Exotic Hadron Spectroscopy

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PIC08, Perugia

Outline

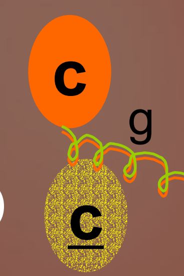
- What is exotic, what can be exotic?
- Spectroscopic opportunities of B-Factory
- Recently observed $c\underline{c}$-like XYZ states
- New observations of (explicitly) exotic states
- Possible analogs of XYZ states in $s\underline{s}$ and $b\underline{b}$ systems
- Summary

Exotic states

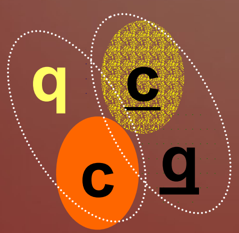
- States beyond $q\bar{q}$ are not forbidden by QCD
- Some of them can have explicitly exotic properties:
  - J^{PC} forbidden for quarkonia: 0^{+-}, 1^{-+}, 2^{+-}…
  - Decay channels that cannot be constructed from initial $q\bar{q}$ quarks
- The others reveal unnatural properties (like small width)

Phenomenology menu of exotics:

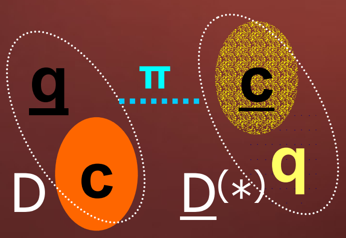
- Hybrids: $c\bar{c}$+ constituent gluons
  - Can bear exotic J^{PC}
  - $D\bar{D}^{**}$ final states dominate over $D\bar{D}$, $D\bar{D}^{*}$
  - Possible large partial widths for hadronic transitions ($\psi\pi\pi$, $\psi\omega$…)
  - Lowest $c\bar{c}$-hybrids predicted by lattice QCD @4.2GeV



- Tetraquarks: diquark-antidiquark $[cq][\bar{c}\bar{q}]$
  - tightly bound by gluon exchange
  - decays: quark rearrangements followed by dissociation (hadronic transitions or open charm decays)



- Molecules: $M(c\bar{q})M(\bar{c}q)$
  - loosely bound meson-antimeson state
  - bind through pion exchange
  - decays: dissociation into constituent mesons



Many $c\bar{c}$-like states reported so far...

State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, Cleo, BaBar	3871.2±0.5 + i(<2.3)	1^{++}	$\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\Upsilon J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4\pm0.7^{+1.2}_{-2.0}$ $3875.6\pm0.7^{+1.4}_{-1.5}$		$D^0D^0\pi^0$	B decays
Z(3930)	Belle	3929±5±2 + i(29±10±2)	2^{++}	D^0D^0, D^+D^-	$\gamma\gamma$
Y(3940)	Belle BaBar	3943±11±13 + i(87±22±26) $3914.3^{+3.8}_{-3.4}$ ±1.6+ i(33^{+12}_{-8} ±0.60)	J^{++}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6}\pm6$ + i($37^{+26}_{-15}\pm8$)	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008\pm40^{+72}_{-28}$ + i($226\pm44^{+87}_{-79}$)	1^{--}	$\pi^+\pi^-J/\psi$	e^+e^- (ISR)
X(4160)	Belle	$4156^{+25}_{-20}\pm15$+ i($139^{+111}_{-61}\pm21$)	J^{P+}	D^*D^*	e^+e^- (recoil against J/ψ)
Y(4260)	BaBar Cleo Belle	$4259\pm8^{+8}_{-6}$ + i($88\pm23^{+6}_{-4}$) 4284^{+17}_{-16} ±4 + i($73^{+39}_{-25}\pm5$) $4247\pm12^{+17}_{-32}$ + i(108±19±10)	1^{--}	$\pi^+\pi^-J/\psi$, $\pi^0\pi^0J/\psi$, K^+K^-J/ψ	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	4324±24 + i(172±33) 4361±9±9 + i(74±15±10)	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle	4433±4±1+ i($44^{+17}_{-13}{}^{+30}_{-11}$)	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	4664±11±5 + i(48±15±3)	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

E. Eichten QWG -- 5th International Workshop on Heavy Quarkonia DESY October 17-20, 2007

+ some new today

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	Belle BaBar	$3875.4 \pm 0.7^{+1.2}_{-2.0}$ $3875.6 \pm 0.7^{+1.4}_{-1.5}$		$D^0 \bar{D}^0 \pi^0$	B decays
Z(3930)	Belle	3929±5±2 + i(29±10±2)	2^{++}	$D^0\bar{D}^0$, D^+D^-	γγ
Y(3940)					B decays
X(3940)					(recoil against J/ψ)
Y(4008)					e^+e^- (ISR)
X(4160)					(recoil against J/ψ)
Y(4260)	Cleo Belle	$4284^{+17}_{-16} \pm 4$ + i($73^{+39}_{-25} \pm 5$) $4247 \pm 12^{+17}_{-32}$ + i(108±19±10)	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	4324±24 + i(172±33) 4361±9±9 + i(74±15±10)	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
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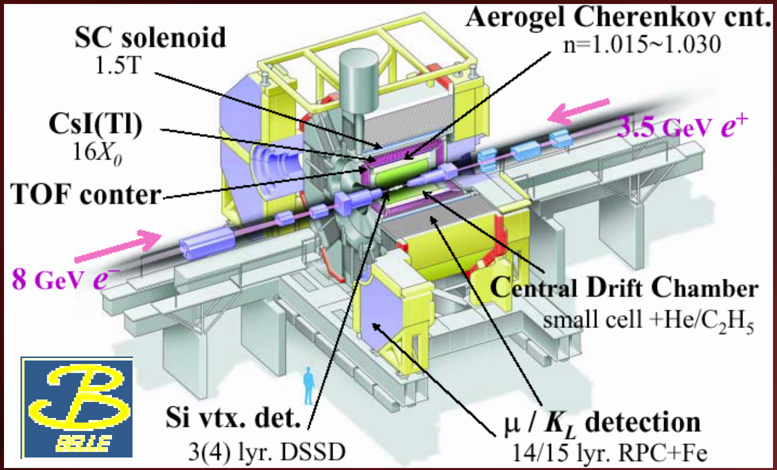
Are they ordinary or exotic states?

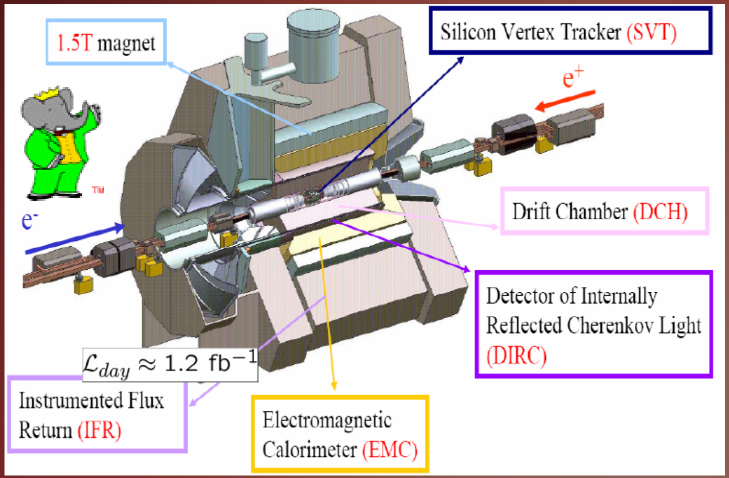
For some of them $c\bar{c}$ assignment possible but their properties are unusual

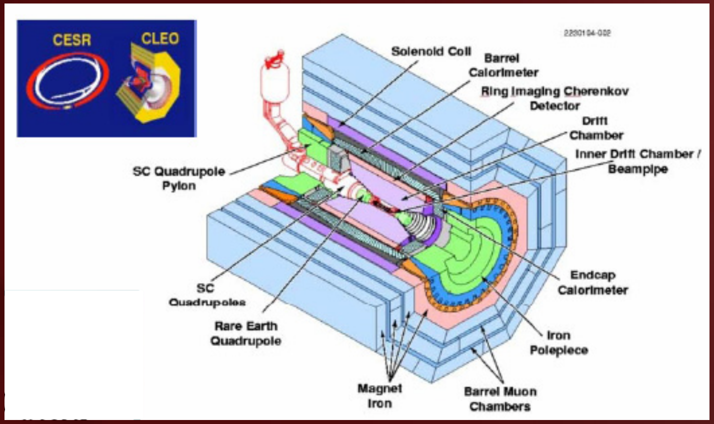
+ some new today

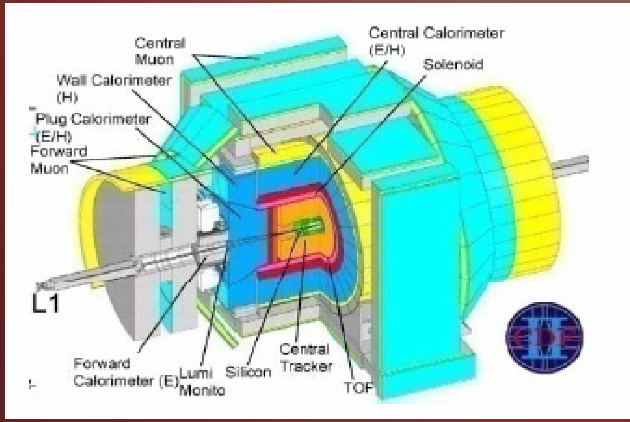
Experiments

- **Collaborative efforts of:**





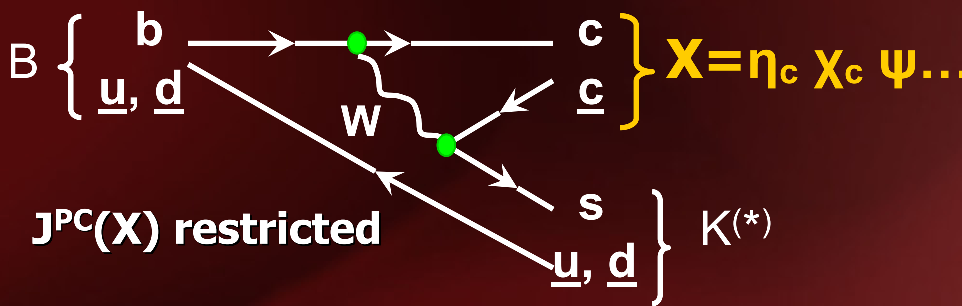




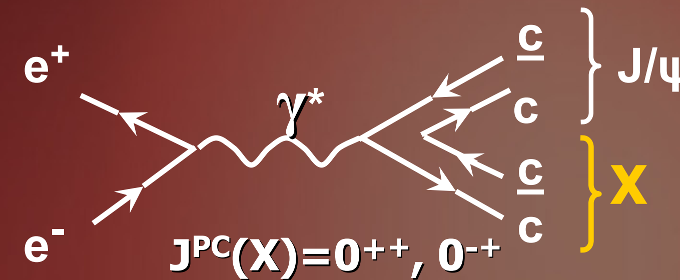
- **I will focus on the most fertile: B-Factories**

Production of $c\bar{c}$ (-like) states in B-Factories

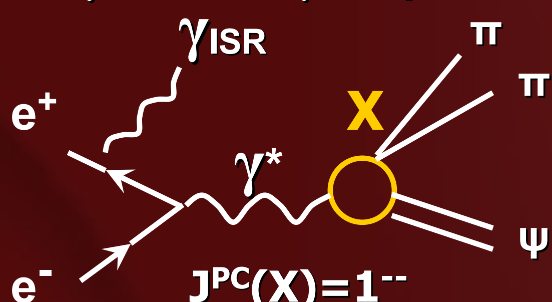
- **B meson decays: $B \to X_{c\bar{c}} K^{(*)}$ (BF~10^{-3})**



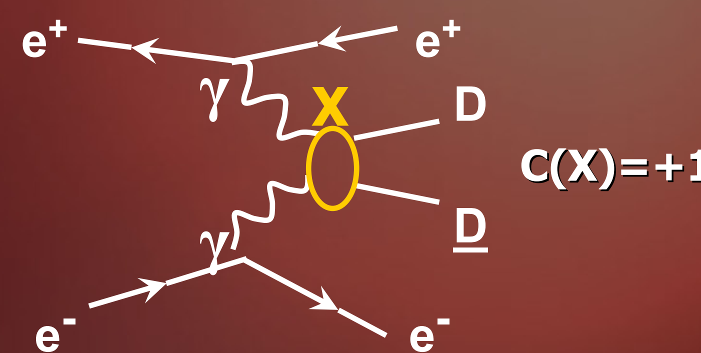
- **e^+e^- annihilation: double $c\bar{c}$ production $e^+e^- \to J/\psi X_{c\bar{c}}$**



- **e^+e^- radiative return (ISR) $e^+e^- \to \gamma_{ISR} X_{c\bar{c}} \to \gamma_{ISR}\, \psi\pi\pi$**



