Radiative Transitions at Belle

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for the Belle Collaboration

ICHEP, July 23, 2010

Outline

1. Radiative Transitions of $\Upsilon(1S)$ to Charmonium-(like) States
   - $\Upsilon(1S) \to \gamma\chi_{cJ}(\to \gamma J/\psi)$
   - $\Upsilon(1S) \to \gamma X(3872)(\to \pi\pi\{\pi^0\}J/\psi)$
2. $X(3872)$ Production and Radiative Transitions
   - $X(3872)$ in $K(J/\psi\pi\pi)$
   - $X(3872) \to J/\psi\gamma$ and $X(3872) \to \psi'\gamma$
3. $1P \to 1S$ radiative transitions of D mesons
   - $D_1^0 \to D^0\gamma$

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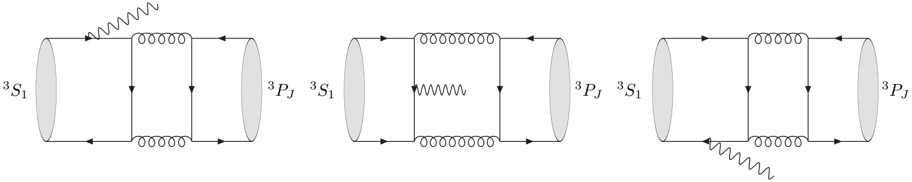
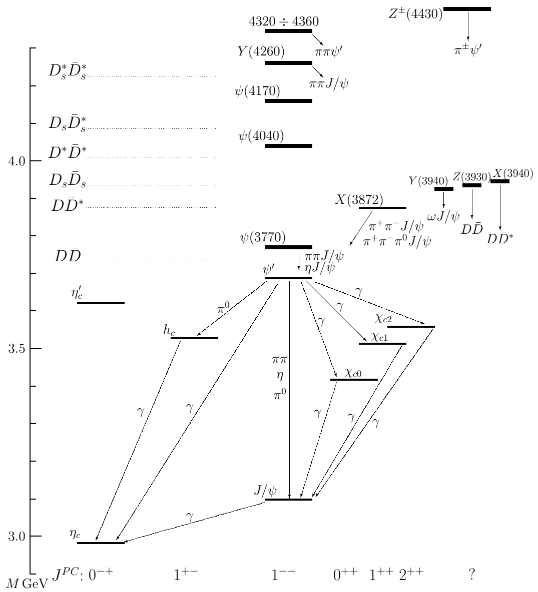
Radiative Transitions



- QED well-understood, QCD strong coupling at low *E* $\implies$ hard
- Radiative transitions described by QED
- Clean probe of the meson structure
- Heavy quark systems (i.e. *b* and *c* quark mesons) test NRQCD
  - Heavy quarks, non-relativistic bound states

Figure Reference: Gao et al., arxiv:hep-ph/0701009v2

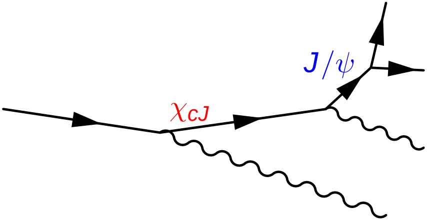
Charmonium ($c\bar{c}$)



- Until recently, charmonium thought to be well-understood
- Charmonium spectroscopy revived in wake of exotic *XYZ* states
- We study $b\bar{b} \to \gamma c\bar{c}$ transitions in $\Upsilon(1S)$

Figure reference: Voloshin, arxiv:0711.4556

Search Topology: $\Upsilon(1S) \to \gamma\chi_{cJ}(1P)$ and $\to \gamma\eta_c(1S)$



