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The $X(3872)$ Meson and
"Exotic" Spectroscopy at CDF II
—Or NOT?—

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A spate of remarkable new hadrons reported in 2003 may lead to unequivocal proof of states beyond conventional $q\bar{q}$ and qqq structure. Claimed baryonic states Θ^+, Φ, and Θ_c^0 would consist of five quarks, and new D_{sJ}^+-states and/or $X(3872)$ might contain four quarks. I review efforts to search for and study this "new" spectroscopy in $\bar{p}p$-collisions with the CDF II detector. Pentaquark searches are negative, and no evidence for exotic analogs of D_{sJ}-states was found. CDF has confirmed the $X(3872)$. My main focus is the production and decay properties of the $X(3872)$, and its possible interpretations.

1. 2003: Annus Mirabilis?

After decades of relatively mundane additions to the hadron spectrum, 2003 may one day be recounted as the dawn of a new era in spectroscopy. This year witnessed reports that may lead to the *first unequivocal proof* that Nature is not limited to simple $q\bar{q}$ and qqq constructions. But these claims are dogged by controversy, and may instead be recalled as an ignominious tale told to future graduate students.

The idea of unconventional quark structures is quite old. If one glosses over delicate distinctions between 2-baryon *nuclei* and 6-quark *particles*—and pardons the anachronism—"exotic" hadrons *pre-date* the quark model. Far back in antiquity Fermi and Yang considered $N\overline{N}$ bound states as a model of the pion.[1] Later the $SU(3)$ symmetry of the Eightfold Way[2] was used to put the deuteron in a dibaryon multiplet[3]—with some evidence for a Λp-state.[4] In the 1964 birth of the quark model Gell-Mann[5] actually mentions $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$ as mesons and baryons—but only their lighter $q\bar{q}$ and qqq siblings were considered relevant at the time.

In the mid-1960s enhancements in KN scattering[6] pointed to $+1$ strangeness baryon resonances, implying minimal $qqqq\bar{s}$ content. These very broad structures required careful partial wave analysis to justify them as resonances, called Z^*'s. About the same time $K\overline{K}$ bound states were suggested to explain a low mass $I=1$ enhance-

ment in $\bar{p}p \to K\overline{K}\pi$.[7] And theoretically, duality arguments for baryon-antibaryon scattering via meson exchanges implied, in quark language, $qq\bar{q}\bar{q}$ systems.[8]

With the advent of QCD in the early 1970s the $q\bar{q}/qqq$-pattern was explained by $SU(3)_c$. It was soon realized that not only were more complex quark structures allowed, but also new types exploiting gluons: "hybrids" with valence gluons added to quarks, and "glueballs" without any quarks at all.[9] It is, however, a *dynamical* issue whether any exotics are manifest in an observationally meaningful way. Using a bag model Jaffe and Johnson not only answered positively, but argued that some known 0^{++} mesons ($f_0, a_0 \dots$) were better viewed as $qq\bar{q}\bar{q}$ than as a $^3P_0$ nonet of $q\bar{q}$. Later, a $K\overline{K}$ state was invoked to explain $\pi\pi \to f_0(980) \to K\overline{K}$ data.[10] Based on a potential model, both $f_0(980)$ and $a_0(980)$ made good $K\overline{K}$ "molecules"—and likely the only ones.[11] The s-quark mass seemed to strike the right balance for binding.

Today exotics remain a dynamic topic.[12] The $f_0(980)$ and $a_0(980)$ are still promoted as $K\overline{K}$-molecules, and hybrid and glueball candidates are bandied about. For a full list of suspects see the PDG's *Non-q$\bar{q}$ Candidates* review.[13] Despite decades of progress, no exotic meson has been conclusively identified. Many are claimed as "probably exotic," but proof is difficult. Candidates are very wide, and thus hard to study; and those with $q\bar{q}$ quantum numbers ("cryptoexotics") mix with ordinary mesons and are thus hard to understand. More mesons *are* known than needed as $q\bar{q}$-states, hinting of *something* exotic. But resonances can arise dynamically, opening another loophole. The ultimate smoking gun, a state with non-$q\bar{q}$ quantum numbers (*e.g.* 1^{-+}), has yet to be acclaimed.[14] This messy soup demands a painfully detailed understanding of data *and* theory before there is consensus on non-$q\bar{q}$ *light* mesons.

For baryons the situation was worse. After great hope for Z^* pentaquarks and dibaryons in the late 1960s and 70s, a grim reality set in in the early 80s.[15] Claims were either ruled out, or were simply unconvincing. The PDG became so disillusioned that they last listed Z^*'s in 1986,[16] and dibaryons in 1988.[17] In spite of this dismal verdict, theoretical and experimental work continued out of the spotlight.

In summary, despite the valiant effort of experimentalists and theorists for nearly forty years, the question of whether Nature elects to form systems beyond $q\bar{q}$ and qqq remains open. But events in 2003 were to begin a new chapter in this saga.

2. The Tevatron and the CDF II Detector

CDF II is a general purpose detector at Fermilab's $\bar{p}p$ collider[18] ($\sqrt{s} \sim 2$ TeV). Originally designed in the late 1970s for high-p_T physics (W, Z, top...), CDF became an important venue for bottom/charm physics[19] as luminosities increased and the detector enhanced. The Tevatron produces hadrons with very large cross sections, as seen in Fig. 1, where b-production is compared to $e^+e^- \to \Upsilon(4S) \to B\overline{B}$. At the same time, CDF has excellent tracking for spectroscopy, illustrated in Fig. 1 by a B_s^0-mass measurement to sub-MeV precision. The challenge is to exploit this bounty: just as b-production is very large, the total inelastic cross section (Fig. 1) is huge!
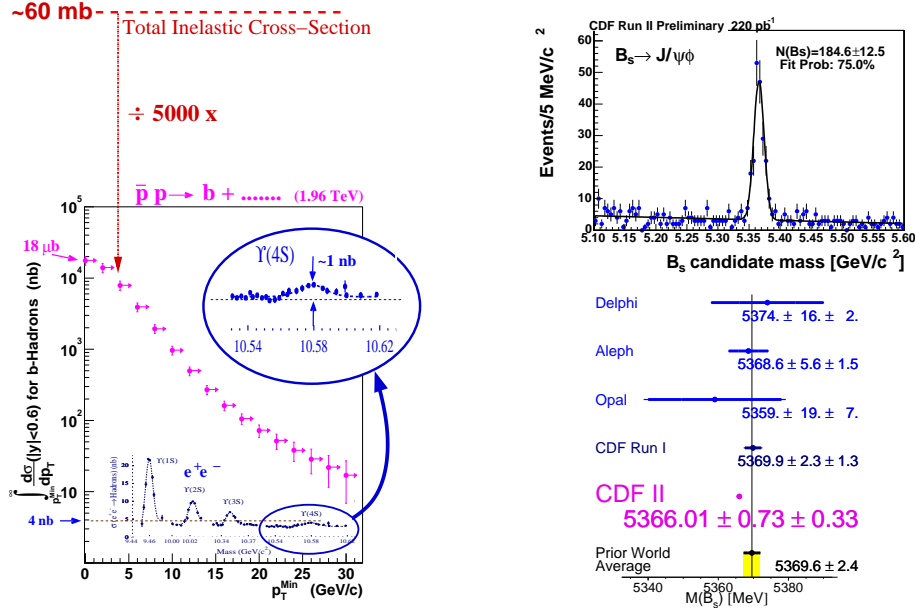
Fig. 1.   **LEFT:** Comparison of the b-quark cross section at the Tevatron,[20] integrated above a minimum p_T, $p_{T,\text{min}}$, to the total inelastic cross section[21] on a log-scale. Overlaid at the bottom is the e^+e^- cross-section[22] on linear scale aligned to match the log-scale at 4 nb, *i.e.* at the $\Upsilon(4S)$ where B-factories operate. **TOP:** The CDF II $J/\psi\phi$ mass distribution (~ 8 MeV/c^2 resolution) used for a B^0_s mass measurement. **Bottom:** Compilation of world B^0_s mass measurements.[13,23]

One lives or dies at a hadron collider by being able to selectively trigger on events.

CDF II is the product of a major upgrade[24] for Run II. Only a cursory description of the detector, sketched in Fig. 2, is given here. The tracking system consists of a Si-strip vertex detector (SVX)[25] comprising 5 layers of double-sided sensors (axial and stereo coordinates), that span radii from 2.5-10.6 cm from the beamline. This is surrounded by the Central Outer Tracker (COT),[26] a 3.1 m long open-cell drift chamber spanning radii of 43-132 cm. Both trackers are immersed in a 1.4 T solenoidal magnetic field, enabling measurement of the transverse momenta, p_T, of charged particles. The SVX is able to resolve the displacement of decay vertices ($\vec{x}_{decay}$) of long-lived c/b-hadrons from the collision point ($\vec{x}_{prim}$), and expressed as:

$$L_{xy} \equiv (\vec{x}_{decay} - \vec{x}_{prim}) \cdot \vec{p}_T / |\vec{p}_T|. \tag{1}$$

Between the COT and solenoid is a TOF[27] system for particle ID, supplementing that from dE/dx-measurements of the COT. Outside the solenoid are scintillator-based EM (Pb) and then hadronic (Fe) sampling calorimeters,[28] with a tower geometry 0.1 wide in pseudorapidity η, and 15° in azimuth ϕ (5° for $|\eta| > 1.2$). Towers with energy depositions are clustered together in $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ to form
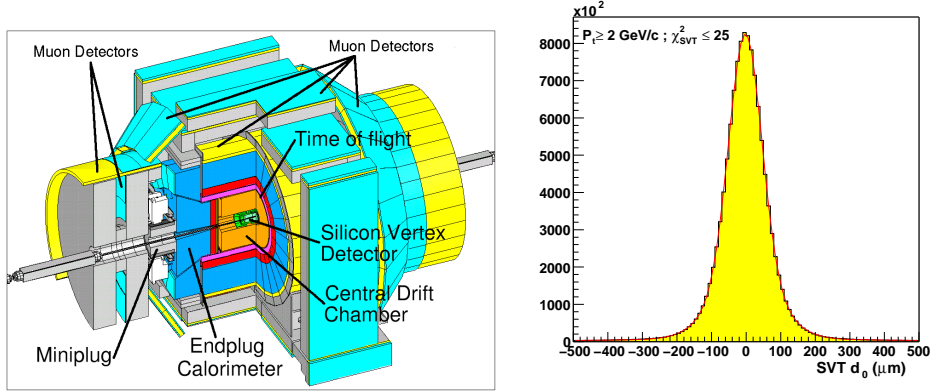
Fig. 2.   **LEFT:** CDF II detector. **Right:** Online impact parameter measured by the SVT.

"jets." The calorimeter design was aimed at W-physics, and is not well suited for low-energy γ-related spectroscopy. Beyond the calorimeters are a series of multi-layer muon chambers.[29] The central muon system (CMU) covers $|\eta| \leq 0.6$, and additional chambers (CMX) extend the coverage up to $|\eta| \leq 1.0$.

The trigger has three Levels. Important here at L-1 is the track trigger (XFT),[30] which uses COT hits to trigger on tracks above a p_T-cut, typically 1.5 or 2.0 GeV/c. At L-1, XFT tracks are matched to hits in triggered μ-chambers. XFT tracks are also fed to the Si-vertex trigger (SVT)[31] for a L-2 decision on tracks displaced from the collision vertex. L-3 is a farm of PC's[32] running offline code using the full event.

Distinctive features of heavy quarks make triggering practical. Traditionally lepton (e, μ) triggers were the backbone of heavy flavor physics at hadron colliders, either through semileptonic decays or $J/\psi \rightarrow \mu^+\mu^-$. Lepton triggers are well established, and we gloss over them other than to note that the CDF $J/\psi \rightarrow \mu^+\mu^-$ trigger requires:[20] two opposite-sign XFT tracks with $p_T \geq 1.5$ (2.0) GeV/c which are matched to CMU (CMX) tracks, and lie in the mass range from 2.7 to 4.0 GeV/c^2.

A dramatic new capability in Run II is a displaced track trigger, thereby keying-in on the long lifetime of weak c/b decays. Originally driven by $B \rightarrow \pi\pi$ physics,[33] this trigger is a tremendous advantage over leptons for accessing fully reconstructed decays. For our purposes the "SVT trigger" is: a L-1 demand for two opposite-sign XFT tracks with $p_T \geq 2.0$ GeV/c, and scalar sum $p_{T1} + p_{T2} \geq 5.5$ GeV/c. At L-2 this seed is used by the SVT to assign r-ϕ SVX measurements and find the impact parameter of the tracks, d_0, with respect to the beamline. An affirmative decision requires that both tracks have $120\,\mu\mathrm{m} \leq d_0 \leq 1.0\,\mathrm{mm}$, a transverse opening angle of $2° \leq |\Delta\phi| \leq 90°$, and $L_{xy} > 200\,\mu\mathrm{m}$. The impact parameter distribution is shown in Fig. 2. The d_0-resolution is $50\,\mu\mathrm{m}$, which includes $\sim 30\,\mu\mathrm{m}$ from the beam profile.

