Recent results on charm and charmonium from BaBar.

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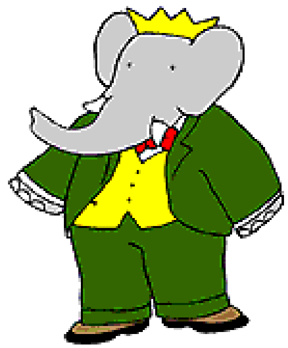
representing the BaBar Collaboration



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□ Outline:

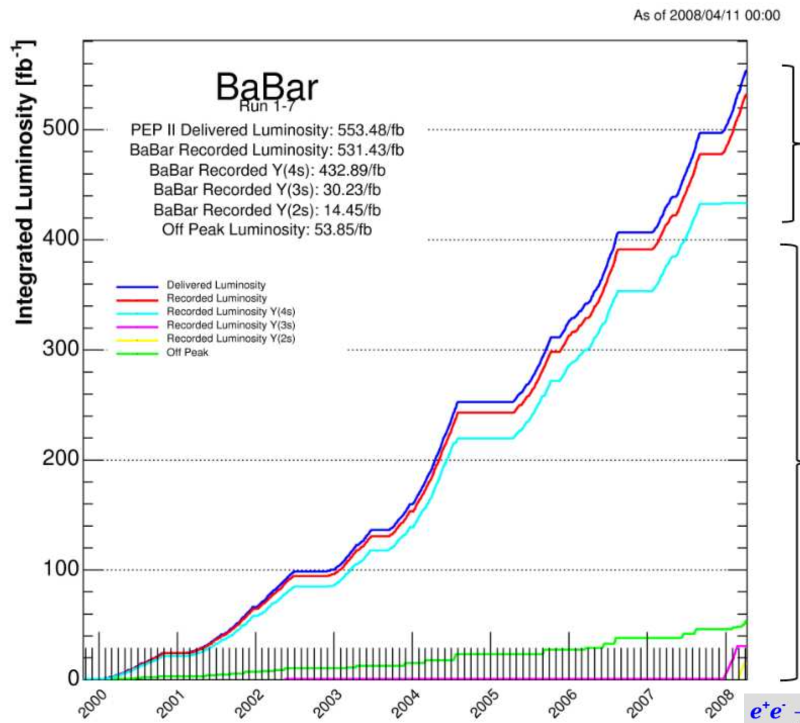
- Introduction: Charm and charmonium spectroscopy at B-factories.
- Selected recent results:
  - Charm: Search for CP violation in D^0 decays.
  - Charmonium: Observation of $\gamma\gamma \to \chi_{c2}(3940) \to D\bar{D}$.
  - Charmonium: Observation of $X(3872) \to J/\psi\omega$.
  - Charged Charmonium?

QCD@Work 2010 - Beppe Nardulli memorial workshop - Martina Franca, Italy, June 20-23

Introduction. Charm physics at BaBar. Integrated luminosity.

□ The cross section for $e^+e^- \to c\bar{c}$ is large.

$e^+e^- \to$	σ nb
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	$\approx$ 40

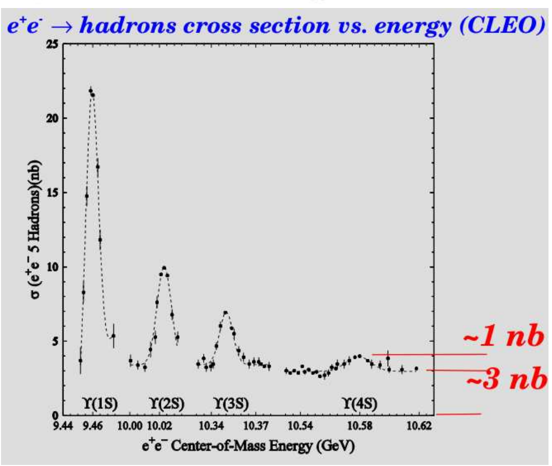


122 M Υ(3S)
100 M Υ(2S)

465 M Υ(4S)→BB pairs

1 fb^{-1} ~ 10^6 $B\bar{B}$, $c\bar{c}$, $\tau^+\tau^-$

Scan of the Υ's region.



□ Charm physics performed using two different processes:

· Inclusive $e^+e^- \to c\bar{c}$.

Selected by the request $p^*(charm) > 2.5$ GeV/c.

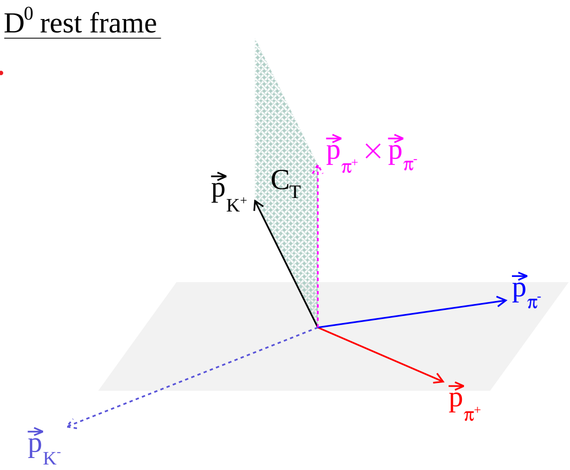
· Exclusive B decays.

Search for CP violation in Cabibbo Suppressed D^0 decays.

☐ The Standard Model allows for CP violation in Cabibbo Suppressed D decays at level of ≈ 0.1 %.
☐ $D^0 \to K^+K^-\pi^+\pi^-$ is the CS decay having the largest branching fraction and four different decay particles.
☐ Using momenta of the decay particles calculated in the D^0 rest frame, we define the triple product correlations C_T and $\overline{C}_T$ as:

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \qquad \overline{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

☐ The product is odd under time-reversal (T) and, assuming the CPT theorem, T-violation is a signal for CP-violation.



☐ We evaluate:

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

where Γ is the decay rate for the process.
☐ Strong interaction dynamics can produce a non-zero value of the A_T asymmetry, even if the weak phases are zero.
☐ Defining as $\overline{A}_T$ the T-odd asymmetry measured in the CP-conjugate decay process

$$\overline{A}_T \equiv \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)}$$

we can construct:

$$\mathcal{A}_{\mathcal{T}} = \frac{1}{2}(A_T - \overline{A_T})$$

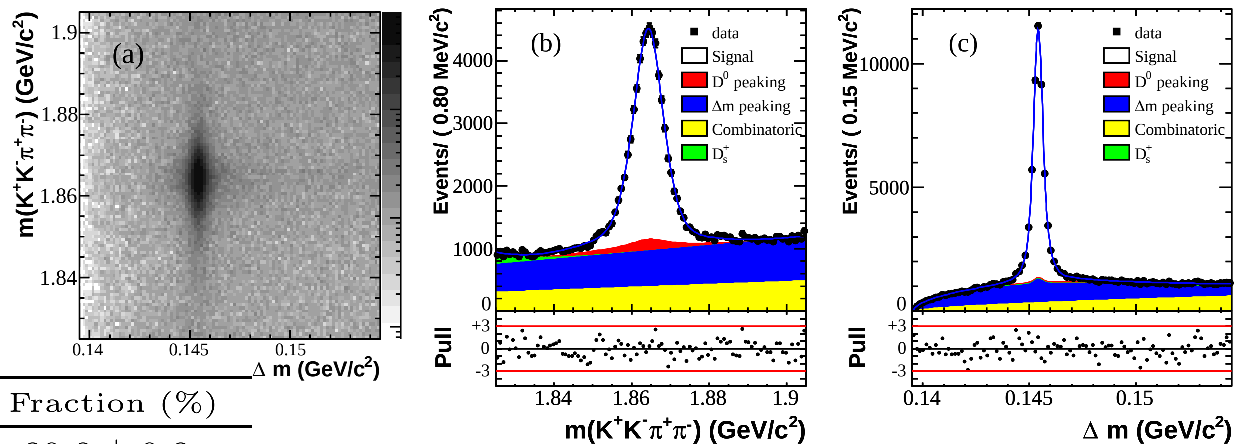
Which is a true T violating process.

Search for CP violation in Cabibbo Suppressed D^0 decays.

