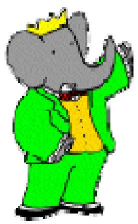
Prompt χ_{c1}, χ_{c2} and X(3872) Production in e^+e^- annihilation

Woochun Park
University of South Carolina



BABAR Representing the BaBar Collaboration

DPF 2006 + JPS 2006 @Honolulu, Hawaii
October 30, 2006

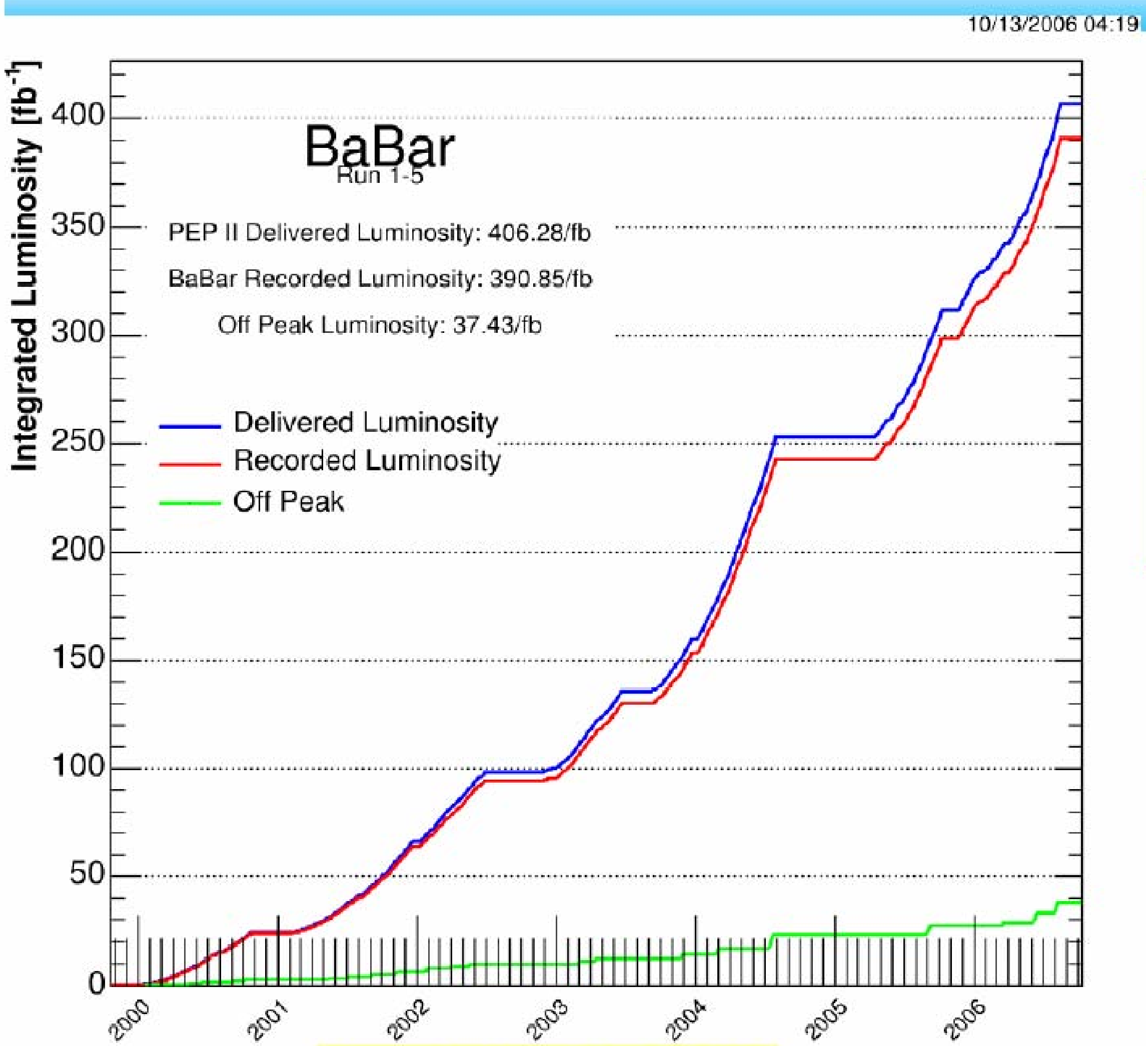
- We've heard a lot of exciting news about charmonium production in e^+e^- annihilation so far from B-factories:
  - Prompt J/ψ and $\psi(2S)$ production is observed.
  - Double charmonium production observed with M_{rec} against J/ψ.
  - X(3872), Z(3930), Y(3940), Z(3940), and Y(4260) observed
  - These are great tools to test NRQCD.