CDF and the Tevatron are not a universal forum for spectroscopy, but the strengths brought to bear nevertheless present important opportunities. I review
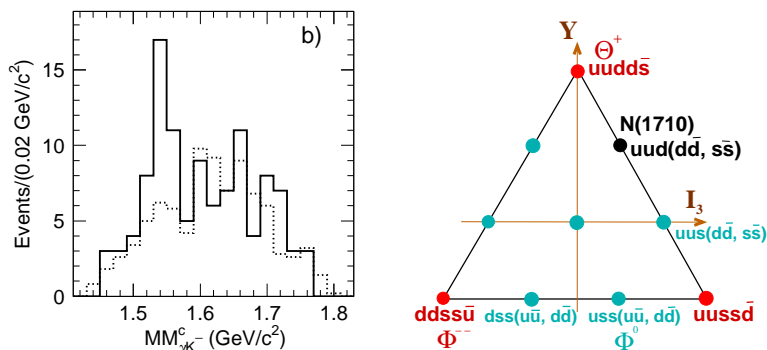
Fig. 3.   **LEFT:** The 'plot that launched a thousand preprints,' the LEPS Θ^+ signal in the nK^+ mass [missing mass recoiling against γK^-] spectra (solid line), and a pK^+ control distribution (dotted line). [*Figure reprinted with permission from T. Nakano et al., Phys. Rev. Lett.* **91**, *012002 (2003). Copyright 2003 by the American Physical Society.*] **RIGHT:** The baryon anti-decuplet of Diakonov *et al.*[35] Note that only the corner states are manifestly exotic.

searches for possible exotic hadrons in CDF II data that were recorded from February 2002 until as recently as August 2004.

3. The Pentaquark Revolution

After decades of disappointments, triumph seemed to be at hand in January 2003: the LEPS Collaboration reported a resonance, now called Θ^+, decaying to nK^+ at $1540\pm10\,\mathrm{MeV}/c^2$ (Fig. 3) in photoproduction ($E_\gamma \sim 1.5\text{-}2.4$ GeV) off of neutrons.[34] With strangeness +1 the Θ^+ is manifestly exotic for a baryon. The minimal quark content is $uudd\bar{s}$, like the old Z-states, but dramatically narrower: $\Gamma_\Theta < 25$ MeV/c^2.

The LEPS search was prompted by the 1997 predictions of Diakonov, Petrov, and Polyakov[35] for a light, ~ 1530 MeV/c^2, and remarkably narrow, $\lesssim 15$ MeV, member of an exotic baryon anti-decuplet anchored by the $N(1710)$ resonance (Fig. 3). The authors motivated the LEPS and DIANA collaborations to conduct a search.[36] After a couple of years both groups independently isolated a signal, although DIANA[37] reported some months after LEPS. DIANA's signal was in the isospin analog pK_S^0 at 1539±2 MeV/c^2 in K^+Xe data ($p_K < 750$ MeV/c). While pK_S^0 has indefinite $s/\bar{s}$ content, the incident K^+ is strong evidence for +1 strangeness.

An avalanche of confirmations ensued (Fig. 4), although individually results are only low to moderate significance. Many are pK_S^0 signals, and thus are evidence for an exotic baryon only by virtue of their consistency in mass with nK^+ observations.

Placing the Θ^+ in an anti-decuplet is not the only option,[41] but failure to find a Θ^{++} partner[42–46] supports Θ^+ as an isosinglet. Finding related states is key, such as excited states[47], but perhaps more telling: other members of the multiplet, *e.g.* the exotic $ddss\bar{u}$ (Fig. 3).[48] In the fall of 2003 NA49 (pp at $\sqrt{s} = 17.2$ GeV) reported -2 strangeness baryons at 1862±2 MeV/c^2 in $\Xi^-\pi^-$, as well as indications of
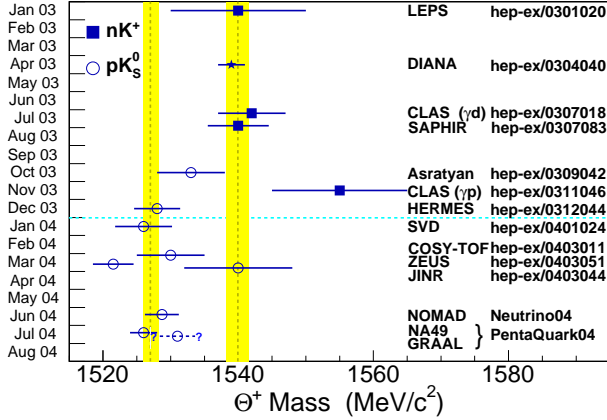
Fig. 4.   Time-line of Θ^+ reports. Dates are from the listed `hep-ex` postings for published results, and conference dates for unpublished[38-40] sightings. Vertical bands show the separate pK_S^0 and nK^+ mass averages and error bands. GRAAL quoted no error, and is excluded from the average. The DIANA result is grouped with "nK^+" because it is flavor specific even though they observe a K_S^0 in the final state.

a partner in $\Xi^-\pi^+$.[49] The $\Xi^-\pi^-$ is necessarily exotic and is interpreted as $ddss\bar{u}$, the $\Phi^{--}(1860)$ [formerly $\Xi_{3/2}^{--}$]; and the other as $udss\bar{d}$, the $\Phi^0(1860)$ [or $\Xi_{3/2}^0$]. To set the scale of the signal, 2191 charged Ξ's were used to obtain 67.5 $\Phi^{--,0}$ candidates—quite a plentiful yield of $\sim 3\%$ of Ξ's—over a background of 76.5. NA49's observation would be an important first step in filling in the anti-decuplet, although the chiral model predicted a heavier mass, around 2070 MeV/c^2.[35]

Pentaquark sightings advanced to the charm sector[50] in March 2004. At a DESY seminar H1 reported[51] a narrow ($\sigma \sim 12$ MeV/c^2) structure at $3099\pm3\pm5$ MeV/c^2 in pD^{*-} and interpreted it as the charm analog of the Θ^+, *i.e.* $uudd\bar{c}$. With 75 pb^{-1} of Deep Inelastic data (ep collisions), they selected 3400 D^{*-}'s after dE/dx particle ID, yielding 50.6 ± 11.2 Θ_c^0's. Another analysis with 4900 D^{*-}'s from photoproduction reproduced the signal—albeit with higher backgrounds—for 43 ± 14 Θ_c^0's. At the same seminar, however, ZEUS reported[52] no signal in 126 pb^{-1} with almost 43k inclusive D^{*-}'s, or ~ 10k in DIS data. ZEUS expects a distinct signal if the Θ_c^0 is a few tenths of a percent of D^{*-}'s, whereas the raw H1 yield per D^{*-} was $\sim 1\%$.

Doubt is not limited to the Θ_c^0. The Φ was quickly challenged by old WA89 data, a high-statistics hyperon experiment.[53] A broader survey concluded that the Φ was "at least partially inconsistent"[54] with a large amount of earlier Ξ data. And, despite many Θ^+ claims, skepticism surfaced here too, including the spectre of kinematic reflections.[55] As widely noted, the nK^+ and pK_S^0 claims do not share a consistent mass (Fig. 4). Also, the absence of Θ^+ in prior KN data limit $\Gamma_\Theta \lesssim 1$ MeV/c^2,[56] too narrow to easily explain.[57] Then, in early 2004, null Θ^+ searches started surfacing.

The Tevatron is an important venue for pentaquark searches by virtue of large hadronic rates and access to all flavors. Conceivably the Tevatron might not be conducive to the manufacture of complex and fragile quark systems, but if so, this too would be interesting. Preliminary results of CDF searches are, so far, all negative.
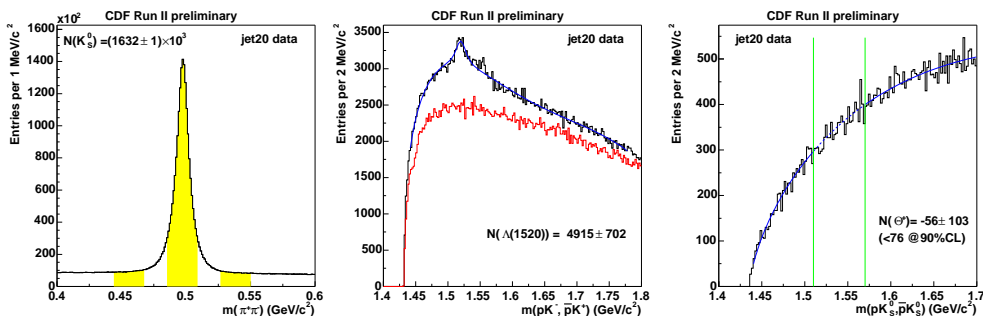
Fig. 5. **LEFT:** The Jet-20 K_s^0 sample used for a Θ^+ search. **Center:** The pK^- spectrum showing the $\Lambda(1520)$ reference signal (upper curve), and same-sign Kp (lower curve). **RIGHT:** The pK_s^0 mass distribution from the Jet-20 sample. Vertical lines mark the Θ^+ search window.

3.1. *The* $\Theta^+(1540)$ *at CDF*[58]

As in many detectors, neutron detection is not viable in CDF, and $\Theta^+(1540) \rightarrow pK_S^0$ is searched for. No CDF trigger preferentially selects these decays. Because Θ^+ production is not understood, two contrasting types of events are used: soft inelastic collisions with minimal trigger requirements, a.k.a. "Min-Bias" events; and hard-scatters which produce jets—at least one that passes a 20 GeV calorimeter jet trigger. The two samples respectively consist of 22.2M and 14.2M events, but as these are very large cross-section triggers the integrated luminosities are only 0.37 nb^{-1} and 0.36 pb^{-1}. Even so, a large sample of 0.67M and 1.6M K_S^0's are available in these respective samples. The K_S^0's from the Jet-20 sample are shown in Fig. 5.

Θ^+ candidates are formed by adding to K_S^0's a charged track, which must be identified by TOF within at least 2σ of a proton. This effectively restricts the protons to momenta from 0.5-2.1 GeV/c. The selection, as well as the use of the TOF, are monitored by reference signals: $\phi \rightarrow K^+K^-$, $\Lambda(1520) \rightarrow K^-$p (Fig. 5), and $K^{*+} \rightarrow K_S^0 \pi^+$. The pK_S^0 mass distribution for Jet-20 data is shown in Fig. 5, the Min-Bias distribution is similar but with about 1/3 the statistics. In both cases no signal is apparent around 1540 MeV/c^2. Counting events in the signal region of 1510 to 1570 MeV/c^2 (vertical bars on the plot) and using K_S^0 sidebands to subtract background, the fitted Θ^+ "excess" is 18 ± 56 Jet-20 candidates and -56 ± 103 for Min-Bias, or: not more than 76 (89) Θ^+ candidates for Jet-20 (Min-Bias) at 90% CL.

Incisive comparisons across the diverse Θ^+ reports are problematic as we lack theoretical bridges to connect them. The only signal in a environment analogous to CDF's comes from HERA, a high-energy ep-collider. There, based on 0.87M K_S^0's, ZEUS sees 221 ± 48 Θ^+'s.[59] In terms of raw K_S^0's, CDF should have a fair signal.
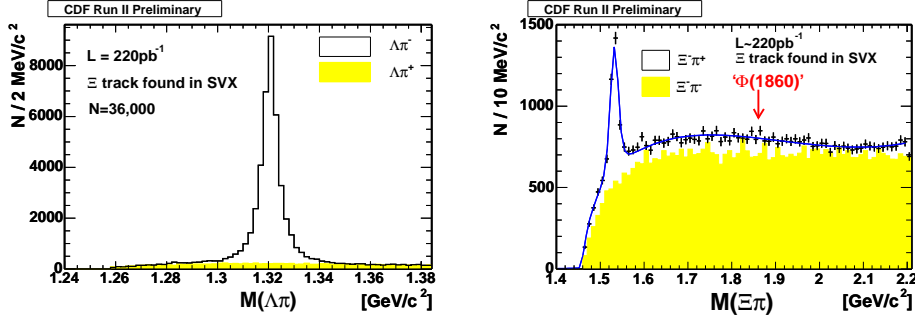
Fig. 6.   **LEFT:** $\Lambda\pi$ mass spectrum (and "wrong-sign" $\Lambda^0\pi^+$ background) for candidates where a Ξ track was found in SVX (SVT trigger sample). **RIGHT:** The $\Xi^-\pi^+$ (points) and $\Xi^-\pi^-$ (shaded histogram) mass distributions. The arrow marks the $\Phi(1860)$-mass reported by NA49.

3.2. *The $\Phi(1860)$ at CDF* [60]

As in the Θ^+ search, no CDF trigger explicitly keys on $\Phi(1860)\rightarrow\Xi\pi$. Two complementary triggers are used: Jet-20 again, and 220 pb^{-1} of SVT triggers. Displaced tracks *are* produced in Ξ decays, but these are *too far* away for the SVT to trigger.

