XYZ particles at Belle

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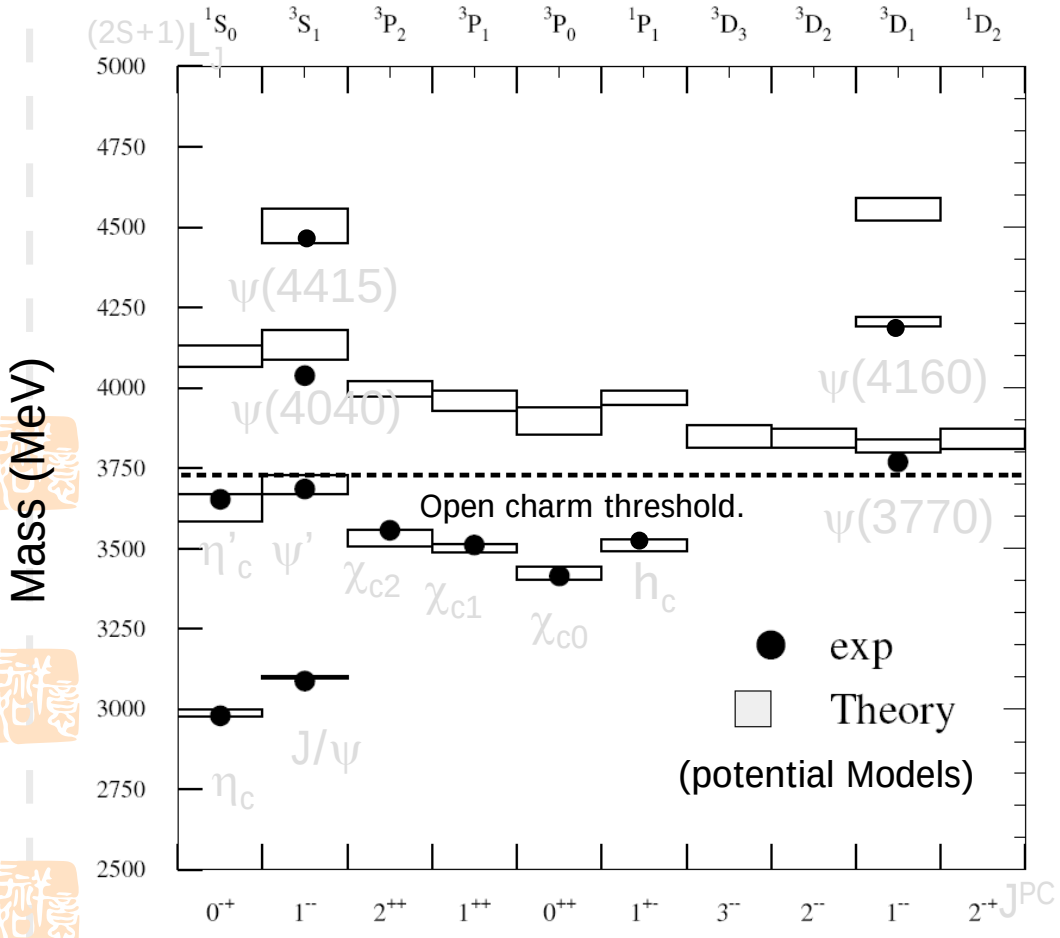
Outline

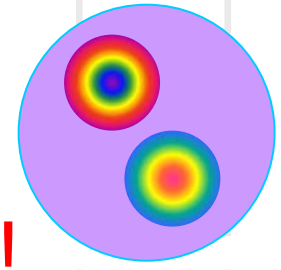
XYZ → charmonium + light meson(s)

- X(3872) – **molecular state?**
- X(3915) – **charmonia?**
- Y(4140) & X(4350) – **tetraquark states?**
- Z^+(4430,4050,4250) – **cannot be harmonia!**
- Search for X/Y in Y(1S) radiative decays

Charmonium spectroscopy



We were very proud:
Potential model worked well for charmonium.



No big progress in last century!

XYZ states

neutral X and Y

Name	J^{PC}	Γ (MeV)	Decay modes	Experiments	interpretation
X(3872)	1^{++}	<2.3	$\pi\pi J/\psi$, $\gamma J/\psi$, DD*, …	Belle/CDF/D0/BaBar	DD* molecule?
X(3940)	$0^{?+}$	~37	DD* (not DD, $\omega J/\psi$)	Belle	η_c''(?)
Y(3940)	$?^{?+}$	~30	$\omega J/\psi$ (not DD*)	Belle/BaBar	
Y(4140)	$?^{?+}$	~11	$\phi J/\psi$	Belle	ccss?
X(4160)	$0^{?+}$	~140	D*D* (not DD, DD*)	Belle	η_c''(?)
Y(4008)	1^{--}	~220	$\pi\pi J/\psi$	Belle (not Babar)	
Y(4260)	1^{--}	~80	$\pi\pi J/\psi$	BaBar/CLEO/Belle	ccg hybrid?
X(4350)	$?^{?+}$	~13	$\gamma\gamma$, $\phi J/\psi$	Belle	ccss?
Y(4360)	1^{--}	~75	$\pi\pi\psi(2S)$	BaBar/Belle	
Y(4660)	1^{--}	~50	$\pi\pi\psi(2S)$, $\Lambda_c\Lambda_c$ (?)	Belle	

charged Z

$Z^{\pm}(4430)$	$?^{??}$	~100	$\psi(2S)\,\pi^{\pm}$	Belle (not Babar)	4-quark?
$Z^{\pm}(4050)$	$?^{??}$	~80	$\chi_{c1}\,\pi^{\pm}$	Belle	4-quark?
$Z^{\pm}(4250)$	$?^{??}$	~180	$\chi_{c1}\,\pi^{\pm}$	Belle	4-quark?

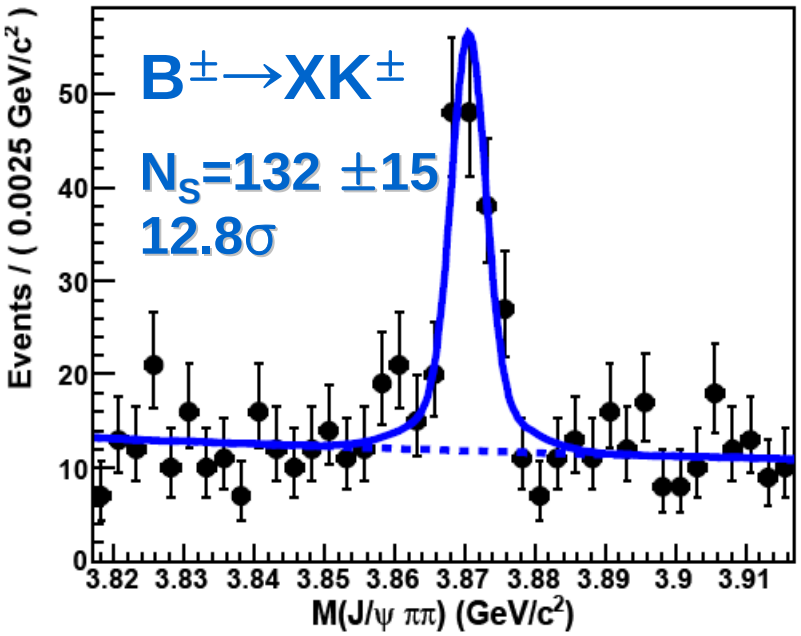
X(3872)