- Question:
  Why have χ_{c1} and χ_{c2} not been observed yet in the continuum?
  - In B decay, inclusive BF is 1.09% (J/ψ), 0.31% ($\psi(2S)$), 0.39%(χ_{c1}), 0.14%(χ_{c2}).
  - In e^+e^- annihilation, J/ψ, $\psi(2S)$, χ_{c0} found but not χ_{c1}, χ_{c2} yet.
  - Search for $\chi_{c1,2}$ with the dominant BF process **γ J/ψ**
    → 36% for χ_{c1} and 20% for χ_{c2}.

BELLE PRL2002 (33fb^{-1})	$\sigma(e^+e^- \to \chi_{c1}X) < 0.35$ $\sigma(e^+e^- \to \chi_{c2}X) < 0.66$	pb

- Search for X(3872) → γ J/ψ in continuum.
  - X(3872) observed in B-decay.
  - Take advantage of the machinery for χ_c.

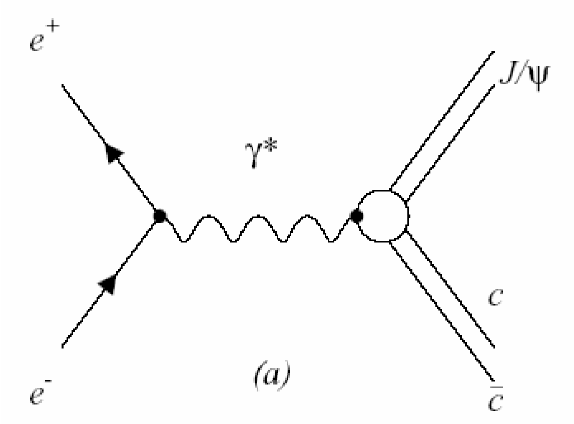
BABAR Data



(as of Oct 13, 2006)

- **Peak Luminosity:**
  1.21×10^{34} cm^{-2} sec^{-1}
- **Recorded:** 391 fb^{-1}
- **This talk based on**
  386 fb^{-1}

Data taking will resume in Jan 2007



MC Samples

- Double-charmonium MC ($\gamma^* \to \chi_c$ J/ψ or $\psi(2S)$) is used as our signal MC.
- To estimate signal detection efficiency inclusively, we use single χ_c and X(3872) MC generated flat distribution over $\cos\theta^*$ and p^* up to 5 GeV/c.
- The χ_c from B decays are used as a control sample to validate data-to-MC comparison.
- $B\bar{B}$ MC is used to estimate $B\bar{B}$ background.
- For the X(3872) search, we take advantage of the χ_c study because of similar kinematics.

Event Selection (I)

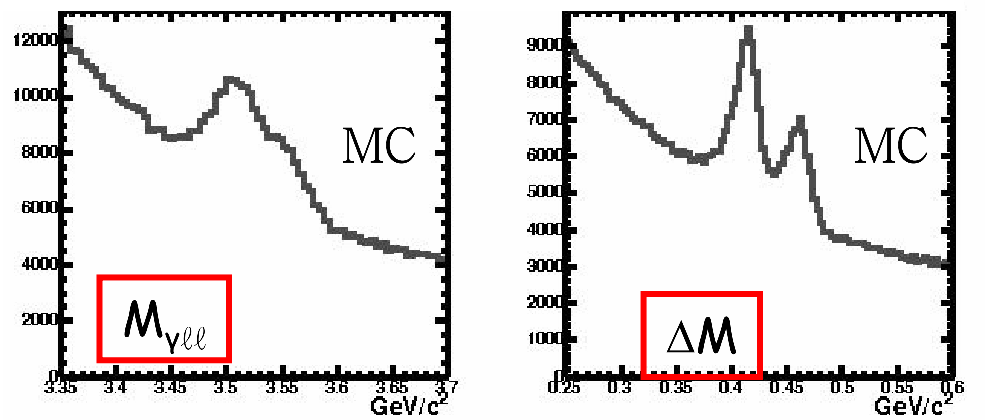
- $N_{ch} > 4$ and $R_2 < 0.8$ to suppress QED type of backgrounds : ISR $\psi(2S)$ and two-photon fusion events.

- Qualified photon candidate must satisfy:
  - $A_{42} < 0.1$: A_{42} measures the azimuthal asymmetry of the cluster about its peak, distinguishing electromagnetic from hadronic showers.
  - $0.01 < LAT < 0.5$: LAT is a measure of the radial energy profile of the cluster and is used to suppress clusters from electronic noise or hadronic interactions.
  - $0.41 < \theta < 2.41$: Photons in electromagnetic calorimeter fiducial volume (polar angle to the beam axis).
  - Reject γ from π^0 if $M_{\pi 0} \in [0.114, 0.146]$ GeV with E_γ = 30MeV, Lat < 0.8
  - Splitoff rejection by requiring at least 9° from any charged track.