- Belle has collected 5.7fb^{-1} e^+e^- collision data at $\Upsilon(1S)$
  - Usually Belle runs at $\Upsilon(4S)$
  - 102×10^6 $\Upsilon(1S)$ events
- Use $\chi_{cJ} \to \gamma J/\psi$ ($\mathcal{B} \approx 1.3\%(\chi_{c0}), 36\%(\chi_{c1}), 20\%(\chi_{c2})$)
- Find $J/\psi \to ee/\mu\mu$ ($\mathcal{B} \approx 12\%$)
- Cuts to suppress Initial State Radiation (ISR) backgrounds
- η_c through $K_S K^+\pi^-$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$

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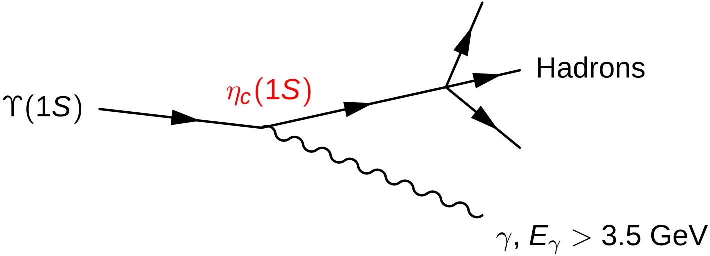

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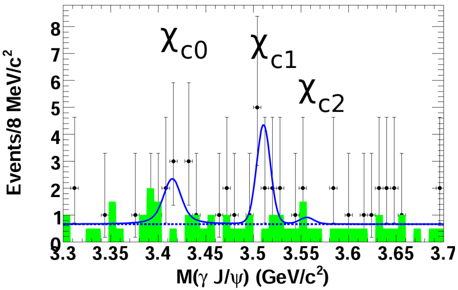
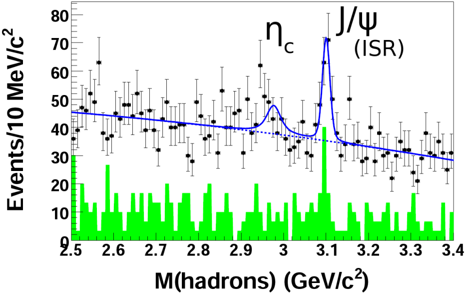
- η_c through $K_S K^+\pi^-$, $\pi^+\pi^- K^+K^-$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$

$\Upsilon(1S) \to \gamma R(\to \gamma J/\psi)$





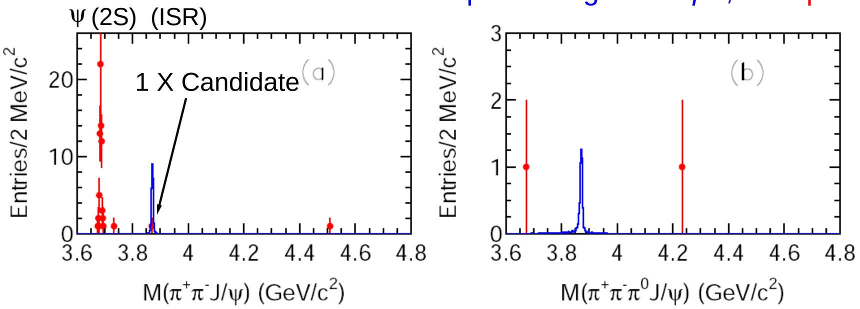
R	N_{sig}^{UP}	$\mathcal{B}^{UP}(10^{-5})$	Theory $\mathcal{B}^*(10^{-5})$
χ_{c0}	11.5	65	0.32
χ_{c1}	13.8	2.3	0.98
χ_{c2}	2.4	0.76	0.56
η_c	86	6.8	4.9

- Fit with fixed shapes, means
- 1.8fb^{-1} of continuum data (scaled)
- No significant signal
- Limits consistent with theory

