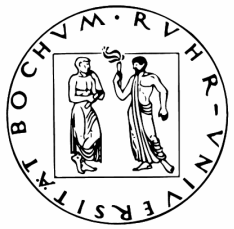
BABAR






9th International Workshop on
Meson Production, Properties and Interaction

# Charm and Charmonium Spectroscopy

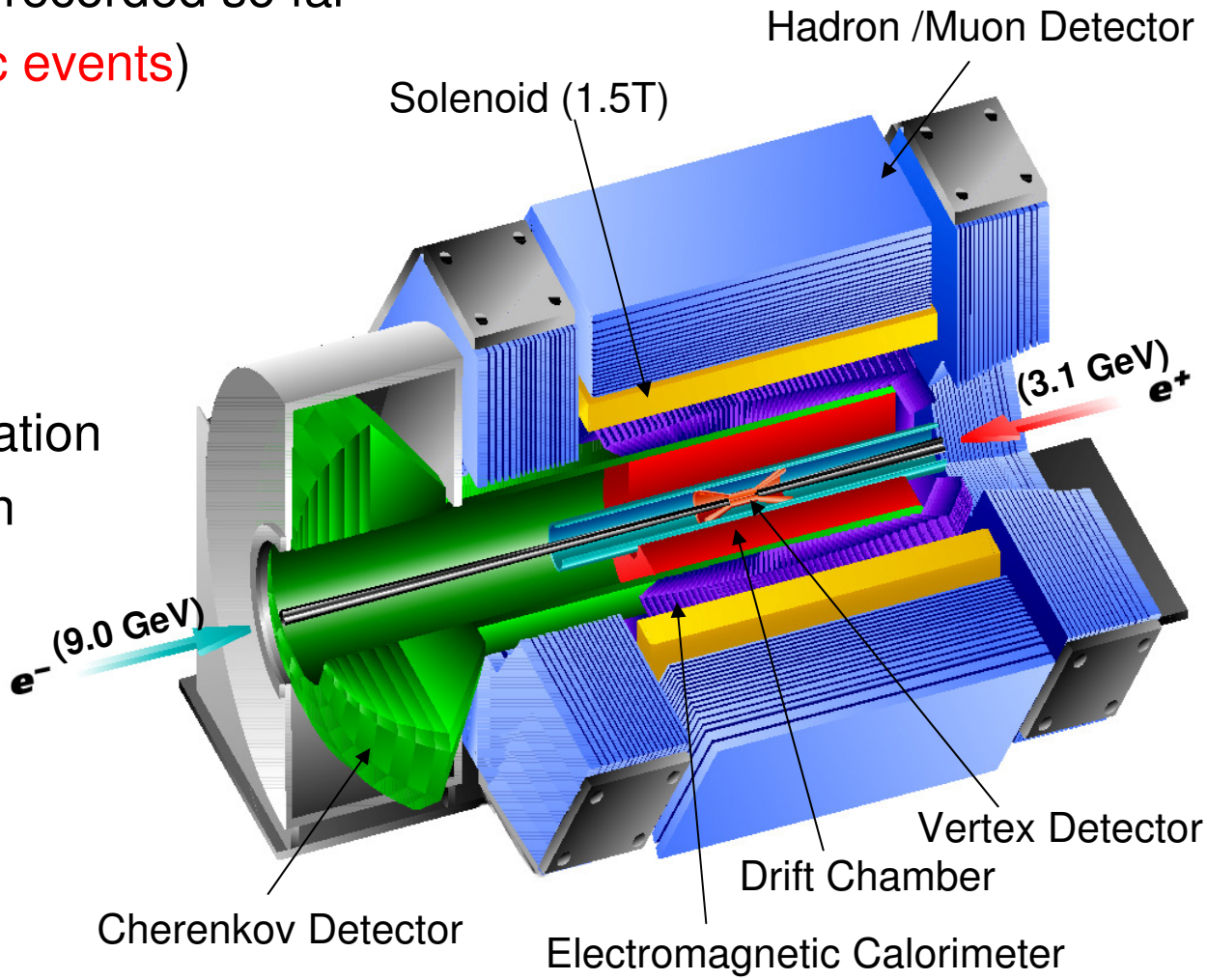
M. Pelizäus (Ruhr-Universität Bochum)
for the Babar Collaboration

June 13, 2006
Cracow, Poland

# The Babar-Experiment

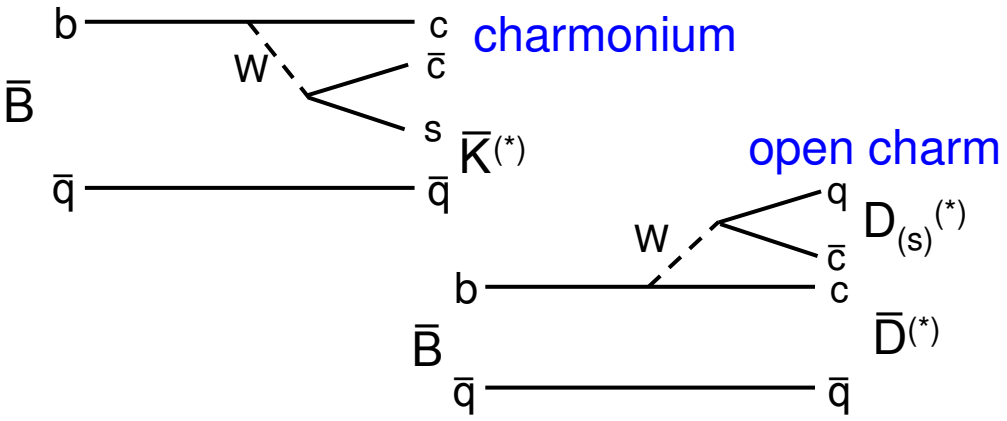
- Asymmetric energy $e^+e^-$ storage rings PEP-II
  - ~90% at 10.58 GeV ($\Upsilon(4S)$); ~10% at 10.54 GeV
  - more than 350 $fb^{-1}$ recorded so far (~1.6x$10^9$ hadronic events)

- Good track and vertex reconstruction
- Good particle identification
- Good photon detection

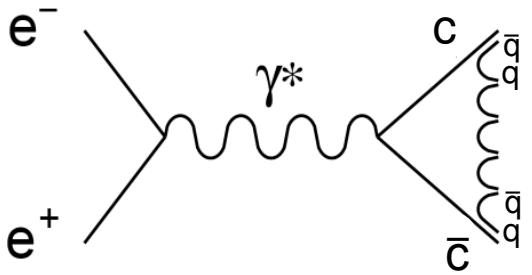


# Production of hidden and open charm states

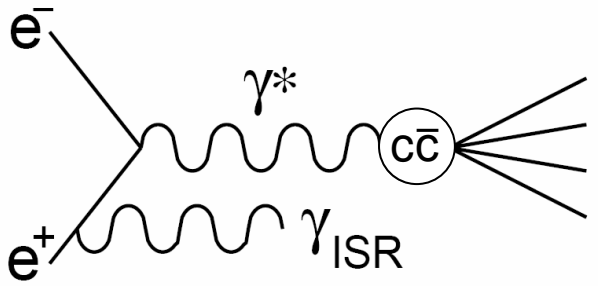
- Production in B decays
  - ~380x10$^6$ B$\bar{\text{B}}$ events
  - provides access to inclusive measurements of absolute branching fractions




- $e^+e^- \to c\bar{c}$ fragmentation processes
  - ~1x10$^9$ charmed particles
  - spectroscopy of open charm states with high precision




- Initial state radiation (ISR) $e^+e^- \to \gamma_{ISR}(c\bar{c})$
  - J/ψ sample: ~14x10$^6$ events
  - resonance production in the energy range $\sqrt{s} < 10.58\ GeV$
  - only production of $J^{PC}=1^{--}$ states



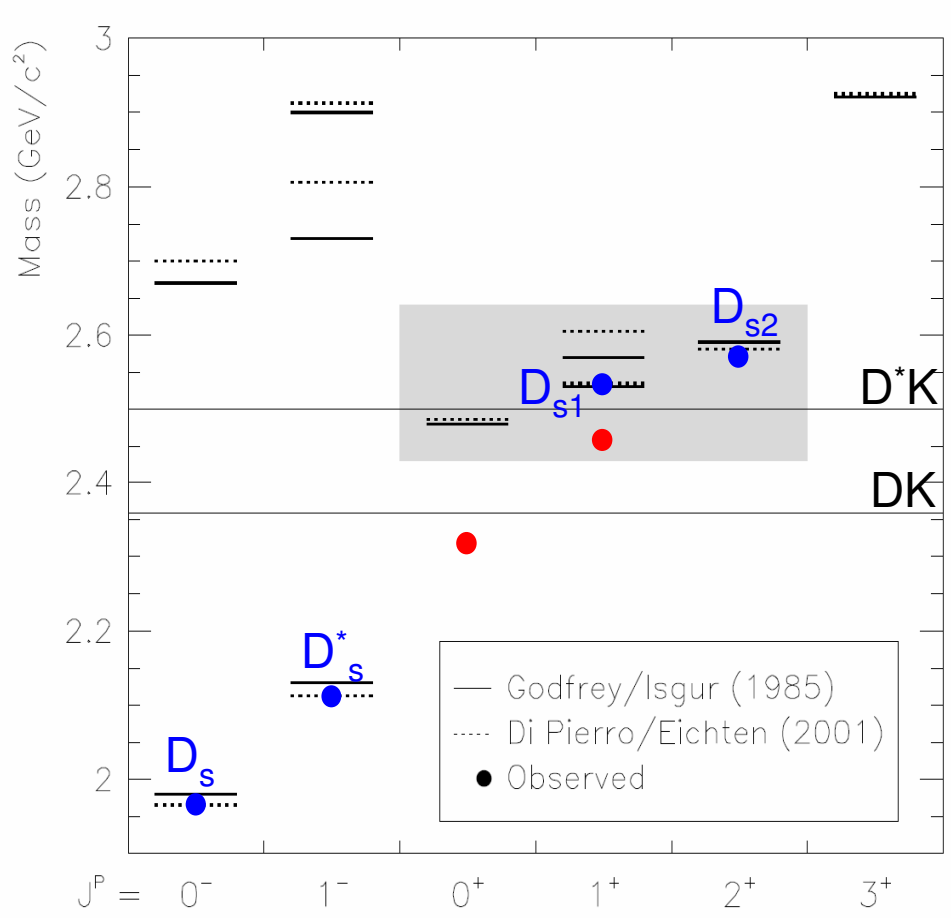

Babar offers excellent options for charm / charmonium spectroscopy

# Spectrum of $c\bar{s}$ mesons

- Picture on $c\bar{s}$ mesons still incomplete
  - established are $D_s$, $D_s^*$, $D_{s1}$, $D_{s2}$
- Candidates for lowest, missing $J^P=0^+,1^+$ states (discovered in 2003)

  $D_{sJ}^*(2317)$ $(\rightarrow D_s\pi^0)$
  m=2317.4±0.9 MeV, Γ<4.6 MeV (PDG)
  $J^P$ consistent with $0^+$

  $D_{sJ}(2460)$ $(\rightarrow D_s^*\pi^0, D_s\gamma, D_s\pi^+\pi^-)$
  m=2459.3±1.3 MeV, Γ<5.5 MeV (PDG)
  $J^P$ consistent with $1^+$
- $c\bar{c}$ assignment in conflict with expectations: Masses lower than predicted, widths very small




- Numerous theoretical explanations for discrepancy
  - possibly exotic states (molecules, tetra-quarks,...)

