Recent Results in
Charm and Charmonium Physics

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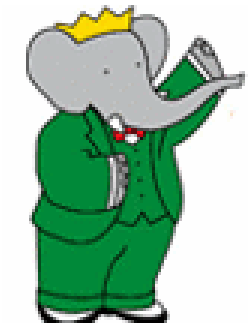
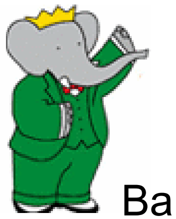
On behalf of the BaBar collaboration



OUTLINE:

- D_s spectroscopy
- Measurement of the decay constant f_{Ds}
- $X(3872) \to J/\psi\omega$
- Z(3930)
- Search for $Z(4430)^-$



BaBar data

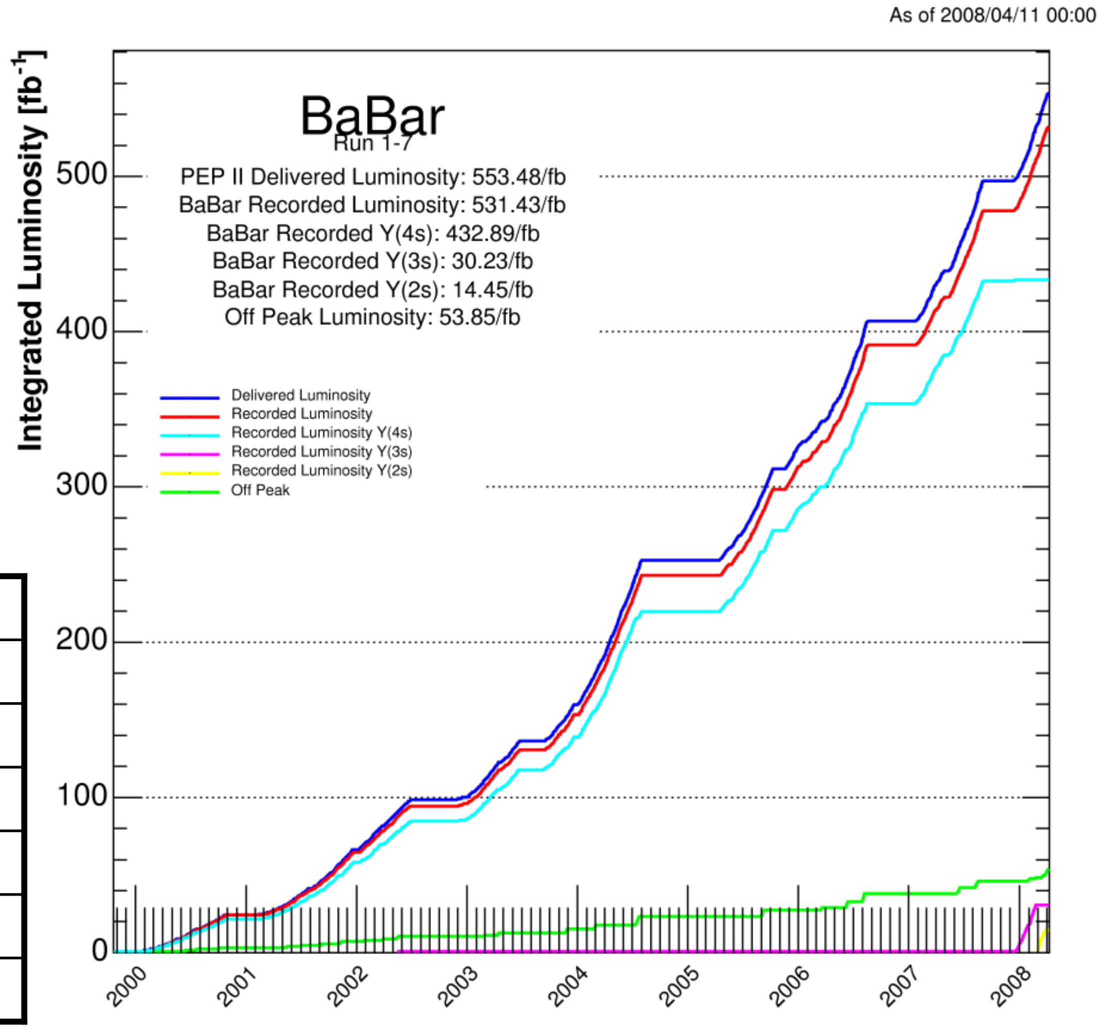
BaBar datasets:

- $\Upsilon(4S)$: $465 \cdot 10^6$ decays
- $\Upsilon(3S)$: $122 \cdot 10^6$ decays
- $\Upsilon(2S)$: $100 \cdot 10^6$ decays

B-factory operates mainly on the $\Upsilon(4S)$ peak, at E_{CM}=10.58 GeV

A B-factory is also a flavor factory

$e^+e^- \rightarrow$	σ (nb)
bb	1.05
cc	1.30
ss	0.35
uu	1.39
dd	0.35
$\tau^+\tau^-$	0.94



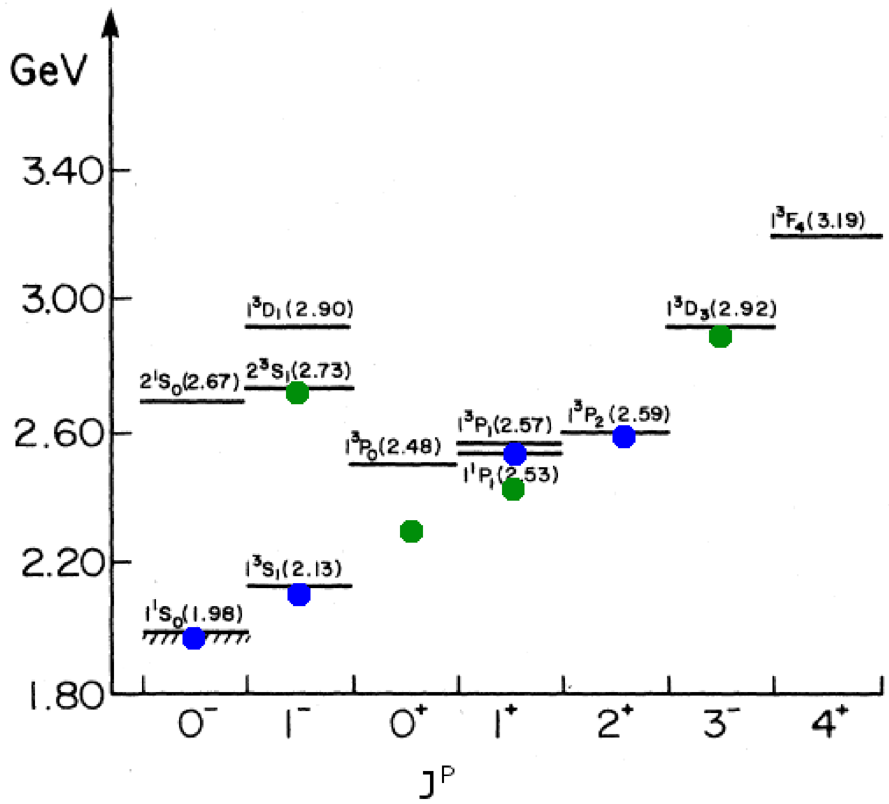
D_s meson spectrum

- D_s (bound states of $c\bar{s}$ quarks)

- Spectroscopy is still evolving

- 4 states observed before the B factories in agreement with the theoretical models
- 2 states observed at B factories: $D_{sJ}^{*}(2317)^{+}$ (in $D_s^{+}\pi^{0}$) and $D_{sJ}(2460)^{+}$ (in $D_s^{*+}\pi^{0}$) do not match theoretical expectations
- 2 additional states $D_{s1}(2700)^{+}$ and $D_{sJ}(2860)^{+}$ observed by BaBar in $D^{*}K$ decay
- New broad structure at 3040 MeV

Godfrey, Isgur model predictions - PRD 32, 189 (1985)
Observed before B-factories
Observed at B-factories



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PRL 97, 222001 (2006)

$D_{sJ}(2700)^+$ and $D_{sJ}(2860)^+$ in DK decay

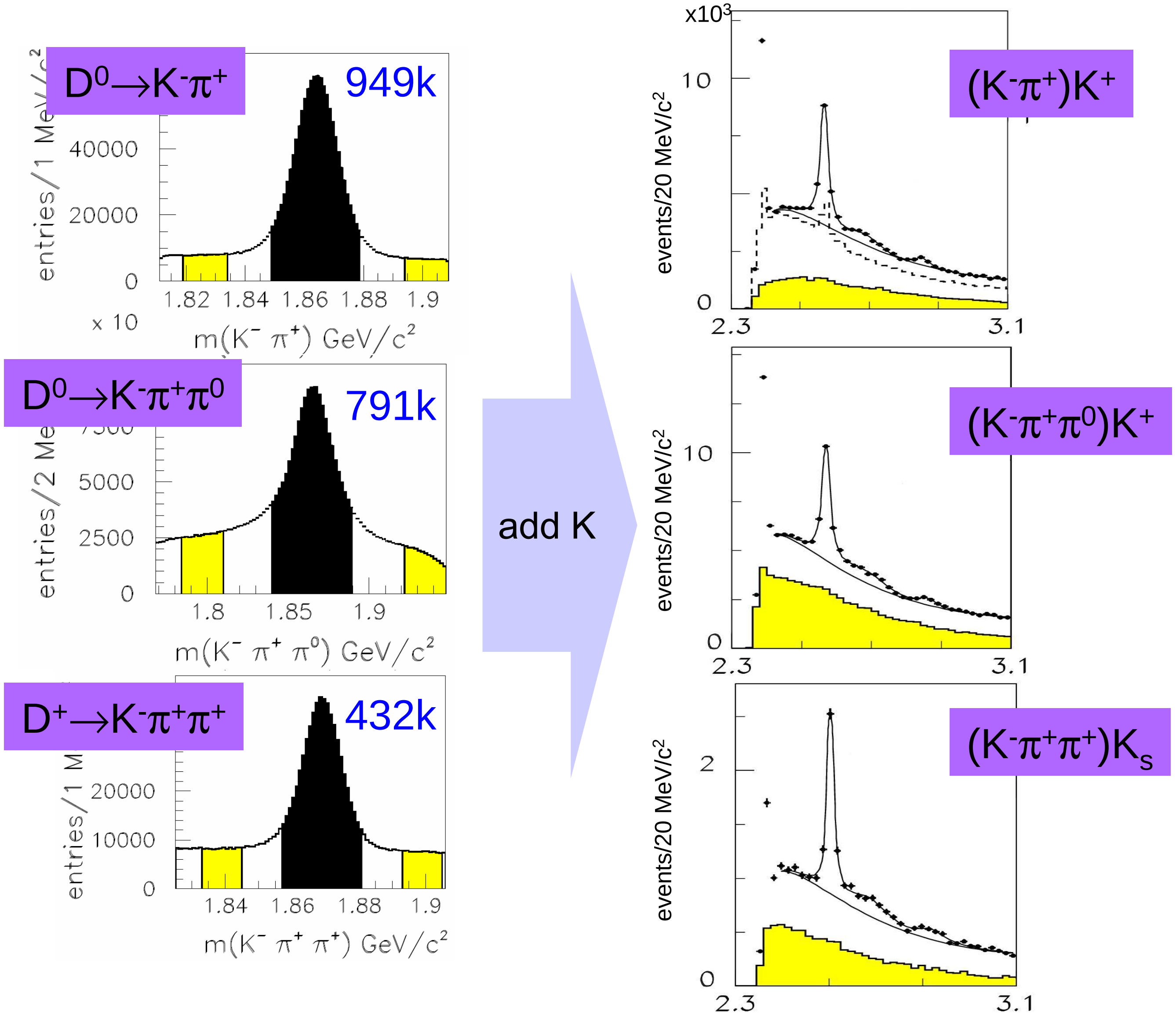
Inclusive search of:

$$e^+e^- \to K^+D^0X$$
$$e^+e^- \to K_sD^+X$$

Momentum:

p*(DK)>3.5 GeV/c

Same features observed for all $D^{0,+}$ reconstruction modes



PRL 97, 222001 (2006)

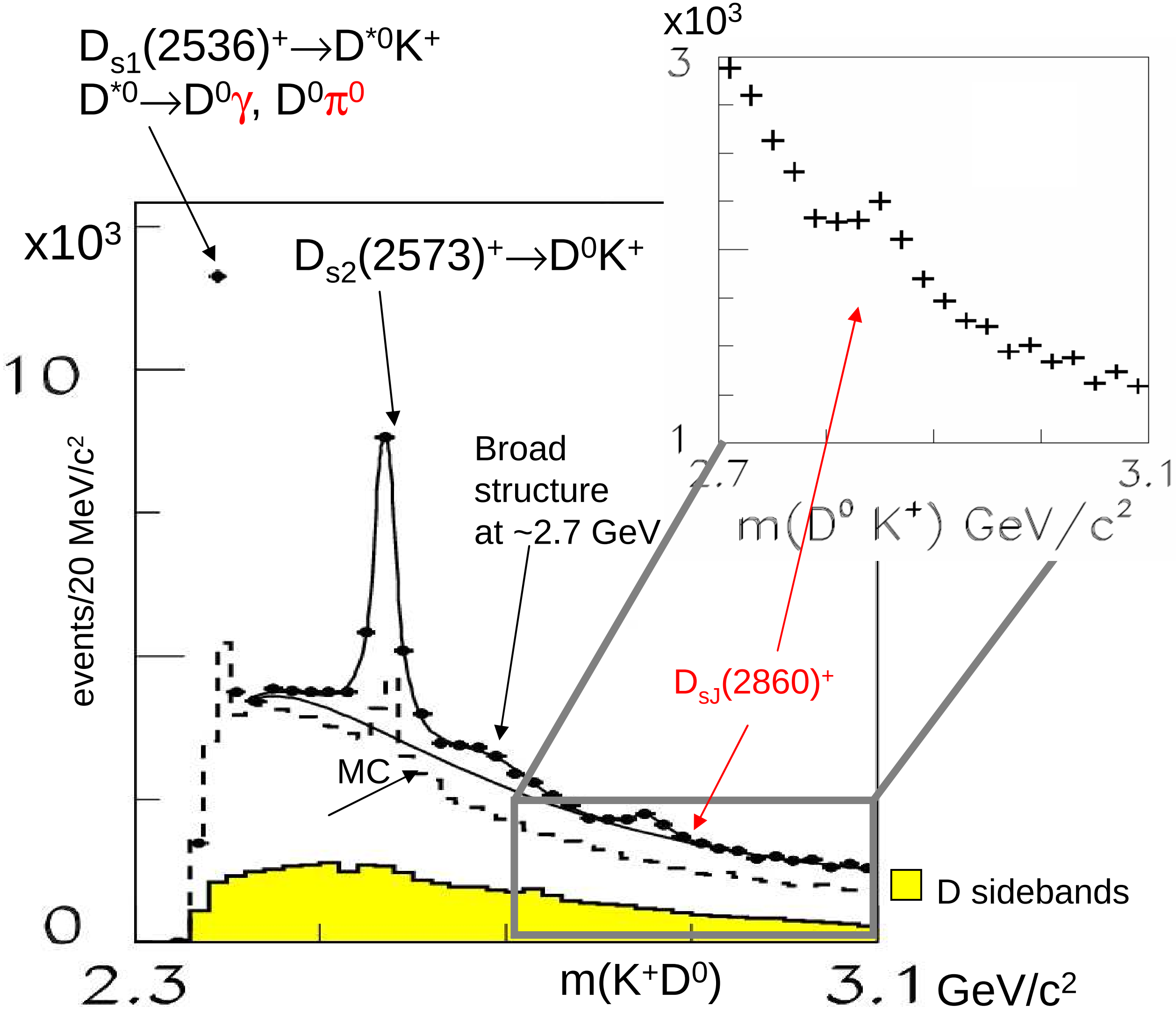
Fit results

Fit to combined data samples yields to:

$D_{s2}(2573)^+$ parameters:
m=2572.2±0.3±1.0 MeV/c^2
Γ=27.1±0.6±5.6 MeV

$D_{s1}(2700)^+$ parameters:
m=2688±4±2 MeV/c^2
Γ=112±7±36 MeV

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



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PRD 80, 092003 (2009)

DK study update

Recent update of the study with double statistics

Results consistent with previous ones

Slightly larger mass and width for the $D_{s1}(2700)$

$D_{s1}(2700)^+$ parameters:

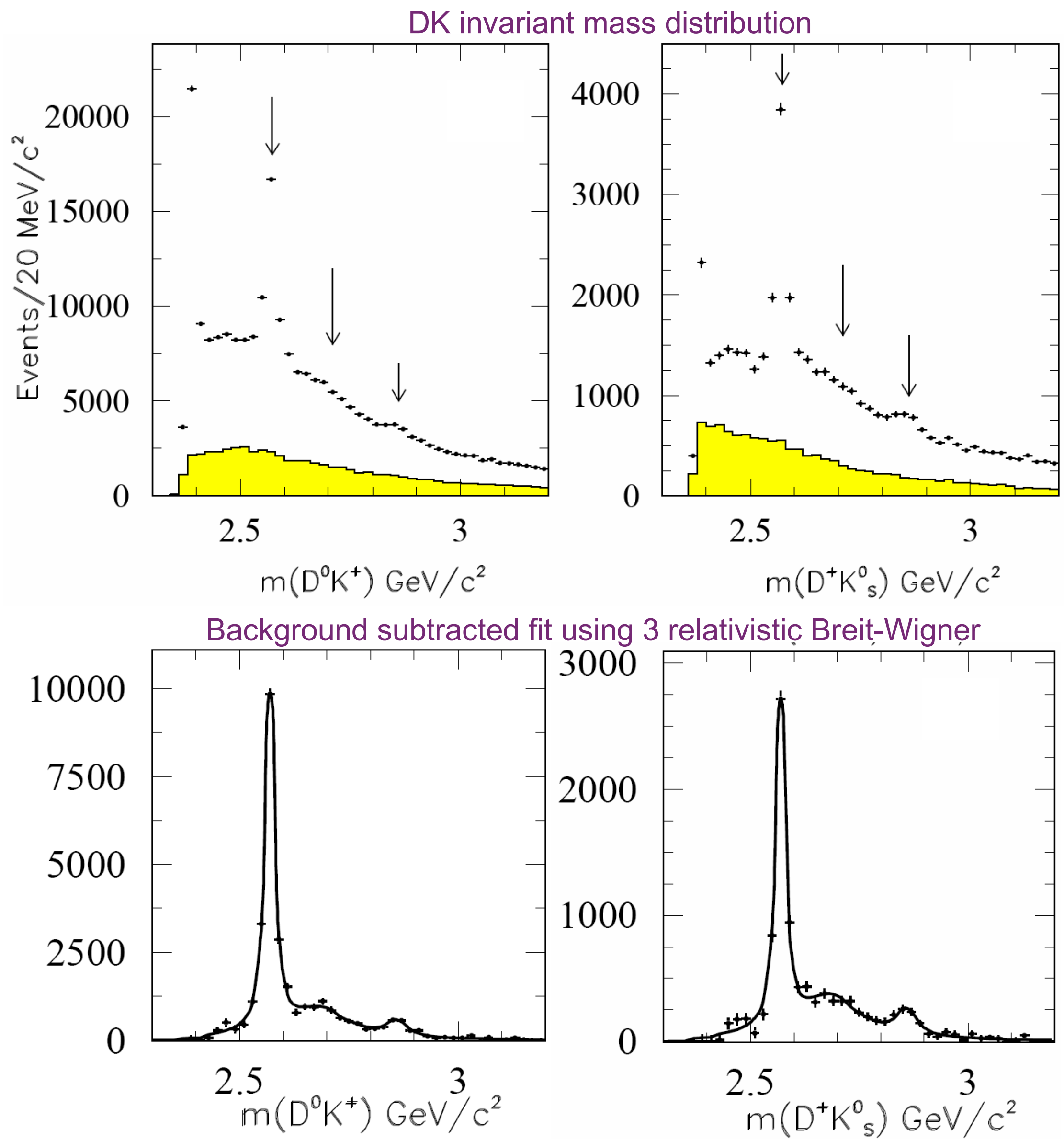
m=2710.0±3.3 MeV/c^2

Γ=178±19 MeV

$D_{sJ}(2860)^+$ parameters:

m=2860.0±2.3 MeV/c^2

Γ=53±6 MeV



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PRD 80, 092003 (2009)

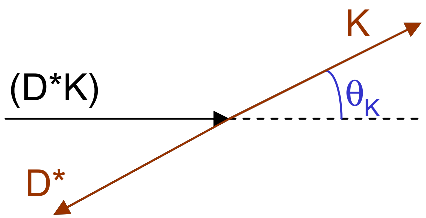
BaBar studies for D_{sJ} in D^*K

Inclusive search of:

$$e^+e^- \to K^+ D^{*0} X \qquad D^{*0} \to D^0\pi^0$$
$$e^+e^- \to K_s D^{*+} X \qquad D^{*+} \to D^0\pi^+, D^+\pi^0$$

Background suppression:
p*(D*K)>3.3 GeV

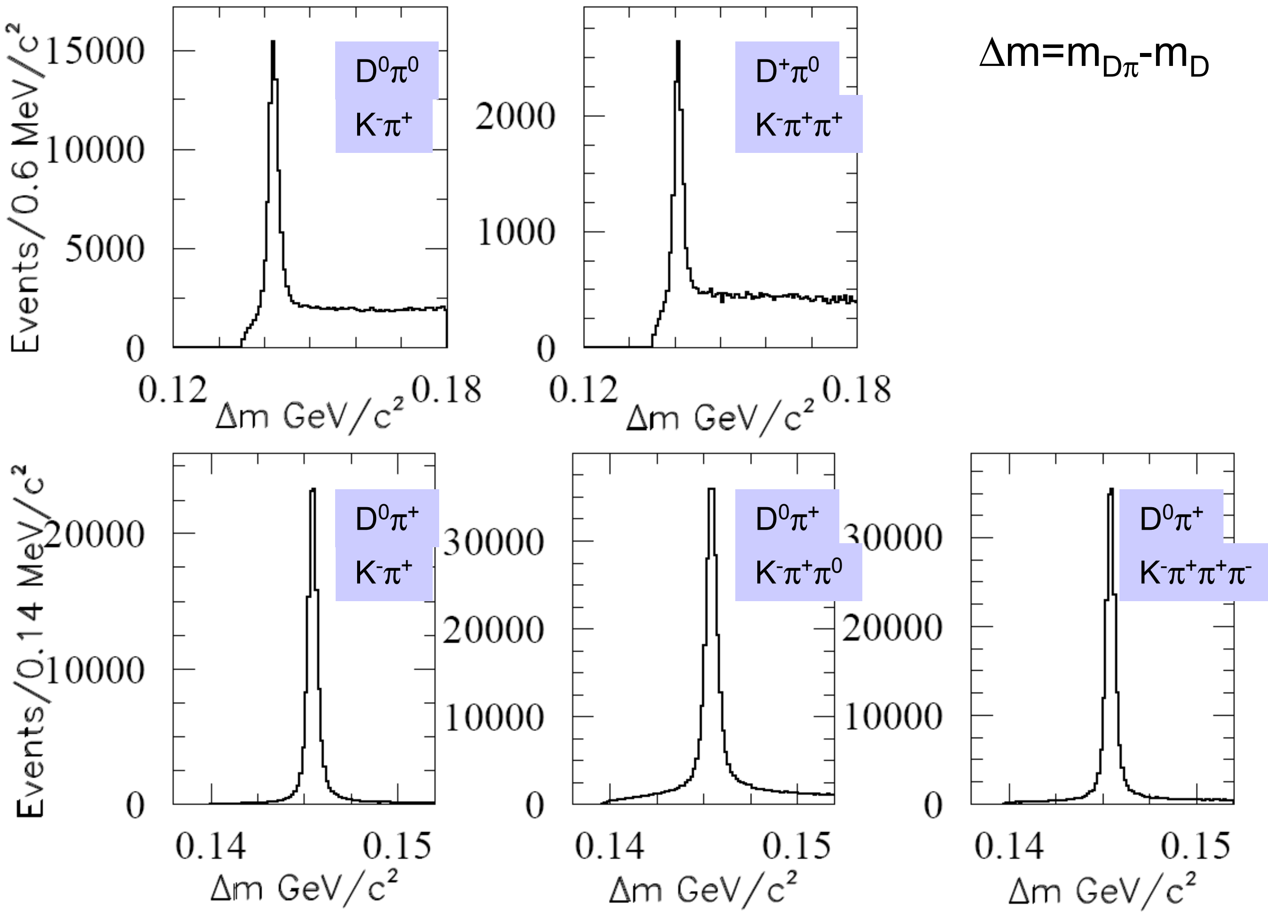
Angular cut:



background peaking at $\cos(\theta_K)$~-1
Required: $\cos(\theta_K)$>-0.8

Clear D* signal in 5 reconstruction modes

$\Delta m = m_{D\pi} - m_D$



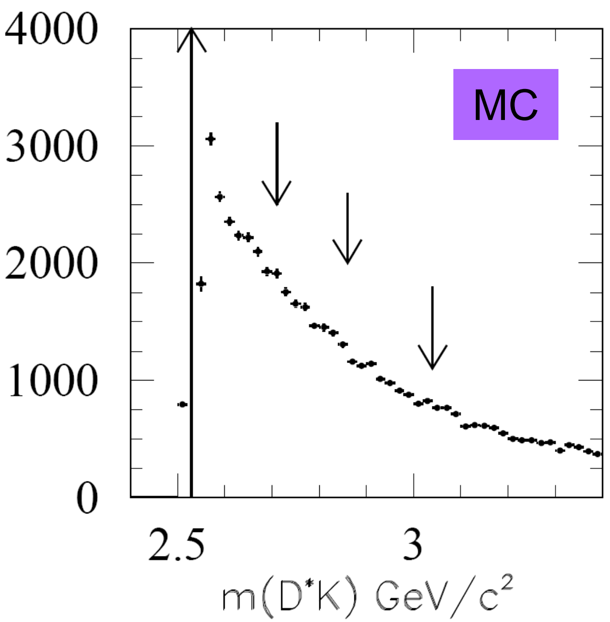
PRD 80, 092003 (2009)

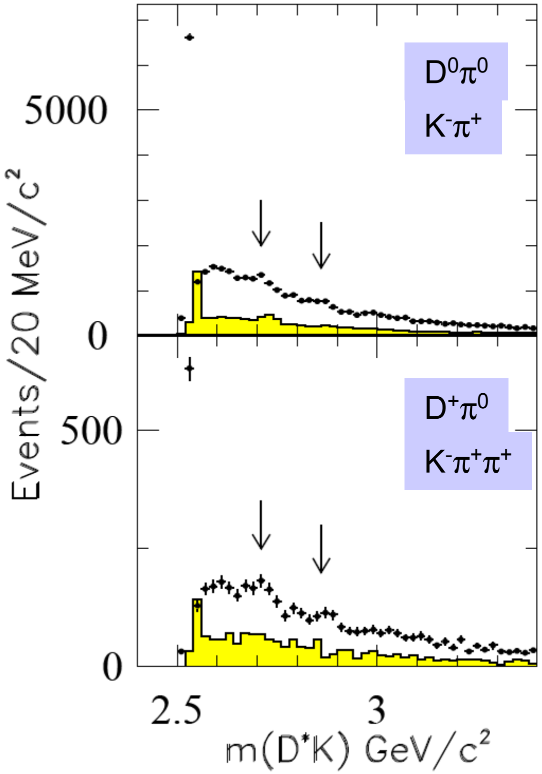
BaBar studies for D_{sJ} in D^*K

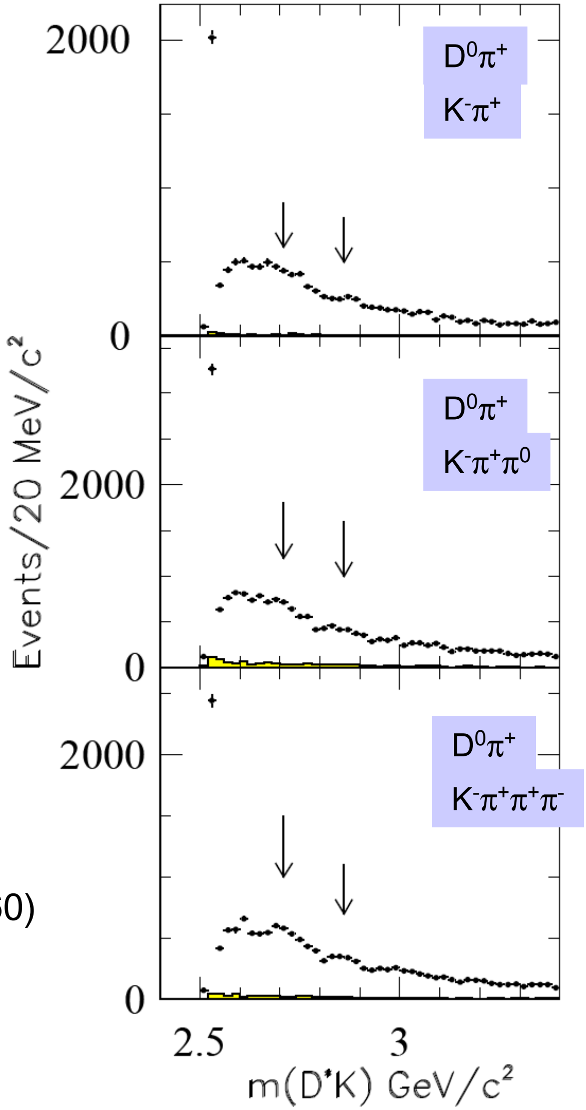
D*K invariant mass distributions

Same structures visible in all reconstruction modes

Not visible in MC







Arrows indicate $D_{s1}^+(2710)$ and $D_{sJ}^+(2860)$

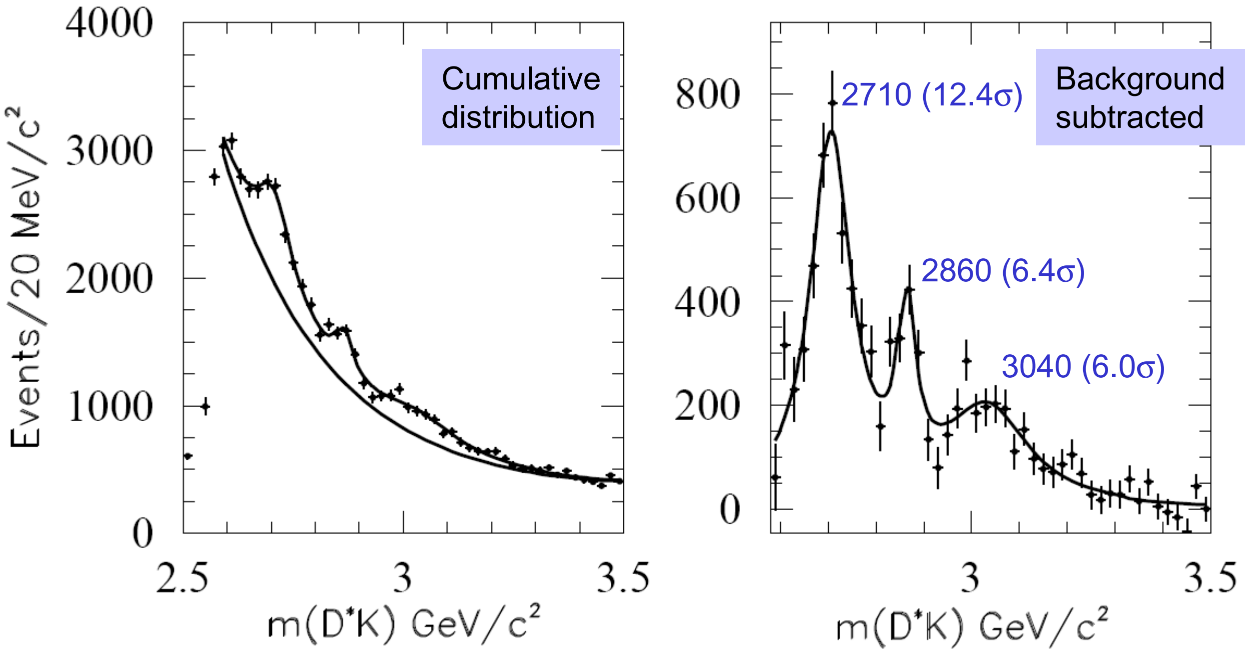
Yellow: background contribution from D* sidebands

