# Hot Topic from Belle : Recent results on quarkonia

Jolanta Brodzicka (Kraków)
on behalf of Belle

BEACH 2010
June 2010, Perugia

## Outline

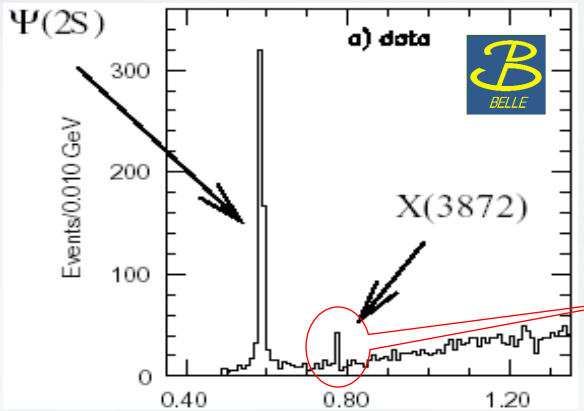
- Puzzling nature of X(3872)
- X(3872), $\chi_{c2} \to J/\psi\gamma$
- X(3872)$\to\psi'\gamma$
- Summary

Preliminary

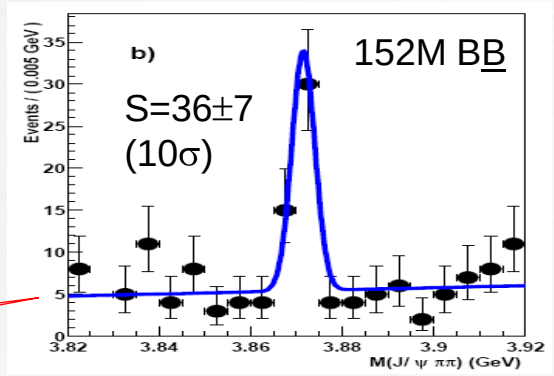
# Discovery of X(3872)

- **X(3872)→J/ψπ⁺π⁻ observed in B→X(3872)K by Belle**

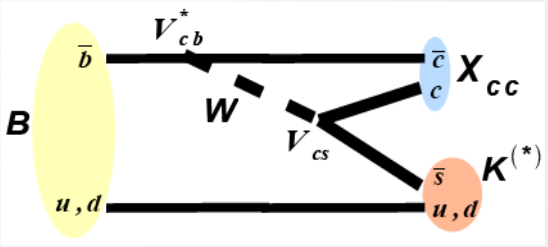
PRL91, 262001 (2003)




M(J/ψπ⁺π⁻)-M(J/ψ)

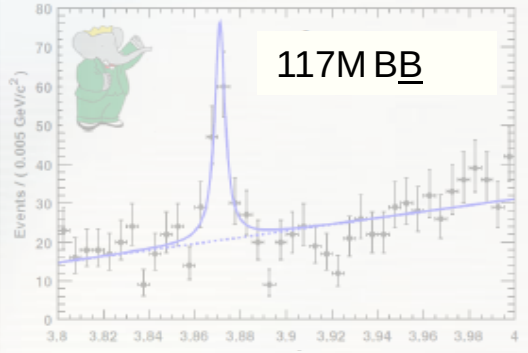



M(J/ψπ⁺π⁻)



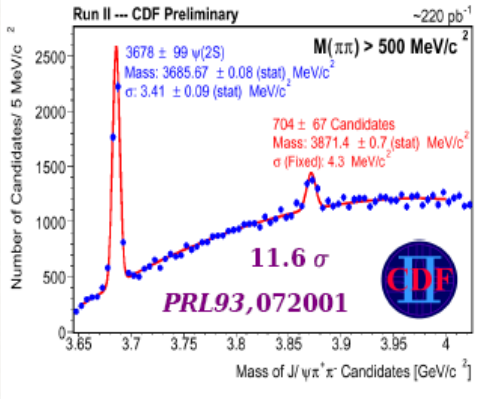

$$M_{X(3872)} = 3871.9 \pm 0.5\,\text{MeV}$$
$$\Gamma_{X(3872)} < 2.3\,\text{MeV}\ @\ 90\%\,\text{CL}$$

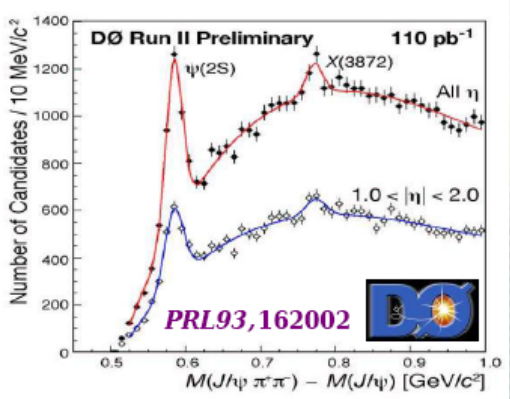
- **Confirmed by BaBar in B decays, CDF, DØ in pp→X(3872)+anything**




M(J/ψπ⁺π⁻)

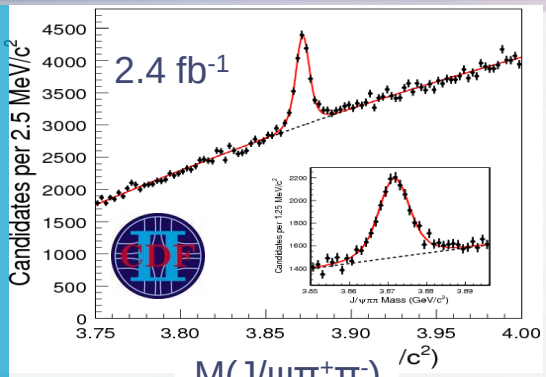
PRD71, 071103 (2005)

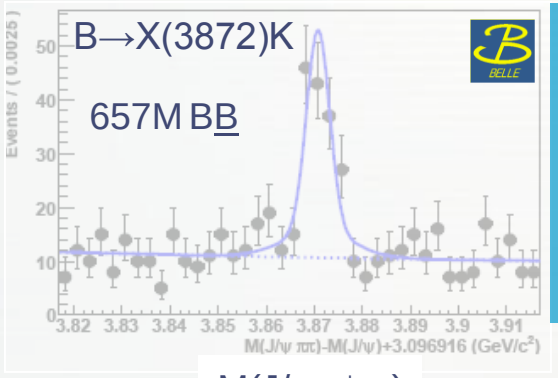


# Try to understand X(3872)

PRL103, 152001 (2009)

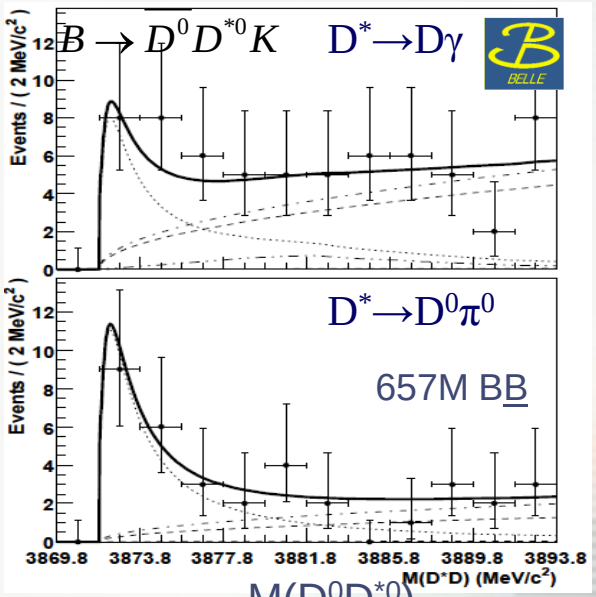



arXiv:0809.1224

| Mode | | Mass MeV |
|---|---|---|
| $X(3872) \to J/\psi\pi\pi$ | Belle | $3871.46 \pm 0.37 \pm 0.07$ |
| $X(3872) \to J/\psi\pi\pi$ | CDF | $3871.61 \pm 0.16 \pm 0.19$ |
| $M_{D^0} + M_{D^{*0}}$ | | $3871.8 \pm 0.4$ |
| $X(3872) \to D^0 \overline{D}^{*0}$ | Belle | $3872.9\ ^{+0.6+0.2}_{-0.4-0.5}$ |
| $X(3872) \to D^0 \overline{D}^{*0}$ | BaBar | $3875.1\ ^{+0.7}_{-0.5} \pm 0.5$ |

PRD81, 031103 (2010)




- **Mass suggests $D^0D^{*0}$ bound state interpretation**
  **Molecular (below threshold) or virtual (above threshold)?**
  **Line-shape crucial to distuinguish**
- **Bound state scenario supported by:** $\frac{BR(X \to \overline{D^0} D^{*0})}{BR(X \to J/\psi\,\pi\pi)} \approx 10$
- **If X(3872) is conventional cc, why so narrow?**

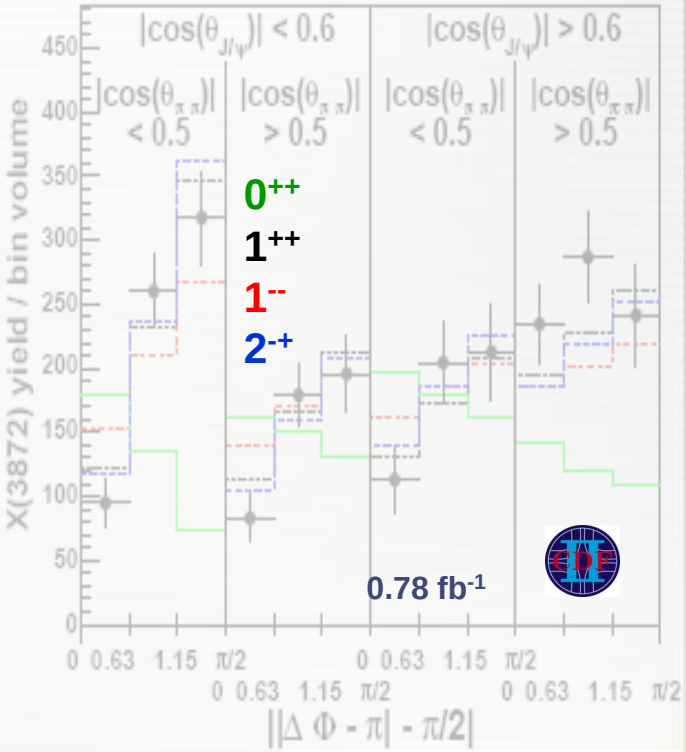
# Try to understand X(3872)