# $D_{sJ}$ studies at Babar

- Put further experimental constraints on the two states

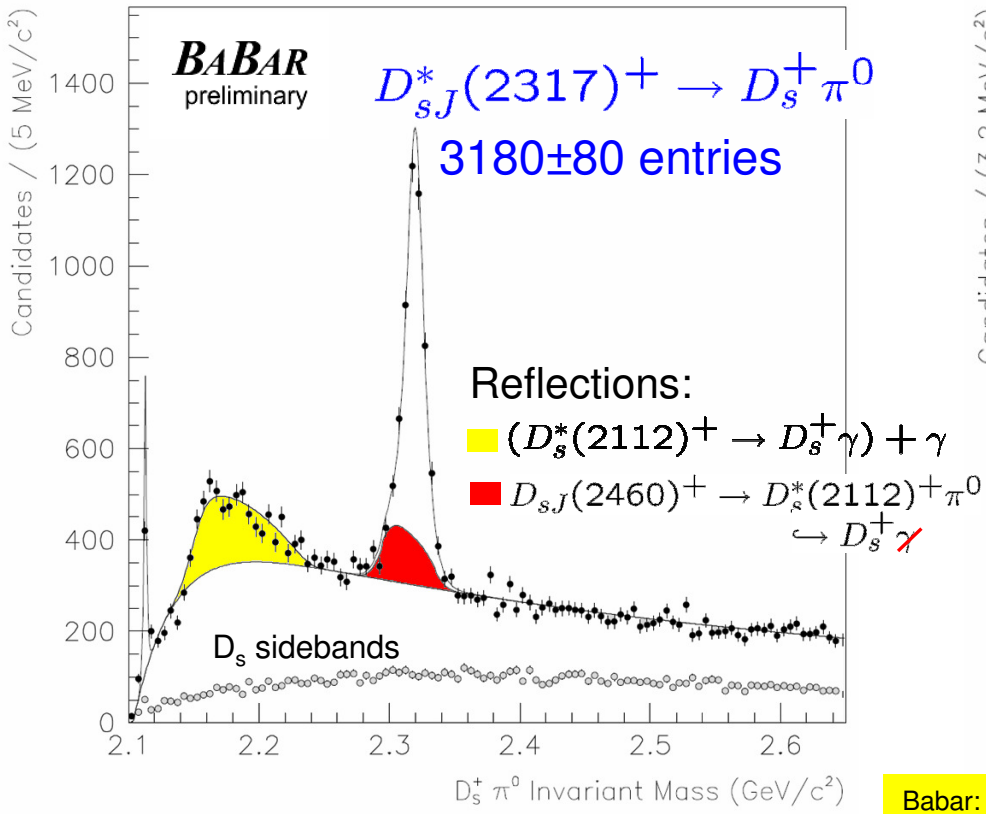
- Comprehensive, exclusive study for
  $e^+e^- \to c\bar{c}$ fragmentation processes
  - investigation of $D_s\pi^0$, $D_s\gamma$, $D_s\pi^0\gamma$, $D_s\pi^0\pi^0$, $D_s\gamma\gamma$, $D_s\pi^+\pi^-$ final states
  - measurement of branching ratios, masses and widths
  - search for doubly charged / neutral $D_{sJ}^*(2317)$ partners in $D_s\pi^\pm$ system (predicted by some molecule models)

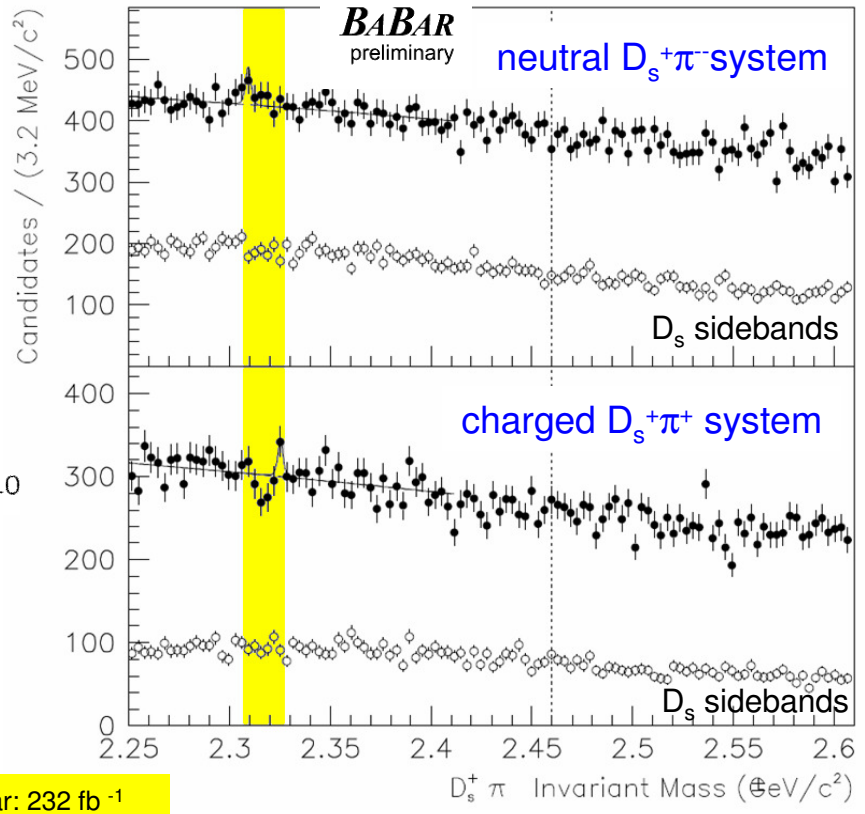
- Inclusive study of $B \to D^{(*)}D_{sJ}$ decays
  - measurement of absolute branching fractions

# Exclusive study of $D_{sJ}^*(2317)$

- Only observed $D_{sJ}^*(2317) \to D_s\pi^0$
  m=(2319.6±0.2±1.4)MeV/c²
  Γ<3.8 MeV (95% CL)
- Upper limits on branching ratios for 5 other decay modes

- No neutral or doubly charged partner states found (→isospin I=0)
  - production 60-80x suppressed wrt $D_{sJ}^*(2317)$ production rate
    (rules out some molecule models)



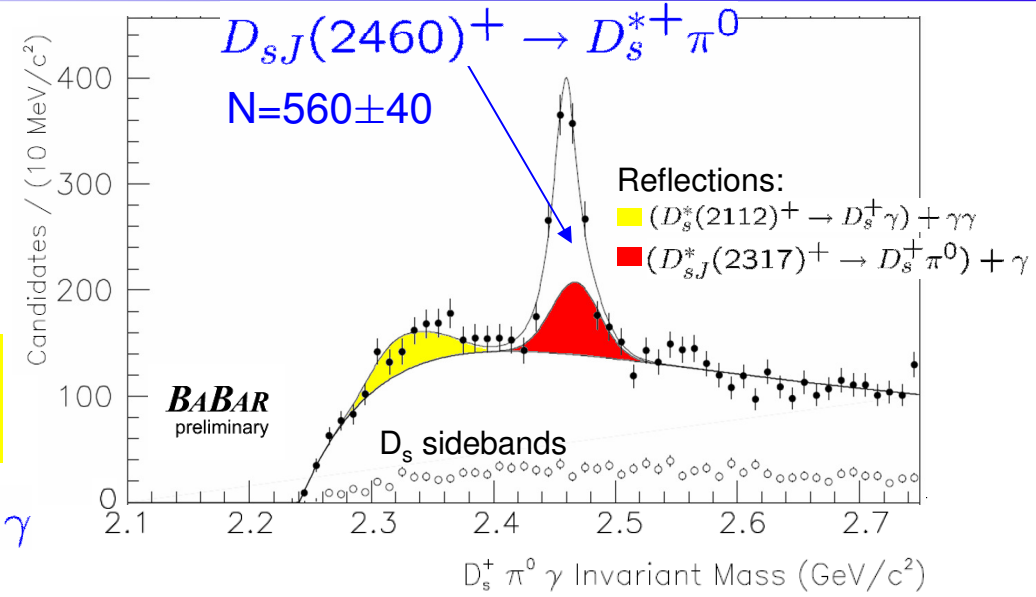



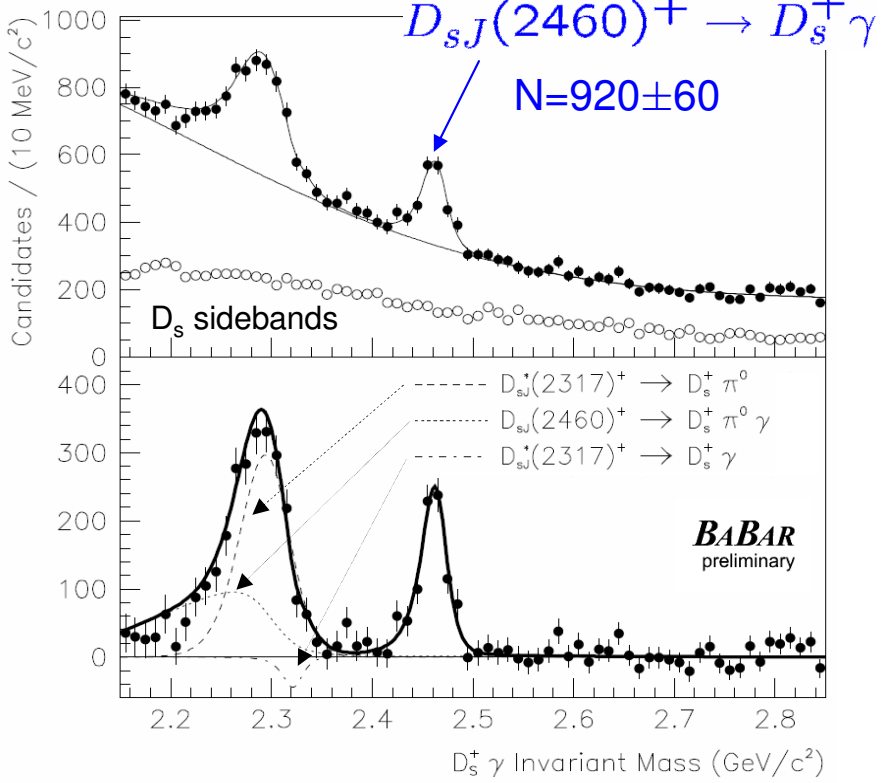

Babar: 232 fb $^{-1}$
hep-ex/0604030
submitted to PRD

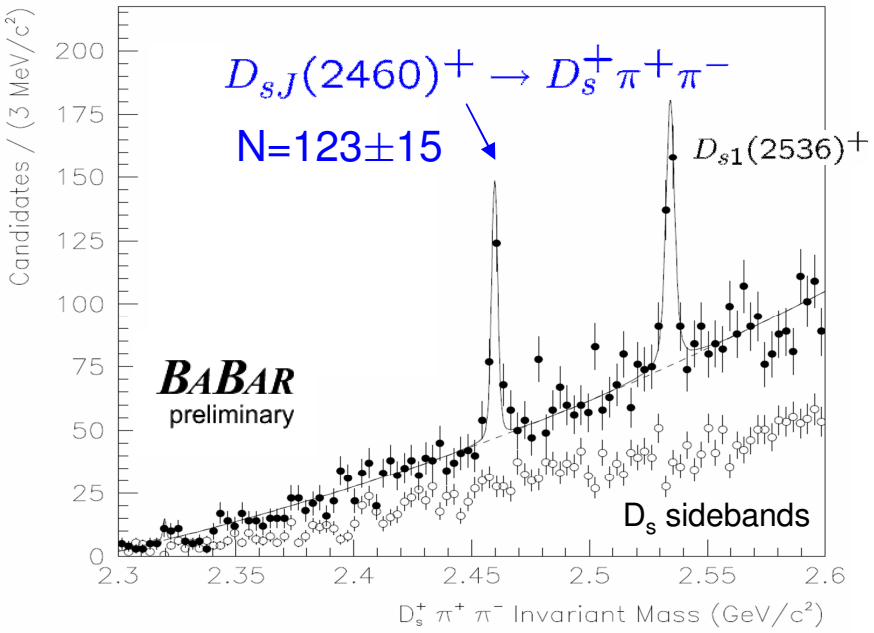
# Exclusive study of $D_{sJ}(2460)$

- Observe decays to $D_s^*\pi^0(\rightarrow D_s\pi^0\gamma)$, $D_s\gamma$ and $D_s\pi^+\pi^-$
- Upper limits on branching ratios for 5 other decay modes

Babar: 232 fb $^{-1}$
hep-ex/0604030
submitted to PRD



# Exclusive study of $D_{sJ}(2460)$

Babar: 232 fb $^{-1}$
hep-ex/0604030
submitted to PRD

- Measurement of two branching ratios

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\gamma)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.34 \pm 0.04 \pm 0.04$$

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-)}{\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.077 \pm 0.013 \pm 0.008$$

- Combined results from three decay modes

  $m=(2460.1\pm0.2\pm0.8)\text{MeV}/c^2$
  $\Gamma<3.5$ MeV (95% CL)

- Additional measurement for $D_{s1}(2536)^+$ from $D_s\pi^+\pi^-$ decay

  $m=(2534.6\pm0.3\pm0.7)\text{MeV}/c^2$
  $\Gamma<2.5$ MeV (95% CL)

# Exclusive study: Summary

- Decay patterns of $D_{sJ}^{*}(2317)$ and $D_{sJ}(2460)$ are compatible with spin-parity assignment $0^{+}$ and $1^{+}$, respectively

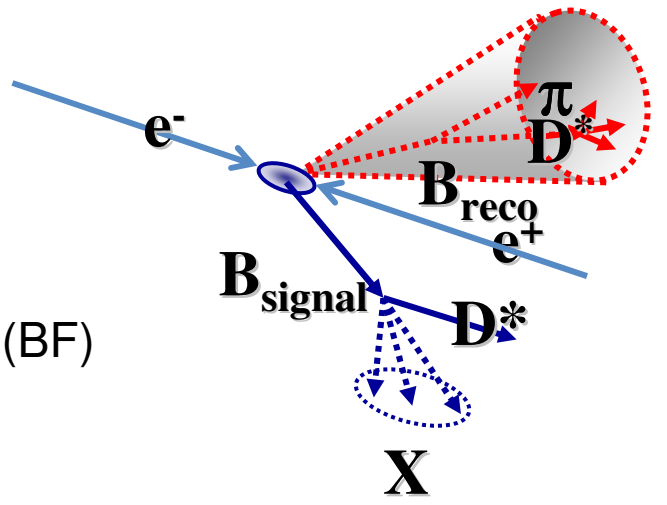
| Final state | $D_{sJ}^{*}(2317)^{+}$ if $J^P = 0^+$ | | $D_{sJ}(2460)^{+}$ if $J^P = 1^+$ | |
|---|---|---|---|---|
| $D_s^+\pi^0$ | ⇑ | △ | ⇓ | ▽ |
| $D_s^+\gamma$ | ⇓ | ▽ | ⇑ | △ |
| $D_s^+\pi^0\gamma$ | ⇑ | | ⇑ | |
| $D_s^*(2112)^+\pi^0$ | ⇓ | ▽ | ⇑ | △ |
| $D_{sJ}^*(2317)^+\gamma$ | – | – | ⇑ | ▽ |
| $D_s^+\pi^0\pi^0$ | ⇓ | ▽ | ⇑ | ▽ |
| $D_s^+\gamma\gamma$ | ⇑ | ▽ | ⇑ | ▽ |
| $D_s^*(2112)^+\gamma$ | ⇑ | ▽ | ⇑ | ▽ |
| $D_s^+\pi^+\pi^-$ | ⇓ | ▽ | ⇑ | △ |

⇑ allowed, ⇓ forbidden

△ observed, ▽ not observed

# Inclusive study of $D_{sJ}(2460)$

- Fully reconstructed $B_{reco}$ and $D^*$ from other $B_{signal} \to D^{(*)}X$, $D_s^{(*)}X$ decay investigate recoil mass $m_X$ for signal




- First measurement of absolute branching fractions (BF) for $\overline{B} \to D^{(*)+/0} D_{sJ}(2460)^-$ decays, e.g.

