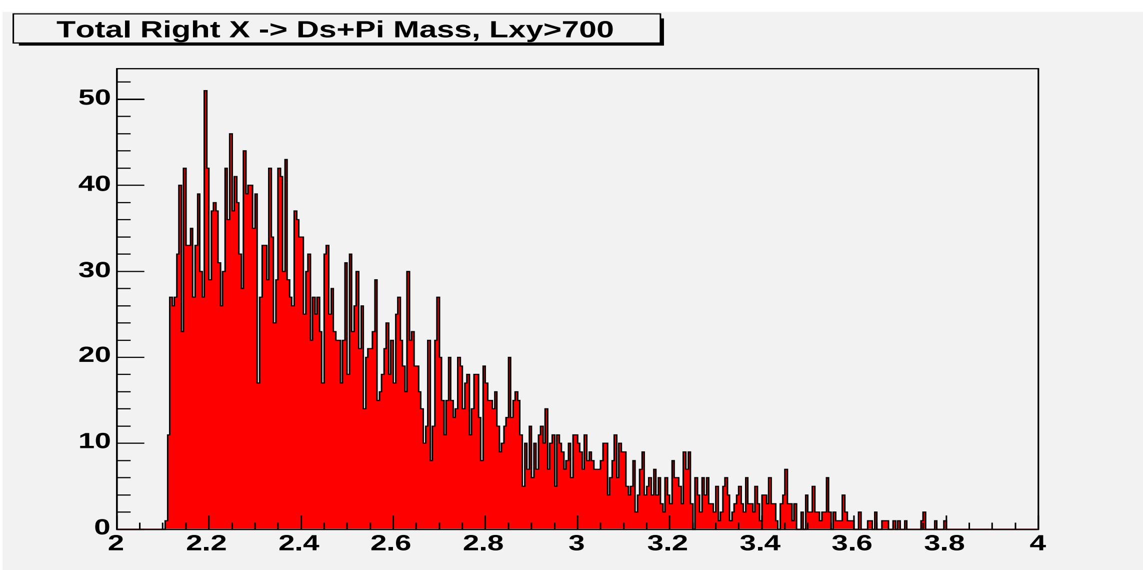


FIG. 28. Di-Mesons charge zero: $\pi^+ D_s^-$ (and $\pi^- D_s^+$) mass plot using the D_s to $\phi\pi$ decay mode only. Here Lxy is greater than 500 microns.

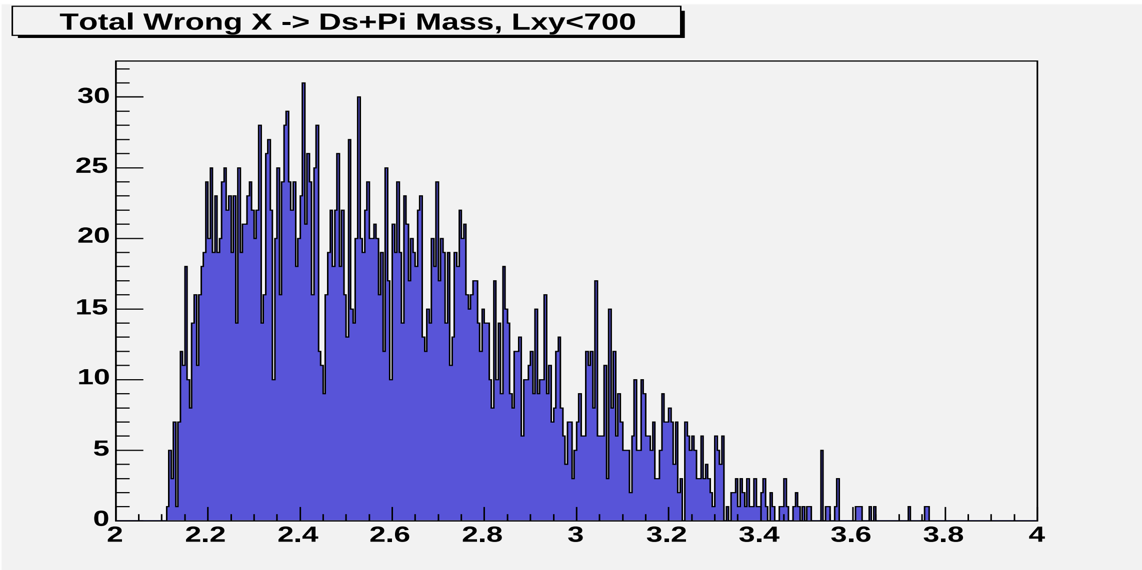


FIG. 29. Di-Mesons charge +2: $\pi^+ D_s^+$ (and $\pi^- D_s^-$) mass plot using the D_s to $\phi\pi$ decay mode only. Here we are looking for a exotic 4-quark state at a mass around 2325 MeV. Here Lxy is less than 700 microns.

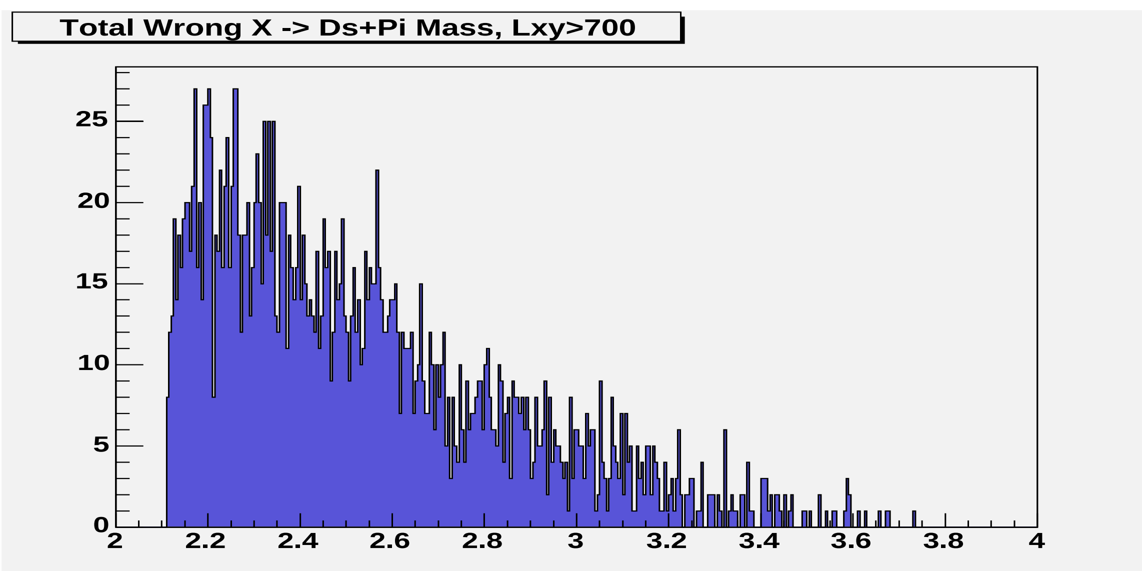


FIG. 30. Di-Mesons charge +2: $\pi^+ D_s^+$ (and $\pi^- D_s^-$) mass plot using the D_s to $\phi\pi$ decay mode only. Here Lxy is greater than 500 microns.

Fig. 27 shows the mass plot for a di-meson search (which includes 4-quark states) in the $D_s^+\pi^-$ and $D_s^-\pi^+$ combination). Here we are looking for a exotic 4 quark state at a mass around 2325 MeV. Unfortunately, the we had a cut of a mass of 4 GeV. We expect to see the B0 and Bs peaks at mass of 5300 MeV for normalization. This plot is for Lxy less than 700 microns. Fig. 28 shows the same plot with Lxy greater than 700 microns.

Fig. 29 and Fig. 30 shows the same plots for charge 2 combination (wrong sign) with Lxy greater than 500 microns.

We are planning to redo all the analysis to extend the mass values up to 7 GeV, include all the Ds decay modes, and include all D+ decay modes, and include the side bands. When these are done, we will check that we see the D0*(2420), the B0 and BS (5300) in the $D^+\pi^-$ and $D^+\pi^-$ channels (as seen in Fig. 31), and the B0 and BS (5300) in the $D_s^+\pi^-$ and $D_s^+\pi^-$ channels (as seen in Fig. 32) (both of these figures are taken from other B group analyses).