- Using 470 fb^{-1}, we study the reaction (arXiv:1003.3397, accepted by Phys. Rev. D (RC)):

$$e^+e^- \to XD^{*+} \to \pi_s^+ D^0 \to K^+K^-\pi^+\pi^-$$

- We require $p^* > 2.5$ GeV/c and remove $D^0 \to K_S^0 K^+ K^-$.
- We define $\Delta m \equiv m(K^+K^-\pi^+\pi^-\pi_s^+) - m(K^+K^-\pi^+\pi^-)$, and plot the 2-D distribution $(m(K^+K^-\pi^+\pi^-))$ *vs* Δm:



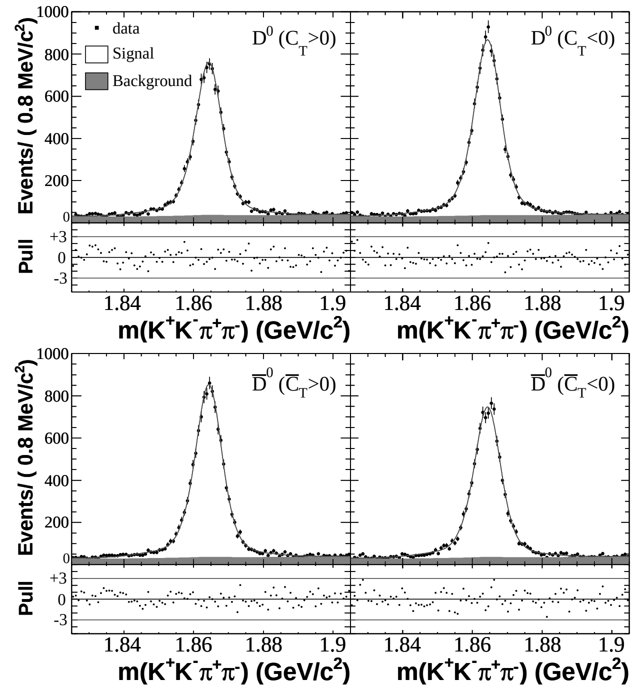
- The distribution has been fit using 5 different categories.

Category	Events	Fraction (%)
1. Signal	46691 ± 241	30.8 ± 0.3
2. D^0 peaking	5178 ± 331	3.4 ± 0.2
3. Δm peaking	57099 ± 797	37.7 ± 0.6
4. Combinatoric	40512 ± 818	26.7 ± 0.6
5. D_s^+	2023 ± 156	1.3 ± 0.1
Total	151503 ± 1223	

Search for CP violation in Cabibbo Suppressed D^0 decays.

☐ Data split in 4 C_T different subsamples. Projections in the D^{*+} cut.

Subsample	Events
(a) D^0, $C_T > 0$	10974 ± 117
(b) D^0, $C_T < 0$	12587 ± 125
(c) $\overline{D}^0$, $\overline{C}_T > 0$	10749 ± 116
(d) $\overline{D}^0$, $\overline{C}_T < 0$	12380 ± 124



☐ Systematic uncertainties in units of 10^{-3}.

Effect	$\mathcal{A}_T$	A_T	$\overline{A}_T$
1. Alternative signal PDF	0.2	0.3	0.2
2. Alternative misreconstructed D^0 PDF	0.5	0.1	0.9
3. Bin size	0.2	0.4	0.3
4. Particle identification	3.5	4.2	2.9
5. $p^*(D^0)$ cut	1.7	1.6	2.4
6. $\cos\theta^*$ dependence	0.9	0.0	0.2
7. Fit bias	1.4	3.0	0.3
8. Mistag	0.0	0.0	0.0
9. Detector asymmetry	1.1	2.1	0.0
Total	4.4	5.8	3.9

☐ We obtain:

$$A_T = (-68.5 \pm 7.3_{\rm stat} \pm 5.8_{\rm syst}) \times 10^{-3},$$

$$\overline{A}_T = (-70.5 \pm 7.3_{\rm stat} \pm 3.9_{\rm syst}) \times 10^{-3}$$

☐ Final state interactions effects have an important role in these decays.

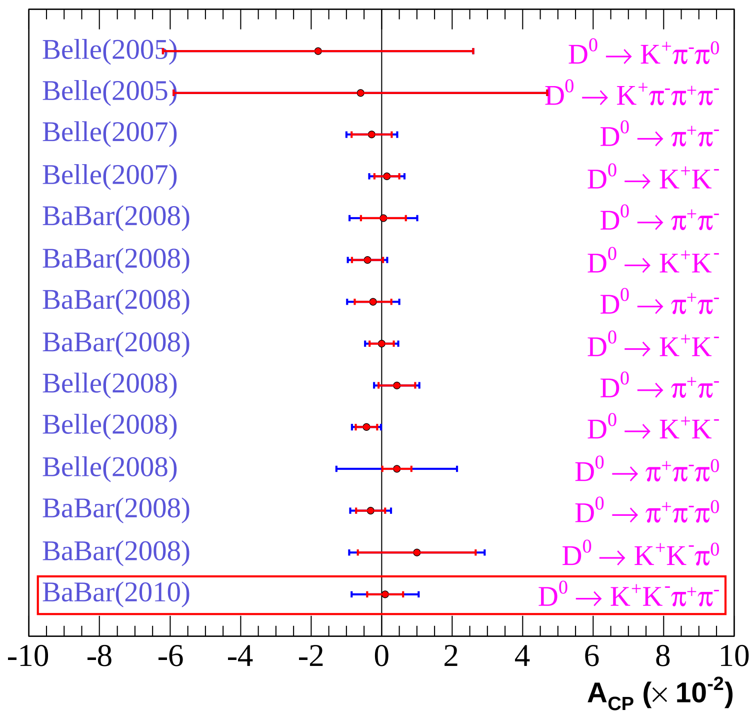
Search for CP violation in Cabibbo Suppressed D^0 decays.

□ The result for the *CP* violation parameter, $\mathcal{A}_T$, is:

$$\mathcal{A}_T = (1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}.$$

□ Consistent with zero. However the Sensitivity reached by Babar with this technique falls in a region where *CP* violation could start to show up.

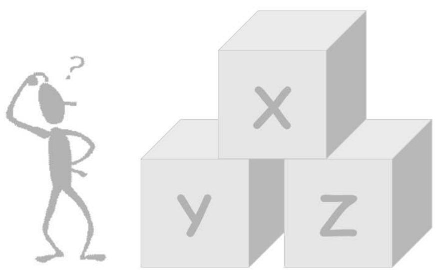
□ Summary of the *CP* violation searches using different techniques: Direct, Dalitz analysis, *CP* violation in Mixing, and finally T-odd correlations.

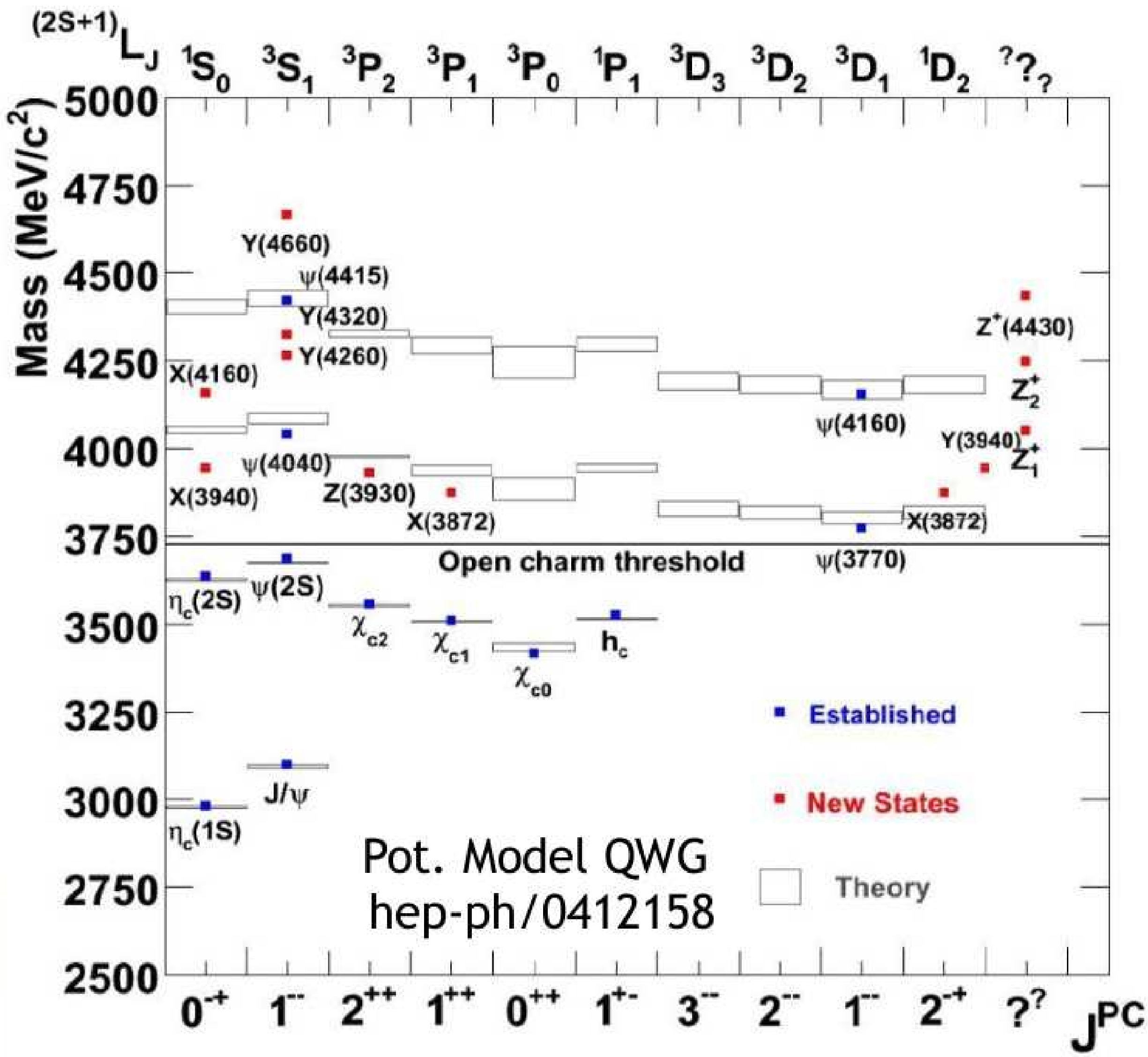


Charmonium physics.