Reconstructing $\Lambda^0\rightarrow p\pi^-$ is straightforward. More subtle is $\Xi^-\rightarrow\Lambda^0\pi^-$. The Ξ is *charged*, with almost half the Λ^0 lifetime, and will often leave hits in the SVX. A specialized reconstruction is used whereby displaced pions are added to Λ^0's to form Ξ^- candidates, and potential Ξ^- SVX-hits are sought for a full Ξ^- track fit. In the SVT data ~ 36k Ξ^-'s are cleanly reconstructed (Fig. 6), and ~ 5k in Jet-20.

A $\Phi\rightarrow\Xi\pi$ search has a good control signal in $\Xi^0(1530)\rightarrow\Xi^-\pi^+$, of which there are $2,200\pm100$ in the SVT data, and 390 ± 30 in Jet-20. The $\Xi^0(1530)$ is prominent in the $\Xi^-\pi^+$ distribution of Fig. 6, but no other structures are seen there, or, in the $\Xi^-\pi^-$ masses. The limit on the number of Φ candidates is expressed relative to the raw number of observed $\Xi^0(1530)$'s. Imposing an 1860-resonance fit in the $\Xi^-\pi^-$ SVT data yields -54 ± 47 candidates, or a 90% CL limit of 51 $\Phi^{--}(1860)$'s. This translates into the limit $R^{--}\equiv N(\Phi^{--})/N(1530)<0.03$ at 90% CL. Similarly, $R^0 < 0.06$, or combining both channels $R^{Tot} < 0.07$ at 90% CL. The limit on the ratio is not corrected for acceptance, but this is not expected to be a large effect. For the Jet-20 samples the limits are $R_{20}^{--} < 0.07$, $R_{20}^0 < 0.06$, and $R_{20}^{Tot} < 0.09$.

CDF's raw sensitivity compares well with NA49's. CDF's Ξ^- sample is more than $10\times$ the ~ 2000 Ξ^-'s of NA49. With a looser selection [61] that is more sensitive to the $\Xi(1530)$, the NA49 Φ yield appears to be $\sim 50\%$ of $\Xi(1530)$, well above CDF's $<10\%$ limits. Note that the $\Xi(1530)/\Xi$ ratio is similar for both experiments.

3.3. *Charm Pentaquarks at CDF* [58,62]

An important distinction for a $\Theta_c^0(3100)\rightarrow pD^{*-}$ search in CDF,[58] versus those for Θ^+ and Φ, is that the SVT trigger is aimed at D decays. In 240 pb^{-1} of data CDF
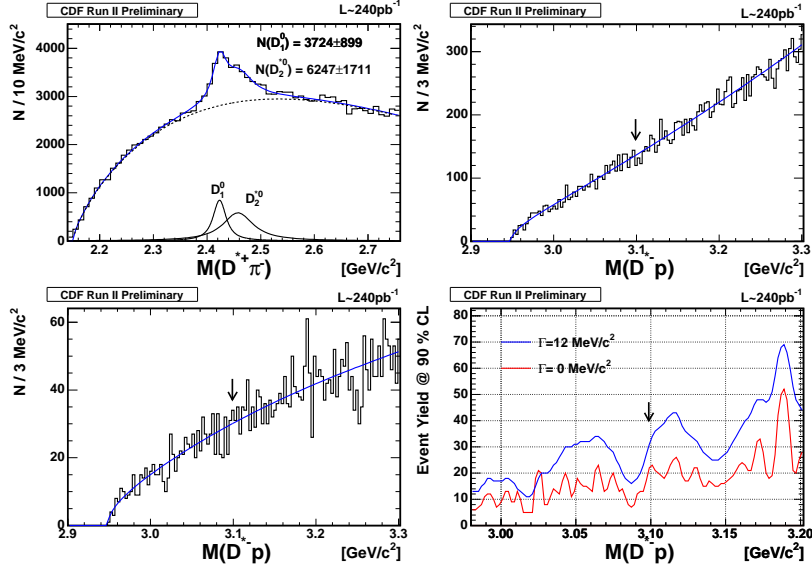
Fig. 7. **TOP-LEFT:** prompt $D^{*+}\pi^-$ mass spectrum, where overlapping $D_1^0(2420)$ and $D_2^0(2460)$ are clearly visible. **TOP-RIGHT:** pD^{*-} masses for the prompt sample (no PID). **BOTTOM-LEFT:** pD^{*-} masses for the long-lived sample (no PID). **BOTTOM-RIGHT:** 90% upper limit as a function of mass in the long-lived sample for two Θ_c widths. The arrows mark H1's Θ_c^0 mass.
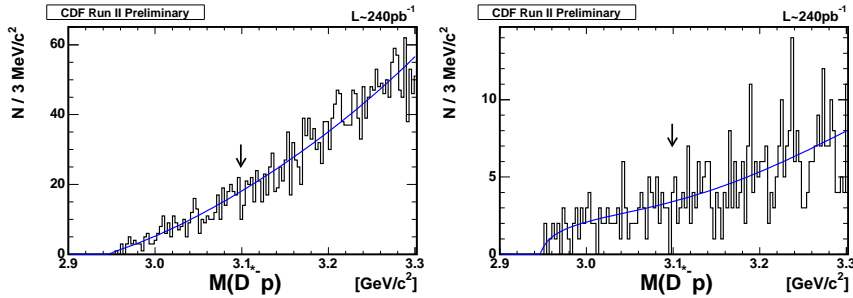

Fig. 8. The pD^{*-} mass spectra for prompt (left) and long-lived (right) selections with p-ID.

has $\sim$3M $D^0 \to K^-\pi^+$ decays. Adding a $p_T > 400$ MeV/c pion yields $\sim$0.5M D^{*+}. Adding another such pion leads to reference states $D_1^0(2420)$ or $D_2^0(2460)$. These are clearly seen in Fig. 7, even though partially overlapping due to their large natural widths. Alternatively, assigning a proton to the latter track produces Θ_c^0 candidates.

Since Θ_c^0's might arise via long-lived b-decays, or prompt production, CDF distinguishes prompt ($|L_{xy}| < 400\,\mu$m & $|L_{xy}|/\sigma_{L_{xy}} < 3$) and long-lived ($L_{xy} > 400\,\mu$m & $L_{xy}/\sigma_{L_{xy}} > 3$) samples. No $D^{*-}p$ excess is seen at $\sim$3099 MeV/c^2 in either case (Fig. 7). Mass dependent 90% CL limits are shown in Fig. 7 for the "b-sample." In
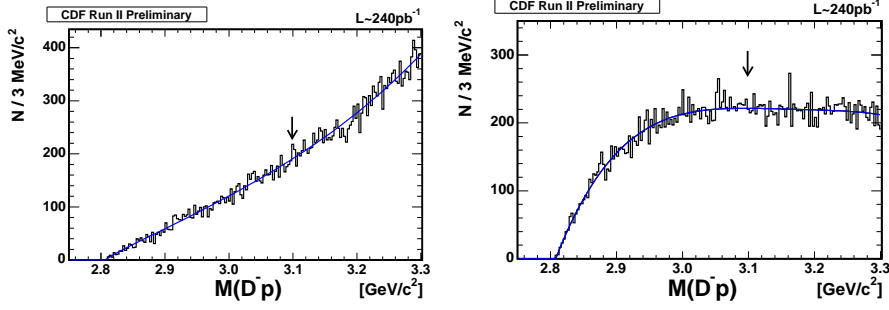
Fig. 9.   The prompt (left) and long-lived (right) pD^- mass spectra (arrows mark H1 mass).
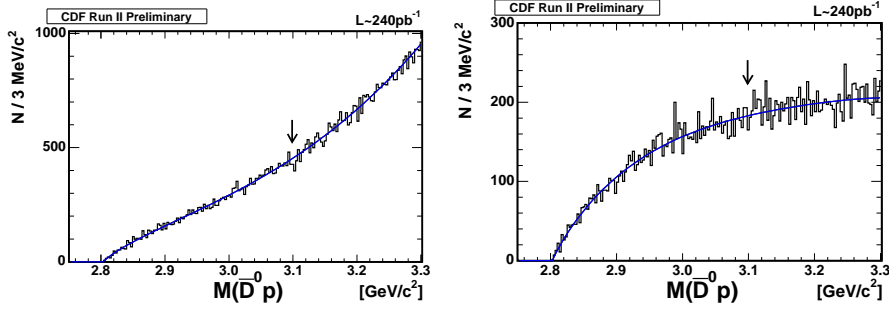
Fig. 10.   The prompt (left) and long-lived (right) $p\overline{D}^0$ mass spectra (arrows mark H1 mass).

the signal region, $3100\pm18\,\mathrm{MeV}/c^2$, the maximum limit is 43 Θ_c^0's ($\Gamma_\Theta = 12$ MeV/c^2), or 71 for prompt. Sensitivity is improved by particle ID. Protons were identified using a likelihood ratio (e, μ, π, K, and p hypotheses) combining dE/dx and TOF measurements, with the cut optimized on 2.5k $\Lambda_c \to pK^-\pi^+$ decays. The new pD^{*-} plots are in Fig. 8. The maximum yields become 32 prompt and 15 long-lived Θ_c^0's, although part of this reduction is due to the efficiency ($\sim 70\%$) of the proton cut.

CDF extended their search[62] to various analog channels: $\Theta_c^0 \to pD^-$, and $\Theta_c^+ \to p\overline{D}^0$ ($uuud\bar{c}$), and even pD^0 ($uudc\bar{u}$). Figure 9 shows the results for pD^- after proton ID for prompt and long-lived samples. The $p\overline{D}^0$ results are in Fig. 10. The pD^0 plots are not shown here, but are similar to Fig. 10. No signals are apparent, and the upper limits ($\Gamma_\Theta = 12$ MeV/c^2) on candidates may be summarized as:

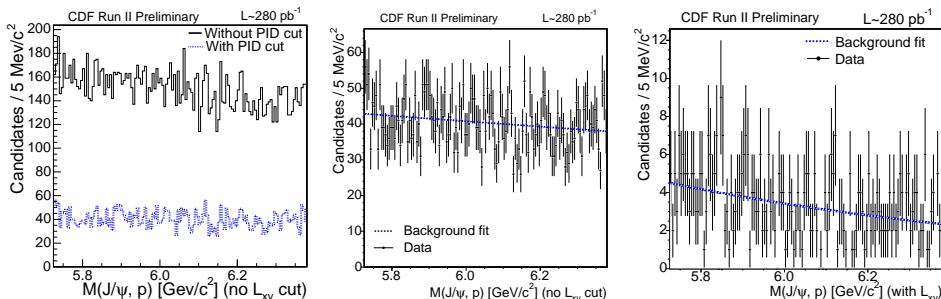| Mode	Content	Prmt & L-L 90% CL		Reference Mode & Yield
pD^{*-}	$uudd\bar{c}$	< 32	< 15	$D_1^{*0}(2420) \to D^{*+}\pi^-$ $3.7 \pm 0.9\,\mathrm{k}$
				$D_2^{*0}(2460) \to D^{*+}\pi^-$ $6.2 \pm 1.7\,\mathrm{k}$
pD^-	$uudd\bar{c}$	< 84	< 118	$D_2^{*0}(2460) \to D^+\pi^-$ $31.7 \pm 1.3\,\mathrm{k}$
$p\overline{D}^0$	$uuud\bar{c}$	< 122	< 214	$D_2^{*-}(2460) \to D^0\pi^-$ $15.3 \pm 1.6\,\mathrm{k}$
pD^0	$uudc\bar{u}$	< 245	< 174	" "

Fig. 11.   **LEFT:** The pJ/ψ mass distribution without particle ID (top histogram) and with proton ID cuts (bottom). **CENTER:** The pJ/ψ masses with proton ID (enlargement of lower histogram in the left plot), with a linear background fit. **RIGHT:** The pJ/ψ masses with proton ID and $L_{xy} > 100\,\mu$m cut for a long-lived pentaquark search.

CDF's $\Theta_c^+(3100)$ limits are below H1's report, yet their precursor D^{*-} sample dwarfs that of H1 by two orders of magnitude, and all other null searches[52,63–65] by more than ten times. If the Θ_c^+ exists, it is remarkably suppressed at the Tevatron!

3.4. *Bottom Pentaquarks at CDF*[66]

The Tevatron offers potentially exclusive access to *b*-pentaquarks. CDF has made one such search: $R_s^+(uuds\bar{b})$, predicted at $\sim$5920 MeV/c^2,[67] decaying *weakly* to pJ/ψ. Candidates are made by combining J/ψ's (280 pb^{-1}) with a charged track. The reference mode is 2.4k of $B^+ \to J/\psi K^+$. Proton ID again uses the combined likelihood. The pJ/ψ spectrum both before and after the ID is shown in Fig. 11. With proton ID the maximum 90% CL over 5800-6305 MeV/c^2 is 76 R_s^+'s. As a weak decay, R_s^+ could be long-lived: for $L_{xy} > 100\,\mu$m (Fig. 11) the limit is 21 R_s^+'s.