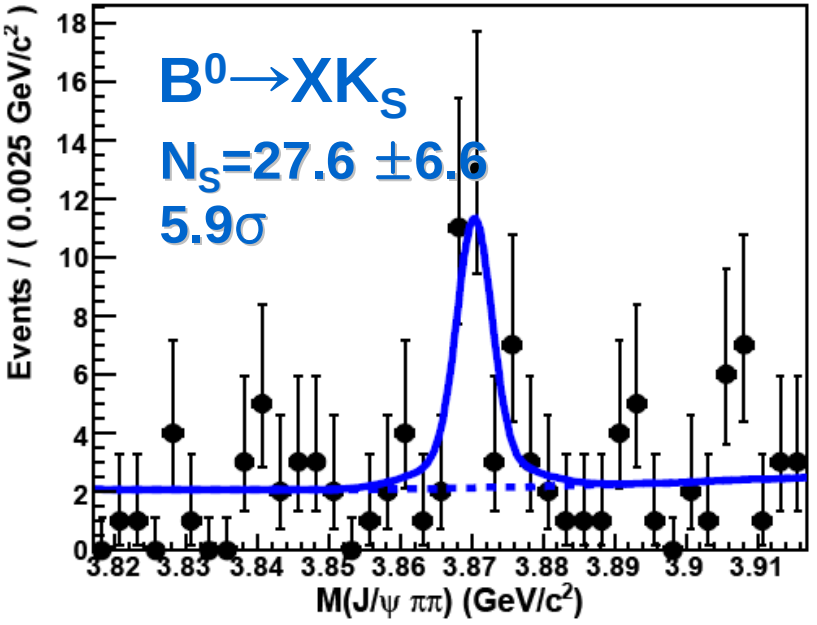
first observed at Belle

X(3872)→$\pi^+\pi^-$ J/ψ

arXiv:0809.1224 605 fb^{-1}

recent results

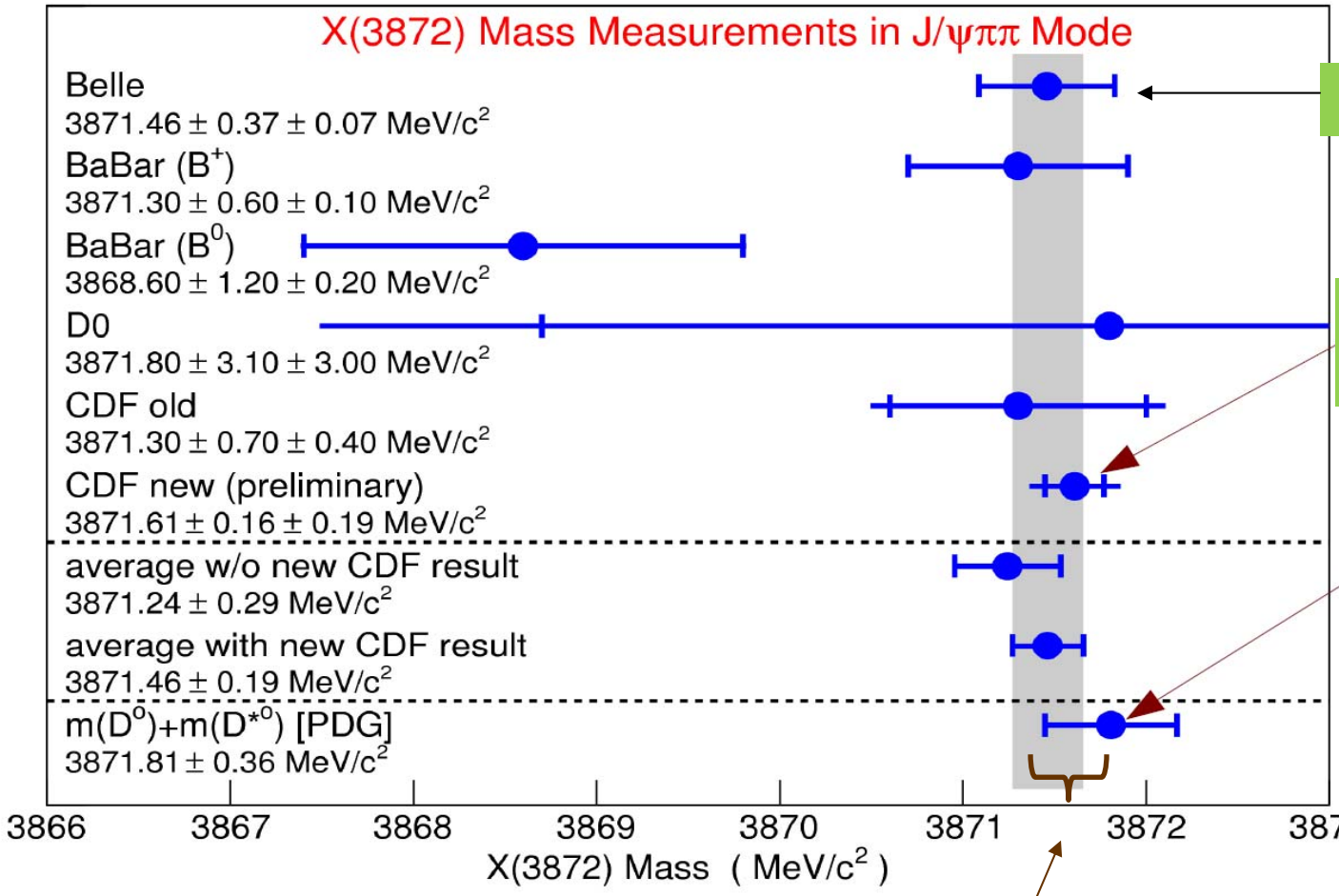




M(X(3872))=(3871.46±0.37±0.07) MeV
by combining two modes together

M(X(3872)) $\pi^+\pi^-J/\psi$ mode only

$\langle M_X \rangle = 3871.46 \pm 0.19$ MeV



new Belle meas.

new CDF meas PRL103.152001.

$M_{D0} + M_{D*0}$.

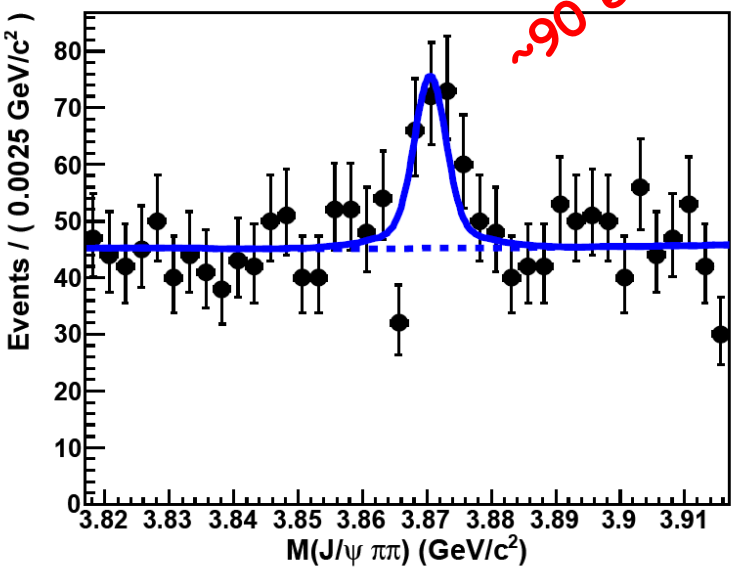
BES III can improve on this

Δm(deuteron) = -2.2 MeV

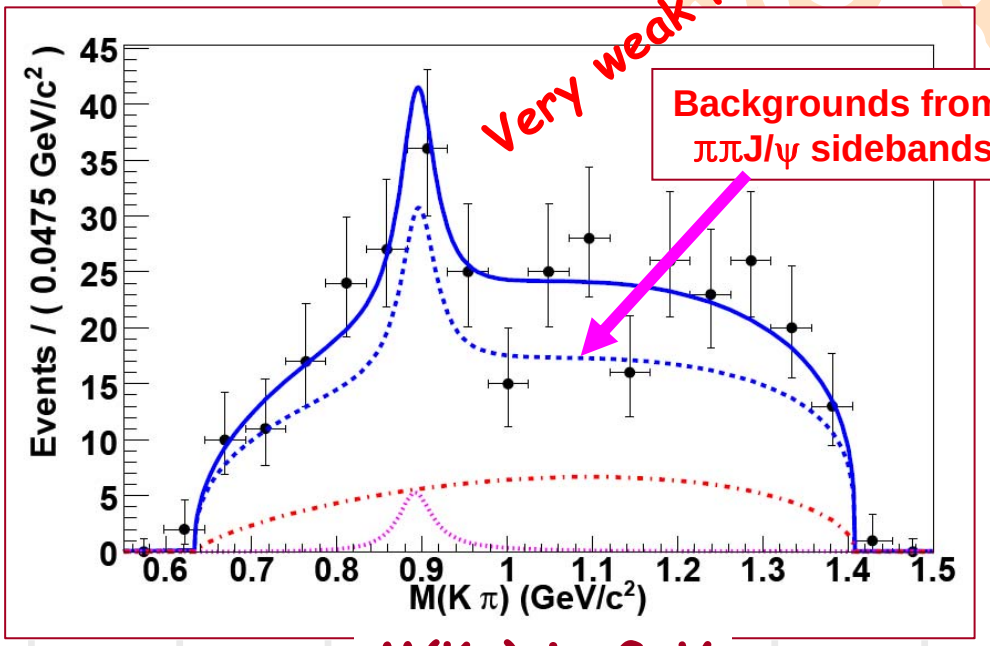
Δm = -0.35 ± 0.41 MeV

arXiv:0809.1224 605 fb^{-1}

B→Kπ X(3872)



M(ππJ/ψ) in GeV



M(Kπ) in GeV

$$\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$$

$$\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

Bf(B→J/ψ K*⁰)/Bf(B→J/ψ Kπ$_{NR}$) ~ 4. **Similar ratios for χ_{c1}, ψ(2S)!**

X is very different from other charmonia.

$$B \to X(3872)(\to D^{*0}\bar{D}^{0})K$$

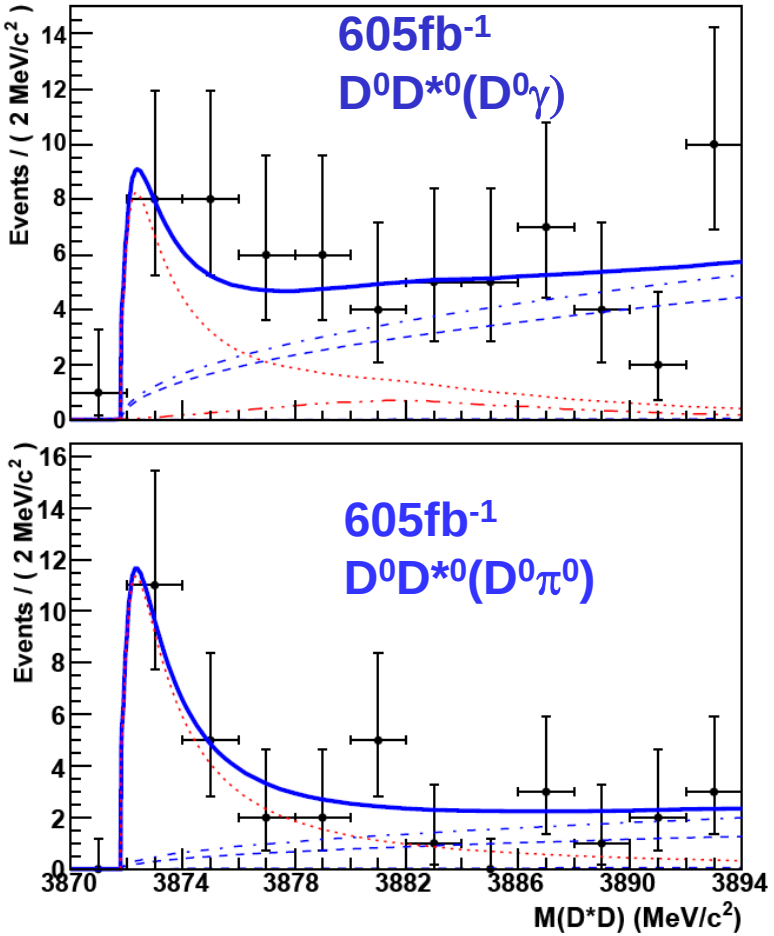
arXiv:0810.0358

- Fit with a phase-space modulated BW convolved with the mass-dependent Gaussian (Can also use other parameterizations to do the fit!)