We will also look at the charm Pentaquark (charge 0 and +2) candidates which we estimate to have a mass of about 2980 MeV in the *proton* with a D^+ or D^- (and *antiproton* with D^+ or D^-) combinations.

At the moment, we are not able to do the side band subtractions, but this will be done in the next stage.

The following is a summary figures of kinds of figures that we plan to reproduce as part of the checks taken from other B group talks.

(1) Fig. 31 taken from other B group analyses, shows that as a check we expect to see the B0 and BS (5300) in the $D^+\pi^-$ and $D^+\pi^-$ channels.

(2) Fig. 32 taken from other B group analyses shows that as a check we expect to see the B0 and BS (5300) in the $D_s^+\pi^-$ and $D_s^+\pi^-$ channels.

(3) Fig. 33 taken from other B group analyses (Bauer and Paus), shows that we as a check expect to see the $D*$ mesons in the $D^+\pi^-$ and $D^+\pi^-$ channels.

(3) Fig. 34 taken from other B group analyses (Bauer and Paus), shows the mass spectrum for $D_s^+\pi^-$ and $D_s^+\pi^-$ channels. This figure does not show the peak around 2.12 that we see in our spectrum. We plan to follow up on this as the analysis progresses. Their $D_s^+\pi^-$ mass spectrum looks more like our $D_s^+\pi^+$

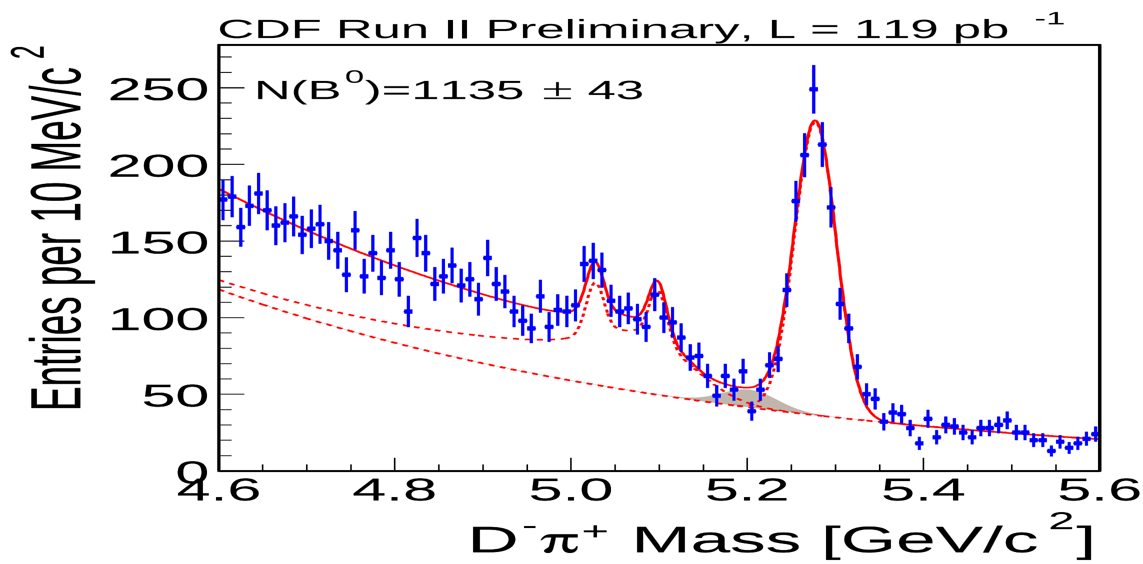


FIG. 31. A Figure that we plan to reproduce as a check, taken from other B group analyses. It shows the B0 and BS (5300) in the $D^+\pi^-$ and $D^+\pi^-$ channels.

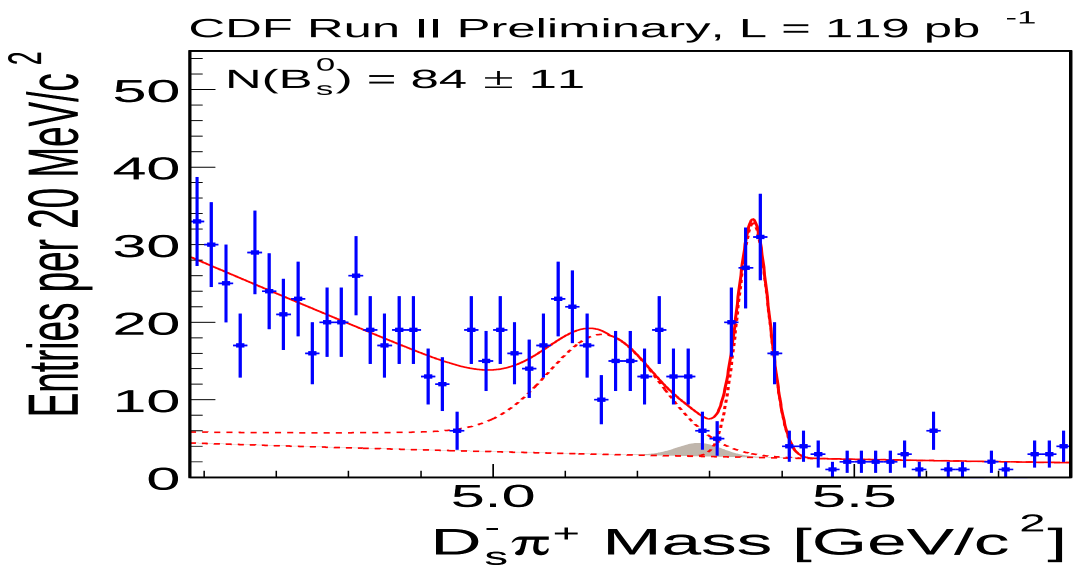


FIG. 32. A Figure that we plan to reproduce as a check, taken from other B group analyses. the B0 and BS (5300) in the $D_s^+\pi^-$ and $D_s^+\pi^-$ channels.

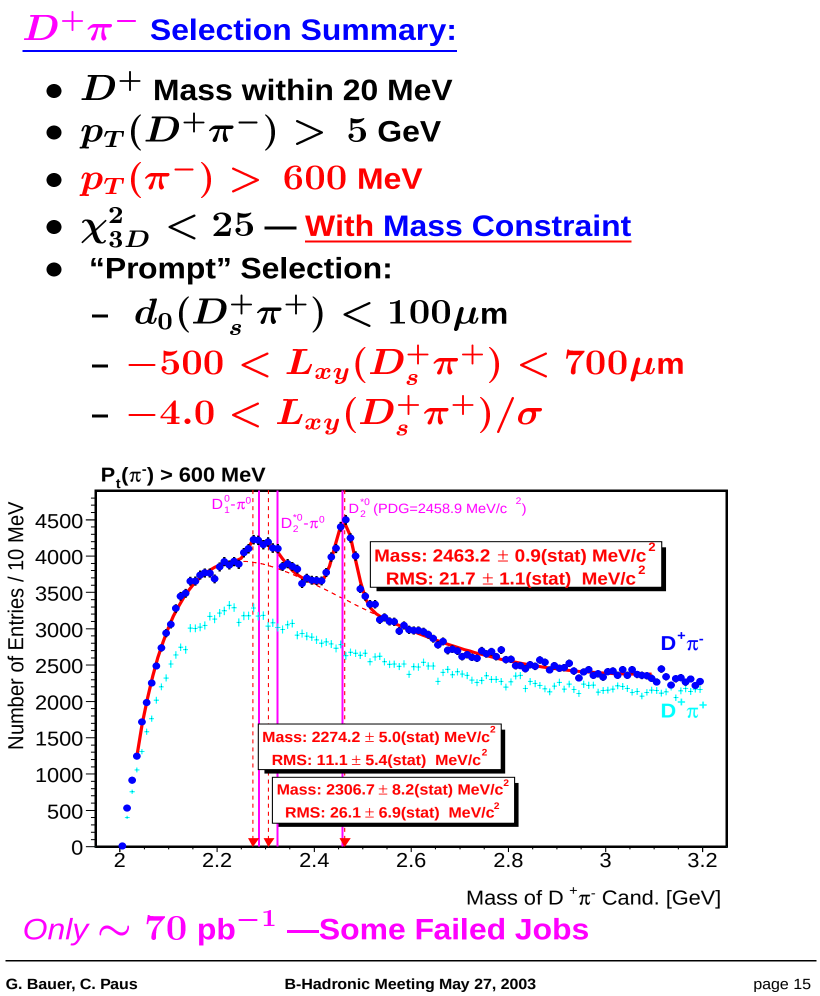


FIG. 33. This figure taken from other B group analyses (Bauer and Paus), shows that we as a check expect to see the $D*$ mesons in the $D^+\pi^-$ and $D^+\pi^-$ channels.