3.5. *Pentaquark Reprise*

All CDF searches lack any hint of pentaquarks, even though the size of precursor samples exceeds the most comparable positive experiment. But in this, CDF is not unique. A wide range of experiments now report null results (Table 1). Many also have larger reference signals than do claimants. The Φ and Θ_c^0 have a single sighting in contrast to a mounting number of non-observations. The Θ^+ has about a dozen confirmations to its credit, but they are now outnumbered by null searches.

The primary refuge for reconciling null searches with sightings lies in the possible peculiarities of production. Most sightings are at low energies, often in exclusive reactions. Production at higher energies is predominantly through fragmentation, or via B-decay, which are quite different from low-energy processes. Models of inclusive pentaquark production are rudimentary, but several have been proffered.

In one, the fragmentation probability, $f(\bar{c} \to \Theta_c^0)$, is estimated from that of D and Λ_c^+.[84] That author finds $f(\bar{c} \to \Theta_c^0) \simeq$ (2-7)$\times 10^{-3}$, consistent with H1's raw D^{*-}

Table 1. Summary of experiments reporting negative pentaquark searches since LEPS reported the Θ^+. Entries are the citation number in this review. Instances where one of these experiments has also reported a signal are indicated by a "√." For the production modes "A" represents a nucleus, and "h" some set of hadron projectiles (e.g. p, π,...).

Pentaquark Channel	1st Observation	CLAS γp	HERMES γD	SPHINX pA	FOCUS γA	COMPASS μA	HyperCP hA	SELEX hA	WA89 ΣA	E690 pA	HERA-B pA	BES $\psi(S)$	BABAR $\Upsilon(4S)$	Belle	PHENIX $-AA-$	STAR	ALEPH $-Z^0-$	DELPHI	L3	Zeus ep	CDF II $\bar{p}p$
$\Theta^+ \to NK$	LEPS[34]	√	√	68	69	—	70	71	—	72	73	74	75	65	76	77	63	44	78	√	58
$\Theta^{++} \to pK^+$	—	42	43	—	—	—	—	—	—	—	—	—	46	65	—	—	—	44	—	45	—
$N_5/\Xi_5 \to \Lambda K$	STAR[48]	—	—	—	—	—	—	—	—	—	—	—	79	—	—	√	—	—	—	—	—
$\to \Sigma^0 K$	—	—	—	—	—	—	—	—	—	—	—	—	80	—	—	—	—	—	—	—	—
$\Phi \to \Xi^- \pi^\pm$	NA49[49]	—	81	—	69	82	—	—	53	72	73	—	79	83	—	—	63	—	—	45	60
$\Theta_c^0 \to pD^{*-}$	H1[51]	—	—	—	64	—	—	—	—	—	—	—	—	65	—	—	63	—	—	52	58
$\to pD^-$	—	—	—	—	64	—	—	—	—	—	—	—	—	65	—	—	63	—	—	—	62
$\Theta_c^+ \to p\overline{D}^0$	—	—	—	—	—	—	—	—	—	—	—	—	—	65	—	—	63	—	—	—	62
$\to pD^0$	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	62
$R_s^+ \to pJ/\psi$	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	66

(Negative Pentaquark Search Exps. — Fixed Target: CLAS … HERA-B; Low−E e^+e^-: BES, BABAR, Belle; High-E Collider: PHENIX … CDF II.)

and Θ_c^0 rates. Translating to the Tevatron for 200 pb^{-1}: 8-28 M Θ_c^0's are produced! Alternatively, a "coalescence" model[85] scales the joint p and D^{*-} production rates to a regime where the p and D^{*-} form a Θ_c^0. Using H1's rate to set the absolute scale, there are ~ 50M Θ_c^0's for 200 pb^{-1}. CDF efficiencies have not been applied, but it is surprising that a signal should elude CDF with H1-like Θ_c^0-rates.

Another approach is a statistical ("microcanonical") model for pp interactions.[86] This *does* favor low-energy Θ^+ production due to the importance of $p+p \to \Theta^+ + \Sigma^+$. But even so, the model predicts a fairly flat high-energy limit of $\sim 1\%$ Θ^+'s/event— a huge rate for CDF, even if low-p_T is favored. The prediction for the Φ^{--}/Ξ^- ratio is $\sim 2\%$ at the SPS—in line with NA49. But the ratio increases with energy by $\sim 3\times$ at the Tevatron, exacerbating the inconsistency posed by CDF's null result.

If the key to Θ^+ and Φ production at low energies is the incorporation of quarks from an initial baryon, then it is difficult to translate lessons from low-energy experiments to the central rapidities studied by CDF. One such model[87] predicts high rates ($\gtrsim 10^{-3}\,\Theta^+$/event for $pp \to \Theta^+ \dots$)—but at high-rapidities/low-p_T's—making *these* Θ^+'s invisible to CDF. Similarly, it has been argued[88] that the apparent production discrepancies may be due to the kinematic and combinatoric advantages of low-energy, or particularly, exclusive reactions, where most claims arise. This is based, in part, on an analysis which concludes that Θ^+ production in a range of processes falls more rapidly with energy (p_T) than normal hyperons,[89] undermining high-energy searches. But as these authors[89] note: the processes considered, including a *target* fragmentation model, are kinematically linked to the initial baryons and are *not relevant* to the *central* production of CDF. While this particular suppression

is not in play, what suppression lurks in the parton fragmentation is another matter.

One may hesitate relying on these production models for pentaquarks, particularly when "data points" used to normalize some models are themselves uncertain. A simple empirical foil to consider is deuteron production as a stand-in for pentaquarks. The ratio of anti-deuteron to anti-proton production scales well across many high-energy processes (expected in coalescence models). For example, the ratio is very similar in pp collisions at the ISR and photoproduction at HERA. The $\bar{d}/\bar{p}$ ratio is $\sim 10^{-3}$ at $p_T/M = 0.2$, and falls by half at $p_T/M \sim 0.5$.[90] If one takes Φ/Ξ^- ratio as the appropriate analog to $\bar{d}/\bar{p}$, the NA49 ratio of $\sim 3\%$ is at least an order of magnitude more plentiful than implied by the deuteron analogy. Similar scaling of Θ^+ reports gives ratios spanning several factors of ten. Scaling[91] CDF limits gives $\Theta^+/\Lambda^0 \lesssim 0.02\%$—below the deuteron-inspired rates—while the Zeus[59] signal gives $\Theta^+/\Lambda^0 \sim 0.1\%$. The above comparisons cavalierly ignore detection efficiencies, which maybe quite important as the $\bar{d}/\bar{p}$-ratio falls with p_T. As noted by critics, this is an important weakness of fragmentation dominated experiments compared to the low-energy Θ^+ sightings. However, the suppression suggested by $\bar{d}/\bar{p}$ is no where as extreme as sometimes claimed for pentaquarks (*e.g.* $\Theta^+/\Lambda(\underline{1520}) < 10^{-3}$)[92]

The contrast between high-energy fragmentation *à la* CDF and low-energy, especially exclusive, Θ^+ production is sufficient that little inference can be drawn from one to the other without a robust theoretical link. Low-energy Θ^+ proponents can justifiably raise production arguments to explain away high-energy null searches—but only at the risk of abandoning their high-energy compatriots: such as Θ^+ by ZEUS. Indeed, the quantity and quality of negative searches present an impressive challenge, and it seems likely that at least *some* claims will fall. The strongest case rests with the Θ^+, where production advantages may truly favor some observations. Of critical importance are high-statistics studies from experiments claiming signals. These have been advertised as imminent,[88] and the first preliminary result has just appeared from from CLAS: a search for $\gamma p \to \Theta^+ \overline{K}^0$ has *failed* to observe a signal with 95%CL limit of $\Theta^+/\Lambda(1520) < 0.2\%$![93] If any pentaquark claims are yet vindicated, it will be interesting to learn why they are so suppressed at the Tevatron.

4. "Anomalous" D_{sJ}^+ States

Pentaquarks were only the start of spectroscopic excitement in 2003. BABAR announced a narrow state ~ 2317 MeV/c^2 decaying to $D_s^+ \pi^0$ in April.[94] Based on a hint from BABAR,[94] CLEO quickly claimed another at ~ 2460 MeV/c^2 in $D_s^{*+} \pi^0$.[95] The benign interpretation is that these are the missing 0^{++} and 1^{++} D_s^{**} states, which would complete the $L = 1$ family along with $D_{s1}^+(2536)$ (1^{+-}) and $D_{s2}^+(2573)$ (2^{++}). But as such, these new states were much lighter and narrower $(< 10$ MeV) than expected. The D_s^{**} were thought to follow the non-strange D^{**}'s: very broad 0^{++} and 1^{++} states which recent measurements put $\Gamma \sim 240$-400 MeV.[96] The $D_{sJ}^+(2317)$ did not look as the $D_{s0}^+(0^+)$ should. BABAR suggested it might be a $q\bar{q}c\bar{s}$ state.[97]
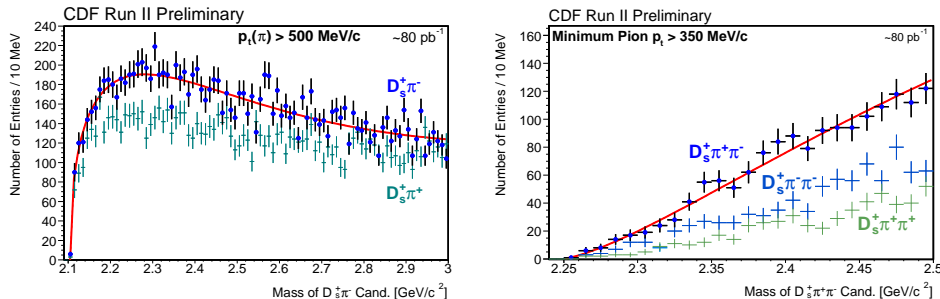
Fig. 12. **LEFT:** Mass distributions of $D_s^+\pi^-$ and $D_s^\pm\pi^\pm$ for pions with $p_T > 500$ MeV$/c$. **RIGHT:** Mass distributions of $D_s^+\pi^+\pi^-$ and $D_s^+\pi^\pm\pi^\pm$ for pions with $p_T > 350$ MeV$/c$.

CDF is ill-suited for low-energy γ-detection, and thus for $D_s^{(*)+}\pi^0$. If, however, these new states were 4-quark systems, or more generally had isospin partners, there could be $D_s^+\pi^-$ or $D_s^+\pi^+\pi^-$ resonances. The latter decay is also allowed if the $D_{sJ}^+(2460)$ is a 1^{++}, but forbidden for 0^{++}. CDF searched for these using 80 pb^{-1} (24.6k D_s^+'s), resulting in the spectra of Fig. 12—no signals are seen.[98] To gauge the sensitivity, BaBar's ~ 1300 $D_{sJ}^+(2317)$'s were based on $\sim 80k$ D_s^+'s, or $\sim 3\times$ that of CDF. While the origin of D_s^+'s can be different for the two experiments, CDF is in the ball-park to see a $D_s^+\pi^-$ analog given the large BaBar signal.[99] For a 1^{++}, $D_s^+\pi^+\pi^-$ would be suppressed relative to $D_s^{*+}\pi^0$. Belle later found a small signal [59.7±11.5 $D_{sJ}^+(2460)$'s] and found the ratio of $D_{sJ}^+(2460) \to D_s^+\pi^+\pi^-$ to $D_s^{*+}\pi^0$ to be $14\pm4\pm2\,\%$.[100] By naïve scaling, this is below CDF sensitivity with 80 pb^{-1}.

The new D_{sJ}^+'s excited spectroscopists, but radical explanations now seem premature. Neither state is mysterious *once* their masses are understood. Small widths arise naturally for the $D_{sJ}(2317)$ and $D_{sJ}^*(2460)$ as 0^+ and 1^+ if they are below the DK and D^*K thresholds respectively. As such, the preferred decay is excluded, and the isospin violating $D_s^{(*)}\pi^0$ is the main hadronic mode. It was soon noted[101] that potential models are free to move D_s^{**} masses more than usually appreciated. It was also argued,[102] light masses follow from chiral symmetry in QCD: the ground state parity doublet, D_s^+ and D_s^{*+} (0^-, 1^-), is paired with 0^+ and 1^+ excited states, and chiral symmetry breaking raises the (0^+, 1^+) doublet close to that of the D_{sJ}'s.

Studies of decay modes and angular analyses support $D_{s0}^*(2317)$ and $D_{s1}'(2460)$ assignments.[103] But there is not unanimity, and exotic proposals persist.[104,105] Lest the dust seem settled, SELEX recently kicked up a new cloud with a narrow state $D_{sJ}^+(2632) \to D_s^+\eta$, and a weaker D^0K^+ signal.[106] New puzzles arise:[107] Why so narrow? Why is the $D_s^+\eta$ rate $\sim 6\times$ larger than D^0K^+? The mystery is heightened by BaBar's failure to see $D_{sJ}^+(2632) \to D^0K^+$ while having a much larger $D_{s2}^+(2573) \to D^0K^+$ yield.[108] SELEX counters[106] that their production is distinctive by virtue of their Σ^- beam. CDF has a large $D_{s2}^+(2573) \to D^0K^+$ sample—it will be interesting to see them search. But so far,

the odds favor the D_{sJ}'s as just D_s^{**}'s.