- Simultaneous fit: 7.9σ.
  $M=3872.9^{+0.6}_{-0.4}$ MeV
  $\Gamma=3.9^{+2.7}_{-1.4}$ MeV

- (Peak at D^0D^{0*} threshold is from X(3872))?

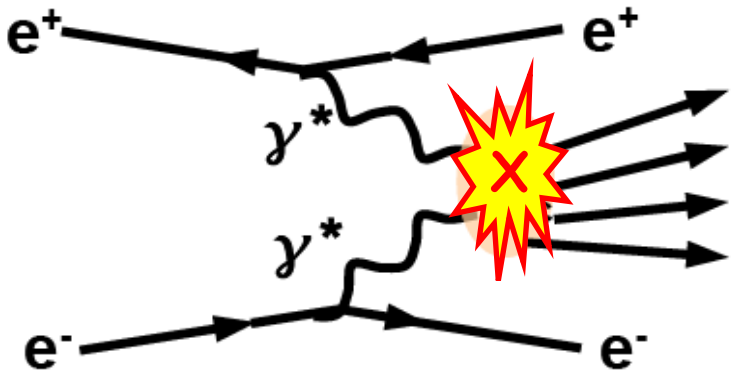
- X(3872) mass below or above D^0D^{0*}?



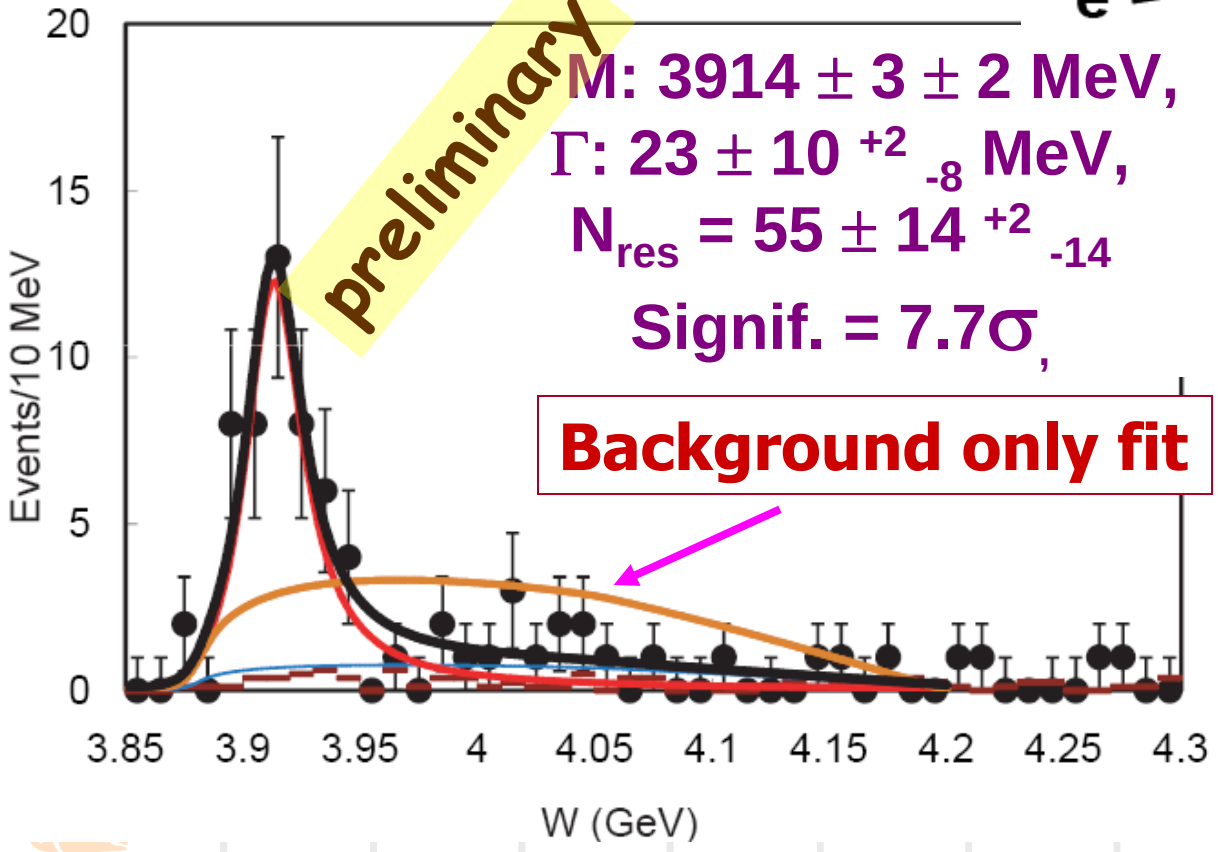
X(3915)

first observed at Belle

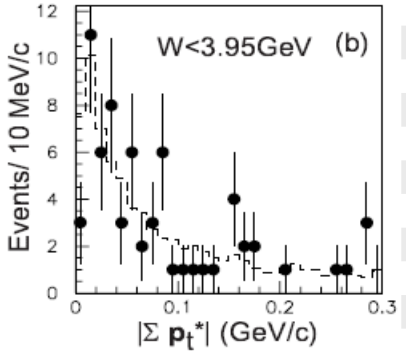
New peak in $\gamma\gamma \rightarrow \omega J/\psi$



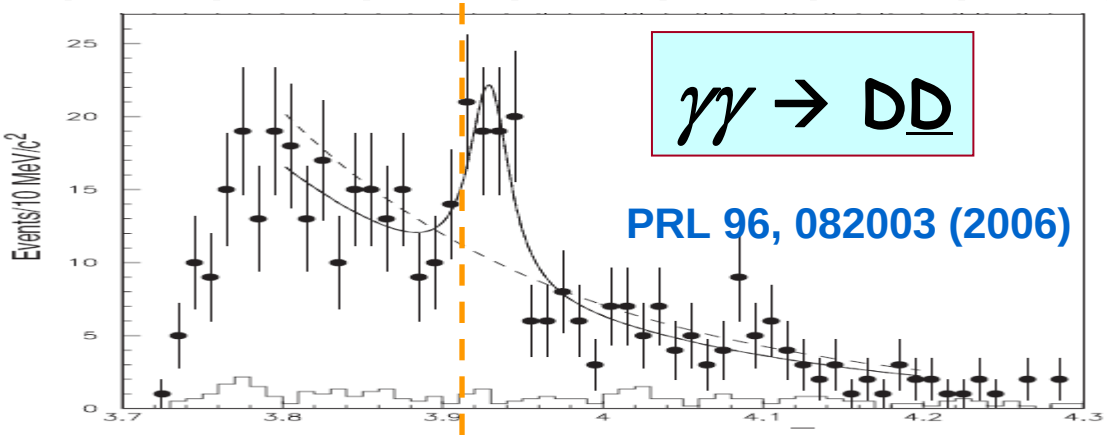
$X(3915) \rightarrow J/\psi\omega$ in $\gamma\gamma$ fusion?



- e^+e^- undetected
- p_t balance required



Could it be the Z(3930)?



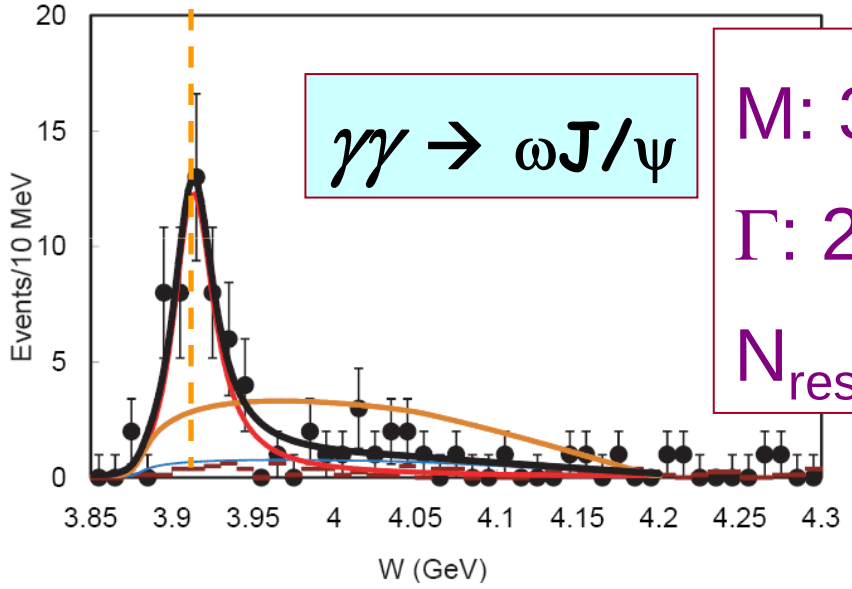
$\gamma\gamma \rightarrow D\bar{D}$

PRL 96, 082003 (2006)

$M = 3929 \pm 5 \pm 2$ MeV

$\Gamma_{tot} = 29 \pm 10 \pm 2$ MeV

Nsig = 64 ± 18 evts



$\gamma\gamma \rightarrow \omega J/\psi$

M: $3914 \pm 3 \pm 2$ MeV,

Γ: $23 \pm 10\ ^{+2}_{-8}$ MeV,

$N_{res} = 55 \pm 14\ ^{+2}_{-14}$ evts

$\Gamma_{\gamma\gamma}$ partial width

$\Gamma_{\gamma\gamma}B(\omega J/\psi) = 69 \pm 16^{+7}_{-18}$ eV ($J^P=0^+$)

$\Gamma_{\gamma\gamma}B(\omega J/\psi) = 21 \pm 4^{+2}_{-5}$ eV ($J^P=2^+$)

For comparison:
$Z(3930)$: $\Gamma_{\gamma\gamma}B(DD) = 180 \pm 50 \pm 30$ eV

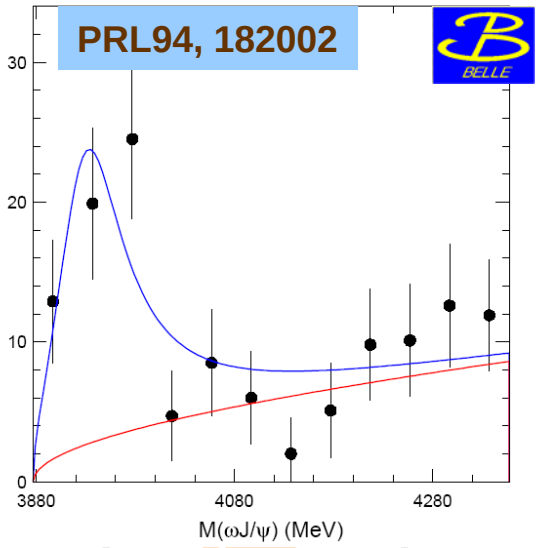
If X(3915) = Z(3930) = χ_{c2}' ➔ $\dfrac{B(\chi_{c2}' \to \omega J/\psi)}{B(\chi_{c2}' \to DD)} \geq 0.08$

Huge for above-open-charm-threshold charmonium

Could it be the Y(3930)?

