Recent *BABAR* results on hadron spectroscopy

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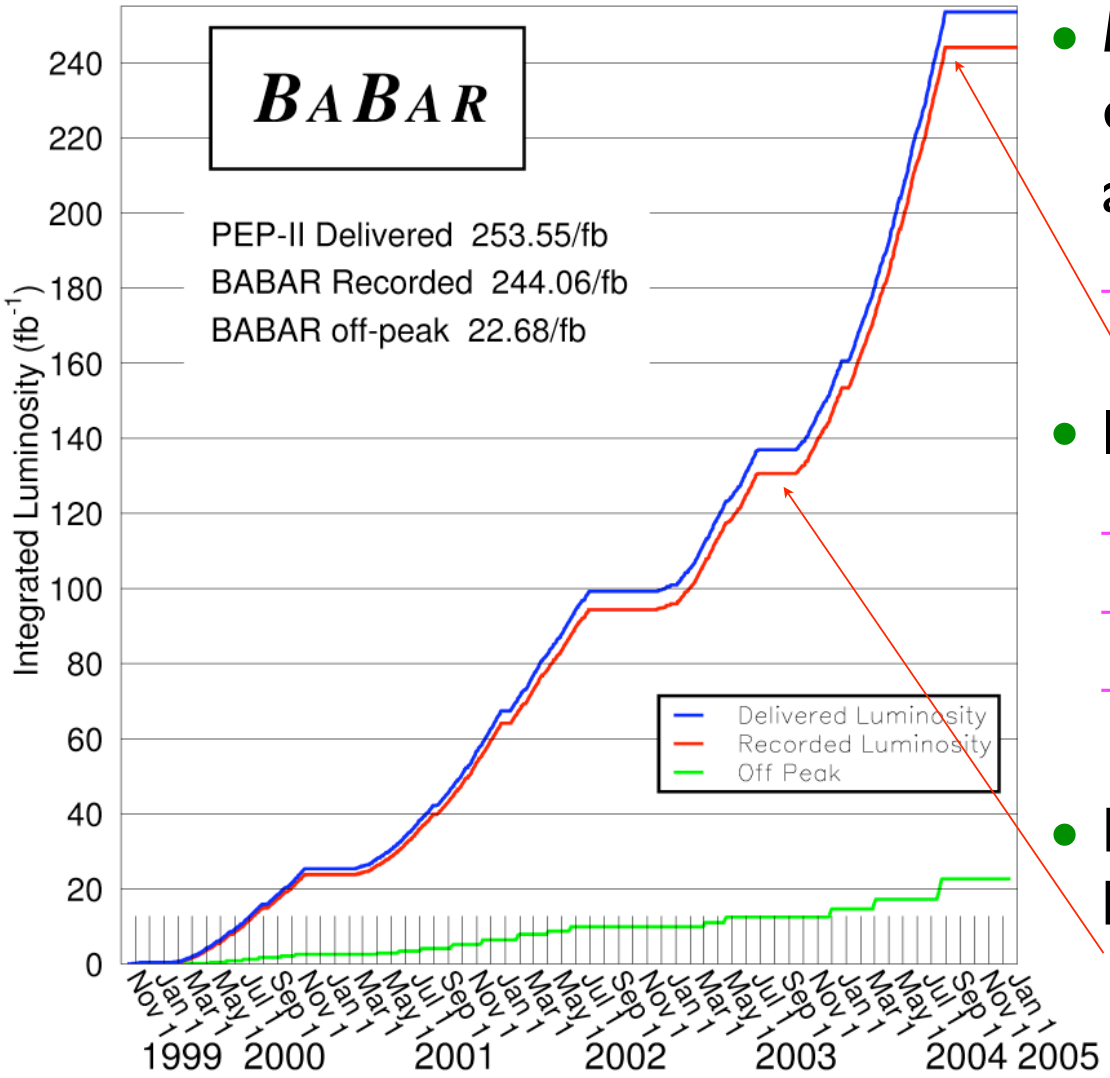
Outline

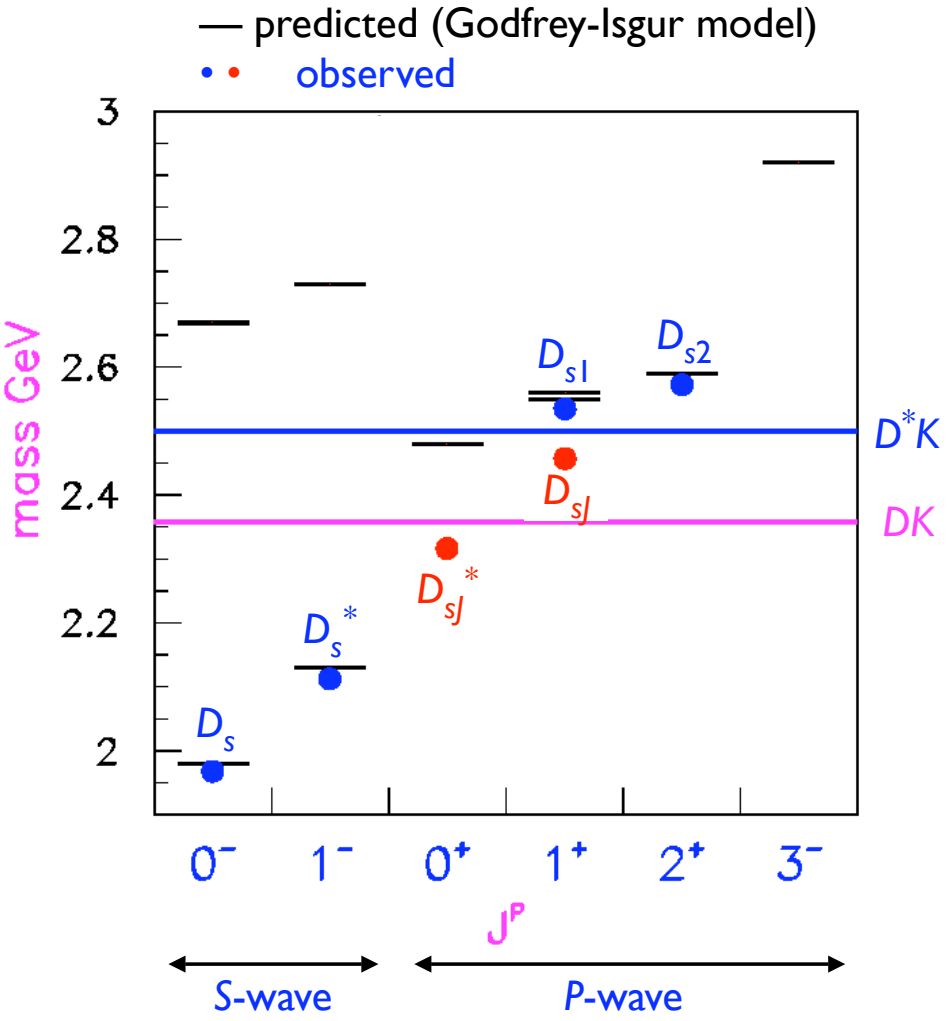
- Charmed strange mesons
  - $D_{sJ}^{*}(2317)^{+}$, $D_{sJ}(2460)^{+}$ production in continuum
  - $D_{sJ}^{*}(2317)^{+}$, $D_{sJ}(2460)^{+}$ production in *B* decays
  - Search for $D_{sJ}^{*}(2632)^{+}$ in continuum production
- Charmonium
  - Study of *X*(3872)
- Pentaquarks
  - Inclusive searches
  - Searches in *B* decays

Data samples



- *BABAR*: 4π magnetic detector at PEP II asymmetric e^+e^- collider
  - Designed for *B* physics (*CP* violation) but general purpose
- In ~250 fb^{-1}:
  - ~500M *B* mesons;
  - ~630M *D* mesons ($e^+e^- \rightarrow c\bar{c}$);
  - ~500M continuum *uds* events ($e^+e^- \rightarrow q\bar{q}$).
- Most results presented here based on 120 ÷ 140 fb^{-1}