Event Selection (II)

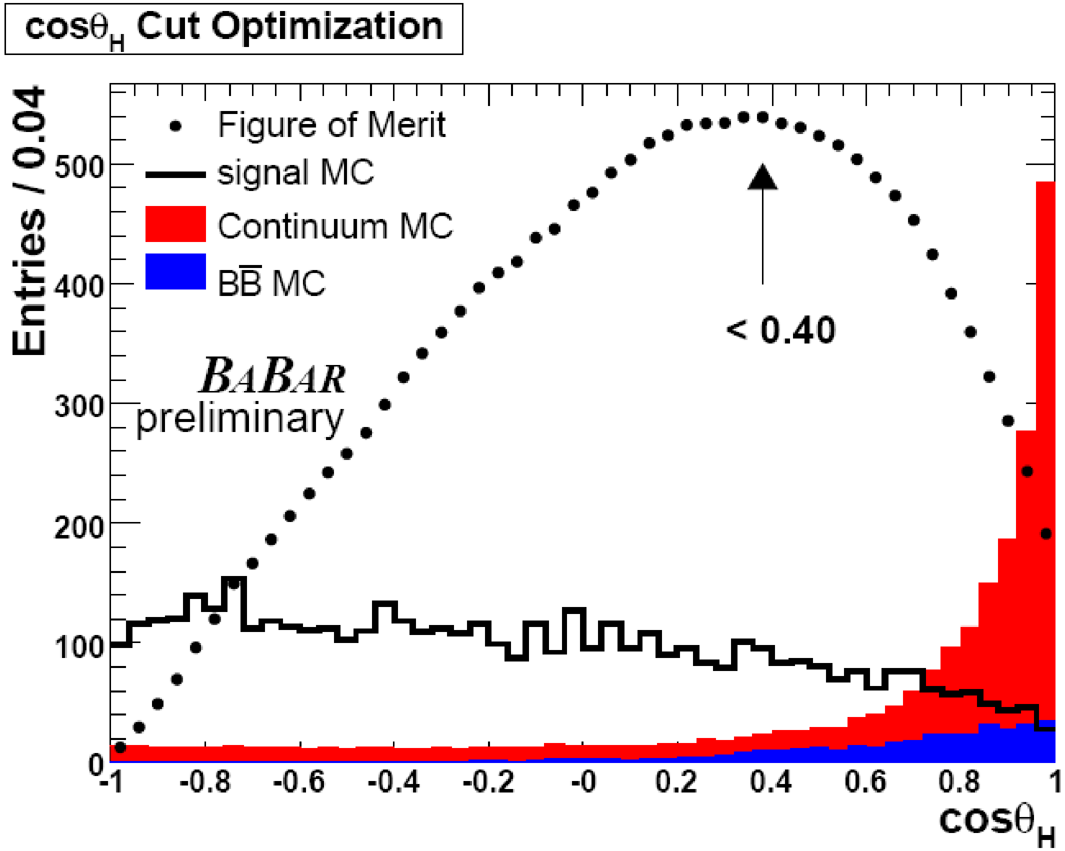
- $p^*(\chi_c, J/\psi) > 2.0$ GeV/c to suppress B-decay contribution.
- Electron id with radiation recovery. Muon identification.
- Geometric constraint on the J/ψ vertex and J/ψ mass constraint.
- $-0.05 < M_{ee} - M_{J/\psi} < 0.03$ GeV and $-0.03 < M_{\mu\mu} - M_{J/\psi} < 0.03$ GeV.
- $|\cos\theta_H(J/\psi)| < 0.9$

- $0.25 < \Delta M\ (M_{\gamma\ell\ell} - M_{\ell\ell}) < 0.60$ GeV for the χ_c search
  - More efficient variable than $M_{\gamma\ell\ell}$ to discriminate χ_{c1} from χ_{c2}.



- $0.60 < \Delta M\ (M_{\gamma\ell\ell} - M_{\ell\ell}) < 0.95$ GeV for the X(3872) search

Event Selection (III)



$\cos\theta_H(\chi_c) < 0.40$

- The figure of merit is $N_{sig}^2/(N_{cont}+N_{BB})$ for the individual cut.
- The optimized cut is not sensitive to the scale of N_{sig}.

Unbinned ML Fit

CBL Parameterization from MC.