- CDF angular analysis: $J^{PC}= 1^{++}, 2^{-+}$ favored
  - Difficult to discriminate further
- Belle evidence of $X(3872)\rightarrow J/\psi\pi^+\pi^-\pi^0$

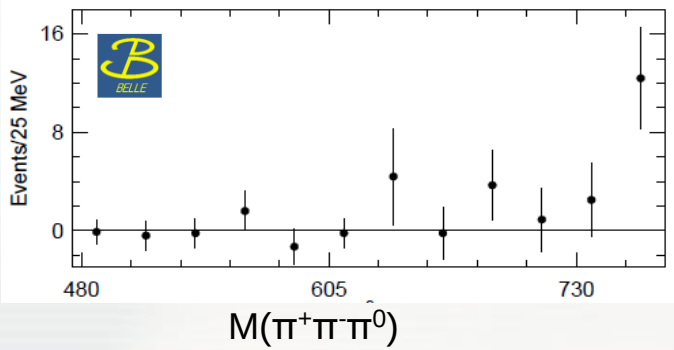
$$\frac{BR(X \rightarrow J/\psi\pi^+\pi^-\pi^0)}{BR(X \rightarrow J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

⇨ Large isospin violation. Unlikely for usual c̲c̲

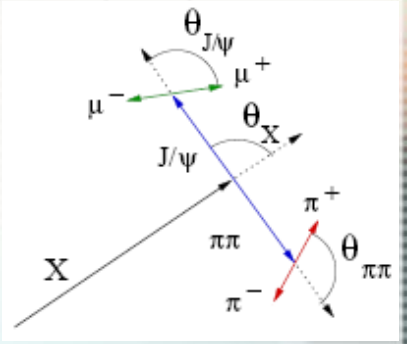
PRL98, 132002 (2007)




arXiv:0505037



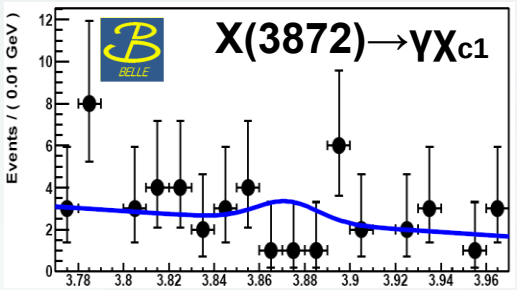

⇨ ω(782)-like



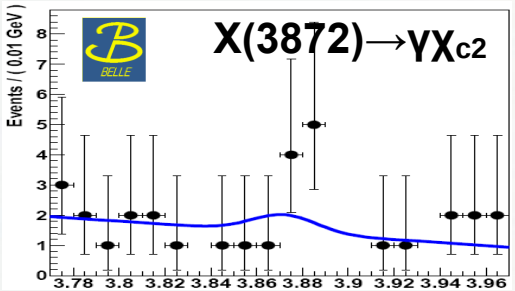

- Babar confirmation of $X(3872)\rightarrow J/\psi\omega$ arXiv:1005.5190
  Decay in P-wave favoured→ $J^P=2^-$ preferred
- Is X(3872) a missing $\eta_{c2}(2D)$ charmonium?

# Radiative decays of X(3872)

- Radiative transistions of charmonia: well predicted by quark models
- Good way to probe charmonium interpretation of X(3872)




M(γχc1)

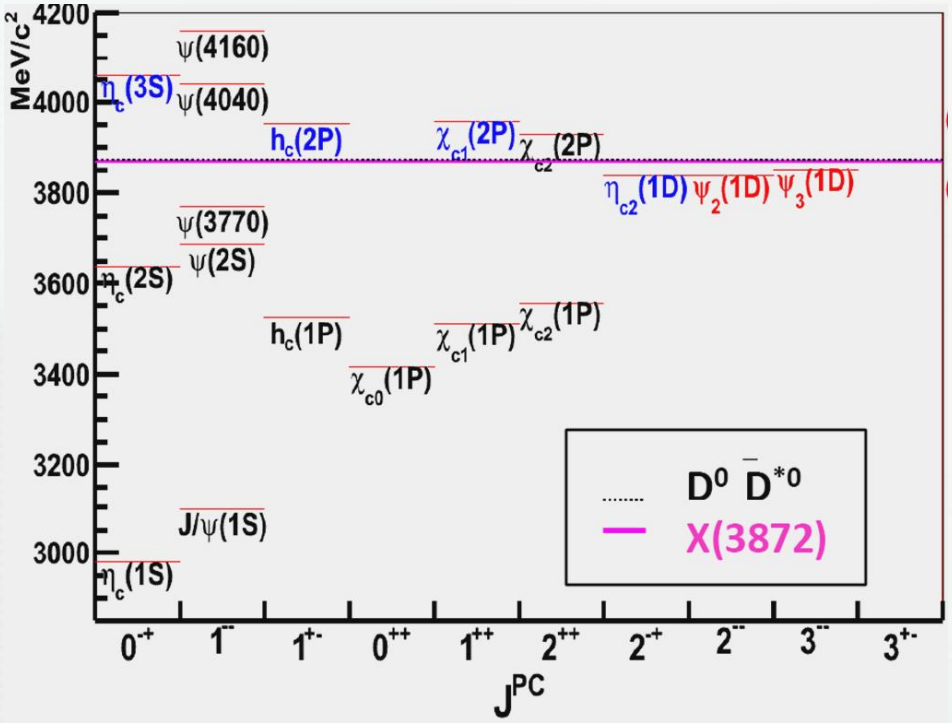



M(γχc2)

arXiv:0408116

$$\frac{BR(X \to \gamma\chi_{c1})}{BR(X \to J/\psi\pi\pi)} < 0.89 \ @\ 90\%CL$$

$$\frac{BR(X \to \gamma\chi_{c2})}{BR(X \to J/\psi\pi\pi)} < 1.1 \ @\ 90\%CL$$




ψ2 BR(X→γχc1) too small
ψ3 BR(X→γχc2) too small
hc' ruled out by angular analysis
ηc2 BR(X→J/ψππ) too large
ηc'' X(3872) too light and narrow
χc1' BR(X→γJ/ψ) too small

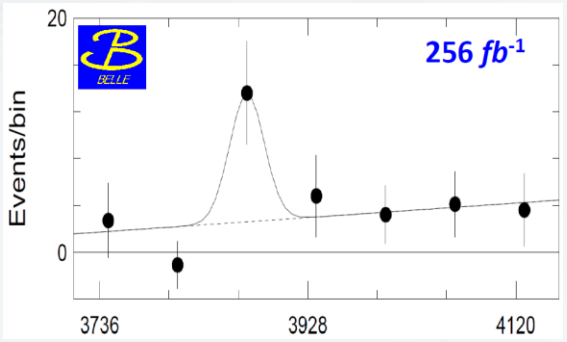
**No good charmonium candidate**

arXiv:0407033

# Radiative decays - first evidence

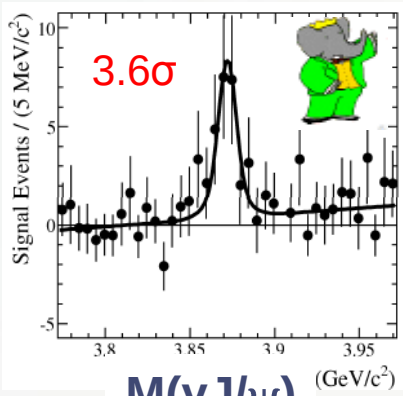
arXiv:0505037

X(3872)→γJ/ψ



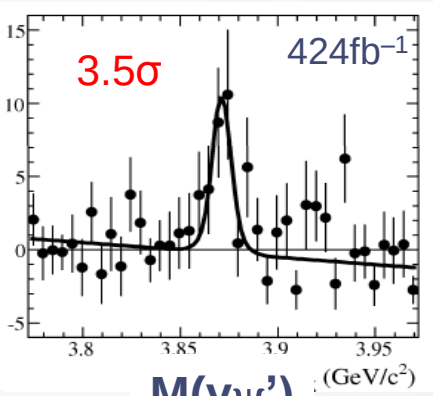

M(γJ/ψ)

X(3872)→γJ/ψ




M(γJ/ψ)

X(3872)→γψ'




M(γψ')

PRL102, 132001 (2009)

$$\frac{BR(X \to \gamma J/\psi)}{BR(X \to J/\psi\,\pi\pi)} = 0.14 \pm 0.05$$

$$\frac{BR(X \to \gamma\psi')}{BR(X \to \gamma J/\psi)} = 3.5 \pm 1.4$$

$$\frac{BR(X \to \gamma\psi')}{BR(X \to J/\psi\,\pi\pi)} = 1.1 \pm 0.4$$

$$BR(B^+ \to X(3872)K^+) \times BR(X \to \gamma J/\psi) = (1.8 \pm 0.6 \pm 0.1) \times 10^{-6}$$

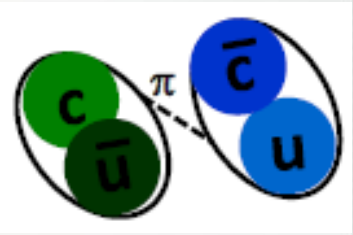
$$BR(B^+ \to X(3872)K^+) \times BR(X \to \gamma J/\psi) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

**Important implications:**

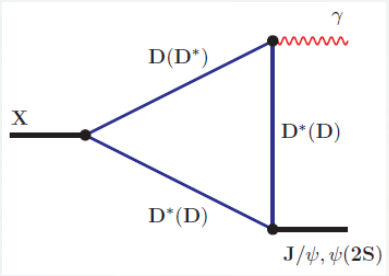
- **Imply even C-parity of X(3872)**
- **Shed light on X(3872) nature**