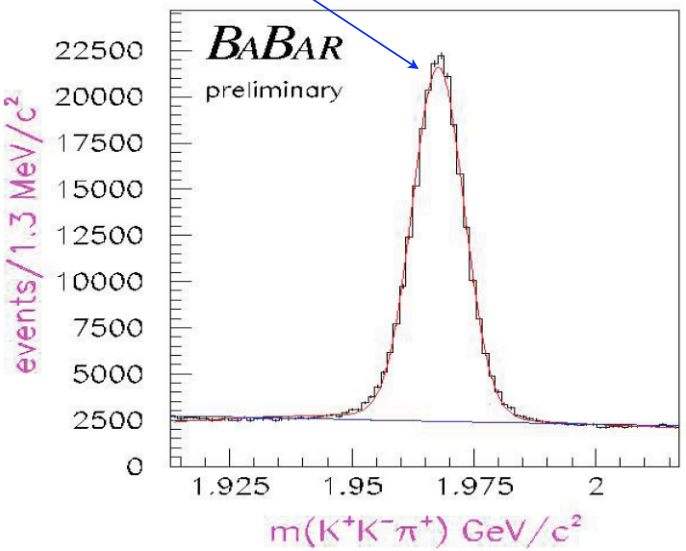
D_{sJ} states

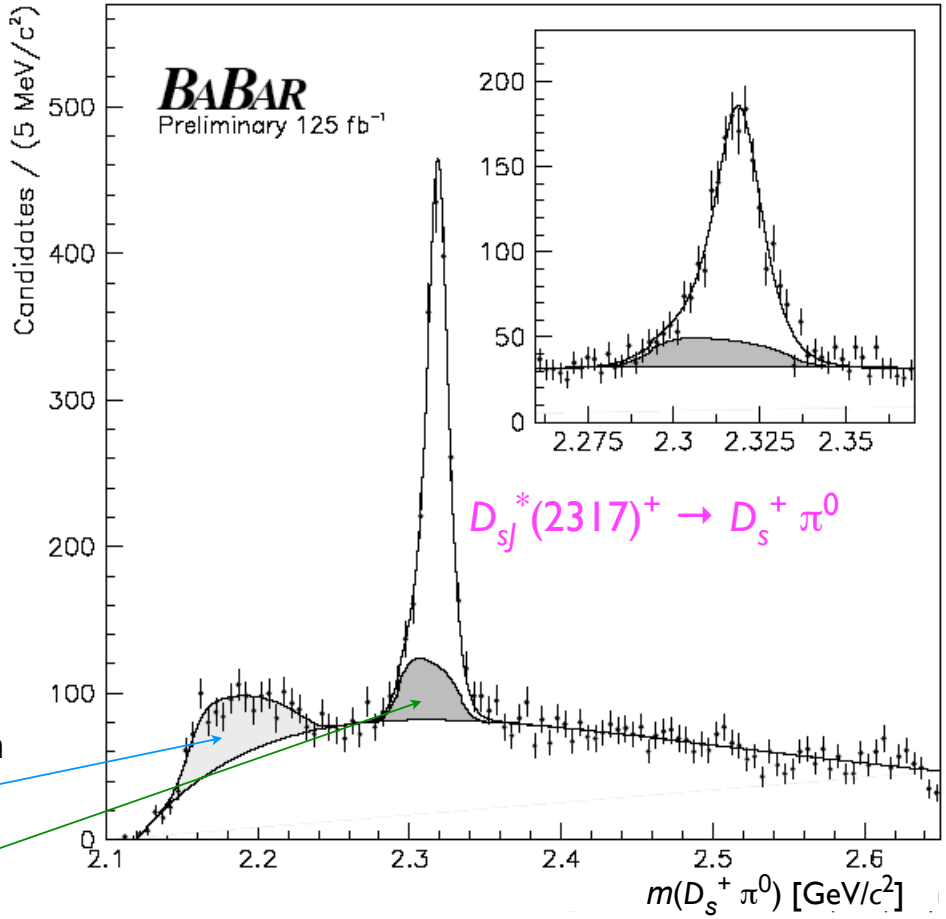


- Two new $c\bar{s}$ states:
  $D_{sJ}^*(2317)^+$, $D_{sJ}(2460)^+$
  - well established (confirmed by several experiments);
  - quantum numbers consistent with *P*-wave;
- Still things to understand:
  - mass lower than expected;
  - narrow width;
  - isospin-violating decays:
    $D_{sJ}^*(2317)^+ \rightarrow D_s^+\pi^0$,
    $D_{sJ}(2460)^+ \rightarrow D_s^*(2112)^+\pi^0$,

$D_{sJ}^{*}(2317)^{+} \rightarrow D_s^{+}\pi^0$ in continuum e^+e^-

Clean $D_s^+ \rightarrow \phi\,\pi^+$ ($\bar{K}^{*0}\,K^+$) $\rightarrow K^+K^-\pi^+$ sample





Feed-down/reflections from

$D_s^{*}(2112)^{+} \rightarrow D_s^{+}\gamma$

$D_{sJ}(2460)^{+} \rightarrow D_s^{+}\pi^0\gamma$

$N(D_{sJ}^{*+}) = 1275 \pm 75$

$m(D_{sJ}^{*+}) = (2318.9 \pm 0.3 \pm 0.9)$ MeV/c^2

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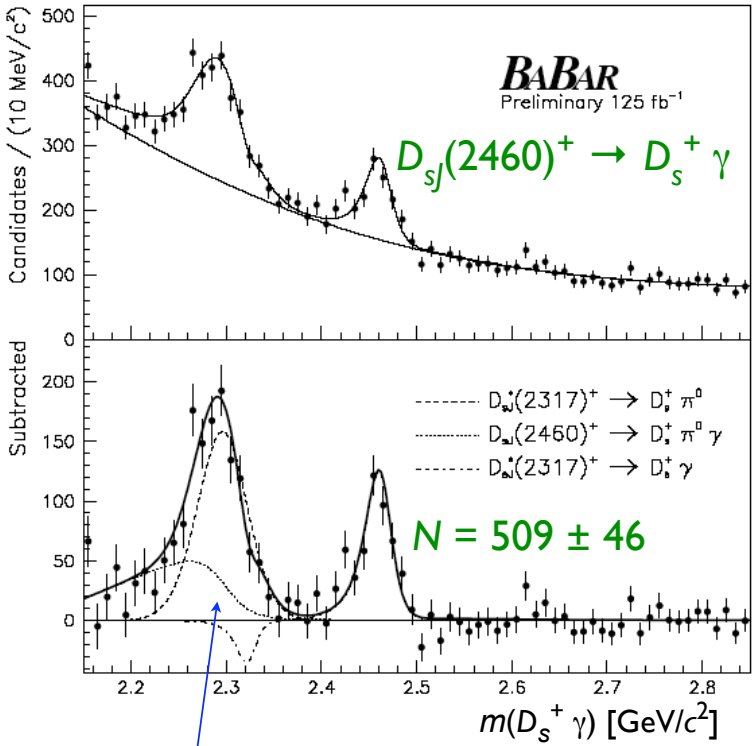
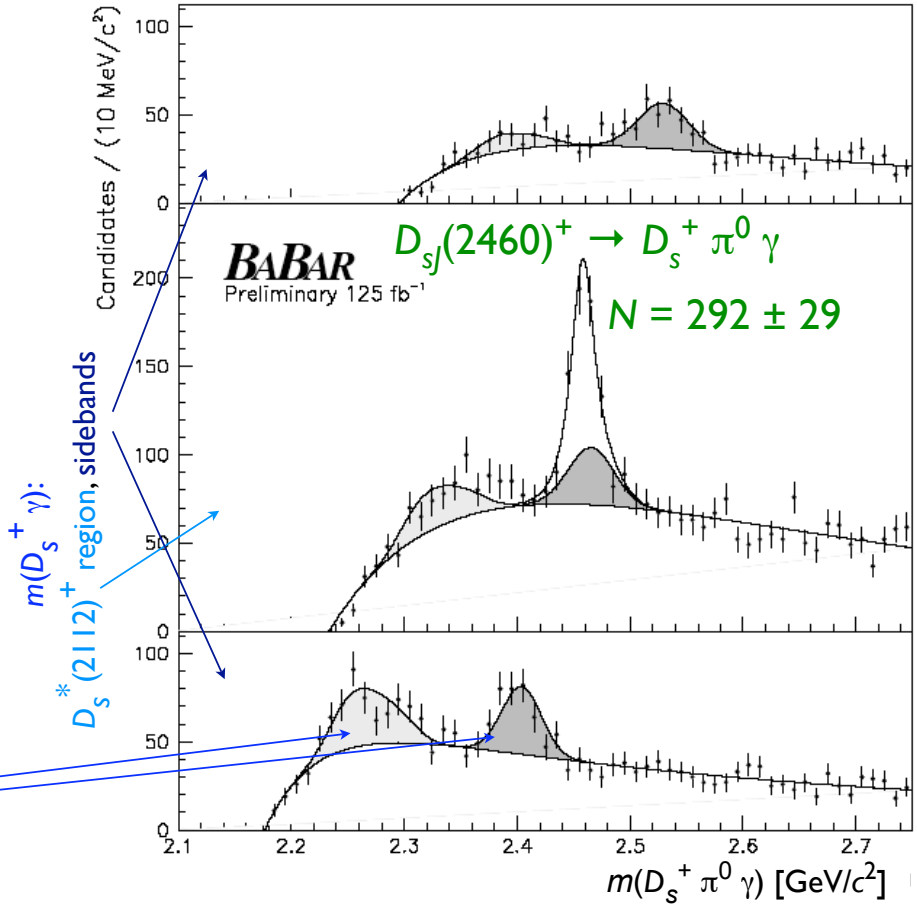
125 fb^{-1}

$D_{sJ}(2460)^+ \rightarrow D_s^+(\pi^0)\gamma$ in continuum





- Yields extracted from fits accounting for reflections with π^0/γ
- For $D_s^+ \pi^0 \gamma$, contributions from intermediate $D_s^*(2112)^+$ $D_{sJ}^*(2317)^+$ considered: data found consistent with ~100% $D_{sJ}(2460)^+ \rightarrow D_s^*(2112)^+ \gamma$

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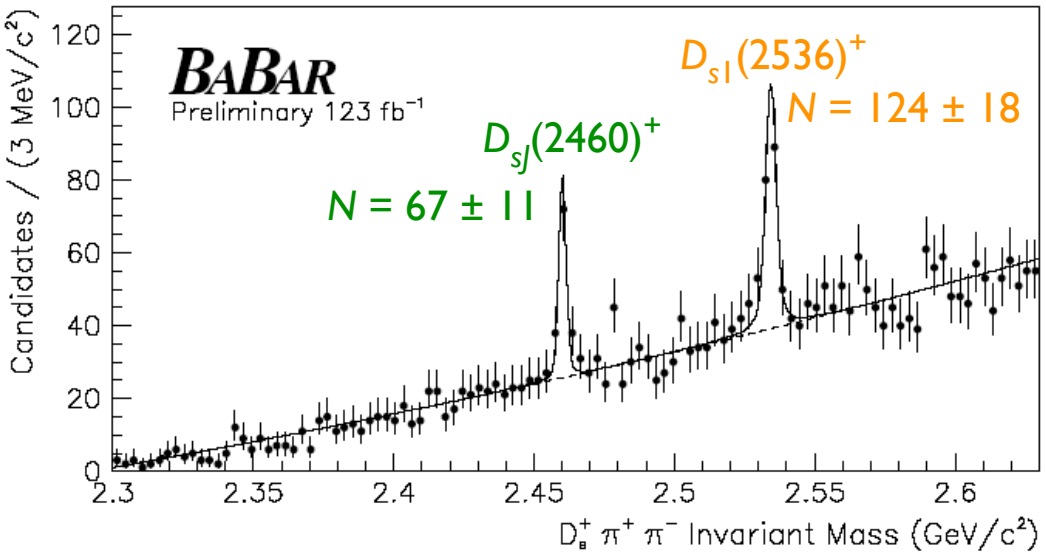
$D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-$ in continuum



$m(D_{sJ}^+) = (2459.4 \pm 0.3 \pm 1.0)$ MeV/c^2 (combined)

$m(D_{sJ}^{*+}) = (2534.3 \pm 0.4 \pm 1.2)$ MeV/c^2

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\gamma)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.375 \pm 0.054 \pm 0.057$$