□ Charmonium spectroscopy is expanding a lot after the B-factories discoveries of many new charmonium states.

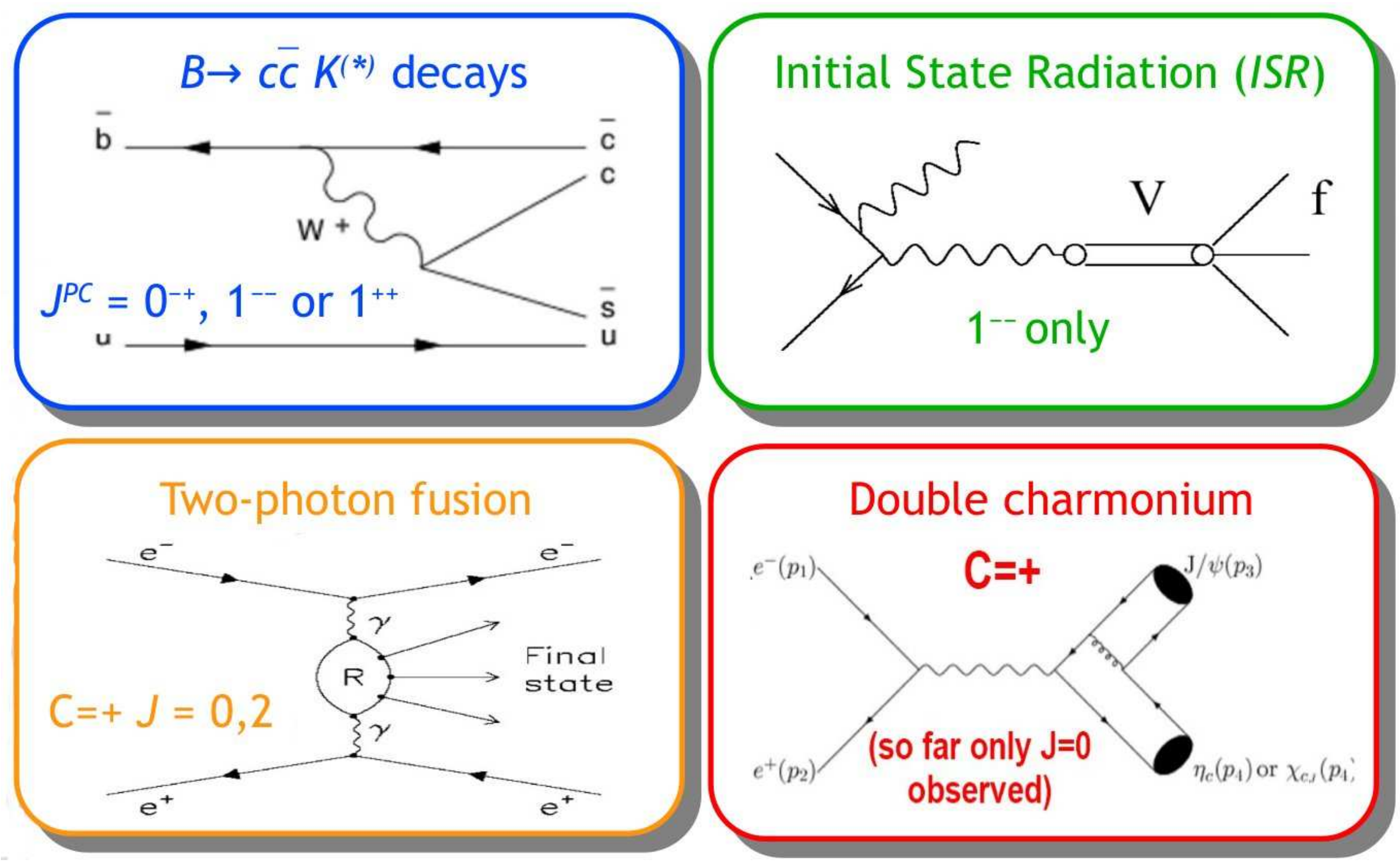
□ Not clear if all these states can be accomodated in the standard quark model.





Charmonium physics at B-factories.

□ Charmonium physics is studied using several processes.



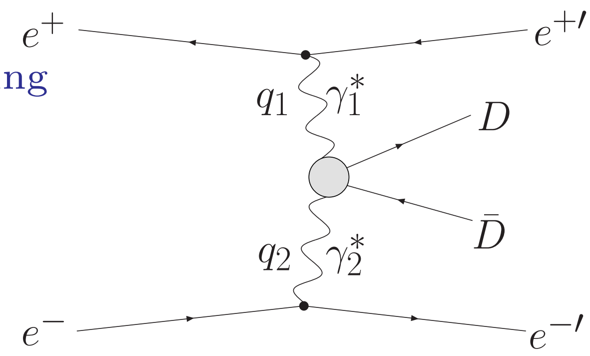
Observation of $\gamma\gamma \to Z(3930)$.

□ Two-photon collisions are a rich source of charmonium states.

□ At B-factories the two scattered electrons are not detected and therefore q is small and the photons are quasi-real. Yang's theorem forbids the production of spin-1 states.

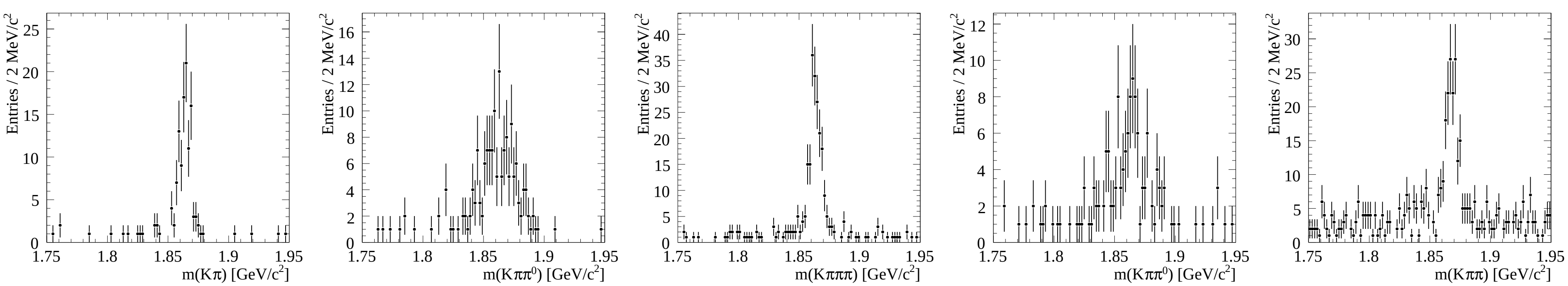
□ Belle first observed the $\chi_{c2}(2P)(3930)$ candidate in $\gamma\gamma \to D\bar{D}$.(Phys.Rev.Lett.96:082003,2006)

□ We search for this state in BaBar with 384 fb^{-1} using the following $D\bar{D}$ decay modes.(Phys. Rev. D 81, 092003, 2010)



Channel		D decay mode	$\overline{D}$ decay mode
N4	$D^0\overline{D}^0$	$D^0 \to K^-\pi^+$	$\overline{D}^0 \to K^+\pi^-$
N5	$D^0\overline{D}^0$	$D^0 \to K^-\pi^+$	$\overline{D}^0 \to K^+\pi^-\pi^0$
N6	$D^0\overline{D}^0$	$D^0 \to K^-\pi^+$	$\overline{D}^0 \to K^+\pi^-\pi^-\pi^+$
N7	$D^0\overline{D}^0$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$\overline{D}^0 \to K^+\pi^-\pi^0$
C6	D^+D^-	$D^+ \to K^-\pi^+\pi^+$	$D^- \to K^+\pi^-\pi^-$

□ D signals.