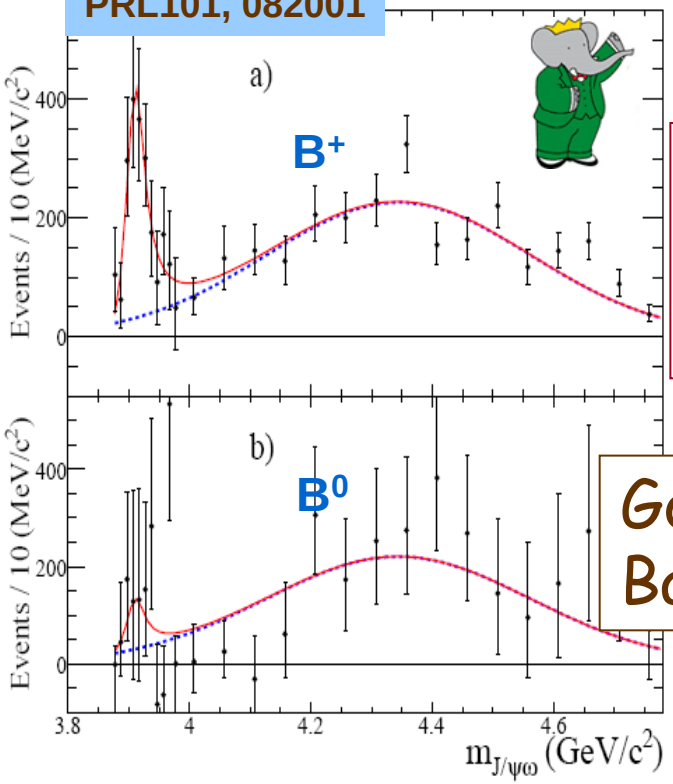
B→K ωJ/ψ

PRL94, 182002



M≈3943 ± 17 MeV
Γ≈ 87 ± 34 MeV

PRL101, 082001



M≈3915 ± 5 MeV
Γ≈ 33 ± 13 MeV

X(3915):

M: 3914 ± 3 ± 2 MeV,

Γ: 23 ± 10 $^{+2}_{-8}$ MeV,

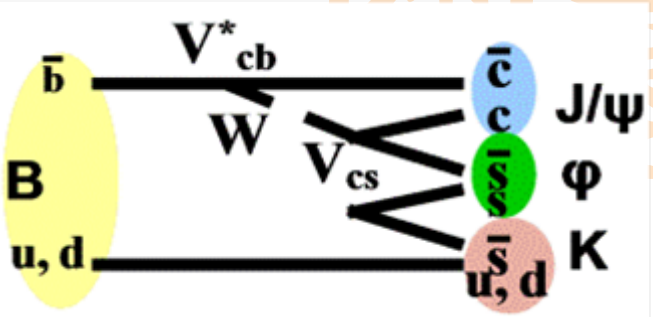
Good overlap with BaBar "Y(3940)" values

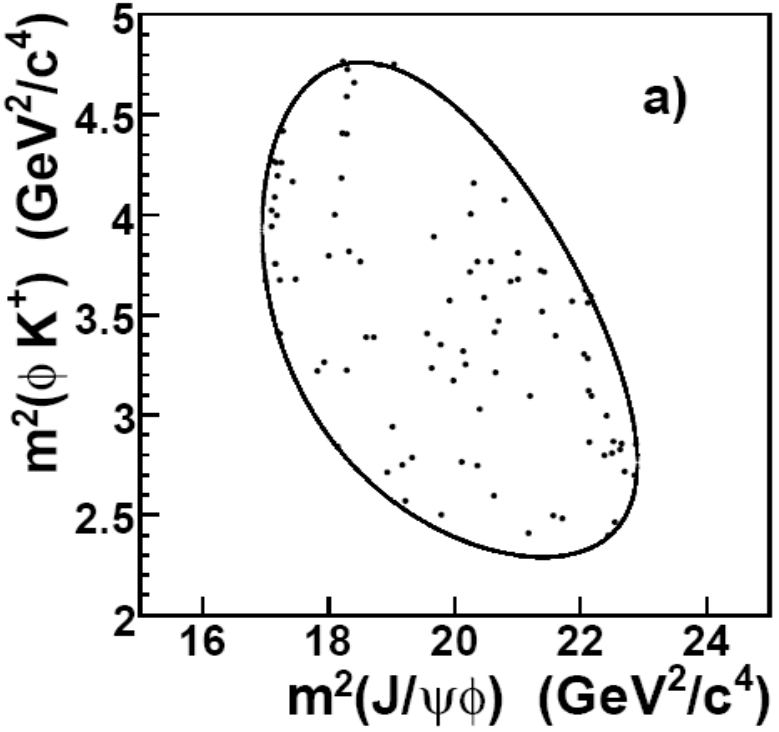
States decaying into $J/\psi\phi$

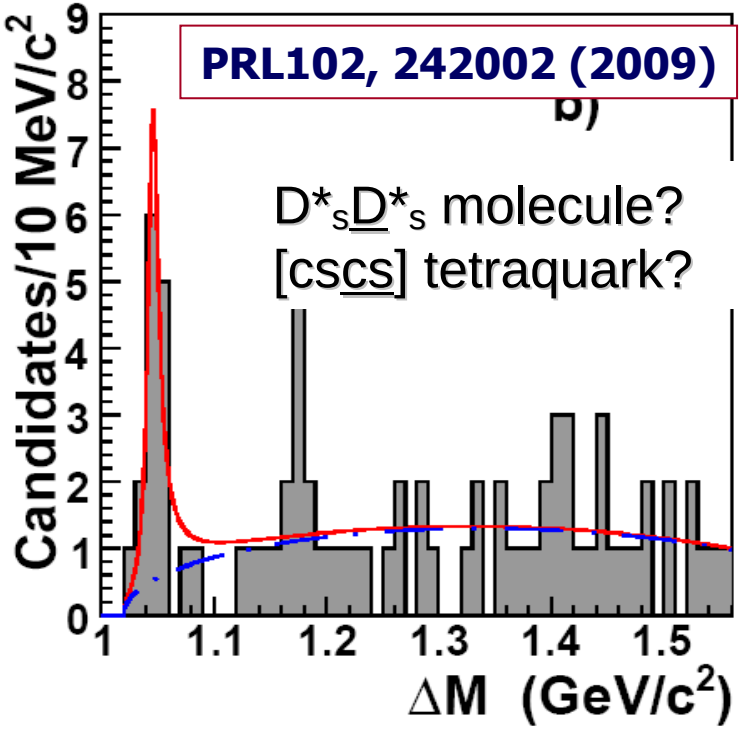
Evidence for Y(4140) and a New Resonance at 4.35 GeV

The CDF Y(4140)→φJ/ψ

- **$B^+ \rightarrow Y(4140)K^+$**
- **14 ± 5 events, $>3.8\sigma$**
- **Mass: $4143.0 \pm 2.9 \pm 1.2$ M…**
- **Width: $11.7^{+8.3}_{-5.0} \pm 3.7$ MeV (It is narrow!)**







Y(4140) not significant at Belle

- Belle: $B \to J/\psi\phi K$ with 772M $B\bar{B}$

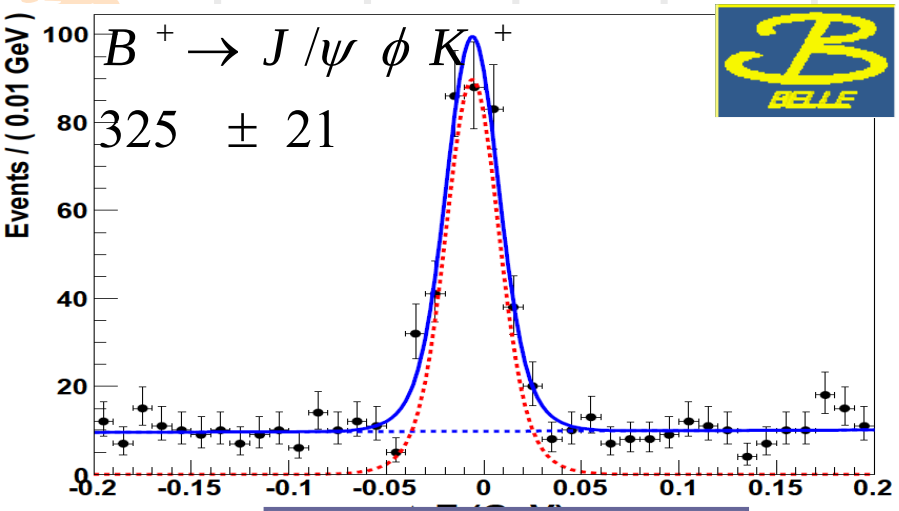
  $M(J/\psi\phi)$ fit with Y(4140) parameters fixed