5. The $\boldsymbol{X}$-Files

After a series of null results we close with a state CDF *has* confirmed, but whose nature is a mystery: the $X(3872)$. It is a tale we begin by recounting a bit of history.

5.1. *A Little Charmonium History*

Our understanding of hadrons was revolutionized by studying $c\bar{c}$-states, starting with the J/ψ in 1974.[109] Mapping $c\bar{c}$-states was largely done in the 70s in e^+e^- annihilation. A limitation of e^+e^- is that only systems with photon quantum-numbers are formed—*i.e.*, only J/ψ, $\psi(2S)$, $\psi(3770)$, ... are directly accessed. Almost all $c\bar{c}$-states below the $\psi(2S)$ (*i.e.* η_c [$^1S_0$] and χ_c [$^3P_{0,1,2}$]) were reached via radiative $\psi(2S)$ decays. Once these were found, e^+e^- colliders were at a dead-end. Heavier 1^{--} states, *e.g.* $\psi(3770)$, are useless as they are above the $D\overline{D}$ threshold and are broad, with tiny decay rates to lighter $c\bar{c}$-states. The hunt shifted to other venues.

The h_c ($^1P_1$) is the lone state inaccessible [110] via γ-decays of the $\psi(2S)$. Searches for this state shifted to hadronic production, notably $\bar{p}p$ annihilation. From the mid-1980s a few h_c claims surfaced.[111,112] These were consistent, but individually weak observations, leading the PDG to classify the h_c as "needing confirmation."

By the early 1990s all $c\bar{c}$-states below the $\psi(2S)$ were ostensibly[113] seen—only those above $D\overline{D}$ remained. But such states rapidly decay to open charm, making them broad and difficult to find. For example, the $\psi(3770)$ ($^3D_1$) is just above $D\overline{D}$, and yet $\Gamma \sim 20$ MeV/c^2. Heavier states grow ever fatter. The $^3D_2$ is an exception, its spin-parity (2^{--}) prohibits $D\overline{D}$ decay. The $^3D_2$ is prime quarry for charmonium hunters: a narrow state which might be seen in the distinctive $J/\psi\pi^+\pi^-$ mode.

In 1994 E705 (300 GeV/c π/p-Li) published, along with a hint of the h_c, a 2.8σ excess in $J/\psi\pi^+\pi^-$ at ~ 3836 MeV/c^2.[112] The $^3D_2$ was the obvious interpretation, but the $c\bar{c}q\bar{q}$ option[114] was noted. The 58 ± 21 excess was a large fraction of their raw 77 ± 21 $\psi(2S)$ yield; but no excess was seen by E672/E706[115] (515 GeV/c π^--Be)—a higher statistics [224 ± 48 $\psi(2S)$] result with better resolution. A signal might also be expected in CDF Run I data given their much larger $\psi(2S)$ sample [$\sim 2k$] and superior resolution. Nothing was noticed there at ~ 3836 MeV/c^2,[116] nor by BES in $e^+e^- \to J/\psi\pi^+\pi^-+anything$.[117] But it is unclear how the latter translates to E705.

5.2. *Discovery of the $X(3872)$*

In the early days of b-physics it was realized that b-hadrons often decay to $c\bar{c}$ since a favored chain is $b \to cW^-$, $W^- \to s\bar{c}$.[118] Indeed, CLEO found $B \to J/\psi+anything$ to be $\sim 1\%$.[119] In the early 1980's, this was viewed as a tool for studying b-physics. Decades later, some in Belle appreciated that this could be "inverted" to exploit B's *for studying charmonium*. The $c\bar{c}$ dead-end for e^+e^- colliders could be evaded by using feeddown from B's instead of $\psi(2S)$'s. Belle demonstrated this by observing
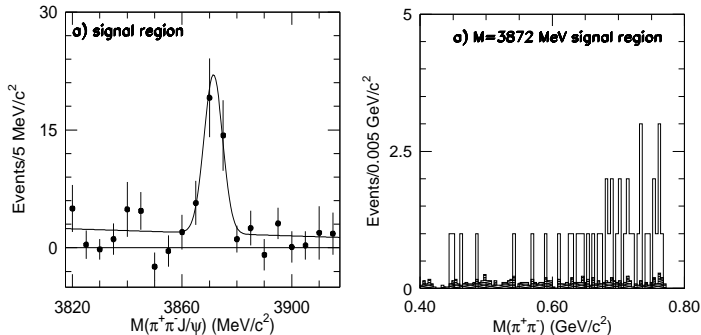
Fig. 13.   **LEFT:** The $J/\psi\pi^+\pi^-$ mass spectrum from Belle[125] showing the $X(3872)$. **RIGHT:** The corresponding dipion masses. The hatched histogram are sidebands normalized to signal area.

$B^+ \to \psi(3770)K^+$,[120] and more significantly, used $B \to KK_sK^\pm\pi^\pm$ to rediscover the $\eta_c(2S)$.[121] Crystal Ball claimed[122] the $\eta_c(2S)$ at ~ 3594 MeV/c^2 over twenty years ago; but Belle now found it at ~ 3654 MeV/c^2, and was so confirmed.[123]

In Belle's $\eta_c(2S)$ studies a stray bump was spotted that turned out to be a reflection of a new $J/\psi\pi^+\pi^-$ resonance at $3872.0\pm0.6\pm0.5$ MeV/c^2 (Fig. 13),[124] later dubbed $X(3872)$. The impulse was to take this as the long-sought $^3D_2$, but *that* was expected at ~ 3820 MeV/c^2.[126] It should also have a prominent $\chi_{c1}\gamma$ decay, which was not seen. Being virtually at the $D^0\overline{D}^{*0}$ mass, Belle speculated the $X(3872)$ could be a $D^0\overline{D}^{*0}$ "molecule."[114] The exotic prospects[105,127–131] provoked great interest, and it is questionable whether standard $c\bar{c}$[132,133] can accommodate this state.

5.3. *The $X(3872)$ at CDF*

5.3.1. *Observation and Mass Measurement[134]*

Belle announced their discovery of $B^+ \to X(3872)K^+$ in August 2003 at the Lepton-Photon Symposium.[125] Coincidently, a continuation of a Run I search for the $^3D_2$ was being prepared in CDF. Once Belle's preprint appeared, the search was expedited and $X \to J/\psi\pi^+\pi^-$ was sighted eight days later. CDF publicly confirmed the $X(3872)$ at a Quarkonium Workshop held at Fermilab in September.[135]

The CDF search began with 220 pb^{-1} of $J/\psi \to \mu^+\mu^-$ triggers. The challenge at the Tevatron is background, and due to large particle multiplicities per event this can be fierce when combining two charged particles to a J/ψ. Because of fluctuations in multiplicity, some events have many background candidates with little prospect of signal. A loose preselection was made, and events with more than 12 $J/\psi\pi\pi$ candidates with masses below 4.5 GeV/c^2 were rejected. The preselection was mainly based on track quality cuts and fitting the $J/\psi\pi\pi$ system to a common vertex.

The selection was tightened by demanding: smaller $\mu^+\mu^-\pi^+\pi^-$-vertex fit χ^2's; $M(\mu^+\mu^-)$ be within 60 MeV/c^2 ($\sim 4\sigma$) of the J/ψ; $p_T(J/\psi) > 4$ GeV/c; $p_T(\pi) >$

400 MeV/c; and $\Delta R(\pi) < 0.7$ for both pions, where $\Delta R(\pi)$ is relative to the $J/\psi\pi\pi$ system. The resulting mass distributions are shown in Fig. 14. A large $\psi(2S)$ peak is seen, as well as a smaller bump at ~ 3872 MeV/c^2. No structure is apparent in $J/\psi\pi^{\pm}\pi^{\pm}$. Gaussian fits to the peaks yield 5790 ± 140 $\psi(2S)$ and 580 ± 100 $X(3872)$.

Belle noted (Fig. 13) that the X strongly favored high $M(\pi\pi)$. CDF confirmed this by splitting the sample into $M(\pi\pi)$ above, and below, 500 MeV/c^2 (Fig. 14). No X-signal is discernible in the low-mass sample. For high-$M(\pi\pi)$ the X-mass is $3871.3 \pm 0.7 \pm 0.4$ MeV/c^2, with a resolution dominated σ of $4.9 \pm 0.7 \, (stat)$ MeV/c^2. This mass is in good agreement with, and similar precision to Belle's (Fig. 15). The remarkable proximity of the X to the $D^0\overline{D}^{*0}$ threshold fuels molecular speculations.

5.3.2. $X(3872)$ Production at CDF[138]

Properties of X production present an opportunity to garner insights into its nature. Given Belle's discovery, B's are clearly an important source of the X, but is this how CDF's signal arises? If not, can direct X production in $\bar{p}p$ collisions shed light into its nature? Specifically, does X production in CDF differ from charmonia?

Charmonia production has been extensively studied in $\bar{p}p$,[139–144] and provided the experimental impetus[139] for the so-called "NRQCD factorization model."[142] At the Tevatron, charmonia arise as a mixture of "direct" production from fragmentation plus feeddown from higher-mass states. An important source of feeddown is b-hadrons: they produce $\sim 10 - 20\%$ of J/ψ, χ_c, and $\psi(2S)$. The actual fractions depend upon species and p_T. If the X is not simple $c\bar{c}$, it may have a very different production rate, particularly if it is a fragile molecule bound by only an MeV or so.

A standard method[139] to separate b sources from "prompt," *i.e.* either directly
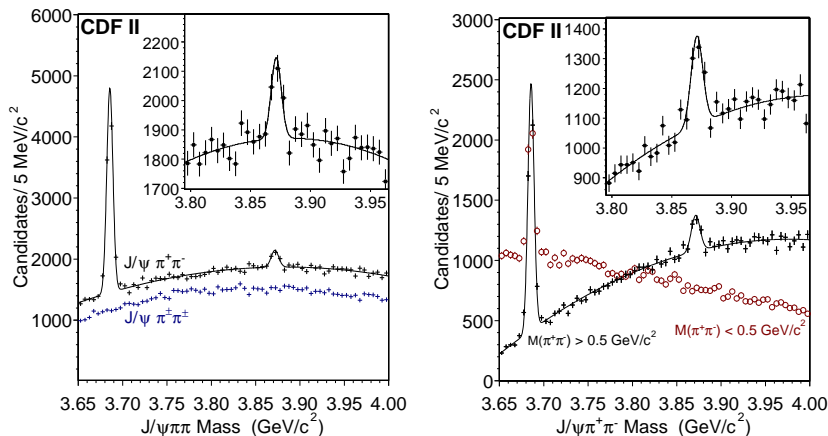

Fig. 14. **LEFT:** The $J/\psi\pi\pi$ mass distributions for same, and opposite, sign pions of the full selection. **RIGHT:** The $J/\psi\pi^+\pi^-$ mass for $M(\pi\pi) < 500$ and > 500 MeV/c^2 subsamples. [*Figures reprinted with permission from D. Acosta et al., Phys. Rev. Lett. **93**, 072001 (2004). Copyright 2004 by the American Physical Society.*]
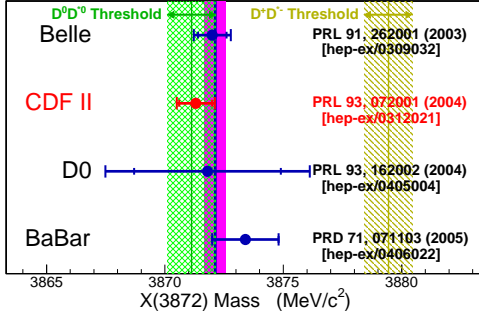
Fig. 15. Summary of X-mass measurements for all observations[124,134,136,137] compared to the $D^0\overline{D}^{*0}$ and D^+D^{*-} thresholds. Vertical lines indicate central values, and bands the range of uncertainty in measured masses—the dark solid band is for the $X(3872)$.

produced or from decays of short-lived particles, is to measure a particle's apparent "lifetime." Since the X does not decay weakly, its true lifetime is far too short for it to travel a discernible distance. Any observed displacement, L_{xy} (Eq. 1), is ascribed to "$b \to X \ldots$" decays. In the X selection $p_T(J/\psi)$ is above 4 GeV/c, ensuring sufficient boost such that b decays can not mimic prompt production. The displacement is converted into "uncorrected proper-time" by $ct \equiv M \cdot L_{xy}/p_T$. This is "uncorrected" because the mass and p_T of the $J/\psi\pi^+\pi^-$ are only part of the b-decay, and so ct is not the true proper decay-time. The ct distribution will not give the correct b lifetime, but it still quantifies the *fraction* of $b \to X \ldots$ decays.