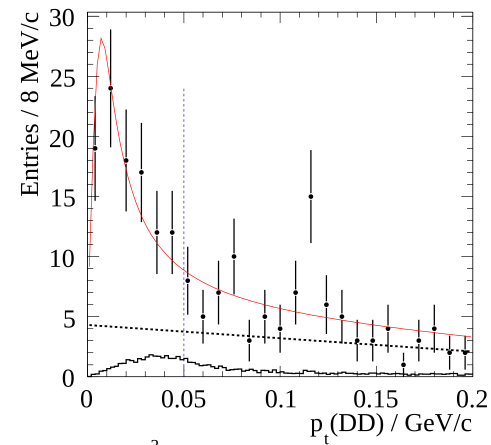


Observation of $\gamma\gamma \to Z(3930)$.

□ Since the scattered electrons have high momentum and small angles, the $\gamma\gamma \to D\bar{D}$ final state is evidenced by the balance of p_t, the $D\bar{D}$ transverse momentum.

□ Distribution of $p_t(D\overline{D})$. The fitted lineshape consists of the expected $\gamma\gamma$ lineshape obtained from MC plus a linear background (dotted line).

□ The histogram shows the shape of the $p_t(D\overline{D})$ distribution from simulated $D^*\overline{D}$ events with missing π^0 or γ.



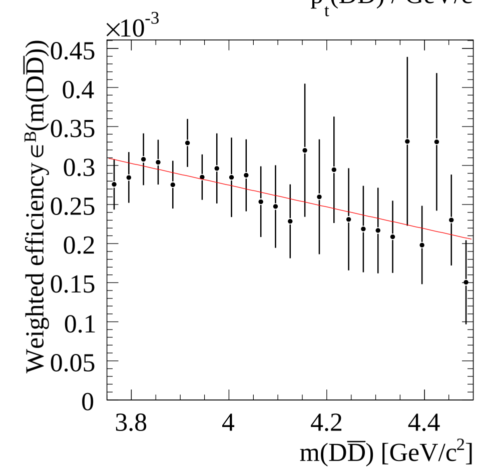
□ The weighted efficiency is defined as:

$$\epsilon^B(m(D\overline{D})) = \frac{5}{2}\frac{\sum_{i=1}^{5} N_i(m(D\overline{D}))}{\sum_{i=1}^{5}\frac{N_i(m(D\overline{D}))}{\epsilon_i^B(m(D\overline{D}))}}$$

where $N_i(m(D\overline{D}))$ is the number of $D\overline{D}$ candidates for channel i, and:

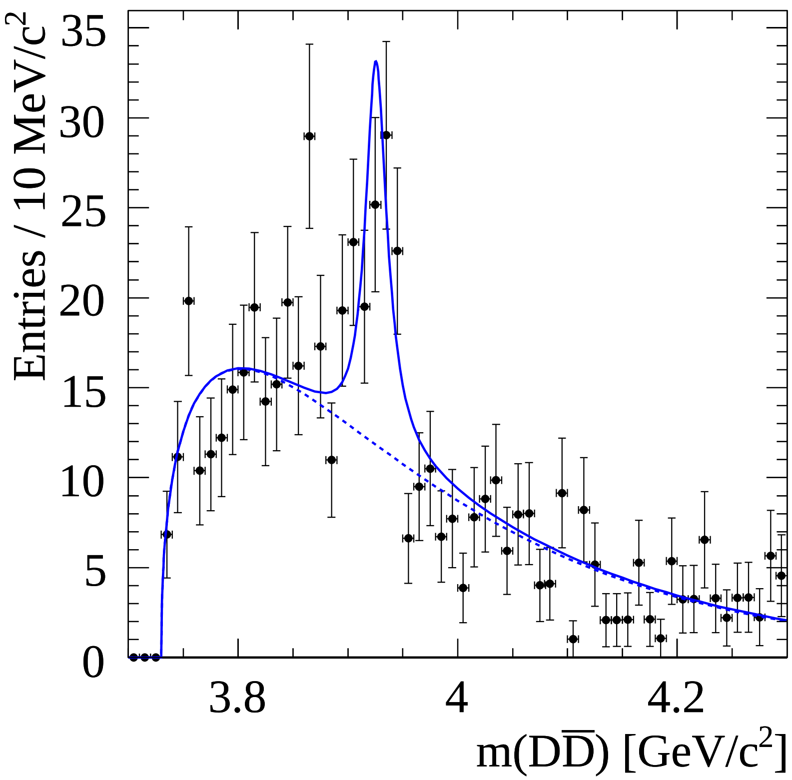
$$\epsilon_i^B(m(D\overline{D})) = \epsilon_i(m(D\overline{D})) \times \mathcal{B}_i$$

where ϵ_i is the efficiency and $\mathcal{B}_i$ is the branching fraction for channel i.



Observation of $\gamma\gamma \to Z(3930)$.

□ Efficiency-corrected $D\overline{D}$ mass distribution.
The dashed curve shows the background lineshape.



□ The mass and total width of the $Z(3930)$ state are measured to be:

$m = (3926.7 \pm 2.7(\text{stat}) \pm 1.1(\text{syst}))\ \text{MeV}/c^2$
$\Gamma = (21.3 \pm 6.8(\text{stat}) \pm 3.6(\text{syst}))\ \text{MeV}$

□ Fitted using a relativistic Breit-Wigner convoluted with a mass dependent resolution function.
□ Uncertainty on the mass scale 0.9 MeV/c^2.
□ Statistical significance: 5.8 σ

□ In agreement with the Belle measurements.

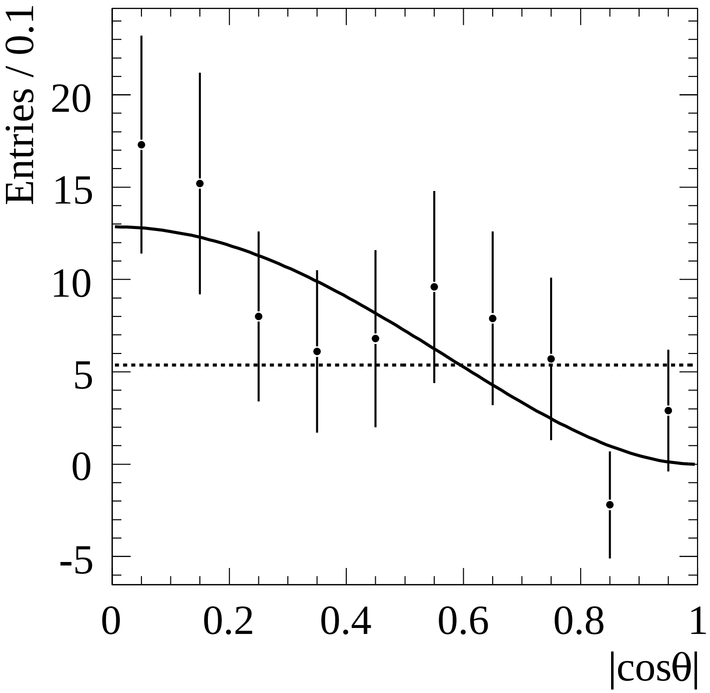
$Z(3930)$ angular analysis.

□ The decay angle θ is defined as the angle of the D meson in the $D\overline{D}$ system relative to the $D\overline{D}$ lab. momentum vector.

□ Signal yield as a function of $|\cos\theta|$ derived from fits to the efficiency-corrected $D\overline{D}$ spectrum.

□ Solid: spin 2 with dominating helicity-2 contribution.

□ Dotted straight line is for spin 0.



□ The production and decay mechanisms allow only positive C-parity and J=even.

□ The preferred assignment for spin and parity of the $Z(3930)$ state is therefore $J^{PC} = 2^{++}$.