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.082 \pm 0.018 \pm 0.011$$

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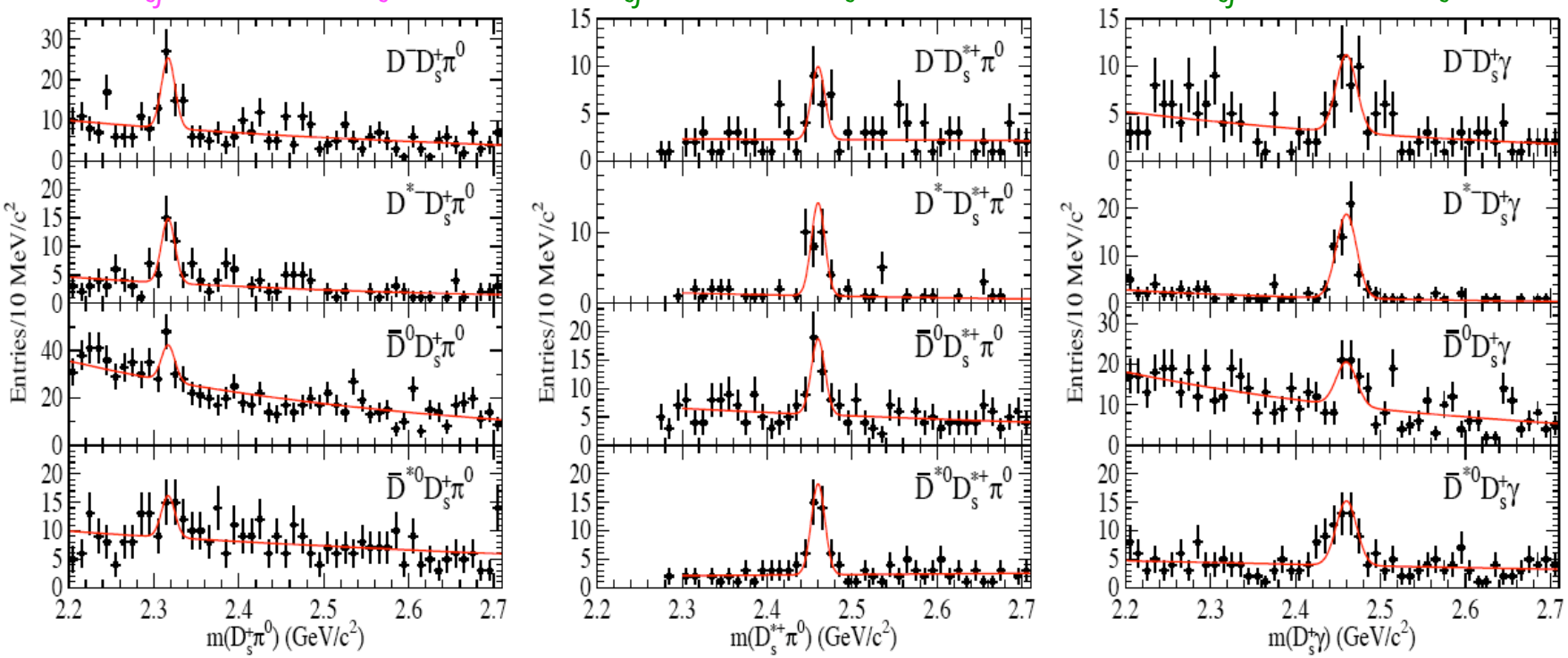
$D_{sJ}^{*}(2317)^{+}, D_{sJ}(2460)^{+}$ in $B \to D^{(*)} D_{sJ}^{(*)}$

$D_{sJ}^{*}(2317)^{+} \to D_s^{+} \pi^0$ $D_{sJ}(2460)^{+} \to D_s(2112)^{*+} \pi^0$ $D_{sJ}(2460)^{+} \to D_s^{+} \gamma$



- Reconstructed decays:

  $\bar{D}^0 \to K^+ \pi^-, K^+ \pi^- \pi^0, K^+ \pi^- \pi^+ \pi^-; D^- \to K^+ \pi^- \pi^-$

  $D_s^+ \to \phi \pi^+, K^{*0} K^+$

  $D^{*+} \to D^+ \pi^0; D^{*0} \to D^0 \pi^0, D^{*0} \to D^0 \gamma$

  $D_s^{*+} \to D_s^+ \gamma$

- B decays are reconstructed through the kinematic variables m_{ES}, ΔE.

$B \to D^{(*)} D_{sJ}^{(*)+}$: branching fractions

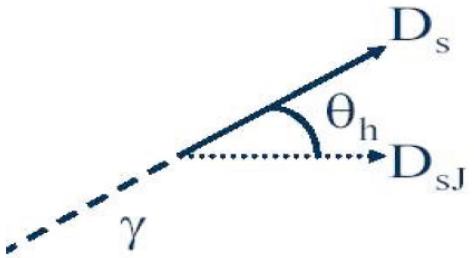
B mode		Yield	Cross-feed	Efficiency (10^{-4})	$\mathcal{B}(10^{-3})$	Significance
$B^0 \to D_{sJ}^*(2317)^+ D^-$	$[D_s^+\pi^0]$	34.7 ± 8.0	0.3	1.6	$1.8 \pm 0.4 \pm 0.3^{+0.6}_{-0.4}$	5.5
$B^+ \to D_{sJ}^*(2317)^+ \overline{D}^0$	$[D_s^+\pi^0]$	32.7 ± 10.8	0.3	2.6	$1.0 \pm 0.3 \pm 0.1^{+0.4}_{-0.2}$	3.1
$B^0 \to D_{sJ}(2460)^+ D^-$	$[D_s^{*+}\pi^0]$	17.4 ± 5.1	0.1	0.5	$2.8 \pm 0.8 \pm 0.5^{+1.0}_{-0.6}$	4.2
$B^+ \to D_{sJ}(2460)^+ \overline{D}^0$	$[D_s^{*+}\pi^0]$	29.0 ± 6.8	2.2	0.8	$2.7 \pm 0.7 \pm 0.5^{+0.9}_{-0.6}$	5.1
$B^0 \to D_{sJ}(2460)^+ D^-$	$[D_s^+\gamma]$	24.8 ± 6.5	0.5	2.6	$0.8 \pm 0.2 \pm 0.1^{+0.3}_{-0.2}$	5.0
$B^+ \to D_{sJ}(2460)^+ \overline{D}^0$	$[D_s^+\gamma]$	31.9 ± 9.0	1.4	4.1	$0.6 \pm 0.2 \pm 0.1^{+0.2}_{-0.1}$	4.3

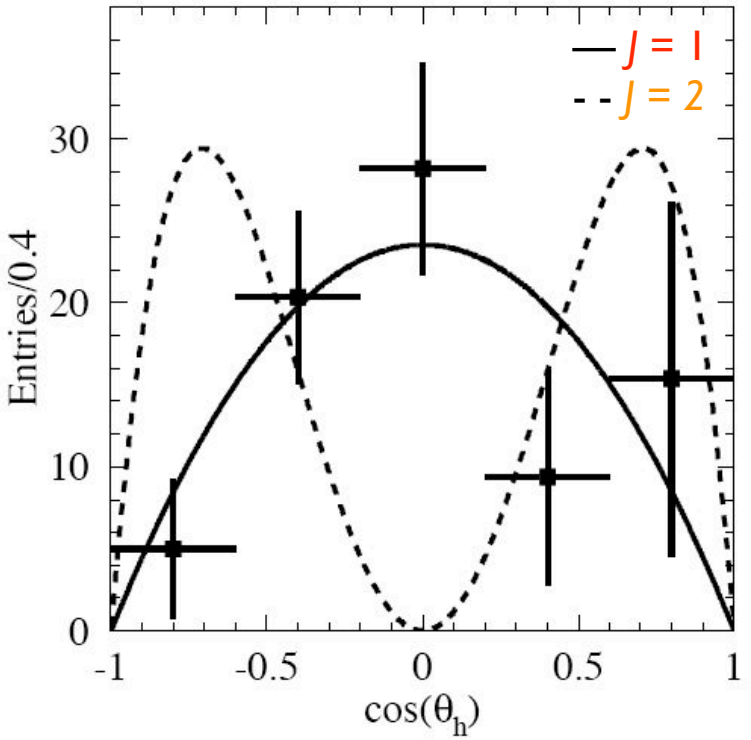
- Modes with $\overline{D}^*$ previously unobserved
- Branching fractions about an order of magnitude smaller than for $B \to \overline{D}\, D_s$ with scalar D_s

Phys. Rev. Lett. 93:181801
113 fb^{-1}

$D_{sJ}(2460)^+$ quantum numbers

- Study of helicity state of $D_{sJ}(2460)^+$:
  - helicity angle defined as angle between B and D_s in D_{sJ} rest frame;
  - use low-statistics, low-background $B \to D_{sJ}(2460)^+ D$, $D_{sJ}(2460)^+ \to D_s^+ \gamma$ modes;
  - extract yields in separate bins of $\cos(\theta_h)$
- $J = 1$ preferred





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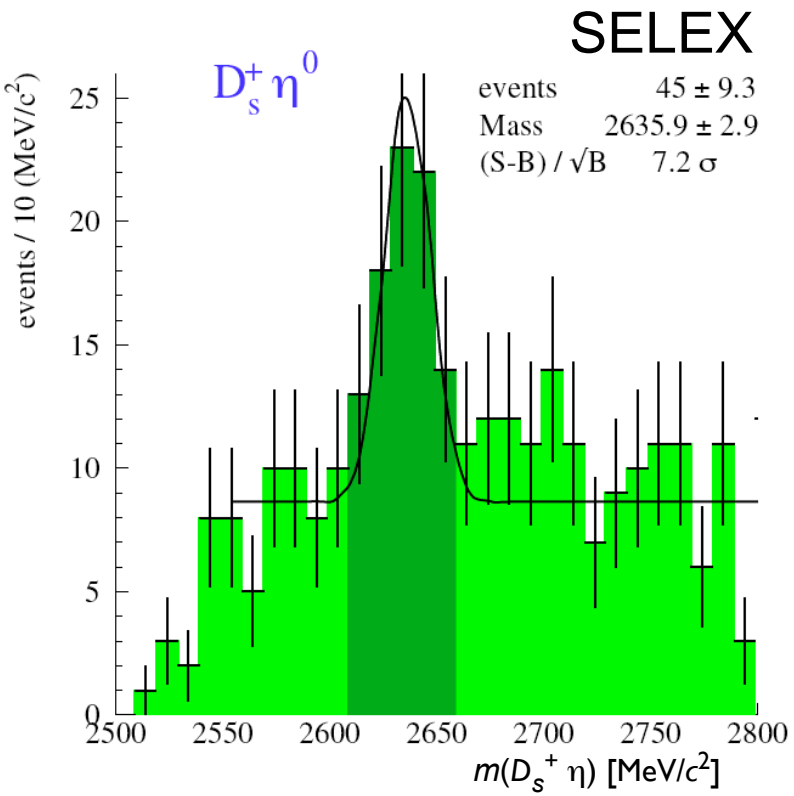
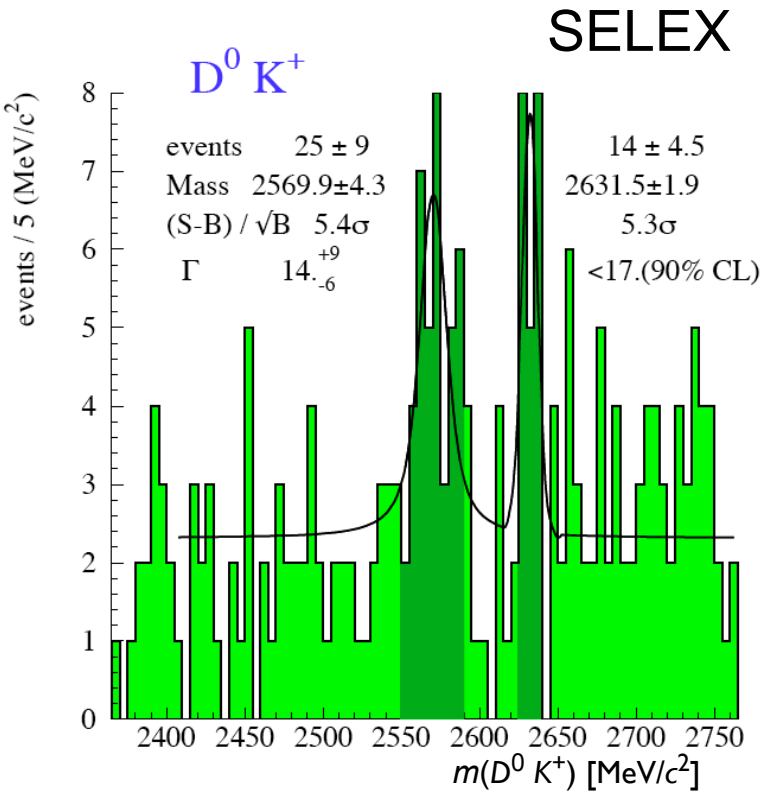
The SELEX $D_{sJ}^{*}(2632)^{+}$ state