PRD 80, 092003 (2009)

Fit to D^*K distribution

Combined spectrum from all reconstruction modes
Fit with smooth background + 3 relativistic Breit-Wigner

Additional broad structure observed at 3040 MeV/c^2



$D_{s1}(2710)^+$ parameters:
$m = 2710 \pm 2^{+12}_{-7}$ MeV/c^2
$\Gamma = 149 \pm 3^{+39}_{-52}$ MeV

$D_{sJ}(2860)^+$ parameters:
$m = 2862 \pm 2^{+5}_{-2}$ MeV/c^2
$\Gamma = 48 \pm 3 \pm 6$ MeV

$D_{sJ}(3040)^+$ parameters:
$m = 3044 \pm 8^{+30}_{-5}$ MeV/c^2
$\Gamma = 239 \pm 35^{+46}_{-42}$ MeV

Systematic uncertainty obtained varying the selection criteria (p^*, $\cos\theta_K$, Δm)
Statistical significance evaluated from $\Delta\chi^2$ after removing one resonance and repeating the fit

Taking into account efficiency and averaging on $D^{*0}K^+$ and $D^{*+}K^0$ decays, we obtain:

$$\frac{B(D^*_{s1}(2710)^+ \to D^*K)}{B(D^*_{s1}(2710)^+ \to DK)} = 0.91 \pm 0.13 \pm 0.12 \qquad \frac{B(D^*_{sJ}(2860)^+ \to D^*K)}{B(D^*_{sJ}(2860)^+ \to DK)} = 1.10 \pm 0.15 \pm 0.19$$

PRD 80, 092003 (2009)

Angular Analysis

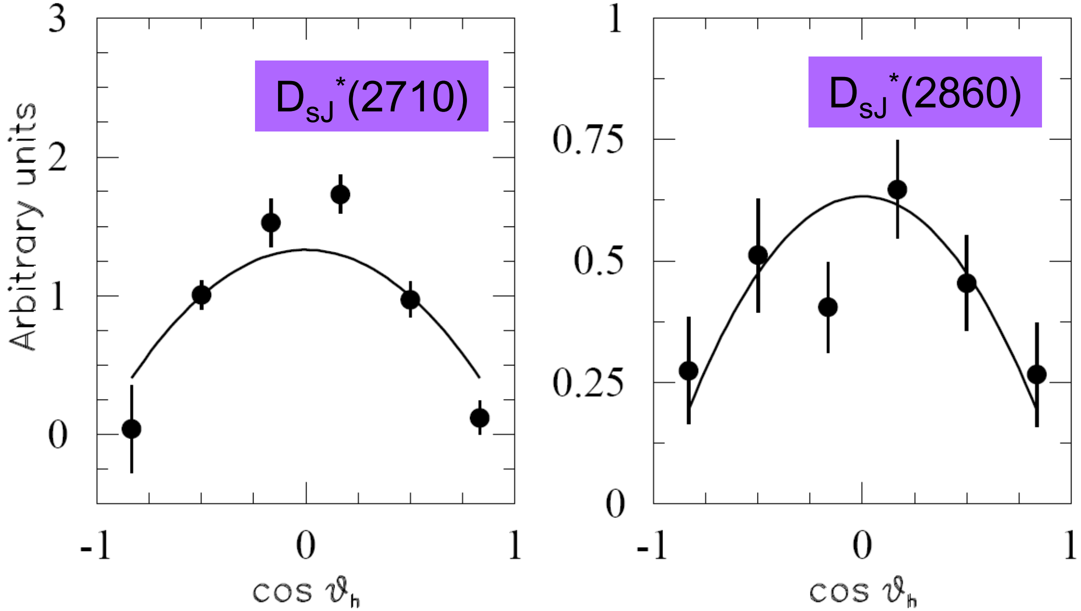
Angular distribution are obtained from the yield of the states in different θ_h regions
θ_h: angle between the π fron the D* decay wrt the K, in the D* reference frame

$1-\cos^2\theta_h$
expected for natural J^P
($J^P = 0^+, 1^-, 2^+, \ldots$)

Both distribution consistent with natural parity

$D_{sJ}(3040)$ too broad to obtain reliable results with this technique

Efficiency corrected distributions



For the $D_{s1}^*(2710)$, two different assignment for $J^P=1^-$ are proposed by P. Colangelo et al. (PRD 77, 014012 (2008)):

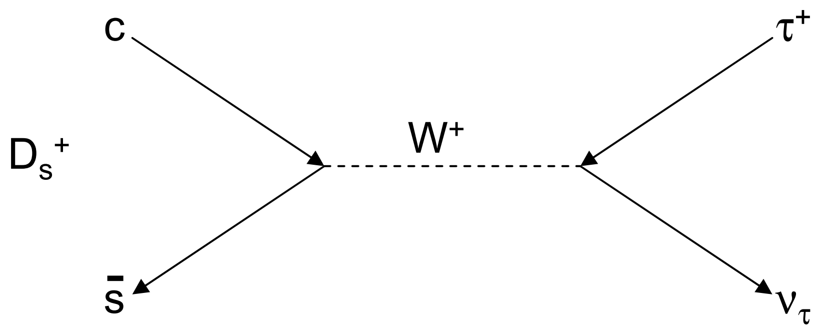
- L=2 ground state (1^3D_1) $\rightarrow$ ratio of BR expected: 0.043±0.002
- L=0 first radial excitation (2^3S_1) $\rightarrow$ ratio of BR expected: 0.91±0.04

data support 2^3S_1 assignment

For the the $D_{sJ}^*(2860)$, quantum numbers still not defined ($J^P=3^-$ and $J^P=0^+$ are proposed)

Measurement of the branching fraction $D_s^+ \to \tau^+ \nu_\tau$ and extraction of the decay constant f_{Ds}

In the standard model the D_s^+ can decay to leptonic final states through the annihilation of c and $\bar{s}$ quarks into a virtual W^+ boson



These decays provide a clean probe for the measurement of the meson decay constant f_{Ds}, describing the amplitude for the two quark to have 0 spatial separation

$$\Gamma(D_s^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} M_{D_s^+}^3 \left(\frac{m_\ell}{M_{D_s^+}} \right)^2 \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2} \right)^2 |V_{cs}|^2 \, f_{D_s}^2$$

↑ helicity suppression ↑ phase space

The D_s^+ has spin 0, so the leptonic decay is helicity suppressed. This motivates the study of $\tau^+\nu_\tau$ final state

Predictions for f_{Ds} come from lattice calculation:
f_{Ds}=(247±2) MeV (J. Shigemitsu, FPCP 2010, Torino)

The measurement can be used to validate lattice QCD calculations and could provide hints for new physics effects

Measurement of the branching fraction $D_s^+ \to \tau^+ \nu_\tau$ and extraction of the decay constant f_{Ds}

427 fb^{-1}

hep-ex/1003.3063

$$e^+e^- \to c\bar{c} \to D_s^{*+} \overline{D}_{TAG} \overline{K} X$$
$$D_s^{*+} \to D_s^+ \gamma$$
$$D_s^+ \to \tau^+ \nu_\tau$$

D_{TAG}: reconstructed D meson to suppress hadronic background

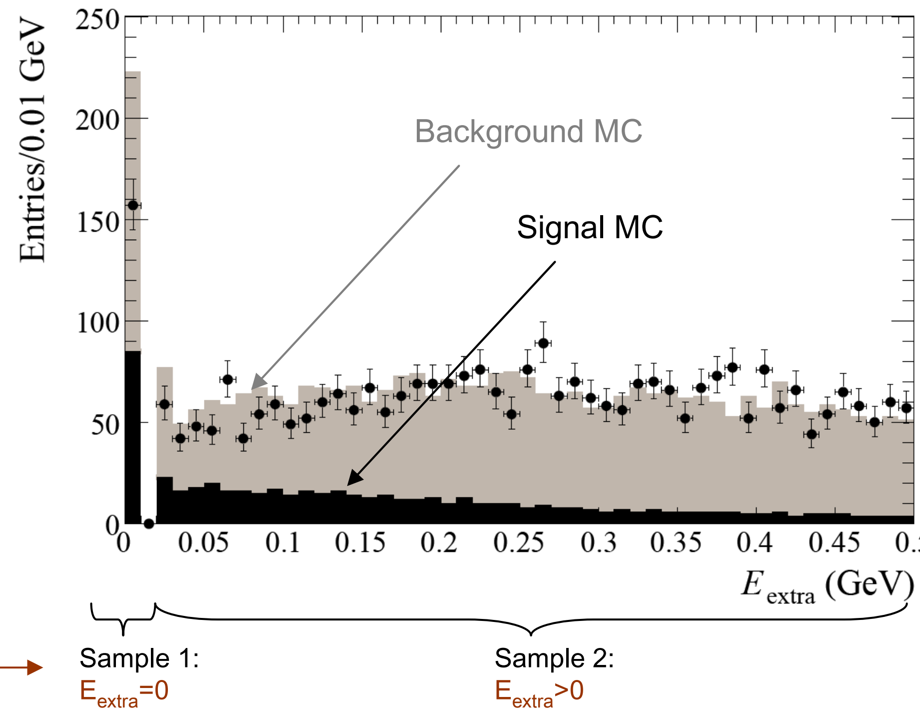
K: required to balance strangeness in the event

γ in D_s^* decay is the signal photon

E_{extra}: sum of the CM energies of all photons (of at least 30 MeV) in the event that are not associated to reconstructed particles, used for signal - background separation

Data divided in two samples: →

- D_s^* candidate is defined as the missing particle: 4-momentum: $P_{Ds^*} = P_{ee} - (P_{Dtag} + P_K + P_X)$
- a single electron is required in the event (for $\tau \to e\nu\nu$ decay)
- E_{extra} required to be in the region 0-0.5 GeV
- Simultaneous unbinned max-likelihood fit to recoil mass (against the signal photon) and E_{extra} (for E_{extra}>0)
- branching fractions are obtained from peak in the recoil mass distribution, normalizing to $D_s^+ \to K_S^0 K^+$ decay



Measurement of the branching fraction $D_s^+ \to \tau^+ \nu_\tau$ and extraction of the decay constant f_{Ds}

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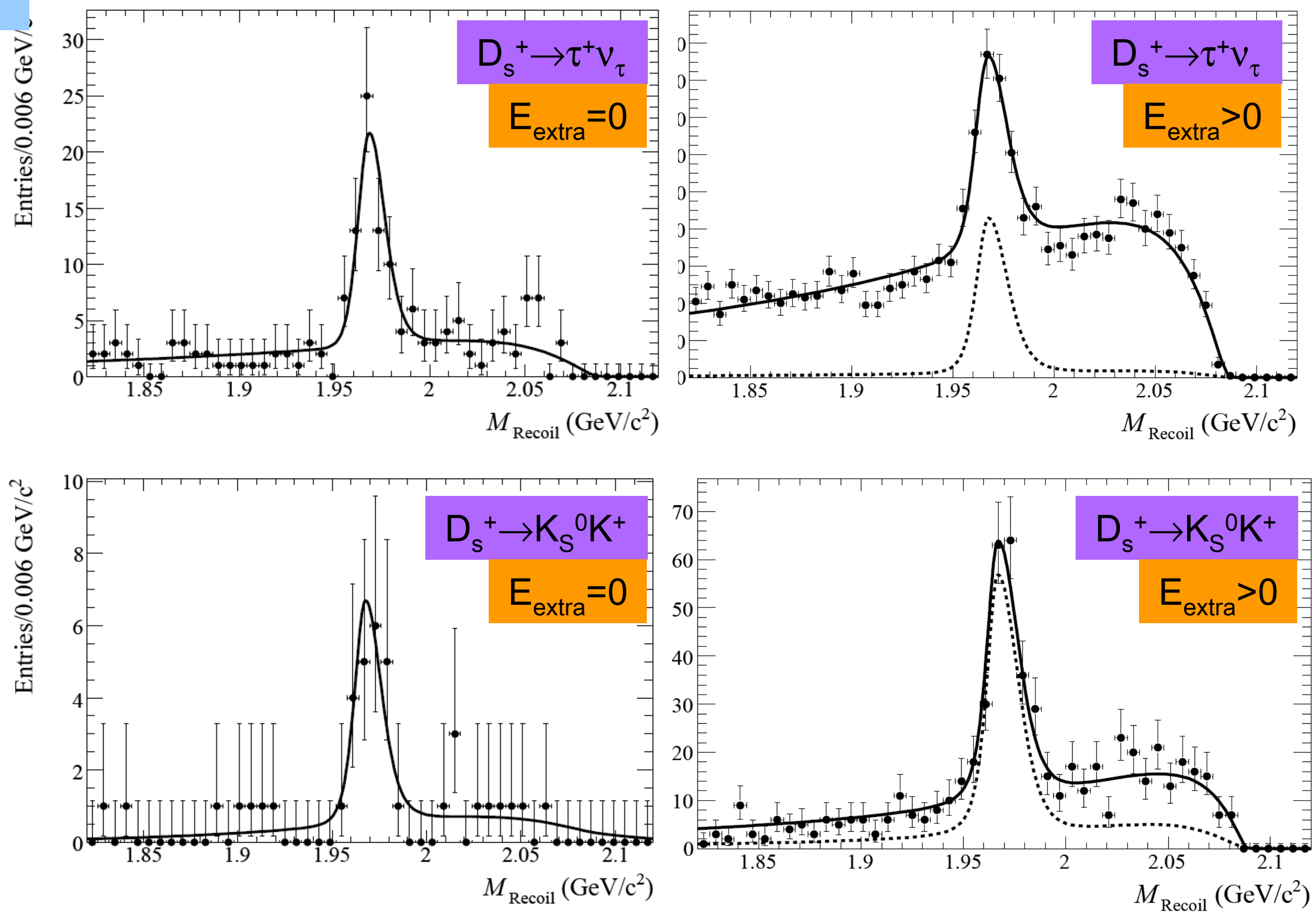
hep-ex/1003.3063