Upper limits at 90% CL, * Gao et al., arxiv:hep-ph/0701009v2

$\Upsilon(1S) \to \gamma X(3872)(\to \pi\pi\{\pi^0\}J/\psi)$

Expected signal *shape*, data points



$\mathcal{B}(\Upsilon \to \gamma X(\pi\pi J/\psi)) < 2.2 \times 10^{-6}$

$\mathcal{B}(\Upsilon \to \gamma X(\pi\pi\pi^0 J/\psi)) < 3.9 \times 10^{-6}$

- Right, low mass event likely from ISR
  $ee \to \gamma_{ISR}\eta J/\psi \to \gamma_{ISR}\pi\pi\pi^0\ell\ell$
- Also searched for $Y(4140) \to \phi(K^+K^-)J/\psi(\ell^+\ell^-)$ no candidates:
  $\mathcal{B} < 2.4 \times 10^{-6}$

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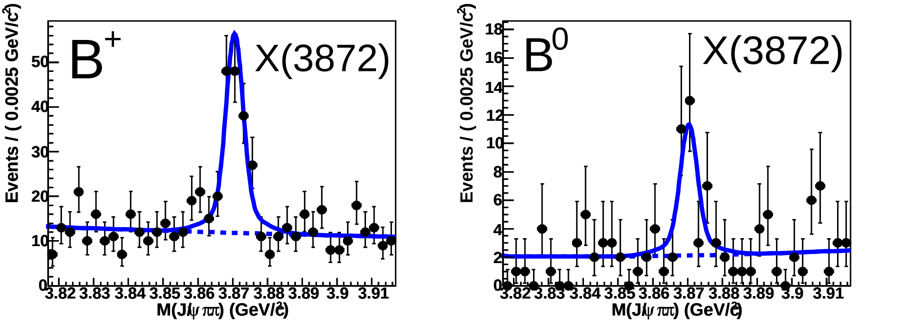
$B \to KX(3872)(\to J/\psi\pi\pi)$

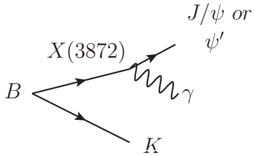
Belle preliminary results, 605 fb^{-1}, arXiv:0809.1224



- What is the $X(3872)$?
  - (Standard charmonium, diquark–anti-diquark, meson molecule, $q\bar{q}g$, etc.)
- $\mathcal{B}(B^+ \to K^+X(3872)(\to J/\psi\pi\pi)) = (8.10 \pm 0.92 \pm 0.66) \times 10^{-6}$
  $\mathcal{B}(B^0 \to K^0X(3872)(\to J/\psi\pi\pi)) = (6.65 \pm 1.63 \pm 0.55) \times 10^{-6}$
- M($X(3872)$) consistent in both channels to ≈ 1 MeV
  - Rules out certain models expecting a doublet

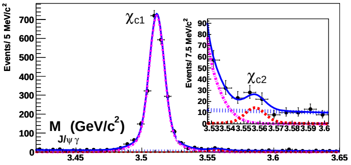
Radiative Modes of χ_{cJ} and $X(3872)$

Preliminary Results, http://belle.kek.jp/results/winter10/X_psigamma/

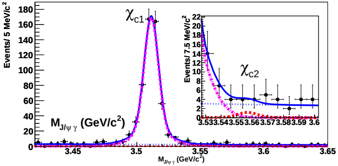


- Molecular model of $X(3872)$: $X \to \gamma\psi'$ suppressed w.r.t $X \to \gamma J/\psi$
- BaBar: $\frac{\mathcal{B}(X\to\psi'\gamma)}{\mathcal{B}(X\to J/\psi\gamma)} = 3.5 \pm 1.4$
- We use 712fb^{-1} of $\Upsilon(4S)$ data
- First, look at $B \to K\chi_{cJ}(\gamma J/\psi)$
- First evidence (3.6 σ) for $B^+ \to K^+\chi_{c2}(J/\psi\gamma)$

Mode	$\mathcal{B}$(Mode) (10^{-5})
$B^\pm \to \chi_{c1}K^\pm$	$49 \pm 1 \pm 3$
$B^\pm \to \chi_{c2}K^\pm$	$1.11^{+0.36}_{-0.34} \pm 0.09$