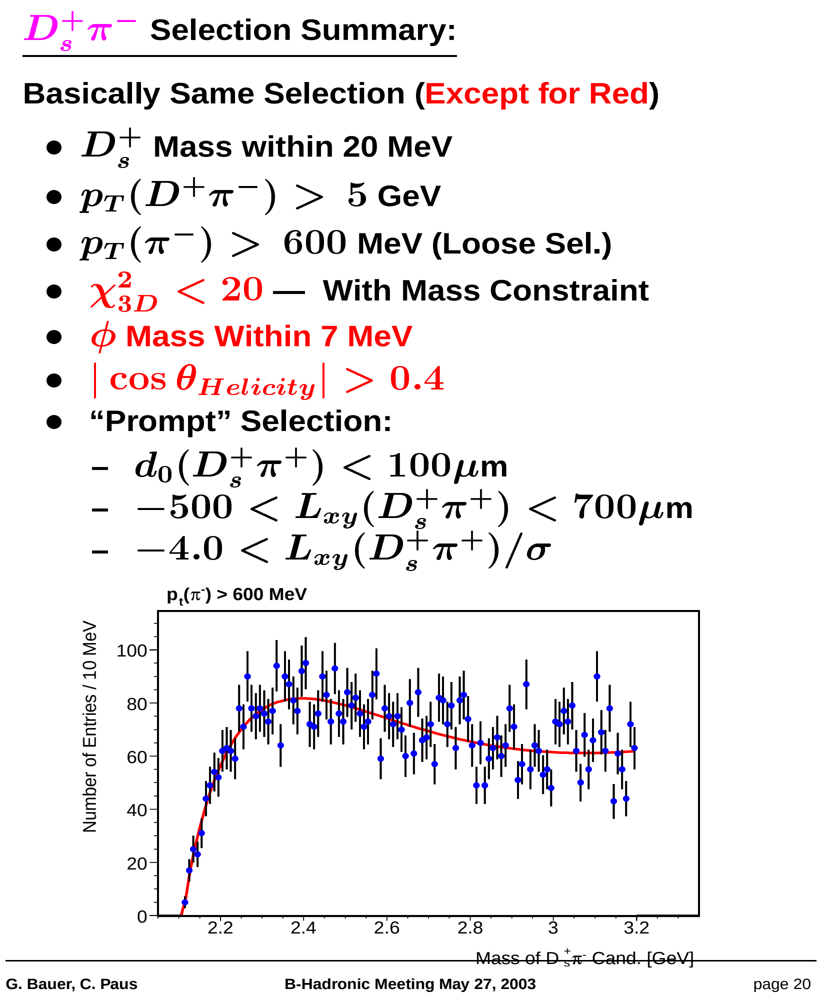


FIG. 34. This figure taken from other B group analyses (Bauer and Paus), shows the mass spectrum for $D_s^+\pi^-$ and $D_s^+\pi^-$ channels.

VII. NEXT PHASE

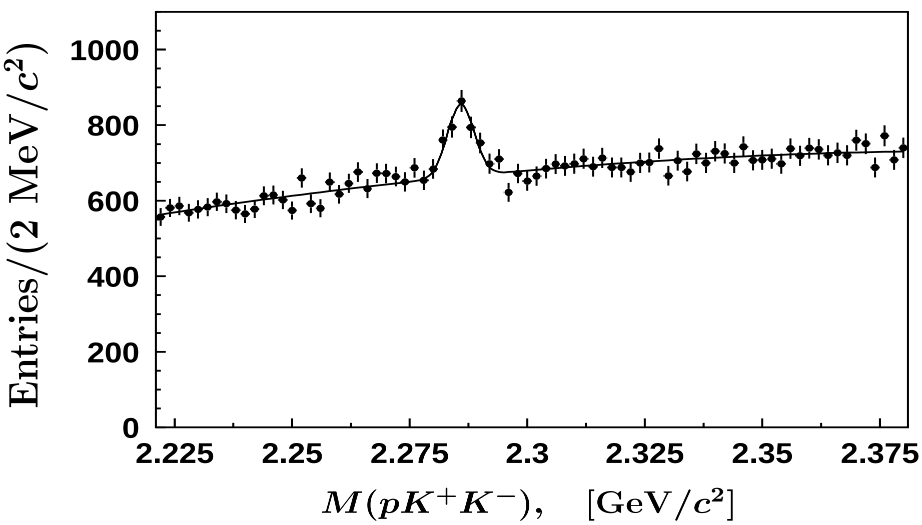
Plans for optimizing cuts: For the di-meson four-quark states we aim as much as possible to use standard B-group cuts, e.g. the cuts the for D_s. For example, we plan to use the same cuts as were used optimized by the B-group study of (π^+ D^-) spectrum, where they observed the D*(2460), and their study of *piplus* D_s^+ spectrum. These cuts are shown in Fig. 33 and Fig. 34. The B group $D_s^+\pi^-$ cuts are: (a) D_s^+ mass within 20 MeV.(b) Pt of the ($D_s^+\pi^-$) greater than 5 GeV.(c) PT of the π^- greater than 600 MeV. (d) Chisquare(3D) less thab 20 with mass contraint. ϕ mass within 7 MeV. (e) Cosine ($\theta_{helicity}$) greater than 0.4. (f) Prompt selection d0($D_s^+\pi^-$) less than 100 micron; Lxy ($D_s^+\pi^-$)) greater than -500 micron and less than 700 micron; and Lxy greater than -4 sigma.

In that search, one searches for a particle of mass around 2.4 GeV decaying to a D_s with mass 1.9 GeV and a pion. Therefore, one expects the Ds to carry most of the transverse momentum.

This is why this search required the minimum 0.6 GeV Pt cut on the momentum of the pion and a 5 GeV Pt cut on the momentum of the D meson.

However, when a Pentaquark state decays into a final state pion is replaced with a proton, it is expected that the proton carries a much higher fraction of the momentum of the Pentaquark. Therefore, the transverse momentum cut on the proton must be higher than the 0.6 GeV cut on the pion which is used in the $(D_s^+\pi^-)$ search. The cut should closer to the Pt cut that is used to initially select the Ds. We are looking for a state of a mass of about 3 GeV decaying to a Ds of mass 1.9 GeV and a proton of mass 0.93 GeV. Therefore, the Pt cut of on the proton should be about half of the Pt cut on the pair. If we use the B group cut of Pt greater 5 GeV for the then the cut on $(D_s^- \, proton)$ pair, than the Pt cut on the proton should be about 2.5 GeV.

In order to study the effect of the Pt cut on the proton in an unbiased way, we plan to use a sample of Λ_C decays to *proton* ϕ (very low branching ratio). For the Λ_C of mass 2.285 GeV, a proton mass lf 0.93 GeV and a Φ mass of 1.02 GeV we expect that the optimal Pt cut of the proton should also be about half of the Pt of the *proton* ϕ pair.



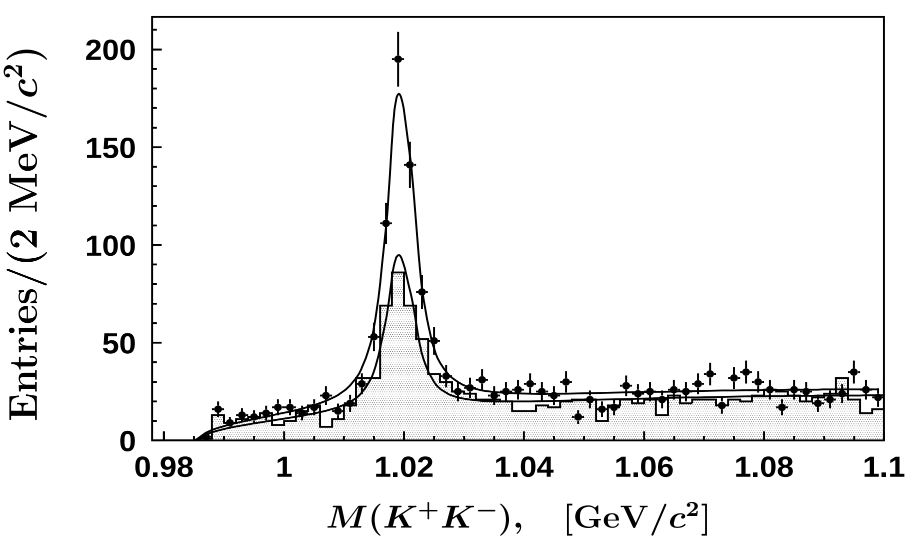


FIG. 35. Λ_c^+ to pKK from Belle (top). Bottom plot shows the KK mass spectrum for the events in the Λ_c peak. Branching ratios are showing in the next figure.

