Hadron Spectroscopy Results from Belle

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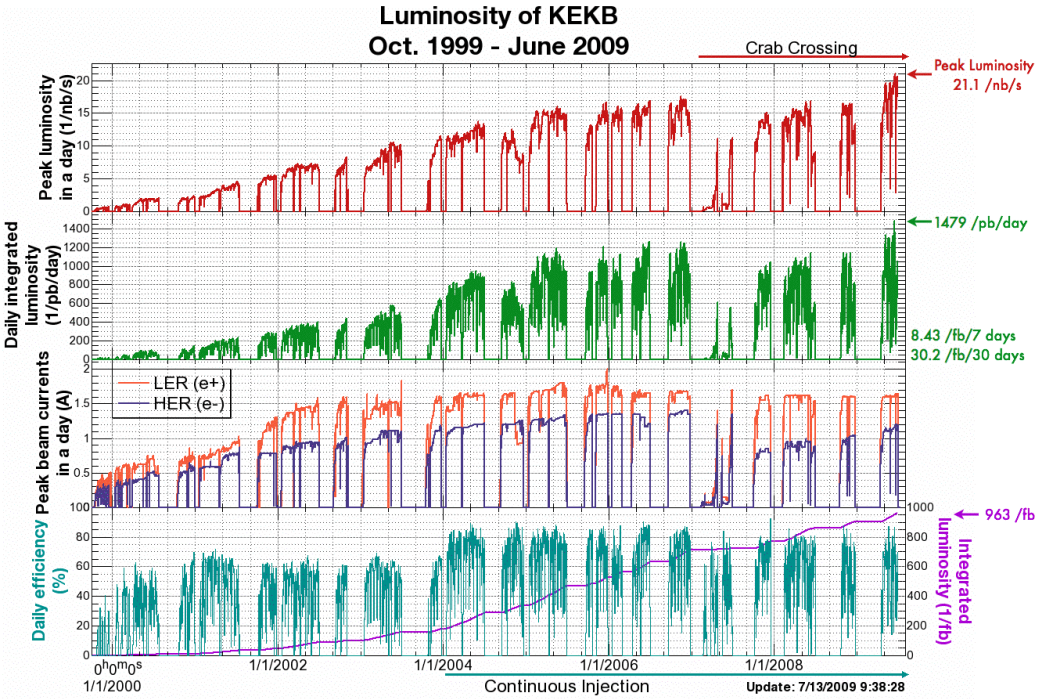
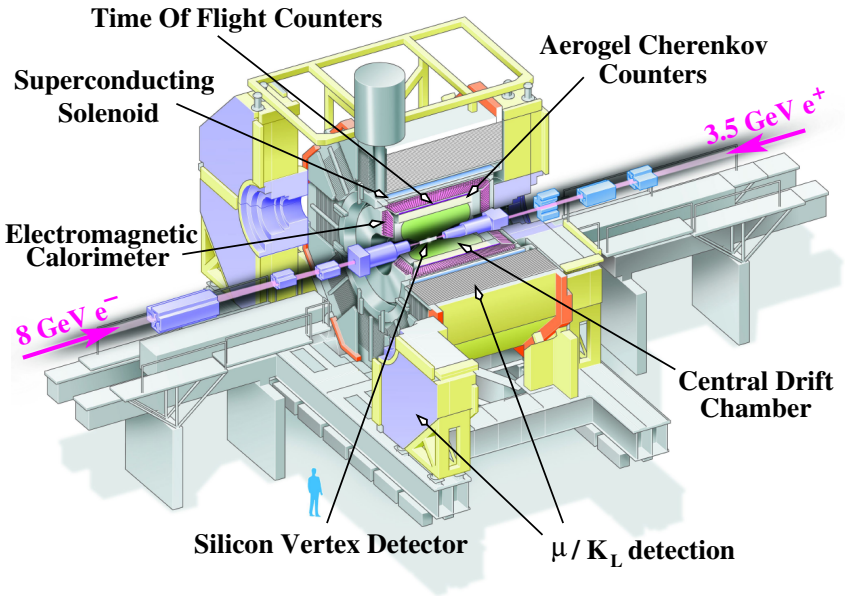
On behalf of the
Belle Collaboration

The 2009 Meeting of the Division of Particles and Fields
of the American Physical Society
Wayne State University
Detroit, MI
26 - 31 July, 2009

Belle @ KEKB

e^- (8 GeV) $\longrightarrow\!\!\!\!\leftarrow$ e^+ (3.5 GeV) collider





- large solid angle spectrometer
- excellent tracking
- excellent particle ID

- $\mathcal{L}_{\text{peak}} > 2.1 \times 10^{34}$ /cm^2/s
- $\int \mathcal{L} dt \sim 960$ /fb

Huge sample to search for new states!