□ Assuming spin $J = 2$, the product of the branching fraction to $D\overline{D}$ times the two-photon width of the $Z(3930)$ state is:

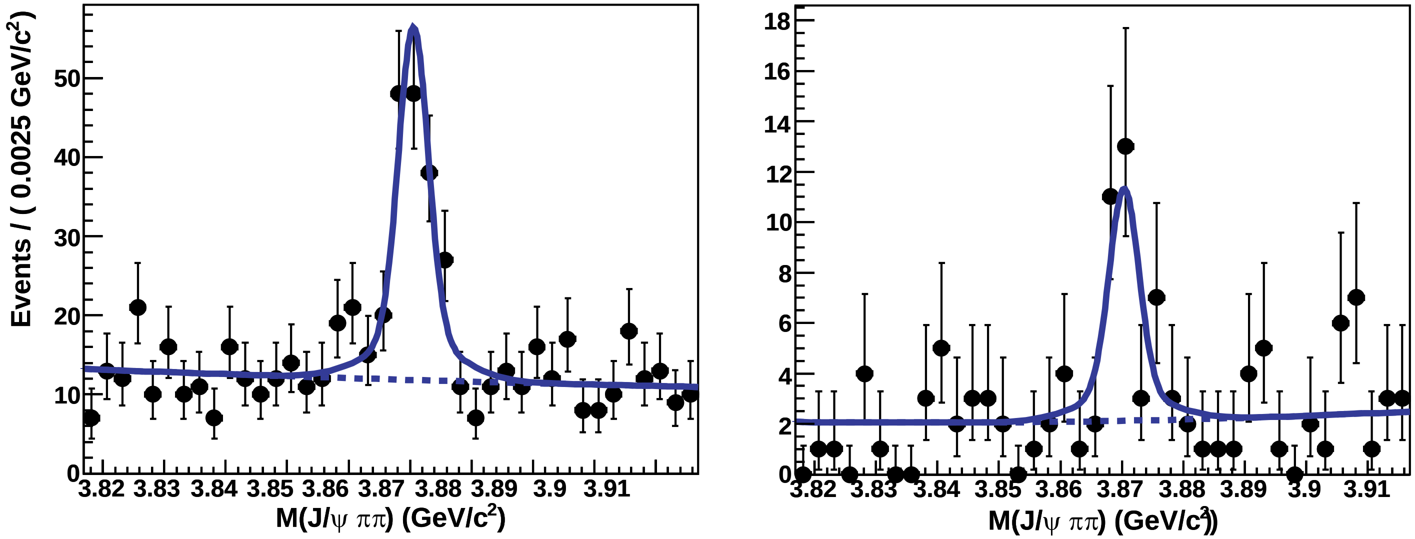
$$\Gamma_{\gamma\gamma} \times \mathcal{B}(Z(3930) \to D\overline{D}) = (0.24 \pm 0.05(\mathrm{stat}) \pm 0.04(\mathrm{syst}))\,\mathrm{keV}$$

□ The parameters obtained are consistent with the expectations for the $\chi_{c2}(2P)$ state.

New results on $X(3872)$.

- The $X(3872)$ was discovered by Belle in B decays and confirmed by BaBar, D0, and CDF.
- $J/\psi\pi^+\pi^-$ mass spectra from B decays associated to a charged and neutral kaon.

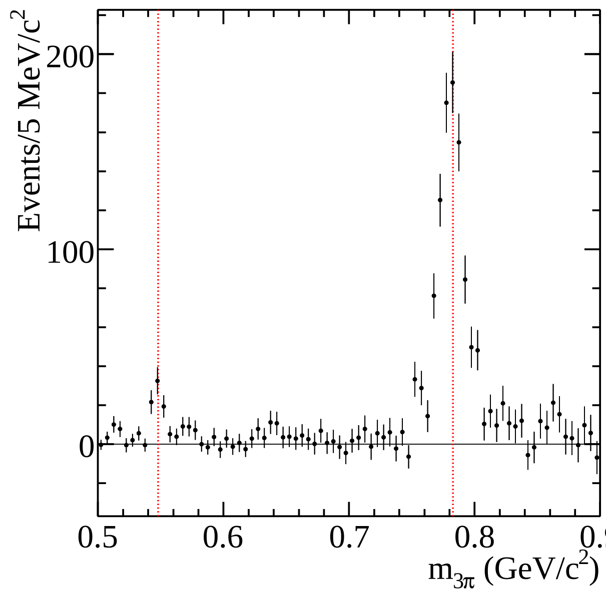
$$B^\pm \to J/\psi\pi^+\pi^- K^\pm \qquad\qquad B^0 \to J/\psi\pi^+\pi^- K^0_S$$

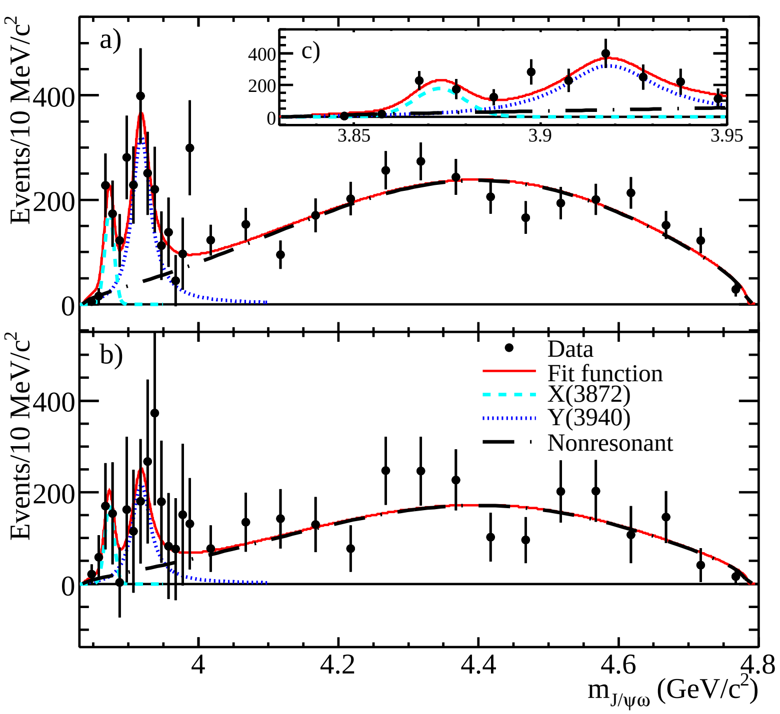


- Angular analysis from CDF favours $J^{PC} = 1^{++}$ and 2^{-+}.
- $X(3872)$ observed in $J/\psi\pi^+\pi^-$, $J/\psi\gamma$, $\psi(2S)\gamma$, and $D^{*0}\bar{D}^0$. Therefore C=+1.

Study of $B \to J/\psi\omega K$.

- BaBar: New analysis of $B \to J/\psi\pi^+\pi^-\pi^0 K$.
- Study of charged and neutral B decays. Fit the m_{ES} distribution in slices of $m_{3\pi}$.
- $m_{3\pi}$distribution for $B^+ \to J/\psi\pi^+\pi^-\pi^0 K^+$.
- Clear η and ω signals.
- Extend to a lower limit the cut on the mass of the ω.
- The corrected $m_{J/\psi\omega}$distribution for (a) B^+, (b) B^0 decays; (c)(inset) shows the low-mass region of (a) in detail.





Study of $B \to J/\psi\omega K$.

□ For the X meson, (4σ significance), the fitted mass is:

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

□ Mass and width values for the Y meson are:

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

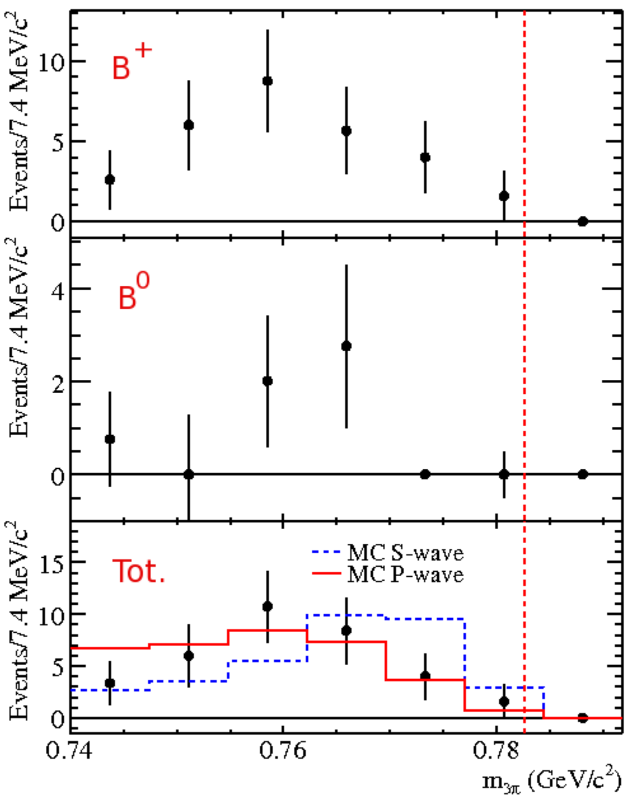
$$\Gamma_Y = 31^{+10}_{-8}(\text{stat}) \pm 5(\text{syst})\ \text{MeV}$$

□ The $m_{3\pi}$ distribution for events with $3.8625 < m_{J/\psi\omega} < 3.8825$ GeV/c^2 for B^+, B^0, and the combined distribution.

□ The solid (dashed) histogram represents reconstructed MC P-wave (S-wave) events normalized to the number of data events.