Hadronic modes with a p: $S = -1$ final states

Γ_1	$p\overline{K}^0$		(2.3 ± 0.6) %
Γ_2	$pK^-\pi^+$	[a]	(5.0 ± 1.3) %
Γ_3	$p\overline{K}^*(892)^0$	[b]	(1.6 ± 0.5) %
Γ_4	$\Delta(1232)^{++}K^-$		$(8.6 \pm 3.0) \times 10^{-3}$
Γ_5	$\Lambda(1520)\pi^+$	[b]	$(5.9 \pm 2.1) \times 10^{-3}$
Γ_6	$pK^-\pi^+$ nonresonant		(2.8 ± 0.8) %
Γ_7	$p\overline{K}^0\pi^0$		(3.3 ± 1.0) %
Γ_8	$p\overline{K}^0\eta$		(1.2 ± 0.4) %
Γ_9	$p\overline{K}^0\pi^+\pi^-$		(2.6 ± 0.7) %
Γ_{10}	$pK^-\pi^+\pi^0$		(3.4 ± 1.0) %
Γ_{11}	$pK^*(892)^-\pi^+$	[b]	(1.1 ± 0.5) %
Γ_{12}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(3.6 ± 1.2) %
Γ_{13}	$\Delta(1232)\overline{K}^*(892)$		seen
Γ_{14}	$pK^-\pi^+\pi^+\pi^-$		$(1.1 \pm 0.8) \times 10^{-3}$
Γ_{15}	$pK^-\pi^+\pi^0\pi^0$		$(8 \pm 4) \times 10^{-3}$
Γ_{16}	$pK^-\pi^+\pi^0\pi^0\pi^0$		

Hadronic modes with a p: $S = 0$ final states

Γ_{17}	$p\pi^+\pi^-$		$(3.5 \pm 2.0) \times 10^{-3}$
Γ_{18}	$pf_0(980)$	[b]	$(2.8 \pm 1.9) \times 10^{-3}$
Γ_{19}	$p\pi^+\pi^+\pi^-\pi^-$		$(1.8 \pm 1.2) \times 10^{-3}$
Γ_{20}	pK^+K^-		$(7.7 \pm 3.5) \times 10^{-4}$
Γ_{21}	$p\phi$	[b]	$(8.2 \pm 2.7) \times 10^{-4}$
Γ_{22}	pK^+K^- non-ϕ		$(3.5 \pm 1.7) \times 10^{-4}$

FIG. 36. Λ_c^+ to proton plus other particle branching ratios.

VIII. CONCLUSION

This is a progress report on a a search for Charm, Charm-Strange, Bottom and Bottom-Strange Pentaquark and other Multiquark States in P-Pbar Collisions at CDF. For Charm and Charm-Strange exotic states we search for states in the following two body final states: (1) Neutral and charge +2 (and -2) bound-state Pentaquarks which decay into one Charm or Charm-Strange Meson (e.g. D^+, D^-, D_s^+, D_s^-) plus another Baryon (e.g. proton or antiproton); (2) Neutral and charge +2 (and -2) bound-state exotic four-quark states which decay into one Charm or Charm-Strange meson (D^+, D^-, D_s^+, D_s^-) and another charged meson (π^+,π^-, K^-, K^-).

We see preliminary indication of Pentaquark peaks (at 3100 and 3200 Mev) in two Meson-Baryon final state channels that we have investigated. We have also seen peaks in the 4-quark search Meson-Meson final state. which need to be further investigated. We plan to double or triple the statistics by using additional decay mode, somewhat reducing both Pt cuts (keeping the ratio fixed), and using more of the data taken so far. A side band subtraction analysis is under way.

If these charge 0 and 2 are confirmed in the charm sector, we plan to expand the search to similar particles with charge +1 and -1 in the charm sector (by including neutral D^0 mesons in the search). In addition, we will study the corresponding neutral, charge +1, +2 and -1 and -2 in the Bottom, Bottom-Strange and Bottom-Charm quark sector.

IX. CURRENT PLANS

Baryon-Meson Studies

A. Pentaquark Search in Charge 0 D_s^--*proton* and D_s^+-*antiproton*. For each plot, calculate DM by subracting the measured D_s mass from the unconstrained mass and then adding back the D_s mass from the PDG. Do the follwing studies for both Lxy less than 500 and Lxy greater than 500 microns.

1. compare D_s^--*proton* and D_s^+-*antiproton* and total. (look at ratio versus mass of first two plots)

2. Compare left and tight side bands mass distributions and total. (look at ratio versus mass of first two plots)

3. Fit the total sid- band background to a function.

4. Normalize the side band function to the total number of events in each plot and show it on each of the above plots.

B. Repeat as above for Pentaquark Search in Charge 2 D_s^+-*proton* and D_s^--*antiproton*

C. Repeat as above for Exotic Meson Search in Charge 0 D_s^+-π^- and D_s^--π^+. Check that we see the known B_s^0 peak at 5300 (in Lxy greater than 500 microns). Also look at D_s^+-K^- and D_s^--K^-.

Di-Meson Studies

D. Repeat as above for Exotic Meson Search in Charge 2 D_s^+-π^+ and D_s^--π^-; and for D_s^+-K^- and D_s^--K^-

E. Repeat as above for Pentaquark Search in Charge 0 D^+-*proton* and D^--*antiproton* for both the Cabbibo suppressed channel and for the high statistics D sample.

F. Repeat as above for Pentaquark Search in Charge 2 D^+-*proton* and D^--*antiproton* for both the Cabbibo suppressed channel and for the high statistics D sample.

G. Repeat as above for Exotic Meson Search in Charge 0 D^+-π^- and D^--π^+ for both the Cabbibo suppressed channel and for the high statistics D sample. Here check that we see the known $D*(2460)$ (in Lxy less that 500 microns) and that we see the known B^0 and B_s^0 peaks at 5300 (in Lxy greater than 500 microns) Also look at D^+-K^- and D^--K^-.

H. Repeat as above for Exotic Meson Search in Charge 2 D^+-π^+ and D^--π^- for both the Cabbibo suppressed channel and for the high statistics D sample. Also look at D^+-K^- and D^--K^-

Subsequent Steps

G. Include searches with a D^0 in the final state instead of a charged D, and also look at more Charm pentaquarks possibilities with other charge and strangeness quantum numbers.

H. Look for long lived below threshold Pentaquark states as predicted in the Stewart et al. model.

J. Expand the search to the B-quark sector.

B.

X. APPENDIX A

The following figures are taken from R. Bijker et. al. Spectroscoy of Pentaquarks States hep-ph/0310281 and show all possible low lying (exotic) pentaquark states and predicted masses.

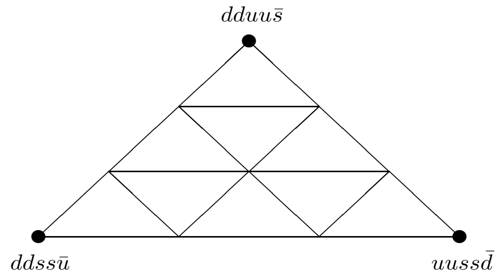


Figure 1: $SU(3)$ flavour multiplet $[33]_{10}$ with E symmetry. The isospin-hypercharge multiplets are $(I, Y) = (0, 2)$, $(1/2, 1)$, $(1, 0)$ and $(3/2, -1)$. Exotic states are indicated with $\bullet$.