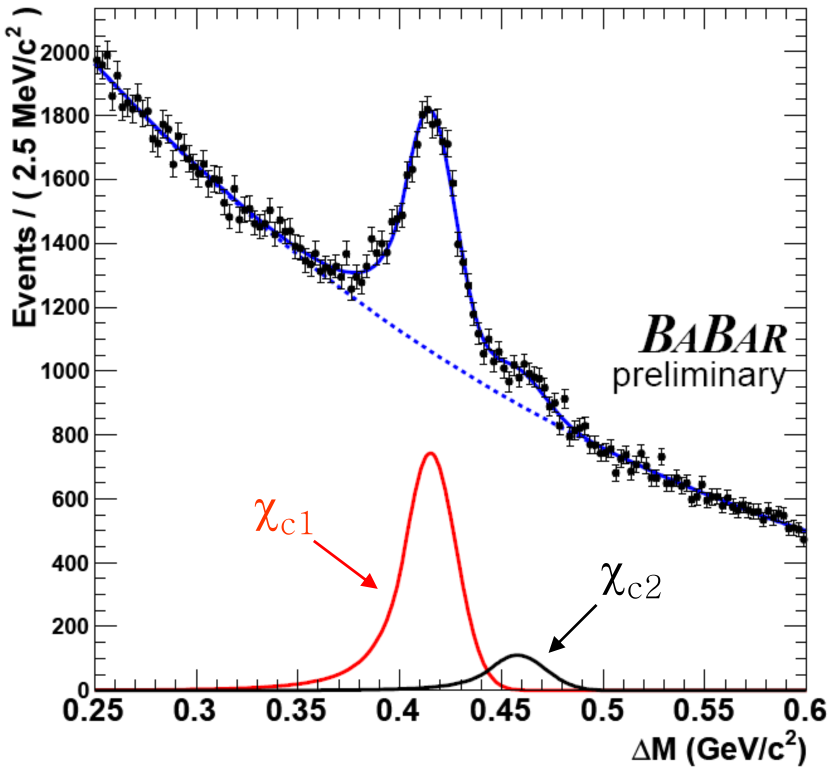
$e^+e^- \to \chi_c X$	m (MeV)	σ (MeV)	α	n
χ_{c1}	412.5	14.0	1.079	4.130
χ_{c2}	458.7	15.3	1.056	4.843
$X(3872)$	773.0	20.5	0.984	5.003

- Signal PDF
  - Crystal Ball Line shape (CBL).
  - Mass difference between χ_c is constrained to PDG 2006 value, 45.5 MeV.
  - To account for possible energy scale or resolution difference between data and MC, mean is shifted by an offset and resolution is scaled by scale factor. It's tuned by our control sample (see the next page).
- Background PDF
  - 3rd order Chebyshev polynomial with all parameters floated.
  - For the purpose of systematic error study, Exponential function is used.

$$e^{-[p_0+p_1(\Delta M)+p_2(\Delta M)^2]}$$

Control Sample

UML fit for the control sample (χ_c from B decays: p*< 1.7 GeV/c)



- To tune offset and scale, we performed an UML fit for the control sample, χ_c from B decays (p* < 1.7 GeV/c).
- To cross check, $N(\chi_{c2})$ to $N(\chi_{c1})$ ratio is calculated and it is consistent with PDG2006.
- These values (offset and scale) will be used and fixed in the UML fit to search for χ_c and X(3872) in continuum (p* > 2.0 GeV/c).

Efficiency

$$\epsilon = \epsilon_r \cdot \epsilon_v \cdot \epsilon_s \cdot f_{N_{trk}}$$

ϵ_r : Reconstruction efficiency is estimated by single χ_c MC.