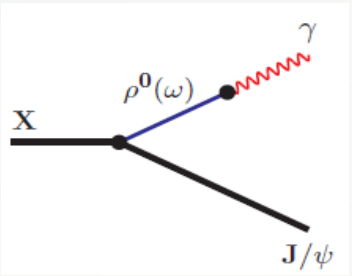
# Radiative decays- problematic interpretation

- $\frac{BR(X \to \gamma\psi')}{BR(X \to \gamma J/\psi)} = 3.5 \pm 1.4$ **is problematic for molecular interpretation of X(3872)**




- **Components of molecule: DD* (+ J/ψρ + J/ψω)**
  **Decay: vector-meson dominance and light-quark annihilation**

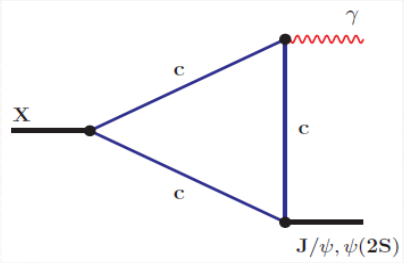



PRD80, 074004 (2009)

arXiv:0909.0380

- **Such decay pattern implies:** $BR(X \to \gamma\psi') \gtrsim BR(X \to \gamma J/\psi)$
- **Solution: admixture of charmonium component (for example $\chi_{c1}(2P)$)**
  ⇨ **Decrease X(3872) →γJ/ψ rate through destructive interference**




- **Radiative decays worth studying further**

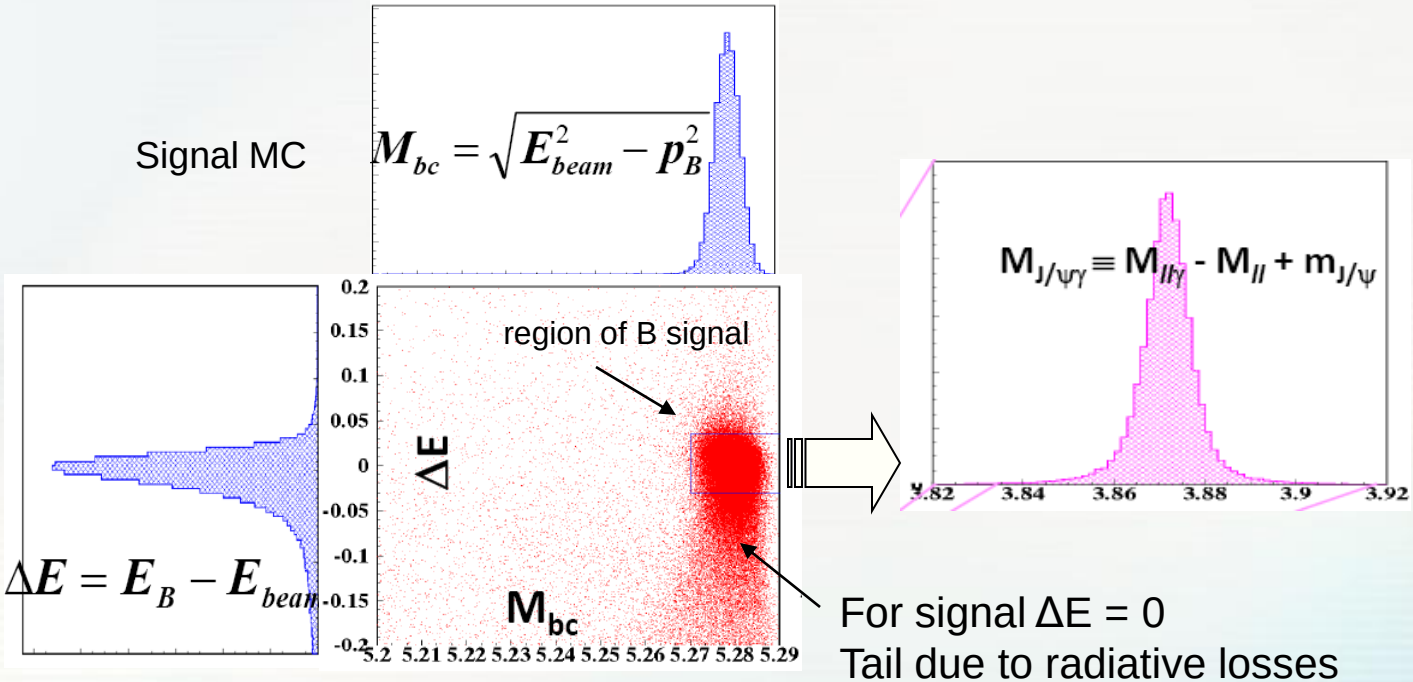
# Radiative decays of quarkonia in B mesons

- **Studied decay chain ⇨**
  **with data sample of 772M B$\underline{\bar{B}}$**

$$B \to J/\psi\,\gamma K \quad K = K^{\pm}, K_s^0$$
$$X(3872), \chi_{c1,c2} \to J/\psi\,\gamma$$
$$J/\psi \to e^+e^-, \mu^+\mu^-$$

- **Method:**
  - **Reconstruct B mesons: signal window cut on ΔE-$M_{bc}$ plane**
  - **Constrain ΔE→0 ⇨ Scale $E_\gamma$ to improve resolution of M(J/ψγ)**
  - **Study M(J/ψγ)**

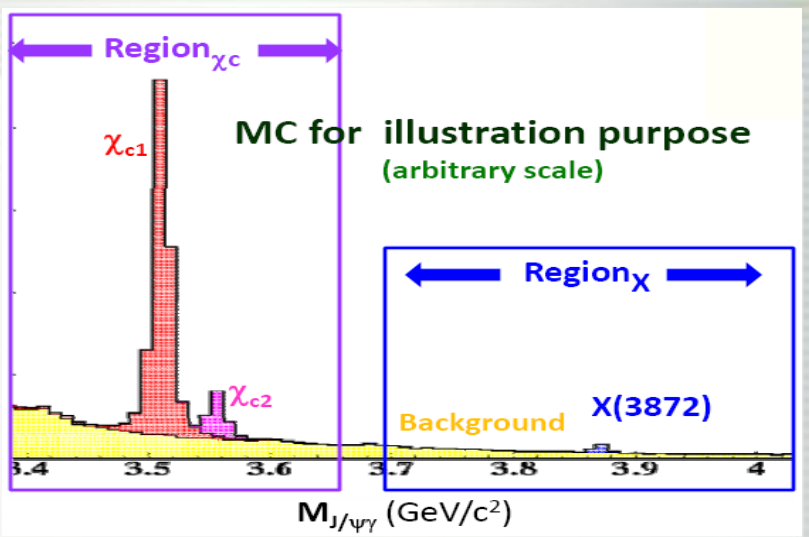
Signal MC



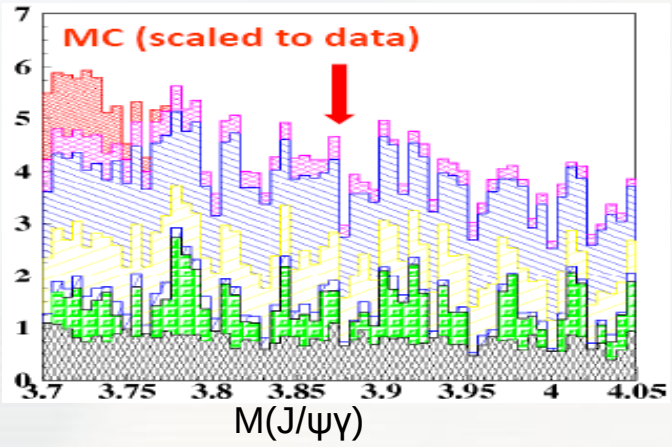

For signal ΔE = 0
Tail due to radiative losses

# Study of $B \to J/\psi\gamma K$

- $\chi_c$ region: $\chi_{c1}$ serves as a reference mode
  $\chi_{c2}$ suppressed by factorization
- Background sources:
  $B \to J/\psi K^*$, $B \to \psi' K$ with $\psi' \to \chi_{c1}\gamma$
  non-J/ψ events, other combinatorial
- Background suppression:
  - $E_\gamma$>290MeV for $\chi_c$ $E_\gamma$>470MeV for X(3872)
  - $\pi^0$ veto, cut on photon helicity angle




} background reduced by 80%, signal by 30%




**Background components:**

- $B^+ \to \psi' K^+$
- $B^0 \to J/\psi K^{*0}$
- $B^+ \to J/\psi K^{*+}$
- $B \to J/\psi K(1270)$, $J/\psi K_2(1430)$