□ Branching fraction:

$$\frac{B(X \to J/\psi\omega)}{B(X \to J/\psi\pi^+\pi^-)} = (0.7 \pm 0.3(B^+)), (1.7 \pm 1.3(B^0))$$

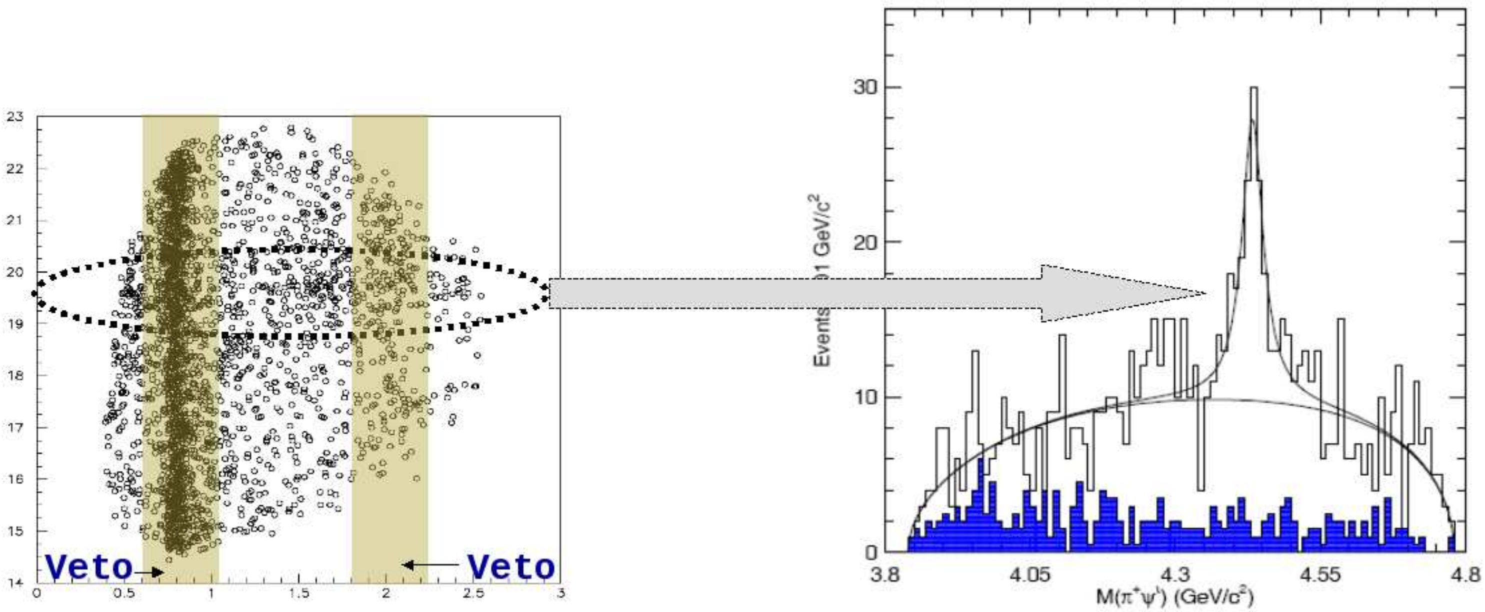


□ The inclusion of one unit of orbital angular momentum in the $J/\psi\omega$ system improves the description of the data.

□ This in turn implies negative parity for the X meson, and hence $J^P = 2^-$ is preferred (62 % against 7 %).

The charged "charmonium" state Z^+.

- **Belle**: Study of $B \to \psi(2S)K\pi$.
- Dalitz plot: $m^2(\psi(2S)\pi) vs. m^2(K\pi)$.
- Perform cuts on the Dalitz plot through a "K^* veto"



- Evidence for a resonance decaying to $\psi(2S)\pi^+$ with the following parameters:

$M = 4433 \pm 4 \pm 1$ MeV

$\Gamma = 44^{+17}_{-13}(stat)^{+30}_{-11}(sys)$ MeV

If true: First observation of an exotic non $q\bar{q}$ state.

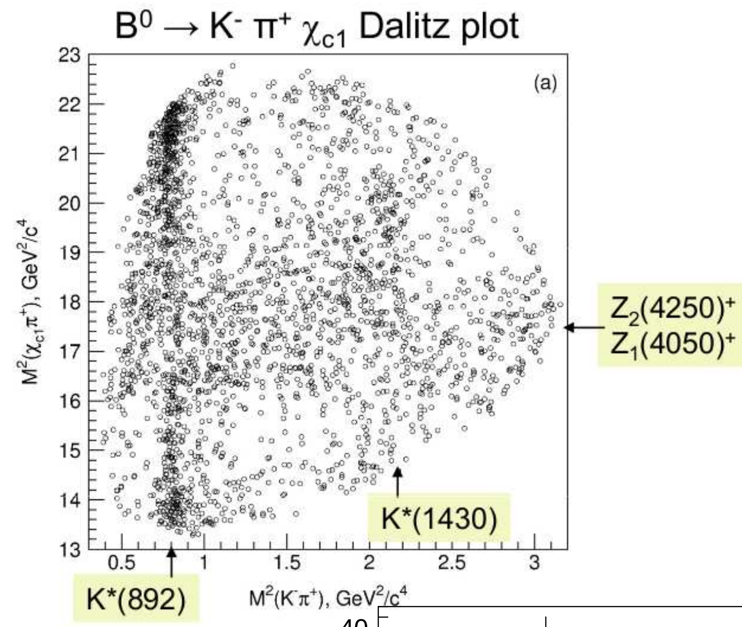
Still other Z^+ states.

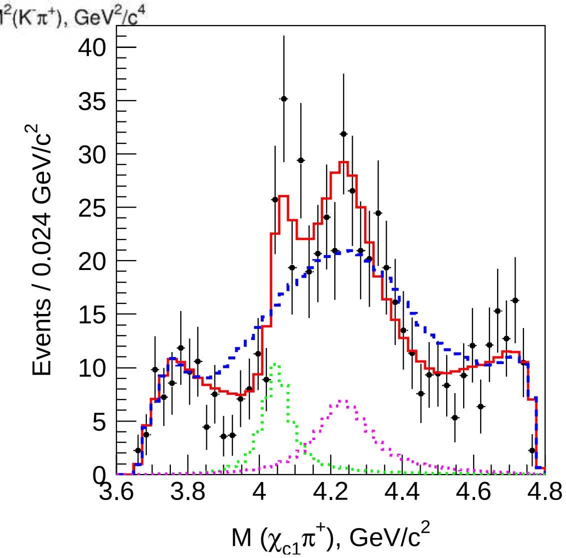
□ **Belle**: Study of $B^0 \to \chi_{c1} K^- \pi^+$.

□ Dalitz plot analysis: claim for two new states decaying to $\chi_{c1}\pi^+$.

□ The masses and widths of the two Z^+ resonances found from the fit are:

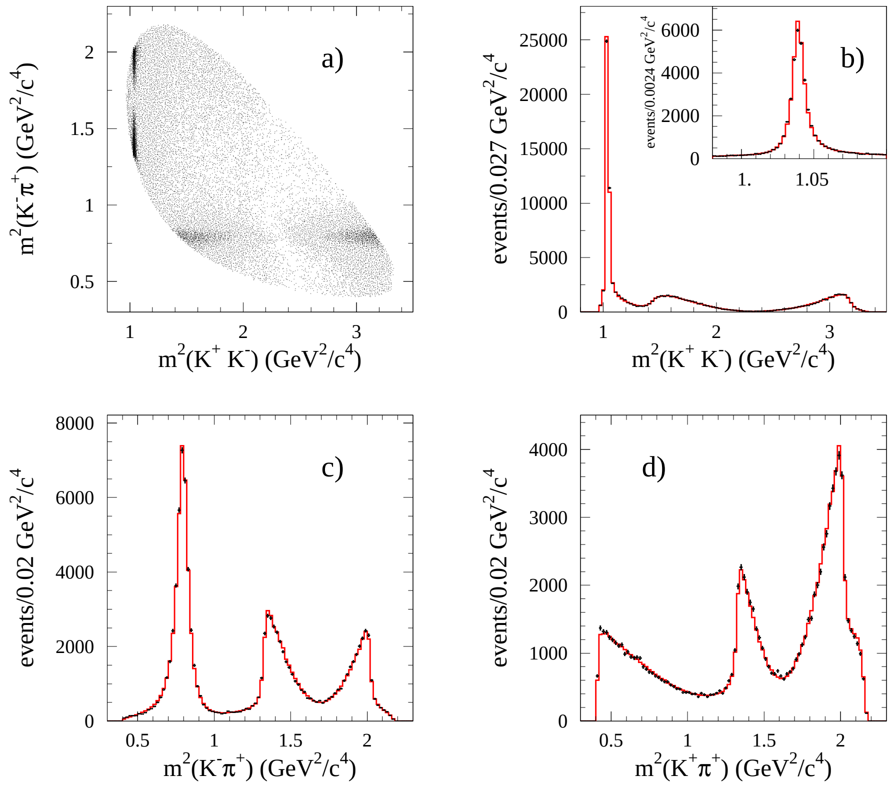
$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-\ 35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-\ 61})\ \mathrm{MeV}$$





The problem.

□ Example from D_s^+ decay.



□ Decay of a spin 0 particle through an isobar model:

$A \to a + R(\to b + c)$

where R has spin J. Angular momentum conservation and interference produces complex structures on the Dalitz plot.