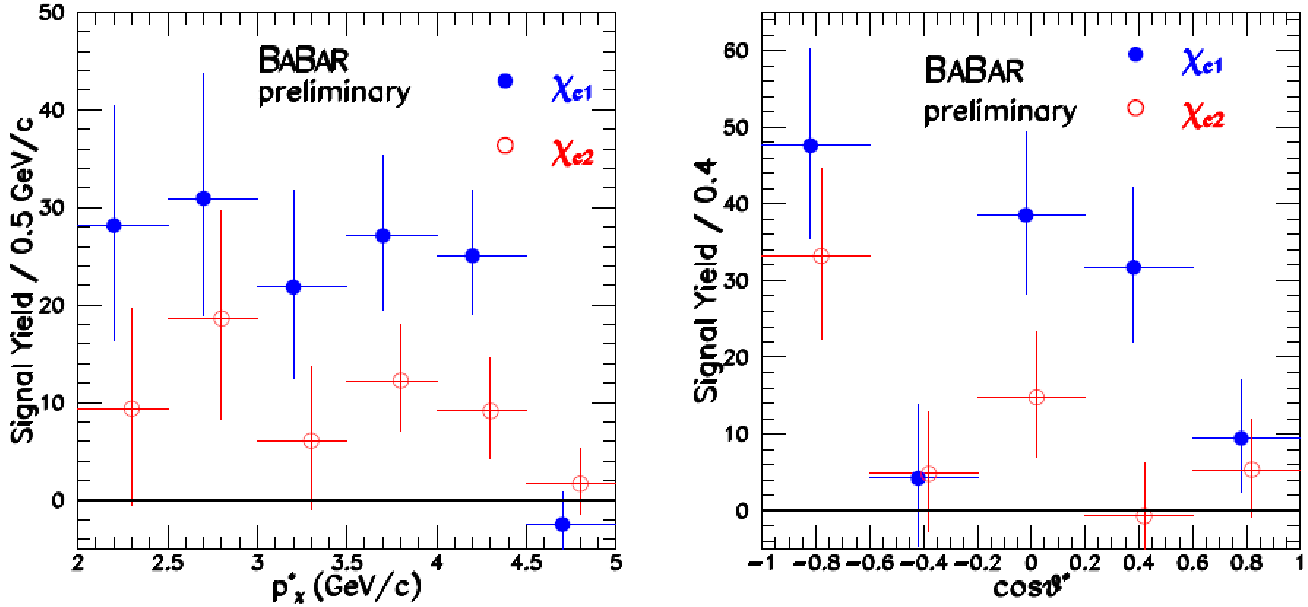
ϵ_v : Survival rate under π^0 veto

ϵ_s : Survival rate under splitoff rejection

$f_{N_{trk}}$: Fraction of signal events that pass $N_{trk} > 4$ cut

(we assume f_{Ntrk} = 1.0)

Reconstruction Efficiency (ε_r)



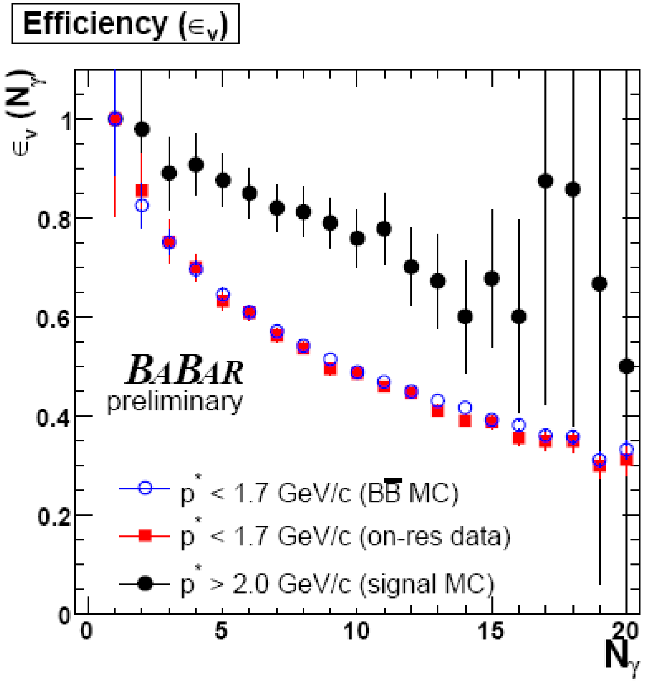
- The ε_r depends on p* and cosθ* of χ_c because of p*(J/ψ) > 2.0 GeV/c and lower coverage in endcap.

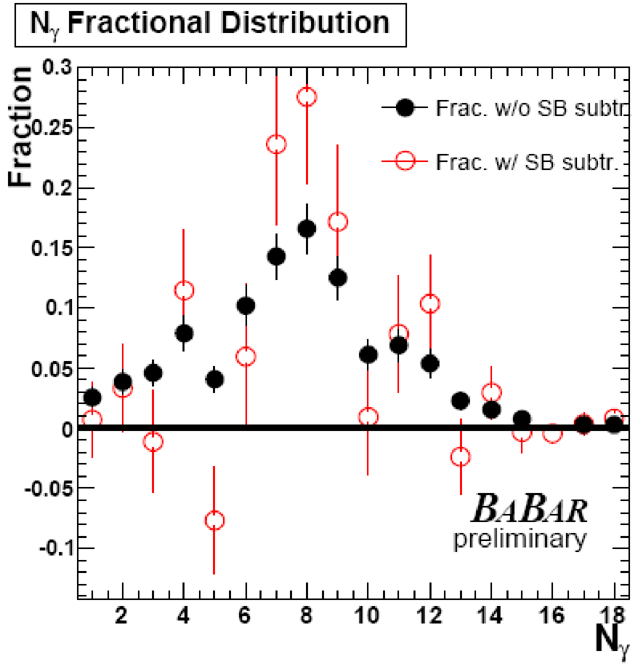
- We need to correct the single particle MC ε_r using the weight matrix of p* and cosθ* and an efficiency matrix in bins of p* and cosθ*.