} from MC

non-J/ψ from data outside of J/ψ signal

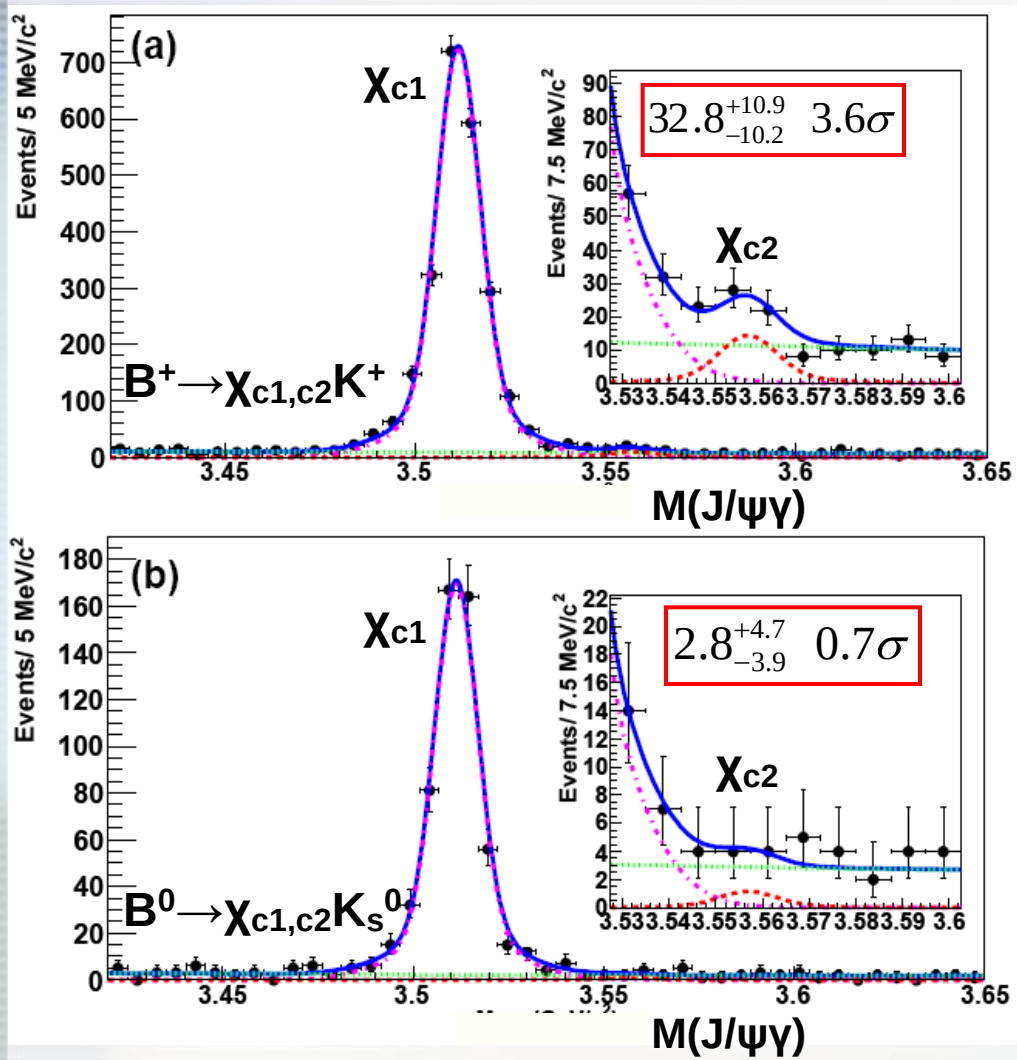
other combinatorial from MC

- M(J/ψγ) fit to data:

⇨ background: 1st order Chebyshev polynomial, signal: double Gaussian

⇨ fit mass and resolution of $\chi_{c1}$, fix mass and resolution of X(3872) and $\chi_{c2}$ wrt to them

# Results for $\chi_{c1,c2} \to J/\psi\gamma$ with $772\times10^6$ BB




| Mode | Events | Significance $\Sigma$ ($\sigma$) |
|---|---|---|
| $B^+ \to \chi_{c1} K^+$ | $2308^{+53}_{-52}$ | |
| $B^+ \to \chi_{c2} K^+$ | $32.8^{+10.9}_{-10.2}$ | **3.6** |

$\mathcal{BR}(B^+ \to \chi_{c2} K^+) = (1.11 \pm 0.35 \pm 0.09) \times 10^{-5}$

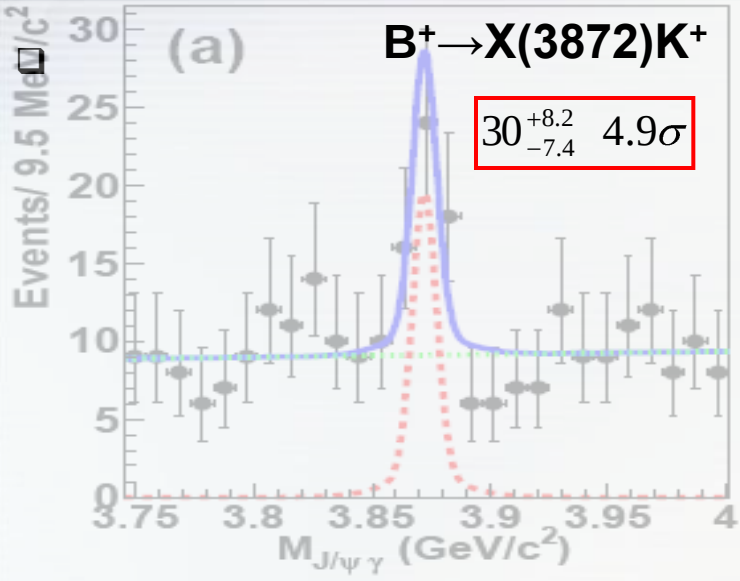
**First evidence**

**Significance includes systematics**

| Mode | Events | $\Sigma$ ($\sigma$) |
|---|---|---|
| $B^0 \to \chi_{c1} K_S^0$ | $542 \pm 24$ | |
| $B^0 \to \chi_{c2} K_S^0$ | $2.8^{+4.7}_{-3.9}$ | **0.7** |

$\mathcal{BR}(B^0 \to \chi_{c2} K^0) < 1.5 \times 10^{-5}$ (@ 90% CL)

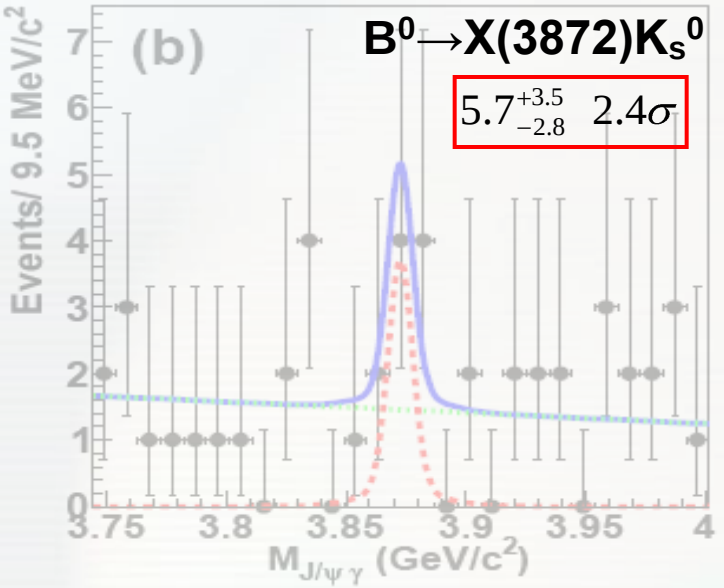
# Results for X(3872)→J/ψγ with 772×10⁶ BB




| Mode | Events | Significance |
|---|---|---|
| $B^+ \to X(3872)\,K^+$ | $30.0^{+8.2}_{-7.4}$ | 4.9 σ |
| $B^0 \to X(3872)\,K_S^0$ | $5.7^{+3.5}_{-2.8}$ | 2.4 σ |

- Significance includes systematic error

$$BR(B^+ \to X(3872)K^+) \times BR(X \to \gamma J/\psi) = (1.78 \pm 0.46 \pm 0.12) \times 10^{-6}$$




$$\frac{BR(X \to J/\psi\gamma)}{BR(X \to J/\psi\pi\pi)} = 0.22 \pm 0.05$$

- Using Belle X→J/ψππ result from arXiv:0809.1224
- Ratio consistent with previous Belle measurement

$$BR(B^0 \to X(3872)K^0) \times BR(X \to \gamma J/\psi) < 2.4 \times 10^{-6}\ @90\%\text{CL}$$

# Study of B→ψ'γ K

- **Studied decay:**
  **using 772M BB̲ data**

$$B \to \psi' \gamma K \quad K = K^{\pm}, K_s^0$$
$$X(3872) \to \psi' \gamma$$
$$\psi' \to e^+ e^-, \mu^+ \mu^-, J/\psi \pi^+ \pi^-$$



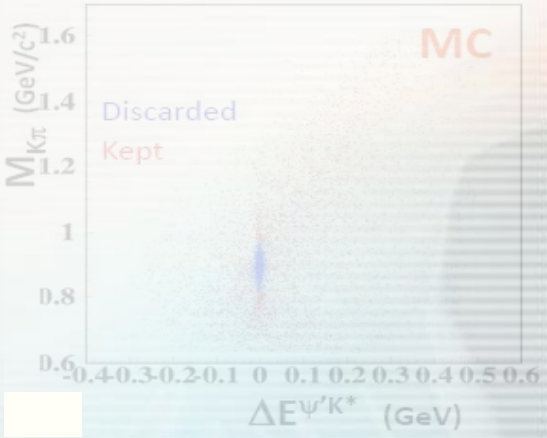

- **Background sources:**
  - **B →ψ'K*, B →ψ'K, B→ψ'Kππ**
  - **non-ψ' component and non-J/ψ for ψ'→J/ψππ**
- **Low energy photons: cuts used in B→J/ψγK inefficient**
- **ψ'K*-veto to reduce background from B→ψ'K***

**B→ψ'γK candidate + additional π ,0 → form ψ'K* and calculate:**

$$\Delta E^{\psi' K^*} \equiv E_{\psi'} + E_K + E_\pi - E_{\text{beam}}^{\text{cms}} \quad M_{K\pi} \equiv M(K\pi) \quad M_{\text{bc}}^{\psi' K^*} \equiv \sqrt{E_{\text{beam}}^{\text{cms}\,2} - (p_{\psi'} + p_K + p_\pi)^2}$$

- **Reject „good" B→ψ'K* candidates with:**

$$|\Delta E^{\psi' K^*}| < 20\text{MeV} \quad M_{K\pi} \in (892 \pm 75)\text{MeV} \quad M_{\text{bc}}^{\psi' K^*} > 5.27\text{GeV}$$