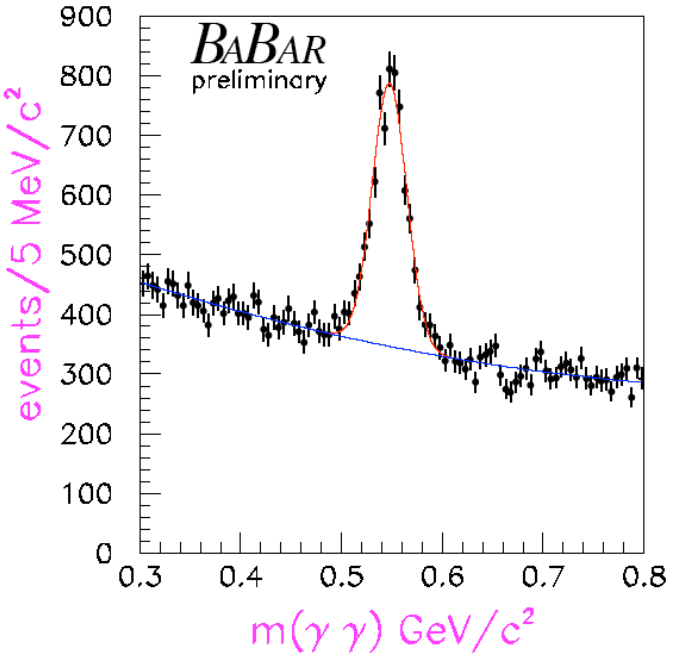
- SELEX has claimed observation of a new D_s state at 2632 MeV/c^2, observed to decay to $D_s^+ \eta$ and $D^0 K^+$

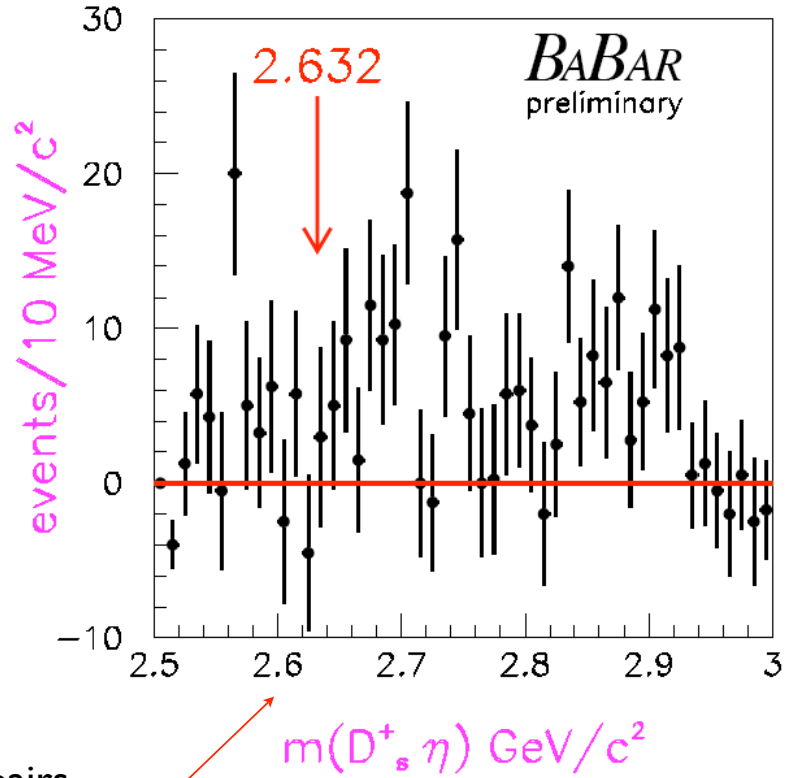




Search for $D_{sJ}^{*}(2632)^{+} \rightarrow D_s^{+}\eta$

η peak in events with reconstructed D_s^+





- subtract contribution from uncorrelated D_s^+ η pairs from D_s^+, η sidebands

No evidence for $D_{sJ}^{*}(2632)^{+}$ peak

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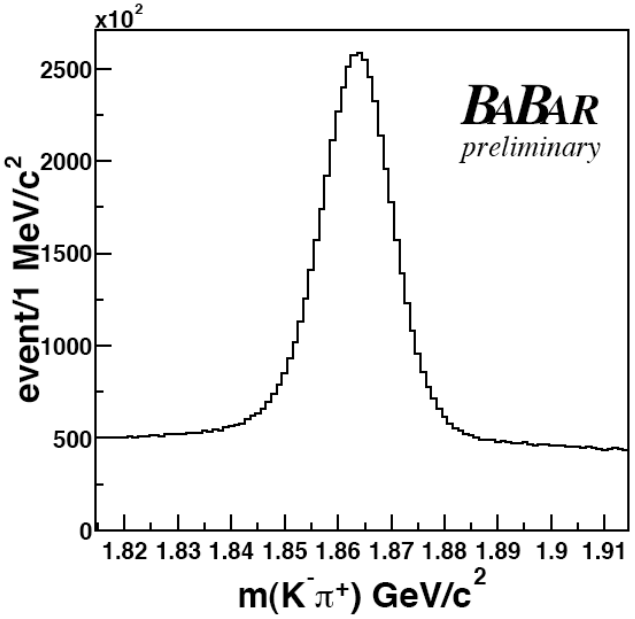
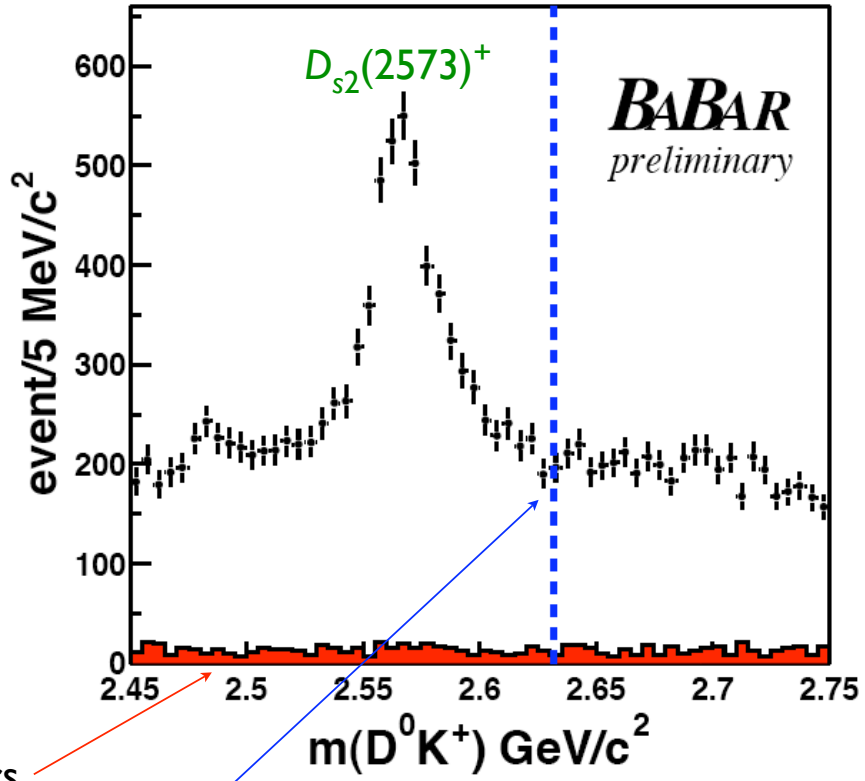
Search for $D_{sJ}^{*}(2632)^{+} \rightarrow D^{0}K^{+}$

D^0 peak in clean $K^-\pi^+$ mode





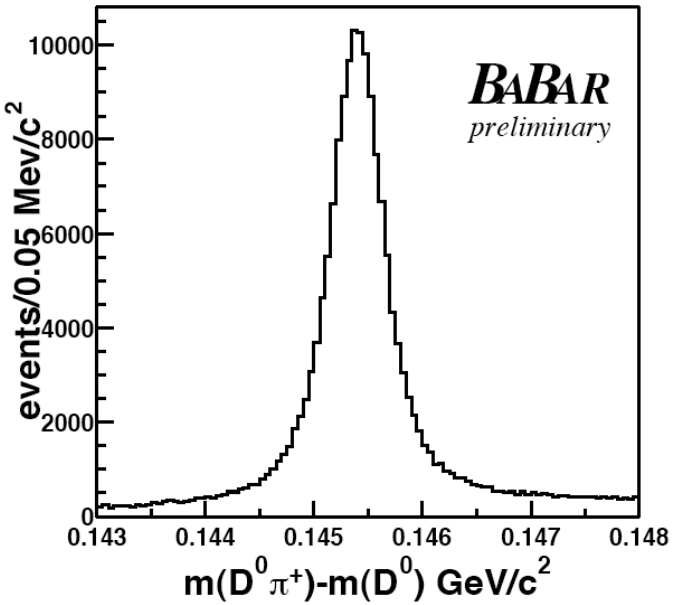
wrong-sign pairs

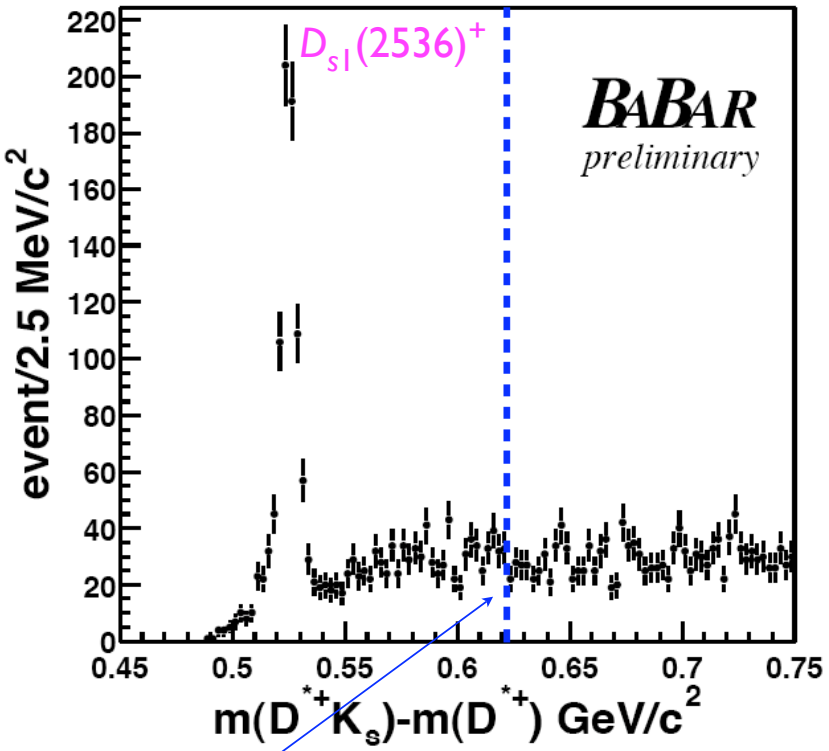
No evidence for $D_{sJ}^{*}(2632)^{+}$ peak