- **$\gamma\gamma$ collision $e^+e^- \to \gamma\gamma \to X_{c\bar{c}} \to D\bar{D}$**

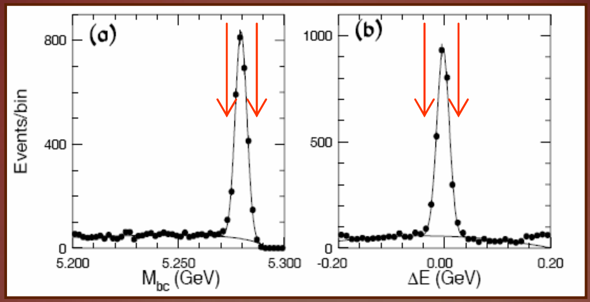


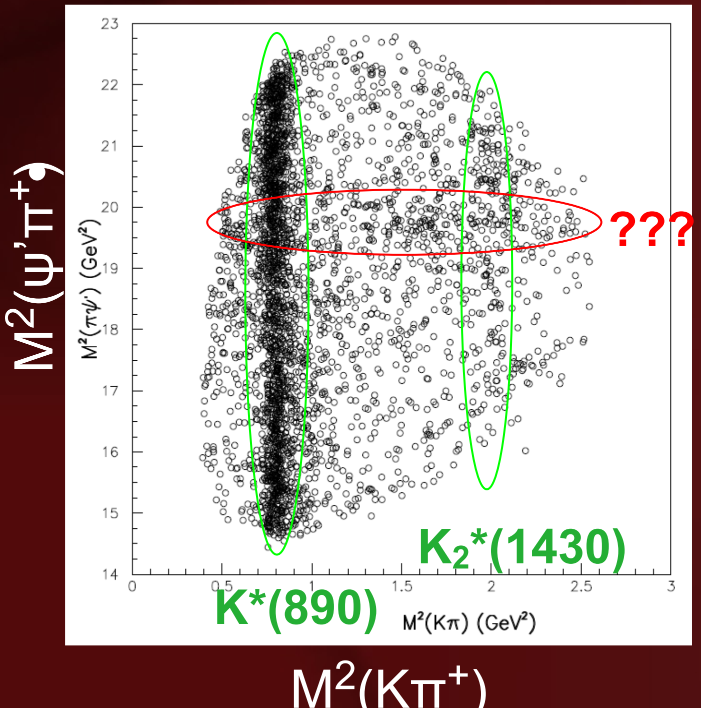
Clean environments to search for new states and study properties of known states

PRL100, 142001 (2008)

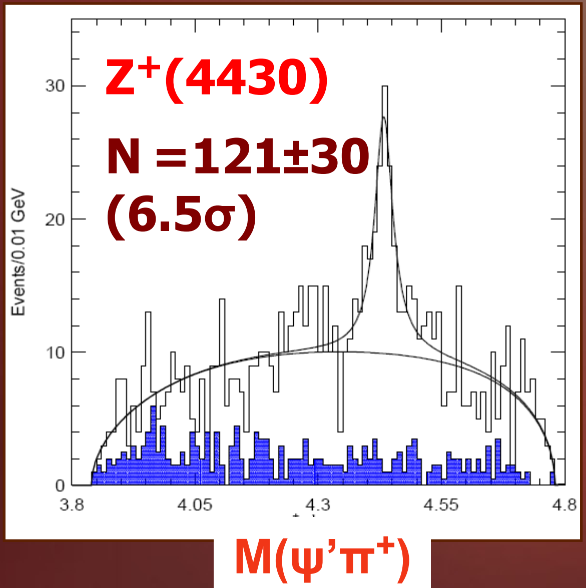
Observation of $Z^+(4430) \to \psi'\pi^+$

- $B \to \psi'\pi^+K$ ($K=K^-, K^0_s$) studied with 657M $B\bar{B}$
- $\psi' \to l^+l^-$, $J/\psi\pi^+\pi^-$ $J/\psi \to l^+l^-$ where $l=e,\mu$
- Clear signals in M_{bc} and ΔE
- K* regions excluded to study $\psi'\pi^+$
- $M(\psi'\pi^+)$ fit: Breit-Wigner + Phase Space like function





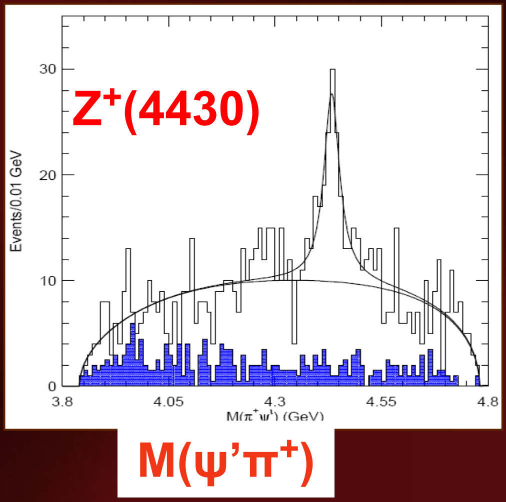
after K* veto



$M = 4433 \pm 4$ MeV $\Gamma = 45^{+18}_{-13}$ MeV

$Z^+(4430) \rightarrow \psi'\pi^+$

- **Z(4430) signal is robust:**
- **Z(4430) is not a reflection, parameters of Z stable**
- **too narrow to be produced by interferences between Kπ partial waves**



$M=4433 \pm 4 \pm 2$ MeV $\Gamma = 45^{+18}_{-13}\,^{+30}_{-13}$ MeV

$BF(B \rightarrow KZ) * BF(Z \rightarrow \psi'\pi^+) = (4.1 \pm 1.0 \pm 1.4) * 10^{-5}$

Statistics too low to determine J^P

First candidate for a charged $c\bar{c}$-like state!

Must be exotic!

Proposed interpretations:

- **[cu][$\bar{c}\bar{d}$] tetraquark with $J^P=1^+$**
  (radial excitation of X(3872))
  neutral partner expected in $\psi'\pi^0/\eta$, $\eta_c'\rho^0/\omega$

  Maiani, Polosa hep-ph/0708.3997
- **$D^*\bar{D}_1(2420)$ threshold effect**

  Rosner PRD 76, 114002(2007)
- **$D^*\bar{D}_1(2420)$ molecule with $J^P=0^-, 1^-, 2^-$**
  decay to $D^*\bar{D}^*\pi$ expected

  Meng, Chao hep-ph/0708.4222

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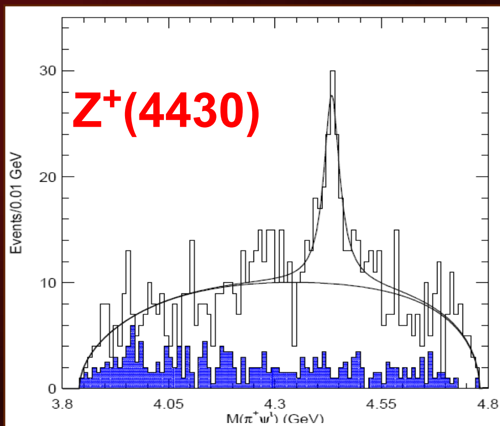

$M(\psi'\pi^+)$

$M=4433 \pm 4 \pm 2$ MeV $\quad \Gamma=45\,^{+18}_{-13}\,^{+30}_{-13}$ MeV

$BF(B \rightarrow KZ)*BF(Z \rightarrow \psi'\pi^+)=(4.1 \pm 1.0 \pm 1.4)*10^{-5}$

Statistics too low to determine J^P

<u>First candidate for a charged cc-like state!</u>

<u>Must be exotic!</u>

Will trigger studies of other $B \rightarrow (c\underline{c})\pi^+K$ decays to search for similar exotics!

Proposed interpretations:

- **[cu][$\underline{cd}$] tetraquark with $J^P=1^+$**
  (radial excitation of X(3872))
  neutral partner expected in $\psi'\pi^0/\eta$, $\eta_c'\rho^0/\omega$
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Rosner PRD 76, 114002(2007)

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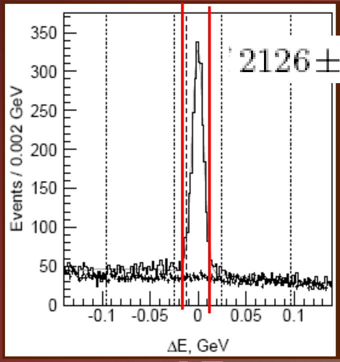
$\underline{B}^0 \to \chi_{c1}\pi^+K^-$ study. More Z's?

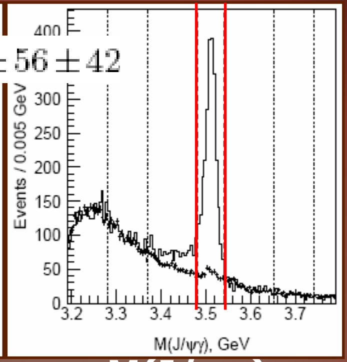
hep-ex/0806.4098
to be submitted to PRD

New!

- $\underline{B}^0 \to \chi_{c1}\pi^+K^-$ studied with 657M $B\underline{B}$
- $\chi_{c1} \to J/\psi\gamma$ $J/\psi \to e^+e^-, \mu^+\mu^-$
- Signal identified using M_{bc}, ΔE and $M(J/\psi\gamma)$
- Dalitz-plot analysis of $\underline{B}^0 \to \chi_{c1}\pi^+K^-$

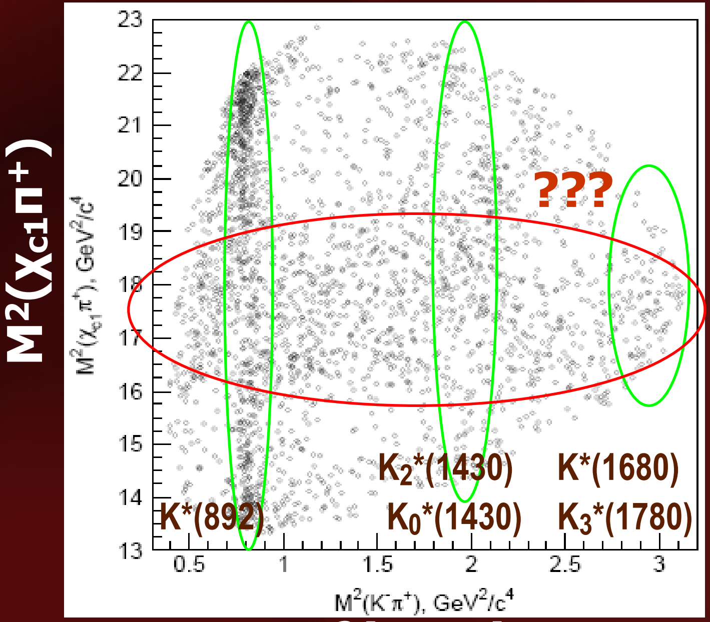


ΔE



M(J/ψγ)

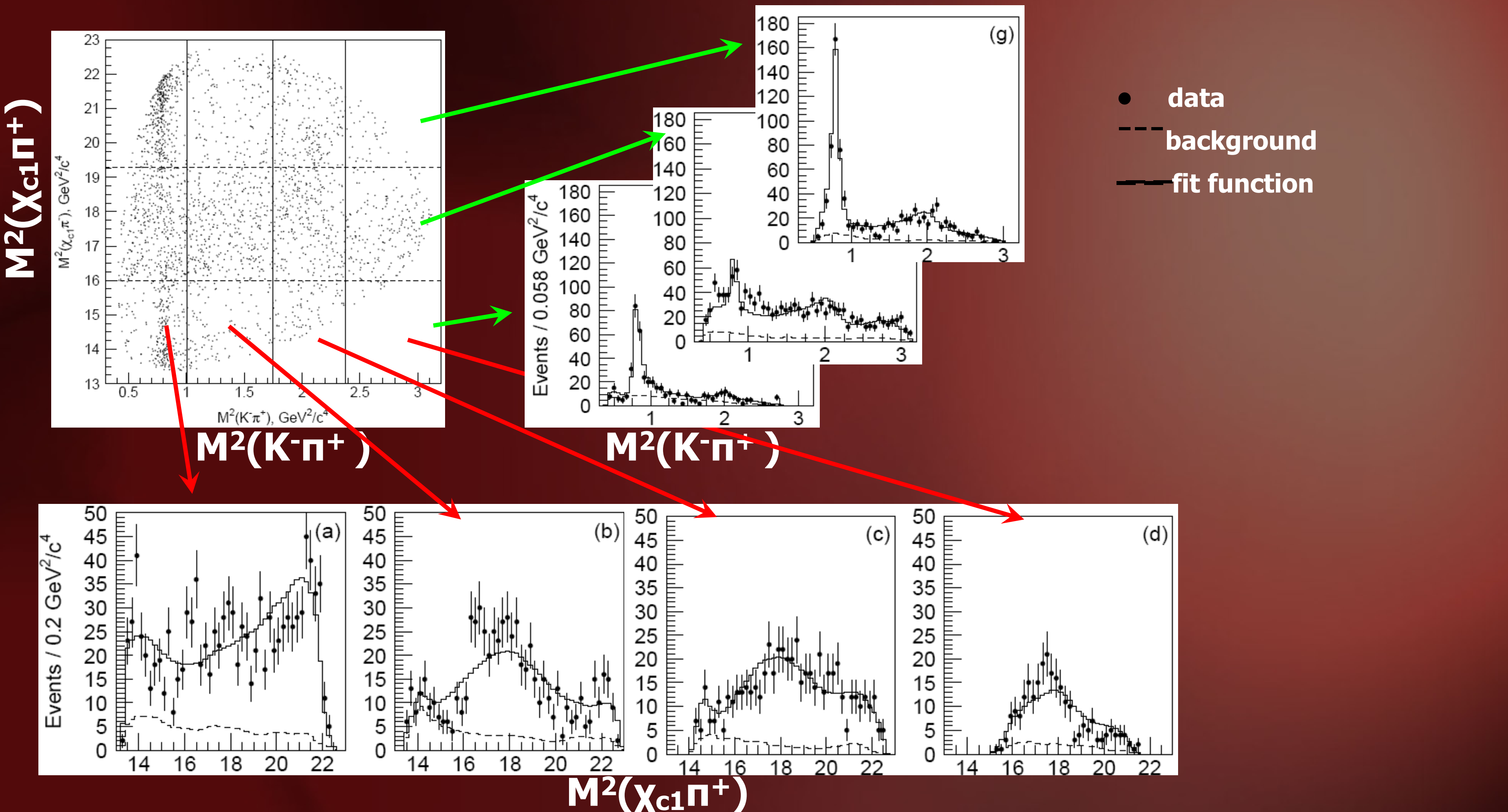
$$\mathcal{B}(\overline{B}^0 \to K^-\pi^+\chi_{c1}) = (3.83 \pm 0.10 \pm 0.39) \times 10^{-4}$$