[but low effciency at $J/\psi\phi$ threshold]

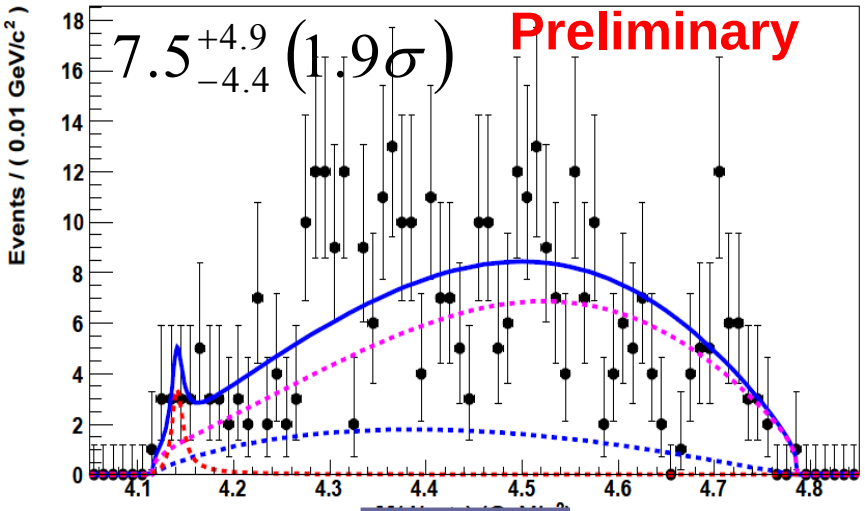
$$Br\left(B^+ \to Y(4140)K^+, Y \to J/\psi\phi\right) < 6\times10^{-6}\ @\ 90\%\ C.L$$

CDF result :

$$Br\left(B^+ \to Y(4140)K^+, Y \to J/\psi\phi\right) = \left(9.0 \pm 3.4 \pm 2.9\right)\times10^{-6}$$

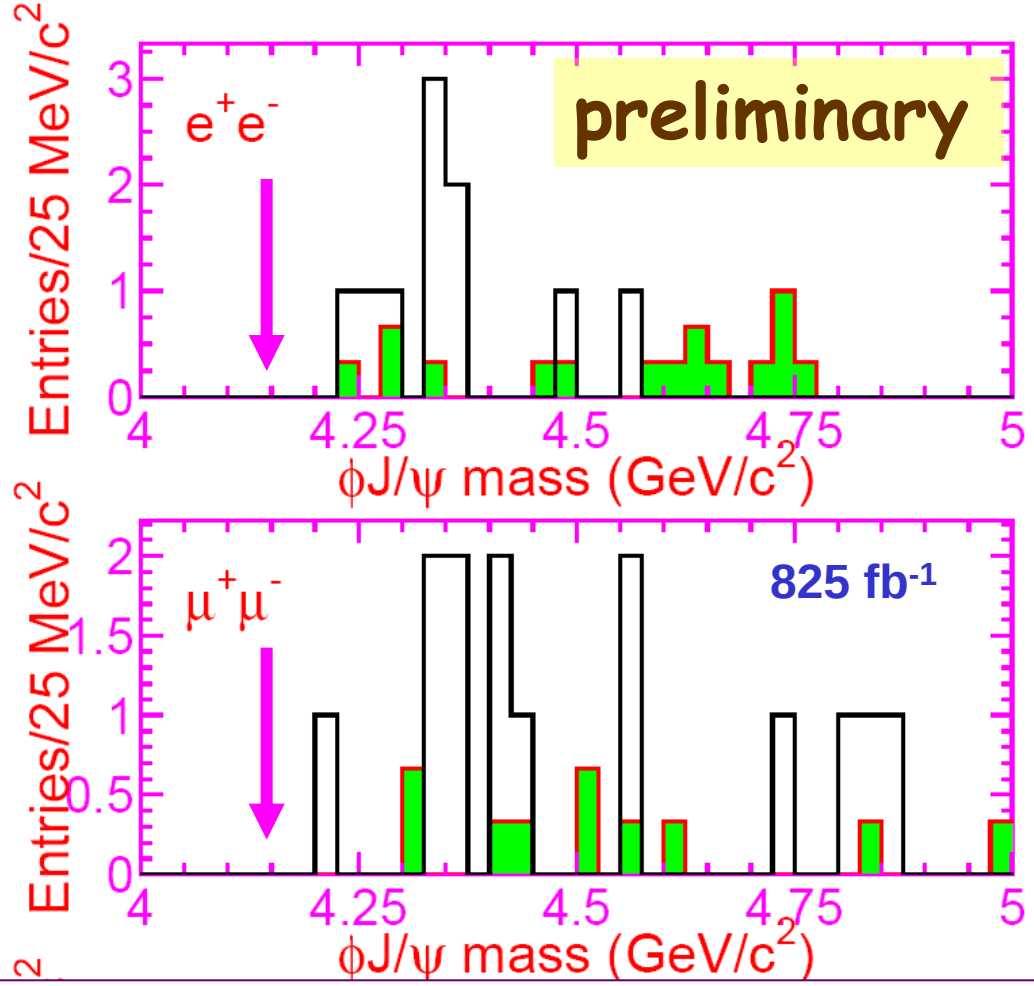


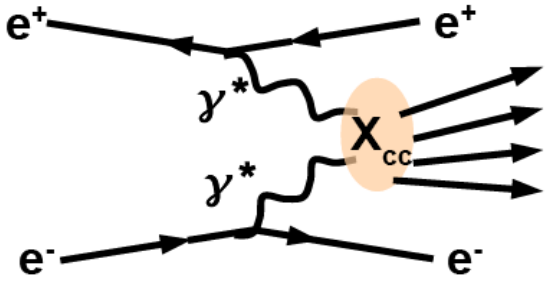
$\Delta E = E_B - \sqrt{s}/2$



$M(J/\psi\phi)$

Searched for Y(4140) in $\gamma\gamma \rightarrow \phi J/\psi$





- No Y(4140)
- A few events accumulate at 4.35 GeV in both

  J/ψ→ee & μμ modes
- **Our upper limits disfavor the scenario Y(4140) being**

  a D_s^{**} D_s^{*} molecule with

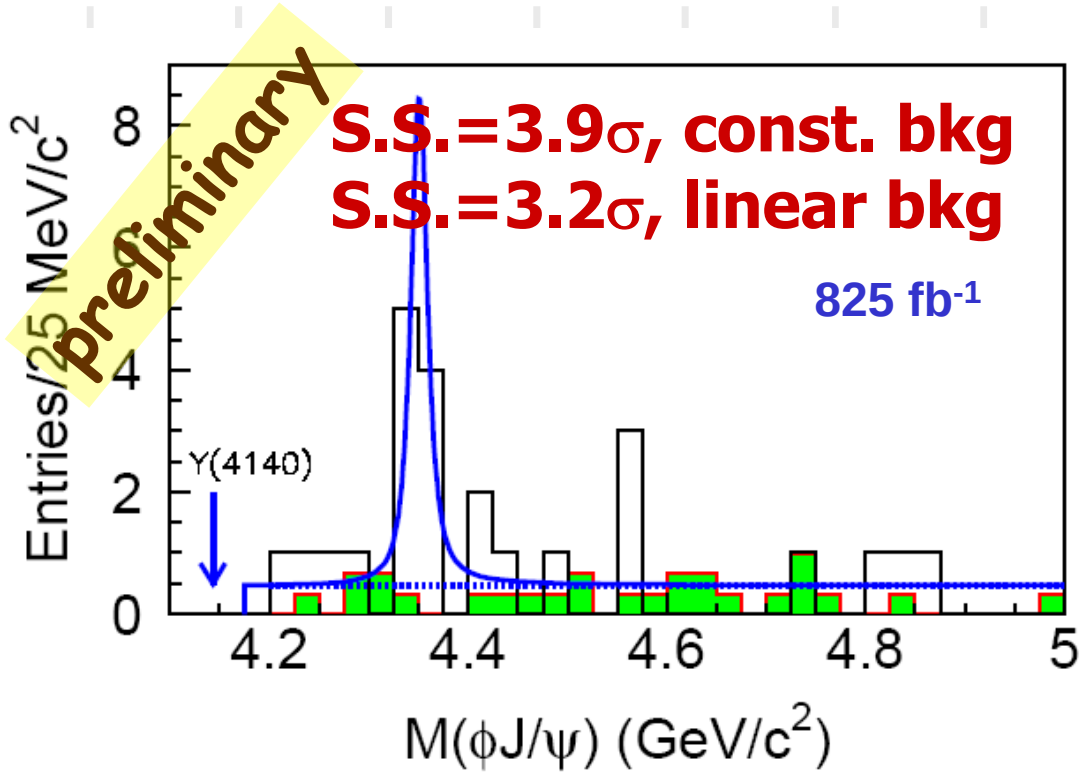
  $J^{PC}=0^{++}$ or 2^{++}

  [PRD80, 054019,2009]

$J^P=0^+$: $\Gamma_{\gamma\gamma}Br(Y(4140)) \rightarrow \phi J/\psi) < 39$ eV @ 90% C.L.

$J^P=2^+$: $\Gamma_{\gamma\gamma}Br(Y(4140)) \rightarrow \phi J/\psi) < 5.7$ eV @ 90% C.L.