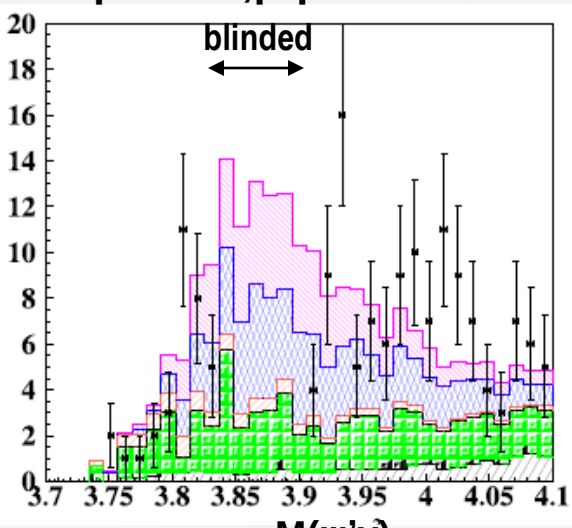



→ **background reduced by 40%**
**signal reduced by 15%**

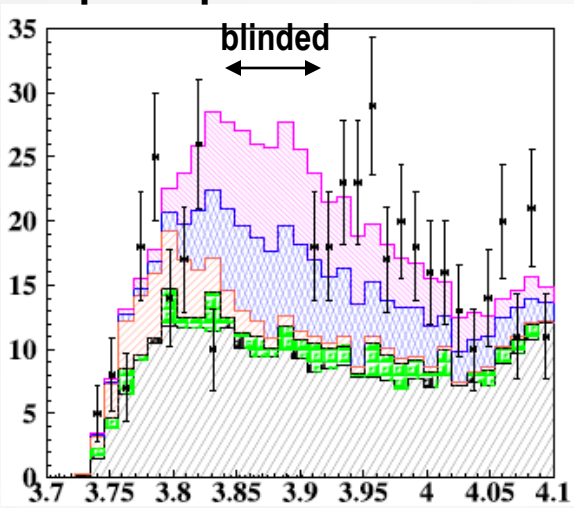
# Background in M(ψ'γ)

- Background after selection cuts:

ψ'→e⁺e⁻,μ⁺μ⁻




ψ'→J/ψπ⁺π⁻




**Background components:**

- $B^0 \to \psi' K^{*0}$
- $B^+ \to \psi' K^{*+}$
- $B^+ \to \psi' K^+$
- $B^0 \to \psi' K_s^0$

} from MC

non-ψ', non-J/ψ from data

other combinatorial from MC

• data with X(3872) region blinded

- Background matches data outside of X(3872) region → MC agree with data
- Parameterization of background components:

B→ψ'K*, ψ'K: using B→ψ'K*,ψ'K MC

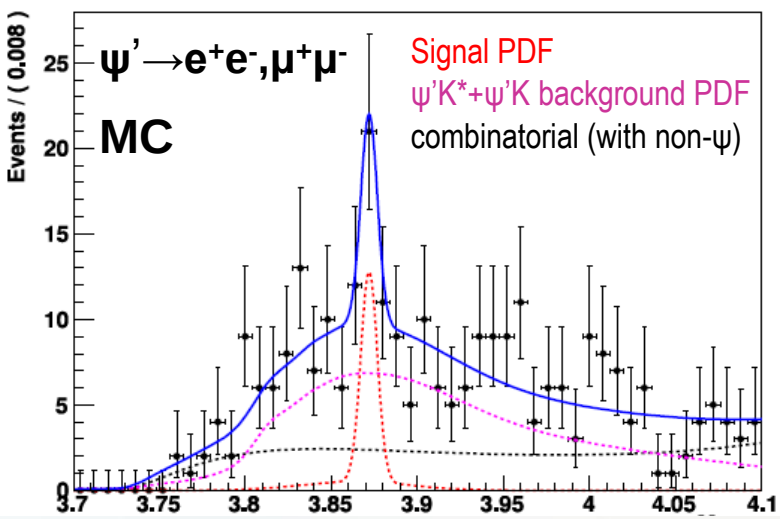
non-ψ: using data outside of ψ signal region

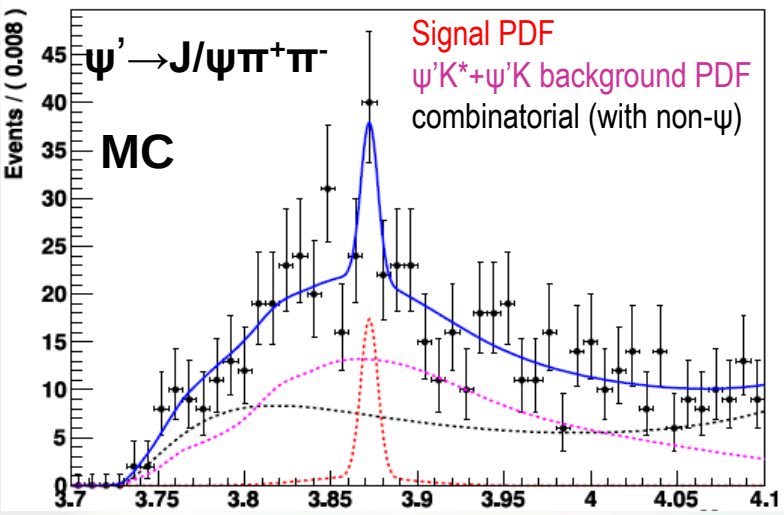
other combinatorial: using inclusive B→ψ'+all MC

} shapes fixed in fit to data

# Fit to M(ψ'γ): parameterization and validation

- **Pseudo-experiment test:** fully simulated MC with embedded X(3872)→ψ'γ signal
- **Example of B+→XK+ , X→ψ'γ test:** (assuming BaBar's BR)



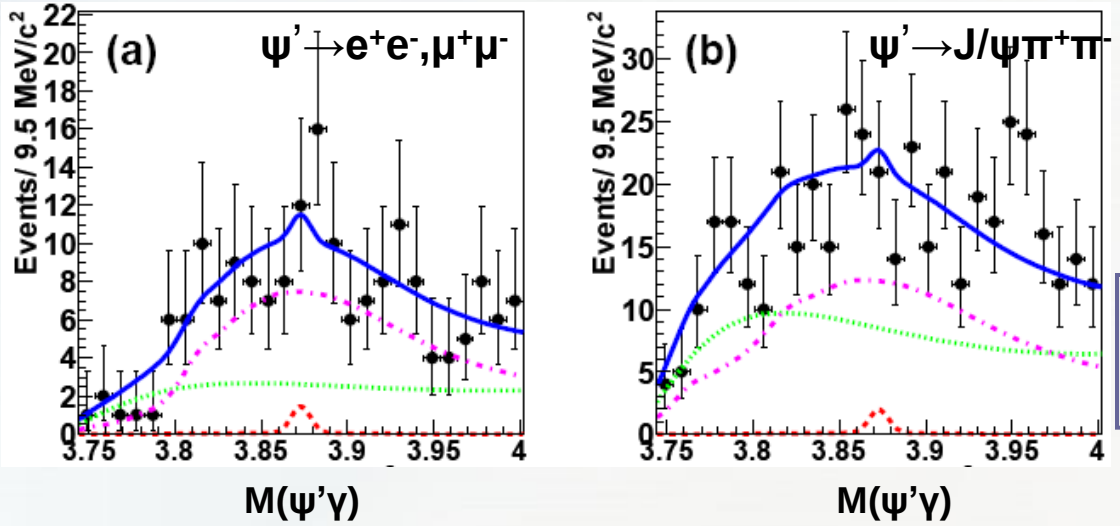

- **Simultaneous fit to both ψ' decay modes**
- **Signal: double Gaussian**
  - ⇨ **X(3872) mass fixed wrt fitted $\chi_{c1}\to J/\psi\gamma$ mass**
  - ⇨ **$\sigma X(3872)$ fixed wrt fitted $\sigma\chi_{c1}$**
- **Background: shapes fixed from MC/data**

- **Fit successfully tested with 50 pseudo-experiments and Toy MC samples**

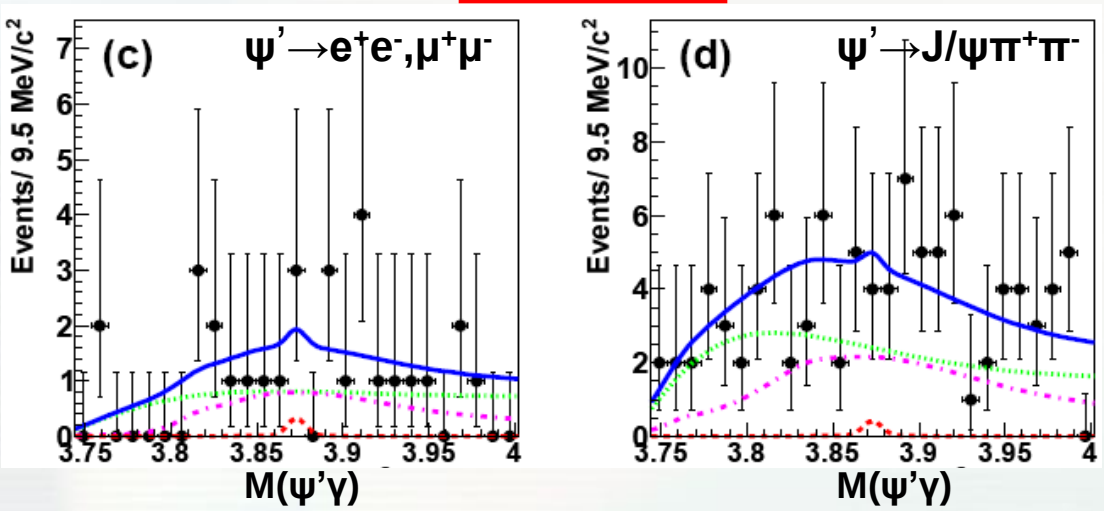
- **Expected X(3872)→ψ'γ signals assuming BaBar's BR:**
  **~58 events in $B^+\to X(3872)K^+$**
  **~18 events in $B^0\to X(3872)K_s^0$**

# Results for X(3872)→ψ'γ with 772×10⁶ BB

- $B^+ \to \psi'\gamma K^+$ $\quad 5.0^{+11.9}_{-11.0} \quad 0.4\sigma$




- $B^0 \to \psi'\gamma K_s^0$ $\quad 1.5^{+4.8}_{-3.9} \quad 0.2\sigma$




Fit components:
Signal
ψ'K*+ψ'K background
combinatorial (with non-ψ)

- **No signal observed**

$$BR(B^+ \to X(3872)K^+) \times BR(X \to \psi'\gamma) < 3.4 \times 10^{-6} \ @90\%CL$$

$$\frac{BR(X \to \psi'\gamma)}{BR(X \to J/\psi\gamma)} < 2.1 \ @90\%CL$$

$$BR(B^0 \to X(3872)K^0) \times BR(X \to \psi'\gamma) < 6.6 \times 10^{-6} \ @90\%CL$$