- $\underline{B}^0 \to \chi_{c1}\pi^+K^-$ amplitude: coherent sum of Breit-Wigner contributions
- $M(\chi_{c1}\pi)$, $M(K\pi)$ used to describe the reaction angular variables: $\theta_{\chi_{c1}}$, $\theta_{J/\psi}$, $\varphi_{\chi_{c1}}$, $\varphi_{J/\psi}$ integrated out in the analysis
- Binned maximum likelihood fit performed
- Models tried: known $K^* \to K\pi$ only; K^*'s + one $Z \to \chi_{c1}\pi^+$; K^*'s + two Z states

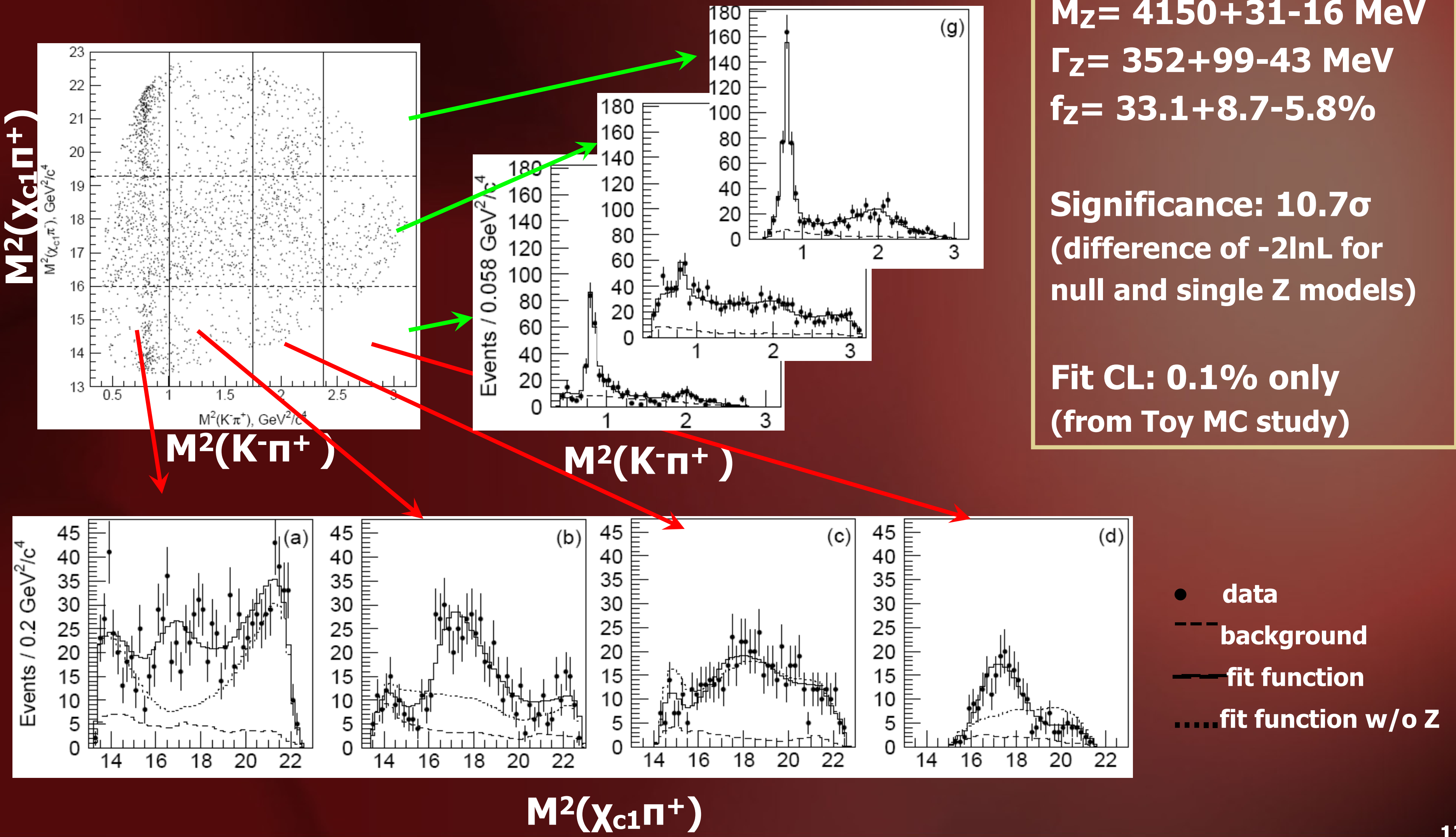
$B^0 \to \chi_{c1}\pi^+K^-$ Dalitz plot analysis: no Z

- **Null model: all known low-lying $K^-\pi^+$ resonances only: κ, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$, $K_3^*(1780)$**



$B^0 \to \chi_{c1}\pi^+K^-$ Dalitz plot analysis: one Z

- **Single Z model: all known low-lying $K^-\pi^+$ resonances and one $Z \to \chi_{c1}\pi^+$ exotic resonance ($J_Z=0$)**



M_Z= 4150+31-16 MeV
Γ_Z= 352+99-43 MeV
f_Z= 33.1+8.7-5.8%

Significance: 10.7σ
(difference of -2lnL for null and single Z models)

Fit CL: 0.1% only
(from Toy MC study)

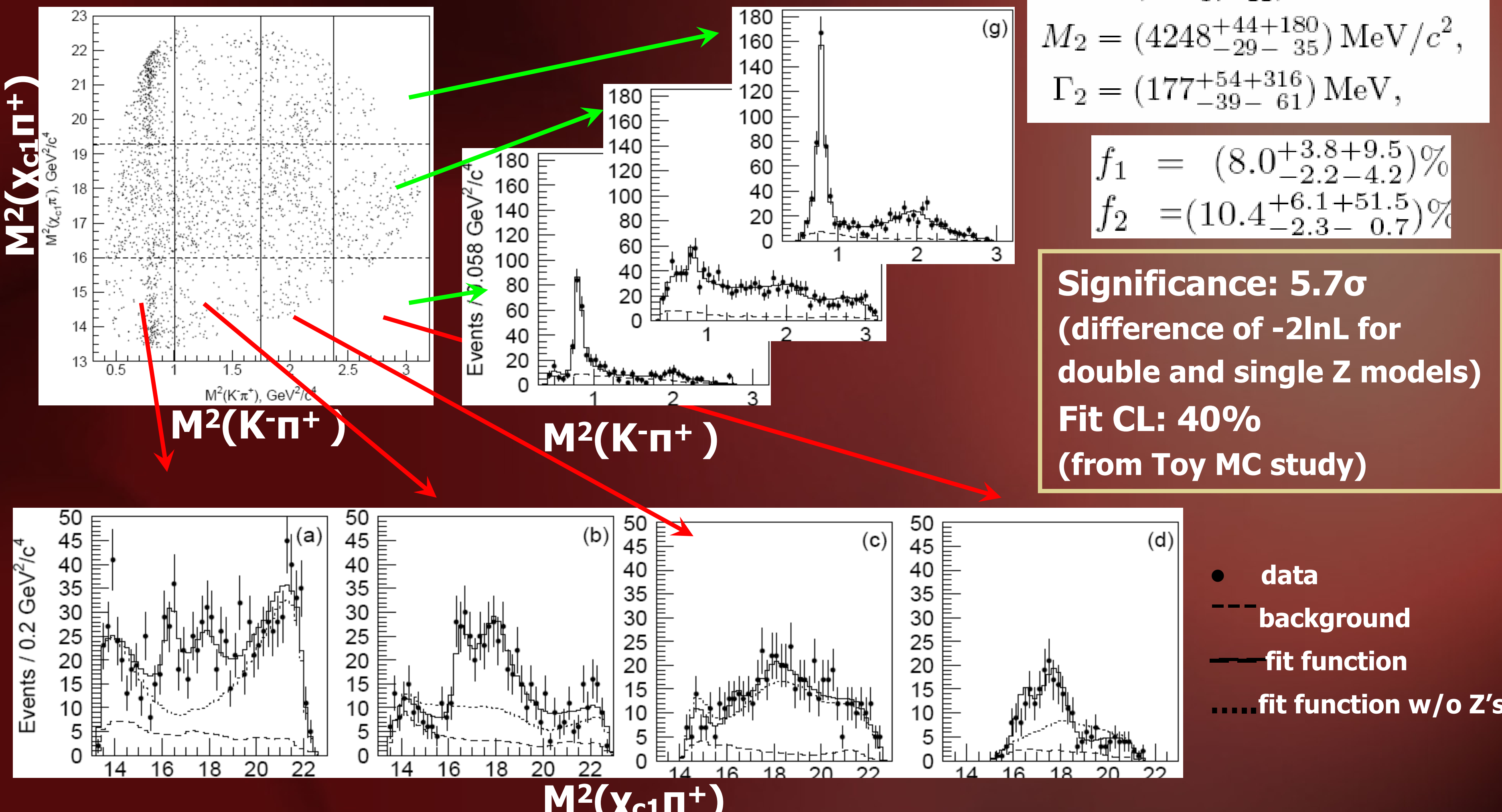
$B^0 \to \chi_{c1}\pi^+K^-$ Dalitz plot analysis: two Z's

- Double Z model: all known low-lying $K^-\pi^+$ resonances and two $Z_{1,2} \to \chi_{c1}\pi^+$ exotic resonances ($J_{1,2}=0$)

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

$$f_1 = (8.0^{+3.8+9.5}_{-2.2-4.2})\%$$
$$f_2 = (10.4^{+6.1+51.5}_{-2.3-\ 0.7})\%$$

Significance: 5.7σ
(difference of -2lnL for double and single Z models)
Fit CL: 40%
(from Toy MC study)



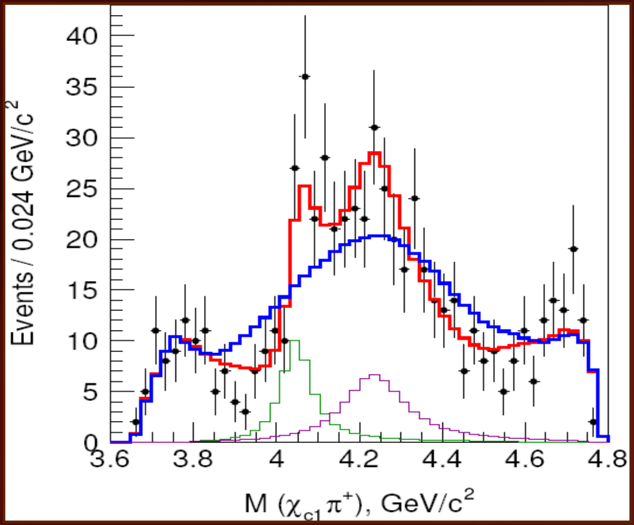
$B^0 \to \chi_{c1} \pi^+ K^-$: other models