$$B(D_s^+ \to \tau^+ \nu_\tau) = (4.5 \pm 0.5 \pm 0.4 \pm 0.3)\%$$

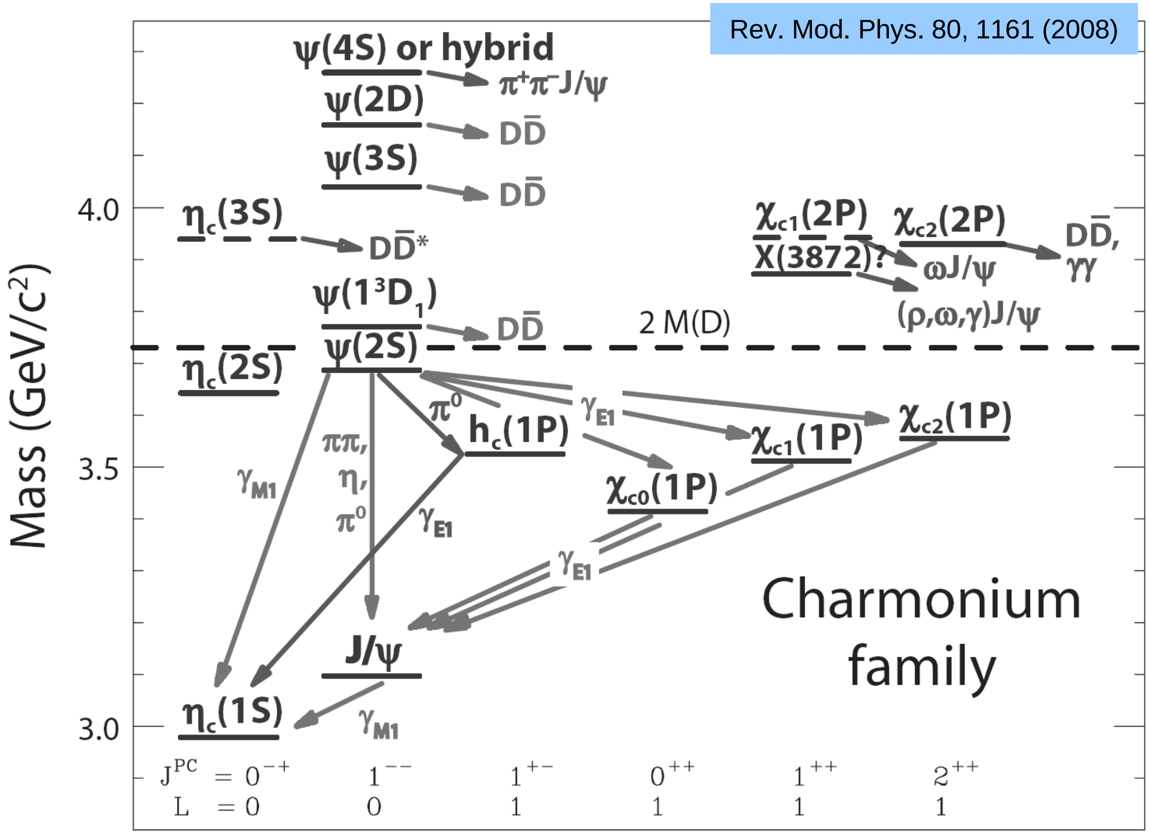
$$f_{D_s} = (233 \pm 13 \pm 10 \pm 7) MeV$$

uncertainty from external and theoretical quantities

$$f_{D_s} = (247 \pm 2) MeV$$
Lattice QCD

$$f_{D_s} = (259.7 \pm 7.8 \pm 3.4) MeV$$
CLEO: PRD 80, 112004 (2009)

The Charmonium spectrum



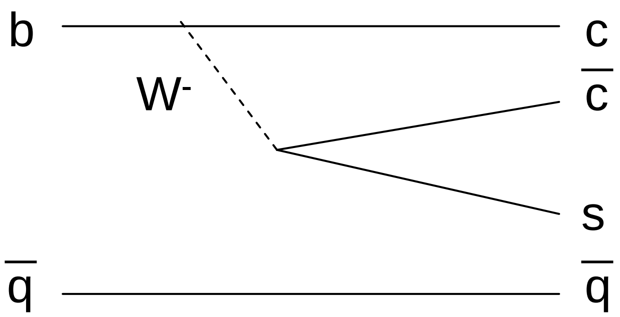
- Renewed interest in charmonium spectroscopy after results from B-factories, concerning the observation of states with unpredicted properties
- Expected narrow states below the open charm threshold, wide states above this threshold
- Several new states observed: X(3872), Y(3940), Z(3930), Y(4260),…

Experimental and theoretical efforts to explain the observed properties, including non conventional explanations:

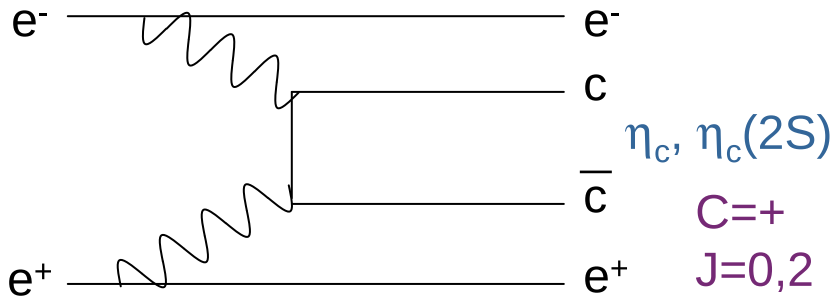
- Hybrids (with gluonic degree of freedom, expected mass > 4.2 GeV)
- Tetraquarks - DD molecules (compatible with small width above threshold and existence of charged states)

Charmonium Production at B-factories

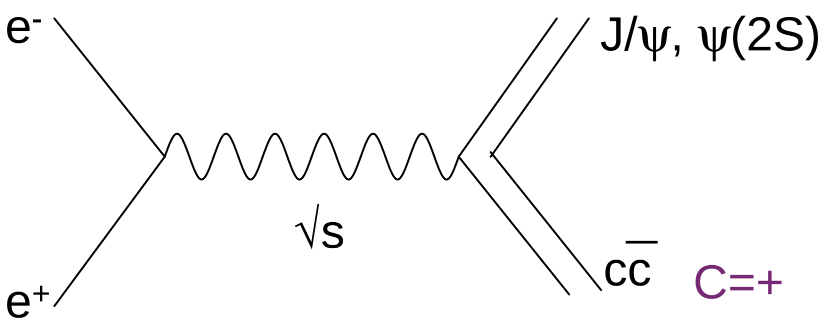
Color suppressed B decays



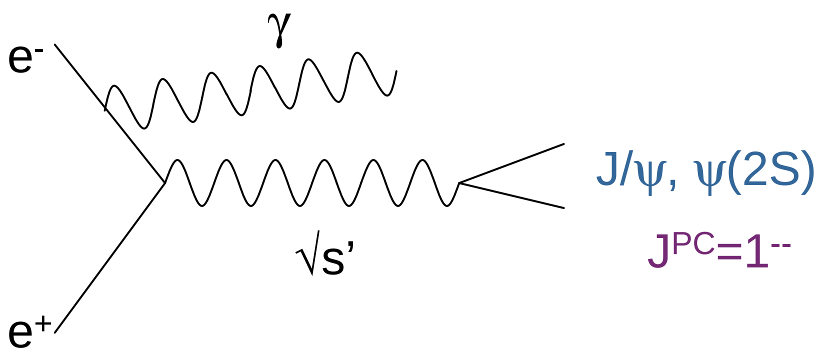
Two photons production



Double charmonium production



Initial state radiation



The X(3872) observation

Discovered by Belle and confirmed by CDF, D0, BaBar

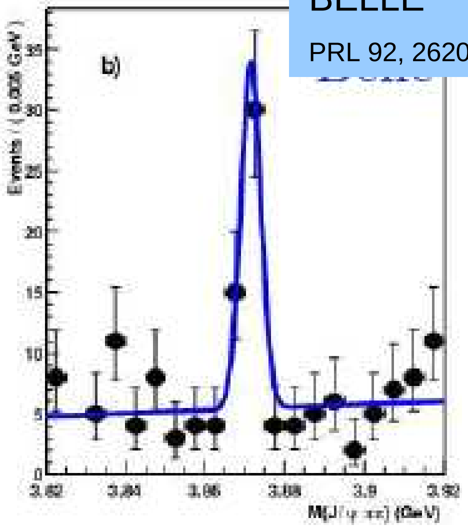
$B^+ \to K^+ X(3872)$
$X(3872) \to J/\psi\, \pi^+\pi^-$
(compatible with $J/\psi\, \rho^0$)

M_X=3871.9±0.5 MeV/c^2
Γ_X<2.3 MeV/c^2 at 90%CL
at $D^0\overline{D}^{0*}$ threshold
$J^{PC}=1^{++}$ favored

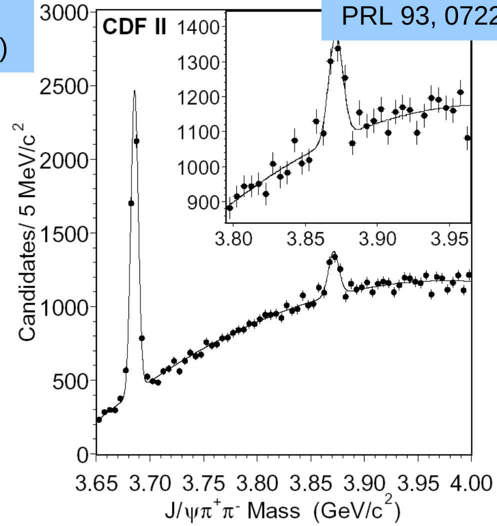
Observed decays:
$J/\psi\, \gamma$
$D^0\overline{D}^0\pi^0$

Angular analysis:
CDF favors $J^{PC}=1^{++}$, 2^{-+}
Belle favors $J^{PC}=1^{++}$

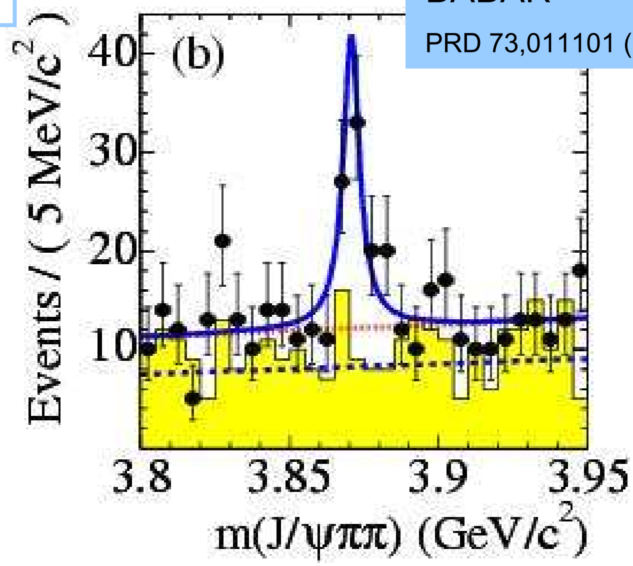
BELLE
PRL 92, 262001 (2003)



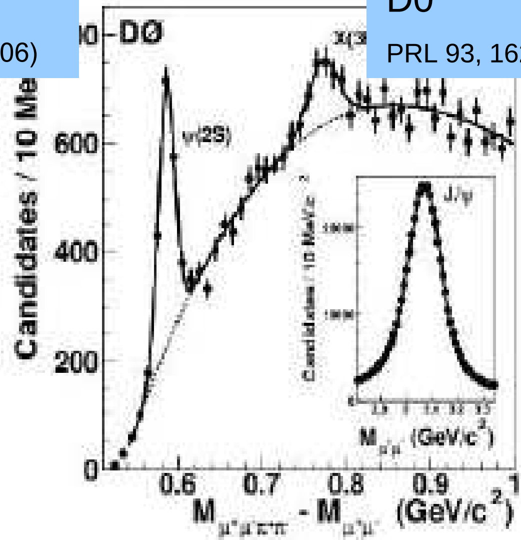
CDF
PRL 93, 072201 (2004)



BABAR
PRD 73,011101 (2006)



D0
PRL 93, 162002 (2004)



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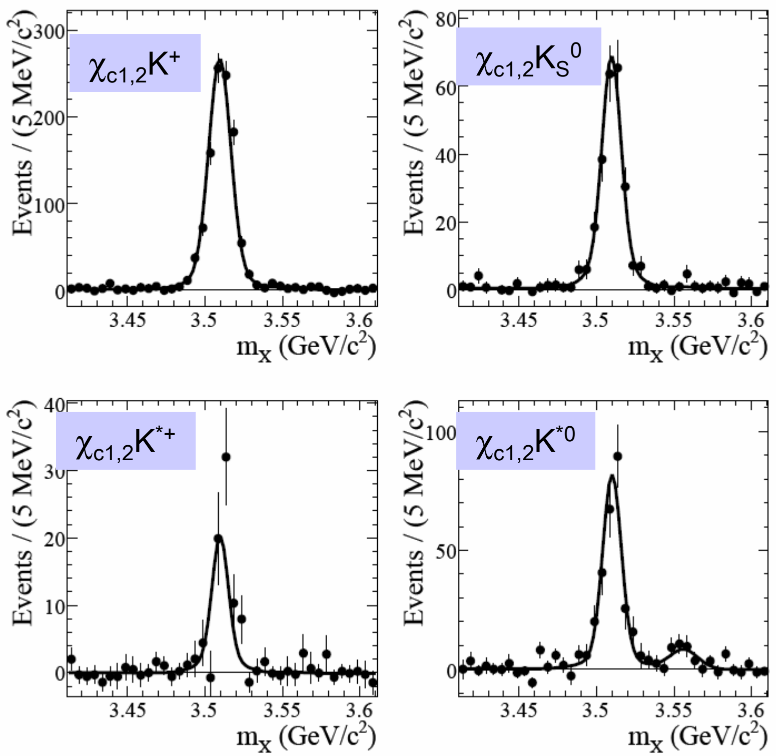
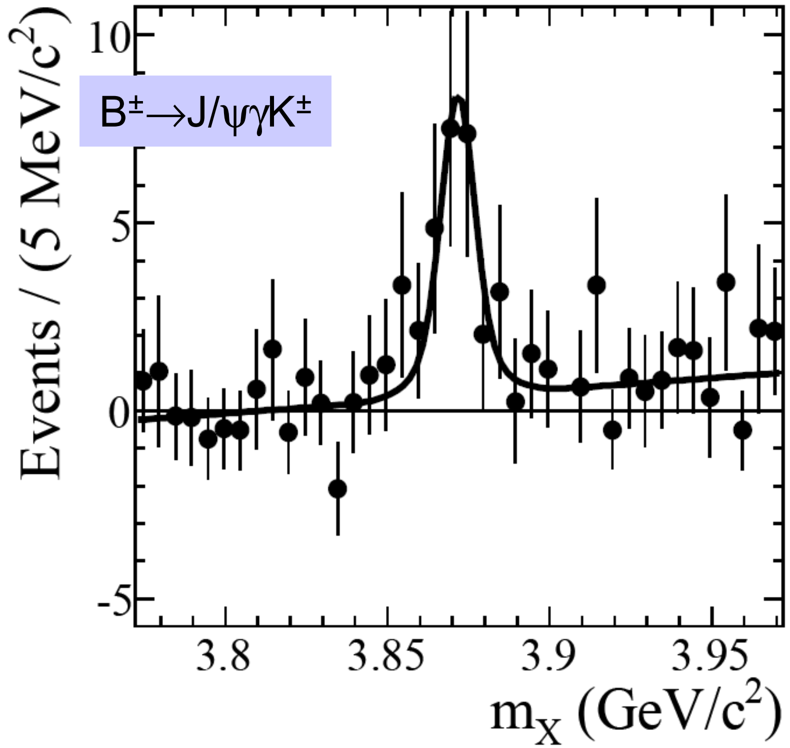
X(3872) → J/ψ γ

PRL 102,132001 (2009)

Analysis strategy:
- Reconstruct B → (J/ψ,ψ') γ K$^{(*)}$
- Separate signal from background by assigning a weight to each event and project the events in the two categories (sPlot, NIM A 555, 356 (2005))