... and many have been found @ Belle

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Observed also by
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	BaBar, BESII
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	BaBar CDF, D0,
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	BaBar
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

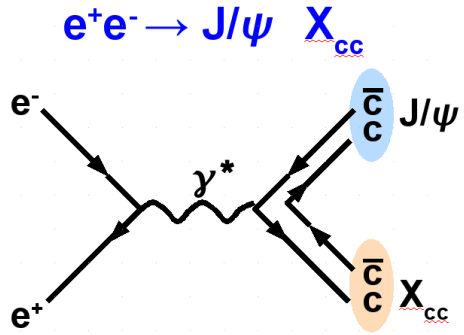
Table taken from arxiv:arXiv:0901.2371 (S. Olsen's proc. to PANIC08) + added two more states ($X(3915)$ and $X(4630)$).

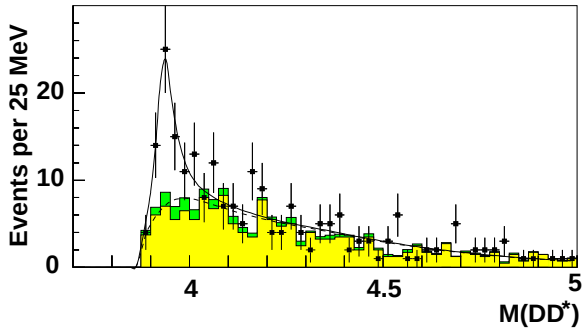
$c\bar{c}$-like states @ 3.90 – 3.95 GeV

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
X(3915)	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \rightarrow$ X(3915)
Z(3930)	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \rightarrow$ Z(3940)
X(3940)	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \rightarrow J/\psi$X(3940)
Y(3940)	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	B $\rightarrow$ KY(3940)

$X(3940)$, $Y(3940)$ and $Z(3930)$ (around 2005)

X(3940)





PRL100, 202001

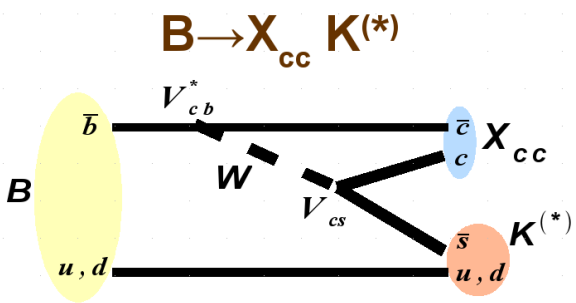
not seen in $\omega J/\psi$ or $D\bar{D}$

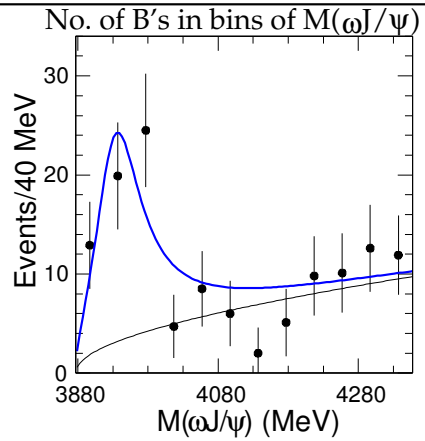
$M = 3942^{+7}_{-6} \pm 6$ MeV

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

⇕ probably different

Y(3940)