# Summary

| Mode | Signal | Product BR | |
|---|---|---|---|
| | | Belle | BaBar |
| $B \to \chi_{c2} K$ | $\chi_{c2} \to J/\psi\gamma$ | [$10^{-5}$] | |
| $B^+$ | $32.8^{+10.9}_{-10.2}$ | $1.11^{+0.36}_{-0.34}$ 0.09 | <1.8 |
| $B^0$ | $2.8^{+4.7}_{-3.9}$ | <1.5 @90%CL | <2.8 |
| $B \to X(3872) K$ | $X(3872) \to J/\psi\gamma$ | [$10^{-6}$] | |
| $B^+$ | $30.0^{+8.2}_{-7.4}$ | $1.78^{+0.48}_{-0.44}$ 0.12 | 2.8 0.8 0.1 |
| $B^0$ | $5.7^{+3.5}_{-2.8}$ | <2.4 @90%CL | <4.9 |
| $B \to X(3872) K$ | $X(3872) \to \psi'\gamma$ | [$10^{-6}$] | |
| $B^+$ | $5.0^{+11.9}_{-11.0}$ | <3.3 @90%CL | 9.5 2.7 0.6 |
| $B^0$ | $1.5^{+4.8}_{-3.9}$ | <6.6 @90%CL | <19.0 |

- $X(3872) \to J/\psi\gamma$ clearly observed
- Most precise measurement, agrees with previous evidence
- No $X(3872) \to \psi'\gamma$ signal observed
- Disagree with Babar's evidence
- Pure molecular interpretation of X(3872) is back?
- Big effort to understand nature of X(3872). Getting there?

# Backup

- 

# Systematic errors in M(J/ψγ)

| Sources | Systematic error (%) | | | | | |
|---|---|---|---|---|---|---|
| | $B \to \chi_{c1} K$ | | $B \to \chi_{c2} K$ | | $B \to X(3872) K$ | |
| | $K^+$ | $K_S^0$ | $K^+$ | $K_S^0$ | $K^+$ | $K_S^0$ |
| K-identification | 0.6 | _ | 0.6 | _ | 0.5 | _ |
| $K_S^0$ reconstruction | _ | 4.5 | _ | 4.5 | _ | 4.5 |
| Lepton identification | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| γ identification | 2 | 2 | 2 | 2 | 2 | 2 |
| MC | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 |
| Secondary $\mathcal{BR}$ | 4.5 | 4.5 | 4.1 | 4.2 | 0.7 | 0.7 |
| $N_{B\bar{B}}$ | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Tracking | 3.0 | 4.0 | 3.0 | 4.0 | 3.0 | 4.0 |
| PDF | 0.7 | 1.1 | 3.8 | 3.8 | 1.8 | 1.8 |
| Fit bias | _ | _ | 0.5 | 2.1 | 0.5 | 0.2 |
| MC, data diff | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| $Cos\theta_{hel}$ | _ | _ | 3.8 | 3.8 | 4.2 | 4.2 |
| Total | 6.8 | 8.6 | 8.4 | 9.9 | 6.8 | 8.6 |

# Systematic errors in M(ψ'γ)

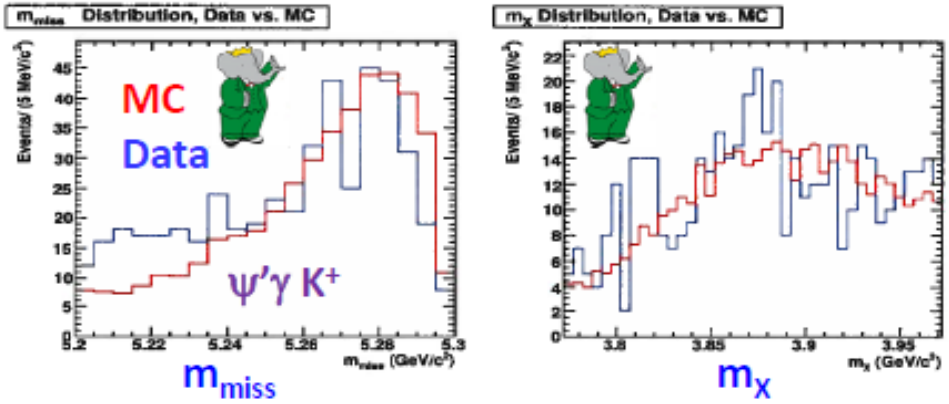
| Sources | Systematic error (%) | |
|---|---|---|
| | $B^+ \to (\psi'\gamma)K^+$ | $B^0 \to (\psi'\gamma)K_S^0$ |
| K-identification | 0.9 | _ |
| $K_S^0$ reconstruction | _ | 4.5 |
| Lepton identification | 1.1 | 1.1 |
| γ identification | 3 | 3 |
| MC | 0.4 | 0.4 |
| Secondary $\mathcal{BR}$ | 2.4 | 2.4 |
| $N_{B\bar{B}}$ | 1.4 | 1.4 |
| Tracking | 4.2 | 5.2 |
| PDF | 50 | 50 |
| Fit bias | 16 | 6 |
| Total | 53 | 51 |

# Belle/BaBar comparison

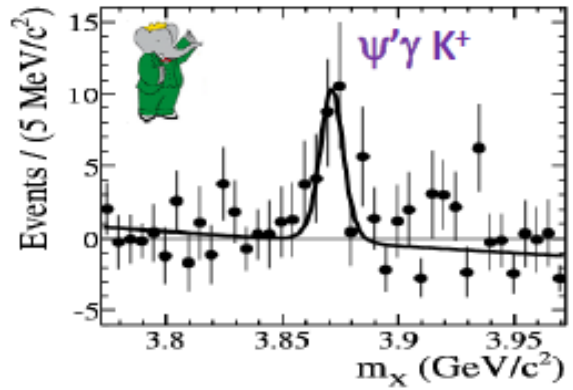
| Mode | Belle | | | BaBar | | |
|---|---|---|---|---|---|---|
| | ε (%) | Yield | $\mathcal{BR}$ | ε (%) | Yield | $\mathcal{BR}$ |
| $B \to \chi_{c1} K$ | | | , x $10^{-4}$ | | | , x $10^{-4}$ |
| $K^+$ | 14.8 | 2308±52 | 4.9±0.1±0.3 | 11.0 | 1018±34 | 4.5±0.1±0.3 |
| $K^0$ | 13.2 | 542±24 | $3.78^{+0.17}_{-0.16} \pm 0.33$ | 8.7 | 242±16 | 4.2±0.3±0.3 |
| $B \to \chi_{c2} K$ | | | , x $10^{-5}$ | | | , x $10^{-5}$ |
| $K^+$ | 16.6 | $32.8^{+10.9}_{-10.2}$ | $1.11^{+0.36}_{-0.34} \pm 0.09$ | 12.3 | 14.0±7.9 | <1.8 |
| $K^0$ | 13.2 | $2.8^{+4.7}_{-3.9}$ | <1.5 | 11.1 | 6.1±3.9 | <2.8 |
| $B \to X(3872) (J/\psi\gamma) K$ | | | , x $10^{-6}$ | | | , x $10^{-6}$ |
| $K^+$ | 18.3 | $30^{+8.2}_{-7.4}$ | $1.78^{+0.48}_{-0.44} \pm 0.12$ | 14.5 | 23.0±6.4 | 2.8±0.8±0.1 |
| $K^0$ | 14.5 | $5.7^{+3.5}_{-2.8}$ | <2.4 | 11.1 | 5.3±3.6 | <4.9 |
| $B \to X(3872) (\psi'\gamma) K$ | | | , x $10^{-6}$ | | | , x $10^{-6}$ |
| $K^+$ | 14.7 | $5.0^{+11.9}_{-11.0}$ | < 3.4 | 10.4 | 25.4±7.3 | 9.5±2.7±0.6 |
| $K^0$ | 10.8 | $1.5^{+4.8}_{-3.9}$ | < 6.6 | 8.4 | 8.0±3.9 | <19 |

# Comparison

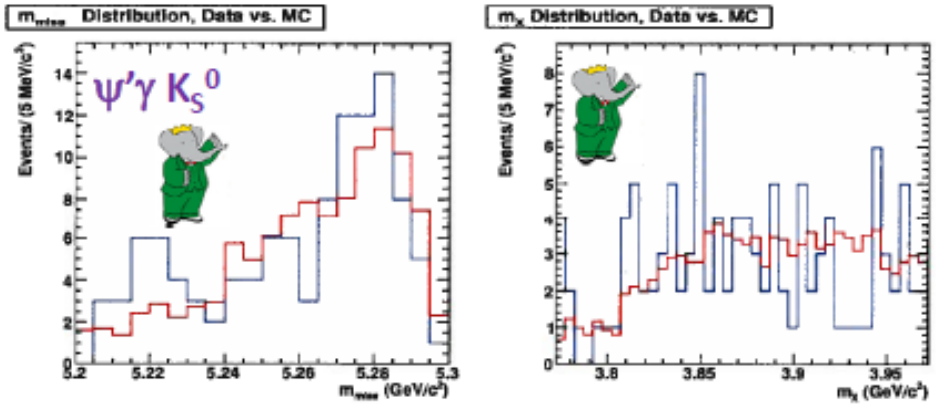
- BaBar used 1d UML fit to $m_{miss}$ and use $_s$Plot to project signal in $m_X$
- We use 1d UML fit to $M_{\psi'\gamma}$ to extract yield