□ Not all the structures in the projections are due to resonances.

BaBar search for Z^+.

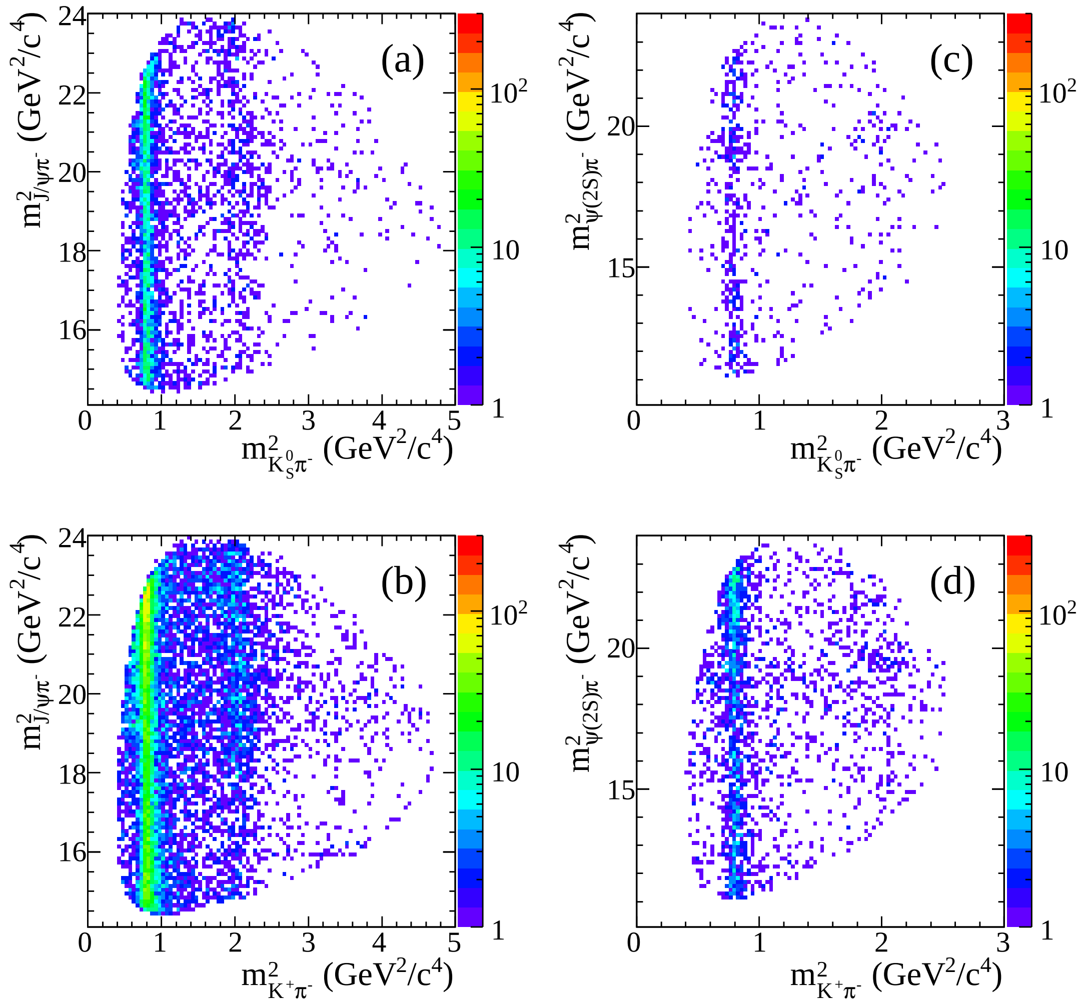
□ Study of (Phys.Rev.D 79 112001 (2009)):

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

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

$B^- \to \psi(2S) \pi^- K_S^0$

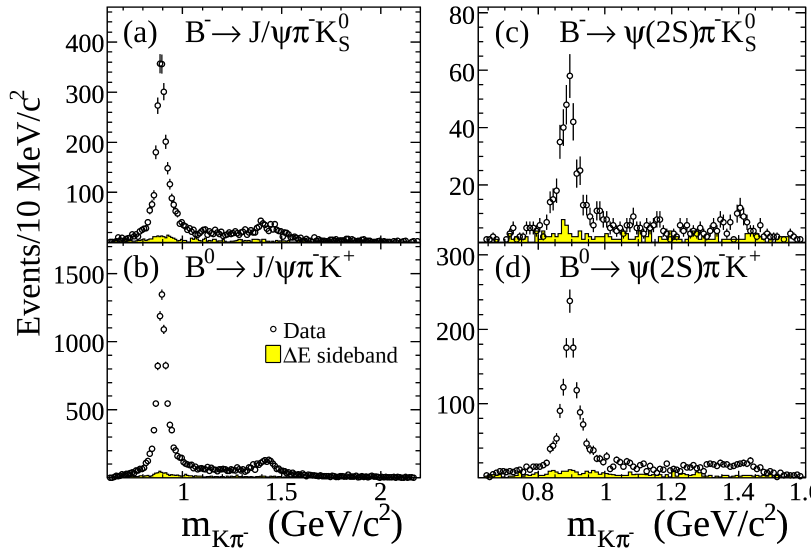
$B^0 \to \psi(2S) \pi^- K^+$



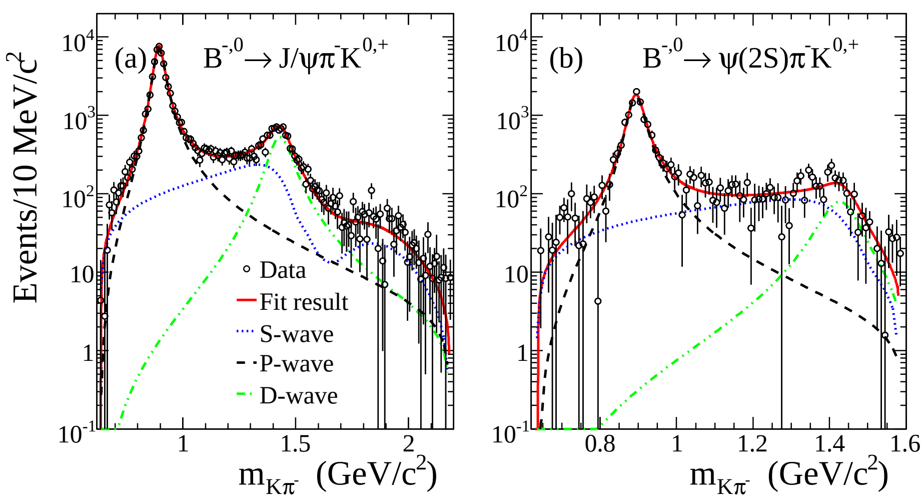
□ ψK mass spectra compatible with absence of any resonance.

BaBar search for Z^+.

- Compare $B \to J/\psi K\pi$ with $B \to \psi(2S)K\pi$.
- All the physics along the $K\pi$ axis.

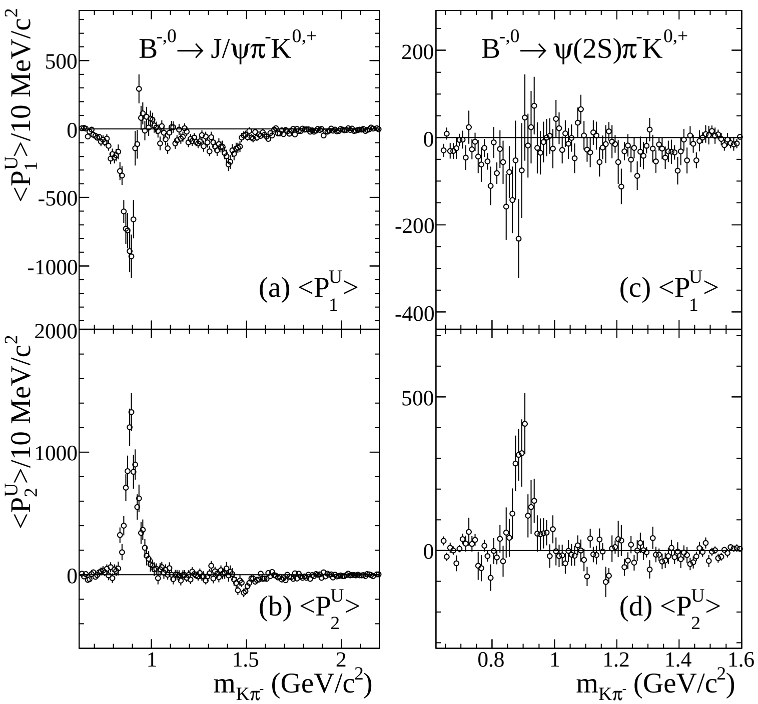


- Mass spectra fitted using known K^* resonances ($K^*(890)$, $K^*(1430)$, $K\pi$ S-wave).