not seen in DD*

Belle: PRL94, 182002

$M = 3943 \pm 11 \pm 13$ MeV

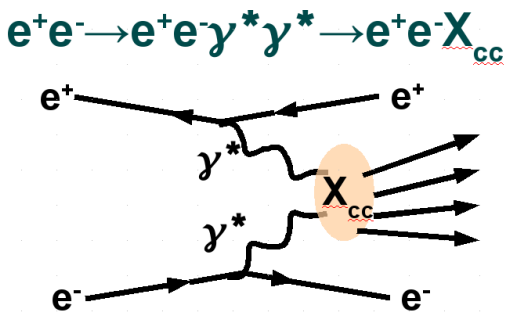
$\Gamma = 87 \pm 22 \pm 26$ MeV

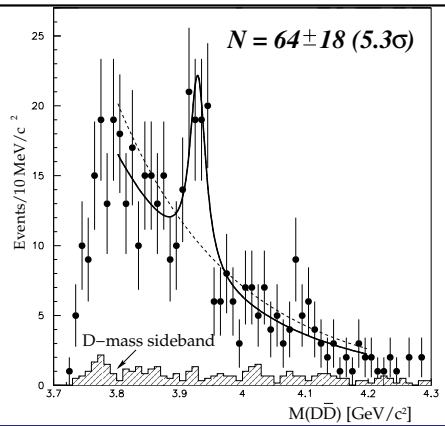
BaBar: PRL101, 082001

$M = 3914.3^{+3.8}_{-3.4} \pm 1.6$ MeV

$\Gamma = 33^{+12}_{-8} \pm 0.6$ MeV

Z(3930)





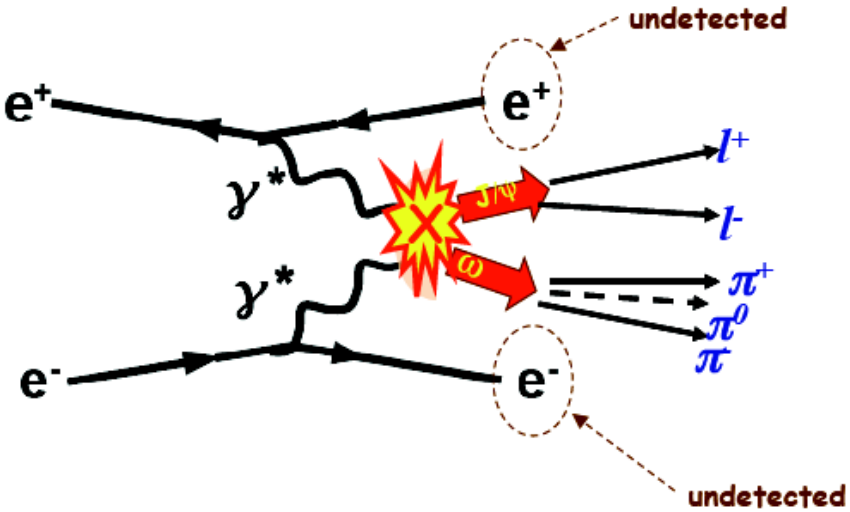
PRL96, 082003

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

$\Gamma = 29 \pm 10 \pm 2$ MeV

Mass, angular distributions and $\Gamma_{\gamma\gamma} \times \mathcal{B}(Z \to D\bar{D})$ consistent with $\chi'_{c2} - 2^3P_2$ charmonium!

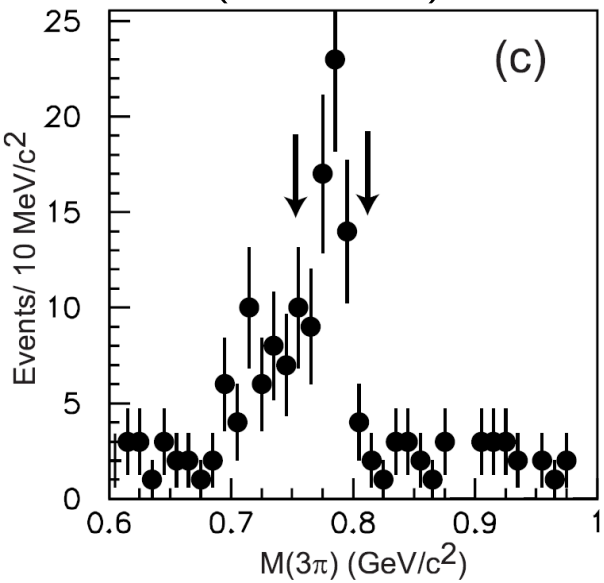
Search for $\gamma\gamma \to XYZ(3900-3950) \to \omega J/\psi$



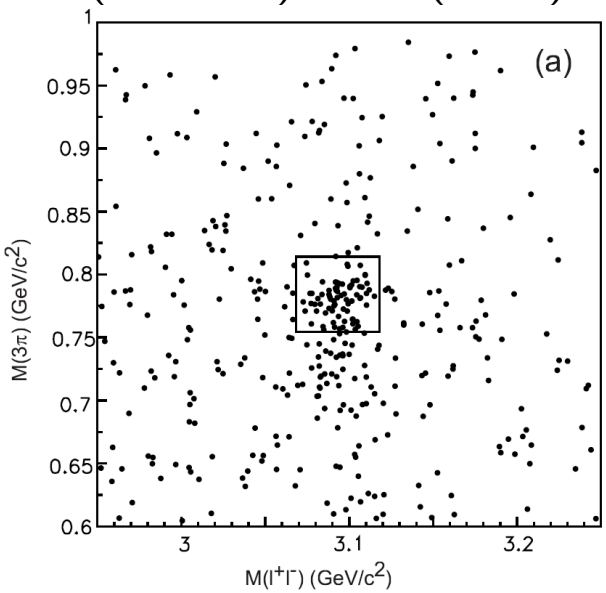
Selection:

- 4 tracks ($\geq$ 1 lepton, no kaons)
- $\sum_i q_i = 0$
- $\geq 1\pi^0$ $\leftarrow$ select best one
- veto $\psi(2S)\pi^0$
- $W = M(\ell^+\ell^-\pi^+\pi^-\pi^0) - M(\ell^+\ell^-) + M_{J/\psi} < 4.3$ GeV
- $|\sum \mathbf{p_t^*}| < \mathbf{0.1}$ **GeV**
- ...

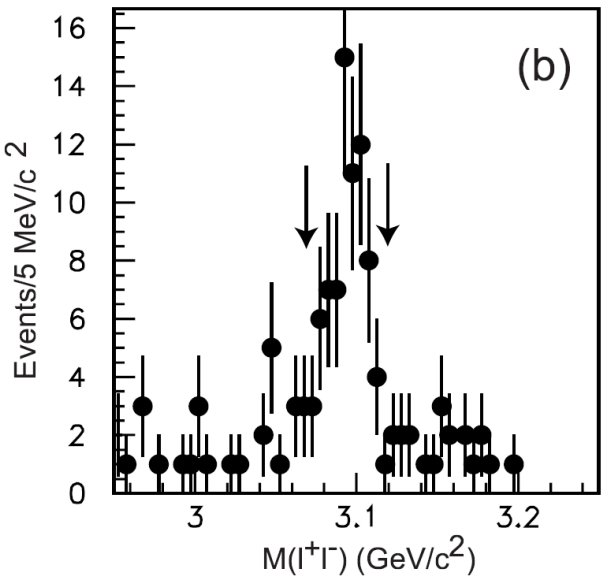
$M(\pi^+\pi^-\pi^0)$



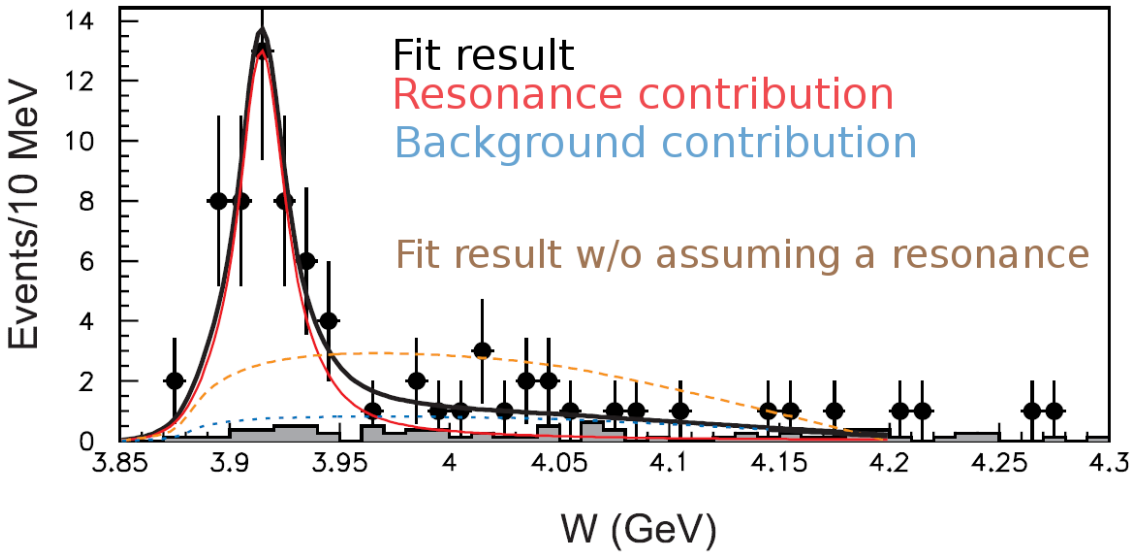
$M(\pi^+\pi^-\pi^0)$ vs. $M(\ell^+\ell^-)$



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



New peak in $\gamma\gamma \to \omega J/\psi$ @ 3915 GeV (Belle preliminary)



X(3915)

$M = 3914 \pm 3 \pm 2$ MeV
$\Gamma = 23 \pm 9^{+2}_{-3}$ MeV
$N_{\rm sig} = 54 \pm 11 \pm 4$
Significance $= 7.5\sigma$

$\hookrightarrow$ consistent with $Y(3940)$ values!