DØ took a step in this direction when they compared the fractions of signal that had $ct > 100\,\mu$m, and found $30.0 \pm 1.8\,(stat)\%$ for $\psi(2S)$ and $31.8 \pm 6.7\,(stat)\%$ for X.[136] By this measure the states look identical, but the prompt and b production sources are not actually disentangled, nor is the ct-resolution specified. Parenthetically we note that DØ considered other production features using this type of binary comparison. In each case the X and $\psi(2S)$ were indistinguishable; but lacking theoretical models one cannot assess the significance of such null comparisons.

CDF's separation[138] of prompt and b components begins with the same sample used in the mass measurement. Since precise vertexing is fundamental for measuring L_{xy}, additional SVX and beamline criteria are applied. The sample is reduced by $\sim 15\%$, where the main loss is from rejecting candidates with L_{xy} errors above $125\,\mu$m. An unbinned likelihood fit is performed in mass and ct to obtain the long-lived fraction. The mass is modeled by a Gaussian for signal and a quadratic polynomial for background. In ct, the long-lived signal is an exponential smeared by the resolution function (double Gaussian), and the prompt part is the resolution function. Long-lived backgrounds are also modeled by resolution smeared exponentials.

The fit results are portrayed in Fig. 16 by projecting the likelihood PDF onto the ct distribution of the data, which is well described. In this sample $28.3 \pm 1.0 \pm 0.7\,\%$ of $\psi(2S)$'s are long-lived—similar to Run I.[139] The $M(\pi\pi) > 500$ MeV/c^2 sample is used for the X fit, but the signal is still deeply buried in background in the ct projection. The long-lived X-fraction is $16.1 \pm 4.9 \pm 2.0\,\%$, which is smaller than the $\psi(2S)$, but only by a bit more than 2σ. The *absence* of $b \to X$-decays is excluded by 3σ based on Monte-Carlo "pseudo-experiments." It must be stressed that these fractions de-
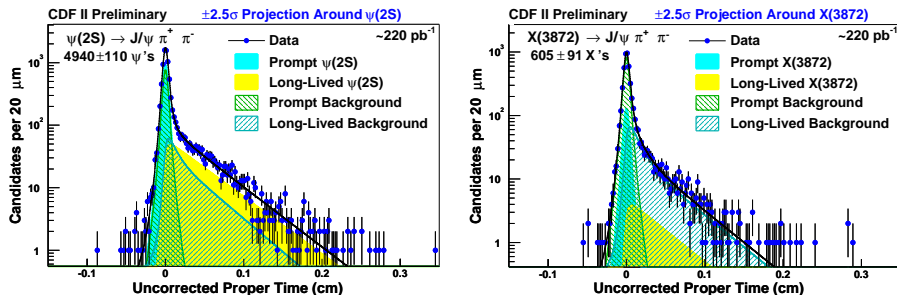
Fig. 16. "Lifetime" projections of likelihood fits onto data. **LEFT:** The $\psi(2S)$ distribution with full PDF and its breakdown into signal (shaded) and background (hatched) classes. Signal and background are further separated into prompt and long-lived components. The projection is for candidates within $\pm 2.5\sigma$ of the $\psi(2S)$ mass in order to be reflective of its signal-to-background ratio. **RIGHT:** Corresponding distribution for the $X(3872)$.

pend on the sample selection, mainly p_T,[139] and are therefore *sample specific*.

CDF's long-lived fractions for X and $\psi(2S)$ are quite similar, but factors that might otherwise distinguish X production from $c\bar{c}$ may scale $\bar{p}p \to X$ and $b \to X$ rates together, *canceling* in the ratio. Indeed, an analysis of inclusive X production[145] in the NRQCD formalism[146] lends credence to this view. Although posed in molecular terms, the arguments are more general: matrix elements for the X as 1^{++} are argued to scale with those of the χ_{c1}, yielding universal X-to-χ_{c1} scaling in inclusive processes. By setting the scale with a measured $B \to X$ branching ratio, other production ratios are predicted—like those below (Tables 2 and 3). The predictions are crudely successful, but they only test internal consistency amongst the data, as an X data-point must set the scale. We take the larger lesson of this analysis to be a case for a more *general* insensitivity of inclusive production ratios, such as B decay relative to $\bar{p}p \to X$. Thus, the long-lived X fraction measured by CDF is probably not so telling. A more incisive test is to consider the prompt and b sources separately, but we lack models for crisp predictions as well as knowledge of the branching ratio $\mathcal{B}_X \equiv \mathcal{B}_X[X \to J/\psi\pi^+\pi^-]$. Still, we may forge ahead with some crude comparisons.

Using CDF's $X(3872)$ and $\psi(2S)$ yields, N_X and N_ψ (Fig. 16), and long-lived fractions f_{LL}, one can estimate the production rate of X relative to $\psi(2S)$, *i.e.*,

$$\frac{\sigma(\bar{p}p \to X \ldots)}{\sigma(\bar{p}p \to \psi(2S) \ldots)} = \frac{(1 - f_{LL}^X)N_X}{(1 - f_{LL}^\psi)N_\psi} \cdot \frac{\mathcal{B}_\psi[\psi(2S) \to J/\psi\pi^+\pi^-]}{\mathcal{B}_X[X \to J/\psi\pi^+\pi^-]} \cdot \frac{\epsilon_\psi}{\epsilon_X}, \qquad (2)$$

where ϵ_X/ϵ_ψ is the (unreported) ratio of CDF efficiencies for X and $\psi(2S)$. Given the relatively soft kinematic cuts, ϵ_X/ϵ_ψ likely deviates from unity by tens of percents rather than factors of two[147]—a modest uncertainty for our purposes. The results are shown in Table 2 along with CDF data for J/ψ[139] and χ_c,[140] where the b-hadron feeddown was removed by a lifetime analysis, as well as that from $\psi(2S)$ and χ_c to J/ψ. These values are corrected for efficiency, unlike the crude estimate done here for the X—so that we must preserve the ϵ_X/ϵ_ψ factor. The cross section

Table 2. Ratio of charmonium production cross sections relative to the $\psi(2S)$ derived from CDF measurements at the Tevatron[139,140] and PDG[13] branching ratios. The $X(3872)$ ratio is determined from the raw measurement of the CDF lifetime analysis, and requires an efficiency correction, ϵ_ψ/ϵ_X.

State	p_T Range (GeV/c)	$\sigma[c\bar{c}]/\sigma[\psi(2S)]$
J/ψ	> 5.5	$\sim 5.0 \pm 1.0$
χ_{c1}	> 5.5	$\sim 4.3 \pm 1.1$
$\psi(2S)$		1
$X(3872)$	$\int \epsilon(\text{CDF Analysis}) \cdot dp_T$	$(0.045 \pm 0.008)/\mathcal{B}_X \cdot \epsilon_\psi/\epsilon_X$

Table 3. Exclusive $B^+ \to [c\bar{c}]K^+$ branching ratios are compared to inclusive branching ratios for "$B^+/B^0/B_s^0/b\text{-}baryon$" mixture decaying to charmonium, and to the $X(3872)$. Charmonium values are from the PDG[13] unless otherwise noted, the exclusive X is a Belle[124] and BaBar[137] average (updated to PDG'04), and the inclusive X is derived from CDF's lifetime analysis. The X values have residual unknowns: $\mathcal{B}_X(X \to J/\psi\pi^+\pi^-)$, and CDF's X-to-$\psi(2S)$ efficiency ratio, "ϵ_X/ϵ_ψ."

State		$\mathcal{B}(B^+ \to [c\bar{c}]K^+) \times 10^{-4}$	$\mathcal{B}(b \to [c\bar{c}]\ldots) \times 10^{-2}$	Ratio
η_c	$(^1S_0)$	9.0 ± 2.7	—	—
J/ψ	$(^3S_1)$	10.0 ± 0.4	1.16 ± 0.10	$8.6 \pm 0.8\,\%$
χ_{c0}	$(^3P_0)$	6.0 ± 2.3	—	—
χ_{c1}	$(^3P_1)$	6.8 ± 1.2	1.5 ± 0.5	$4.5 \pm 1.7\,\%$
$\psi(2S)$	$(^3S_1)$	6.8 ± 0.4	0.48 ± 0.24	$14 \pm 7\,\%$
$\psi(3770)$	$(^3D_1)$	4.8 ± 1.3^{120}	—	—
$X(3872)$	$(??)$	$(0.14 \pm 0.03)/\mathcal{B}_X$	$(0.011 \pm 0.006)/\mathcal{B}_X \cdot \epsilon_\psi/\epsilon_X$	$(13 \pm 8) \cdot \epsilon_\psi/\epsilon_X\,\%$

ratios are known to vary mildly with p_T, making the values in Table 2 depend on the p_T range. This is a potentially important *caveat* for the X, as its p_T behavior is (so-far) unknown.[148] With these qualifiers, we can compare the measured production ratios. It has been estimated that production of some D-states can be nearly as large as the $\psi(2S)$.[149] The X plausibly follows a $c\bar{c}$ pattern *if* $2\% \lesssim \mathcal{B}_X \lesssim 10\%$. A much larger $\mathcal{B}_X$ suppresses the cross section, perhaps indicating a non-$c\bar{c}$ character.

Adapting Eqn. 2 to CDF's long-lived component, one can estimate the *inclusive* branching ratio of "$B^+/B^0/B_s^0/b\text{-}baryon$" mixture decaying to $X+anything$ relative to that for $\psi(2S)$. Then, $\mathcal{B}(b \to X \ldots)$ may be obtained from multiplication by the known $\mathcal{B}(b \to \psi(2S)\ldots)$. Table 3 lists the result along with known inclusive branching ratios for $c\bar{c}$ states, as well as the corresponding *exclusive* $\mathcal{B}(B^+ \to [c\bar{c}]K^+)$. $\mathcal{B}(B^+ \to XK^+)$ is an average of B-factory measurements, up to the unknown $\mathcal{B}_X$. Both the *inclusive* and *exclusive* branching ratios tell a familiar story: modest $\mathcal{B}_X$ pushes $b \to X$ branching ratios into the $c\bar{c}$ realm, and large $\mathcal{B}_X$ implies suppression. The last column shows the ratio of exclusive to inclusive branching ratios: the X is consistent—*independent* of $\mathcal{B}_X$— with $c\bar{c}$, albeit with very large errors.

With modest $\mathcal{B}_X$, say $\sim$ 2-10%, the X falls into line with the standard $c\bar{c}$ in Tables 2 and 3. Alternatively, large $\mathcal{B}_X$, as in some exotic scenarios, could imply production and b-decay rates suppressed by up to an order of magnitude. Thus the lesson to be learned hinges upon the size of $\mathcal{B}_X(X \to J/\psi\pi^+\pi^-)$. BaBar has recently shown promising results indicating that they hope to soon measure $\mathcal{B}_X$.[150]
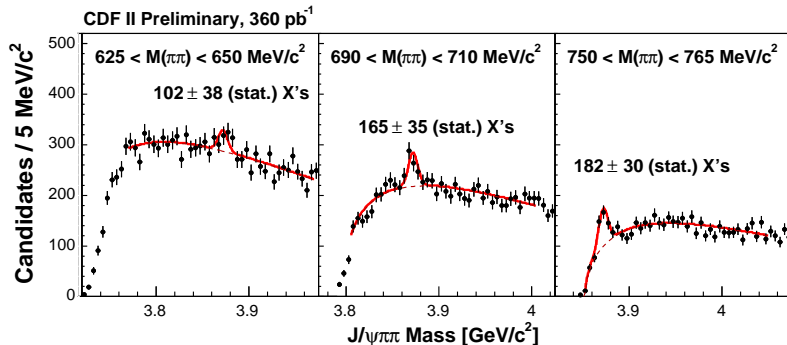
CDF II Preliminary, 360 pb^{-1}

625 < M($\pi\pi$) < 650 MeV/c^2

102 ± 38 (stat.) X's

690 < M($\pi\pi$) < 710 MeV/c^2

165 ± 35 (stat.) X's

750 < M($\pi\pi$) < 765 MeV/c^2

182 ± 30 (stat.) X's

Candidates / 5 MeV/c^2

J/$\psi\pi\pi$ Mass [GeV/c^2]

Fig. 17.   Three examples of $M(\pi\pi)$ "slices" around the X of the $J/\psi\pi^+\pi^-$ mass distribution.

5.3.3. *The Dipion Mass Spectrum* [151]

A feature of $X(3872)$ decay is its propensity for high-mass dipions (Figs. 13 & 14). Dipion spectra are often noted as window to the X. As is well known, $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ prefers high $M(\pi\pi)$.[152] High masses are no surprise for the X as $c\bar{c}$ in a $^3S_1$—but this is untenable as it should then be directly made in e^+e^-. Interest in $\psi(2S)$ decay lead to general treatments of $\pi\pi$-transitions between quarkonia. Dipion spectra have been calculated using a QCD multipole expansion (ME) of the color electric/magnetic fields for $^3S_1$,[153] $^1P_1$,[154] and ^3D_J[153] $c\bar{c}$ going to $^3S_1\pi^+\pi^-$. Other J^{PC} states involve, at lowest L, dipions in a 1^{--}, and for the masses of interest, are dominated by the ρ-pole. The ME predicts that $M(\pi\pi)$ favors low masses for $^1P_1$, and is *relatively* flat for ^3D_J-states, both at odds with Fig. 13. The $^3S_1$ and ρ options do so peak. Normally $[c\bar{c}] \rightarrow J/\psi\rho^0$ is forbidden by isospin, but a state so close to the $D^0\overline{D}^{*0}$ mass (Fig. 15) can violate isospin via virtual coupling to $D^0\overline{D}^{*0}$.