	Model	Significance of one Z^+	One Z^+ vs. two Z^+	Significance of two Z^+
1	default (see text)	$10.7\,\sigma$	$5.7\,\sigma$	$13.2\,\sigma$
2	no κ	$15.6\,\sigma$	$5.0\,\sigma$	$16.6\,\sigma$
3	no $K^*(1410)$	$13.4\,\sigma$	$5.4\,\sigma$	$14.8\,\sigma$
4	no $K_0^*(1430)$	$10.4\,\sigma$	$5.2\,\sigma$	$14.4\,\sigma$
5	no $K^*(1680)$	$13.3\,\sigma$	$5.6\,\sigma$	$14.8\,\sigma$
6	no $K_3^*(1780)$	$12.9\,\sigma$	$5.6\,\sigma$	$14.4\,\sigma$
7	add non-res. contribution	$9.0\,\sigma$	$5.3\,\sigma$	$10.3\,\sigma$
8	add non-res. contribution, no $K^*(1410)$	$11.3\,\sigma$	$5.1\,\sigma$	$13.5\,\sigma$
9	add non-res. contribution, no $K^*(1680)$	$11.4\,\sigma$	$5.3\,\sigma$	$13.7\,\sigma$
10	add non-res. contribution, no $K_3^*(1780)$	$10.8\,\sigma$	$5.4\,\sigma$	$13.2\,\sigma$
11	add non-res. contribution, release constraints on κ mass & width	$9.5\,\sigma$	$5.3\,\sigma$	$10.7\,\sigma$
12	add non-res. contribution, new K^* (J=1)	$7.7\,\sigma$	$5.4\,\sigma$	$9.2\,\sigma$
13	add non-res. contribution, new K^* (J=2)	$6.2\,\sigma$	$5.6\,\sigma$	$8.1\,\sigma$
14	LASS parametrization of S-wave component	$13.1\,\sigma$	$5.7\,\sigma$	$14.6\,\sigma$

- **Including new K* doesn't give good description. The Z contribution(s) still necessary/significant**
- **Fit results taken into account in systematic errors and Z significance**

$Z^+_{1,2} \longrightarrow \chi_{c1}\pi^+$ exotic states

- Model with two Z's significantly favored by data
- Spin of $Z_{1,2}$ not determined: J=0 and J=1 hypotheses result with comparable fit qualities
- Non-zero charge suggests multiquark interpretation



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

- fit for null model
- fit for double Z model
- Z_1 contribution
- Z_2 contribution

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

$$\phi_{Z_2^+} - \phi_{Z_1^+} = 1.7^{+0.2}_{-0.3}.$$

$$f_1 = (8.0^{+3.8+9.5}_{-2.2-4.2})\%$$
$$f_2 = (10.4^{+6.1+51.5}_{-2.3-\ 0.7})\%$$

$$\mathcal{B}(\overline{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+\chi_{c1}) = (3.1^{+1.5+3.7}_{-0.9-1.7}) \times 10^{-5},$$
$$\mathcal{B}(\overline{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+\chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-\ 0.5}) \times 10^{-5}.$$

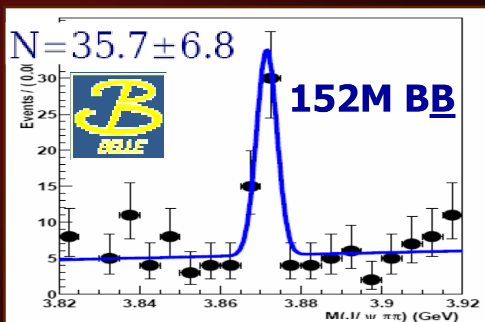
New!

$c\underline{c}$-like example: X(3872)

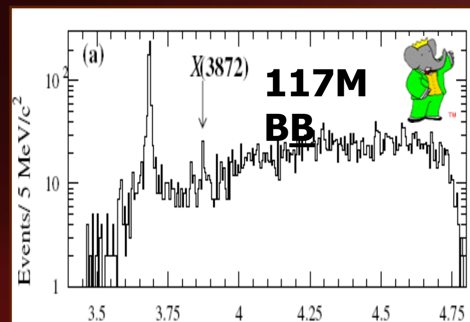
- $X(3872) \to J/\psi\pi^+\pi^-$ observed in $B^+ \to X(3872)K^+$ by Belle

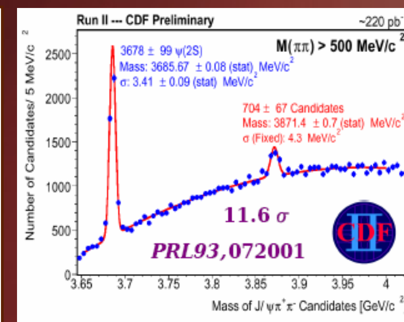
PRL91, 262001 (2003)

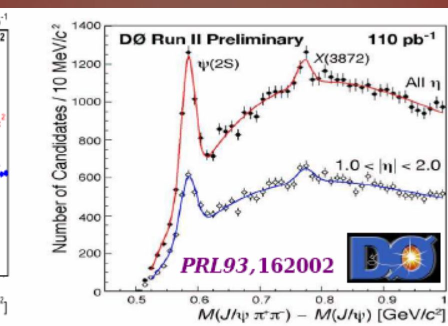
- Confirmed by BaBar, CDF, D0



M($J/\psi\pi^+\pi^-$)





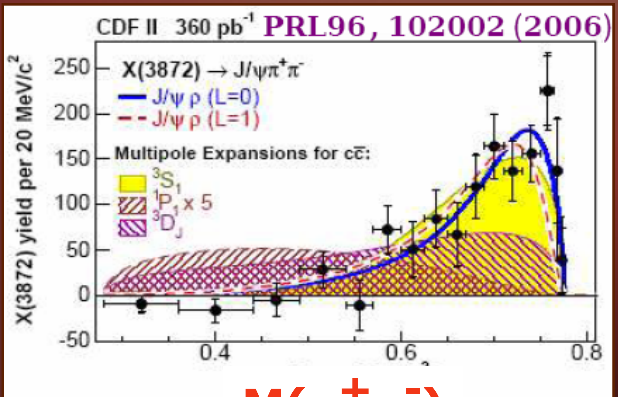


- m_X=3871.2±0.5 MeV $m_X-(m_{D^{*0}}+m_{D^0})$=-0.6±0.6MeV Γ<2.3MeV
- $M(\pi^+\pi^-)$ suggests $X(3872) \to J/\psi\ \rho$ (S- or P-wave)
- Other decay modes: $J/\psi\gamma$, $J/\psi\omega$, $D\underline{D}\pi$

  no $X \to D\underline{D}$ found

- J^{PC}= 1^{++}, 2^{-+} favored

  (from angular analysis by Belle/CDF, $M(\pi^+\pi^-)$, decay modes)



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

What is X(3872) ?

- $c\bar{c}$? No obvious assignment

- $D^0\bar{D}^{*0}$ molecule?

  Braaten et al. hep-ph/0710.5482

  $m_X \approx m_{D^{*0}} + m_{D^0}$ not accidental

  Favors $D\bar{D}\pi$ over $J/\psi\pi\pi$

  Non-trivial line shape

  Production in B^0 suppressed in regard to B^+

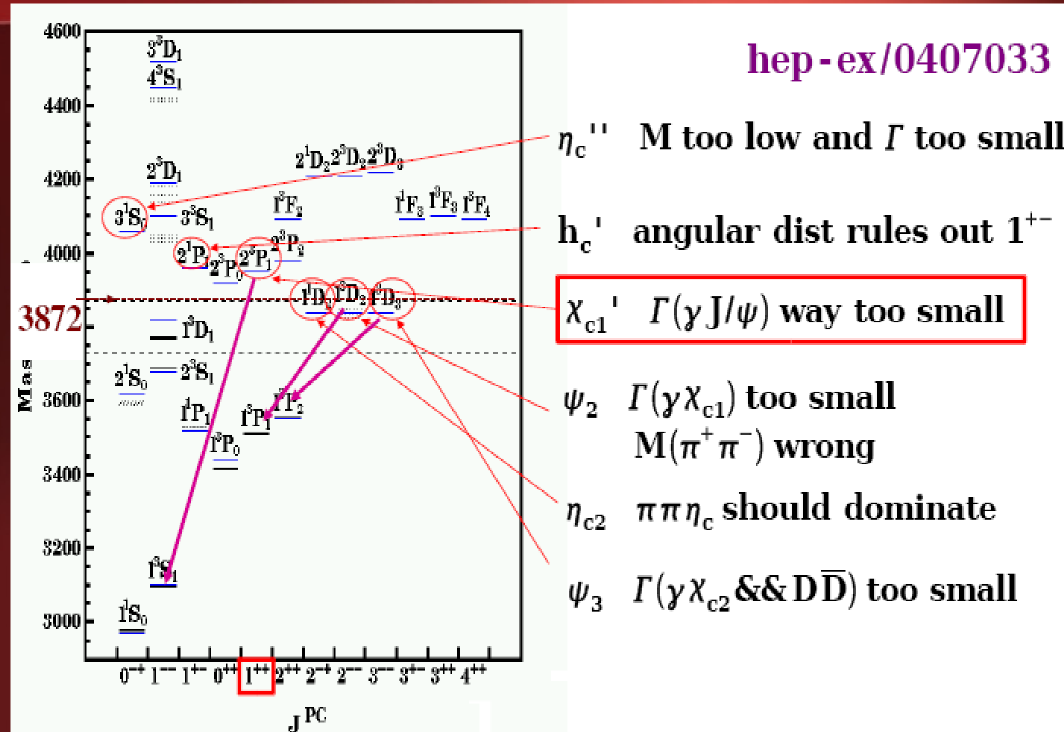
- 4-quark?

  Maiani, Polosa et al. PRD 71, 014028 (2005)

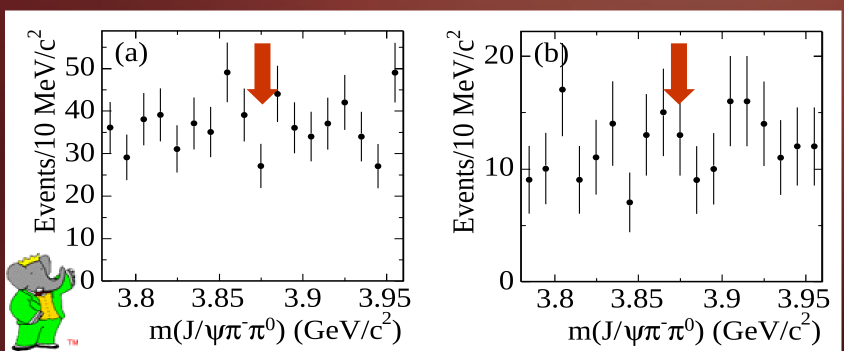
  X_u [uc][$\overline{uc}$] X_d [dc][$\overline{dc}$]

  Different mass of X produced in B^0 and B^+

  Finding charged X is critical (no evidence so far)



PRD71, 031501 (2005)

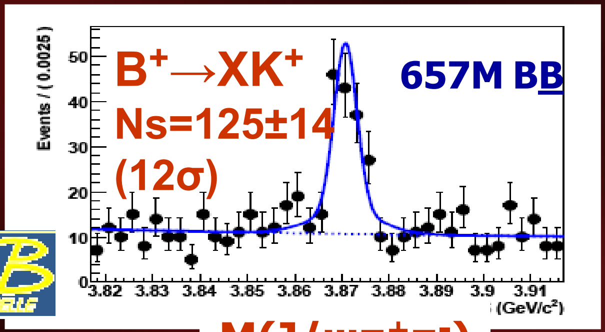


$M(J/\psi\pi^-\pi^0)$

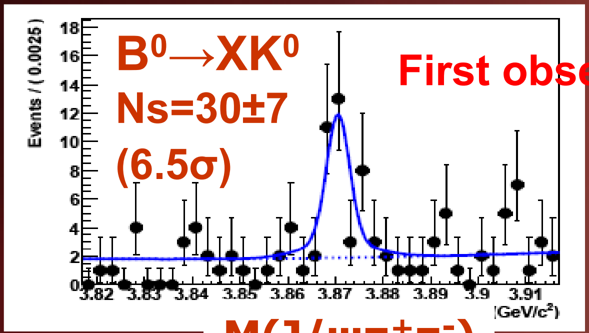
BELLE-CONF-0711
PRD77, 111101(2008)

X(3872) in B^+ and B^0 decays

- **Study of $X(3872)\to J/\psi\pi^+\pi^-$ in $B^+\to XK^+$ and $B^0\to XK^0_S$**
- **After M_{bc} and ΔE selection:**



M(J/ψπ+π-)