$$\epsilon_r = w_{1i}^{p^*} \; \epsilon_{ij} \; w_{j1}^{\cos\theta^*}$$

i =1, 6
j =1, 5

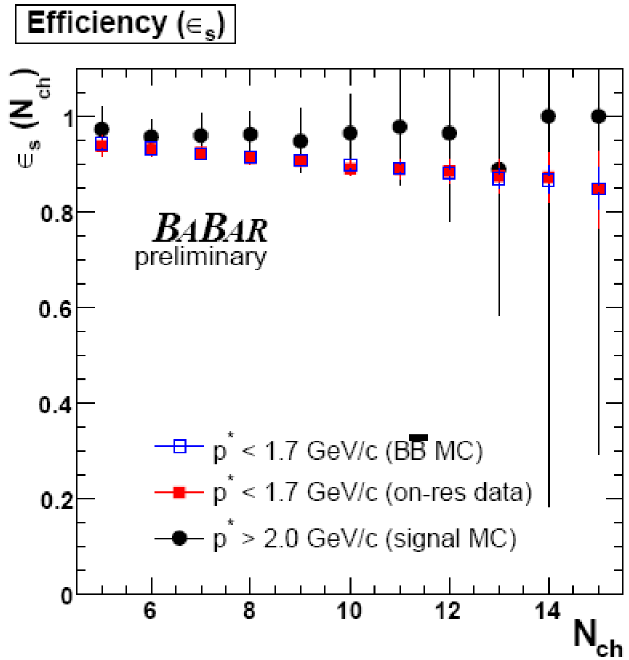
π^0 veto efficiency (ε_v)

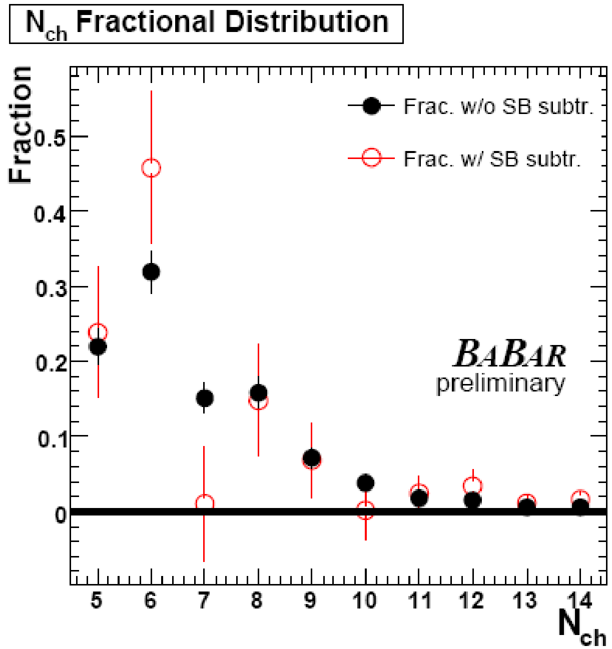




- The ε_v is dependent on the number of photons in the event.
- We need:
  - The efficiency as a function of photon multiplicity $\varepsilon_v(N_\gamma)$
  - N_γ distribution of signal events.
- The ε_v is the weighted average of $\varepsilon_v(N_\gamma)$ [weighted by the fraction of N_γ].
- Corrected by data-to-MC scale from the control sample (~ 1%).
- An alternative N_γ distribution (without sideband distribution) is used to estimate systematics.

Splitoff Rejection efficiency (ε_s)





- The ε_s is dependent on the N_{ch} in the event.
- We need:
  - The efficiency as a function of charged track multiplicity $\varepsilon_s (N_{ch})$
  - N_{ch} distribution of signal events.
- The ε_s is the weighted average of $\varepsilon_s(N_{ch})$ [weighted by the fraction of N_{ch}].
- Corrected by data-to-MC scale from the control sample (~ 0.4%).
- An alternative N_{ch} distribution (w/o sideband distribution) is used to estimate systematics.