Same analysis strategy applied to B → J/ψ γ K(*) to reconstruct $\chi_{c1,2}$ and validated on MC samples





$$B(B^\pm \to X(3872)K^\pm, X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

This decay mode fix C=+ for the X(3872)

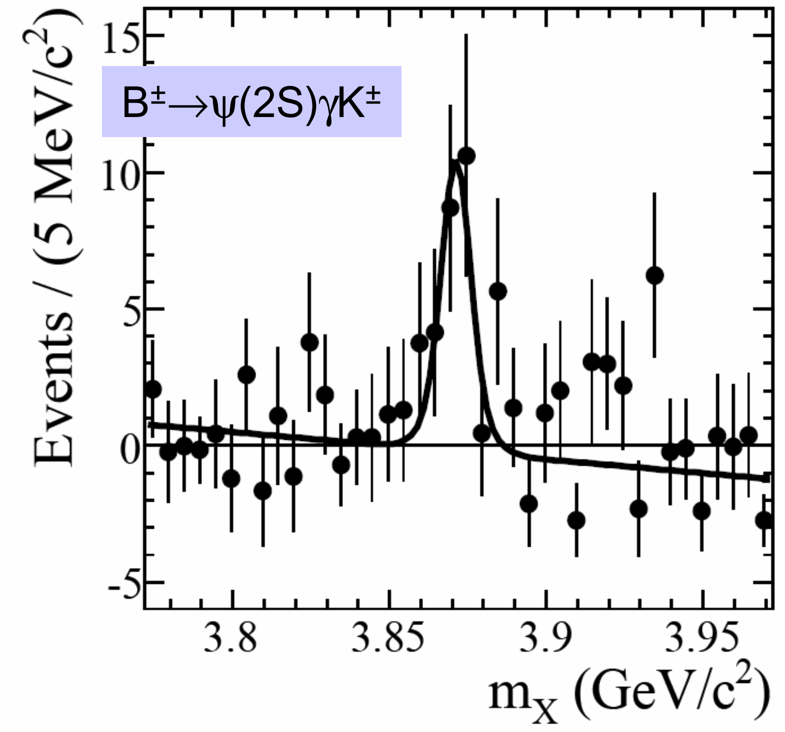
PRL 102,132001 (2009)

X(3872) → ψ(2S) γ

Molecular model predicts small branching ratio
A large branching ratio could indicate a significant $c\bar{c}$ component

$$B(B^{\pm} \to X(3872)K^{\pm}, X(3872) \to \psi(2S)\gamma) =$$
$$= (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$$

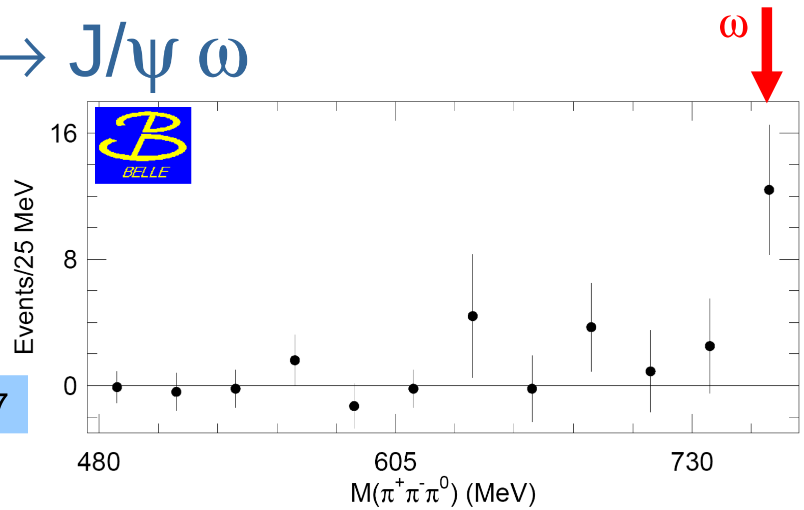
$$\frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4$$



No ψ(2S)γ signal observed in a recent Belle analysis (QWG7)

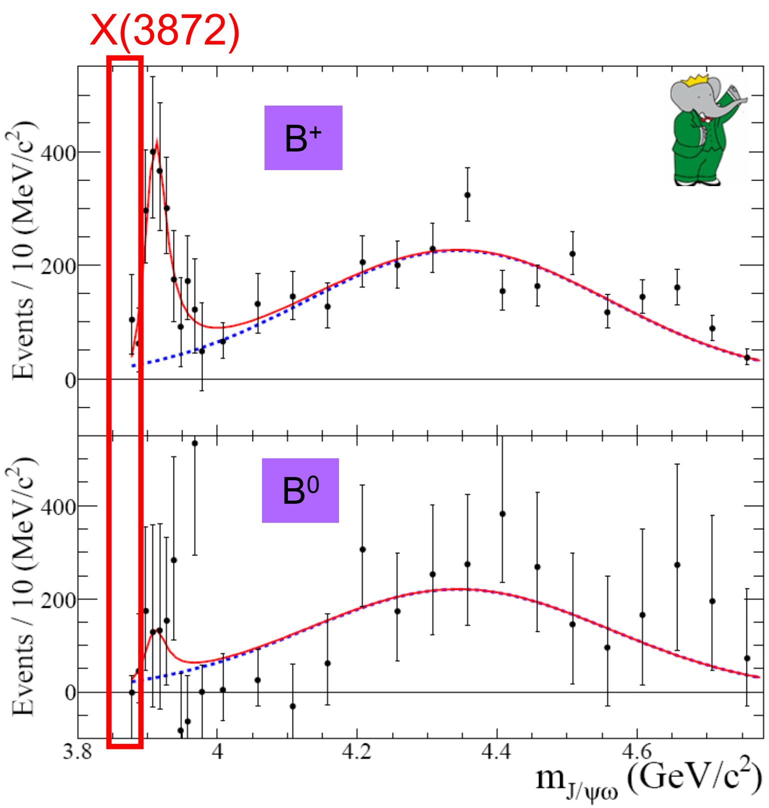
$$\frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872) \to J/\psi\gamma)} < 2.1 (90\% CL)$$

X(3872) → J/ψ ω



Belle reported an excess of events in $m_{3\pi}$ above 750 MeV, for $B \to J/\psi(3\pi)K$ with $J/\psi(3\pi)$ mass consistent with the X(3872)

hep-ex/0505037



No evidence of X(3872) signal in a previous BaBar result

The ω mass cut used in this analysis:
$0.7695 < m_{3\pi} < 0.7965$ GeV (B^+)

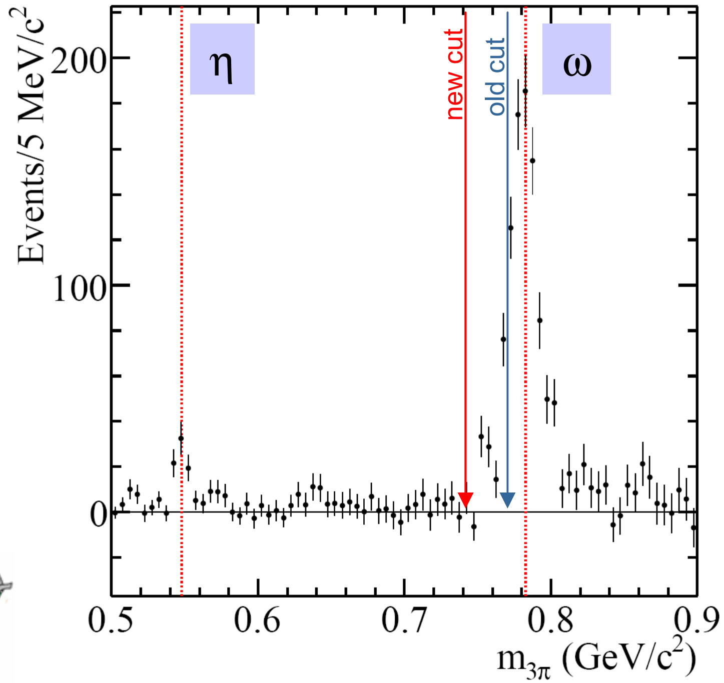
PRL 101, 082001 (2008)

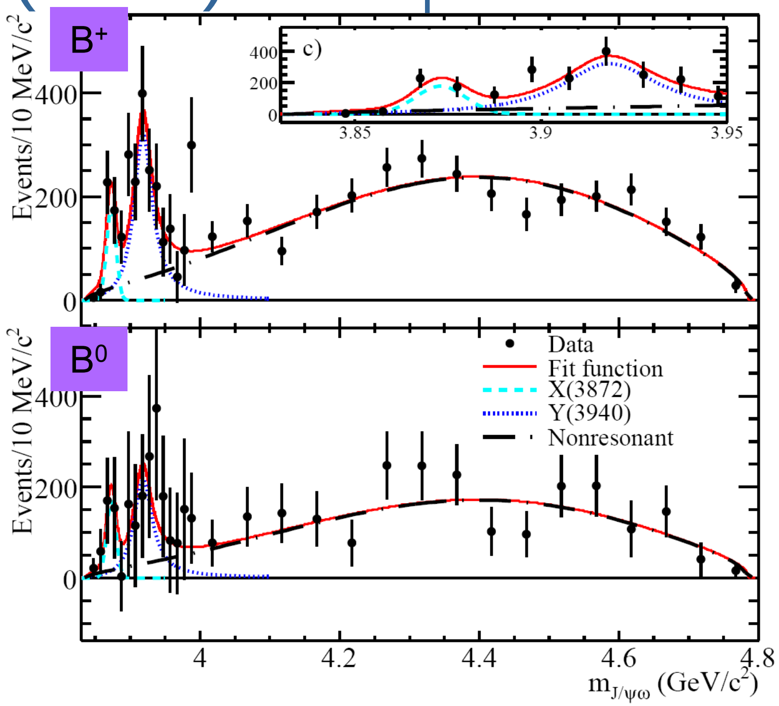
426 fb^{-1}

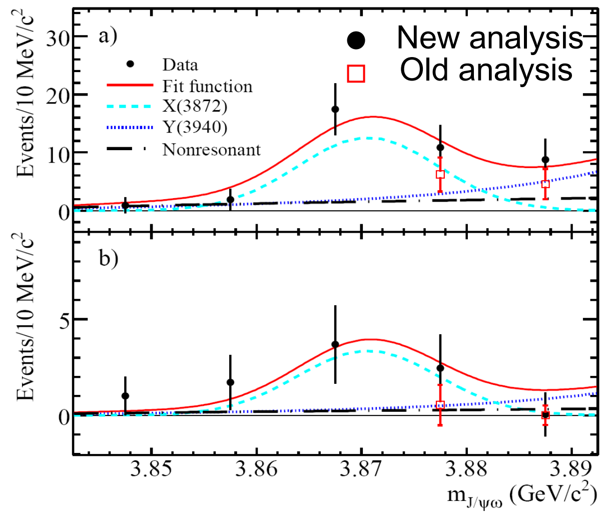
hep-ex/1005.5190

BaBar reanalysis: X(3872) → J/ψ ω

- Same selection criteria used in previous analysis, with low ω mass limit lowered to 0.7400 GeV/c^2
- m_{ES} fit (after ΔE requirement) in intervals of the variable of interest to extract B-signal contribution
- Fit distributions after efficiency correction
- 4σ evidence of X(3872) in J/ψω







X(3872) → J/ψ ω : fit results

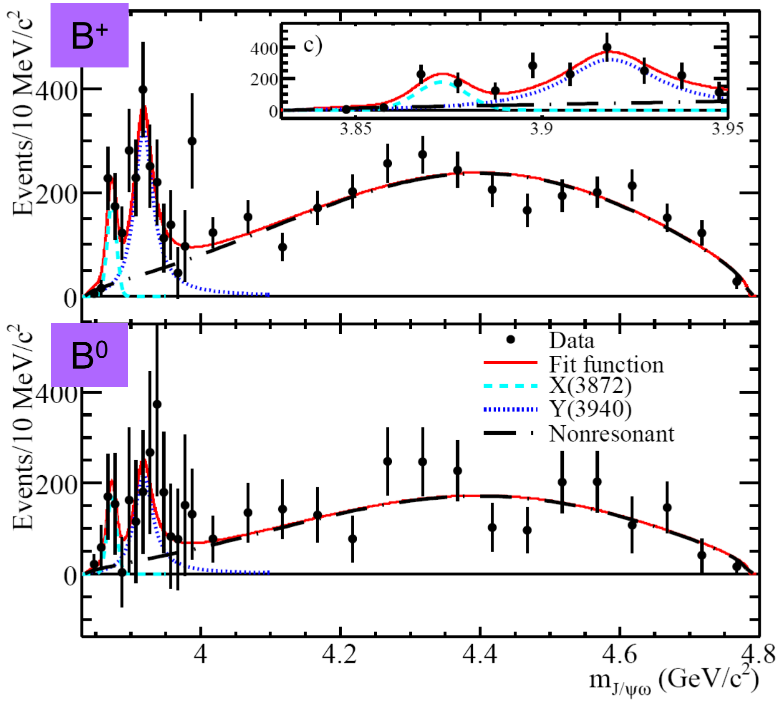
$$m_X = (3873.0^{+1.8}_{-1.6} \pm 1.3) MeV/c^2$$

$$N_X^+ = 21 \pm 7$$

$$N_X^0 = 6 \pm 3$$

$$\frac{B(X \to J/\psi\omega)}{B(X \to J/\psi\pi^+\pi^-)} = 0.7 \pm 0.3$$ for B⁺ events

$$\frac{B(X \to J/\psi\omega)}{B(X \to J/\psi\pi^+\pi^-)} = 1.7 \pm 1.3$$ for B⁰ events



Consistent with Belle result: $$\frac{B(X \to J/\psi\omega)}{B(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

$$B(B^+ \to XK^+) \times B(X \to J/\psi\omega) = (0.6 \pm 0.2 \pm 0.1) \times 10^{-5}$$

$$B(B^0 \to XK^0) \times B(X \to J/\psi\omega) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-5}$$

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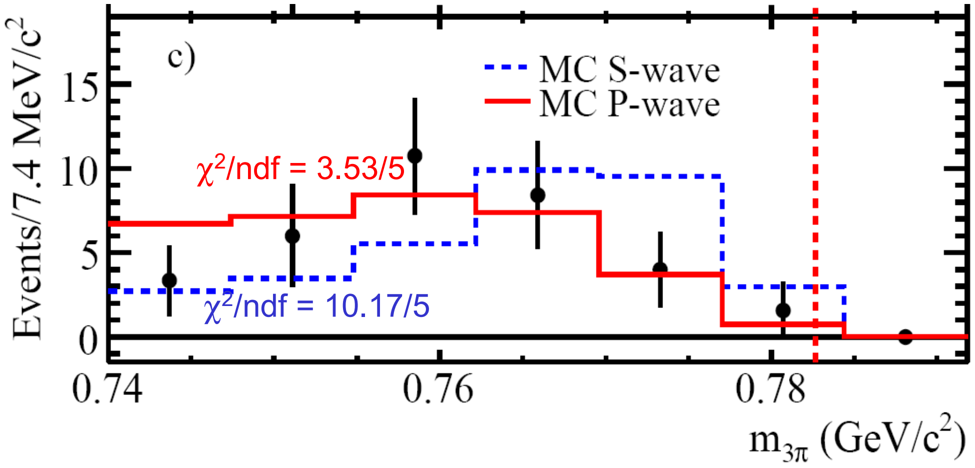
X(3872) → J/ψ ω: $m_{3\pi}$ distribution