Product of decay width and $\mathcal{B}$

J^P	$\Gamma_{\gamma\gamma}\mathcal{B}(X(3915) \to \omega J/\psi)$
0^+	$69 \pm 16^{+7}_{-18}$ eV
2^+	$21 \pm 4^{+2}_{-5}$ eV

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

If $X(3915)$=$Z(3930)$=χ'_{c2}

$\Downarrow$

$$\frac{\mathcal{B}(\chi'_{c2} \to \omega J/\psi)}{\mathcal{B}(\chi'_{c2} \to D\overline{D})} \geq 0.08$$

Huge for above-open-charm-threshold charmonium!

There are no good $c\overline{c}$ candidates for $X(3940)$, $Y(3940)$ and $X(3915)$.

X(3872)'s mass and decay modes

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
X(3872)	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$,$D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$

$X(3872)$'s Mass in $\pi\pi J/\psi$ decay mode [arxiv:0809.1224]

Search for $X(3872)$'s neutral partner:

- Mass difference: $\delta M \equiv M_{XK^+} - M_{XK^0}$

diquark-antidiquark
Maiani et. al. PRD71 014028
$\delta M^{th.} = 8 \pm 3$ MeV

$\delta M^{exp.}$
$=$
$0.18 \pm 0.89 \pm 0.26$ MeV

No evidence of neutral partners!

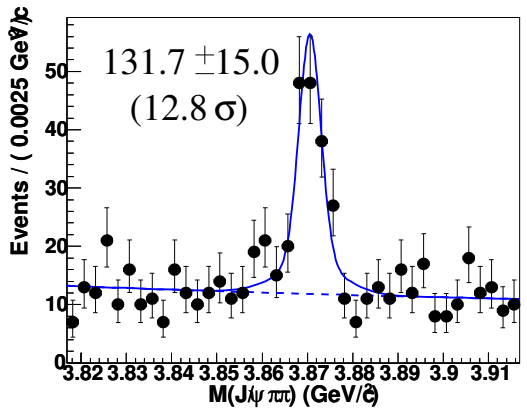
$$\frac{\mathcal{B}(B^0 \to X(3872) K^0)}{\mathcal{B}(B^+ \to X(3872) K^+)} = 0.82 \pm 0.22 \pm 0.05$$

This measurement: (B^+ and B^0 samples)
$M_{X(3872)} = 3871.46 \pm 0.37 \pm 0.07$ MeV

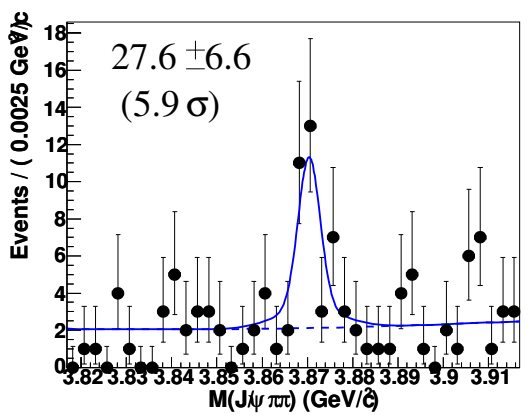
World average (T.Kuhr @ QWG08):
$M_{X(3872)} = 3871.5 \pm 0.2$ MeV

$M_{D^0} + M_{D^*} = 3871.81 \pm 0.25$ MeV
(PDG08 + PRL98,092002)