Mode	$\mathcal{B}$(Mode) (10^{-5})
$B^0 \to \chi_{c1}K^0$	$37.8^{+1.7}_{-1.6} \pm 3$
$B^0 \to \chi_{c2}K^0$	< 2.6 @ 90% CL



Radiative Modes of χ_{cJ} and $X(3872)$

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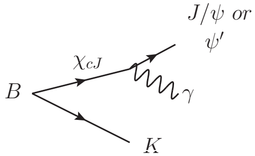

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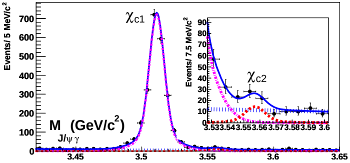

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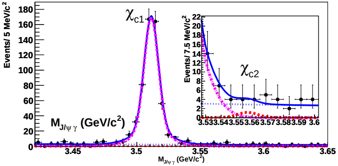


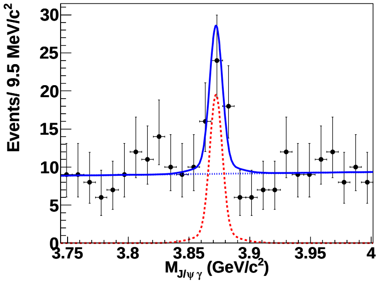
$B \to K\ X(3872)(\to J/\psi\gamma)$

Belle Preliminary Results, http://belle.kek.jp/results/winter10/X_psigamma/

Now look in the $X(3872)$ signal region of $M(J/\psi\gamma)$

$B^{\pm} \to K^{\pm}X(3872)(\to J/\psi\gamma)$

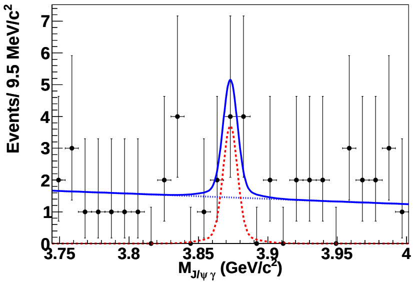
$$\mathcal{B} = (1.78^{+0.48}_{-0.44} \pm 0.12) \times 10^{-6}$$



BaBar*: $\mathcal{B} = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$
*PRL 102, 132001 (2009)

$B^0 \to K^0X(3872)(\to J/\psi\gamma)$

$$\mathcal{B} < 6.6 \times 10^{-6}\ (90\%CL)$$

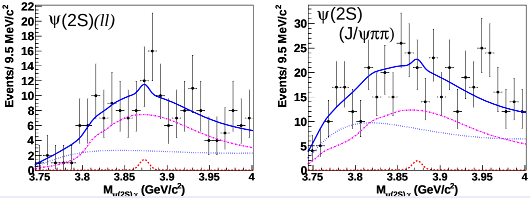


BaBar*: $\mathcal{B} < 4.9 \times 10^{-6}$

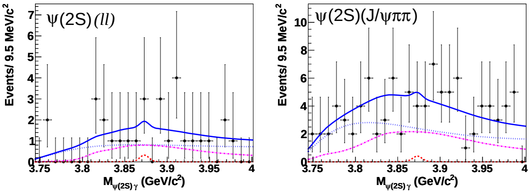
$B \to K\ X(3872)(\to \gamma\psi')$

Belle Preliminary Results, http://belle.kek.jp/results/winter10/X_psigamma/

$B^{\pm} \to K^{\pm}X$: $\mathcal{B}(B^{+} \to K^{+}X(3872)) < 3.4 \times 10^{-6}$

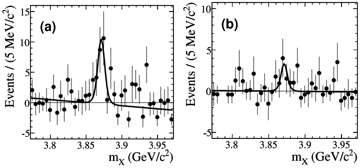


$B^{0} \to K^{0}_{S}X$: $\mathcal{B}(B^{)} \to K^{0}X(3872)) < 6.6 \times 10^{-6}$