hep-ex/0408087
125 fb^{-1}

Search for $D_{sJ}^{*}(2632)^{+} \rightarrow D^{*+}K_S$

D^{*+} peak in clean $D^0\,\pi^+$ mode



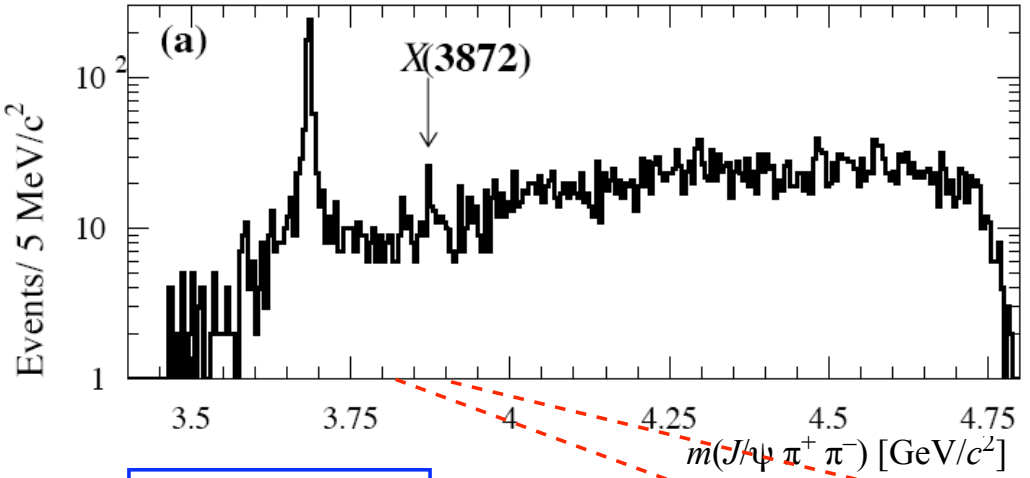


No evidence for $D_{sJ}^{*}(2632)^{+}$ peak

hep-ex/0408087
125 fb^{-1}

The X(3872) state

- First observed by Belle in the $m(J/\psi\,\pi^+\pi^-)$ spectrum in $B^- \to J/\psi\,\pi^+\pi^-\,K^-$ decays confirmed by CDF, D0 and *BABAR*:
  m(X) = (3871.4 ± 1.4) MeV/c^2
  - does not fit well with predicted charmonium states (mass, width, suppressed radiative and $D\bar{D}$ decays,...);
  - only well-established decay mode is $X(3872) \to J/\psi\,\pi^+\pi^-$ ($X(3872) \to J/\psi\,\rho^0$?)
  - could be a $D\bar{D}^*$ "molecule"



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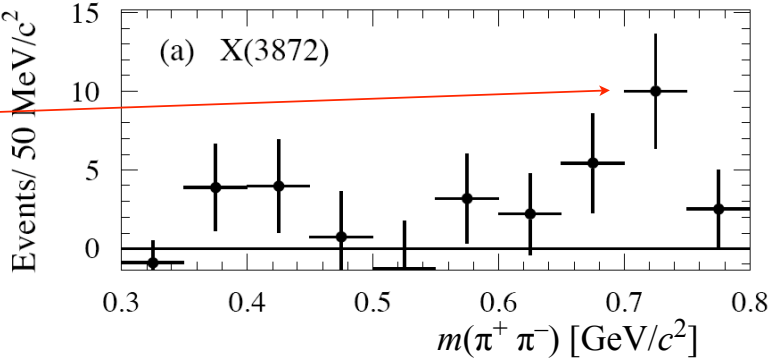
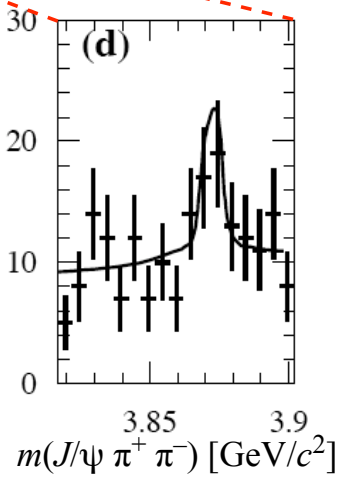
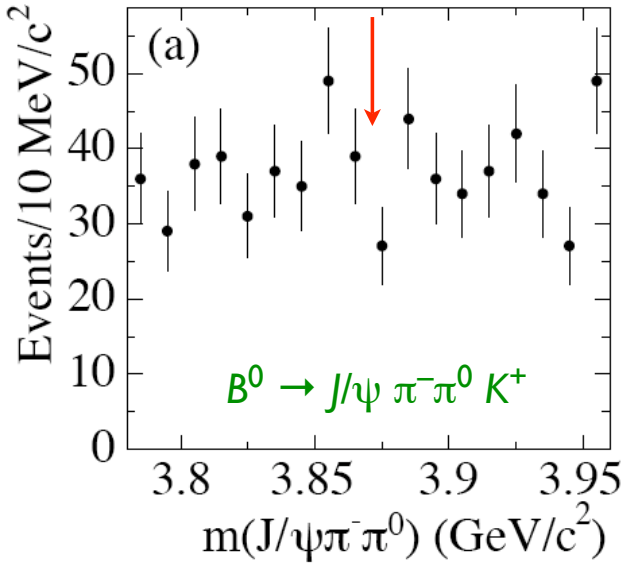




Search for $X^-(3870)$ in $B \to X^- K$

- If $X(3872) \to J/\psi\ \rho^0$, then X might be iso-vector and have a charged partner
  - If $I_{X(3872)} = 1$ and I conserved in B decays $\Rightarrow \mathcal{B}(B \to X^- K) \sim 2 \times \mathcal{B}(B \to X^- K)$;
  - search performed in charged and neutral B modes: no enhancement seen in $m(J/\psi\ \pi^-\pi^0)$: iso-vector hypothesis disfavoured with < 1/600 probability



$\mathcal{B}(B^0 \to X^- K^+, X^- \to J/\psi\ \pi^-\pi^0) < 5.4 \times 10^{-6}$

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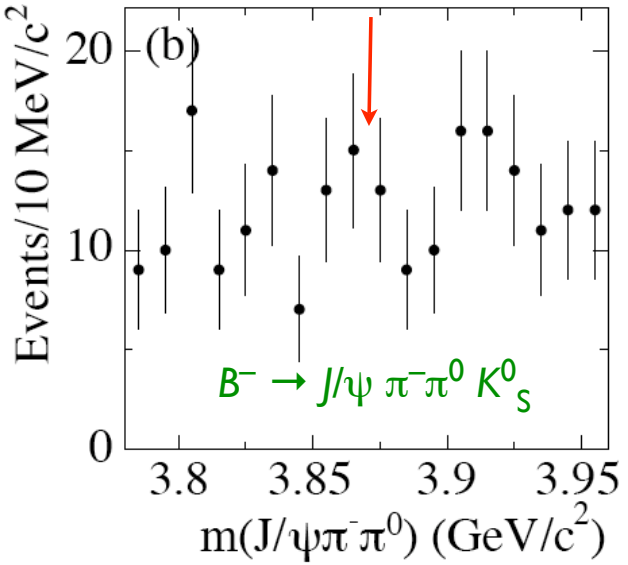
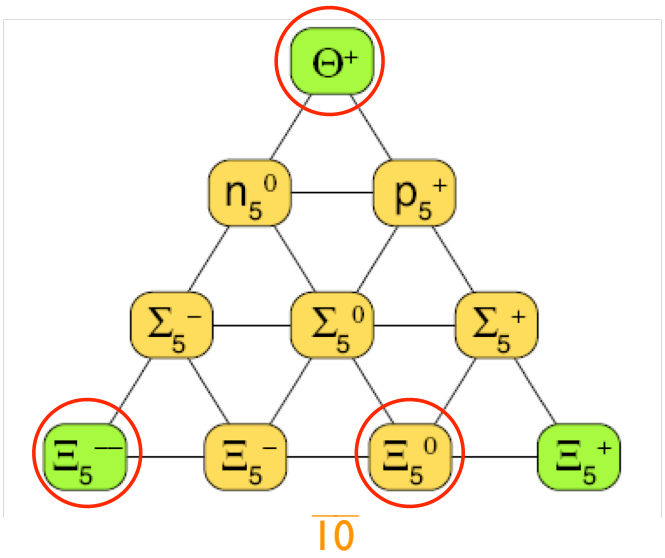
212 fb^{-1}



$\mathcal{B}(B^- \to X^- \bar{K}^0, X^- \to J/\psi\ \pi^-\pi^0) < 22 \times 10^{-6}$

Pentaquark candidates

- Observation reported of several narrow states with unconventional quark content:
  - Θ_5^+: > 10 claims; observed in $m(n\,K^+)$, $m(p\,K^0_S)$; m = (1542 ± 5) MeV/c^2; Γ < 8 MeV;
  - Ξ_5^{--}: seen by NA49 in $m(\Xi^-\,\pi^-)$ (also Ξ^0 partner); m = (1862 ± 2) MeV/c^2; Γ < 18 MeV;
  - Θ_{5c}^0: seen by H1 in $m(D^{*-}\,p)$; m = (3099 ± 3 ± 5) MeV/c^2; Γ < 28 MeV;
  - can be arranged in multiplets just like ordinary baryons



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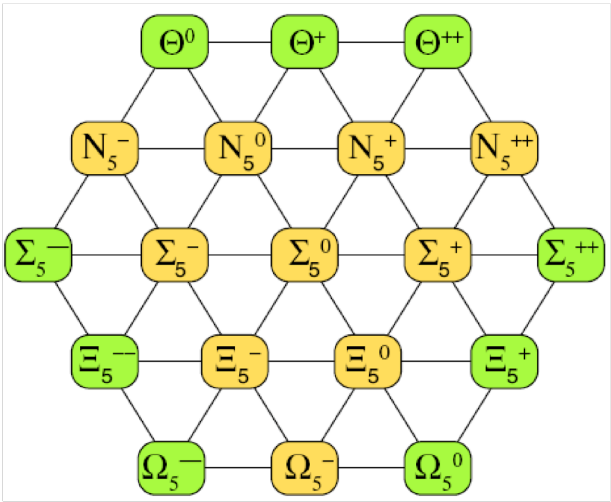