BaBar search for Z^+.

- Angular information introduced through the P_L moments (Legendre Polynomials):
- Background subtracted and efficiency corrected.
- $B \to J/\psi K\pi$ data similar to those from $B \to \psi(2S)K\pi$.



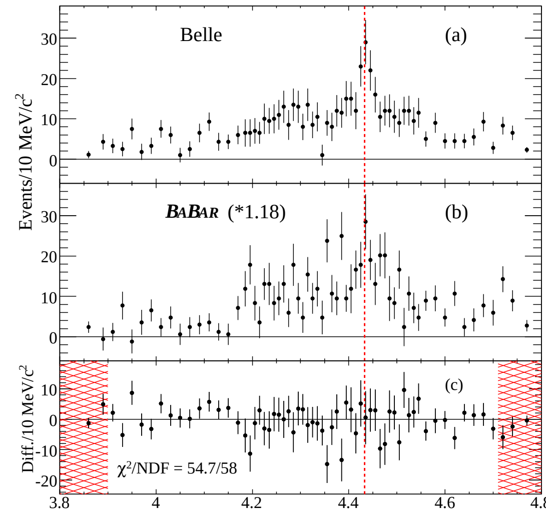
- Where:

$$N = S_0^2 + P_0^2 + D_0^2$$
$$\langle P_1 \rangle = S_0 P_0 \cos(\delta_{S_0} - \delta_{P_0}) + 2\sqrt{\frac{2}{5}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0})$$
$$\langle P_2 \rangle = \sqrt{\frac{2}{5}} P_0^2 + \frac{\sqrt{10}}{7} D_0^2 + \sqrt{2} S_0 D_0 \cos(\delta_{S_0} - \delta_{D_0})$$
$$\langle P_3 \rangle = 3\sqrt{\frac{6}{35}} P_0 D_0 \cos(\delta_{P_0} - \delta_{D_0})$$
$$\langle P_4 \rangle = \frac{3\sqrt{2}}{7} D_0^2$$

- S_0, P_0, and D_0 are amplitudes with helicity 0.
- The above system cannot be solved directly because of the presence of more unknown quantities than equations.

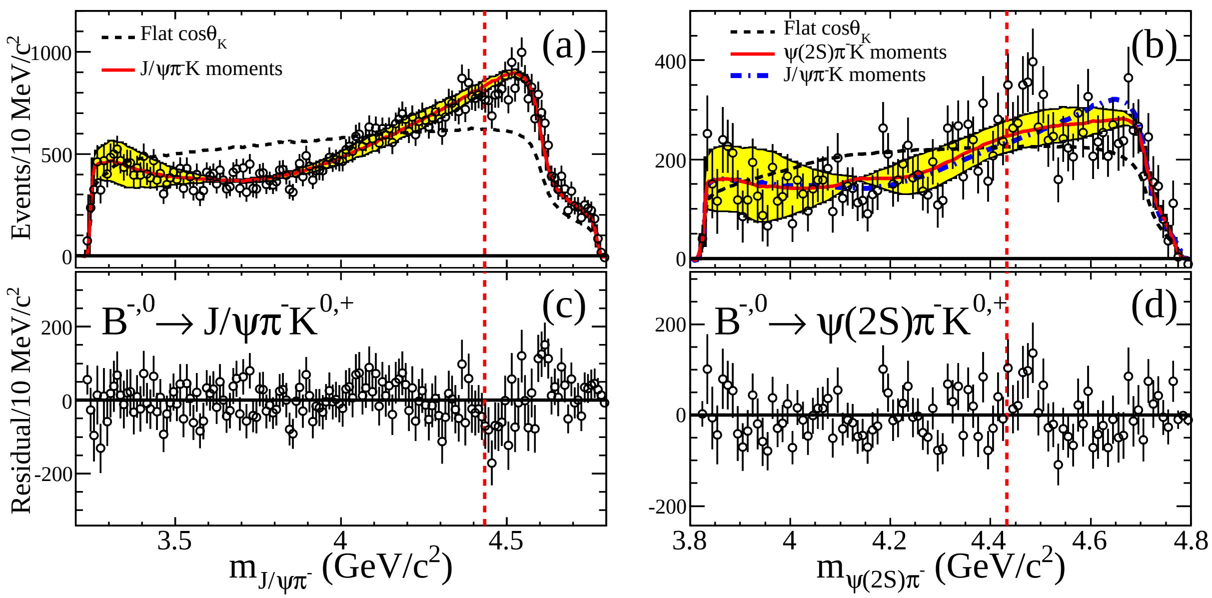
BaBar search for Z^+.

□ The $\psi(2S)\pi$ projections from BaBar and Belle are compatible.



□ Produce a Monte Carlo weighted by the resonant structure, efficiency, and angular moments.

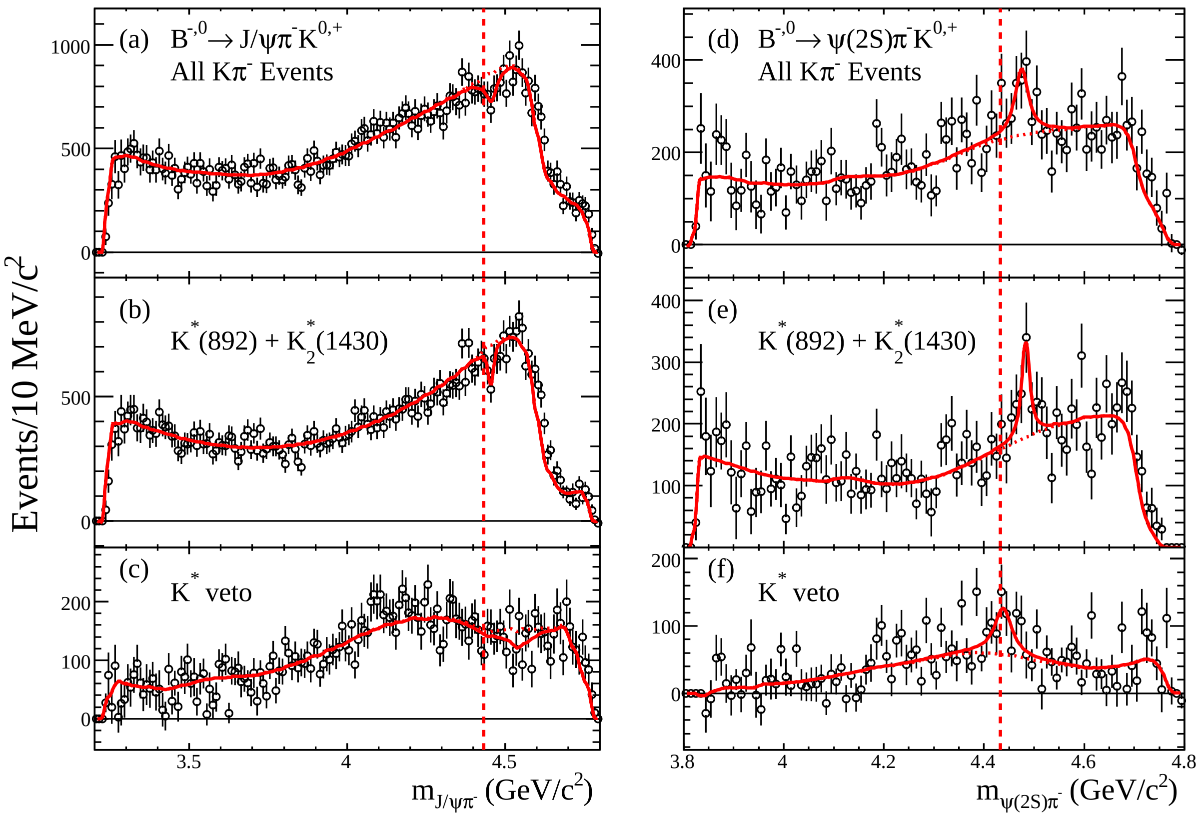
□ The effects on the $J/\psi\pi$ and $\psi(2S)\pi$ mass projections.



BaBar search for Z^+.

☐ Try to introduce a narrow resonance on top of these weighted distributions.

☐ Structures may appear in different regions of the Dalitz plot but not at the positions of the Belle resonance.



☐ Conclusion: No evidence for $Z^+ \to \psi(2S)\pi^+$. Maximum significance is $\approx 2\ \sigma$

Conclusions.

□ CP violation in charm is still a foundamental issue. Methods which minimize systematics have been developed such as T-odd correlations.

□ This strategy can be fully exploited at LHCB and SuperB.

□ CP violation in charm decays is a foundamental probe for New Physics.

□ The understanding of the Charmonium spectrum is still to come. Many new results. Room for exotics such as multiquark or hybrid states.

□ BaBar data analysis still in progress. New results are in preparation for summer conferences.