- No signal observed
- Set the limits shown
- BaBar $_{s}$Plot fits:

$X(\psi'\gamma)K^{+}$ $\qquad$ $X(\psi'\gamma)K_{S}$



BaBar
$\mathcal{B}(B^{+} \to X(3872)(\psi'\gamma)K^{+}) =$
$(9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$
PRL 102, 132001 (2009)

X(3872) Signal, $\psi'K, \psi'K^{*}$ background, Combinatorial

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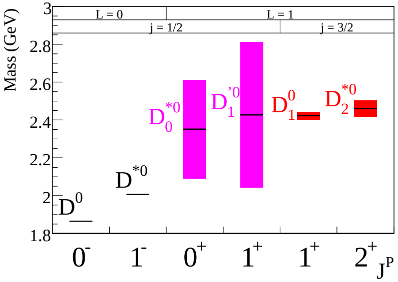
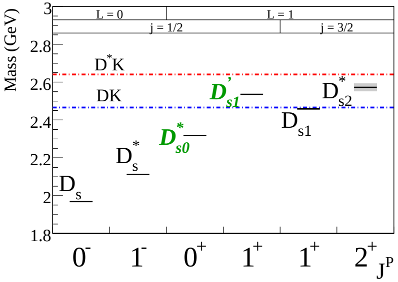
$1P \to 1S$ radiative transitions of D mesons



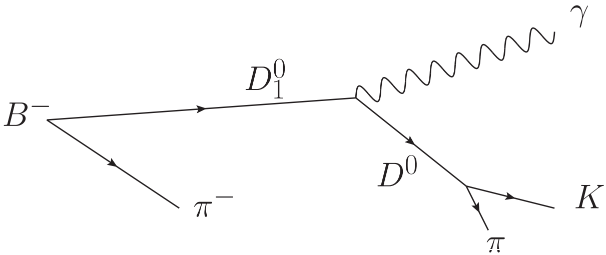


- Expected that D and D_s meson systems should have $\approx$ properties i.e. broad $j = 1/2$ doublet ($D_0^{*0}/D_1^{\prime 0}$) and narrow $j = 3/2$ doublet (D_2^{*0}/D_1^0)
- Found unexpected narrow D_s states below thresholds
- Use D^{**} ($L = 1$ D mesons) as a complementary test of theory
- Use the radiative transitions of D^{**} as a probe of the wavefunction

Search Strategy for $D_1^0 \to D^0\gamma$

$D_1^0 \to D^0\gamma$ golden mode

Large $\mathcal{B}$, $D_1^0 \to D^0\pi^0$ forbidden



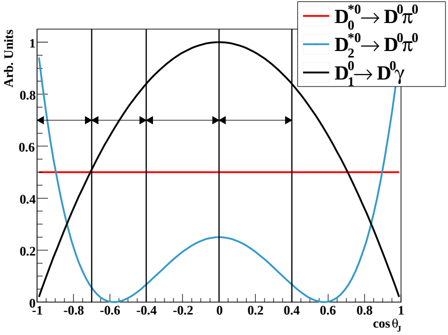
- Use standard $\Upsilon(4S) \to B\bar{B}$ variables
  $\Delta E = E_\text{B} - E_\text{beam}$ and
  $M_\text{bc} = \sqrt{E_\text{beam}^2 - p_B^2}$
- π^0 veto using decay angle $\cos\theta_\gamma$
- Bin in helicity angle of the D^0 w.r.t. D_1^0