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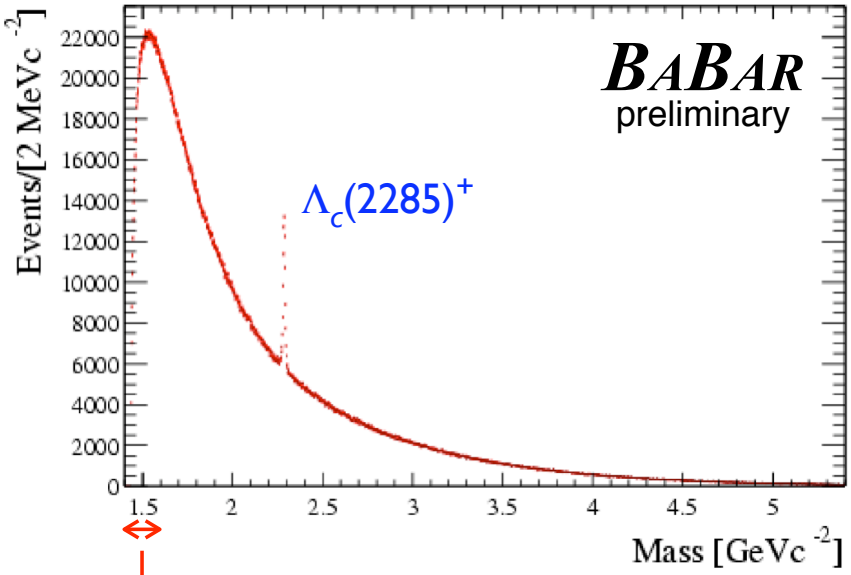
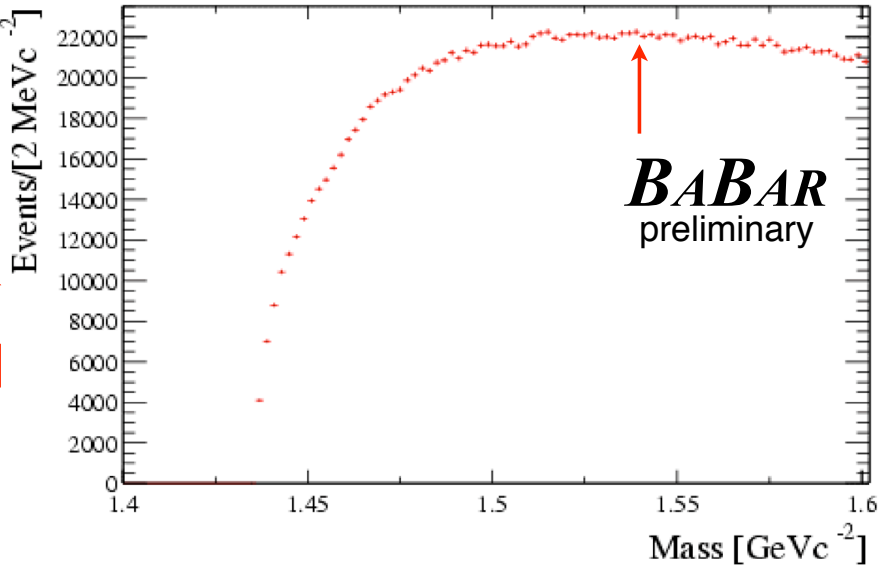
• unconventional quantum numbers

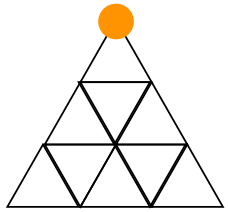
Inclusive search for $\Theta_5^+ \rightarrow p\,K_S$



- Full-inclusive search
- K^0_S from clean sample paired with well-identified protons
- Clear $\Lambda_c^+(2285)$ signal observed
- Several different selections tried

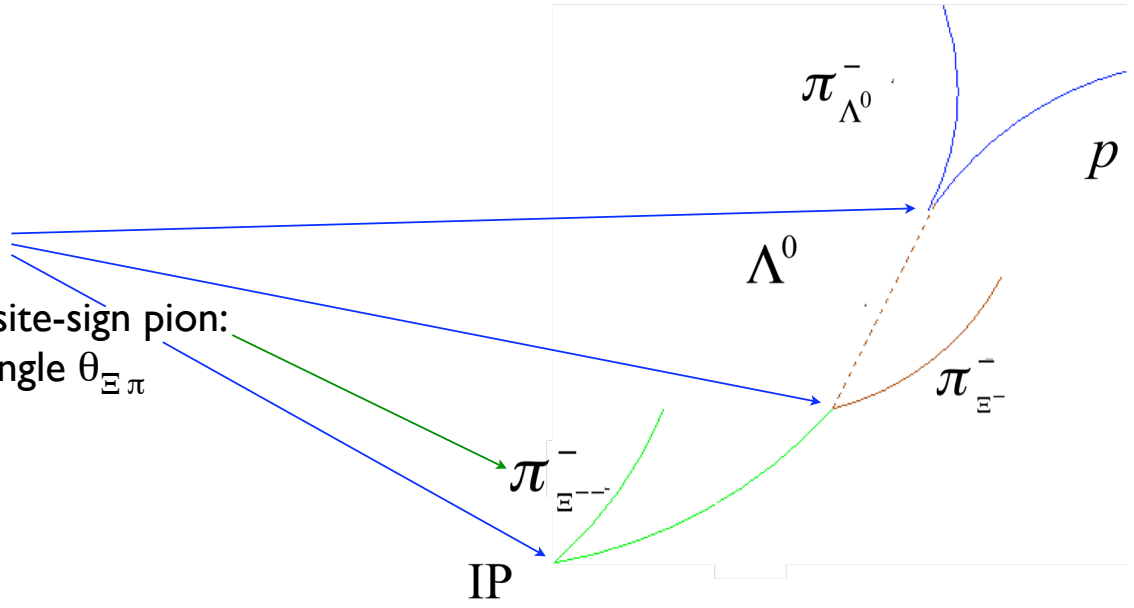


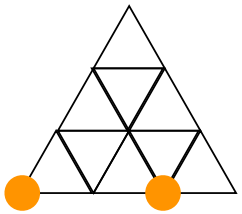
No signal found



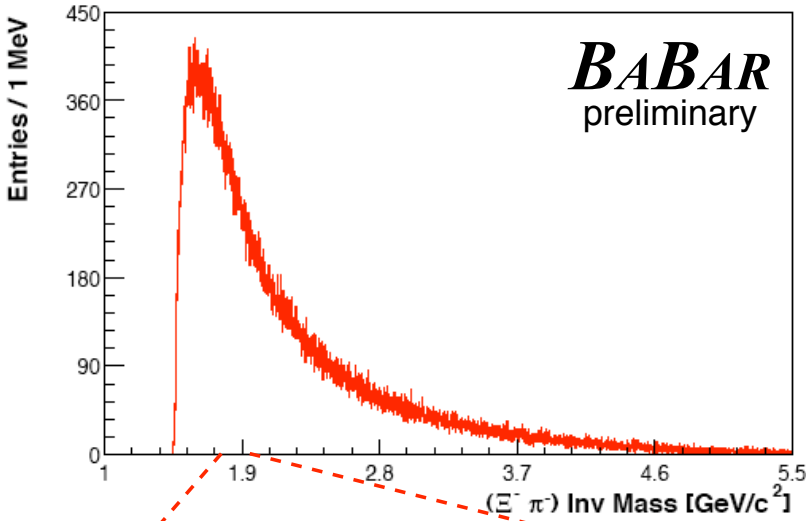
Search for $\Xi_5^{--} \rightarrow \Xi^-\pi^-$, $\Xi_5^{0} \rightarrow \Xi^-\pi^+$ (I)

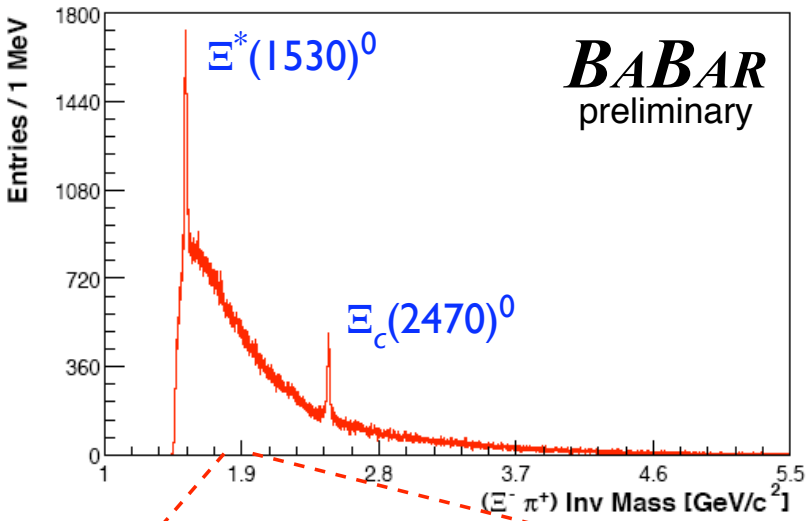
- Completely reconstruct Ξ^- candidates in decay chain
  $\Xi^- \rightarrow \Lambda^0 \pi^-$,
  $\Lambda^0 \rightarrow p\ \pi^-$
- Cut on invariant masses
- Require displaced vertexes
- Pair with like-sign or opposite-sign pion: require minimal aperture angle $\theta_{\Xi\pi}$