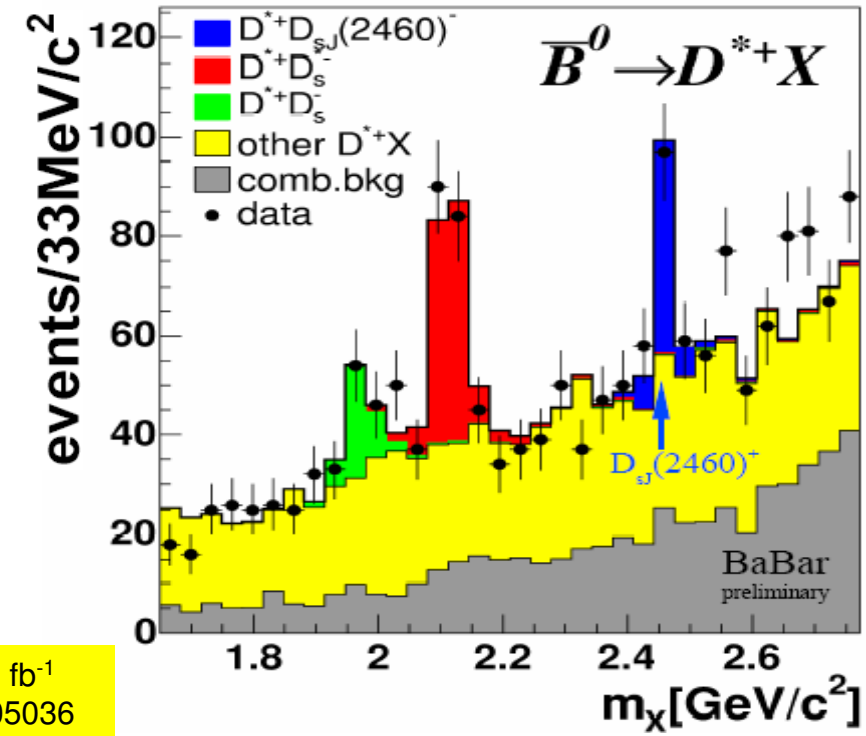
$$\mathcal{B}(\overline{B}^0 \to D^{*+} D_{sJ}(2460)^-) = (0.88 \pm 0.20 \pm 0.14)\%$$

- Combine with previously measured product BF and BRs / use

$$\mathcal{B}(D_s^+ \to \phi\pi^+) = (4.62 \pm 0.62)\%$$

$$\mathcal{B}(D_{sJ}(2460)^+ \to D_s^{*+}\pi^0) = (56 \pm 13 \pm 9)\%$$
$$\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\gamma) = (16 \pm 4 \pm 3)\%$$
$$\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-) = (4 \pm 1)\%$$

Sum of known BFs is: (77±17)%




Babar: 211 fb$^{-1}$
hep-ex/0605036
submitted to PRD

# Exclusive study of the DK system

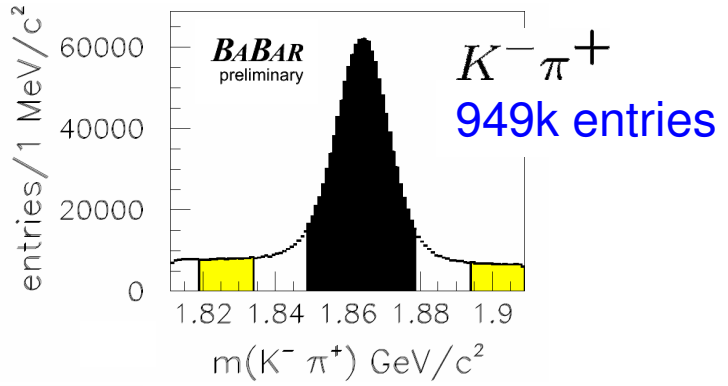
- Exlusive study of the DK system in $e^+e^- \to c\bar{c}$ processes

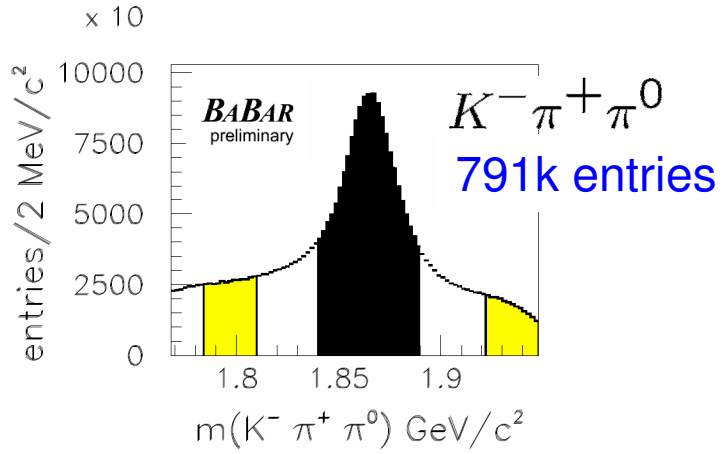
$$e^+e^- \to (D^0 K^+) X \hookrightarrow K^-\pi^+, K^-\pi^+\pi^0$$

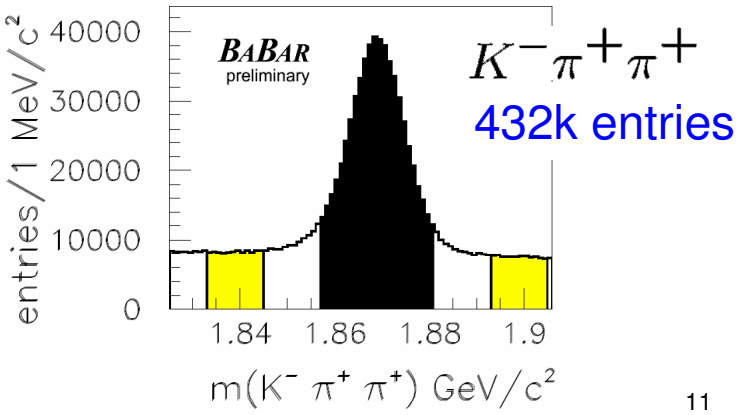
$$e^+e^- \to (D^+ K_S^0) X \hookrightarrow K^-\pi^+\pi^+$$

- Good kaon / pion identification
- Clean $K_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$ selection
- Kinematic fit to common vertex
- CMS momentum $p^*(DK) > 3.5$ GeV

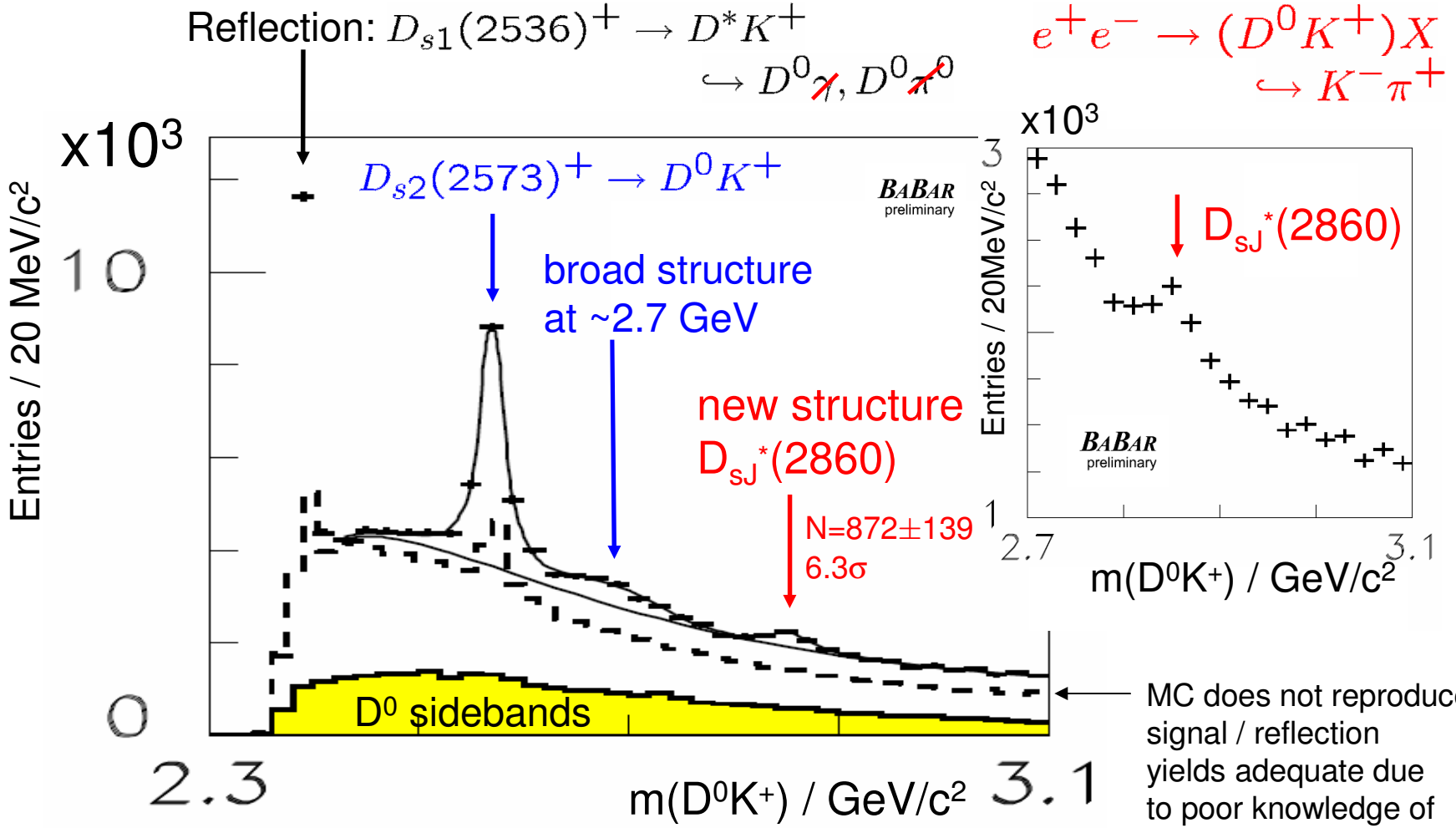
Babar: 240 fb$^{-1}$
preliminary



# Observation of a new resonance at 2.86 GeV




MC does not reproduce signal / reflection yields adequate due to poor knowledge of charm production in fragmentation processes

- New structure at 2.86 GeV
  - absent in $D^0$ sidebands and $e^+e^- \to c\bar{c}$ MC events
  - no reflection from $D^*$ decays
  - not due to kaon/pion misidentification

Babar: 240 fb$^{-1}$ preliminary

# Further studies of $D_{sJ}^*(2860)$

- New structure also apparent in $K^+D^0(\rightarrow K^-\pi^+\pi^0)$ and $K_SD^+(\rightarrow K^-\pi^+\pi^+)$ with consistent mean and width