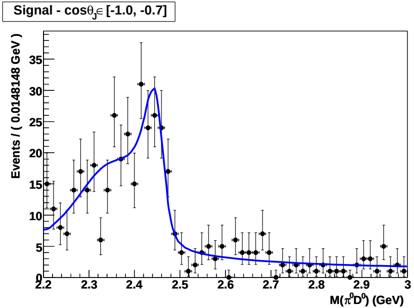
- Reconstruct through $D^0 \to K\pi$
- $\cos\theta_\text{thrust}$ cuts for continuum ($q\bar{q}$) suppression
- Fit resonance peak in $M(\gamma D^0)$

Disentangling γD^0 from $\pi^0 D^0$ Feed-down

Belle Preliminary Results

Most dangerous background is $D^{**} \to \pi^0 D^0$



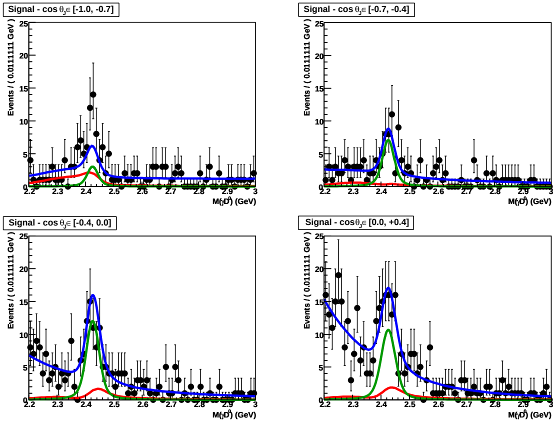


- (Left) Angular distributions of signal and feed-down (D_2^{*0}/D_0^{*0})
- Non-trivial shapes due to $D_{0/2}^{*0}$ interference (changes across helicity bins)
- Has component which peaks near signal resonance (right)
- Reconstruct and fit to $B^- \to \pi^- D^{**}(\to \pi^0 D^0)$ in helicity bins
- Fix feed-down background in $M(\gamma D^0)$ distribution

$D_1^0 \to D^0\gamma$ Final Fit in Helicity Bins

Belle Preliminary Results

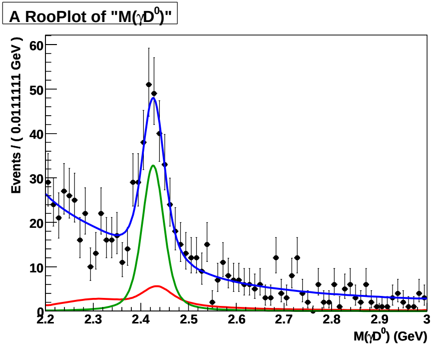
Cross-feed (fixed), signal



- 605 fb^{-1} $\Upsilon(4S)$ data
- Simultaneous fit to helicity bins
  - Signal yield, σ, μ floated
- Excess in backward bin (top-left)
  - Feed-down requires further study (see backup)
- Clear signal peak
- (Plan to look in $D^0 \to K3\pi$ also)

$D_1^0 \to D^0\gamma$, $D^0 \to K\pi$, Sum over Helicity Bins

Belle Preliminary Results



Overall fit
signal
D^{**} feed-down

$$\mathcal{B}(B^- \to D_1^0\pi^-) \times \mathcal{B}(D_1^0 \to D^0\gamma) = (5.0 \pm 0.5(stat.) \pm 1.5(sys.)) \times 10^{-5}$$

Corresponds to (using $\mathcal{B}(B^- \to \pi^- D_1^0) = 1.02 \cdot 10^{-3}$ and $\Gamma(D_1^0) = 20.4$ MeV)

Our measurement
$\mathcal{B}(D_1^0 \to \gamma D^0) = .050$

c.f. theory*:
$\mathcal{B}(D_1^0 \to \gamma D^0) = .028$

* Godfrey, PRD 72, 054029 (2005)