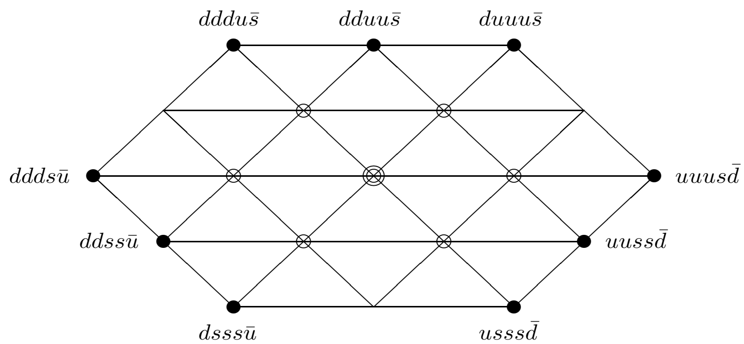


Figure 2: $SU(3)$ flavour multiplet $[42]_{27}$ with F_2 symmetry. The isospin-hypercharge multiplets are $(I, Y) = (1, 2)$, $(3/2, 1)$, $(1/2, 1)$, $(2, 0)$, $(1, 0)$, $(0, 0)$, $(3/2, -1)$, $(1/2, -1)$ and $(1, -2)$. Exotic states are indicated with $\bullet$.

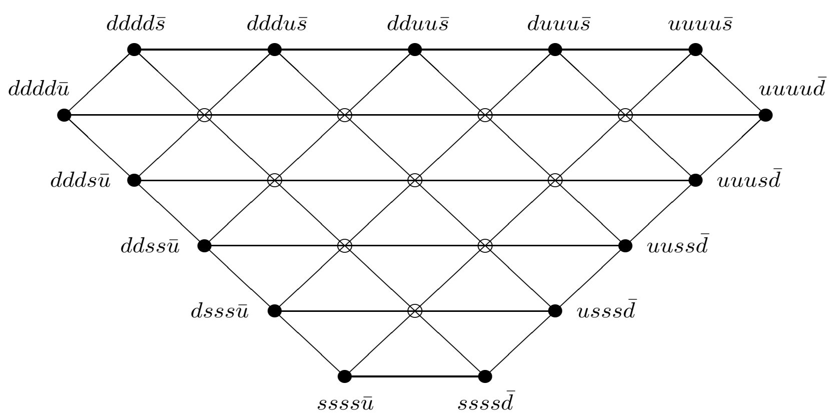


Figure 3: $SU(3)$ flavour multiplet $[51]_{35}$ with A_1 symmetry. The isospin-hypercharge multiplets are $(I, Y) = (2, 2)$, $(5/2, 1)$, $(3/2, 1)$, $(2, 0)$, $(1, 0)$, $(3/2, -1)$, $(1/2, -1)$, $(1, -2)$, $(0, -2)$ and $(1/2, -3)$. Exotic states are indicated with $\bullet$.

FIG. 37. Spectrocopy of low lying exotic Pentaquark from hep-ph/0310281

Table 6: $q^4\bar{q}$ pentaquark states with exotic quantum numbers. The electric charge is $Q = I_3 + Y/2$.

$SU_f(3)$	Y	I	Q	Flavour States	Notation
$[33]_{10}$	2	0	1	$dduu\bar{s}$	Θ^+
	-1	3/2	-2,1	$ddss\bar{u}, uuss\bar{d}$	$\Xi_{3/2}$
$[42]_{27}$	2	1	0,1,2	$dddu\bar{s}$, $dduu\bar{s}$, $duuu\bar{s}$	Θ_1
	0	2	-2,2	$ddds\bar{u}$, $uuus\bar{d}$	Γ
	-1	3/2	-2,1	$ddss\bar{u}$, $uuss\bar{d}$	Π
	-2	1	-2,0	$dsss\bar{u}$, $usss\bar{d}$	Ω_1
$[51]_{35}$	2	2	-1,0,1,2,3	$dddd\bar{s}$, $dddu\bar{s}$, $dduu\bar{s}$, $duuu\bar{s}$, $uuuu\bar{s}$	Θ_2
	1	5/2	-2, 3	$dddd\bar{u}$, $uuuu\bar{d}$	Φ
	0	2	-2, 2	$ddds\bar{u}$, $uuus\bar{d}$	Γ
	-1	3/2	-2, 1	$ddss\bar{u}$, $uuss\bar{d}$	Π
	-2	1	-2, 0	$dsss\bar{u}$, $usss\bar{d}$	Ω_1
	-3	1/2	-2,-1	$ssss\bar{u}$, $ssss\bar{d}$	Ψ

FIG. 38. Spectrocopy of low lying exotic Pentaquark from hep-ph/0310281 table 8

Table 8: Mass splittings of exotic pentaquark states within a $SU_{\rm sf}(6)$ multiplet calculated using Eq. (11) with the parameters of Eq. (12). The lowest pentaquark state of each spin-flavour multiplet is normalized to the observed mass of the $\Theta^+(1540)$ resonance. The orbital excitations are taken to be degenerate. The states are labeled by their spin s, hypercharge Y, isospin I, spin-flavour multiplet $[f]$ and orbital excitation L_t^p. The notation is the same as in Table 6.

					Mass (MeV)			
$SU_{\rm f}(3)$	s	Y	I	Notation	[51111] $1^-_{F_2}$	[42111] $0^+_{A_1}$, $1^-_{A_1,F_2}$	[33111] $1^-_{F_2}$	[32211] $1^-_{F_2}$
$[33]_{10}$	1/2	2	0	Θ^+	**1540**	**1540**	**1540**	**1540**
		-1	3/2	$\Xi_{3/2}$	2305	2305	2305	2305
$[33]_{10}$	3/2	2	0	Θ^+		1655	1655	1655
		-1	3/2	$\Xi_{3/2}$		2420	2420	2420
$[33]_{10}$	5/2	2	0	Θ^+			1846	
		-1	3/2	$\Xi_{3/2}$			2612	
$[42]_{27}$	1/2	2	1	Θ_1	1660	1660	1660	1660
		0	2	Γ	2247	2247	2247	2247
		-1	3/2	Π	2348	2348	2348	2348
		-2	1	Ω_1	2449	2449	2449	2449
$[42]_{27}$	3/2	2	1	Θ_1	1775	1775	1775	1775
		0	2	Γ	2362	2362	2362	2362
		-1	3/2	Π	2463	2463	2463	2463
		-2	1	Ω_1	2564	2564	2564	2564
$[42]_{27}$	5/2	2	1	Θ_1		1966		
		0	2	Γ		2553		
		-1	3/2	Π		2654		
		-2	1	Ω_1		2755		

FIG. 39. Spectrocopy of low lying exotic Pentaquark from hep-ph/0310281 Table 8A.

Table 8: Continued

$SU_f(3)$	s	Y	I	Notation	Mass (MeV) [51111] $1^-_{F_2}$	[42111] $0^+_{A_1}$, $1^-_{A_1,F_2}$	[33111] $1^-_{F_2}$	[32211] $1^-_{F_2}$
$[51]_{35}$	1/2	2	2	Θ_2		1899	1899	
		1	5/2	Φ		2231	2231	
		0	2	Γ		2332	2332	
		-1	3/2	Π		2433	2433	
		-2	1	Ω_1		2534	2534	
		-3	1/2	Ψ		2635	2635	
$[51]_{35}$	3/2	2	2	Θ_2	2014	2014		
		1	5/2	Φ	2346	2346		
		0	2	Γ	2447	2447		
		-1	3/2	Π	2548	2548		
		-2	1	Ω_1	2649	2649		
		-3	1/2	Ψ	2750	2750		
$[51]_{35}$	5/2	2	2	Θ_2	2205			
		1	5/2	Φ	2537			
		0	2	Γ	2638			
		-1	3/2	Π	2739			
		-2	1	Ω_1	2840			
		-3	1/2	Ψ	2941			

FIG. 40. Spectrocopy of low lying exotic Pentaquark from hep-ph/0310281 Table 8B.

Table 9: Spin-flavour contribution to the masses of exotic pentaquark states calculated using Eq. (13). The notation and the labeling of the states is the same as in Table 8. The observed Θ^+ is tentatively assigned to the [42111] multiplet (see section 4). The orbital excitations are taken to be degenerate.