Babar: 240 fb$^{-1}$
preliminary

- Fit to sum of all 3 data samples yields to

$D_{sJ}^*(2860)^+$
m=2856.6±1.5±5.0 MeV/c$^2$
Γ=48±7±10 MeV

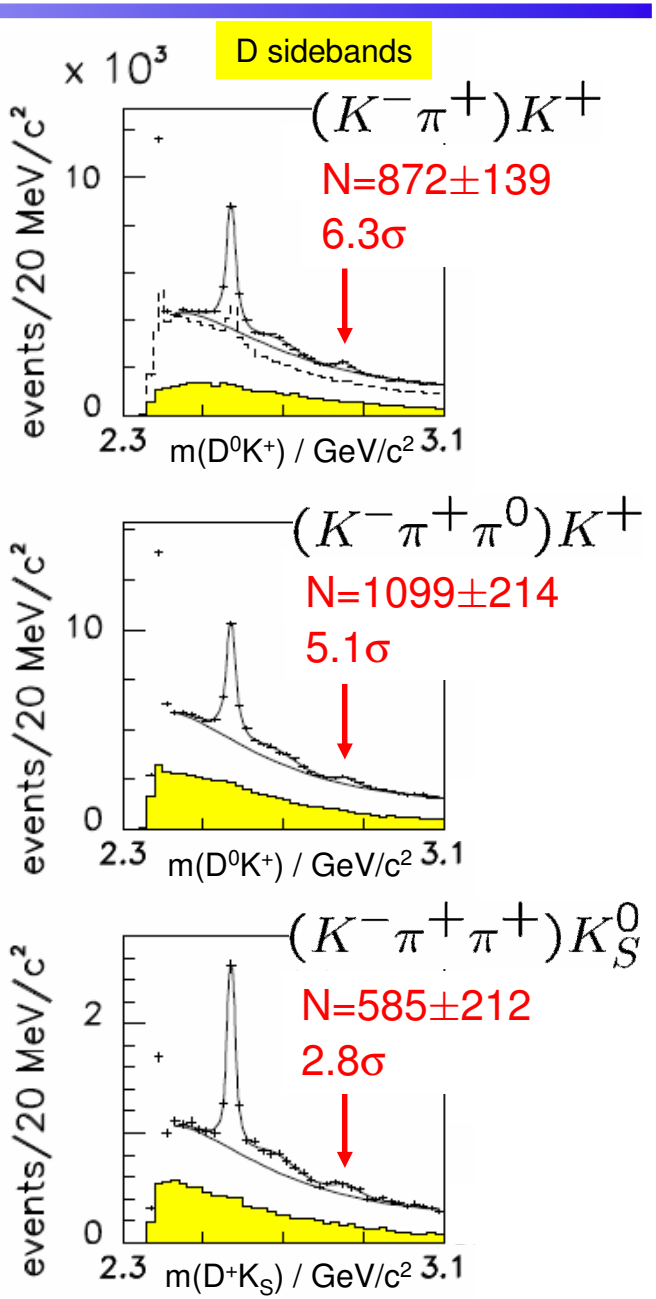
$D_{s2}(2572)^+$
m=2572.2±0.3±1.0 MeV/c$^2$
Γ=27.1±0.6±5.6 MeV

broad structure at ~2.7 GeV needed to fit data
(best parameterization: Gaussian)
also indication for activity in that region at low p* values for $D^0\rightarrow K^-\pi^+$ sidebands (reflection?)

if resonance: $X(2690)^+$ (Breit Wigner parameterization)
m=2688±4±2 MeV/c$^2$, Γ=112±7±36 MeV

- Decay to DK implies natural spin-parity
  - is $D_{sJ}^*(2860)$ the missing $J^P=3^-$ cs̄ state?

- No indication for $D_{sJ}^*(2860)\rightarrow D^*K$ decays found



# Charmonium candidates X(3872) and Y(4260)

- Below $D\bar{D}$ threshold
  - detailed information about $J/\psi, \psi', \chi_{cJ}$
  - less knowledge on $\eta_c, \eta', h_c$
- Above $D\bar{D}$ threshold many predicted states still undetected

- Two candidates in this region are

  $X(3872)$ $(\rightarrow J/\psi\pi^+\pi^-, J/\psi\gamma, D^0\bar{D}^0\pi^0)$

  $m=3871.2\pm0.6$ MeV, $\Gamma<2.3$ MeV (90%CL)

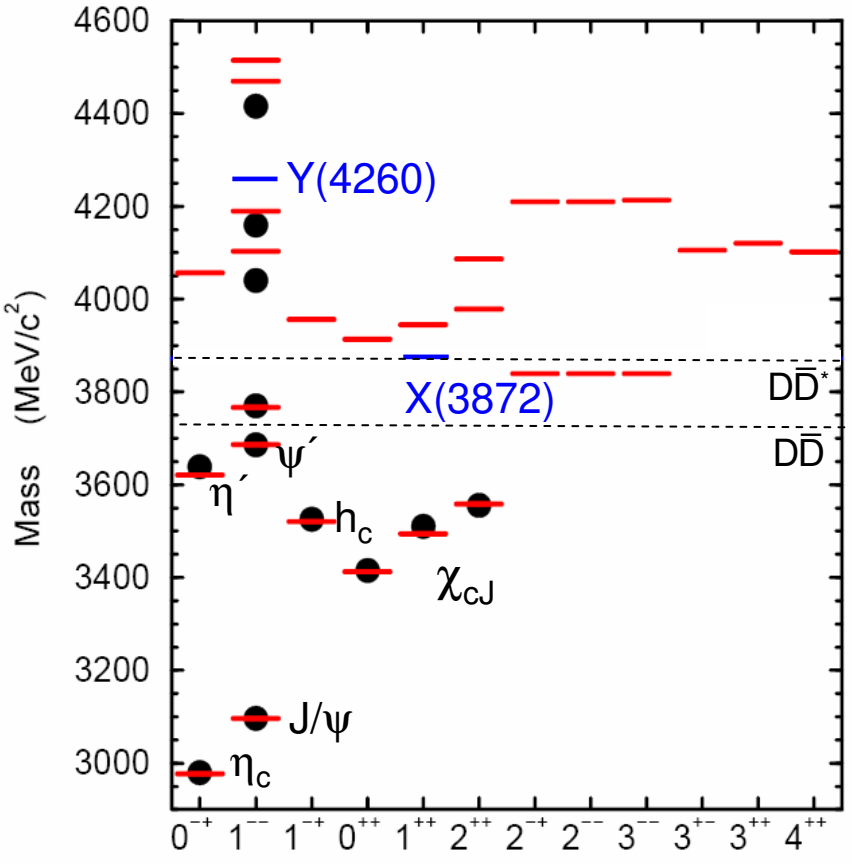
  $J^{PC}$ possibly $1^{++}$

  $Y(4260)$ $(\rightarrow J/\psi\pi^+\pi^-, J/\psi\pi^0\pi^0)$

  $m=4259^{+8}_{-10}$ MeV, $\Gamma=88^{+24}_{-23}$ MeV

  $J^{PC}=1^{--}$

- Both states do not fit well into conventional charmonium picture
  - possibly exotic matter ($c\bar{c}g$ hybrids, molecules, tetra quarks, ...)
  - detailed experimental survey necessary to distinguish

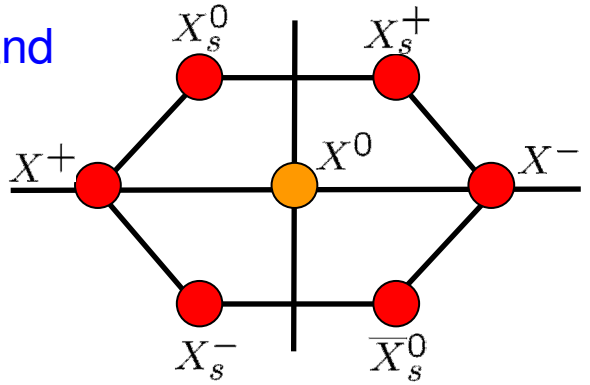



Other $c\bar{c}$ candidates above $D\bar{D}$ threshold are X(3940), Y(3940) and Z(3930) recently reported by Belle

# Exotic interpretations of X(3872)

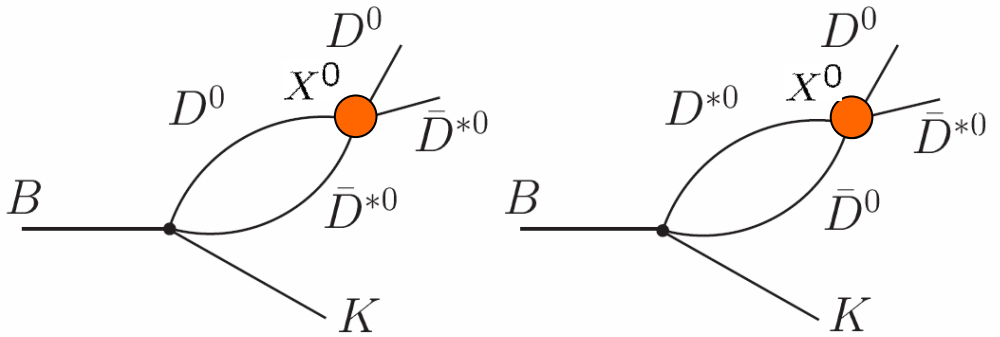
- Tetra quark model
  - predicts nonet with two neutral states
    $X_u=[cu][\bar{c}\bar{u}]$ and $X_d=[cd][\bar{c}\bar{d}]$
  - $X_u$ and $X_d$ mix to two neutral states produced in $B^0$ and $B^+$ decays with same rate but
    mass difference of $\Delta(m)=(7\pm2)$ MeV
  - two charged partners $X^+=[cu][\bar{c}\bar{d}]$ and $X^-=[cd][\bar{c}\bar{u}]$ should exist

Maiani et al.
PRD71, 014028 (2005)




- S-wave $D\bar{D}^*$ molecule
  - motivated by proximity to $D^0\bar{D}^{0*}$ threshold
  - 10x suppressed BR
    of $B^0\to KX$ wrt $B^+\to K^+X$ decay

Braaten, Kusunoki
PRD71, 074005 (2005)




- Wide variety of other models proposed

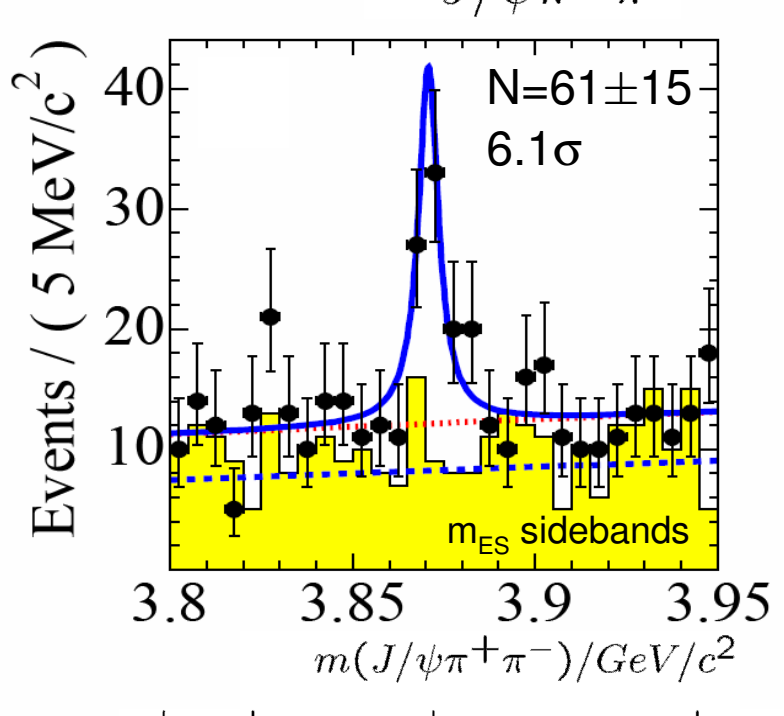
see e.g. Swanson
hep-ph/0601110
for detailed review

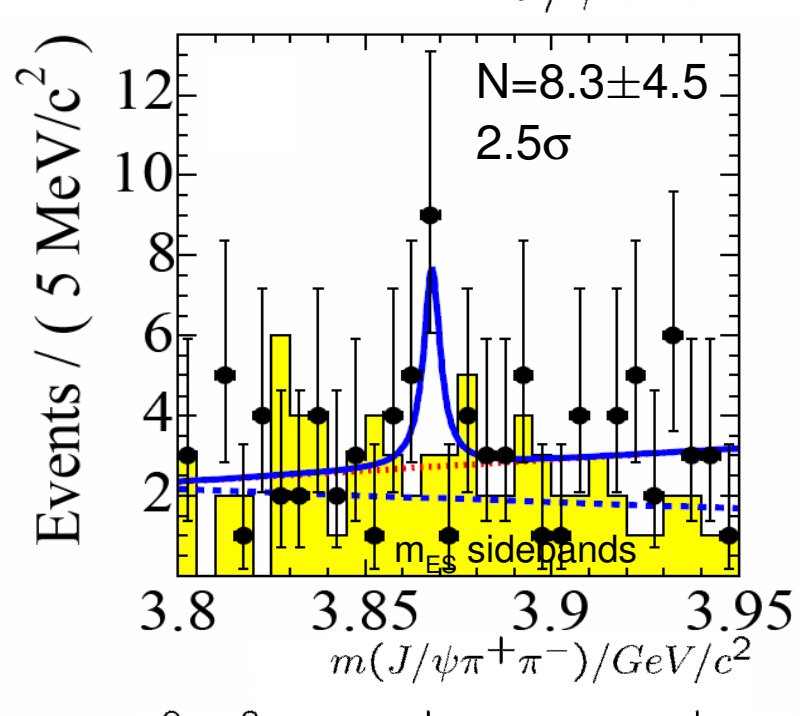
# Exclusive study of X(3872)