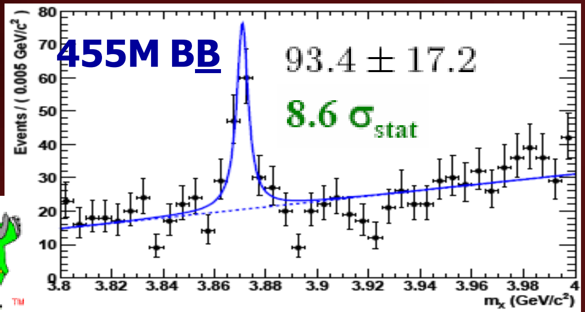


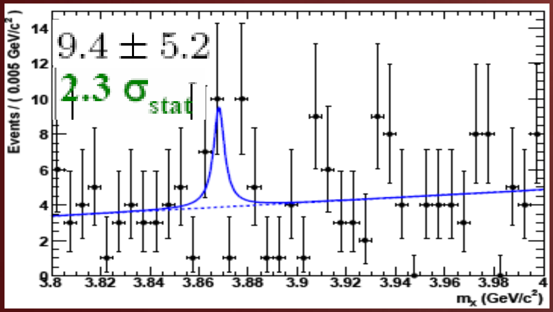
M(J/ψπ+π-)

First observation!

$$R^{0/+} = \frac{\mathcal{B}(B^0\to X(3872)K^0)}{\mathcal{B}(B^+\to X(3872)K^+)} = 0.94 \pm 0.24 \pm 0.10$$

$$\delta M_X = M(X \text{ from } B^+) - M(X \text{ from } B^0) = 0.22 \pm 0.90 \pm 0.27 \text{ MeV}$$





$$\delta M_X = (2.7 \pm 1.6 \pm 0.4)\ \text{MeV}/c^2$$

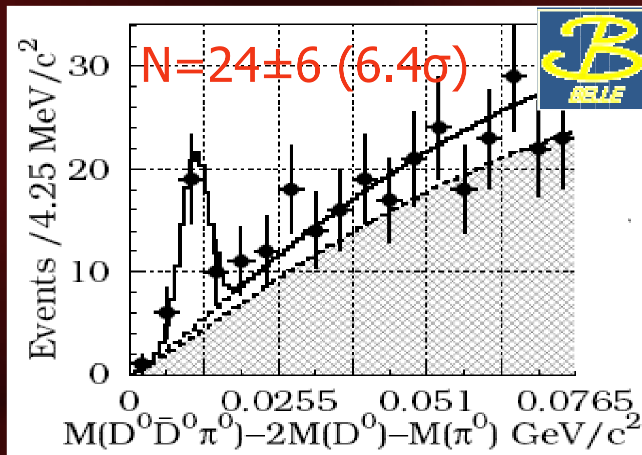
$$R^{0/+} = 0.41 \pm 0.24 \pm 0.05$$

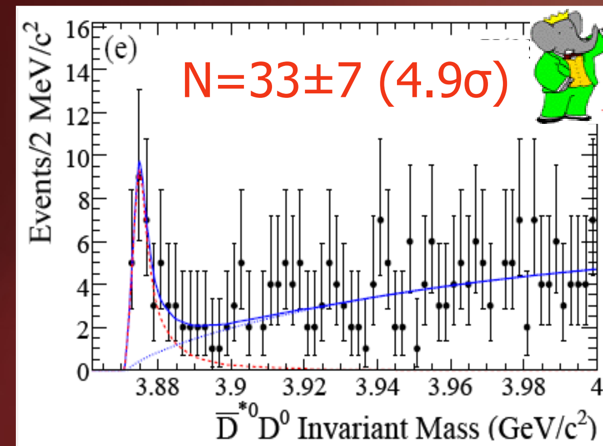
- **Similar properties of X(3872) from B^+ and B^0 decays**

$X(3872) \to D^0\bar{D}^{*0} / D^0\bar{D}^0\pi$ (?)

- **Belle: $B^+ \to \bar{D}^0 D^0 \pi^0 K$ (447M $B\bar{B}$) BaBar: $B^+ \to \bar{D}^{*0} D^0 K$ (383M$B\bar{B}$)**

PRL97, 162002(2006)





PRD77, 011102(2008)

$M(X)=3875.4 \pm 0.7^{+0.4}_{-1.7} \pm 0.9$ MeV

$M(X)=3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV

$\Gamma=3.0^{+1.9}_{-1.4} \pm 0.9$ MeV

$$\frac{BR(X \to D^0\bar{D}^0\pi^0)}{BR(X \to J/\psi\pi^+\pi^-)} \sim 10$$

- **Mass ~4σ above M(X) for $X \to J/\psi\pi\pi$**
- **Is this X(3872) or are there two states X(3872) and X(3875)?**
- **More precise measurement of mass/width/line shape needed**

Maiani, Polosa et al.
hep-ph/0707.3354

X_u [uc][$\bar{u}\bar{c}$] $\to \bar{D}^0 D^0 \pi^0$ = X(3875)

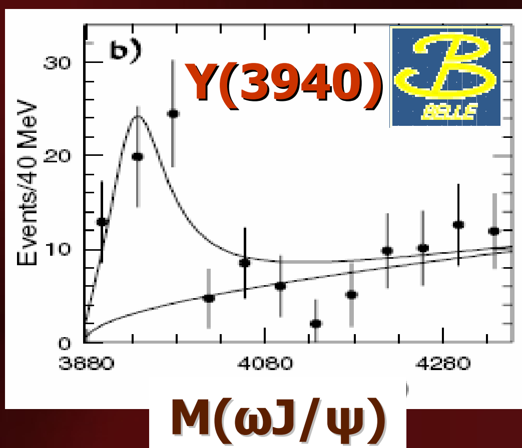
X_d [dc][$\bar{d}\bar{c}$] $\to J/\Psi \pi^+\pi^-$ = X(3872)

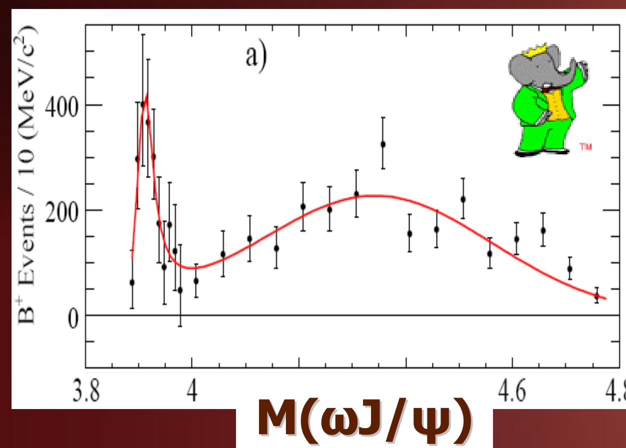
$Y(3940) \to J/\psi\omega$

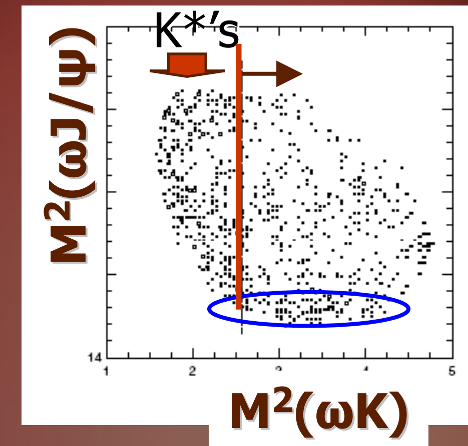
Belle PRL 94, 182002 (2005)

Babar hep-ex/0711.2047 submitted to PRL

- Study of $B \to KJ/\psi\omega$ $\omega \to \pi^+\pi^-\pi^0$
- M_{bc}, ΔE and $M(\pi^+\pi^-\pi^0)$ selection







$BF(B \to KY) * BF(Y \to J/\psi\omega) =$

Belle $(7.1 \pm 1.3 \pm 3.1) * 10^{-5}$

Babar $(4.9 \pm 1.0 \pm 0.5) * 10^{-5}$

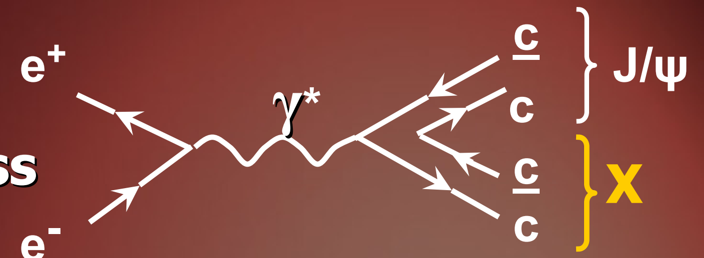
	Mass (MeV)	Γ (MeV)
Belle 253 fb^{-1}	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb^{-1}	$3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst)$	$33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst)$

➡ mass/width discrepancy needs further study

- Y(3940) above $D\underline{D}$ threshold but has large $c\underline{c}$ transition
- Candidate for $c\underline{c}$-gluon hybrid? (but hybrids predicted >4GeV)
- Re-scattering $D\underline{D}^* \to J/\psi\omega$?

Double $c\bar{c}$ production: $e^+e^- \to J/\psi X_{c\bar{c}}$

PRL 98, 082001 (2007)



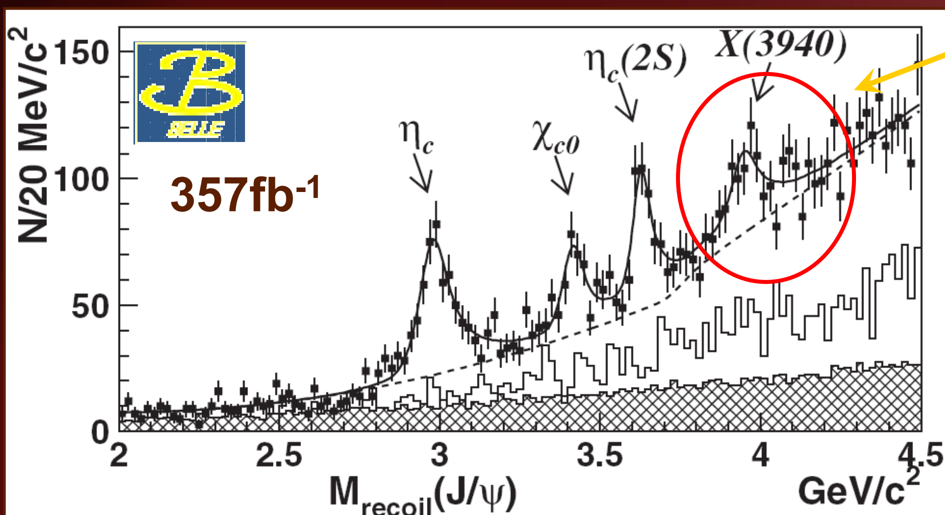
- Factory of 0^{++} and 0^{-+} charmonia
- Method: reconstruct J/ψ, study recoil mass

  $M_{recoil}(J/\psi) = \sqrt{(E_{cm} - E_{J/\psi})^2 - p^2_{J/\psi}}$
- Surprises:

  below $D\bar{D}$: $c\bar{c}$ states with large x-sections O(10-20fb)

  above $D\bar{D}$: new state X(3940)

N=266±63 (5σ)
M=3936±14 MeV
Γ=39±26 MeV
one state or more?



BF(X(3940)→J/ψω)<26% @90%CL

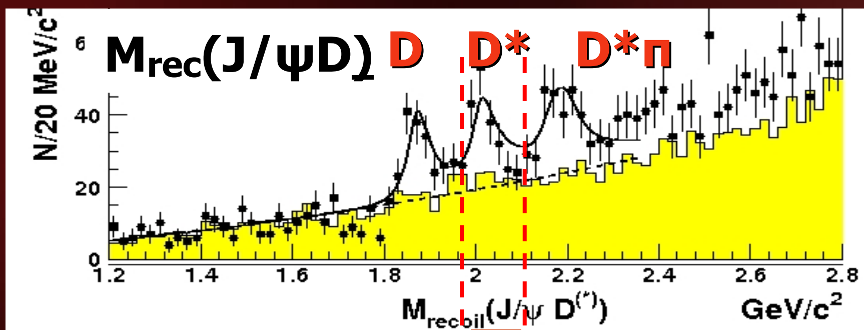
Unlikely that X(3940) is Y(3940) but not excluded

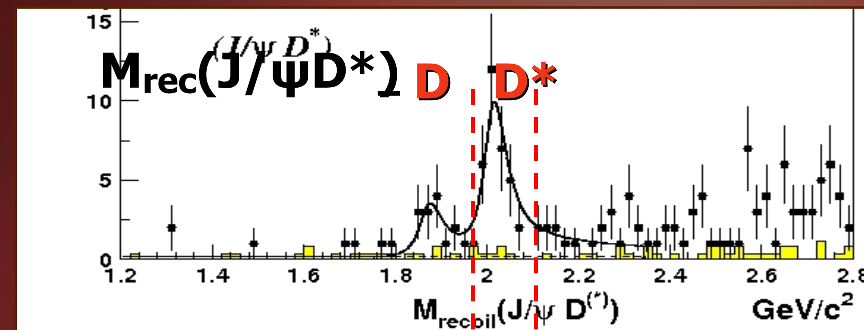
- Method has limitation: σ~30MeV; recoil system not reconstructed