$SU_f(3)$	s	Y	I	Notation	Mass (MeV) [51111] $1^-_{F_2}$	[42111] $0^+_{A_1}$, $1^-_{A_1,F_2}$	[33111] $1^-_{F_2}$	[32211] $1^-_{F_2}$
$[33]_{10}$	1/2	2	0	Θ^+	1263	**1540**	1678	1817
		-1	3/2	$\Xi_{3/2}$	2028	2305	2444	2582
$[33]_{10}$	3/2	2	0	Θ^+		1655	1793	1932
		-1	3/2	$\Xi_{3/2}$		2420	2558	2697
$[33]_{10}$	5/2	2	0	Θ^+			1985	
		-1	3/2	$\Xi_{3/2}$			2750	
$[42]_{27}$	1/2	2	1	Θ_1	1383	1660	1798	1936
		0	2	Γ	1970	2247	2385	2524
		-1	3/2	Π	2071	2348	2486	2625
		-2	1	Ω_1	2172	2449	2587	2726
$[42]_{27}$	3/2	2	1	Θ_1	1498	1775	1913	2051
		0	2	Γ	2085	2362	2500	2638
		-1	3/2	Π	2186	2463	2601	2739
		-2	1	Ω_1	2287	2564	2702	2841
$[42]_{27}$	5/2	2	1	Θ_1		1966		
		0	2	Γ		2553		
		-1	3/2	Π		2654		
		-2	1	Ω_1		2755		

FIG. 41. Spectrocopy of low lying exotic Pentaquark from hep-ph/0310281 Table 9A.

Table 9: Continued

$SU_f(3)$	s	Y	I	Notation	Mass (MeV) [51111] $1^-_{F_2}$	[42111] $0^+_{A_1}$, $1^-_{A_1,F_2}$	[33111] $1^-_{F_2}$	[32211] $1^-_{F_2}$
$[51]_{35}$	1/2	2	2	Θ_2		1899	2037	
		1	5/2	Φ		2231	2369	
		0	2	Γ		2332	2470	
		-1	3/2	Π		2433	2571	
		-2	1	Ω_1		2534	2672	
		-3	1/2	Ψ		2635	2773	
$[51]_{35}$	3/2	2	2	Θ_2	1737	2014		
		1	5/2	Φ	2069	2346		
		0	2	Γ	2170	2447		
		-1	3/2	Π	2271	2548		
		-2	1	Ω_1	2372	2649		
		-3	1/2	Ψ	2473	2750		
$[51]_{35}$	5/2	2	2	Θ_2	1928			
		1	5/2	Φ	2260			
		0	2	Γ	2362			
		-1	3/2	Π	2463			
		-2	1	Ω_1	2564			
		-3	1/2	Ψ	2665			

FIG. 42. Spectrocopy of low lying exotic Pentaquark from hep-ph/0310281 Table 9B.

XI. APPENDIX B: OUR OWN BEST ESTIMATES USING CONSTITUENT DIQUARK-TRIQUARK CONCEPTS

As described below, we assume that the newly reported state $\Theta^+_{\bar{s}}(1540)$ and is identified with the Pentaquark states $\bar{s}uudd$. We assume that state $\bar{s}uuud$ has a mass of 1540+(1232-938)=1834 (assuming it is heavier by the Delta(1232)-proton mass difference,. Using these values, we estimate the following masses for the corresponding Pentaquark states in the charm sector: (a) The $P^0_{\bar{c}s}$ $=\bar{c}sudd$ should be around 3120 MeV and decay to Proton plus D^-_s (and the corresponding antiparticle); (b) The $P^{++}_{\bar{s}c}$ $=\bar{s}cudd$ should be around 3200 MeV and decay to Proton plus D^+_s (and the corresponding antiparticle); (c) The $P^0_{\bar{c}d}$ $=\bar{c}duud$ should be around 2960 MeV and decay to Proton plus D^- (and the corresponding antiparticle);(d) The $P^{++}_{\bar{d}c}$ $=\bar{d}cuud$ should be around 3060 MeV and decay to Proton plus D^+ (and the corresponding antiparticle).

And in the b sector: (a) The $P^+_{\bar{b}}$ $=\bar{b}uudd$ should be around 6400 MeV (and the corresponding antiparticle); (b) The $P^+_{\bar{b}s}$ $=\bar{b}sudd$ should be around 6535 MeV (and the corresponding antiparticle)

There are many different models for Pentaquark states, which result in different quantum numbers and masses for the various baryons. These include Skyrmion or chiral-soliton models, Lattice QCD calculations, and constituent quark models including diquark and triquark states. Within the constituent quark model of Cheung [5] the $\Theta^{\pm}_{\bar{s}}(1540)$ = $\bar{s}uudd$ is predicted to be between 1481 and 1562 MeV (a range of 81 MeV). The Cheung model also predicts that the $P^0_{\bar{c}d}$ $=\bar{c}duud$ has a mass between 2938 and 2997 MeV, a range of 59 MeV. Since the upper estimate of 1562 MeV is 22 MeV higher than the measured mass of 1540 MeV, we estimate $P^0_{\bar{c}d}$ $=\bar{c}duud$ mass to be 2997-22x(59/81) =2997-16 MeV or 2980 MeV.

Lipkin estimates the mass of the $P^0_{\bar{c}d}$ $=\bar{c}duud$ to be 2985 MeV. Huang uses Lipkins model and gets 2990 MeV. Lippkin also states that his prediction for the $P^0_{\bar{c}d}$ $=\bar{c}duud$ of 2985 MeV [6] (with an error of 50 MeV) may be an overestimate since the same model predicts a mass of 1592 for the $\Theta^{\pm}_{\bar{s}}(1540)$).

Cheung's model also predicts that the $P^+_{\bar{b}}$ $=\bar{b}uudd$ has a mass between 6340 and 6422 MeV (a range of 80 MeV). Based on this we estimate the $P^+_{\bar{b}}$ $=\bar{b}uudd$ mass to be 6422 -22x(80/81) = 6400 MeV. Lipkin's estimate for the mass of this state is similar (as shown in the Table below)

Lipkin's model [6] attempts to fit the baryon masses with the assumption that the constituent quark masses for the (u, s, c and b) of 360, 540, 1710 and 5050 MeV depend on the flavor of the spectator quark. For example, the difference between the strange and u quark masses is 179 MeV when the spectator is a d-quark, 103 MeV when the spectator is a c-quark and 91 MeV when the spectator is a b quark.

Therefore, the anticharm-strange Pentaquarks should be between 103 and 179 MeV more massive then the anticharm Pentaquarks with only light quarks. We take the average of 140 MeV as the difference between the strange and u quark mass in a Pentaquark that already contains one charm quark. Similarly, the antistrange-bottom Pentaquark and the antibottom-strange Pentaquarks should be between 91 and 179 MeV more massive then the antibottom Pentaquark with only light quarks (i.e. 135 MeV on average).

Within Lipkin's model, the charm quark is heavier than the u quark by 1360 MeV when the d quark is a spectator (Table 4 in hep-ph/0307243). If we assume that $P^{++}_{\bar{s}}$ $\bar{s}uuud$ Pentaquark has a mass of 1834 MeV (194 MeV higher than the 1540 to account for $\Delta(1232)$ nucleon(938) mass difference), then the mass of the $P^{++}_{\bar{s}c}$ $=\bar{s}cudd$ should be 1834+1360 = 3194 MeV (or about 3200 MeV). We have not found any other estimates for the mass of this state.

In summary the following are the expected mass ranges for the various Pentaquark states that we look for. When there are more than one estimate, the second entry is our best estimate. The tables below are preliminary and we plan to update it in the near future.

In the tables we use the following masses from the particle data group: π^0 (u$\overline{u}$) = 135 Mev, π^+(u$\overline{d}$) = 139.6 MeV,Proton (uud) = 938.3 , Neutron(ddu)=939.6 MeV, Φ(s$\overline{s}$)=1020.0 MeV, K^0 (d$\overline{s}$) = 497.7 MeV, K^+(u$\overline{s}$)= 393.7, Λ^0 (uds) = 1115.7 MeV, Σ^+(uus)=1189.4, D^0(u$\overline{c}$) = 1864.5 MeV, D^+(c$\overline{d}$) =1869.3 MeV, D^+_s(c$\overline{s}$) =1968.6 MeV, Λ^+_c(udc) =2284.9 MeV, Σ^{++}_c(uuc) = 2452.8, MeV.

In addition, if the state $D_s*(2317)$ which was observed by BaBar to decay into a D^-_s plus a π^0 is a (c$\overline{s}$)(d$\overline{d}$) (c$\overline{s}$)(u$\overline{u}$) four-quark state. Then a similar four-quark state (c$\overline{s}$)(u$\overline{d}$) decaying into D^-_s π^+ and the state (c$\overline{s}$)(d$\overline{u}$) decaying into a D^-_s π^- should be there at a somewhat higher mass (e.g. 2325 MeV). By replacing the proton with charged a pion or kaon in the final state, we search for exotic four-quark states, as well as known non-exotic states (as shown in the Table).