$B^+ \to K^+ X(3872)$
$\hookrightarrow J/\psi\pi^+\pi^-$

Babar: 232M B$\bar{B}$
PRD 73, 011101 (2006)

$B^0 \to K^0_S X(3872)$
$\hookrightarrow J/\psi\pi^+\pi^-$




$\mathcal{B}^+(B^+ \to XK^+, X \to J/\psi\pi^+\pi^-)$
$= (10.1 \pm 2.5 \pm 1) \times 10^{-6}$

$\mathcal{B}^0(B^0 \to XK^+, X \to J/\psi\pi^+\pi^-)$
$= (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$

$0.13 < \mathcal{B}^0/\mathcal{B}^+ < 1.1$ (90%CL)
$\Delta(m) = (2.7 \pm 1.3 \pm 0.2)\text{MeV}/c^2$

Neither tetra-quark nor D$\bar{D}^*$ models excluded strictly, need more data

Babar: 234M B$\bar{B}$
PRD 71, 031501 (2005)

No charged partners found in B→ K(J/ψ$\pi^0\pi^\pm$)

isospin I=0
in conflict with tetra-quark model

# Exclusive study of X(3872)

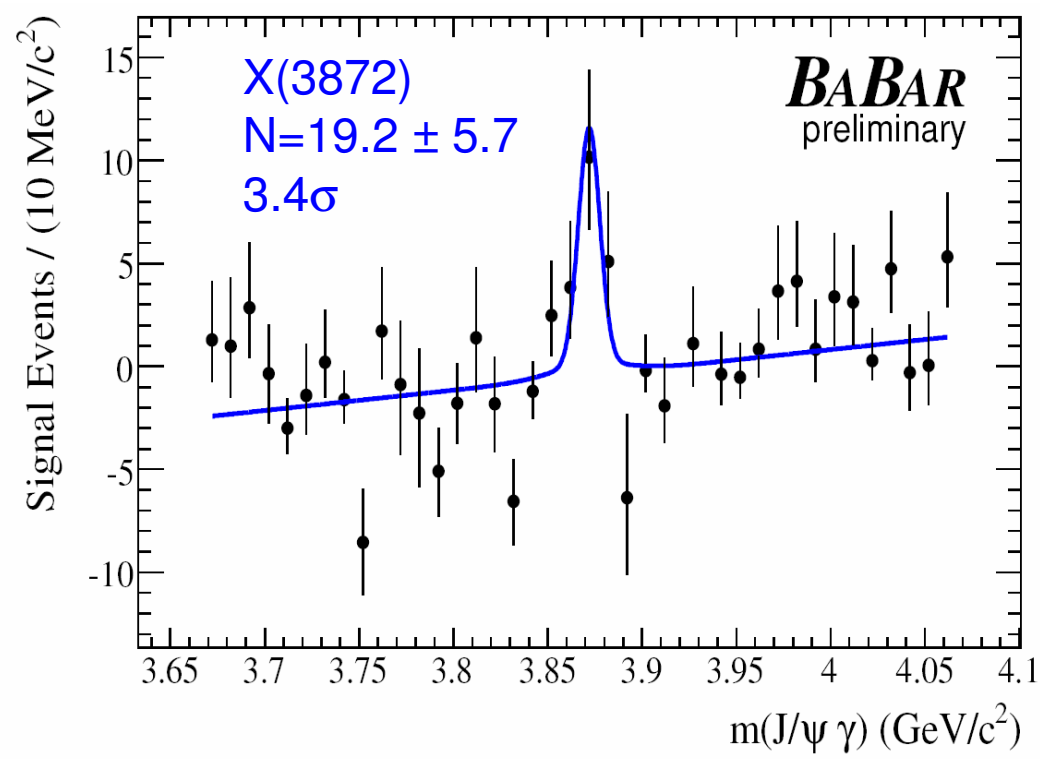
Babar: 287M $B\bar{B}$
Preliminary

- $B^+ \to K^+X \to K^+(J/\psi\gamma)$, decay to $J/\psi\gamma$ implies C=+1
  - $[\pi\pi]$ system in $J/\psi\pi^+\pi^-$: I=1, most probably P-wave $[\pi\pi]$
    ➡ X(3872): I=0, C=+1, $J^P=1^+$ favoured
  - $X \to J/\psi\pi^+\pi^-$ violates isospin conservation → small width / radiative decay

$$\mathcal{B}(B^+ \to X(3872)K^+, X(3872) \to J/\psi\gamma) = (3.4 \pm 1 \pm 0.3) \times 10^{-6}$$

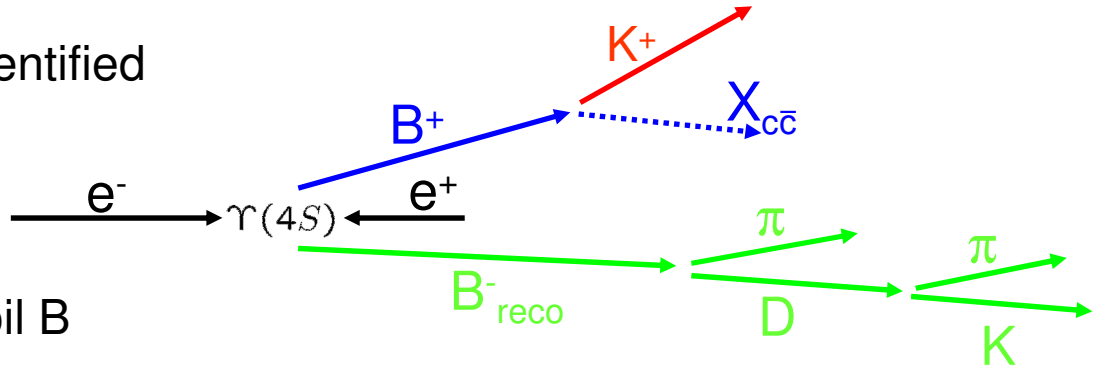
$$\frac{\mathcal{B}(X(3872) \to J/\psi\gamma)}{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)} = (34 \pm 14)\%$$

- Confirms observation of $4\sigma$ signal by Belle with consistent BF/BR

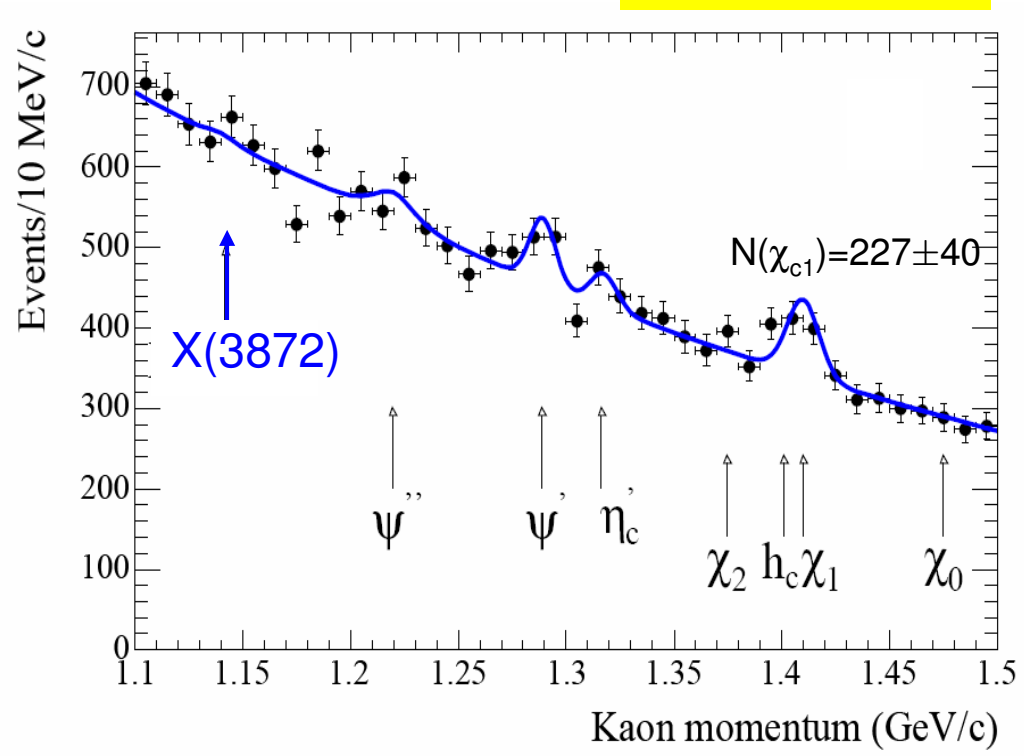


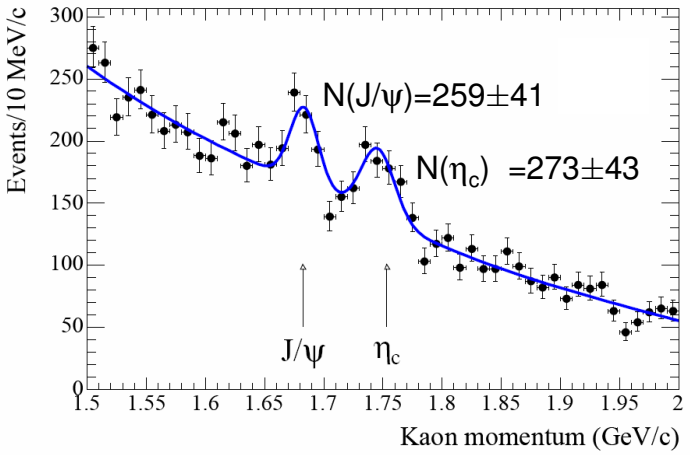
# Inclusive study of X(3872)

- Fully reconstructed $B^-_{reco}$ and identified $K^+$ from other $B^+ \to K^+ X_{c\bar{c}}$ decay
- Two body decay: Measured $K^+$ momentum in rest frame of recoil B defines $m(X_{c\bar{c}})$




Babar: 232M $B\bar{B}$
PRL 96, 052002 (2006)




$$\mathcal{B}(B^+ \to K^+ X(3872)) < 3.2 \times 10^{-4}\ (90\%\mathrm{CL})$$

$$\mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-) > 4.2\%\ (90\%\mathrm{CL})$$

# Discovery of Y(4260)

- Negative search result for X(3872) production in ISR events with $\gamma_{ISR}$ detected, but discovered ...

- Y(4260) in $e^+e^- \to \gamma_{ISR}(\pi^+\pi^- J/\psi)$
  - $\gamma_{ISR}$ need not to be detected
  - ISR implies $J^{PC}=1^{--}$
  - fit with one resonance hypothesis yields to:

$$m = (4259 \pm 8^{+2}_{-6}) \mathrm{MeV}/c^2$$

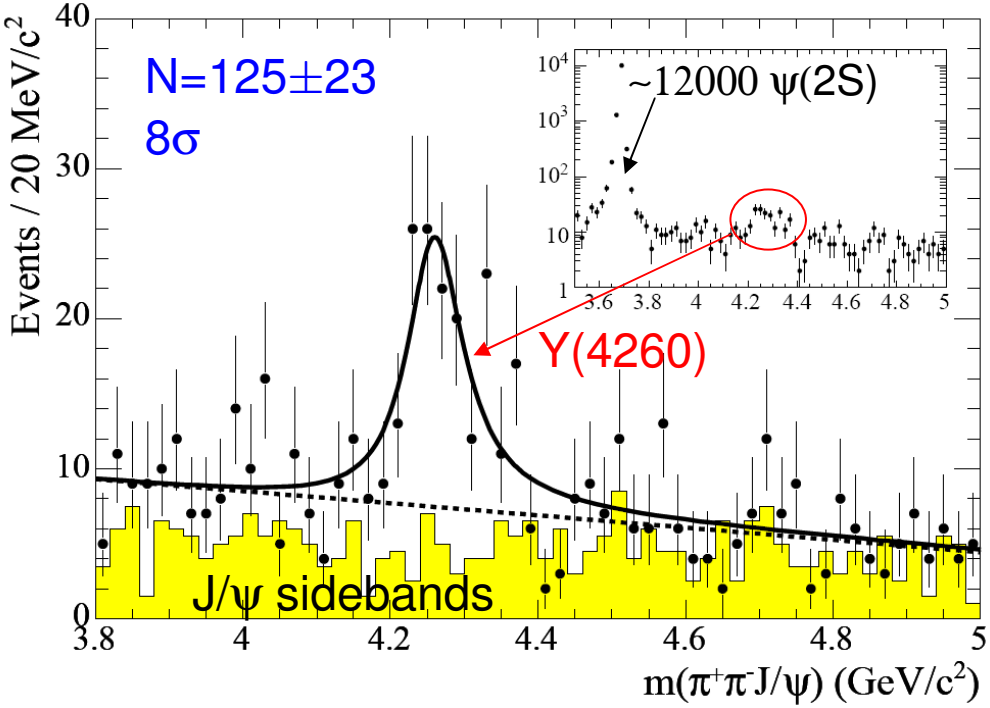
$$\Gamma = (88 \pm 23^{+6}_{-4}) \mathrm{MeV}$$

$$\Gamma^Y_{ee} \times \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) = (5.5 \pm 1^{+0.8}_{-0.7}) eV$$