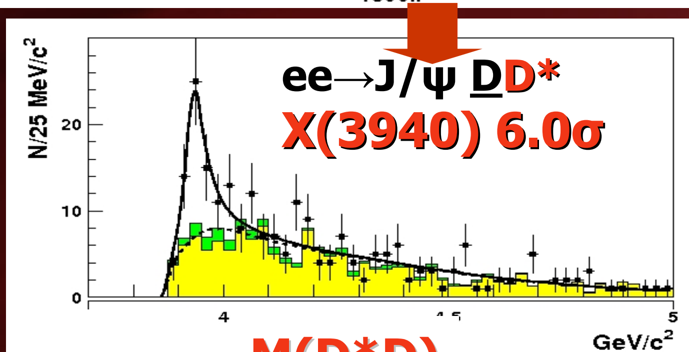
PRL100, 202001 (2008)

$X(3940) \to D\underline{D}^*$ and $X(4160) \to D^*\underline{D}^*$

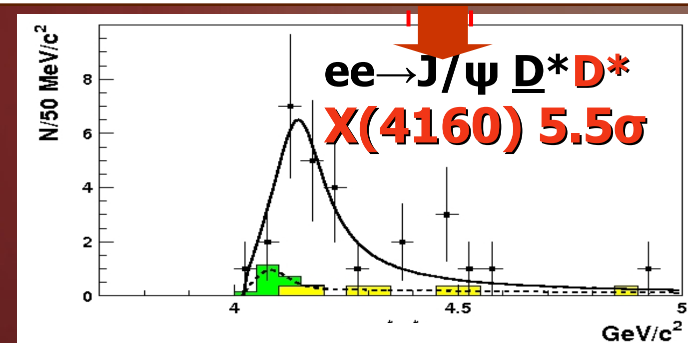
- **Reconstruct J/ψ and one $D^{(*)}$, associated $D^{(*)}$ seen as peak in $M_{recoil}(J/\psi D^{(*)})$**







M(D*D̲)



M(D*D̲*)

$M = 3942^{+7}_{-6} \pm 6$ MeV

$\Gamma = 37^{+26}_{-15} \pm 12$ MeV

$M = 4156^{+25}_{-20} \pm 15$ MeV

$\Gamma = 139^{+111}_{-61} \pm 21$ MeV

$C_X = +1$ so $X(4160) \neq \psi(4160)$

- **Possible assignments: $\eta_c(3S)$ $\eta_c(4S)$**
  (but X masses ~100-150MeV above predictions for η_c's)

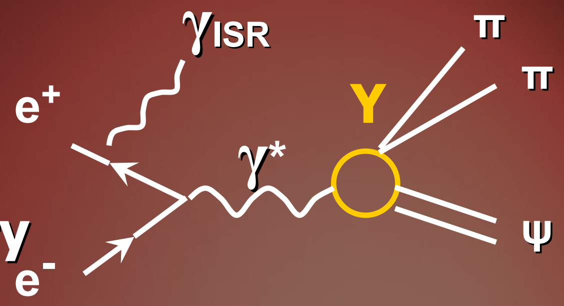
J. Brodzicka @ PIC08

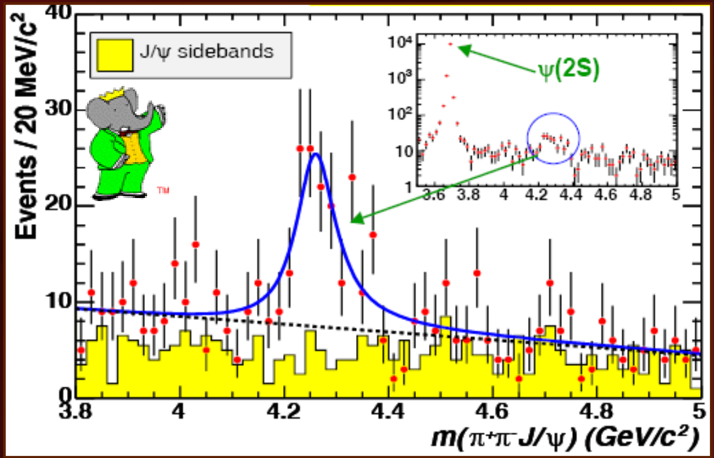
PRL 95, 142001 (2005) for 232fb-1

PRL 98, 212001 (2007) for 298fb-1

Y family through ISR

- ISR gives access to $J^{PC}=1^{--}$ states
- Hard photon emission suppressed, 'compensated' by high luminosity of B-factory

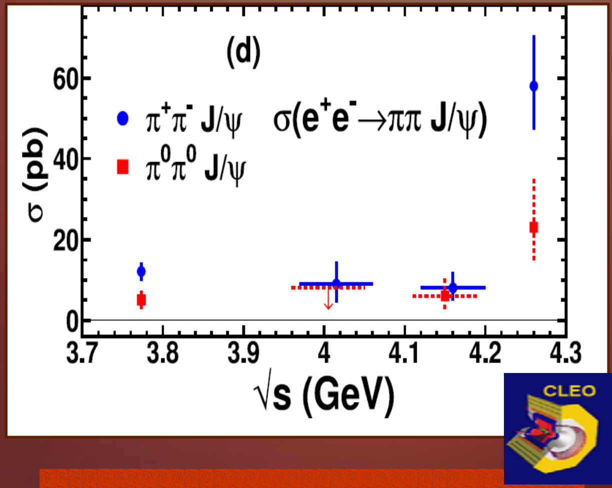


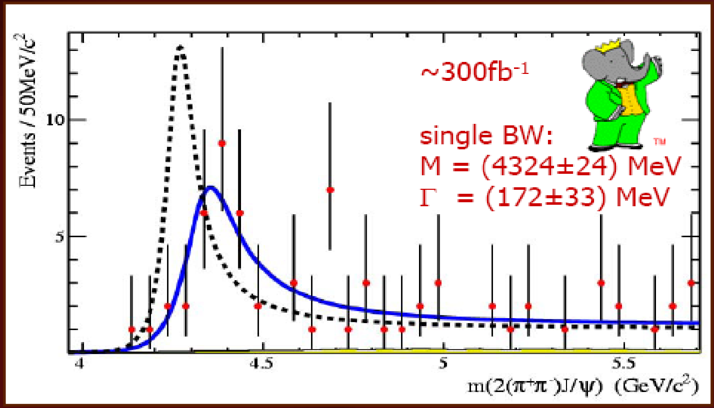


Y(4260)→J/ψππ

$M = 4259 \pm 8^{+2}_{-6}$ MeV

$\Gamma = 88 \pm 23^{+6}_{-4}$ MeV





Y(4360)→ψ'ππ

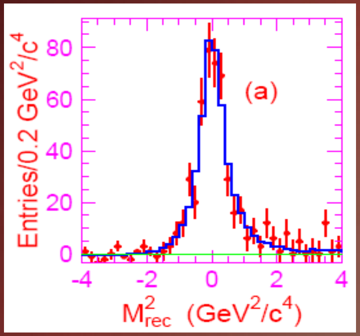
$M = 4324 \pm 24$ MeV

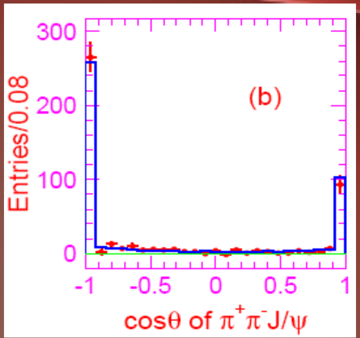
$\Gamma = 172 \pm 33$ MeV

PRD74, 091104 (2006)
PRL 96, 162003 (2006)
for $13pb^{-1}$@4.26GeV

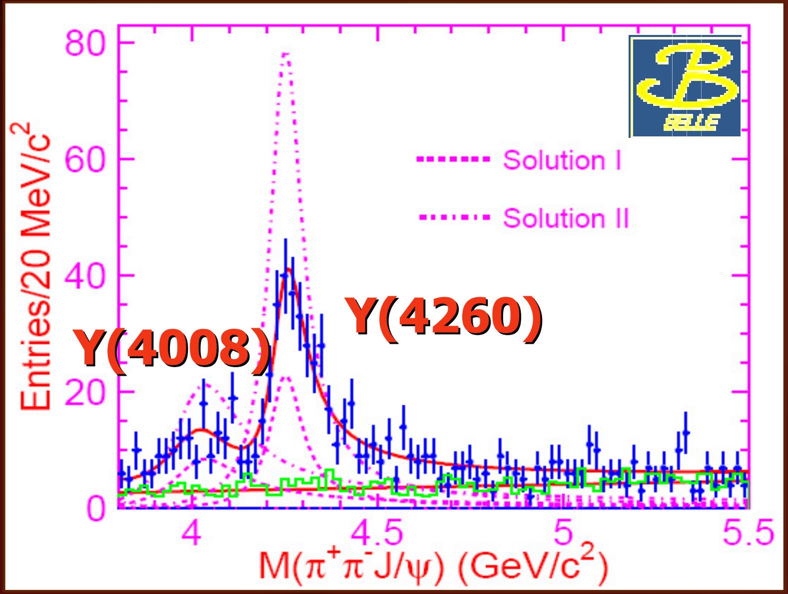
PRL 99, 182004 (2007)

Y→J/ψππ via ISR





- Study of $e^+e^- \to J/\psi \pi^+\pi^- \gamma_{ISR}$ (548 fb^{-1})
- J/ψ→ee, μμ + ππ; no extra tracks
- ISR photon is not detected
- Missing mass used to identify process
- Fit to M(J/ψππ) with two coherent Breit-Wigners
- Y(4260) confirmed
- Y(4008) resonance? Re-scattering from DD*? Coupled-channel effect?

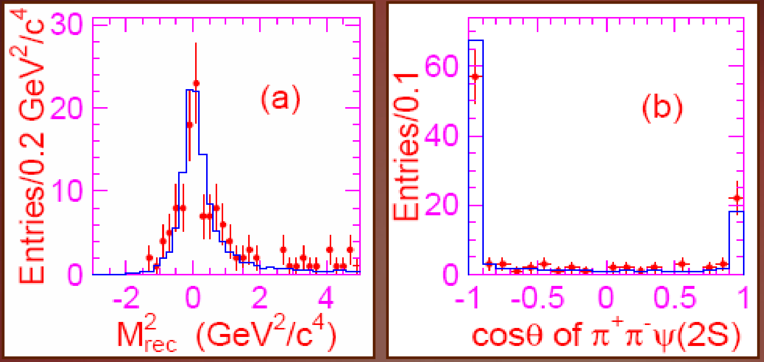


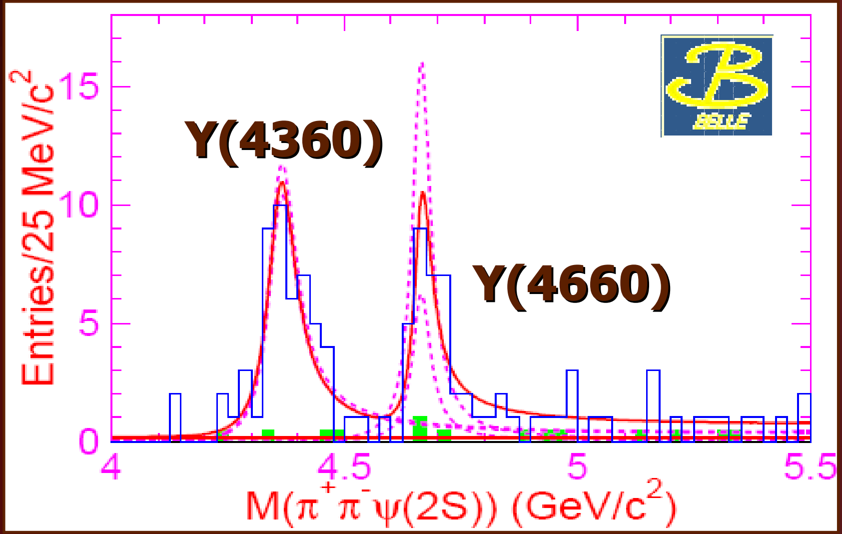
Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{\rm tot}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{\rm tot}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
ϕ	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$

Y→ψ'ππ via ISR

PRL 99, 142002 (2007)