Fit to $\phi J/\psi$ invariant mass



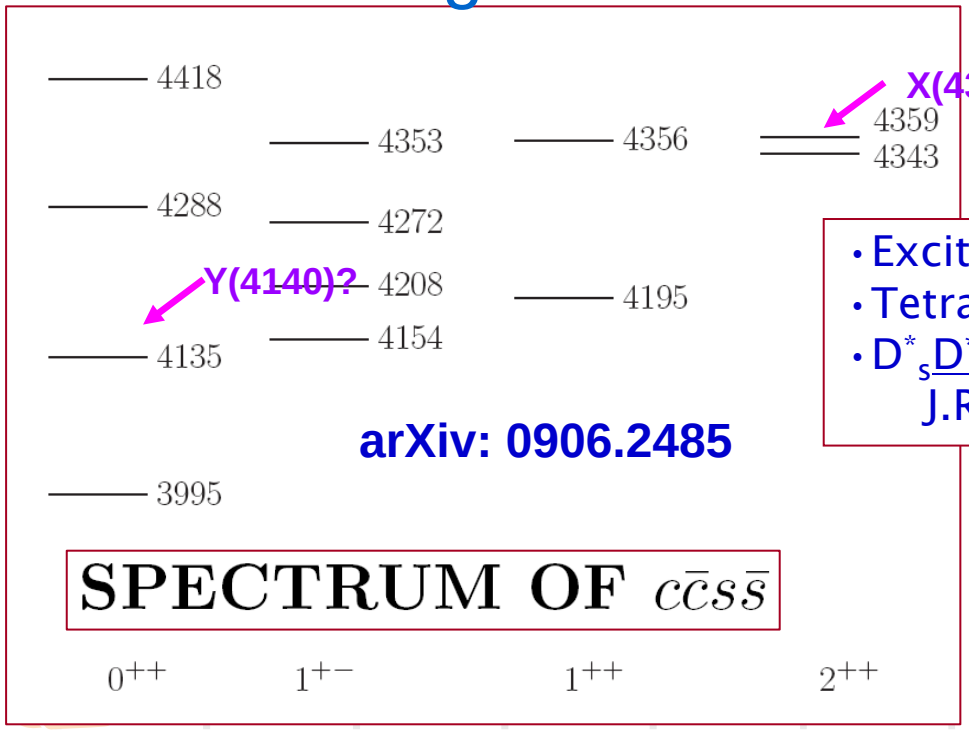
- unbinned maximum likelihood method
- BW convoluted with Double Gaussian resolution function
- mass resolution is 5.5 MeV at 4.35 GeV

$J^P=0^+$: $\Gamma_{\gamma\gamma}Br(X(4350) \rightarrow \phi J/\psi) = 6.4^{+3.1}_{-2.3} \pm 1.1$ eV

$J^P=2^+$: $\Gamma_{\gamma\gamma}Br(X(4350) \rightarrow \phi J/\psi) = 1.5^{+0.7}_{-0.5} \pm 0.3$ eV

Preliminary results (X(4350))

- $M(X(4350))=4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV/c^2
- $\Gamma=13.3^{+17.9}_{-9.1} \pm 4.1$ MeV/c^2
- $N(X(4350))=8.8^{+4.2}_{-3.2}$
- Statistical significance: **3.2-3.9σ**



- Excited P-wave charmonium?
- Tetraquark? Fl. Stancu, arXiv: 0906.2485
- $D^*_s\overline{D^*_{s0}}$ molecule at 4.34±0.09 GeV? J.R.Zhang et al., arXiv:0905.4672

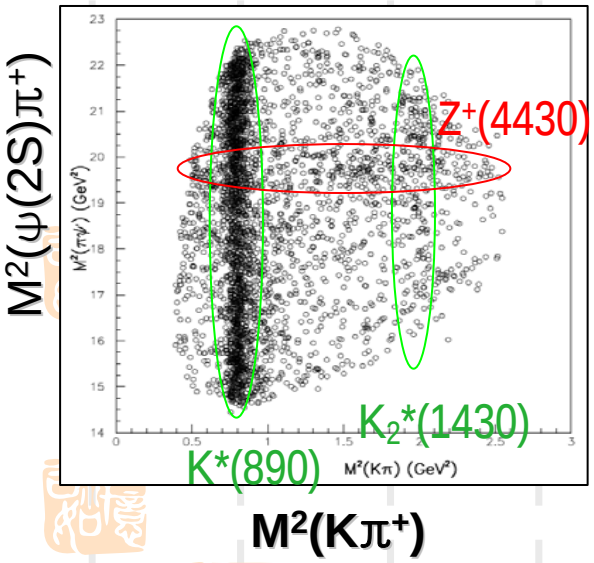
Charged state $Z^+(4430)$ and more

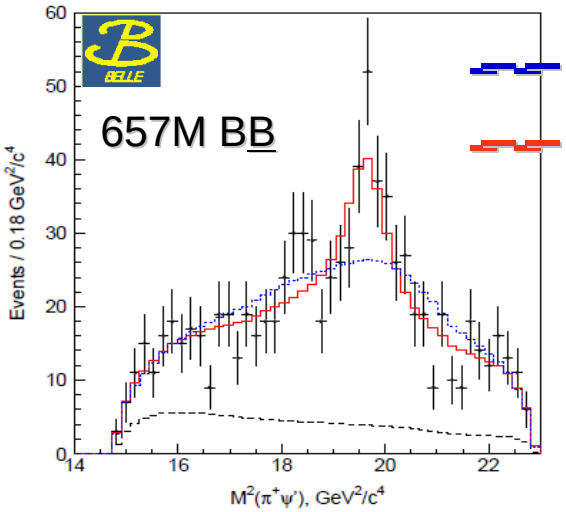
Unambiguous tetraquark state?

$Z(4430)^{\pm} \to \psi(2S)\,\pi^{\pm}$

- Found in $\psi(2S)\,\pi^+$ from $B \to \psi(2S)\,\pi^+ K$, Z parameters from fit to $M(\psi(2S)\,\pi^+)$ (**NOT confirmed by Babar**)
- Confirmed through Dalitz-plot analysis of $B \to \psi(2S)\,\pi^+ K$
- $B \to \psi(2S)\,\pi^+ K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^* \to K\,\pi^+$ resonances only

  all known $K^* \to K\,\pi^+$ and $Z^+ \to \psi(2S)\,\pi^+$ ⇨ favored by data





Significance: 6.4σ

fit for model with K*'s only

fit for model with K*'s and Z

$$M = 4433\,^{+15\,+19}_{-12\,-13}\ MeV$$

$$\Gamma = 107\,^{+86\,+74}_{-43\,-53}\ MeV$$

PRD80, 031104 (2009)

- [cu][cd] tetraquark? neutral partner in $\psi'\,\pi^0$ expected
- $D^*\underline{D}_1(2420)$ molecule? should decay to $D^*\underline{D}^*\,\pi$

Two $Z^{\pm} \to \chi_{c1} \pi^{\pm}$

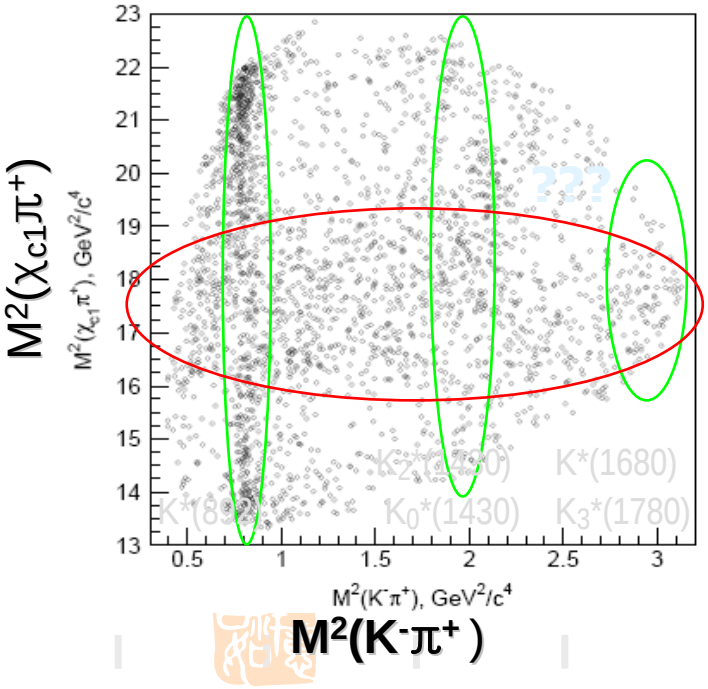
- Dalitz-plot analysis of $B^0 \to \chi_{c1} \pi^+ K^-$ $\chi_{c1} \to J/\psi \gamma$ with 657M $B\bar{B}$
- Dalitz plot models: known $K^* \to K \pi$ only

  K^*'s + one $Z \to \chi_{c1} \pi^{\pm}$

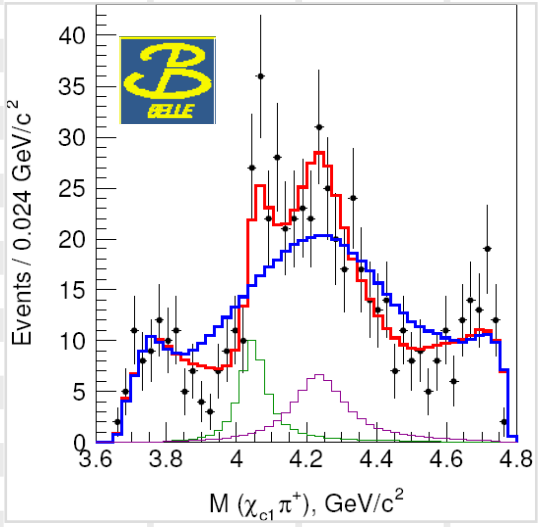
  K^*'s + two $Z^{\pm}$ states ⇨ favored by data

Significance: 5.7σ

PRD 78, 072004 (2008)