  - isospin I=0

$e^+e^- \to \gamma_{ISR}(\pi^+\pi^- J/\psi)$

Babar: 233 fb$^{-1}$
PRL 95, 142001 (2005)




Confirmation

- **CLEO-c** scan: Enhanced cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$ ($\pi^0\pi^0 J/\psi$) at $\sqrt{s}$=4.26 GeV
- **CLEO-III**: Observation in $e^+e^- \to \gamma_{ISR}(\pi^+\pi^- J/\psi)$ at $\sqrt{s}$=10.58GeV

# Search for other Y(4260) decays in ISR proccesses

- $e^+e^- \to \gamma_{ISR}(\phi\pi^+\pi^-)$ ($\gamma_{ISR}$ detected)

$$\Gamma^{Y}_{ee} \times \mathcal{B}(Y(4260) \to \phi\pi^+\pi^-) < 0.4\ eV\ (90\%CL)$$

Babar: 232 fb$^{-1}$ preliminary

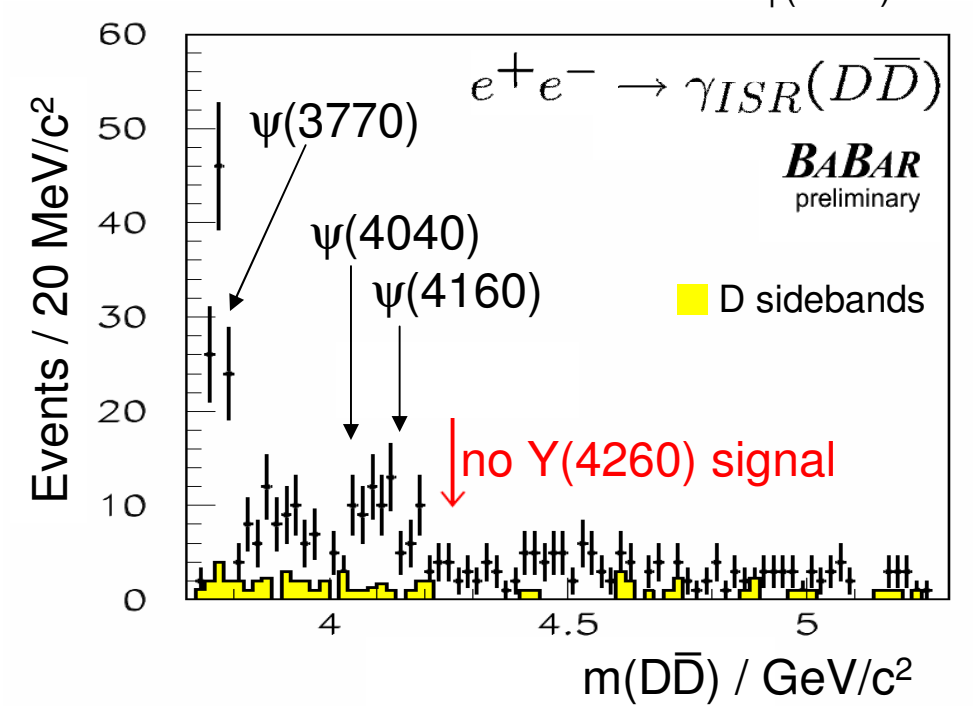
- $e^+e^- \to \gamma_{ISR}(D\bar{D})$

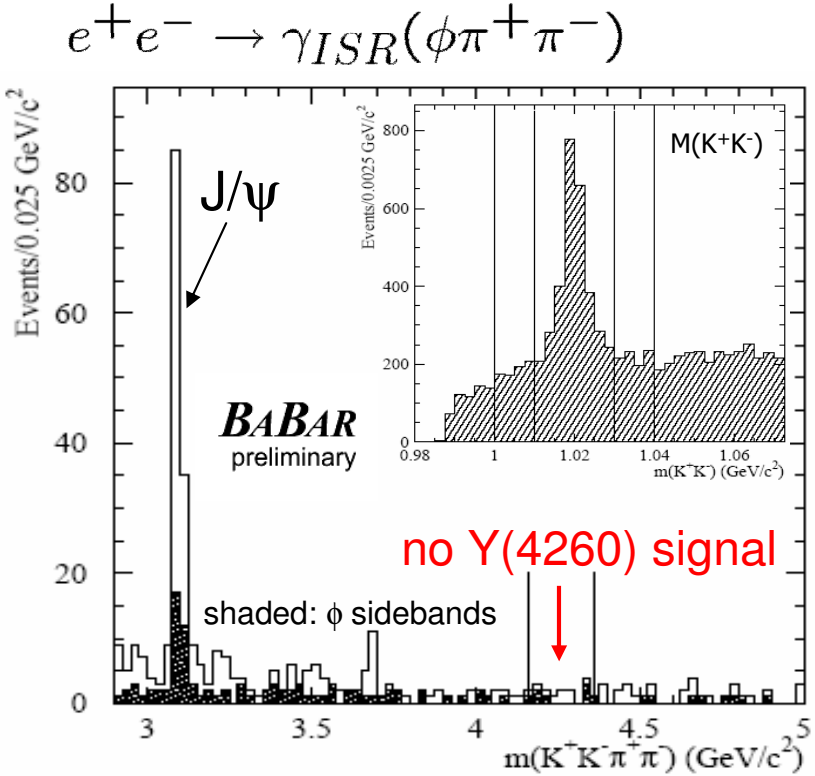
($\gamma_{ISR}$ need not to be detected)

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 7.6\ (95\%CL)$$

Babar: 289 fb$^{-1}$ preliminary

at least 70x smaller than same BR for ψ(3770)




Also no signal found for $e^+e^- \to \gamma_{ISR}(p\bar{p})$ ($\gamma_{ISR}$ detected)

$$\frac{\mathcal{B}(Y(4260) \to p\bar{p})}{\mathcal{B}(Y(4260) \to J\psi\pi^+\pi^-)} < 0.13\ (90\%CL)$$

Babar: 232 fb$^{-1}$
PRD 73, 012005 (2006)

# Charmonium candidates X(3872) and Y(4260)

- X(3872) ($\rightarrow J/\psi\pi^+\pi^-$, $J/\psi\gamma$, $D^0\bar{D}^0\pi^0$)
  - m=3871.2±0.6 MeV/$c^2$, $\Gamma$<2.3 MeV (90% CL)
  - no charged partner states found $\rightarrow$ isospin I=0
  - $J/\psi\gamma$ decay $\rightarrow$ C=+1
  - preferable $J^P=1^+$ (from $[\pi\pi]$ system in $J/\psi\pi^+\pi^-$ decay)
  - possibly $X_{c1}(2P)$ (but mass lower than expected)
  - exotic interpretations not excluded
  - further experimental information required

- Y(4260) ($\rightarrow J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$)
  - $m = (4259 \pm 8^{+2}_{-6})\mathrm{MeV}/c^2, \Gamma = (88 \pm 23^{+6}_{-4})\mathrm{MeV}$
  - no indication of $\phi\pi^+\pi^-$, $D\bar{D}$ and $p\bar{p}$ decays
  - production in ISR events $\rightarrow J^{PC}=1^{--}$
  - isospin I=0
  - charmonium and exotic interpretations need further investigation

# Summary

- Discovery of new states in recent years has pushed experimental / theoretical activity in charm / charmonium spectroscopy

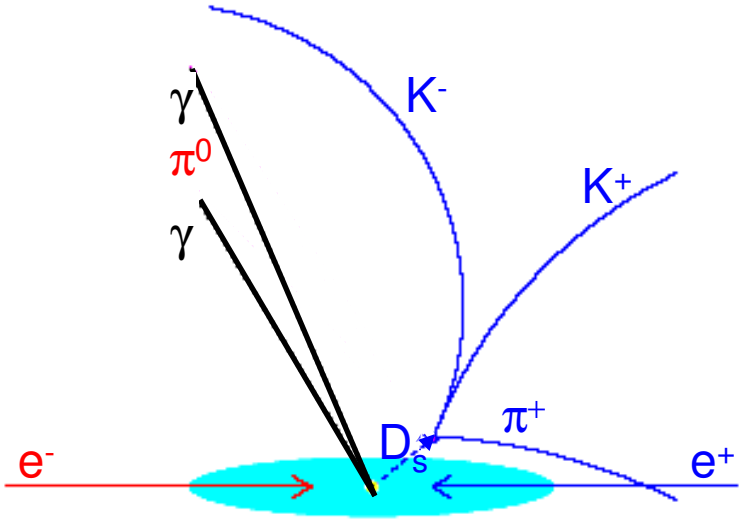
- Comprehensive study of $D_{sJ}^{*}(2317)$ and $D_{sJ}(2460)$
  - precise measurement of mass, width and branching ratios
  - first measurement of absolute $D_{sJ}(2460)$ branching fractions

- Discovery of $D_{sJ}^{*}(2860)$ state decaying to DK (brand new)

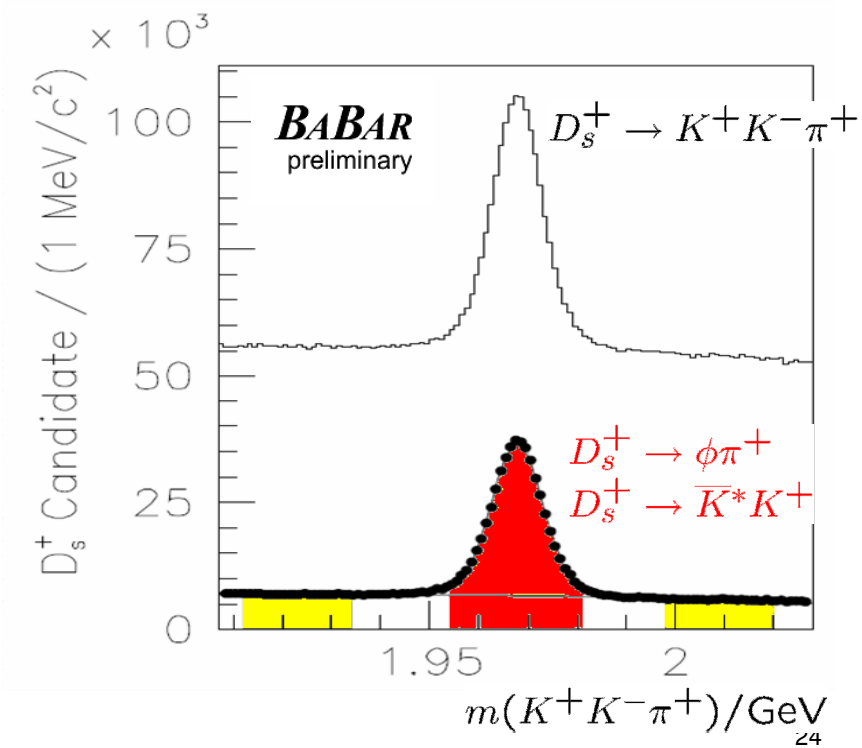
- Charmonium candidates X(3872) and Y(4260)
  - studies on production processes and decay modes
  - further investigation required to understand the nature of these states

# Backup Slides

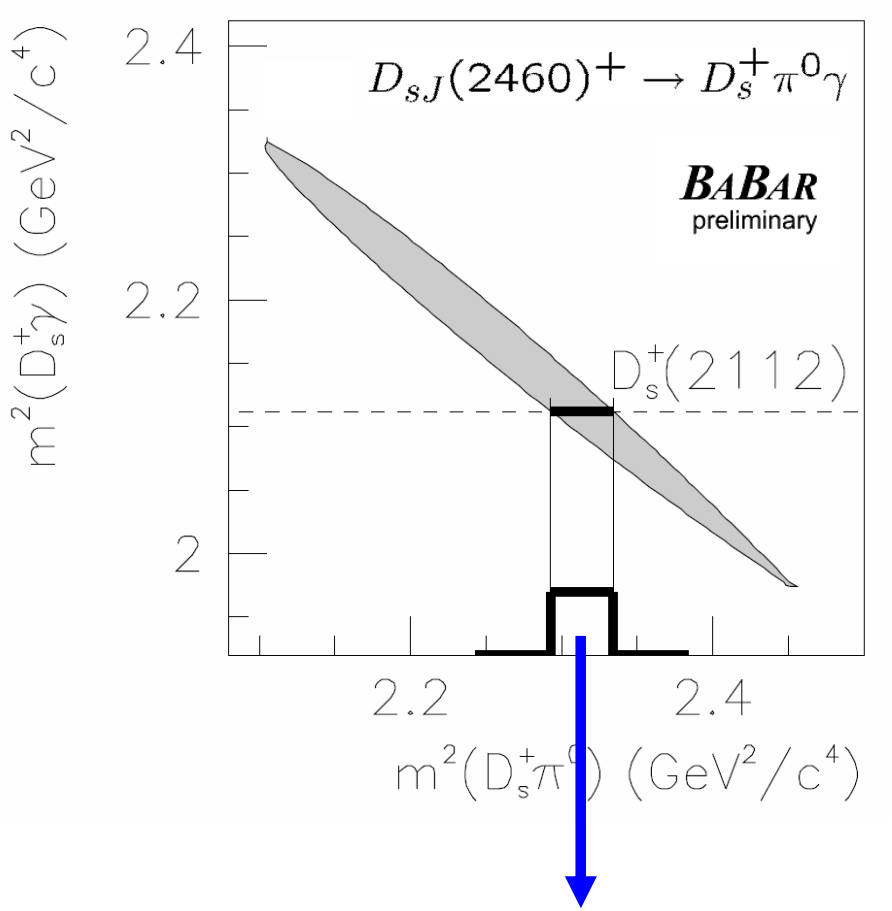
- Clean $D_s^+ \to K^+K^-\pi^+$ sample
  - well identified $K^\pm$ und $\pi^\pm$ candidates
  - common vertex required
  - Momentum: $p_{CM}(D_s)>2.2$ GeV/c
  - >400.000 reconstructed
    $D_s \to \phi(K^+K^-)\pi^+$ and
    $D_s \to \bar{K}^*(K^-\pi^+)K^+$ decays