Systematic Error Study

Uncertainty from p*/cosθ* distribution

$e^{-[p_0+p_1(\Delta M)+p_2(\Delta M)^2]}$, uncertainty of δ and β

PDG 2006

$\mathcal{B}(\chi_{c1} \to \gamma J/\psi) = (35.6 \pm 1.9)\%$ and $\mathcal{B}(\chi_{c2} \to \gamma J/\psi) = (20.2 \pm 1.0)\%$,

$\mathcal{B}(J/\psi \to e^+e^-) = (5.94 \pm 0.06)\%$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06)\%$

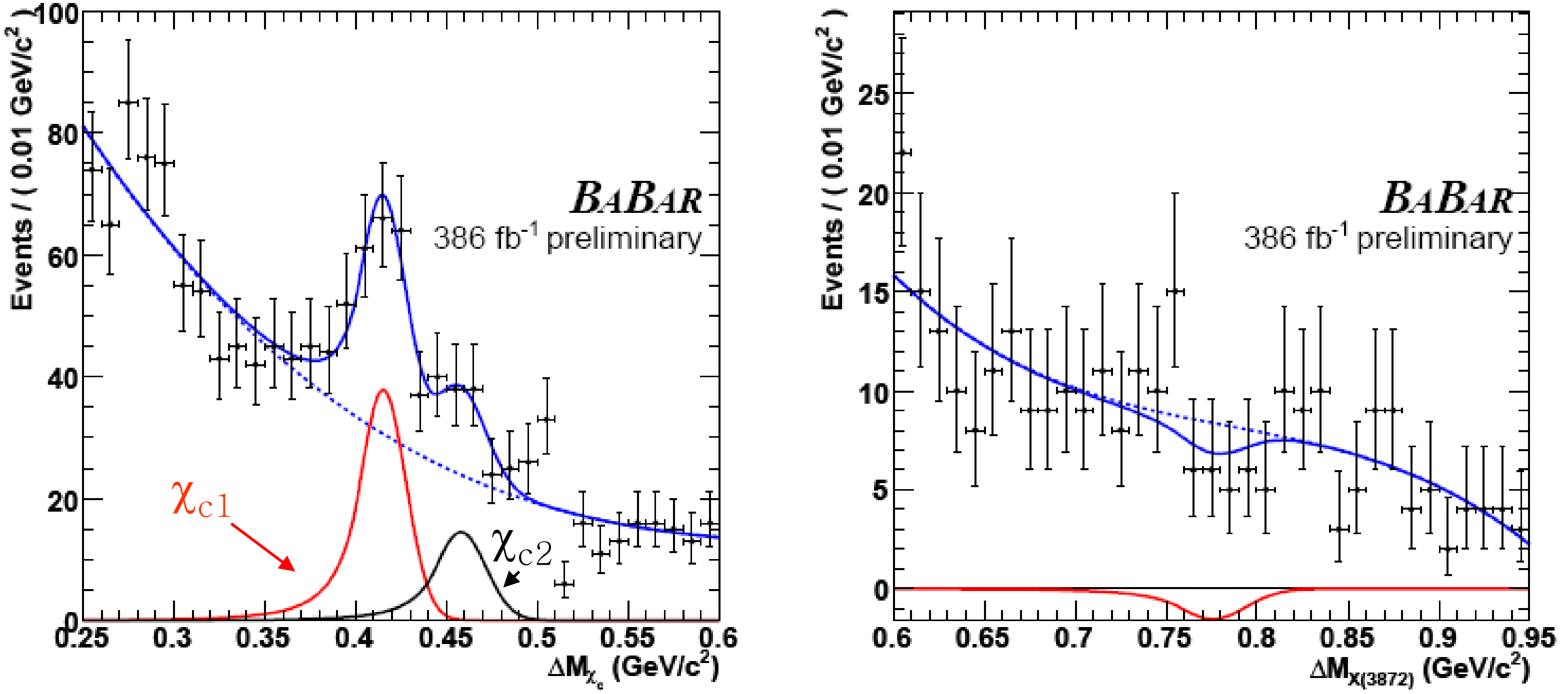
Deviation from alternative distribution of N_γ / N_{ch} or $\varepsilon_v(N_\gamma)$ / $\varepsilon_s(N_{ch})$.

	χ_{c1} (%)	χ_{c2} (%)	$X(3872)$ (%)
$p^*/\cos\theta^*$ correction	13.3	26.5	28.3
pdf	3.5	11.2	15.1
Tracking	0.2	0.2	0.2
Charged PID	7.2	7.2	7.2
Photon PID	1.8	1.8	1.8
BF_{final}	5.4	5.0	0.7
Background	7.1	5.4	–
π^0 veto	1.3	1.3	1.3
Splitoff rejection	0.4	0.4	0.4
Total	18.1	30.7	33.1

ISR ψ(2S) background is estimated from MC as 9.5 ev for the χ_{c1} and 3.0 ev for the χ_{c2}.