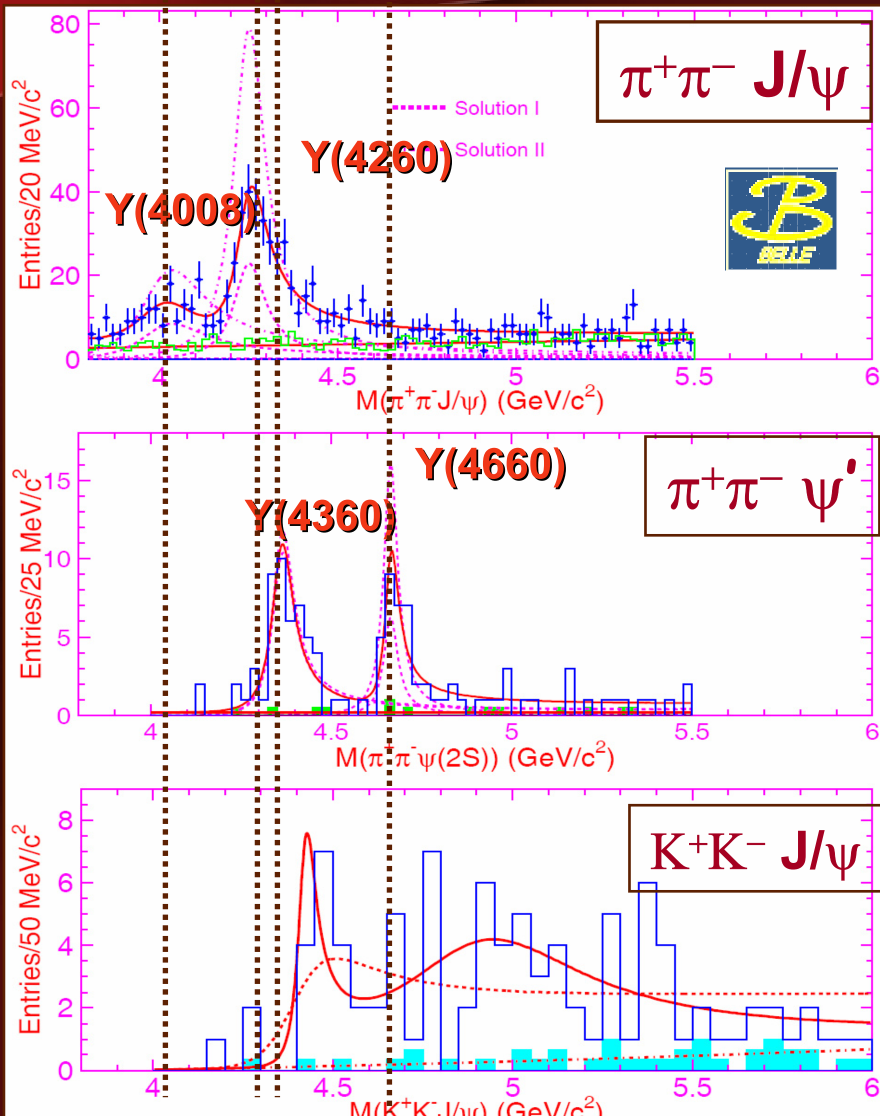
- Study of $e^+e^- \to \psi' \pi^+\pi^- \gamma_{ISR}$ (673 fb^{-1})
- $\psi' \to J/\psi \pi\pi$, $J/\psi \to ee, \mu\mu$ + ππ
- no additional tracks allowed
- γ_{ISR} not detected
- Two significant peaks in M(ψ'ππ) : one close to Babar's Y(4360) but narrower
- M(ψ'ππ) fitted with two coherent Breit-Wigners





Parameters	Solution I	Solution II
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

1^{--} Y states via ISR

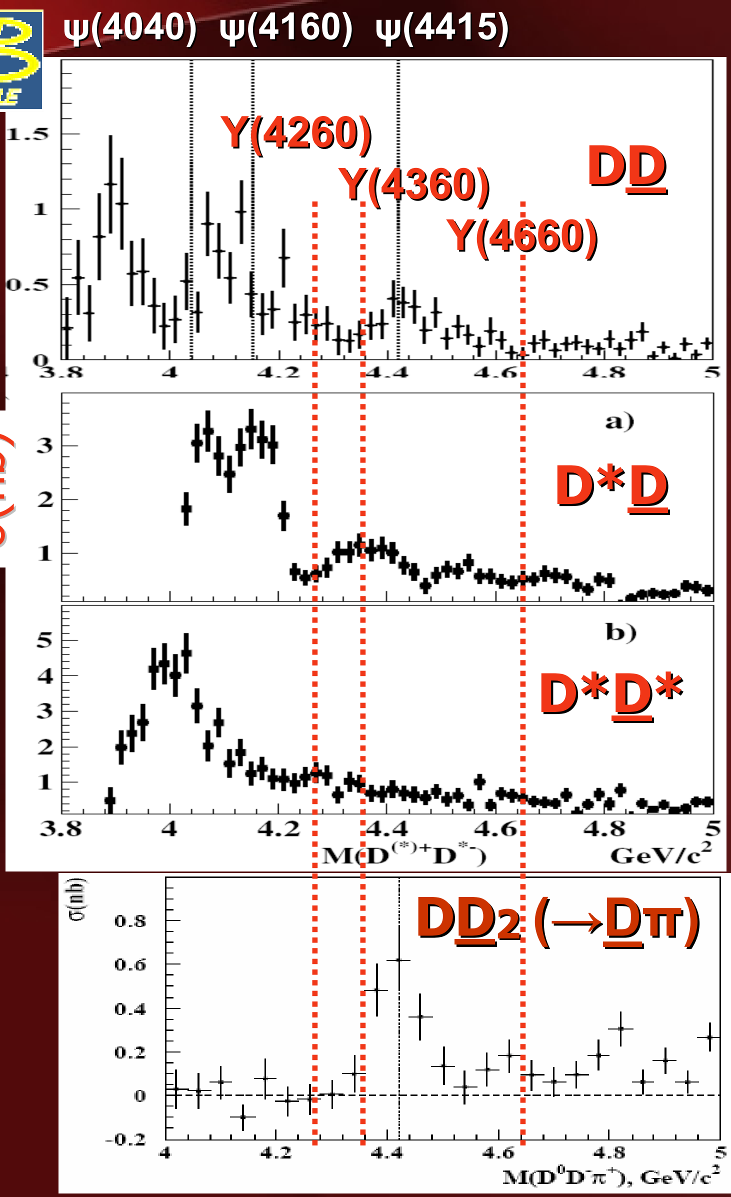


- Y states above $D\bar{D}$ threshold but don't match well the peaks in $D^{(*)}D^{(*)}$ x-sections
- Large widths for ψππ transition: unlike for conventional $c\bar{c}$
- No $c\bar{c}$ assignments available in this mass region (too many 1^- states observed)

Other options:

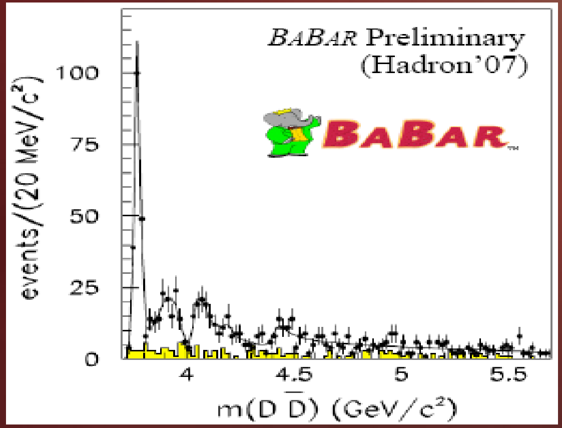
- Charm-meson threshold effects
- $D\bar{D}_1$ or $D^*\bar{D}_0$ molecules
- $cq\bar{c}\bar{q}$ tetraquarks
- ccg hybrid
  $D\bar{D}_1$ mode should dominate
- Coupled-channel effects

Exclusive $D^{(*)}\bar{D}^{(*)}$ x-sections with ISR



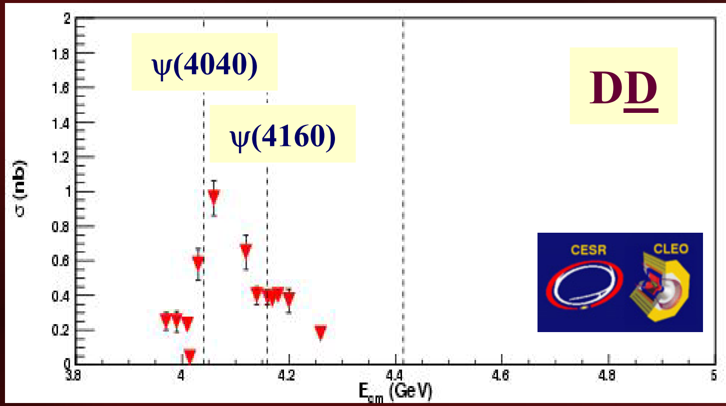
- PRD 77, 011103 (2008) for 673fb^{-1}
- PRL 98, 092001 (2007) for 548fb^{-1}
- PRL 100, 062001 (2008) for 673fb^{-1}

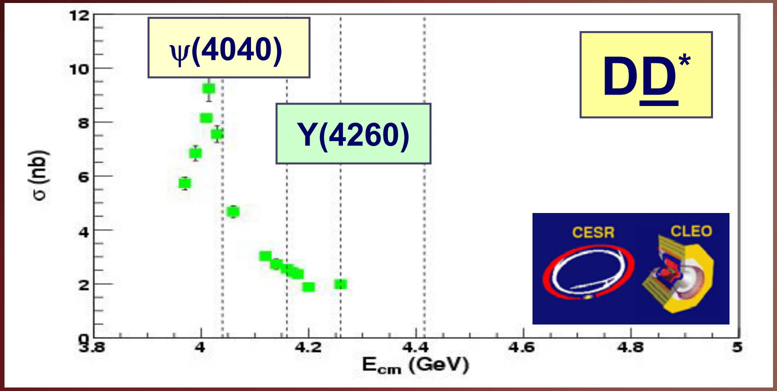
- D$\bar{D}$*, D*$\bar{D}$* using partial reconstruction; D$\bar{D}$, D$\bar{D}$π: fully recon.
- Difficult interpretation in terms of resonances (many maxima/minima, model dependent coupled-channel and threshold effects...)

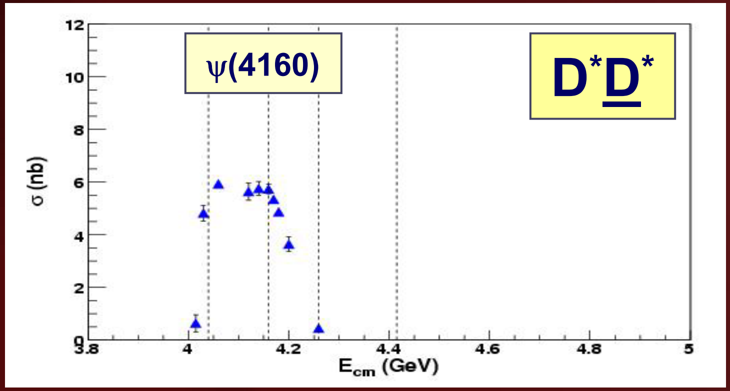


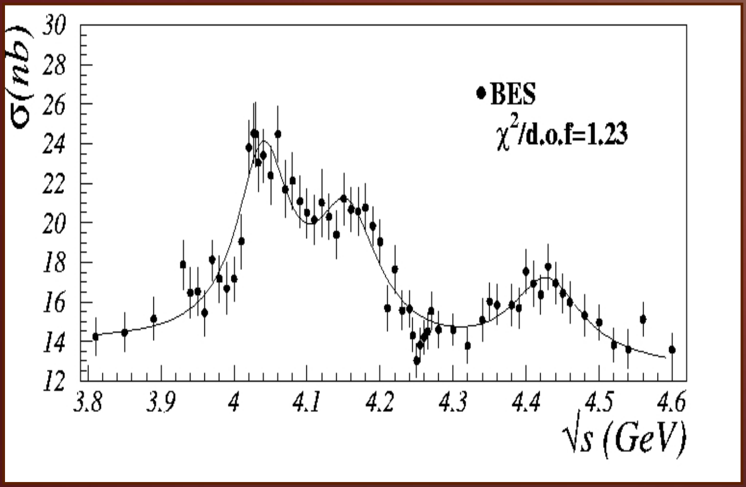
Hadronic x-sections

- From CLEO: scan at 3.97-4.26GeV in 12 points
- Total hadronic x-section above D$\underline{D}$ from BES