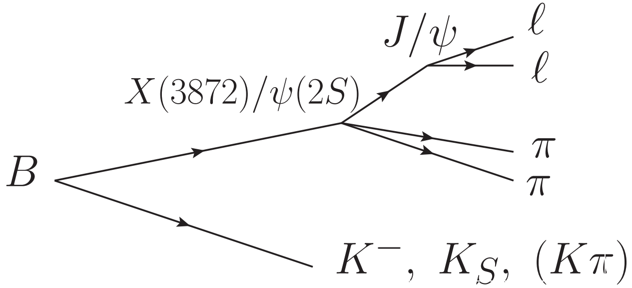
Conclusion

- Set limits for $\Upsilon(1S) \to \gamma$ Charmonium(-like) states (approaching theory predictions)
  - $\Upsilon(1S) \to \gamma\chi_{cJ}$
  - $\Upsilon(1S) \to \gamma\eta_c$
  - $\Upsilon(1S) \to \gamma X(3872)$
- Searched for $X(3872)$ Radiative Transitions
  - First observation of $B^+ \to K^+\chi_{c2}(\to \gamma J/\psi)$
  - Confirm observation of $X(3872) \to \gamma J/\psi$
  - No $X(3872) \to \gamma\psi'$ signal found
- First measurement of a $1P \to 1S$ D meson radiative transition
  - First observation of $D_1^0 \to D^0\gamma$
  - More work required on feed-down from $B^- \to \pi^-\pi^0 D^0$

Backup

Backup material

$B \to KX(3872)(\to J/\psi\pi\pi)$



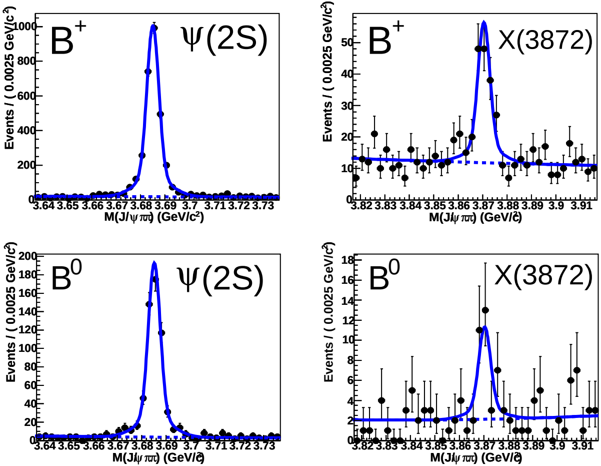
- Certain diquark/anti-diquark models have the X as one state in a doublet with mass difference δm
- Then, X from neutral B and charged B different states
- $\delta m = (7 \pm 2)/\cos\theta$ MeV. θ (mixing angle) $\approx 20^o$ (7.44 MeV)
- Cf $B^- \to K^- X(3872)(\to J/\psi\pi\pi)$ (Belle's discovery mode) and $B^0 \to K^0 X(3872)(\to J/\psi\pi\pi)$

$B \to KX(3872)(\to J/\psi\pi\pi)$

ψ' region in $M(J/\psi\pi\pi)$ — $X(3872)$ region

$B^- \to K^-(J/\psi\pi\pi)$

$B^0 \to K_S(J/\psi\pi\pi)$

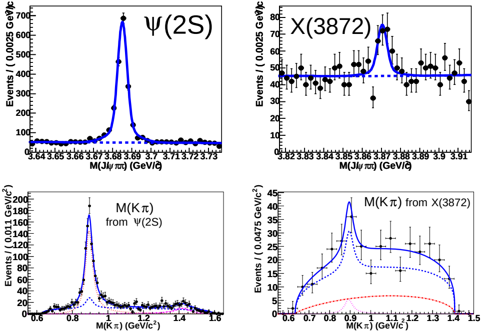


- First statistically significant observation of $B^0 \to K_S X(3872)$
- Mass difference between charged and neutral decays consistent with zero

$$\delta m = +0.18 \pm 0.89 \pm 0.26 \text{ MeV}, \quad \frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^- \to X(3872)K^-)} = 0.82 \pm .22 \pm .05$$