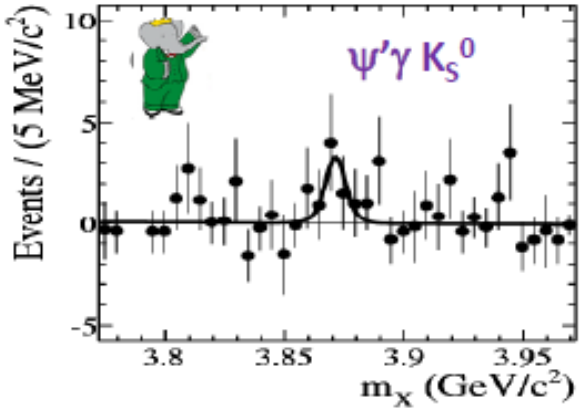



Raw distribution from Fulsom's thesis



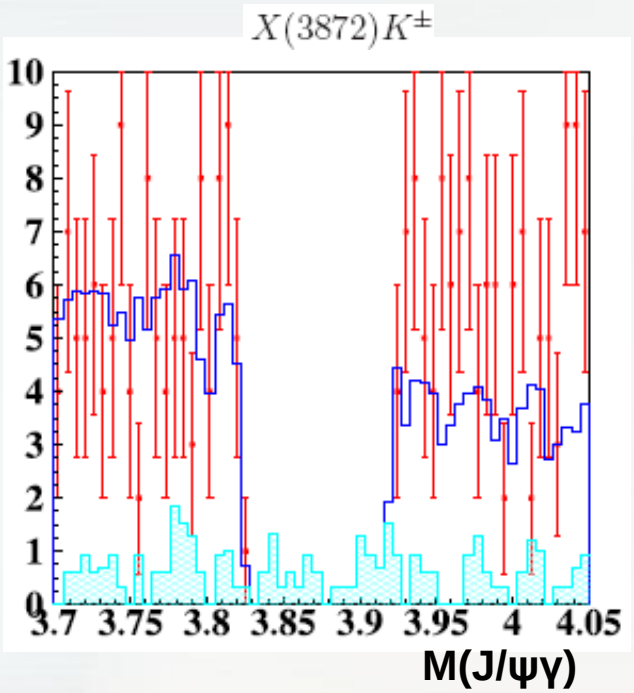

$_s$Plot projection in $m_X$ bins

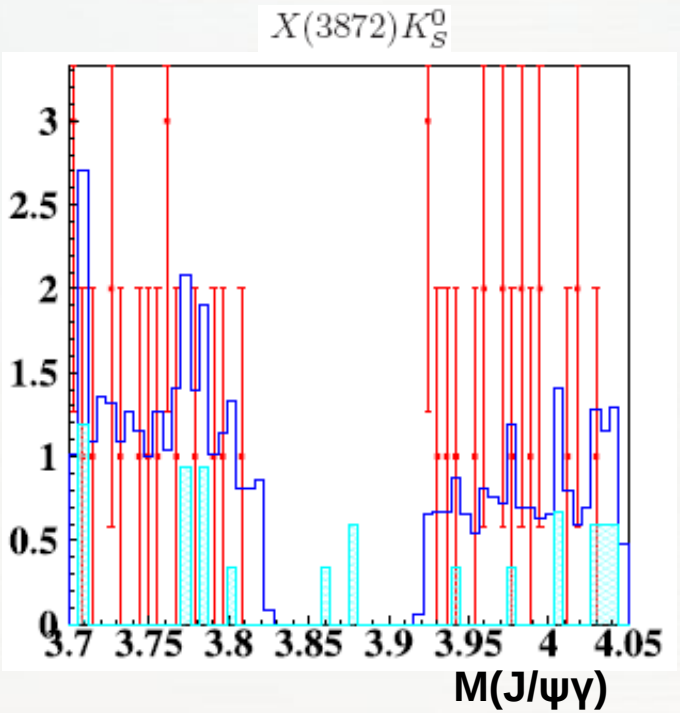


# Background in M(J/ψγ)

- Background in M(J/ψγ) from scaled MC compared with background in data




- M(J/ψγ) data sideband: red
- non-J/ψ from M($l^+l^-$) data sidebands: sky blue
- J/ψ inclusive + non-J/ψ from MC: dark blue

# Fits to M(J/ψγ)

Table 4: Fit parameters of $B^{\pm,0} \to \chi_{c1,c2} K^{\pm,0}$.

| Parameter | $K^{\pm}$ | $K^0_S$ |
|---|---|---|
| $M(\chi_{c1})$ | Float | 3.5114 GeV |
| $M(\chi_{c2})$ | $M(\chi_{c1}) + \delta M$ | $M(\chi_{c1}) + \delta M$ |
| $\delta M$ | +45.54 MeV/$c^2$ | +45.54 MeV/$c^2$ |
| $\sigma_2/\sigma_1$ | Float | 2.56 |
| $Area_2/Area$ | 0.2453 | 0.2453 |
| $\sigma_1(\chi_{c1})$ | Float | 0.00556 GeV |
| $\sigma_1(\chi_{c2})$ | $\sigma_1(\chi_{c1}) \times \kappa_\sigma$ | $\sigma_1(\chi_{c1}) \times \kappa_\sigma$ |
| $\kappa_\sigma$ | 1.0874 | 1.0874 |
| chebyshev $2^{nd}$ polynomial | Float | Float |

Table 5: Fit parameters of $B^{\pm,0} \to X(3872) K^{\pm,0}$.

| Parameter | Values |
|---|---|
| $M(X3872)$ | $m_{X\,(3872)\mathrm{w}} + \delta$ |
| $\delta$ | +0.72 MeV/$c^2$ |
| $\sigma_2/\sigma_1$ | 3.141 |
| $Area_2/Area$ | 0.1788 |
| $\sigma_1(X3872)$ | $\sigma_1(X3872)_{MC} \times \kappa\sigma_{\chi_{c1}}$ |
| $\kappa\sigma_{\chi_{c1}}$ | 1.1526 |
| $m_{X\,(3872)\mathrm{w}}$ | 3.8715 GeV (Table 1) |
| $\sigma_1(X3872)_{MC}$ | 0.004460 |
| chebyshev $1^{st}$ polynomial | Float |

# Backup

- **X(3872)→J/ψγ background subtraction**

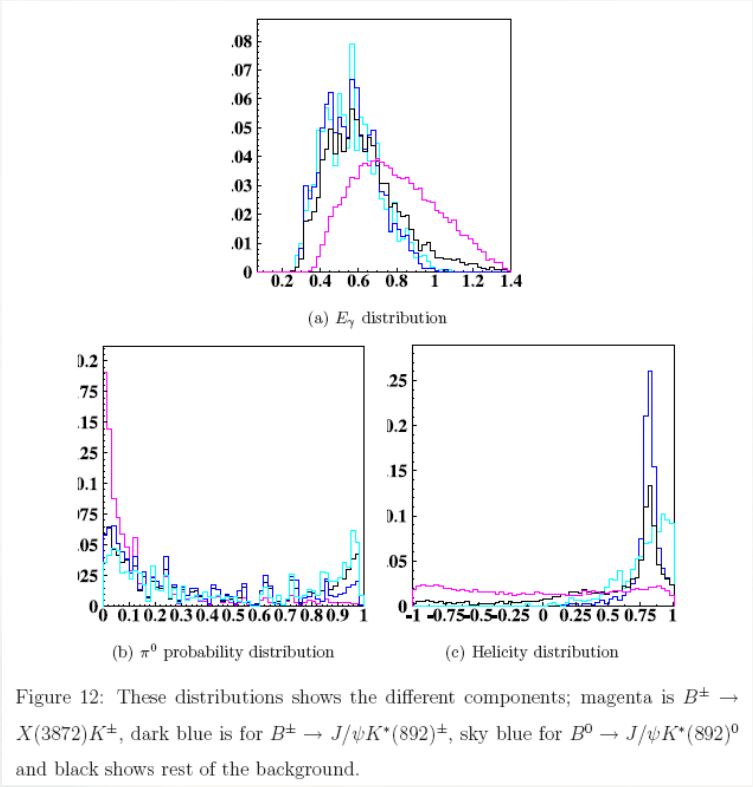
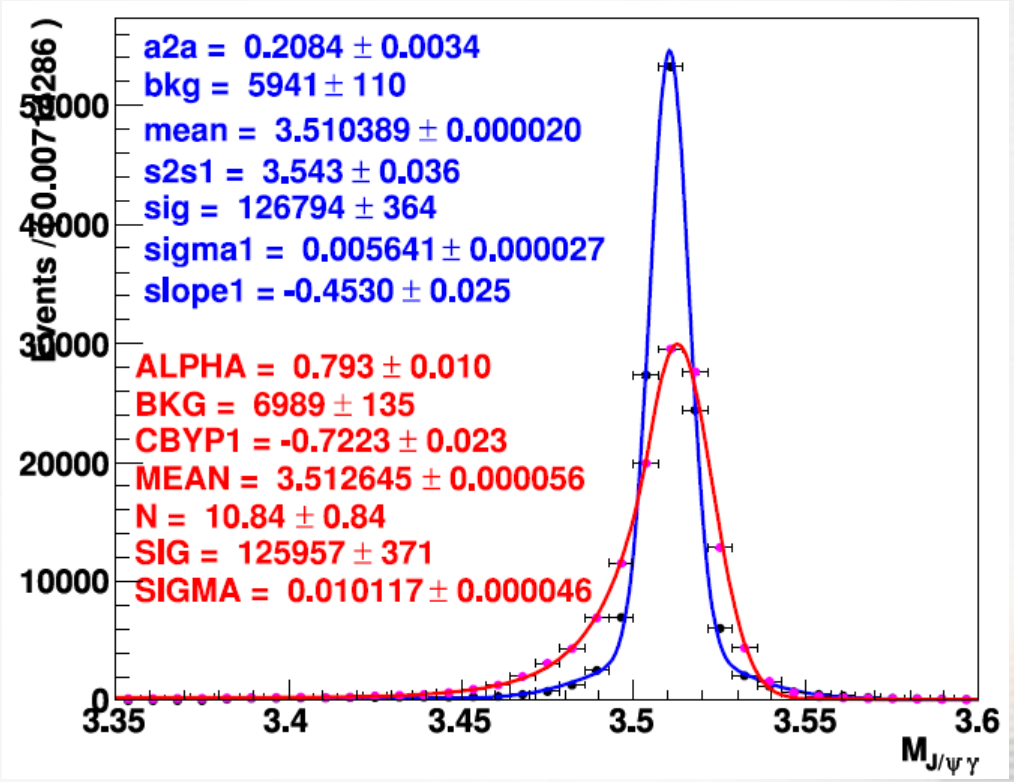