Belle's original observation gave clear evidence for high $\pi\pi$-masses, but only a rough shape. CDF's large sample offers a sharper view.[147,151,155] An enlarged sample of ~ 360 pb^{-1} is used. The selection is as before, except fiducial cuts are applied to select a kinematic region of good efficiency: $p_T(X) > 6$ GeV/c^2 and $|\eta(X)| < 0.6$. The sample is divided into slices of $M(\pi\pi)$, and the $J/\psi\pi^+\pi^-$ distribution is fit to obtain the signal yields for each slice (Fig. 17). The raw yields are corrected for detector and kinematic selection efficiencies using Monte Carlo simulation. An important ingredient is the simulation's p_T spectrum. This was varied so that the simulation matched the observed spectra for the $\psi(2S)$ and X. In this way no assumption was made about the nature of X production. Within the limited precision, $p_T(X)$ is quite similar to that of the $\psi(2S)$. The statistical error on the $p_T(X)$ shape is propagated into a small systematic uncertainty on the $M(\pi\pi)$ efficiency corrections.

The efficiency corrected spectrum for the $\psi(2S)$ is shown in Fig. 18, along with a fit of a multipole expansion model.[153] This model has been fit to higher statistics
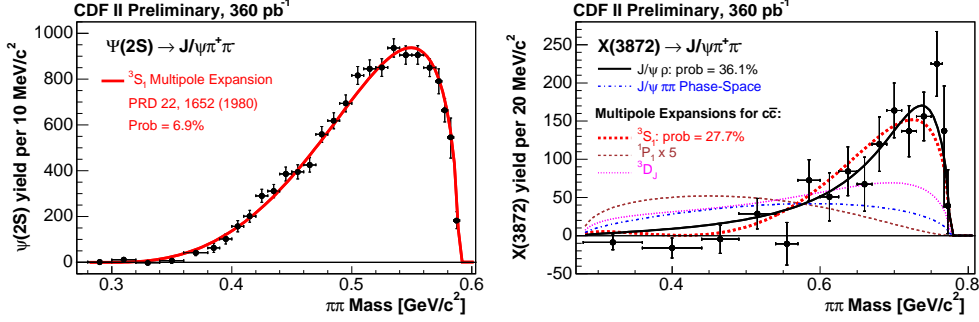
Fig. 18.   **LEFT:** Dipion spectrum for $\psi(2S)$ fit with a multipole expansion calculation. **RIGHT:** Dipion spectrum for $X(3872)$ with fits of multipole predictions for $^3S_1$, $^1P_1$, and ^3D_J charmonia, as well as a phase-space modulated Breit-Wigner (constant width) distribution for decay to $J/\psi\rho^0$, and three-body phase space. The $^1P_1$ fit is multiplied by 5 for better visibility.

(23k) BES data,[152] and the CDF results agree with BES better than 1σ.

Also in Fig. 18 is the corrected X spectrum, along with fits for $^3S_1$, $^1P_1$, and $^3D_J \rightarrow J/\psi\pi^+\pi^-$ ME's, the ρ (Breit-Wigner×phase-space), and simple phase space. Only the $^3S_1$ and ρ fits describe the data—the two shapes are almost indistinguishable. The $^3S_1$ $c\bar{c}$ assignment for the X being untenable *seemingly* forces the ρ option.

However, Υ's serve as a cautionary tale: the basic ME *fails* to describe $\pi\pi$-masses for $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$.[156] One hypothesis is that the $\Upsilon(3S)$ is so close to the $B\overline{B}$ threshold that coupling to $B\overline{B}$ distorts the spectrum.[157] This scenario has been challenged as inadequate,[158] but the mechanism itself is quite conventional. Whatever the X is, it is well situated to couple to $D^0\overline{D}^{*0}$, potentially affecting $M(\pi\pi)$.

A definitive test for the ρ is $X \rightarrow J/\psi\pi^0\pi^0$—forbidden for ρ's, but half the $\pi^+\pi^-$ rate for $I=0$ dipions. But B-factories are not yet sensitive.[159] Belle has reported $X \rightarrow J/\psi\pi^+\pi^-\pi^0$, where the pions look like a virtual ω.[159] The case would be complete with $J/\psi\omega$ decay: the ω requires the dipions in $J/\psi\pi^+\pi^-$ to be odd C-parity, and thus a ρ. Belle quotes an ω-to-ρ branching ratio of 1.0 ± 0.5[160], signaling large isospin breaking. Very recently Belle reported $J/\psi\gamma$ decay,[160] providing compelling support for the ρ. Confirmation may be desired, but all this fits neatly into a picture where the X has $C=+$, and decays into $J/\psi\rho$ and $J/\psi\omega$ with isospin badly broken.

Belle has pushed the ρ-analysis a step further by noting that a Breit-Wigner is distorted by a centrifugal barrier if the J/ψ-ρ angular momentum, $L_{\psi\rho}$, is non-zero. A phase-space factor, the J/ψ momentum in the X rest-frame, q_ψ^*, generalizes to $(q_\psi^*)^{2L_{\psi\rho}+1}$. Higher $L_{\psi\rho}$ softens the $M(\pi\pi)$ fall-off at the upper limit ($q_\psi^* \rightarrow 0$), and the $\pi\pi$-peak shifts to lower masses. The fit in Fig. 18 corresponds to $L_{\psi\rho}=0$, and CDF has not yet provided an $L=1$ fit. But, as with Belle data,[161] the agreement will clearly deteriorate—favoring an S-wave decay, and even parity for the X.

Table 4.   Summary of arguments against $c\bar{c}$ assignments for the $X(3872)$. This ignores mass predictions from potential models, which also creates varying degrees of problems for $c\bar{c}$ states.[132,133] The dipion J^{PC} is for lowest L. "Unseen modes" are expected to have been observed if the X is that state.

$n^{2s+1}L_J$	J^{PC}	State	$\pi\pi$ J^{PC}	Unseen Mode	Other Objections
1^1D_2	2^{-+}	η_{c2}	1^{--}		$J/\psi\pi^+\pi^-$ expected to be very small $(\eta_c\pi^+\pi^- \gg J/\psi\pi^+\pi^-)$[132]
1^3D_2	2^{--}	ψ_2	0^{++}	$\chi_{c1}\gamma$[124]	$M(\pi\pi)$ in $J/\psi\rho$ decay favors S-wave $\rightarrow$ Even Parity $J/\psi\rho$,[151,161] $J/\psi\omega$,[159] & $J/\psi\gamma$[160] decays $\rightarrow C=+$
1^3D_3	3^{--}	ψ_3	0^{++}	$\chi_{c2}\gamma$[162]	$J/\psi\rho$,[151,161] $J/\psi\omega$,[159] & $J/\psi\gamma$[160] decays $\rightarrow C=+$
2^1P_1	1^{+-}	h_c'	0^{++}		Wrong $\cos\theta_{J/\psi}$ distribution[159]
2^3P_0	0^{++}	χ_{c0}'	1^{--}	$D\overline{D}$[120]	$D\overline{D}$ not suppressed $\rightarrow$ too broad
					Wrong ℓ-π angular dist. in $J/\psi\pi\pi$ decay[160]
					Not Seen in $\gamma\gamma$ Fusion[165]
2^3P_1	1^{++}	χ_{c1}'	1^{--}		$Br(J/\psi\gamma)/Br(J/\psi\pi\pi)=0.14\pm0.05$[160]—too small[161]
2^3P_2	2^{++}	χ_{c2}'	1^{--}	$D\overline{D}$[120]	$D\overline{D}$ not suppressed $\rightarrow$ too broad
					Not seen in $\gamma\gamma$ Fusion[165]
3^1S_0	0^{-+}	η_c''	1^{--}		spin splitting ties mass to $\psi(4040) \rightarrow$ too heavy
					$\Gamma(\eta_c,\eta_c')\sim 20$ MeV $\rightarrow$ too broad

5.4. $X(3872)$ *Reprise*

The identity of the $X(3872)$ is a pressing issue in spectroscopy. The natural interpretation is a $c\bar{c}$ state.[132,133] In an effort to sort out options, an extensive search has been made for other decays—none are seen in: $\chi_{c1}\gamma$,[124] $\chi_{c2}\gamma$,[162] $J/\psi\eta$,[163] D^+D^- and $D^0\overline{D}^0$,[120] but, very recently, $J/\psi\gamma$[160] and $D^0\overline{D}^0\pi^0$,[164] have been. In the end, a case can be made against *all* $c\bar{c}$ candidates, as is summarized in Table 4. But the *caveat* is: once one concedes that the X is unusual—and sitting on $D^0\overline{D}^{*0}$ offers some grounds—then the usual $c\bar{c}$ expectations may be questioned. But we go on to consider alternatives: 1) four-quark states[105,130,131], 2) $c\bar{c}g$ hybrids,[166–168] 3) $c\bar{c}$-glueball mixtures[169], or 4) dynamic "cusp" from the $D^0\overline{D}^{*0}$ threshold.[170]

In this last scenario the X arises dynamically as a cusp due to the "de-excitation" of the $D^0\overline{D}^{*0}$ threshold.[170] Very close to threshold the S-wave $D^0\overline{D}^{*0}$ de-excitation cross section follows a $1/velocity$ dependence, which competes with the available phase space. If the $D^0\overline{D}^{*0}$ interaction is at all attractive, the $1/v$ factor can dominate and produce a peak, but one which is not a true resonance. A preferred decay is likely $D^0\overline{D}^0\pi^0$ and/or $D^0\overline{D}^0\gamma$, and indeed Belle claims a quite large $D^0\overline{D}^0\pi^0$ rate.[164]

Another suggestion is that the X is a vector glueball mixed with $c\bar{c}$.[169] Although a 1^{--} state, it would be highly suppressed in e^+e^- since photons do not couple to gluons. However, $X \rightarrow J/\psi\rho$, $J/\psi\omega$, and $J/\psi\gamma$ all refute this hypothesis.

The $X(3872)$ as a $c\bar{c}g$ hybrid[166–168] is not very popular as the lightest states are estimated to be $\gtrsim 4$ GeV/c^2, albeit with a fair uncertainty. Numerous states are expected, with exotic and non-exotic J^{PC}'s. The X's proximity to the $D^0\overline{D}^{*0}$ mass is explained by assuming strong coupling to $D^0\overline{D}^{*0}$. The main decays are normally $[c\bar{c}g] \rightarrow [c\bar{c}]gg$ (including $J/\psi\pi^+\pi^-$), and to light hadrons via gg annihilation for $C=+$. A negative-C hybrid is more likely to be narrow, but is excluded by $C=+$

decays like $J/\psi\rho$. Mixing with $c\bar{c}$ or $D^0\overline{D}^{*0}$ opens up typical $c\bar{c}$ modes.[168] Branching ratios of $B \to 0^{+-}$ (exotic) hybrid, thought to be among the lightest, is estimated to be $\sim 10\times$ lower than for normal $c\bar{c}$;[171] but other hybrids could have higher rates. Models of hybrid production at the Tevatron are less developed, but since there are common matrix elements, presumably hybrids are similarly suppressed in $\bar{p}p$. But in the end, hybrid models must contend with the low X-mass and even C.

The idea of the $X(3872)$ as four-quark state spans a range of extremes: from bag-like models in which all quarks play an equal role, to scenarios where quarks act in pairs. The latter can be a deuteron-like "molecule" of two $q\bar{q}'$-pairs, or qq'-$\bar{q}\bar{q}'$ diquarks. Bag models often serve for light-quark exotics; but for the X, four-quark models gravitate to paired quarks given it contains heavy quarks, and is so near the $D^0\overline{D}^{*0}$ mass. A diquark model envisages a rich family of $[qc][\bar{q}\bar{c}]$ states: various pairings with u and d, and two each of 0^{++} and 1^{+-}, and one 1^{++} and 2^{++}.[105] The X is proposed to be the 1^{++}. In addition to charged X^+'s, *two* neutral states are expected: $X_u^0 = [cu][\bar{c}\bar{u}]$ and $X_d^0 = [cd][\bar{c}\bar{d}]$. These can mix with some angle, θ, and the mass difference between eigenstates is estimated to be: $\Delta M_X \sim (7\pm2)/\cos(2\theta)$ MeV/c^2. Since isospin is broken, both X^0 eigenstates decay to $J/\psi\rho$ and $J/\psi\omega$. From the fact that Belle reported a *single narrow* state the authors argue that one X^0 dominates in $B^+ \to XK^+$ decay, and the other in $B^0 \to X'K^0$.