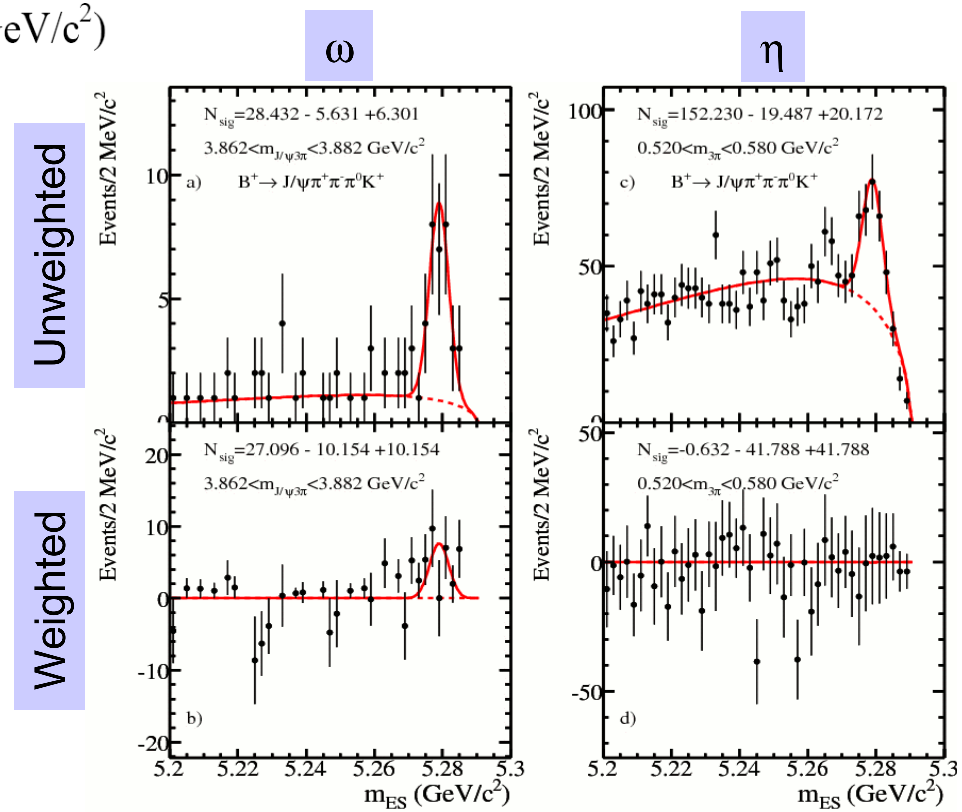
Information on quantum numbers obtained from 3π mass distribution, originated by a centrifugal barrier:
S-wave: Data-MC agreement 7%
P-wave: Data-MC agreement 62%

P-wave for J/ψω indicates P=-
$J^P=2^-$ assignment favored w.r.t 1^+

Is this ω or non-resonant 3π?

Each event in the distribution is assigned a weight prop. to the expected ω angular distribution

This technique projects the ω signal and eliminates background



hep-ex/1005.5190

Results for Y(3940) → J/ψ ω

$m_Y = (3919.1^{+3.8}_{-3.4} \pm 2.0) MeV/c^2$

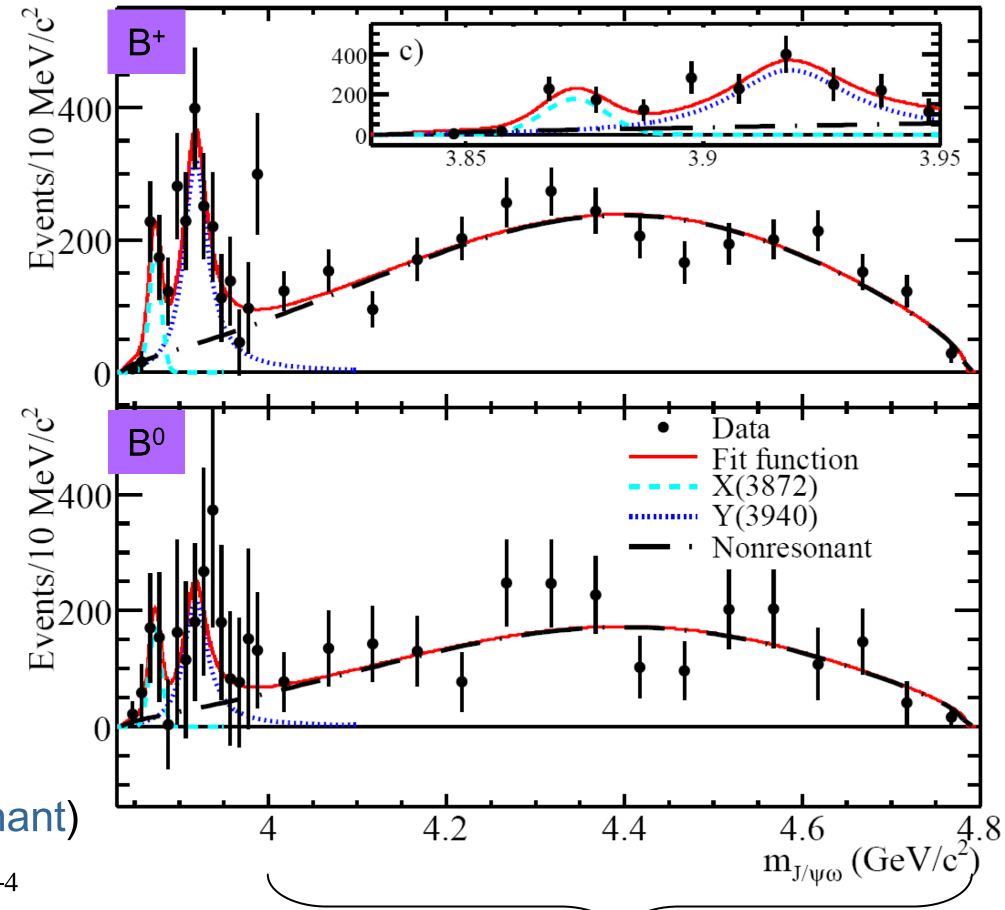
$\Gamma_Y = (31^{+10}_{-8} \pm 5) MeV$

$N_Y^+ = 108^{+25}_{-23}$

$N_X^0 = 19 \pm 8$

$B(B^+ \to YK^+) \times B(Y \to J/\psi\omega) =$
$= (3.0^{+0.7+0.5}_{-0.6-0.3}) \times 10^{-5}$

$B(B^0 \to YK^0) \times B(Y \to J/\psi\omega) =$
$= (2.1 \pm 0.9 \pm 0.3) \times 10^{-5}$



Non-resonant J/ψω contribution
(not background!)

Inclusive branching ratios (X+Y+non-resonant)

$B(B^+ \to J/\psi\omega K^+) = (3.2 \pm 0.1^{+0.6}_{-0.3}) \times 10^{-4}$

$B(B^0 \to J/\psi\omega K^0) = (2.3 \pm 0.3 \pm 0.3) \times 10^{-4}$

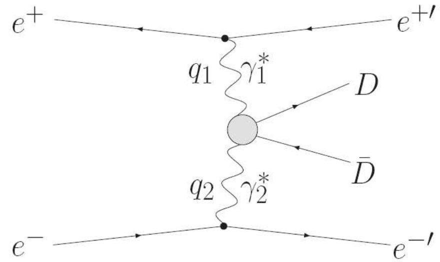
All consistent with previous measurements

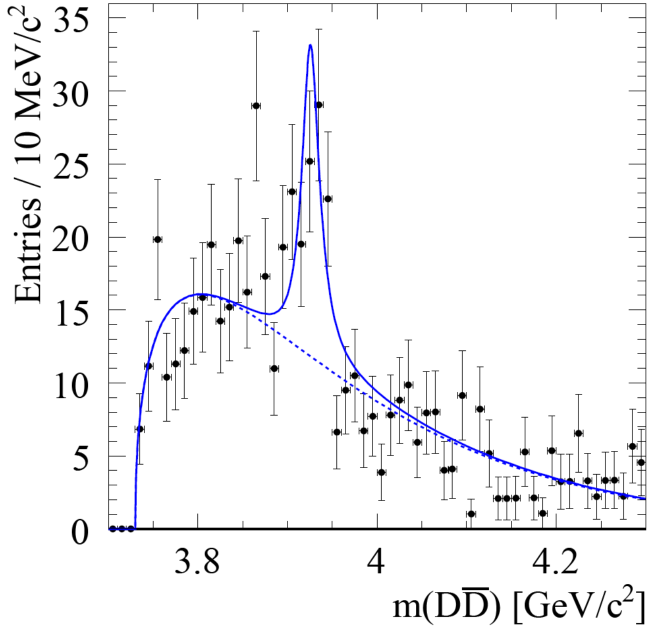
384 fb^{-1}

PRD 81, 092003 (2010)

Z(3930) in two photon fusion

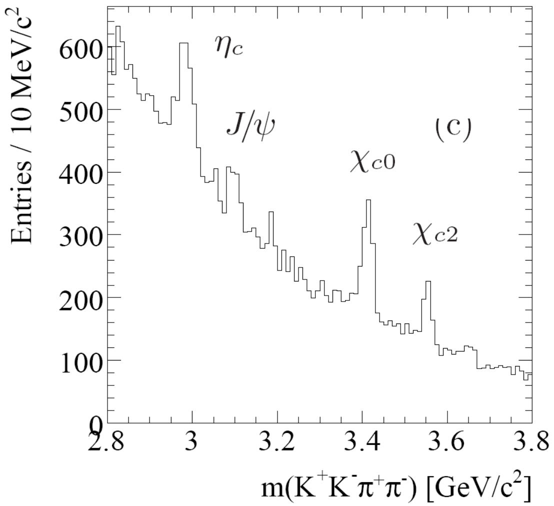
C=+ constrained by production mechanism





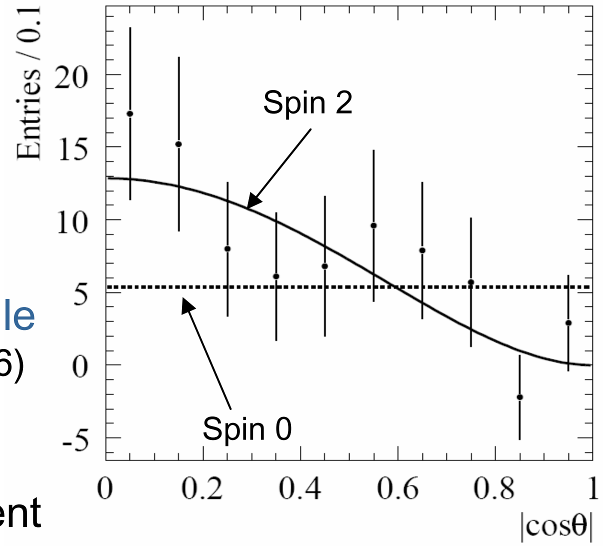
D mesons reconstructed in:
Kπ, Kππ, Kπππ

Selection criteria tested on KKππ final state



$$m = (3926.7 \pm 2.7 \pm 1.1) MeV / c^2$$
$$\Gamma = (21.3 \pm 6.8 \pm 3.6) MeV$$

Consistent with Belle
PRL 96, 082003 (2006)

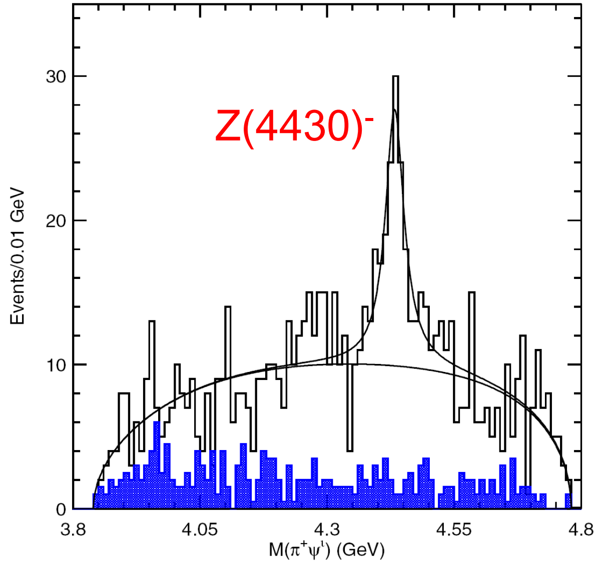


Angular distribution between the D$\bar{D}$ and the beam axis depending on J: $J^{PC}=2^{++}$ consistent with χ'_{c2}(2P) assignment

Charged states: Z(4430)$^-$

In 2008 Belle observed the first charged state in $B \to \psi(2S)\pi^- K$ decays,
by looking at $\psi(2S)\pi^-$ invariant mass

Minimal quark content for this state is $(c\bar{c}d\bar{u})$: evidence of tetraquarks



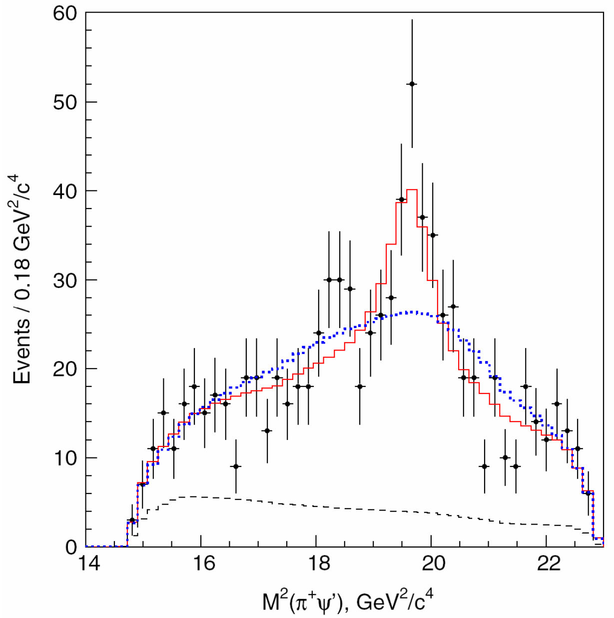
6.5σ significance

PRL 100, 142001 (2008)

$$m = (4433 \pm 4 \pm 2) MeV/c^2$$

$$\Gamma = (45^{+18+30}_{-13-13}) MeV$$

New result by Belle with Dalitz analysis approach



6.4σ significance

PRD 80,031104(R) (2009)

$$m = (4443^{+15+19}_{-12-13}) MeV/c^2$$

$$\Gamma = (107^{+86+74}_{-43-56}) MeV$$

$$B(B^0 \to Z^{\pm} K^{\mp}, Z^{\pm} \to \psi(2S)\pi^{\pm}) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

Z(4430)$^-$: BaBar analysis

PRD 79,112001 (2009)

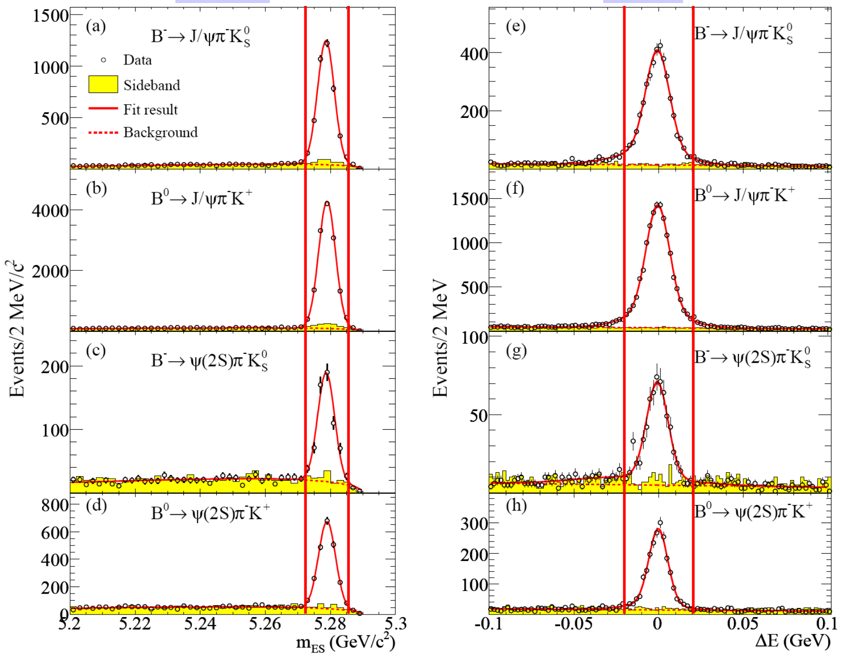
4 decay modes:

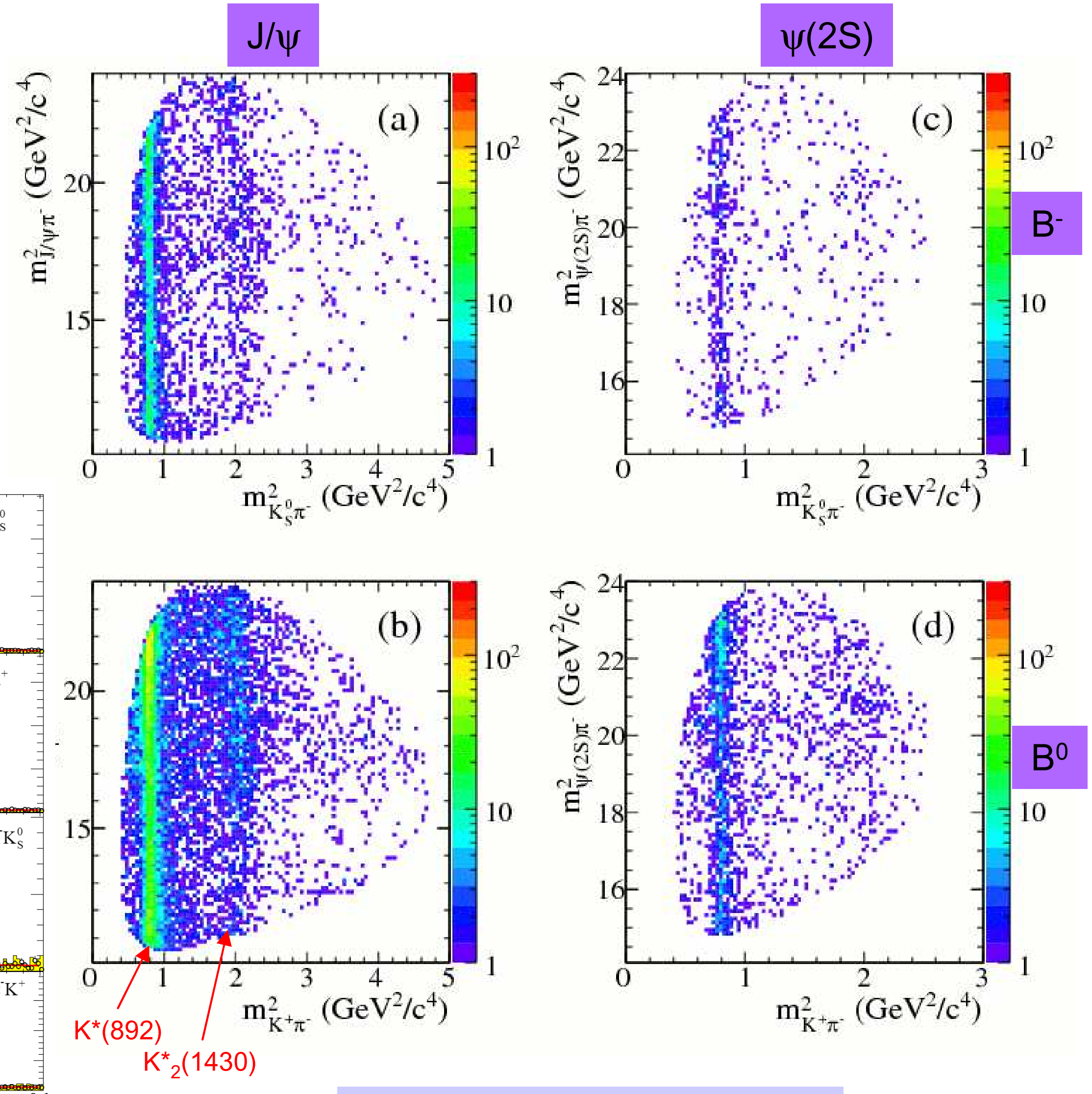
$B^- \to J/\psi\, \pi^-\, K_S^0$
$B^0 \to J/\psi\, \pi^-\, K^+$
$B^- \to \psi(2S)\, \pi^-\, K_S^0$
$B^0 \to \psi(2S)\, \pi^-\, K^+$

413 fb^{-1}

B mesons selected with cuts on:

$$\Delta E = E_B^* - \sqrt{s}/2$$
$$m_{ES} = \sqrt{((s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i)^2 - \vec{p}_B^2}$$

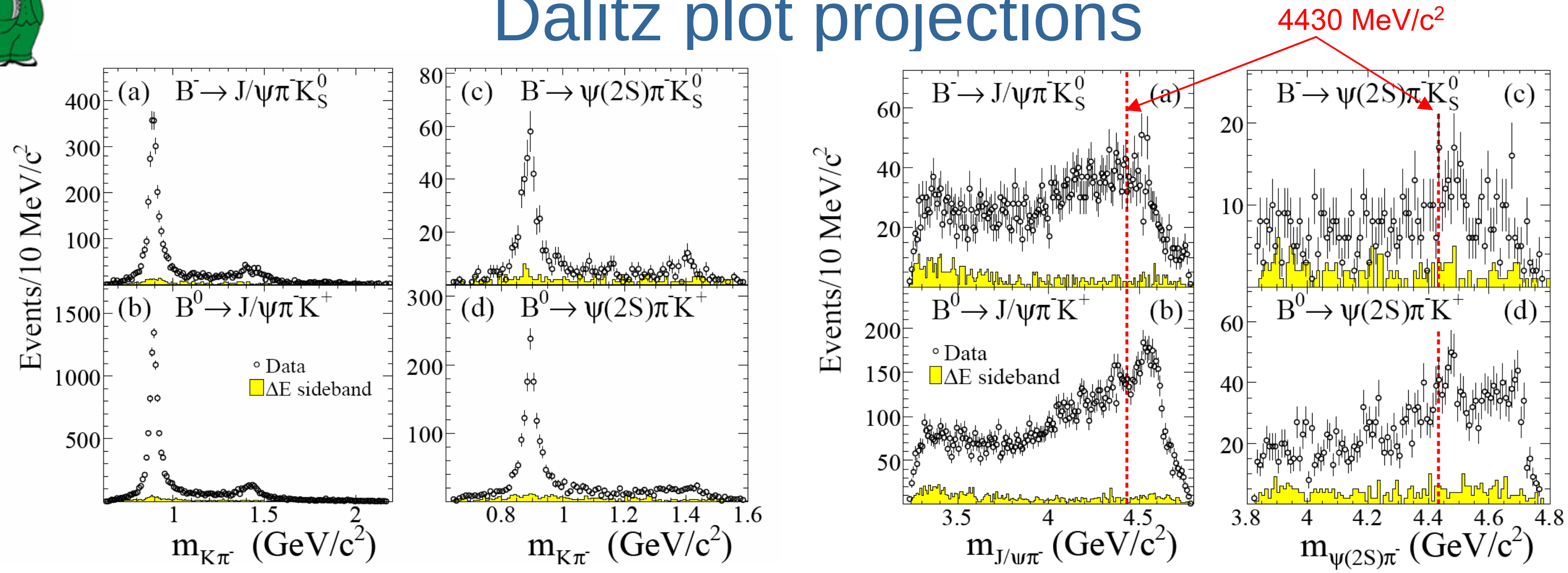


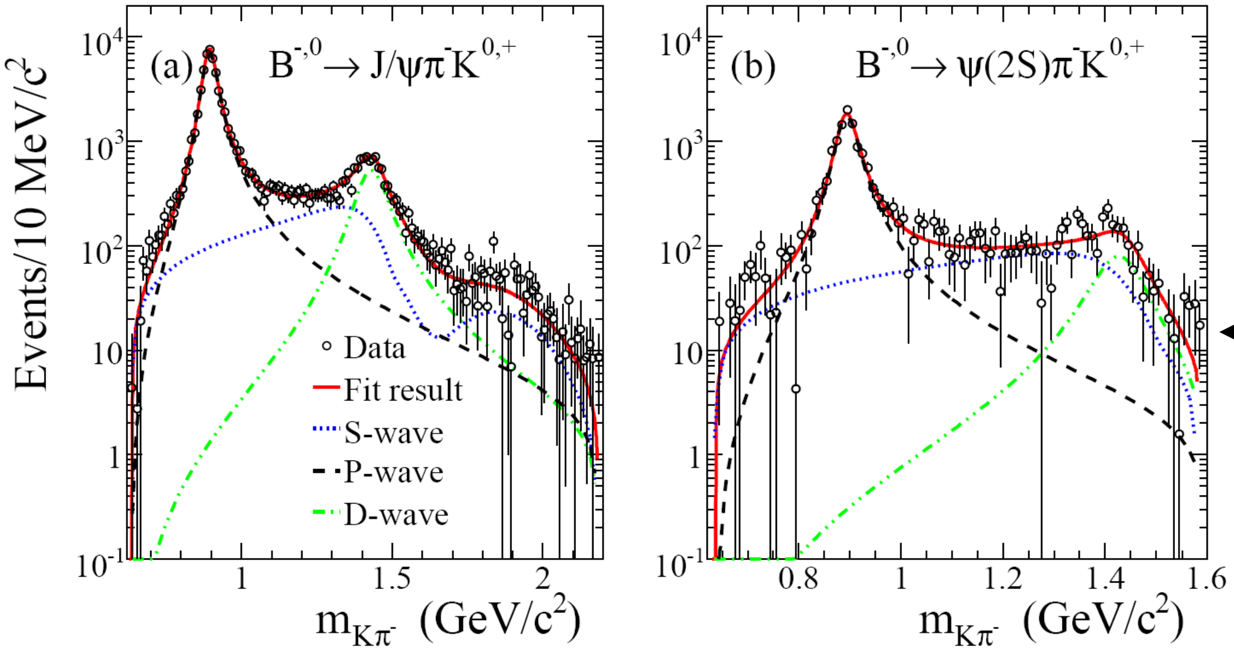


No (ψπ⁻) structure visible

PRD 79,112001 (2009)

Dalitz plot projections

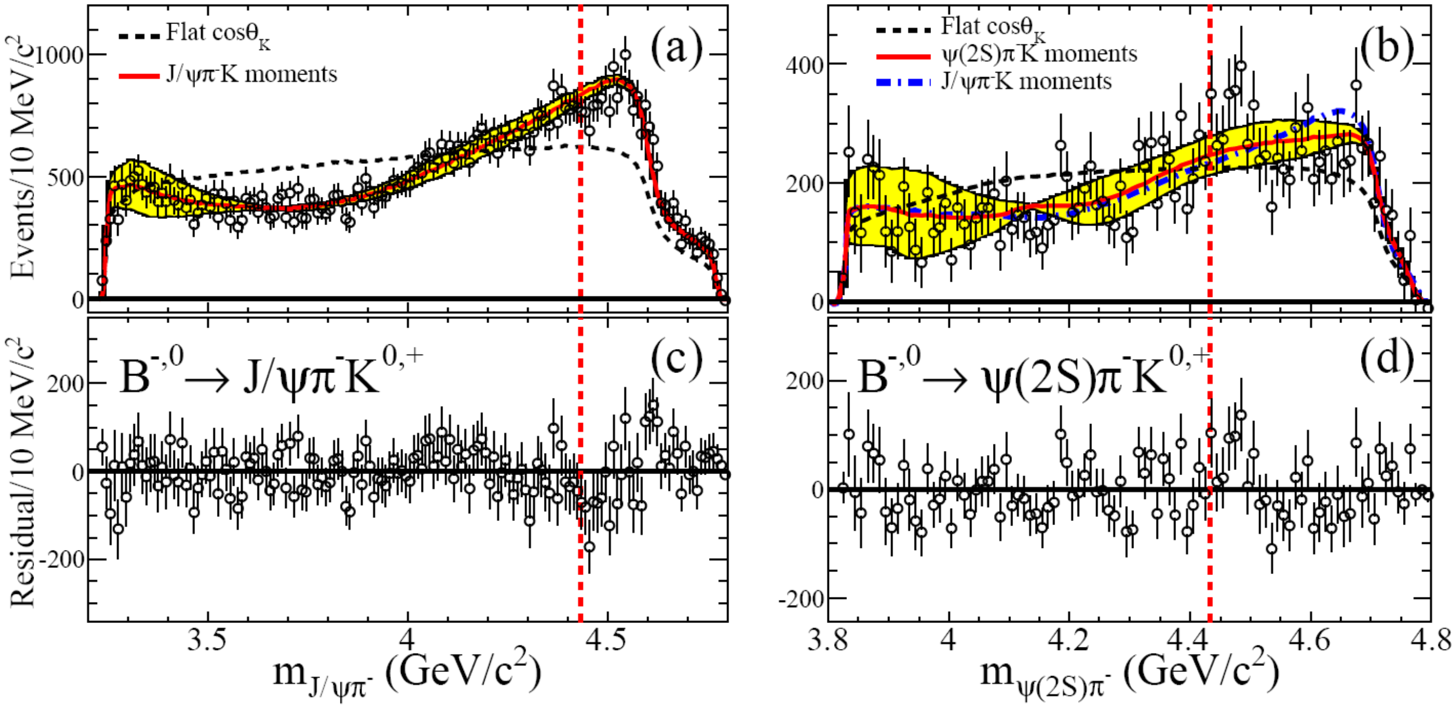


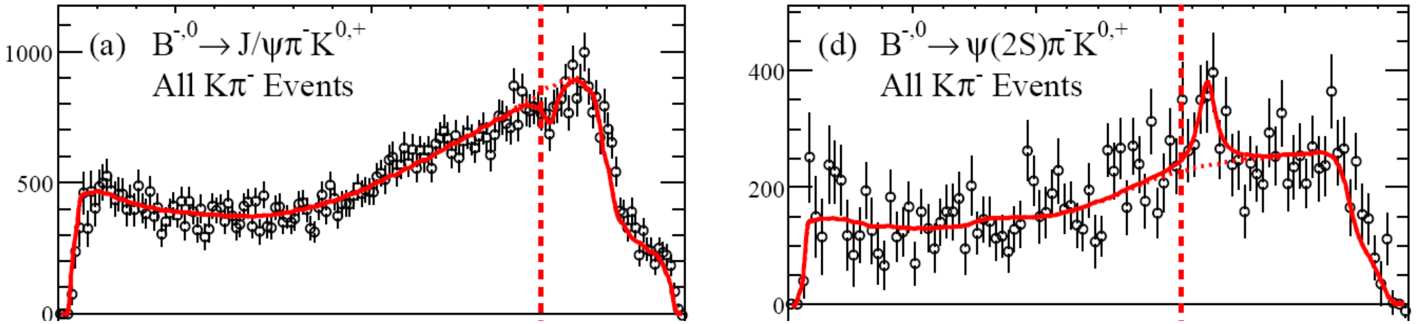


Partial wave analysis: good description of the $K\pi^-$ mass obtained using S, P, D waves

PRD 79,112001 (2009)