$M^2(K^-\pi^+)$



$M(\chi_{c1}\pi^+)$
for $1<M^2(K^-\pi^+)<1.75 GeV^2$

fit for model with K*'s

fit for double Z model

Z_1 contribution

Z_2 contribution

$$M_{Z_1} = 4051 \pm 14^{+20}_{-41}\ \text{MeV}$$

$$\Gamma_{Z_1} = 82^{+21\,+47}_{-17\,-22}\ \text{MeV}$$

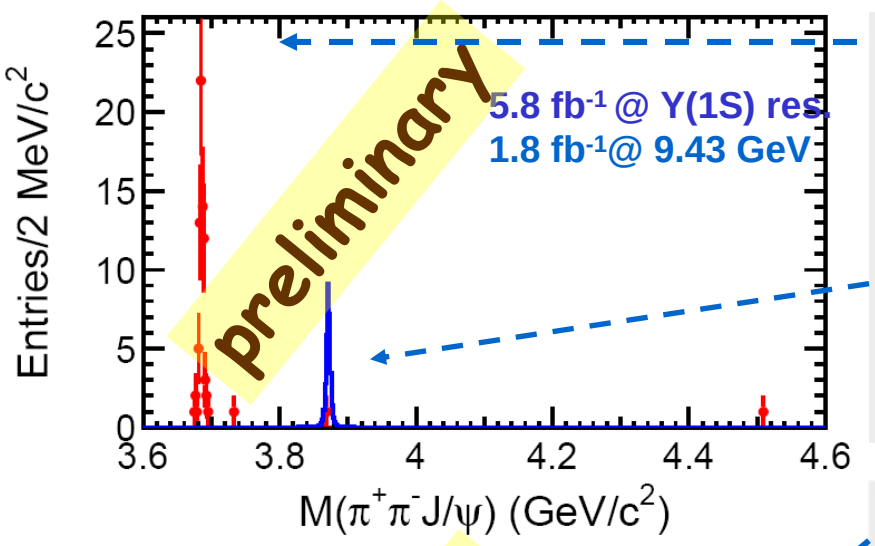
$$M_{Z_2} = 4248^{+44\,+180}_{-29\,-35}\ \text{MeV}$$

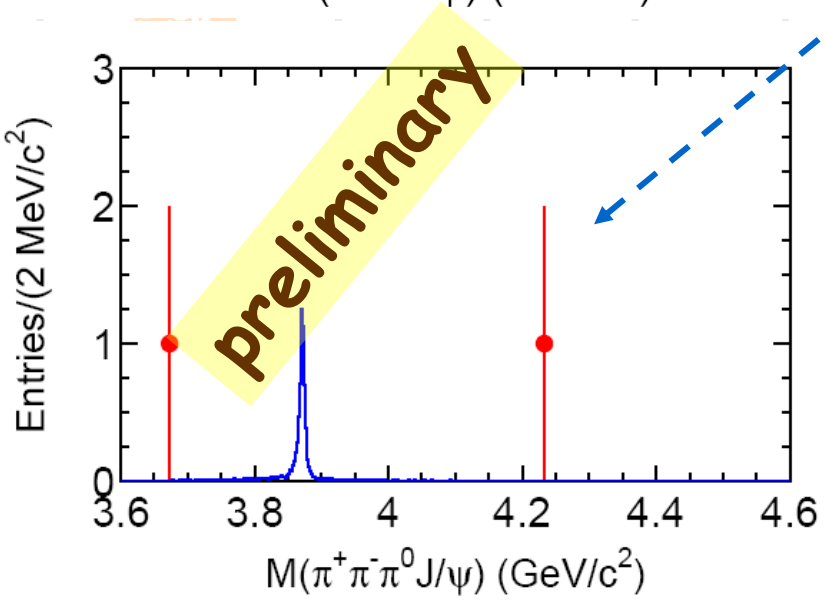
$$\Gamma_{Z_2} = 177^{+54\,+316}_{-39\,-61}\ \text{MeV}$$

Search for X/Y states in Y(1S) radiative decays

NEW!

Y(1S)→ γ X/Y





- σ(e+e- → ψ (2S))=20.2 ±1.1(stat.) pb
- Except for the ISR produced ψ (2S), there are only a few events scattered above the ψ (2S) peak
- No events from J/ψ sidebands. But one candidate around X(3872) mass region
- B(Y(1S)→ γ X(3872))B(X(3872)→ $\pi^+\pi^-$ J/ψ)<2.2x10^{-6}

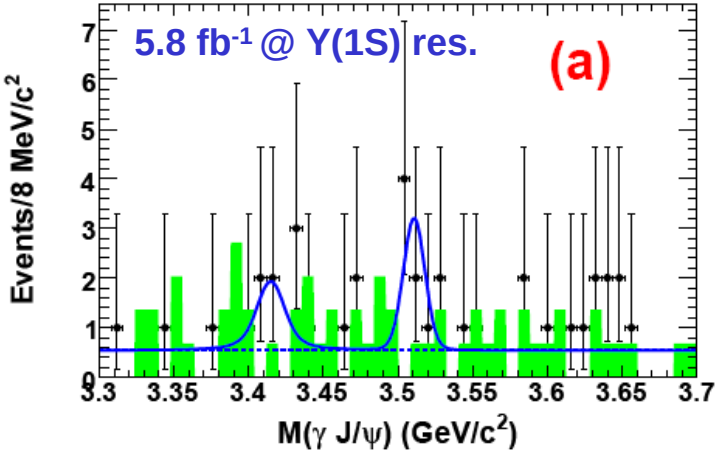
- There are two events scattered above 3.6 GeV. One is at 3.67 GeV, the other is at 4.23 GeV. The orresponding 3π masses are at 0.54 GeV and 1.04 GeV
- B(Y(1S)→ γ X(3872))B(X(3872) → $\pi^+\pi^-\pi^0$J/ψ)<3.4x10^{-6}
- B(Y(1S)→ γ X(3915))B(X(3915)→ ω J/ψ)<3.4x10^{-6}

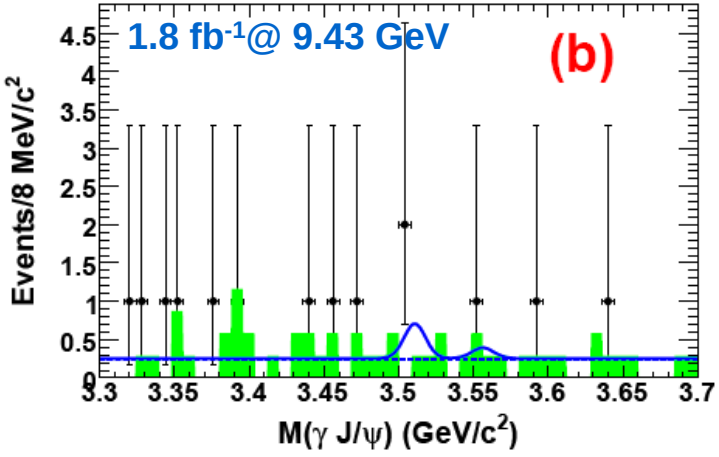
- B(Y(1S)→ γ Y(4140))B(Y(4140)→ φ J/ψ)<2.6x10^{-6}

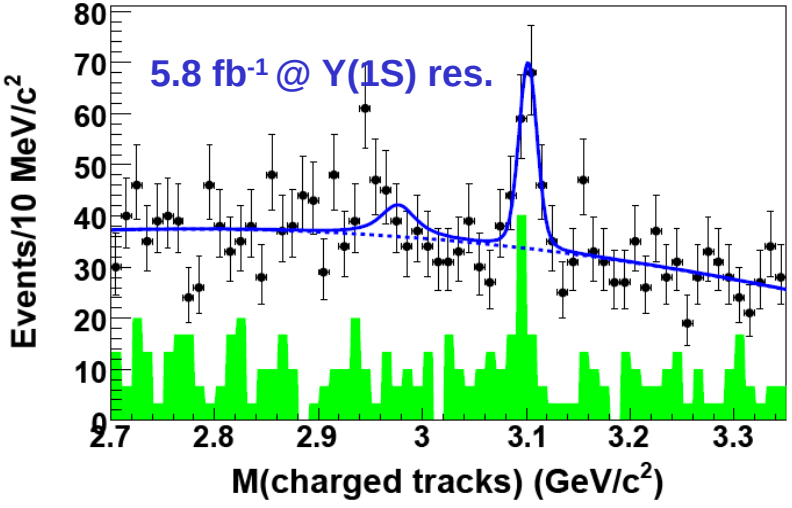
NEW!

$\Upsilon(1S) \to \gamma X_{cJ} / \eta_c$

For comparison, we also studied:







- No clear XcJ or η signal is observed
- $B(\Upsilon(1S) \to \gamma X_{c0}) < 5.0 \times 10^{-4}$
- $B(\Upsilon(1S) \to \gamma X_{c1}) < 1.5 \times 10^{-5}$
- $B(\Upsilon(1S) \to \gamma X_{c2}) < 1.2 \times 10^{-5}$
- $B(\Upsilon(1S) \to \gamma \eta_c) < 6.4 \times 10^{-5}$

- The above upper limits do not contradict with the calculation in K.T.Chao et al.,hep-ph/0701009

$\eta_c \to K_S K\pi$, $K^+K^-\pi^+\pi^-$, $2(\pi^+\pi^-)$, $2(K^+K^-)$ and $3(\pi^+\pi^-)$

Summary of the talk

Many XYZ states were observed in XYZ ➔ charmonium + light meson(s)

- **They do NOT decay into open charm states although they are above the charm pairs mass threshold: unusal for conventional charmonia**
- **Y(4140) is close to the thresholds: what about threshold effects?**
- **Some Masses ~ M($D\bar{D}_1$) for Y(4260) , M($D_s^{*+}D_s^{*}$) for Y(4140): molecules?**
- **Charged Z can not be accomodated within $c\bar{c}$ spectrum**
- **No single model can accomodate all XYZ states**