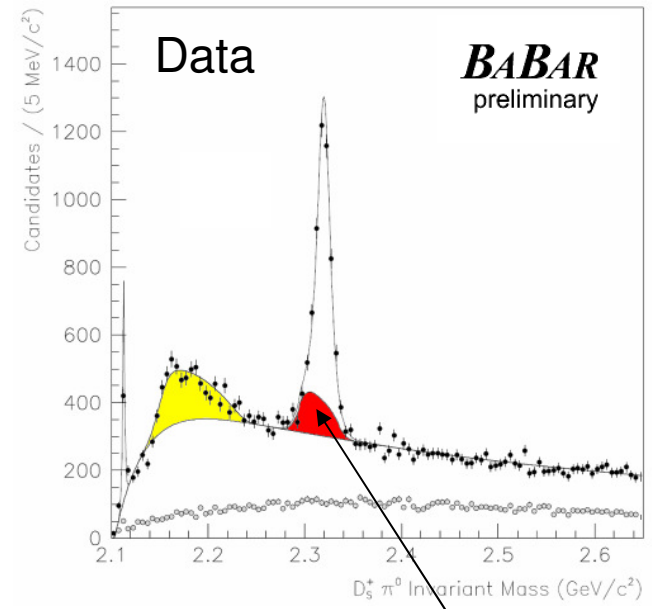

- Combination of $D_s$ candidates with further $\gamma,\pi^0,\pi^\pm$ of same event
  - Momentum: $p_{CM}(D_{sJ})>3.2$ GeV/c

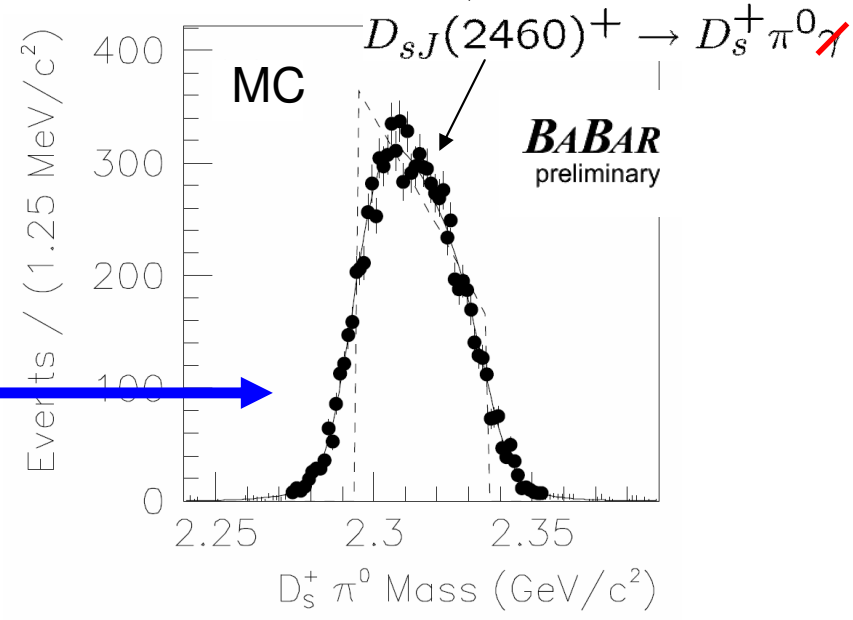


# Reflections in $D_s\pi^0$



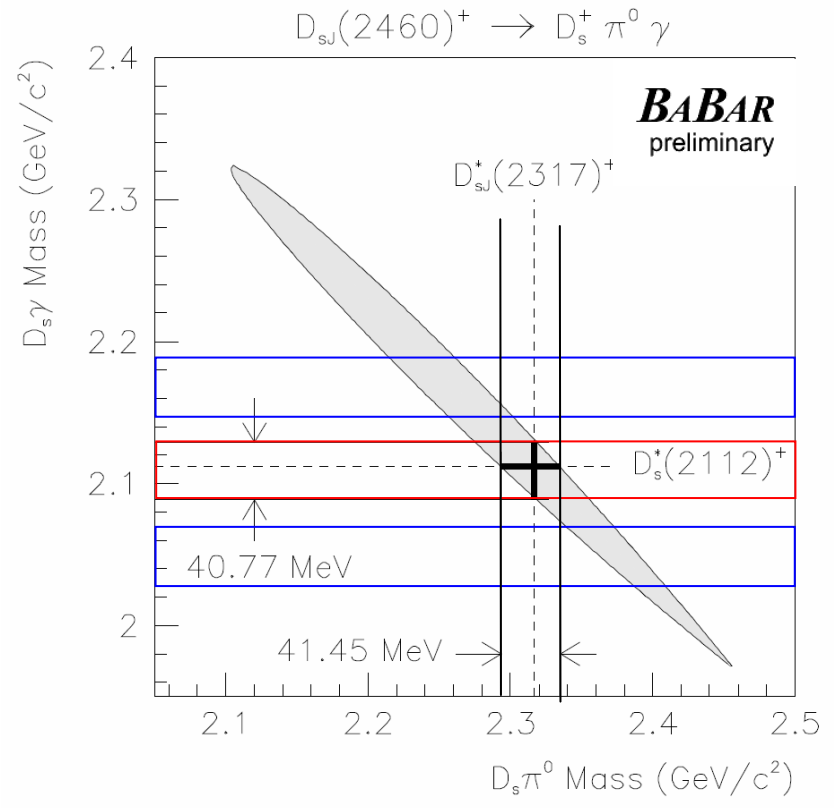

Efficiency / resolution

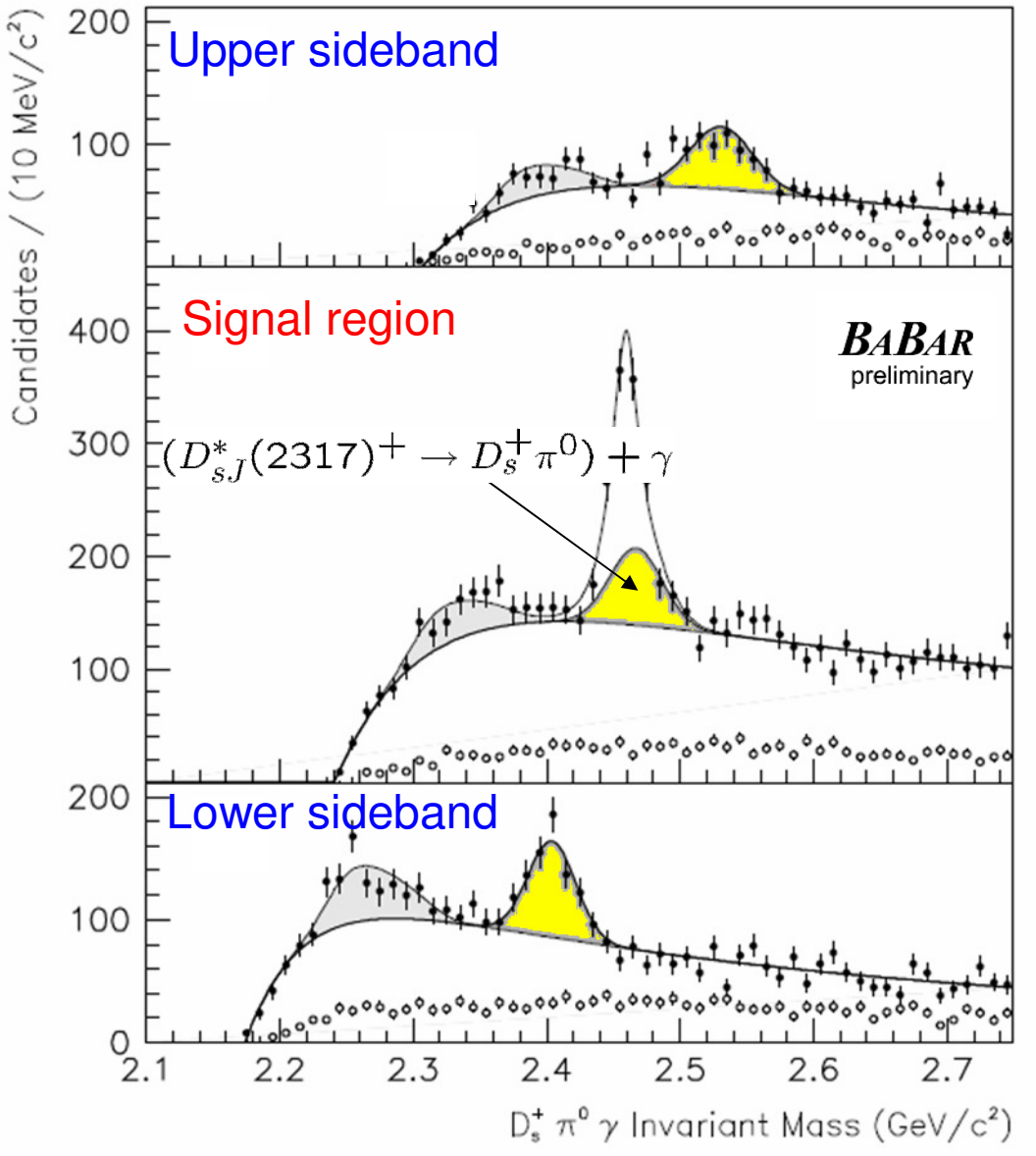


# Reflections in $D_s\pi^0\gamma$

Fraction of reflection underlying signal estimated from upper and lower $D_s^*$ sidebands

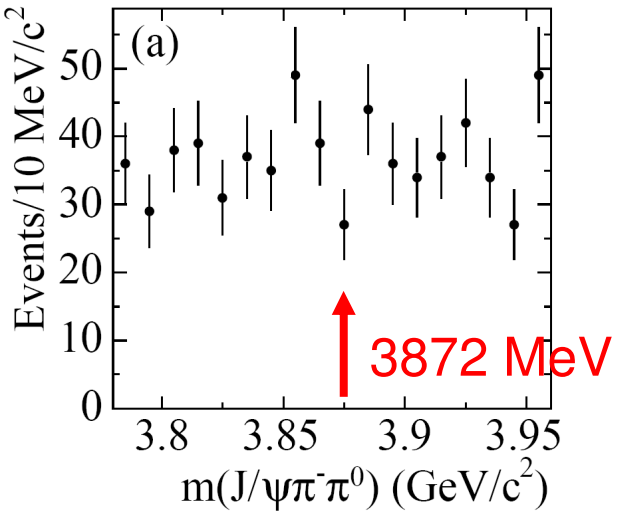


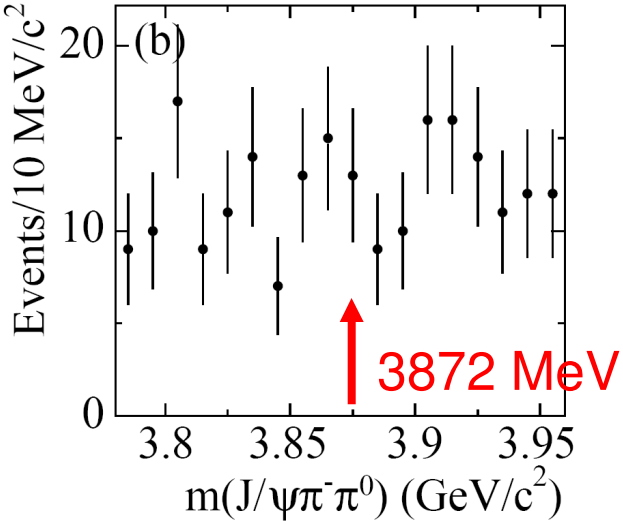
# Search for charged partners of X(3872)