$B \to K^* X(3872)$

$$\mathcal{B}(B^0 \to (K\pi)_{NR} X(3872)) \times \mathcal{B}(X(3872) \to J/\psi\pi\pi) = (8 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$



$K^*(892)^0$ Non-resonant $K\pi$

$K_2^*(1430)^0$ $XK^*(892)^0$

Background

- $\mathcal{B}(B^0 \to K^*(892)^0 X(3872)) \times \mathcal{B}(X(3872) \to J/\psi\pi\pi) < 3.4 \times 10^{-6}$
- Non-resonant $(K\pi)$ unusual for charmonium
- ψ' shows the typical behaviour (K^* dominance also in $B \to J/\psi K\pi$ and $\chi_{c1}K\pi$)

$B \to KX(3872)(\to \gamma\psi')$: Main Analysis Features

Belle Analysis QWG '10 Talk by Vishal Bhardwaj

- $\psi' \to ee$ or $\mu\mu$ or $J/\psi\pi\pi$
- $E_\gamma > 100$ MeV
- $X(3872)$ from $\psi'\gamma$, B from $K^+X(3872)$ or $K_SX(3872)$
- ΔE and M_{bc} signal selection
- $B \to \psi' K^*$ veto. Look for additional $\pi^{0/+}$ to form K^*.

  Reject event if
  - $|\Delta E^{\psi' K^*}| < 20$ MeV
  - $M_{K\pi} \in (892 \pm 75)$ MeV
  - $M_{bc}^{\psi' K^*} > 5.27$ GeV
- Parameterize background functions from MC (using M_{bc}

  data sidebands to confirm understanding):
  - $B^0 \to \psi' K^{*0}$
  - $B^+ \to \psi' K^+$
  - $B^+ \to \psi' K^{*+}$
  - $B^0 \to \psi' K_S$
  - Combinatorial (with/without $\psi'/J/\psi$)
- Given BaBar $\mathcal{B}$, expect 24.1 ± 6.8 events in $B^+ \to K^+X(3872)$ channel, find $5.0^{+11.9}_{-11.0}$

Independent analysis (different selection/fitter) also performed on data sample, consistent result

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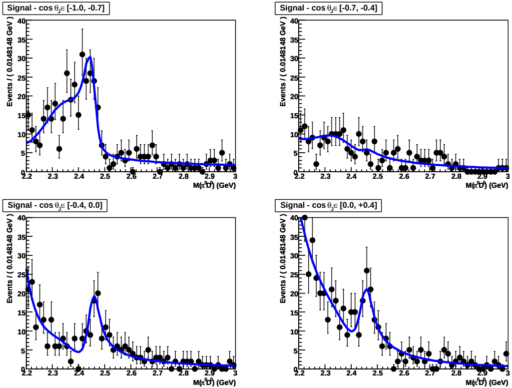
- $\psi' \to ee$ or $\mu\mu$ or $J/\psi\pi\pi$
- $E_\gamma > 100$ MeV
- Form $X(3872)$ from $\gamma\psi'$, B from $KX(3872)$
- Vertex constrain B daughters, cut on vertex prob., reconstructed M_B, $M_{miss} = \sqrt{(p_{e^+e^-} - p_B)^2/c^2}$ (p_B is B momenta when decay products constrained to B mass)
- Fit to M_{miss}, form $_sPlot$ of M_X
  - Crystal Ball function for signal
  - Non-peaking background with ARGUS function
  - Peaking background with shared Crystal Ball parameterisation from signal
- Fit to $_sPlot$ to obtain signal
  - Double gaussian for signal
  - Linear background function

$D^{**0} \to D^0\pi^0$in Data

Belle Preliminary Results



- Fit based on $|A|^2$ with resonance terms
- Terms for D_2^{*0} and D_0^{*0} in amplitude
- ρ interference not taken into account (so far)
- Parameters of low bin decoupled from upper bins