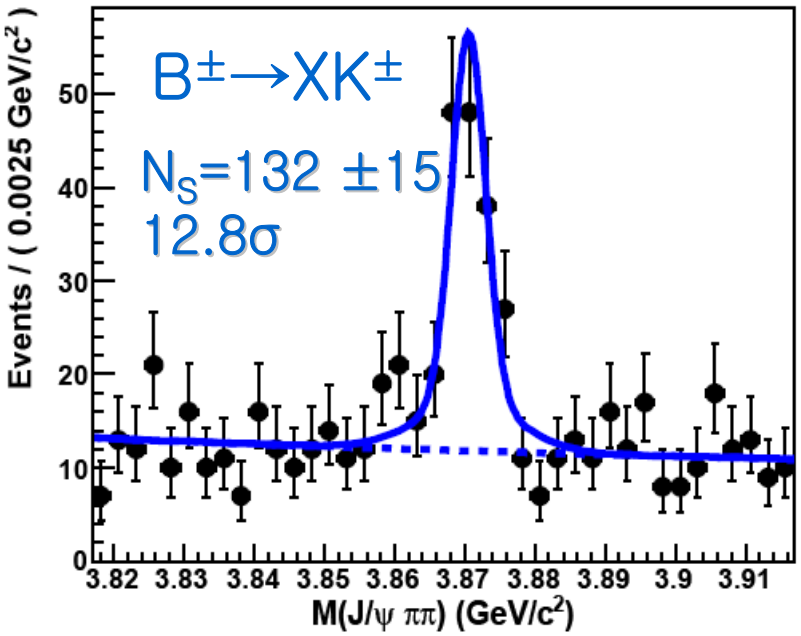
- **New charmonium-like spectroscopy at ~4GeV**
- **Waiting for related predictions from LQCD**

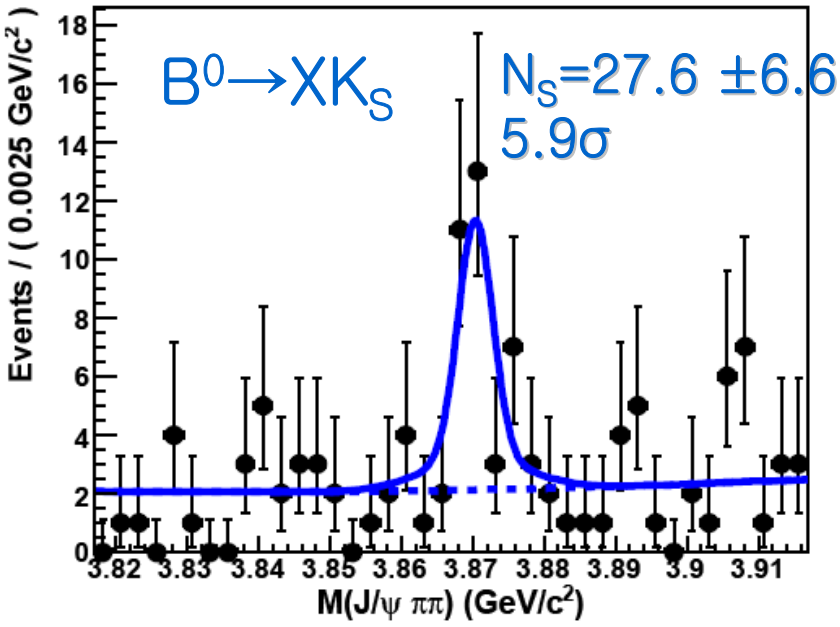
backup

X(3872)→$\pi^+\pi^-$ J/ψ

arXiv:0809.1224 605 fb^{-1}

recent results





$$\delta M_X = M(X \text{ from } B^{\pm}) - M(X \text{ from } B^0) = (0.18 \pm 0.89 \pm 0.26)\ \text{MeV}$$

- **M(X(3872))=(3871.46±0.37±0.07) MeV by combining two modes together**
- $$\frac{B(B^0 \to X(3872)K^0)}{B(B^+ \to X(3872)K^{\pm})} = 0.82 \pm 0.22 \pm 0.05$$

By assuming

$$B(B^0 \to X(3872)K^0) = 2B(B^0 \to X(3872)K_S^0)$$

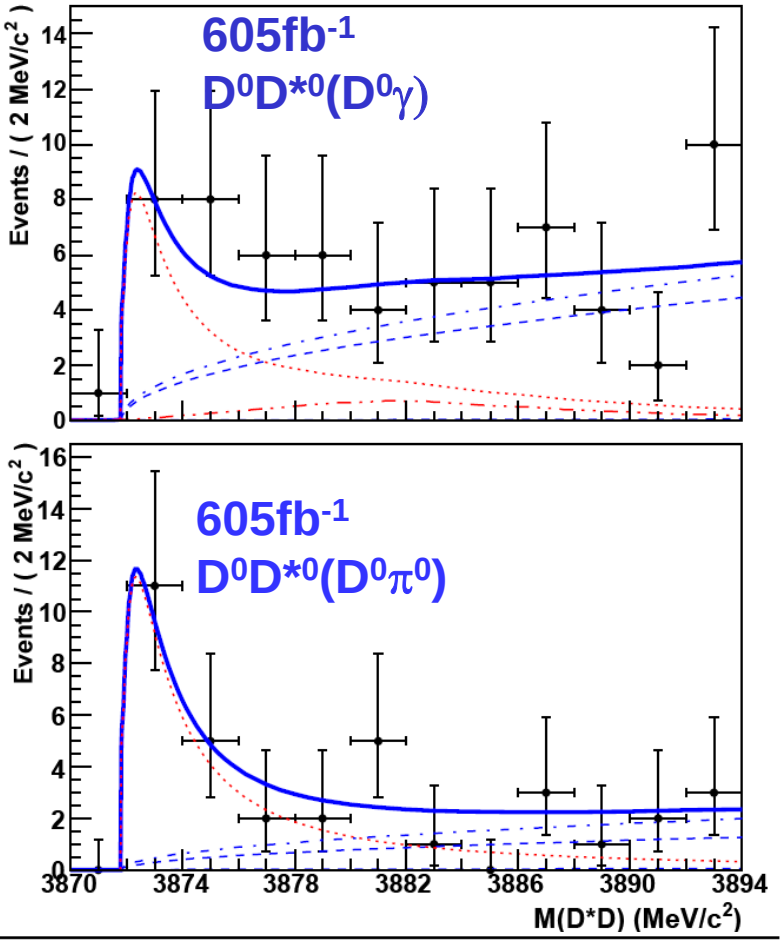
$$B \to X(3872)(\to D^{*0}\bar{D}^0)K$$

arXiv:0810.0358

- Fit with a phase-space modulated BW convolved with the mass-dependent Gaussian (Can also use other parameterizations to do the fit?)
- $B(B^0 \to XK^0)/B(B^+ \to XK^+) = 1.26 \pm 0.65 \pm 0.06$
- Agree with $\pi^+\pi^-$ J/ψ mode

(Peak at D^0D^{0*} threshold is from X(3872))?

X(3872) mass below or above D^0D^{0*}?



sample	M_X (MeV/c^2)	Γ (MeV/c^2)	yield	$\mathcal{B}$ (10^{-4})	σ
$D^{*0} \to D^0\gamma$	3873.4 ± 1.0	$4.2^{+3.7}_{-1.8}$	$26.2^{+9.0}_{-7.6}$	$0.87 \pm 0.28 \pm 0.10$	4.4σ
$D^{*0} \to D^0\pi^0$	3872.8 ± 0.7	$3.1^{+4.1}_{-1.5}$	$22.0^{+10.7}_{-6.4}$	$0.68 \pm 0.26 \pm 0.09$	6.8σ
all (free $D^0\gamma/D^0\pi^0$ ratio)	$3872.9^{+0.6}_{-0.4}$	$3.9^{+2.7}_{-1.4}$	$50.6^{+14.2}_{-11.0}$	$0.81 \pm 0.20 \pm 0.10$	7.9σ
all (fixed $D^0\gamma/D^0\pi^0$ ratio)	$3872.9^{+0.6}_{-0.4}$	$3.9^{+2.8}_{-1.4}$	$50.1^{+14.8}_{-11.1}$	$0.80 \pm 0.20 \pm 0.10$	7.9σ

Dalitz Formalism

Described by 6 variables: M(Kπ), M($\chi_{c1}\pi$), θ(χ_{c1}), φ(χ_{c1}), θ(J/ψ), φ(J/ψ)

angular variables($\Theta\chi_{c1}$, $\Theta_{J/\psi}$, $\phi\chi_{c1}$, $\phi_{J/\psi}$) are integrated first
after integration over φ(χc1), φ(J/ψ) interference terms drop out.

→ $S_x = M^2(K^+\pi^-)$, $S_y = M^2(\pi^+ \chi_{c1}^-)$

Binned likelihood fit (small bins, fully contained subset of 400x400)

Fit function

$$F(s_x, s_y) = S(s_x, s_y) \times \epsilon(s_x, s_y) + B(s_x, s_y)$$

ΔE sideband.

Efficiency

Signal component

$$S(s_x, s_y) = \sum_{\lambda=-1,0,1} |\sum_{R} A_\lambda^R|^2$$

χ_{c1} helicity

Known Kπ resonances (default sets):

κ, K*(892), K*(1410), K*$_0$(1430), K*$_2$(1430), K*(1680), K*$_3$(1780)

and one $Z^+ \rightarrow \pi^+\chi_{c1}$

Amplitude

$$A_\lambda^R = F_B^{(L_B)} \cdot \frac{1}{M_R^2 - s_R - iM_R\Gamma(s_R)} \cdot F_R^{(L_R)} \cdot T_\lambda \cdot (\frac{p_B}{m_B})^{L_B} \cdot (\frac{p_R}{\sqrt{s_R}})^{L_R}$$

B meson and R resonance decay form-factors

Angular part

Z_1, Z_2, Signal Event Density for Dalitz Fit

$$S(s_x, s_y) =$$

$$\sum_{\lambda=-1,0,1} \left| \sum_{K^*} a_\lambda^{K^*} e^{i\phi_\lambda^{K^*}} A_\lambda^{K^*}(s_x, s_y) + \right.$$

$$\left. \sum_{\lambda'=-1,0,1} d^1_{\lambda'\lambda}(\theta)\, a_{\lambda'}^{Z^+} e^{i\phi_{\lambda'}^{Z^+}} A_{\lambda'}^{Z^+}(s_x, s_y) \right|^2,$$