$composition + charge$	$Expected Mass$	$Decay mode$	$threshold$	$allowed?$
	Cheung,(Lipkin)			
$\overline{s}uudd(+)$	1540 (measured)	n K^+	1433.2	Yes $\Theta^+_{\overline{s}}(1540)$ seen
$\overline{s}uudd(+)$	1481, 1540, 1562, (1592)	n K^+	1433.2	Yes $\Theta^+_{\overline{s}}(1540)$ seen
$\overline{u}dssd(-)$	1860 (?)			Ξ^{--} seen by NA49 but not CDF
$\overline{s}duuu(++)$	1540+1232-938=1834(?)			$P^{++}_{\overline{s}}$
	+1360			c to u mass diff)
$\overline{s}cuud(++)$	3194=3200	pD^+_s	2907	$P^{++}_{\overline{s}c}$
$\overline{s}cuud(++)$	3194=3200	$\Lambda^+_C K^+$	2679	$P^{++}_{\overline{s}c}$
$\overline{s}cudd(+)$	1540+1360=2900 ?			$P^{+}_{\overline{s}c}$
$\overline{s}cddd(0)$				$P^{0}_{\overline{s}c}$
$\overline{s}uuub(++)$				$P^{++}_{\overline{s}b}$
$\overline{s}cuub(++)$				$P^{++}_{\overline{s}bc}$
$\overline{c}duud(0)$	2938, 2980, 2997, (2985)	n D^0	2804	Yes $P^0_{\overline{c}}$
$\overline{c}duud(0)$	2938, 2980 ,2997,(2985)	p D^-	2807	Yes $P^0_{\overline{c}}$
	+103, +140, +179 ,+140			s to u mass dif
$\overline{c}uusd(0)$	3041,3120, 3176,(3125)	p D^-_s	2907	Yes $P^0_{\overline{c}s}$
$\overline{c}uusd(0)$	3041,3120, 3176 ,(3125)	Λ^0 D^0	2980	$P^0_{\overline{c}s}$
$\overline{c}uusd(0)$	3041,3120, 3176 ,(3125)	Σ^+ D^-	3059	$P^0_{\overline{c}s}$
$\overline{c}uubd(0)$	3120+4510=7630?			$P^0_{\overline{c}b}$
$\overline{c}uubs(0)$	7630+91=7720			$P^0_{\overline{c}bs}$
$\overline{s}cuud(++)$	3200	pD^+_s	2907	Yes $P^{++}_{\overline{s}c}$
	-140			s to u
$\overline{d}cuud(++)$	3060	p D^+	2807	Non exotic $P^{++}_{\overline{d}c}$
$\overline{b}uudd(+)$	6370, 6400, 6422, (6398)			$P^+_{\overline{b}}$
	+103, +135,+179, (+135)			s to u mass diff
$\overline{b}uusd(+)$	6473, 6535, 6601, (6533)			$P^+_{\overline{b}s}$
$\overline{b}uucd(++)$	6535+991=7526?			$P^{++}_{\overline{b}c}$
$\overline{b}uucs(++)$	7526+91=7617?			$P^{++}_{\overline{b}cs}$

TABLE II. Pentaquark states, expected mass, and threshold mass for various decay modes.

$composition + charge$	$ExpectedMass$	$Decaymode$	$threshold$	$allowed?$
$c\overline{s}(u\overline{u}d\overline{d})(+)$	2317 (measured BaBar)	$D_s^+\pi^0$	2104	seen $D_s^+*(2317)$
$c\overline{s}d\overline{u}(0)$	2325 ??	$D_s^+\pi^-$	2108	YES-search
$c\overline{s}u\overline{d}(++)$	2325 ??	$D_s^+\pi^+$	2108	YES-Search
$b\overline{s}(0)$	5370(measured)	$D_s^+\pi^-$	2108	seen B_s^0
$b\overline{d}(0)$	5279(measured)	$D_s^+\pi^-$	2108	seen B_0
$b\overline{s}(0)$	5370(measured)	$D^+\pi^-$	2009	seen B_s^0
$b\overline{d}(0)$	5279(measured)	$D^+\pi^-$	2009	seen B_0
$b\overline{d}(0)$	5279(measured)	D^-K^+	2462	seen B_0
$c\overline{u}(0)$	2459(measureed)	$D^+\pi^-$	2009	seen $D_0^*(2459)$
$c\overline{u}(0)$	high-mass	$D^+\pi^-$		YES look for D_0^*(high mass)
$c\overline{u}$ (0)	2459(measured)	$D_s^+K^-$		No D_0^* (2462)
$c\overline{u}$ (0)	some-high-mass	$D_s^+K^-$		Yes D_0^* (high mass) search
$c\overline{u}$ (0)	some-high-mass	$D_s^+\pi^-$ reflection from K		Yes D_0^* (high mass) search

TABLE III. non-exotic mesons (to be used for normalization) and checks and exotic four quark states, expected mass, and threshold mass for various decay modes.

Table 13.1: Additive quantum numbers of the quarks.

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

Table 13.2: Suggested $q\overline{q}$ quark-model assignments for most of the known mesons. Some assignments, especially for the 0^{++} multiplet and for some of the higher multiplets, are controversial. Mesons in bold face are included in the Meson Summary Table. Of the light mesons in the Summary Table, the $f_0(1500)$, $f_1(1510)$, $f_2(1950)$, $f_2(2300)$, $f_2(2340)$, and one of the two peaks in the $\eta(1440)$ entry are not in this table. Within the $q\overline{q}$ model, it is especially hard to find a place for the first two of these f mesons and for one of the $\eta(1440)$ peaks. See the "Note on Non-$q\overline{q}$ Mesons" at the end of the Meson Listings.

$N\ ^{2S+1}L_J$	J^{PC}	$u\overline{d}$, $u\overline{u}$, $d\overline{d}$ $I=1$	$u\overline{u}$, $d\overline{d}$, $s\overline{s}$ $I=0$	$c\overline{c}$ $I=0$	$b\overline{b}$ $I=0$	$\overline{s}u$, $\overline{s}d$ $I=1/2$	$c\overline{u}$, $c\overline{d}$ $I=1/2$	$c\overline{s}$ $I=0$	$\overline{b}u$, $\overline{b}d$ $I=1/2$	$\overline{b}s$ $I=0$	$\overline{b}c$ $I=0$
$1\ ^1S_0$	0^{-+}	**π**	**η, η'**	**$\eta_c(1S)$**	$\eta_b(1S)$	**K**	**D**	**D_s**	**B**	**B_s**	**B_c**
$1\ ^3S_1$	1^{--}	**ρ**	**ω, ϕ**	**$J/\psi(1S)$**	**$\Upsilon(1S)$**	**$K^*(892)$**	**$D^*(2010)$**	**D_s^***	**B^***	B_s^*	
$1\ ^1P_1$	1^{+-}	**$b_1(1235)$**	**$h_1(1170)$**, $h_1(1380)$	$h_c(1P)$		**K_{1B}**†	**$D_1(2420)$**	**$D_{s1}(2536)$**			
$1\ ^3P_0$	0^{++}	**$a_0(1450)$***	**$f_0(1370)$***, **$f_0(1710)$***	**$\chi_{c0}(1P)$**	**$\chi_{b0}(1P)$**	**$K_0^*(1430)$**					
$1\ ^3P_1$	1^{++}	**$a_1(1260)$**	**$f_1(1285)$, $f_1(1420)$**	**$\chi_{c1}(1P)$**	**$\chi_{b1}(1P)$**	**K_{1A}**†					
$1\ ^3P_2$	2^{++}	**$a_2(1320)$**	**$f_2(1270)$, $f_2'(1525)$**	**$\chi_{c2}(1P)$**	**$\chi_{b2}(1P)$**	**$K_2^*(1430)$**	**$D_2^*(2460)$**				
$1\ ^1D_2$	2^{-+}	**$\pi_2(1670)$**	$\eta_2(1645)$, $\eta_2(1870)$			**$K_2(1770)$**					
$1\ ^3D_1$	1^{--}	**$\rho(1700)$**	**$\omega(1650)$**	**$\psi(3770)$**		**$K^*(1680)$**‡					
$1\ ^3D_2$	2^{--}					**$K_2(1820)$**					
$1\ ^3D_3$	3^{--}	**$\rho_3(1690)$**	**$\omega_3(1670)$, $\phi_3(1850)$**			**$K_3^*(1780)$**					
$1\ ^3F_4$	4^{++}	**$a_4(2040)$**	**$f_4(2050)$**, $f_4(2220)$			**$K_4^*(2045)$**					
$2\ ^1S_0$	0^{-+}	**$\pi(1300)$**	**$\eta(1295)$, $\eta(1440)$**	**$\eta_c(2S)$**		$K(1460)$					
$2\ ^3S_1$	1^{--}	**$\rho(1450)$**	**$\omega(1420)$, $\phi(1680)$**	**$\psi(2S)$**	**$\Upsilon(2S)$**	**$K^*(1410)$**‡					
$2\ ^3P_2$	2^{++}	$a_2(1700)$	$f_2(1950)$, **$f_2(2010)$**		**$\chi_{b2}(2P)$**	$K_2^*(1980)$					
$3\ ^1S_0$	0^{-+}	**$\pi(1800)$**	$\eta(1760)$			$K(1830)$					