Babar: 193 fb$^{-1}$
PRD 71, 031501 (2005)

$$B^- \to X^- K_S^0 \to J/\psi \pi^0 \pi^- K_S^0$$




$$B^0 \to X^- K^+ \to J/\psi \pi^0 \pi^- K^+$$




- No indication for charged partner states of X(3872)

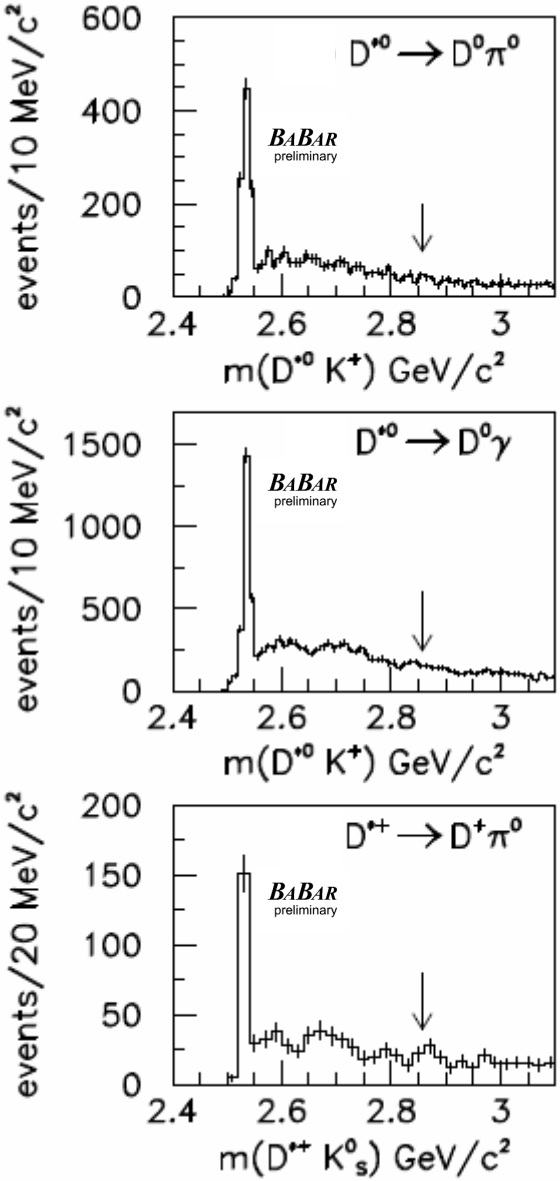
$$\mathcal{B}(B^- \to X^- K_S, X^- \to J/\psi \pi^0 \pi^-) < 22 \cdot 10^{-6} \quad (90\% CL)$$

$$\mathcal{B}(B^0 \to X^- K^+, X^- \to J/\psi \pi^0 \pi^-) < 5.4 \cdot 10^{-6} \quad (90\% CL)$$

# $D_{sJ}^*(2860)$ study

- No evidence for $D_{sJ}^*(2860)$ decays to:

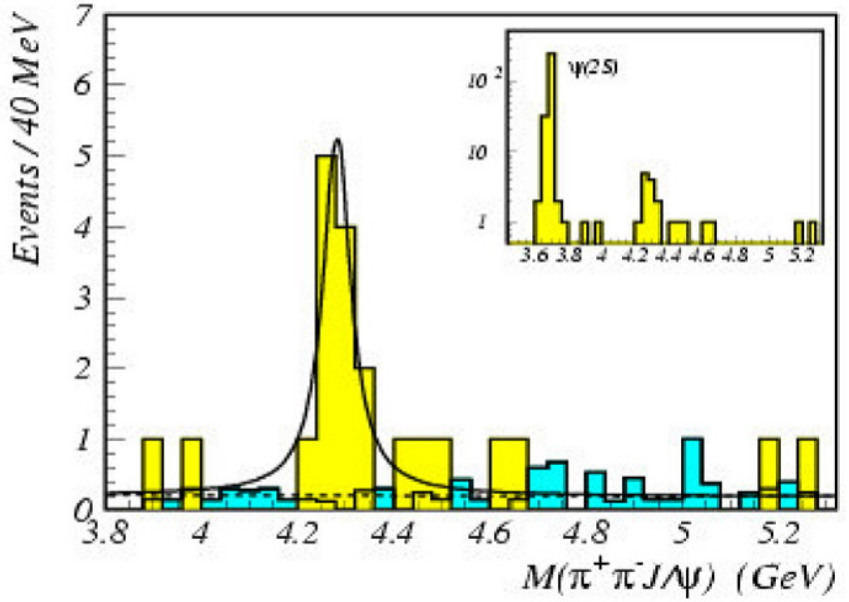
  $D^{*0}\,K^+$, $D^{*0} \rightarrow D^0\,\pi^0$
  $D^{*0}\,K^+$, $D^{*0} \rightarrow D^0\,\gamma$
  $D^{*+}K^0_S$, $D^{*+} \rightarrow D^+\pi^0$



# Confirmation of Y(4260) from CLEO-III / CLEO-c

- ISR production of $\pi^+\pi^- J/\psi$ events in CLEO-III data near $\sqrt{s}$=10.58 GeV

CLEO-III: 13.3 fb$^{-1}$
Preliminary




- Enhanced cross sections at 4.26 GeV from CLEO-c scan

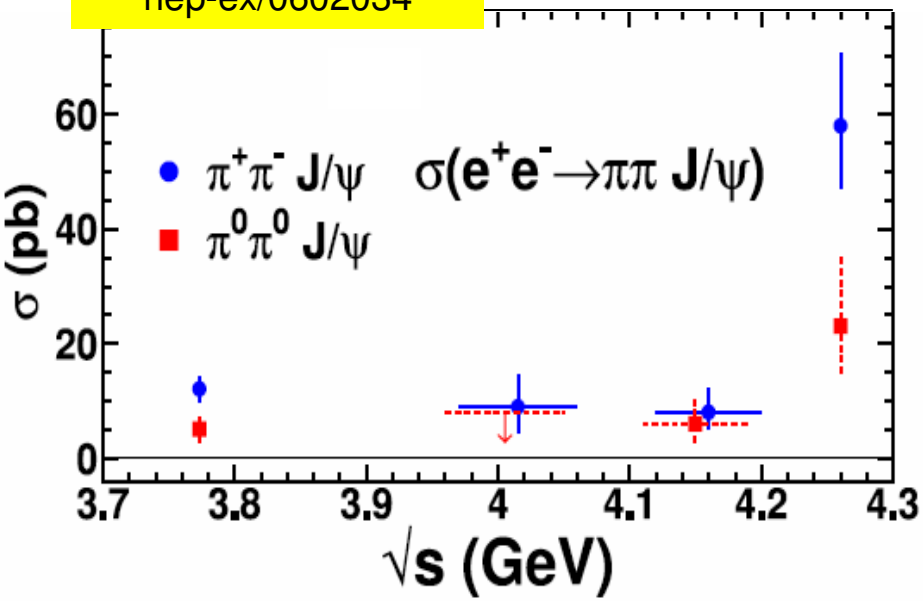
$$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (58^{+12}_{-10} \pm 4)\,\text{pb}$$

N=37 (11 σ)

$$\sigma(e^+e^- \to \pi^0\pi^0 J/\psi) = (23^{+12}_{-8} \pm 1)\,\text{pb}$$

N=8 (5.1 σ)

hep-ex/0602034



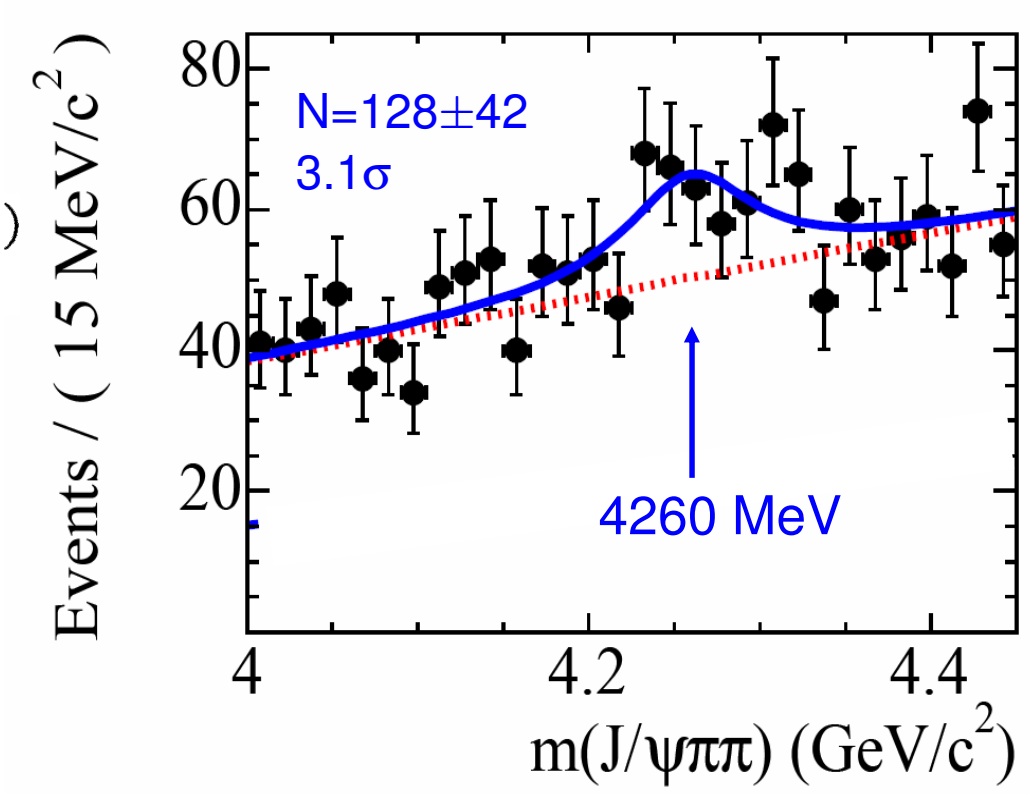
# Y(4260) production in B decays

- Exclusive study of $B^+ \to K^+(J/\psi\pi^+\pi^-)$ decays

Babar: 232M $B\bar{B}$
PRD 73, 011101 (2006)

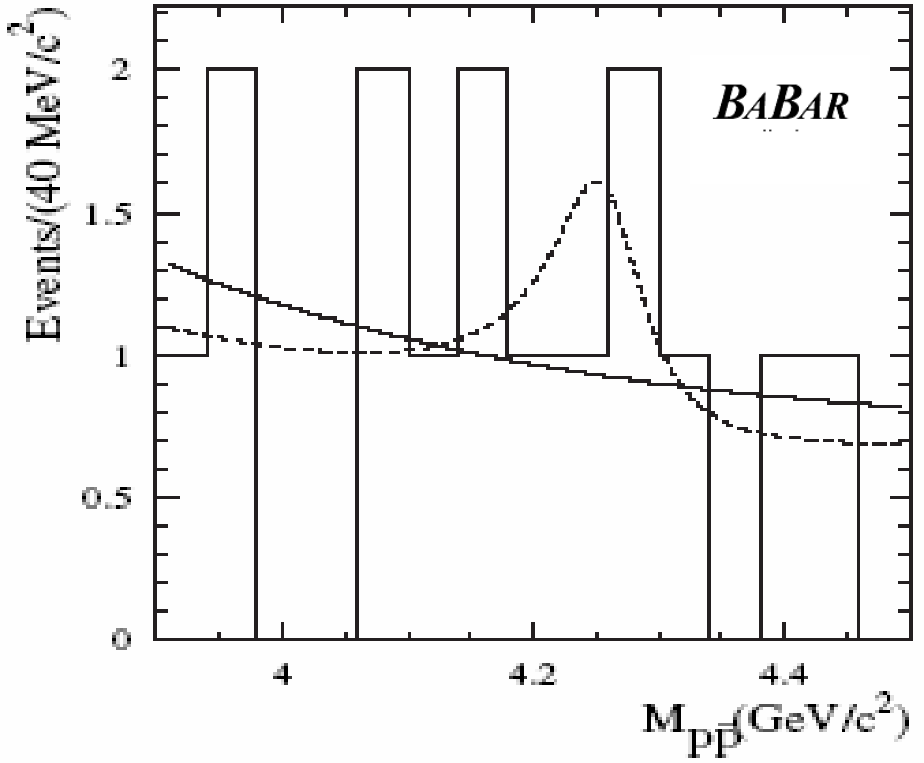
- Indication for production in B decays
  - Signal lineshape uses mass and intrinsic width obtained from signal observed in ISR production
  - Needs confirmation

$$\mathcal{B}(B^+ \to YK^+, Y \to J/\psi\pi^+\pi^-) = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$$



- No indication for Y(4260) decay to $p\bar{p}$ in ISR proccesses

Babar: 232 fb$^{-1}$
PRD 73, 012005 (2006)




$$\frac{\mathcal{B}(Y(4260) \to p\bar{p})}{\mathcal{B}(Y(4260) \to J\psi\pi^+\pi^-)} < 0.13 \ (90\%\mathrm{CL})$$