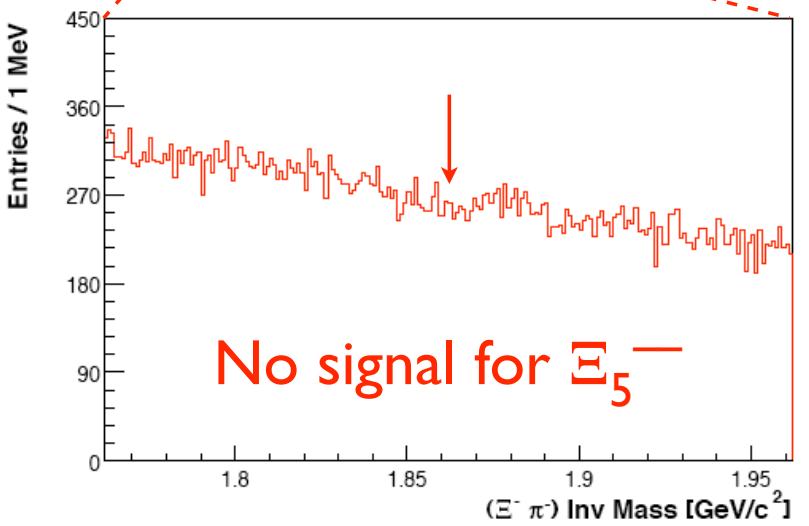


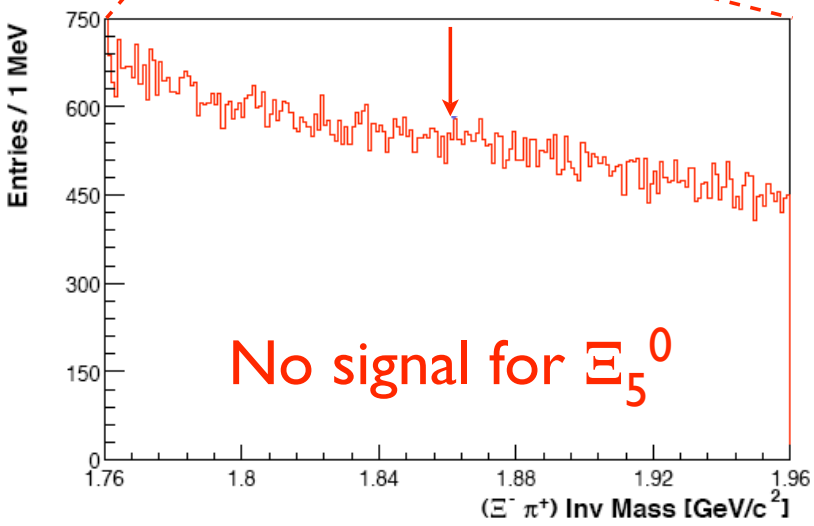


Search for $\Xi_5^- \to \Xi^-\pi^-$, $\Xi_5^0 \to \Xi^-\pi^+$ (II)







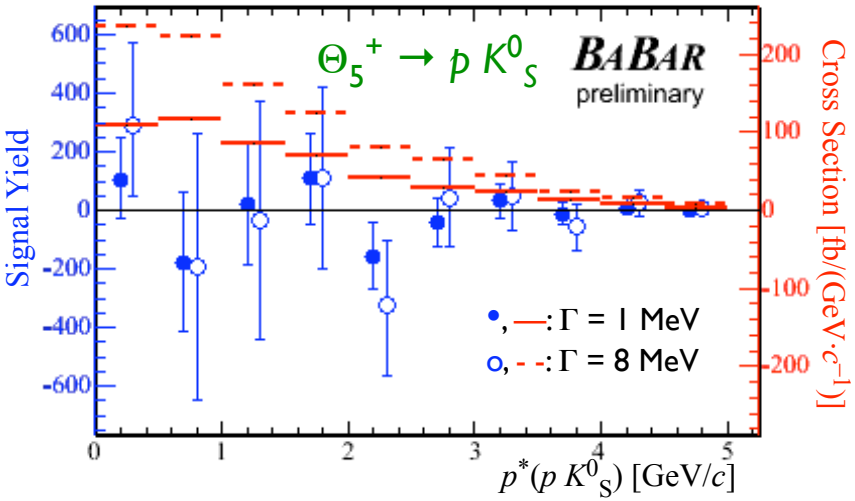


Upper limits for Θ_5^+ and Ξ_5^{--} production

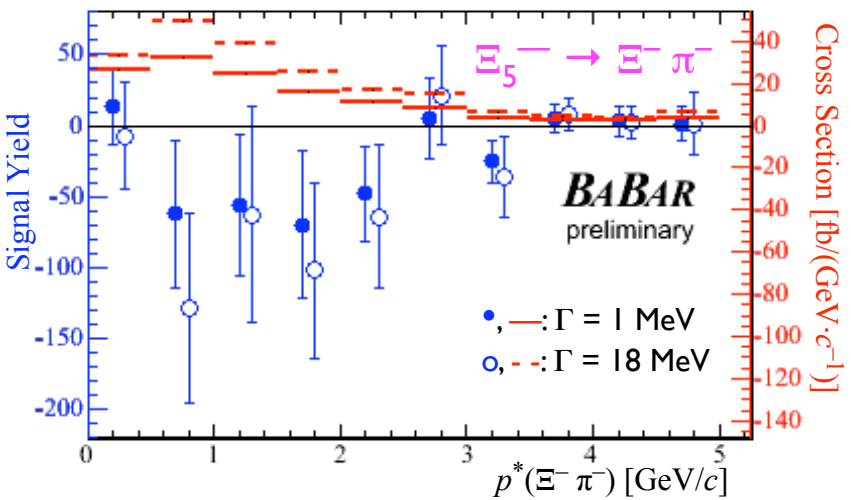
- Yield extracted in separate bins of p^* for two width hypotheses:
  Γ = 1 MeV, Γ = 8 MeV for Θ_5^+;
  Γ = 1 MeV, Γ = 18 MeV for Ξ_5^{--}

hep-ex/0408064
123 fb^{-1}

- All values consistent with null yield ⇒ upper limits (95% CL) extracted, assuming
  $\mathcal{B}(\Theta_5^+ \to p\, K^0_S)$ = 25%;
  $\mathcal{B}(\Xi_5^{--} \to \Xi^- \pi^-)$ = 50%



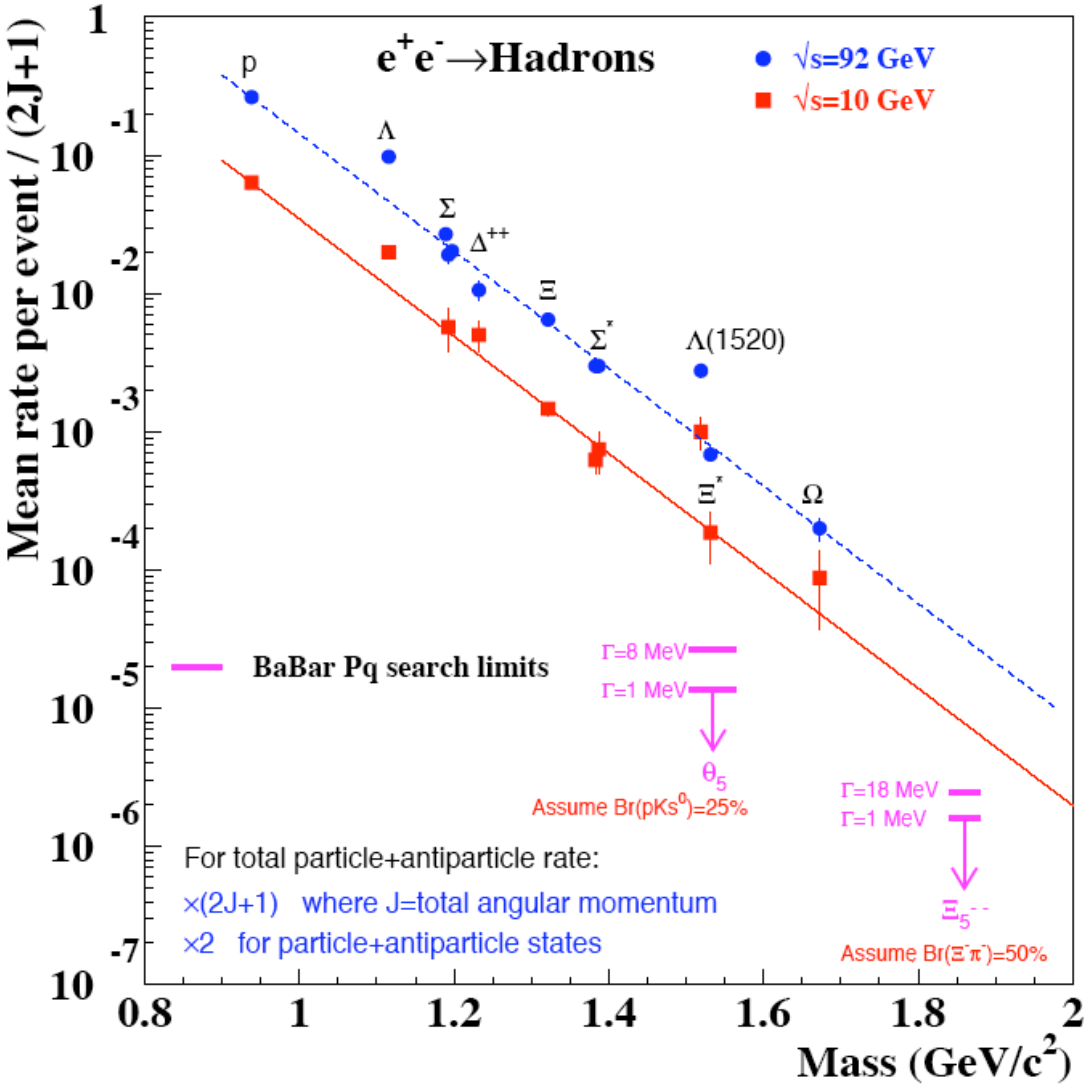
$\sigma(e^+e^- \to \Theta_5^+) < 182.8$ fb (Γ = 1 MeV)
363.1 fb (Γ = 8 MeV)



$\sigma(e^+e^- \to \Xi_5^{--}) < 22.0$ fb (Γ = 1 MeV)
33.7 fb (Γ = 18 MeV)

Comparison with baryon production rates

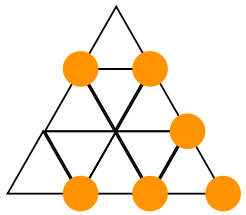
- Rates for baryon production in e^+e^- interaction decrease exponentially as a function of the baryon mass
  - If pentaquark should follow this trend we should expect:
    ~8 × 10^{-4} Θ_5^+/event;
    ~4 × 10^{-5} Ξ_5^{--}/event.
  - Measured upper limits are about a factor 8 and 4 below, respectively