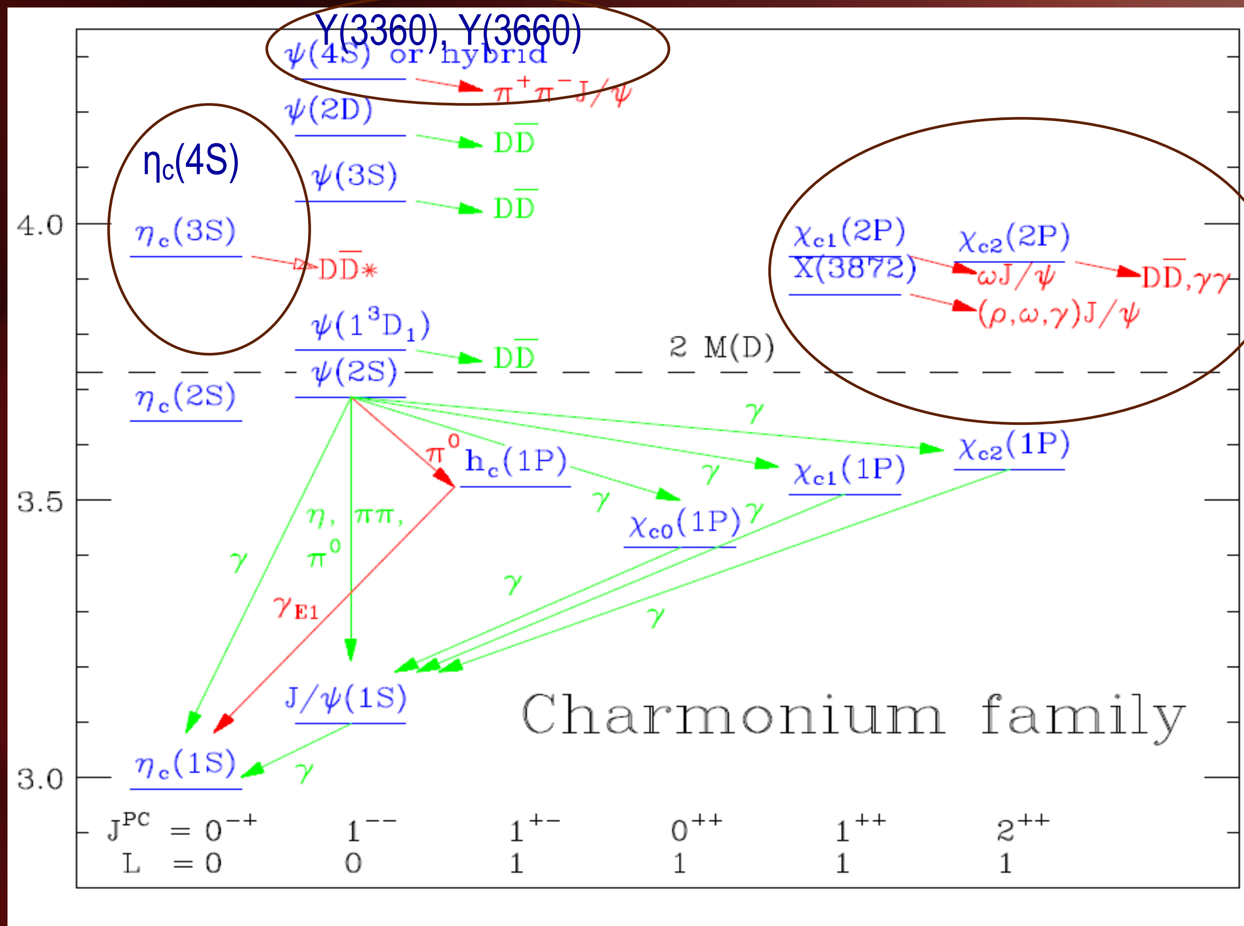






$c\underline{c}$ (-like) state of art

- We have added a few new states…
- Are they conventional $c\underline{c}$? Do we understand them?

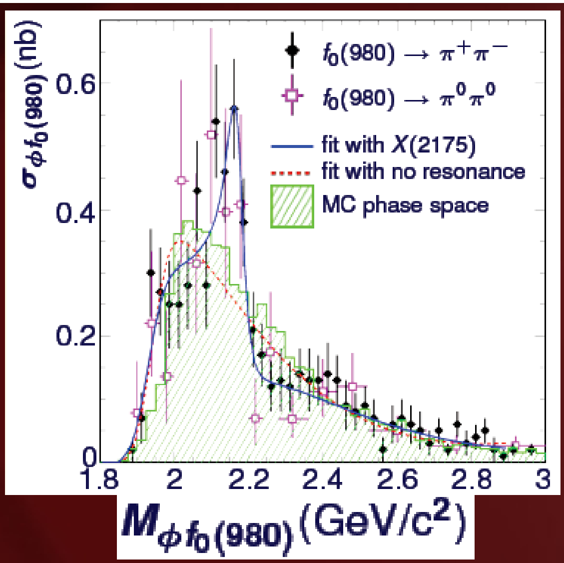


X(2175) strange analog of Y(4260)?

- X(2175) → φ $f_0(980)$, φη (confirmed by BESII)

$e^+e^- \to \gamma_{ISR}\ \phi(\to k^+k^-)\ f(980)$

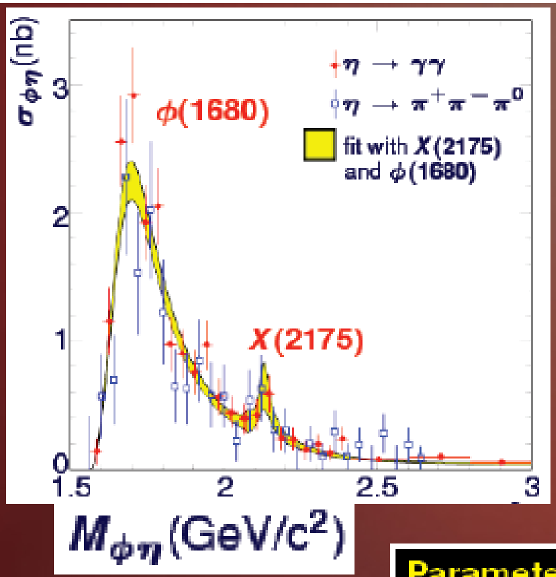
- ISR Process: $e^+e^- \to X(2175)\gamma_{ISR} \to \phi f_0(980)\gamma_{ISR}$
- $\phi \to K^+K^-$
- $f_0(980) \to \pi^+\pi^-,\ \pi^0\pi^0$
- Luminosity 232 fb^{-1}



Parameters
$M_X = 2175 \pm 10$ MeV/c^2
$\Gamma_X = 58 \pm 16$ MeV
$\sigma(M_X) = 0.13 \pm 0.4$ nb

$e^+e^- \to \gamma_{ISR}\ \phi(\to k^+k^-)\ \eta$

- ISR Process: $e^+e^- \to X(2175)\gamma_{ISR} \to \phi\eta\gamma_{ISR}$
- $\phi \to K^+K^-$
- $\eta \to \pi^+\pi^-\pi^0,\ \gamma\gamma$
- Luminosity 232 fb^{-1}



Parameters
$M_X = 2125 \pm 22 \pm 10$ MeV/c^2
$\Gamma_X = 61 \pm 50 \pm 13$ MeV
Significance 2.5 σ

PRD74, 091103 (2006)
PRD76, 092005 (2007)

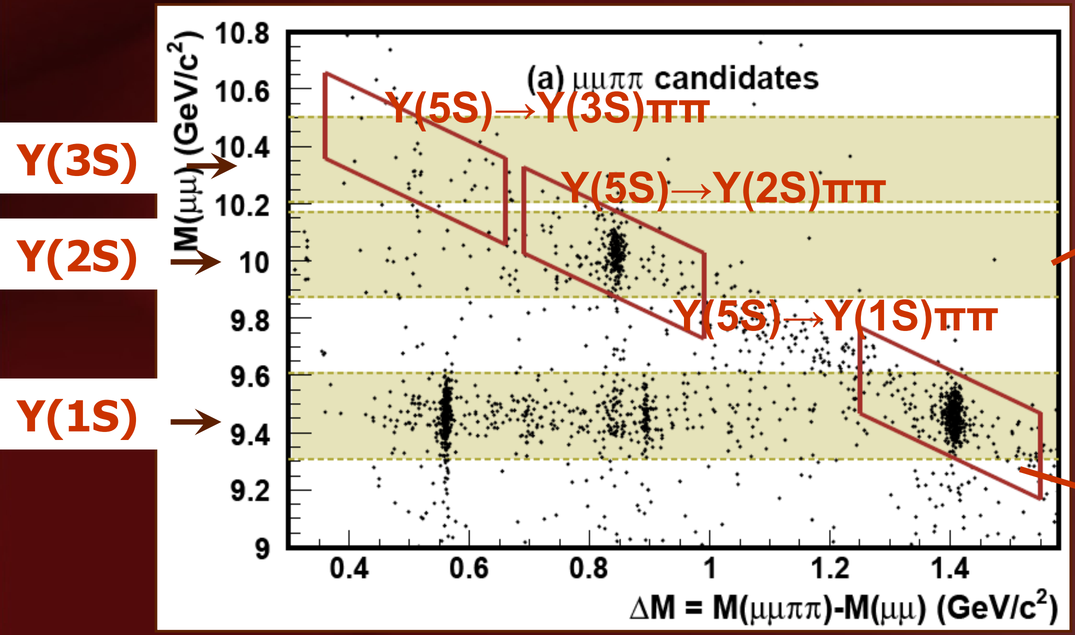
Is there any $b\bar{b}$ analog of Y(4260)?

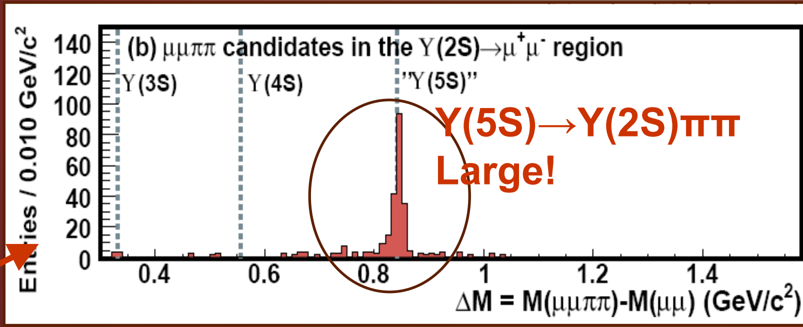
PRL100, 112001(2008)

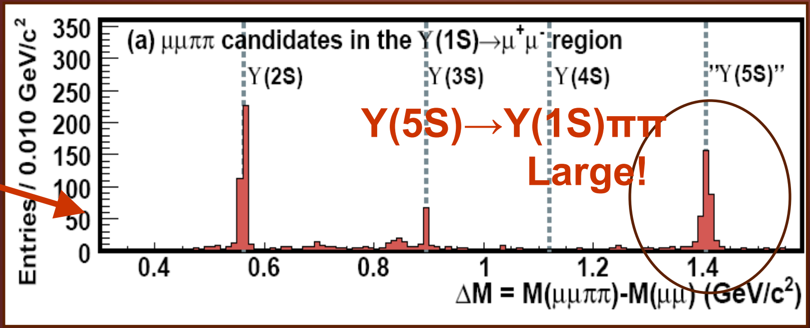
Hou, PRD74, 017504 (2006)

- If $b\bar{b}$ follows the pattern in $c\bar{c}$, Y_b should exist: $Y_b \to \Upsilon(nS)\pi\pi$
- Use $\Upsilon(5S)$ data: 21.7 fb^{-1} collected at $\sqrt{s}$=10869MeV

- Study of dipion transitions:
  $\Upsilon(mS) \to \Upsilon(nS)\pi^+\pi^-$ m>n $\Upsilon(nS) \to \mu^+\mu^-$ n=1,2,3
  Identified using: $\Delta M = M(\Upsilon(mS)) - M(\Upsilon(nS)) = M(\mu\mu\pi\pi) - M(\mu\mu)$







Large Υ(5S)→Υ(nS)ππ Do we see Y_b?

Process	Xsec(pb)	BF(%)	Γ(MeV)
"Υ(5S)"→Υ(1S)ππ	1.61±0.10±0.12	0.53±0.03±0.05	0.59±0.04±0.09
"Υ(5S)"→Υ(2S)ππ	2.35±0.19±0.32	0.78±0.06±0.11	0.85±0.07±0.16
"Υ(5S)"→Υ(3S)ππ	$1.44^{+0.55}_{-0.45}\pm0.19$	$0.48^{+0.18}_{-0.15}\pm0.07$	$0.52^{+0.20}_{-0.17}\pm0.10$

assuming Υ(5S)@10.87GeV σ=0.302±0.015nb

- **Large Υ(5S)→Υ(nS)ππ partial widths!**   **For other b$\underline{b}$: O(keV)**
  Do not agree with hypothesis for pure b$\underline{b}$ state

bb	Γ(total)	Γ(Υ(1S)ππ)
Υ(2S)	32 KeV	6.0 KeV
Υ(3S)	20 KeV	0.9 KeV
Υ(4S)	20.5 MeV	1.8 KeV
"Υ(5S)"	110 MeV	~0.5 MeV!!

cc	Γ(total)	Γ(J/ψππ)
ψ(2S)	337 KeV	107 KeV
ψ(3770)	23 MeV	44 KeV
ψ(4040)	80 MeV	<320 KeV @90%
ψ(4160)	103 MeV	<309 KeV @90%
Y(4260)	83 MeV	O(>MeV)

- **Is it Y_b? Mixture of Υ(5S) and Y_b?**
- **Energy scan around Υ(5S) (December 2007)**
  ~7.9fb^{-1} at 6 energy points. Results coming soon!

Summary

- New charmonium spectroscopy @4GeV
- Candidates for exotic hadrons observed:
  $Z^+(4430) \rightarrow \psi' \pi^+$ $Z_{1,2} \rightarrow \chi_{c1} \pi^+$
- Many other states await understanding
  X(3872) Y(3940) Y-family...
- XYZ spectroscopy also in s and b quark sectors?