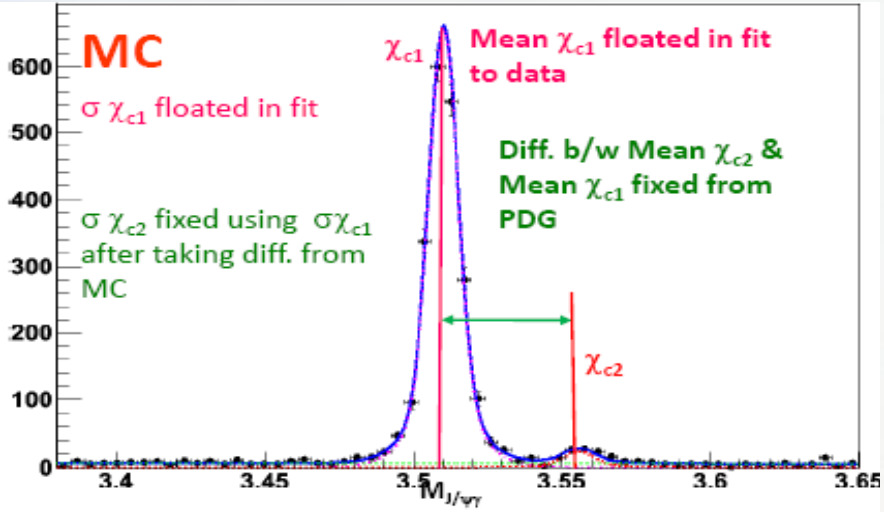

Figure 12: These distributions shows the different components; magenta is $B^{\pm} \to X(3872)K^{\pm}$, dark blue is for $B^{\pm} \to J/\psi K^{*}(892)^{\pm}$, sky blue for $B^{0} \to J/\psi K^{*}(892)^{0}$ and black shows rest of the background.

**ΔE→0 scaling for $\chi_{c1}$**



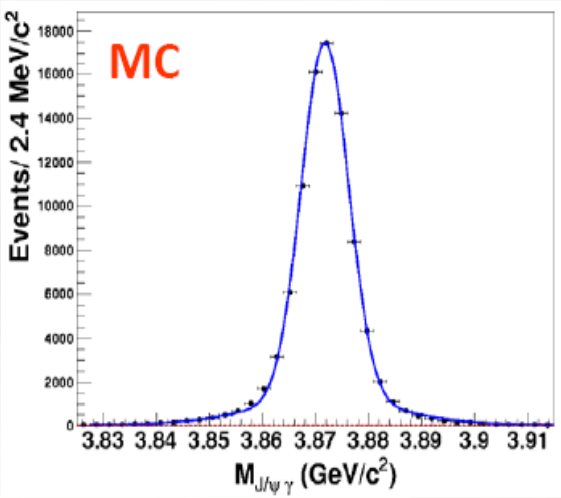
# Fit to M(J/ψγ): parametrization

- $\chi_c$ region




- Signal: double Gaussian
- Background: 2nd order Chebyshev polynomial
- Fit accounts for possible data/MC difference in resolution, mass scale

- X(3872) region




- Signal: double Gaussian
- Background: 1st order Chebyshev polynomial
- Mean X(3872) fixed wrt fitted Mean $\chi_{c1}$ using PDG mass difference of $\chi_{c1}$ and X(3872)
- σX(3872) fixed using fitted $\sigma\chi_{c1}$ after taking difference in resolutions from MC

- Fits checked with Toy MC: no bias found

# X(3872)→J/ψππ

- $$\frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.82 \pm 0.22 \pm 0.05$$

| Mode | Yield | $\epsilon(\%)$ | Significance ($\sigma$) | $\mathcal{B} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ |
|---|---|---|---|---|
| $B^+ \to X(3872)K^+$ | $131.7 \pm 15.0$ | 20.9 | 12.8 | $(8.10 \pm 0.92 \pm 0.66) \times 10^{-6}$ |
| $B^0 \to X(3872)K^0$ | $27.6 \pm 6.6$ | 15.2 | 5.9 | $(6.65 \pm 1.63 \pm 0.55) \times 10^{-6}$ |

Table 1. Some properties of the candidate charmonium states.

| State | nickname | $J^{PC}$ | $M_{predicted}$ (MeV) | $\Gamma_{predicted}$ (MeV) |
|---|---|---|---|---|
| $1^3D_2$ | $\psi_2$ | $2^{--}$ | 3838 | 0.7 |
| $2^1P_1$ | $h_c'$ | $1^{+-}$ | 3953 | 1.6 |
| $1^3D_3$ | $\psi_3$ | $3^{--}$ | 3849 | 4.8 |
| $2^3P_1$ | $\chi_{c1}'$ | $1^{++}$ | 3956 | 1.7 |
| $1^1D_2$ | $\eta_{c2}$ | $2^{-+}$ | 3837 | 0.9 |
| $3^1S_0$ | $\eta_c''$ | $0^{-+}$ | 4060 | $\sim 20$ |

# x(3872)→$\underline{D}^0D^{*0}$

| Sample | $M_X$ (MeV/$c^2$) | $\Gamma$ (MeV/$c^2$) | Yield | $\epsilon \times \mathcal{B}$ | $\mathcal{B}$ ($10^{-4}$) | $\sigma$ |
|---|---|---|---|---|---|---|
| $D^{*0} \to D^0\gamma$ ($XK^+$ and $XK^0$) | $3873.4 \pm 1.0$ | $4.2^{+3.7}_{-1.8}$ | $26.2^{+9.0}_{-7.6}$ | $4.56 \times 10^{-4}$ | $0.87 \pm 0.28 \pm 0.10$ | $4.4\sigma$ |
| $D^{*0} \to D^0\pi^0$ ($XK^+$ and $XK^0$) | $3872.8 \pm 0.7$ | $3.1^{+4.1}_{-1.5}$ | $22.0^{+10.7}_{-6.4}$ | $4.93 \times 10^{-4}$ | $0.68 \pm 0.26 \pm 0.09$ | $6.8\sigma$ |
| All (free $D^0\gamma/D^0\pi^0$ ratio) | $3872.9^{+0.6}_{-0.4}$ | $3.9^{+2.7}_{-1.4}$ | $50.6^{+14.2}_{-11.0}$ | $9.49 \times 10^{-4}$ | $0.81 \pm 0.20 \pm 0.10$ | $7.9\sigma$ |
| All (fixed $D^0\gamma/D^0\pi^0$ ratio) | $3872.9^{+0.6}_{-0.4}$ | $3.9^{+2.8}_{-1.4}$ | $50.1^{+14.8}_{-11.1}$ | $9.49 \times 10^{-4}$ | $0.80 \pm 0.20 \pm 0.10$ | $7.9\sigma$ |
| $B^+ \to XK^+$ | 3872.9 (fixed) | 3.9 (fixed) | $41.3^{+9.1}_{-8.1}$ | $8.17 \times 10^{-4}$ | $0.77 \pm 0.16 \pm 0.10$ | $7.6\sigma$ |
| $B^0 \to XK^0$ | 3872.9 (fixed) | 3.9 (fixed) | $8.4^{+4.5}_{-3.6}$ | $1.32 \times 10^{-4}$ | $0.97 \pm 0.46 \pm 0.13$ | $2.8\sigma$ |

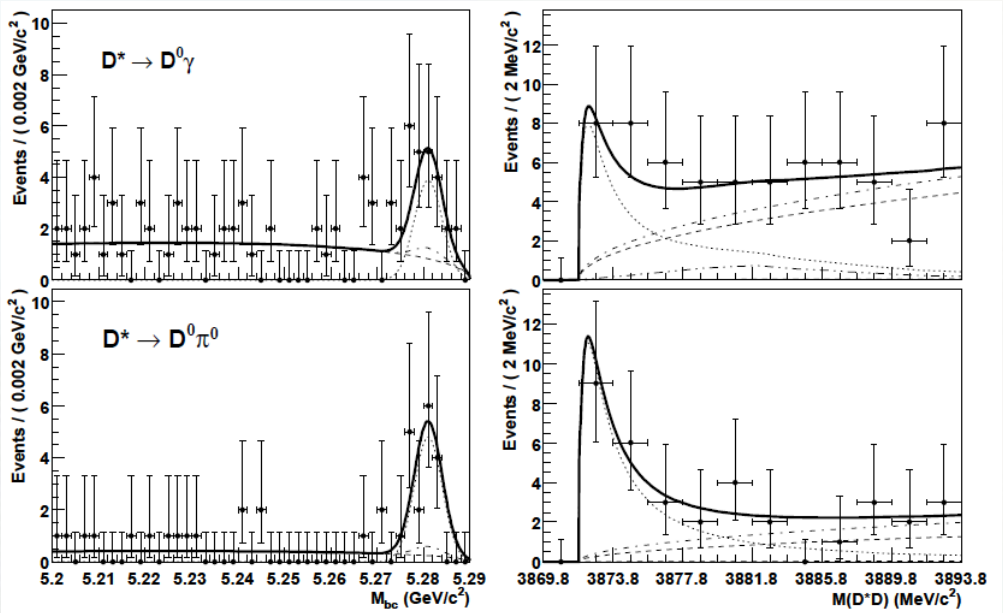



FIG. 3: Distributions of $M_{\rm bc}$ for $M_{D^*D} < 3.88$ GeV/$c^2$ (left) and of $M_{D^*D}$ for $M_{\rm bc} > 5.27$ GeV/$c^2$ (right); the top row is for $D^{*0} \to D^0\gamma$ and the bottom row for $D^{*0} \to D^0\pi^0$. The result of the simultaneous fit is shown by the superimposed lines. The points with error bars are data, the dotted curve is the signal, the dashed curve is the background, the dash-dotted curve is the sum of the background and the $B \to D^*DK$ component, the dot-dot-dashed curve is the contribution from $D^0$–$\bar{D}^0$ reflections, and the solid curve is the total fitting function.

$$\frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 1.26 \pm 0.65 \pm 0.06$$