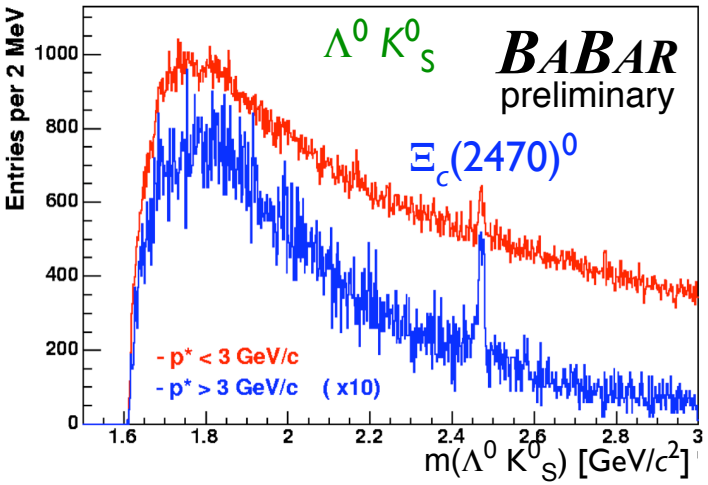


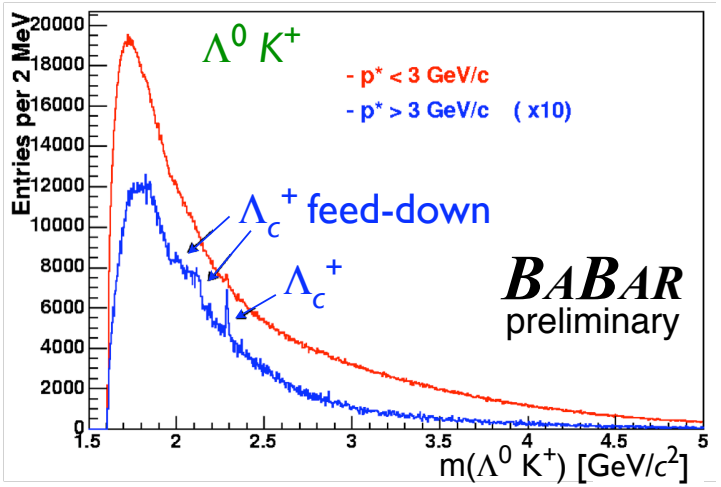
Other inclusive pentaquark searches

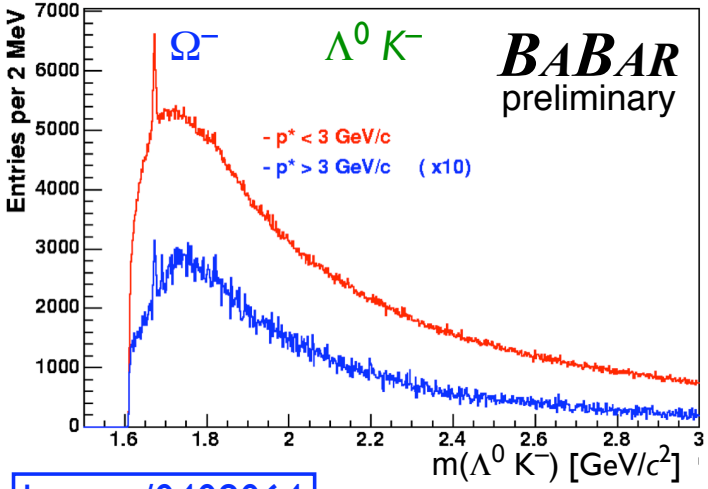
- Other searches performed in inclusive ΛK, ΣK invariant mass spectra:
  - $N_5^+ \to \Lambda^0 K^+, \Xi_5^- \to \Lambda^0 K^-, \Xi_5^0 \to \Lambda^0 K^0_S$;
  - also $m(\Sigma^0 K^+), m(\Sigma^0 K^-), m(\Sigma^0 K^0_S)$

No unexpected peak found









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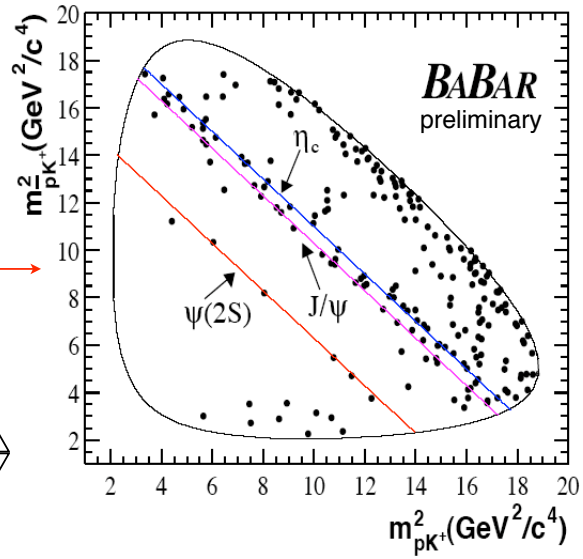
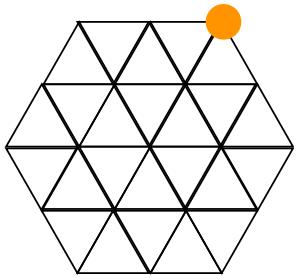
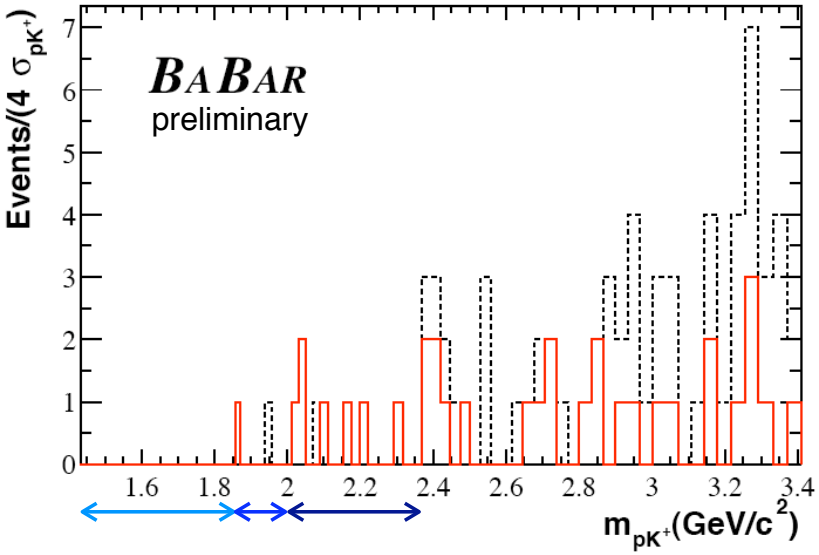
123 fb^{-1}

Search for Θ_5^{*++} in $B^+ \to \bar{p}\,(p\,K^+)$

- $B \to \bar{p}\,p\,K$ decay observed by Belle, confirmed by *BABAR*
- 27-plet member Θ_5^{--} can be looked for in $B^+ \to \bar{p}\,\Theta_5^{++}$, $\Theta_5^{++} \to p\,K^+$ chain:
  - significant contribution from charmonium $\to \bar{p}\,p$;
  - get upper limits from m($p\,K^+$) spectrum







$\mathcal{B}(B^+ \to \bar{p}\Theta_5^{++}) \times \mathcal{B}(\Theta_5^{++} \to p\,K^+)$

$< 1.5 \times 10^{-7}$ $(1.43 < m < 1.85)$ GeV/c^2

$< 2.4 \times 10^{-7}$ $(1.85 < m < 2.00)$ GeV/c^2

$< 3.3 \times 10^{-7}$ $(2.00 < m < 2.36)$ GeV/c^2

hep-ex/0408037
81 fb^{-1}

Charmed pentaquarks in $B^0 \to (\overline{D}^{(*)} p)\overline{p}(\pi)$

- $B^0 \to D^{*-} p \overline{p} \pi^+$ decay observed by CLEO,
  $B^0 \to \overline{D}^0 p \overline{p}$, $B^0 \to \overline{D}^{*0} p \overline{p}$ observed by Belle:

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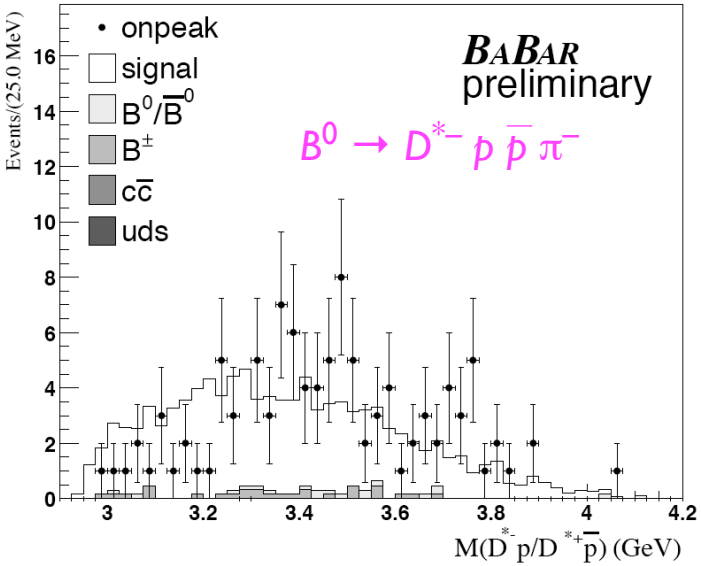
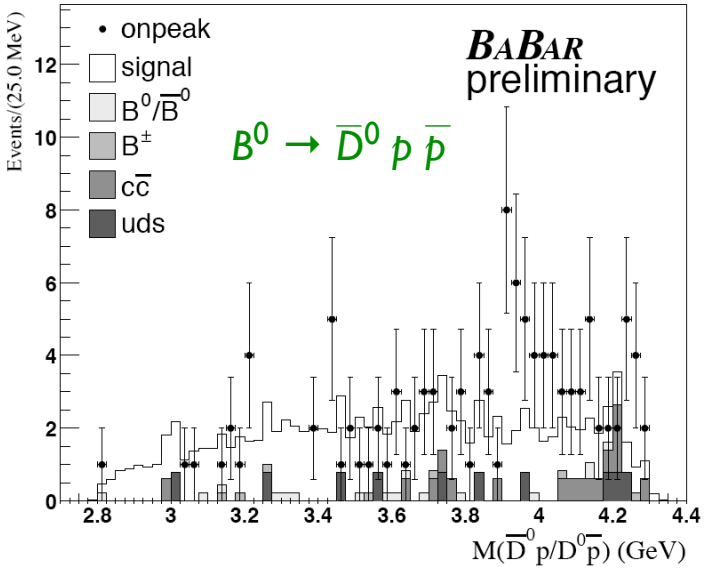
113 fb^{-1}

- reconstruct them in *BABAR*: $B^0 \to D^- p \overline{p} \pi^-$ also observed for the first time;
- look for possible structures in all $D^{(*)}$ $(\overline{p})$ invariant mass spectra (8 combinations): heavy charmed baryons or charmed pentaquarks





No evidence for Θ_{5c}^0 or other new states

Summary

- $D_{sJ}^{*}(2317)^{+}$ and $D_{sJ}(2460)^{+}$ well established experimentally
  - study of quantum numbers and other properties in progress in inclusive and *B*-decays anlayses
- No evidence found for SELEX $D_{sJ}^{*}(2632)^{+}$
- Confirmation of X(3872) in *B* decays
  - nature of this state still unclear (charmonium? $D\bar{D}^{*}$ molecule?): further studies in progress
- No evidence found for recent pentaquark candidates
  - null results for extensive searches of antidecuplet members in high statistics $e^{+}e^{-}$ samples
  - no evidence so far for charmed pentaquark production in *B* decays