Yields

UML fit for the continuum data (p* > 2.0 GeV/c)



- Offset and scale are fixed to the values from the control sample.
- For the χ_c search:

$$N_{\chi_{c1}} = 134^{+23}_{-22} \text{ with } 6.6\ \sigma \text{ statistical significance}$$

$$N_{\chi_{c2}} = 56^{+19}_{-18}\ (< 80 \text{ @ } 90\% \text{ C.L.}) \text{ with } 3.2\ \sigma \text{ significance}$$

- For the X(3872) search:

$$N_{X(3872)} = -8.0 \pm 11\ (< 15 \text{ @ } 90\% \text{ C.L.})$$

Result

$$N_{fit} = \sigma \cdot \mathcal{L} \cdot \mathcal{B} \cdot \epsilon$$

$$N_{fit}^{e^+e^-} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(\chi_c \to \gamma J/\psi) \cdot \mathcal{B}(J/\psi \to e^+e^-) \cdot \epsilon_{e^+e^-}$$
$$N_{fit}^{\mu^+\mu^-} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(\chi_c \to \gamma J/\psi) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \epsilon_{\mu^+\mu^-}$$

$$N_{fit}^{\ell^+\ell^-} = N_{fit}^{e^+e^-} + N_{fit}^{\mu^+\mu^-}$$
$$= \sigma \cdot \mathcal{L} \cdot \mathcal{B}(\chi_c \to \gamma J/\psi) \cdot [\mathcal{B}(J/\psi \to e^+e^-) + \mathcal{B}(J/\psi \to \mu^+\mu^-)] \cdot \epsilon_{\ell^+\ell^-}^{avg}$$

	χ_{c1}	χ_{c2}	$X(3872)$
N_{fit}	134^{+23}_{-22}	56^{+19}_{-18} (< 80 @90% C.L.)	-8.0 ± 11 (< 15 @90% C.L.)
ϵ_r (%)	10.1	9.3	8.4
ϵ_v (%)	79.9	79.9	79.9
ϵ_s(%)	95.8	95.8	95.8
ϵ (%) ($= \epsilon_r \cdot \epsilon_v \cdot \epsilon_s$)	7.7	7.1	6.4
BF_{final} (%)	4.2	2.4	11.9
$\mathcal{L}$ (fb^{-1})	386	386	386
$\sigma(e^+e^- \to \chi_c X) \cdot \mathcal{B}(X \to (N_{ch} > 2))$ (fb)	$107 \pm 18 \pm 19$	$85^{+28}_{-27} \pm 26$	$-2.7 \pm 3.7 \pm 1.0$
@90% C.L. (fb)		< 135	< 5.1

For the X(3872), we assume BF of X(3872) → γ J/ψ is 100%.

Prompt $\psi(2S)$ feed-down

For the cross-section of prompt χ_c production, we should subtract prompt $\psi(2S)$ contribution.

It is

(58.3 ± 11.6) fb for the χ_{c1}

(54.3 ± 10.9) fb for the χ_{c2}

⟺

compared to our measured values (107 ± 26) fb for χ_{c1} and (85 ± 38) fb for χ_{c2}.

from

$$\sigma(e^+e^- \to \psi(2S)X) = (0.67 \pm 0.13) \text{ pb for } p^* > 2.0 \text{ GeV/c}$$

Belle PRL 2002

$$\mathcal{B}(\psi(2S) \to \gamma\chi_c) = (8.7 \pm 0.4)\% \text{ for } \chi_{c1} \text{ and } (8.1 \pm 0.4)\% \text{ for } \chi_{c2}$$

PDG 2006

Conclusion

After subtraction of prompt $\psi(2S)$ contribution,
prompt χ_c production cross-sections in continuum are:

$$\sigma(e^+e^- \to \chi_{c1,direct}X) \cdot \mathcal{B}(X \to (N_{ch} > 2)) = (49 \pm 18 \pm 23) \text{ fb}$$

$$(< 86 \text{ fb } @90\% \ C.L.),$$

$$\sigma(e^+e^- \to \chi_{c2,direct}X) \cdot \mathcal{B}(X \to (N_{ch} > 2)) = (31 \pm 28 \pm 28) \text{ fb}$$

$$(< 87 \text{ fb } @90\% \ C.L.).$$

While χ_c production has been observed in e^+e^- annihilation ~ 10.6 GeV,
the measured cross-sections are compatible with the expected contributions
from prompt $\psi(2S)$ production feed-down to χ_c.
No evidence of prompt χ_c production.

Prompt X(3872) production in continuum is :

$$\sigma(e^+e^- \to X(3872)X) \cdot \mathcal{B}(X(3872) \to \gamma J/\psi) \cdot \mathcal{B}(X \to (N_{ch} > 2))$$

$$= (-2.7 \pm 3.7 \pm 1.0) \text{ fb} \quad (< 5.1 \text{ fb } @90\% \ C.L.).$$

No evidence of prompt X(3872) in e^+e^- annihilation.