CDF data bring constraints to this model. While Belle supposedly produces only one of the X^0's, CDF's search is inclusive: X_u^0 and X_d^0 are produced equally. As is apparent from Fig. 14, no twin of the $X(3872)$ is visible, except for the possibility that CDF sees an unresolved mixture of *both* X_u^0 and X_d^0. CDF fits their X peak by a (resolution dominated) Gaussian with $\sigma = 4.9\pm0.7\,(stat)$ MeV/c^2. From "toy" Monte Carlo studies I find it is difficult to accommodate two peaks with $|\Delta M_X| \gtrsim 8$ MeV/c^2.

A more restrictive condition comes from mass measurements. As an equal mixture of unresolved X's, CDF's mass is the *average* of X_u^0 and X_d^0, and if $B^+ \to XK^+$ is a pure species: $|\Delta M_X| = 2|M_{Belle} - M_{CDF}| = 1.4\pm2.2$ MeV/c^2. For a 1.64σ excursion (95% 1-sided CL), the mass splitting must be less than 5 MeV/c^2. CDF data do not exclude a pair of X^0 states, but they must have a small mass splitting, eroding the strength of isospin breaking, and some of the appeal of this model. OR, the splitting is so large that new modes open up and $J/\psi\pi^+\pi^-$ decays become invisible. BABAR has recently reported a possible $B^0 \to XK_s^0$ signal (2.7σ),[150] which if true, enables a direct measurement: $|\Delta M_X| = 2.7\pm1.3$ MeV/c^2. By the same scaling used above, this translates into a 4.8 MeV/c^2 limit, similar to that inferred from CDF.

A molecule is the most popular exotic interpretation. The proximity of the X and $D^0\overline{D}^{*0}$ masses naturally incites such thinking. A J^{PC} of 1^{++}, and possibly 0^{-+}, are thought the most promising cases to be bound by pion exchange.[128] Generally, $D^0\overline{D}^{*0}$, $D^0\overline{D}^0\pi^0$, and $D^0\overline{D}^0\gamma$, are expected to be major decay modes if energetically allowed. Existence of a $D^0\overline{D}^{*0}$ molecule suggests $D^+\overline{D}^{*0}$, D^+D^{*-}, $D_s^+D_s^{*-}$,... analogs. This simple scheme is undermined by a negative $X^+ \to J/\psi\pi^+\pi^0$ search,[172] which nominally[173] excludes the X as an isovector. But in fact, binding by pion ex-

change is expected to be three times stronger for isosinglets compared to isovectors; and the perturbation due to isospin breaking from the D^0–D^+ mass difference binds $D^0\overline{D}^{*0}$ more tightly while creating repulsion for $D^+\overline{D}^{*0}$ and D^+D^{*-} molecules.[128] Thus, it is in fact quite reasonable for there to be only a *single* $D\overline{D}^*$ molecule.

Swanson[131] has built a particularly detailed molecular model, the crux of which is the near degeneracy of $D\overline{D}^*$, $J/\psi\rho$, and $J/\psi\,\omega$ masses. The X as 1^{++} will be a mix of these components. In this model the latter two pairs are *necessary* to achieve binding, and no other J^{PC} or charged states exist. The X is mostly $D^0\overline{D}^{*0}$ ($\gtrsim 80\%$), with modest ($\sim 10\%$) $D^+\overline{D}^{*-}$ and $J/\psi\,\omega$ fractions, and a tiny ($< 1\%$) $J/\psi\rho$. The $J/\psi\rho$ is only a trace, but it has the largest branching ratio because of the ρ's large width. Unlike many models, $J/\psi\pi^+\pi^-\pi^0$ decay, through a virtual ω, is also large: $\sim 60\%$ of $J/\psi\rho$. The next largest decay is $D^0\overline{D}^0\pi^0$, $\sim 10\%$ of $J/\psi\rho$. The $J/\psi\omega$ prediction prompted Belle to search for it, and by measuring a ω-to-ρ branching ratio of 1.0 ± 0.5,[159,160] one can chalk-up a victory for this model. However, Belle's preliminary report[164] of a $D^0\overline{D}^0\pi^0$ rate more than $10\times$ that of $J/\psi\pi^+\pi^-$ is a failure.

Naïvely one expects the formation of fragile states to be suppressed. This is manifest in "low-energy universality."[174] As an S-wave $D^0\overline{D}^{*0}$ system (1^+), the X is so weakly bound that it is spatially large compared to its meson constituents, and has an unnaturally large D^0–$\overline{D}^{*0}$ "scattering length." Important properties of the system are governed by this large scattering length rather than short-range details of its construction. In particular, its cross section is $\propto \sqrt{E_B}$ for small binding energy E_B. One may imagine evading this suppression if the X is a *mixture* of $D\overline{D}^*$ and $c\bar{c}$ by coupling to the $c\bar{c}$ wave-function to elevate production rates to charmonium levels. But by low-energy universality the non-$D\overline{D}^*$ components of the wave-function also vanish as $\sqrt{E_B}$, again enforcing $\sigma \propto \sqrt{E_B}$. In fact, even if the X arises *from* $c\bar{c}$, say $h'_c(2\,^1P_1)$ or $\chi'_{c1}(2\,^3P_1)$, which is accidentally fine-tuned to the $D\overline{D}^*$ mass, the $c\bar{c}$ part is suppressed by $\sqrt{E_B}$, and *again* $\sigma \propto \sqrt{E_B}$. The same dependence is also present in branching ratios to the X. One's prejudice for suppressed production is born-out in this picture; and, as seen with NRQCD (Sec. 5.3.2), the suppression is similar in *both* the production of, and in B decays to, the X. Significant suppression can be accommodated by data (Table 2) *if $\mathcal{B}_X$ is large*—as in Swanson's model.

Low-energy universality has also been used to construct a model for X formation by coalescence of D^0 and $\overline{D}^{*0}$ in $B^+ \to D^0\overline{D}^{*0}K^+$.[175] It is estimated that $\mathcal{B}(B^+ \to XK^+) \approx (2.7\times10^{-5})\Lambda_1^2/m_\pi^2\sqrt{E_B/0.5\,\mathrm{MeV}}$, where Λ_1 is a cutoff, and E_B the binding energy. The authors propose $\Lambda_1 \approx m_\pi$, and thus: *if $\mathcal{B}_X$ is large, $\mathcal{B}$ is close to the measured value* (Table 3). From this theoretical perspective we get the same message: decay rates favor molecules *if $J/\psi\pi^+\pi^-$ is a very prominent mode.*

$$\sim$$

After almost two years since its discovery the nature of the $X(3872)$ remains uncertain. New pieces to the puzzle are available, and much is unfavorable to $c\bar{c}$ options. A case has been made[161] that the X is most likely 1^{++}—with the $D^0\overline{D}^{*0}$

molecule an increasingly favored option. But as potentially the first unequivocally exotic hadron, clear and compelling evidence must be required.

If one wants to cling to a $c\bar{c}$ assignment, C-parity eliminates all but two: $1\,^1D_2$ and $2\,^3P_1$. The $2\,^3P_1$ has the favored J^{PC}, but one must contend with predictions that make it ~ 100 MeV/c^2 too heavy and the small $X \to J/\psi\gamma$ rate.

On the other hand, the $1\,^1D_2$ prediction is only ~ 30 MeV/c^2 below the X, and it should be narrow because $D\overline{D}$ decay is forbidden. CLEO's $\gamma\gamma$-fusion search was not sensitive enough to exclude it.[165] An objection against the $1\,^1D_2$ is that $\eta_c\pi^+\pi^-$ dominates its dipion transitions. Barnes and Godfrey[132] estimate $1\,^1D_2$ decay rates but ignored the apparently significant $D^0\overline{D}^0\pi^0$ decay.[164] If we arbitrarily extend their model with a partial width $\Gamma(D^0\overline{D}^0\pi^0) = 1$ MeV, then $\Gamma_{Tot} = 1.86$ MeV—a little less than Belle's 2.3 MeV limit on Γ_X. The $\eta_c\pi^+\pi^-$ fraction is then 11%. Belle's preliminary $D^0\overline{D}^0\pi^0$ rate is $\sim 15\times$ that of $J/\psi\pi^+\pi^-$, but with $\sim 50\%$ error.[164] This rate limits $\mathcal{B}_X(X \to J/\psi\pi^+\pi^-) \lesssim 10\%$; but used with $\Gamma(D^0\overline{D}^0\pi^0) = 1$ MeV, we find $\mathcal{B}_X \sim 3\%$. This is, given the uncertainties, a $\mathcal{B}_X$ rate ~ 2-$5\times$ below the $\eta_c\pi^+\pi^-$ prediction, thereby respecting $\eta_c\pi^+\pi^-$ dominance. Furthermore, estimates of $\pi\pi$ transitions usually do not include resonant enhancements, such as from the ρ. The $1\,^1D_2$ can decay to $J/\psi\rho$, but not to $\eta_c\rho$. This could help boost $J/\psi\pi^+\pi^-$ expectations, but only if one is willing to badly break isospin.

Isospin is a general objection to $c\bar{c}$. The $X(3872)$ is well positioned to break it by sitting on $D^0\overline{D}^{*0}$. Belle measures, with $\sim 50\%$ errors, equal branching ratios to $J/\psi\rho$ and $J/\psi\omega$. However, these decays rely upon the width of the ρ/ω to populate the allowed phase space. If one makes a simple estimation of the allowed $(phase\ space)\times$ $(Breit\ Wigner)$, the ρ should have $\sim 5\times$ the rate of the ω. Thus one can argue that $J/\psi\rho$ may be suppressed by isospin, and, allowing for uncertainties, by ~ 2-$10\times$. This is a far cry from the $\sim 200\times$ one would expect from $\psi(2S) \to J/\psi\pi^0$ vs $J/\psi\pi^0\pi^0$ data. This difference sets the scale of isospin breaking desired from $D^0\overline{D}^{*0}$.

A final obstacle for the $1\,^1D_2$ is the sharp fall-off of the $\pi\pi$-spectrum seen by CDF (Fig. 18) and Belle[161]. This favors S-wave decay, whereas the $1\,^1D_2$ must go by P-wave. The data are fairly striking in this respect. A loophole is the possibility of other effects intervening. The S-wave argument is based on the Breit-Wigner shape, which ignores any more complicated *dynamics* in the decay. In particular, the influence of virtual $D^0\overline{D}^{*0}$ coupling on $M(\pi\pi)$ is unknown—recall the $\Upsilon(3S)$ tale.

Admittedly the above arguments for $c\bar{c}$ rely as much on ignorance as they do on our knowledge. But we should not be swept away by the appealing prospects of an exotic X. Are the loopholes for $c\bar{c}$ more contrived than an exotic X would be momentous? There is even some hints *against* molecules. Belle's large $D^0\overline{D}^0\pi^0$ rate bounds $\mathcal{B}_X$ to be rather small, thereby making X production *very* charmonium-like: plug $\mathcal{B}_X = 5\%$ into Tables 2 & 3! This begs the question of how a $D^0\overline{D}^{*0}$ molecule bound by only ~ 1 MeV can escape significant suppression. We may be on the verge of isolating the first unambiguous exotic hadron, or maybe not quite yet.

6. Summary

If 2003 was 'the year of observation' for pentaquarks, 2004 may well be 'the year of non-observation.' CDF has searched in very large samples and found no evidence for $\Theta^+(1540)$, $\Phi(1860)$, or $\Theta_c^0(3100)$. Whether this means that one or more of these states are spurious, or only that pentaquark production is highly suppressed at the Tevatron, is unclear. Both cases are interesting. But the bulk of world data casts a dark shadow over pentaquark prospects—if they are to revive, high-statistics signals will be pivotal. Such analyses are expected soon from low-energy photo-production experiments that have claimed the Θ^+—early reports[93] are discouraging.

Irrespective of the fate of pentaquarks, 2003 also saw important, and uncontroversial, discoveries of D_{sJ}^+ states and the $X(3872)$. The D_{sJ}^+'s look increasingly like $L=1$ $c\bar{s}$ states, albeit in conflict with prior potential models. This is still exciting, if only to specialists. The recent SELEX claim of $D_{sJ}^+(2632)$ kicks up new dust, both because of its unusual properties and the null searches at B-factories. It will be interesting whether CDF can see $D_{sJ}^+(2632) \to D^0 K^+$ in their large charm sample.

The $X(3872)$ remains an exciting exotic candidate. A case has been built against all charmonium options, and a $D^0 \overline{D}^{*0}$ molecule is increasingly popular. The case against $c\bar{c}$ is, however, partially predicated on conventional expectations, and the exceptional qualities of the X creates enough latitude to keep the $c\bar{c}$ door open a crack. Production data seem to point towards charmonium, but a reliable measurement of $\mathcal{B}_X(X \to J/\psi\pi^+\pi^-)$ is needed. More is to be learned from existing data, and samples are growing at the Tevatron and the B-factories.

Are we in the midst of a revolution in spectroscopy? Or only actors in the latest episode of a forty-year snark hunt? We are hopefully on the cusp of learning which.

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