* See our scalar minireview in the Particle Listings. The candidates for the $I=1$ states are $a_0(980)$ and $a_0(1450)$, while for $I=0$ they are $f_0(600)$, $f_0(980)$, $f_0(1370)$, and $f_0(1710)$. The light scalars are problematic, since there may be two poles for one $q\overline{q}$ state and $a_0(980)$, $f_0(980)$ may be $K\overline{K}$ bound states.

† The K_{1A} and K_{1B} are nearly equal (45°) mixes of the $K_1(1270)$ and $K_1(1400)$.

‡ The $K^*(1410)$ could be replaced by the $K^*(1680)$ as the $2\ ^3S_1$ state.

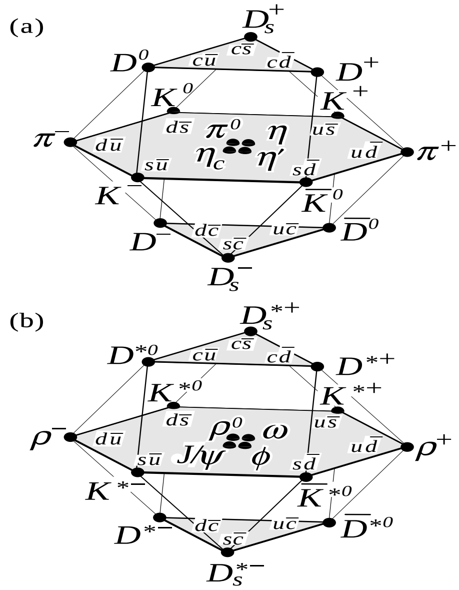


Figure 13.1: SU(4) 16-plets for the (a) pseudoscalar and (b) vector mesons made of u, d, s, and c quarks. The nonets of light mesons occupy the central planes, to which the $c\bar{c}$ states have been added. The neutral mesons at the centers of these planes are mixtures of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ states.

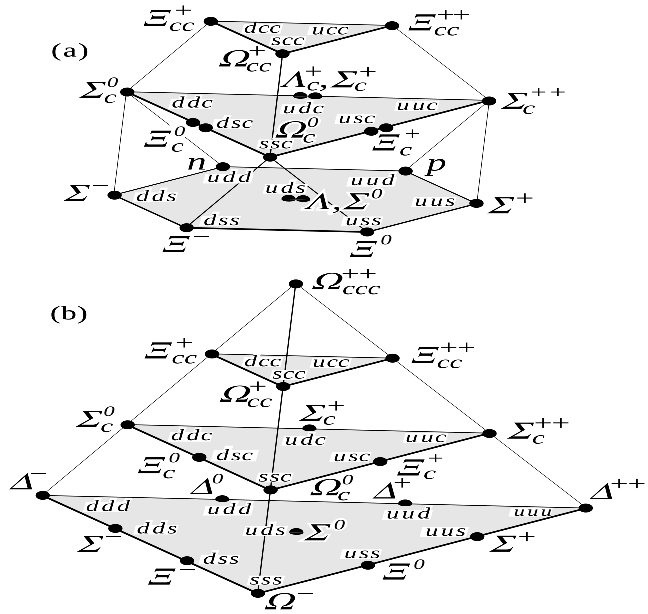


Figure 13.2: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

Table 13.4: Quark-model assignments for many of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for the $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses. For assignments of the charmed baryons, see the "Note on Charmed Baryons" in the Particle Listings.

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

FIG. 43.

$SU_f(3)$	Y	I	Q	$flavor states$	$Notation$
$[33]_{10}$	2	0	1	$dduu\bar{s}$	Θ^+
$[33]_{10}$	-1	3/2	$-2, 1$	$ddss\bar{u}, uuss\bar{d}$	$\Xi_{3/2}$
$[42]_{27}$	2	1	$0, 1, 2$	$dddu\bar{s}, dduu\bar{s}, duuu\bar{s}$	Θ_1
$[42]_{27}$	0	2	$-2, 2$	$ddds\bar{u}, uuus\bar{d}$	Γ
$[42]_{27}$	-1	3/1	$-2, 1$	$ddss\bar{u}, uuss\bar{d}$	Π
$[42]_{27}$	-2	1	$-2, 0$	$ddss\bar{u}, usss\bar{d}$	Ω_1
$[51]_{35}$	2	2	$-1, 0, 2, 3$	$dddd\bar{s}, dddu\bar{s}, dduu\bar{s}, duuu\bar{s}, uuu\bar{s}$	Θ_2
$[51]_{35}$	1	5/2	$-2, 3$	$dddd\bar{u}, uuuu\bar{d}$	Φ
$[51]_{35}$	0	2	$-2, 2$	$ddds\bar{u}, uuus\bar{d}$	Γ
$[51]_{35}$	-1	3/2	$-2, 1$	$ddss\bar{u}, uuss\bar{d}$	Π
$[51]_{35}$	-2	1	$-2, 0$	$ddss\bar{u}, usss\bar{d}$	Ω_1
$[51]_{35}$	-3	$-1/$	$-2, -1$	$sss\bar{u}, sss\bar{d}$	Ψ_2

TABLE IV. Spectroscopy oflow lying exotic pentaquarks from hep-ph/0310281 Table 8 reproduced. Charge Q=$I_3 + Y/2$

$SU_f(3)$	Y	I	Q	$flavorstates$	$Notation$
$[33]_{10}$	2	0	1	$dduu\overline{b}$	Θ_b^+
$[33]_{10}$	-1	$3/2$	$-2,1$	$ddss\overline{c}, uuss\overline{b}$	$\Xi_{3/2}$
$[42]_{27}$	2	1	$0,1,2$	$dddu\overline{b}, dduu\overline{b}, duuu\overline{b}$	$\Theta_{1,b}$
$[42]_{27}$	0	2	$-2,2$	$ddds\overline{c}, uuus\overline{b}$	Γ
$[42]_{27}$	-1	$3/1$	$-2,1$	$ddss\overline{c}, uuss\overline{b}$	Π
$[42]_{27}$	-2	1	$-2,0$	$ddss\overline{c}, usss\overline{b}$	Ω_1
$[51]_{35}$	2	2	$-1,0,2,3$	$dddd\overline{b}, dddu\overline{b}, dduu\overline{b}, duuu\overline{b}, uuu\overline{b}$	$\Theta_{2,b}$
$[51]_{35}$	1	$5/2$	$-2,3$	$dddd\overline{c}, uuuu\overline{b}$	Φ
$[51]_{35}$	0	2	$-2,2$	$ddds\overline{c}, uuus\overline{b}$	Γ
$[51]_{35}$	-1	$3/2$	$-2,1$	$ddss\overline{c}, uuss\overline{b}$	Π
$[51]_{35}$	-2	1	$-2,0$	$ddss\overline{c}, usss\overline{b}$	Ω_1
$[51]_{35}$	-3	$-1/$	$-2,-1$	$sss\overline{c}, sss\overline{b}$	Ψ_2

TABLE V. Spectroscopy oflow lying exotic pentaquarks from hep-ph/0310281 Table 8 with $\overline{d}$, and $\overline{s}$ replaced with $\overline{b}$ and with $\overline{u}$ replaced with $\overline{c}$. Charge Q=$I_3 + Y/2$

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