Z(4430)$^-$: $\psi\pi^-$ mass distribution



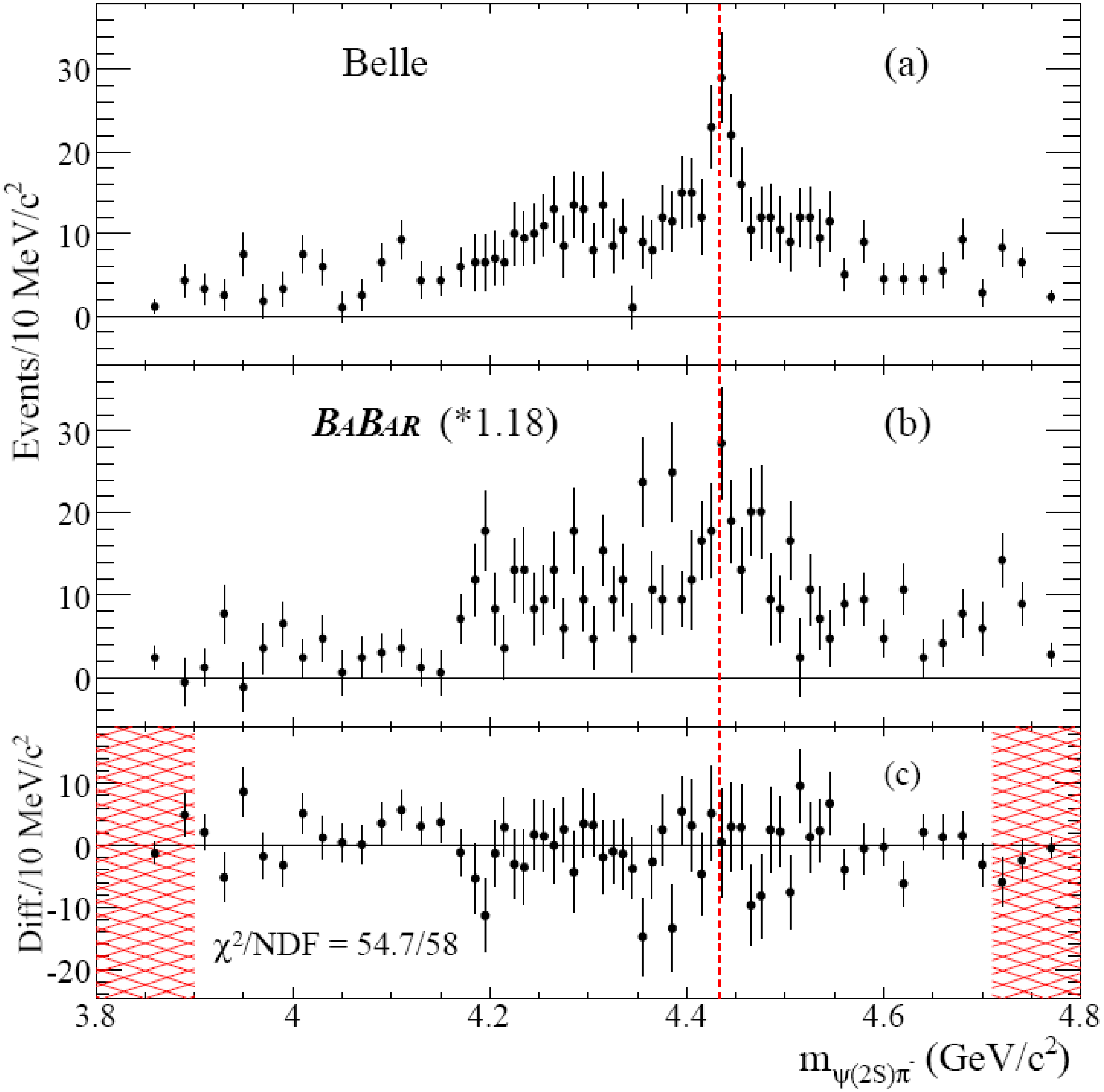


No structure observed ay 4430 MeV/c^2 (also shown fit with additional Breit-Wigner included)

$B(B^- \to Z^- \overline{K}^0, Z^- \to \psi(2S)\pi^-) < 4.7\times10^{-5}$ $B(B^0 \to Z^- K^+, Z^- \to \psi(2S)\pi^-) < 3.1\times10^{-5}$ at 95% CL

PRD 79,112001 (2009)

BaBar - Belle comparison



Direct comparison of the two experiments:

- normalization with integrated luminosity, efficiency, background (corr. factor = 1.18)
- application of K* veto

The two results are statistically compatible (low efficiency regions excluded)

Conclusions

- Large datasets of Charm / Charmonium available at the B-factories

- New informations on charmed meson spectroscopy
  - Data support 2^3S_1 for the $D_{s1}(2710)^+$; $J^P=3^-$ and 0^+ proposed for $D_{sJ}(2860)^+$
  - Observation of a broad $D_{sJ}(3040)^+$
  - Measured D_s decay constant f_{Ds} in agreement with recent unquenched lattice QCD calculations

- Renewed interest in charmonium spectroscopy after the discovery of several new states, with unpredicted properties
  - X(3872) studied in detail but its nature is still not clear
  - Several states observed at mass around 3940 MeV/c^2.
  - The charged state $Z(4430)^-$ still need more experimental studies

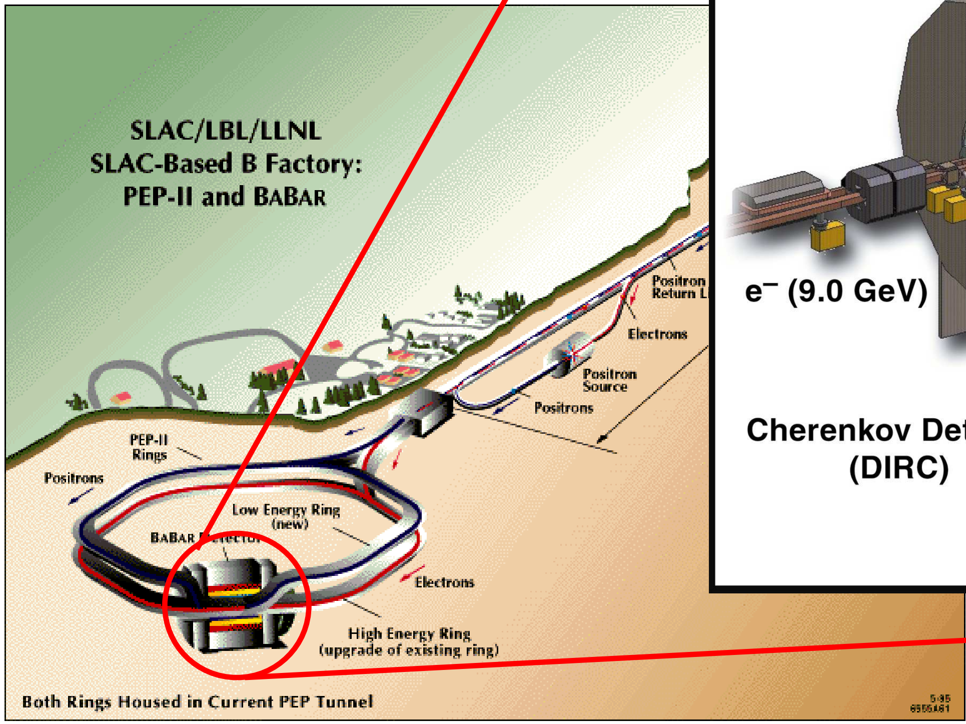
- Several experiments (B-factories, CDF, D0, LHC experiments) with the potential for studies in this field. More results are expected.

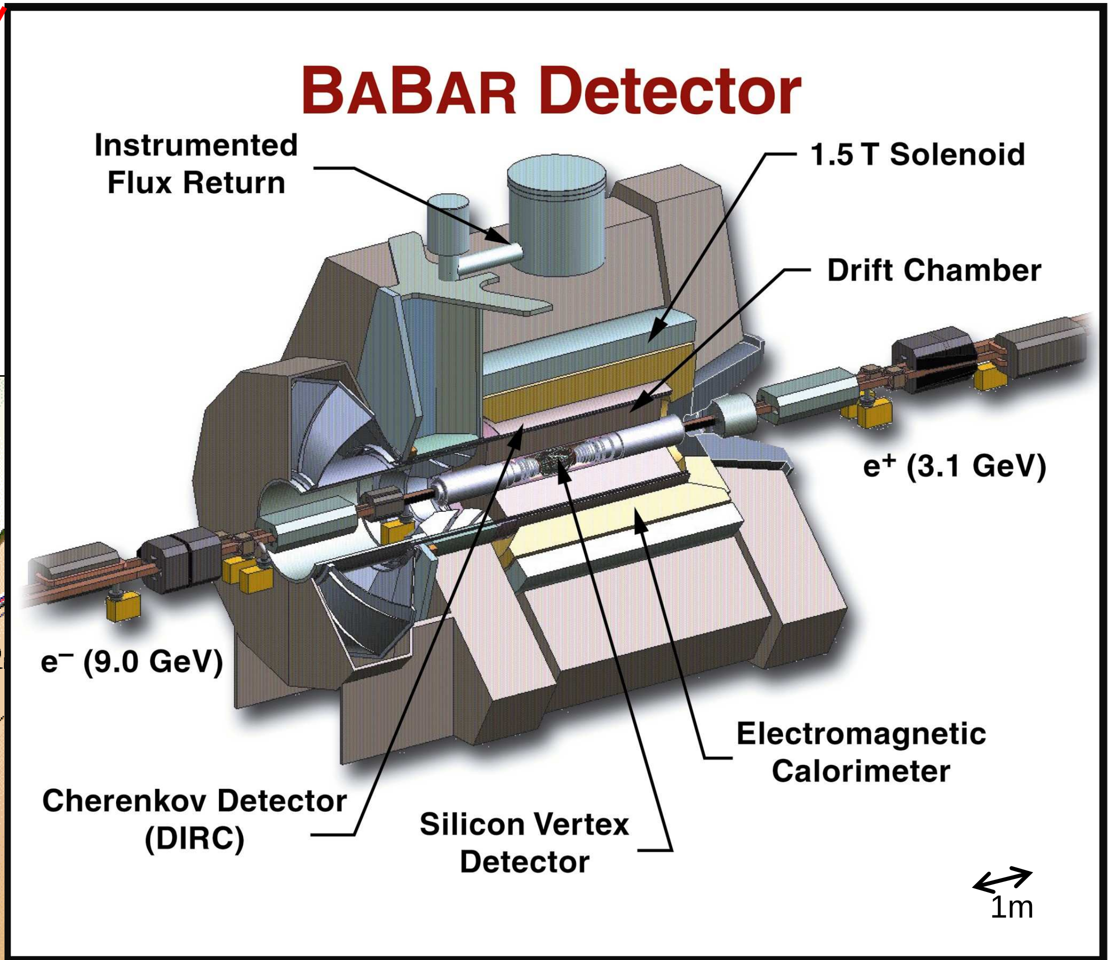
- The Super-B factory will play a leading role in this field.

BACKUP

The BaBar detector at PEP-II

SVT:
97% efficiency – 20µm z resol
SVT+DCH:
$\sigma(p_t)/p_t = 0.13\% \cdot p_t + 0.45\%$
EMC:
$\sigma(E)/E = 2.32\% \cdot E^{-1/4} + 1.85\%$



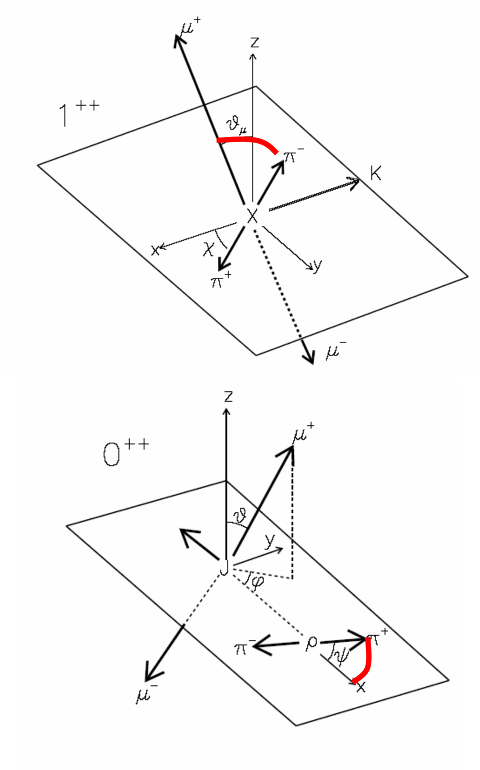


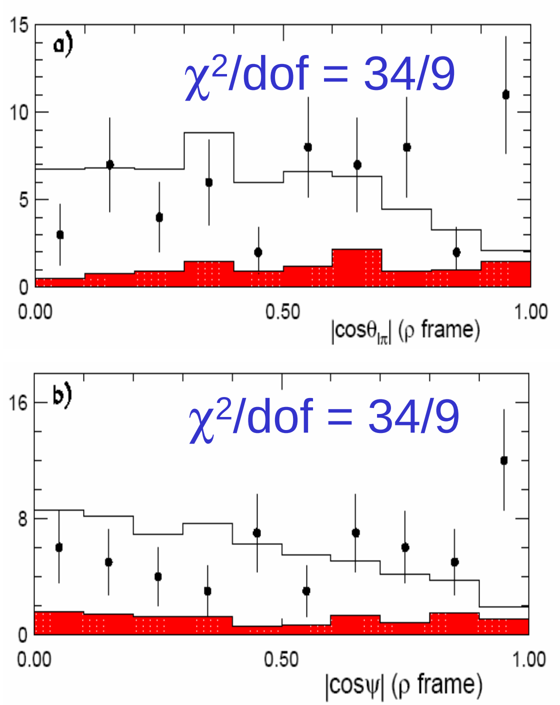
Total recorded luminosity: ~530 fb^{-1} (1999-2008)

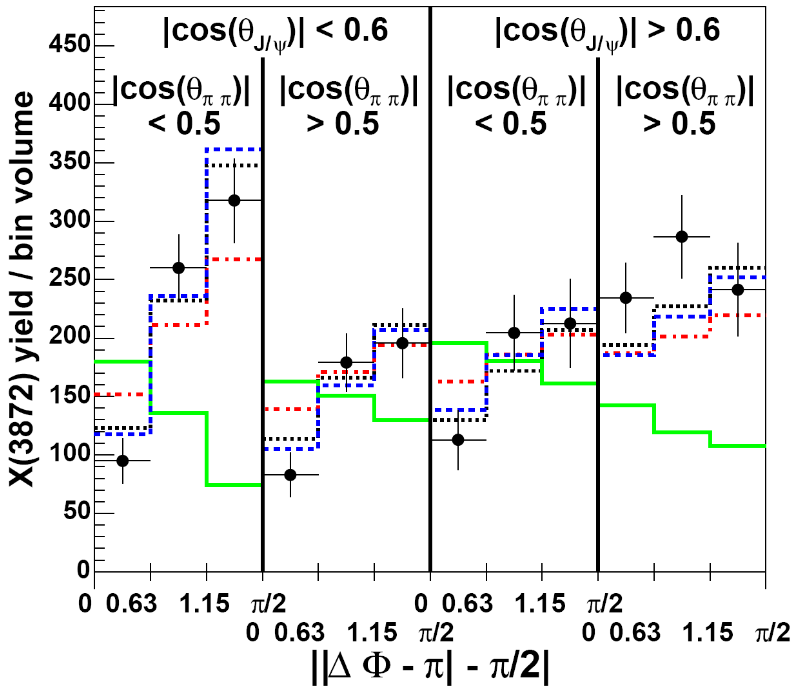
X(3872) - angular distribution

0^{++} and 0^{-+} ruled out by Belle

1^{++} and 2^{-+} favored by CDF







$J^{PC} = 0^{++}, 1^{++}, 2^{-+}, 1^{--}$

hep-ex/0505038

PRL 96, 102002 (2006)

A family of new states

(not presented in this talk)