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



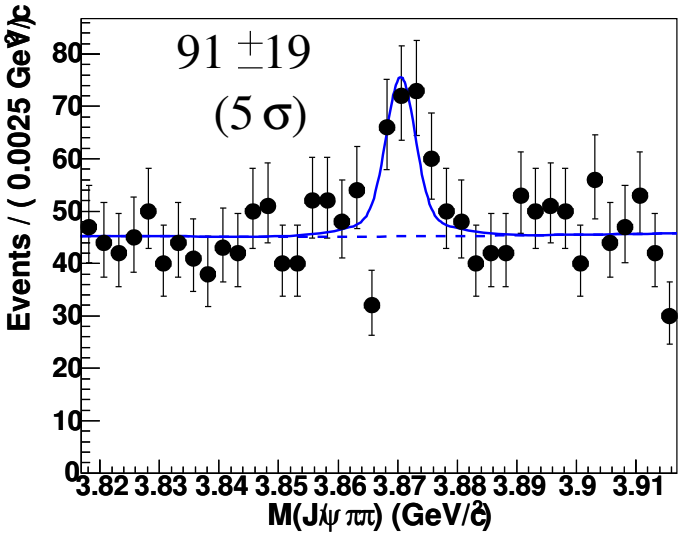
$B^0 \to X(3872) K^0$

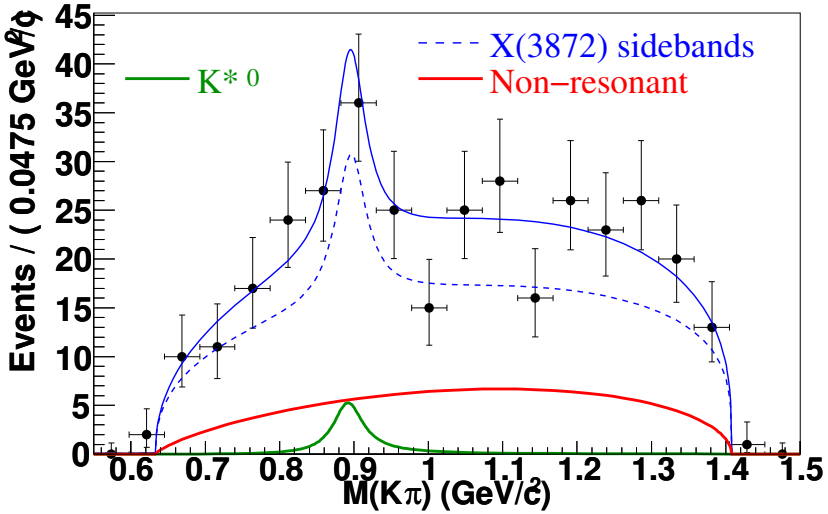


First observation!

First observation of $B^0 \to X(3872)K^+\pi^-$ [arxiv:0809.1224]

Study of $B^0 \to X(3872)K^+\pi^-$; $X(3872) \to \pi\pi J/\psi$





$N_{XK\pi} = 81 \pm 20 \quad N_{XK^{*0}} = 8 \pm 10$

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

$$\mathcal{B}(B \to X(3872)K^{*0}) \times \mathcal{B}(X \to \pi\pi J/\psi) < 3.4 \times 10^{-6} \text{ @ 90\% C.L.}$$

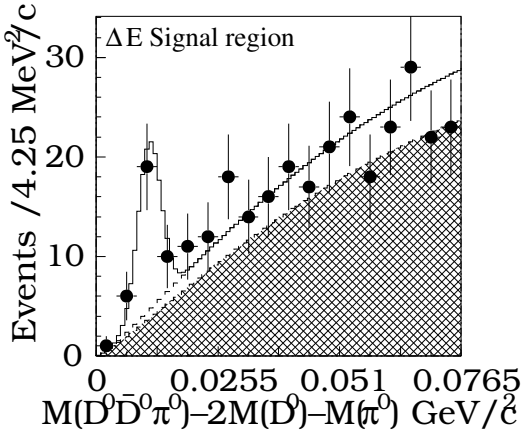
$B^0 \to X(3872)K^+\pi^-$ is dominant; $B^0 \to X(3872)K^{*0}$ is small.

In contrast to $B \to \psi(2S)K\pi$, $J/\psi K\pi$ and $\chi_{c1}K\pi$ where K^* dominates!

Mass of $X(3872)$ in $D^0\overline{D}^{*0}$

Belle PRL97, 162002

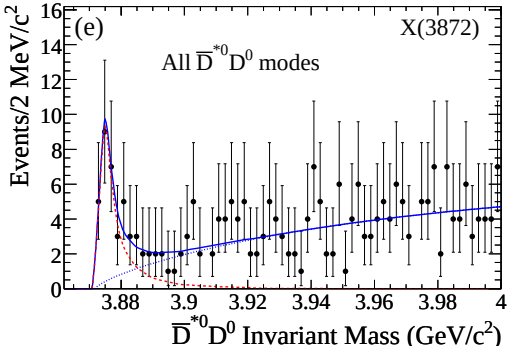
$B \to D^0\overline{D}^0\pi^0 K$



$M = 3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$ MeV

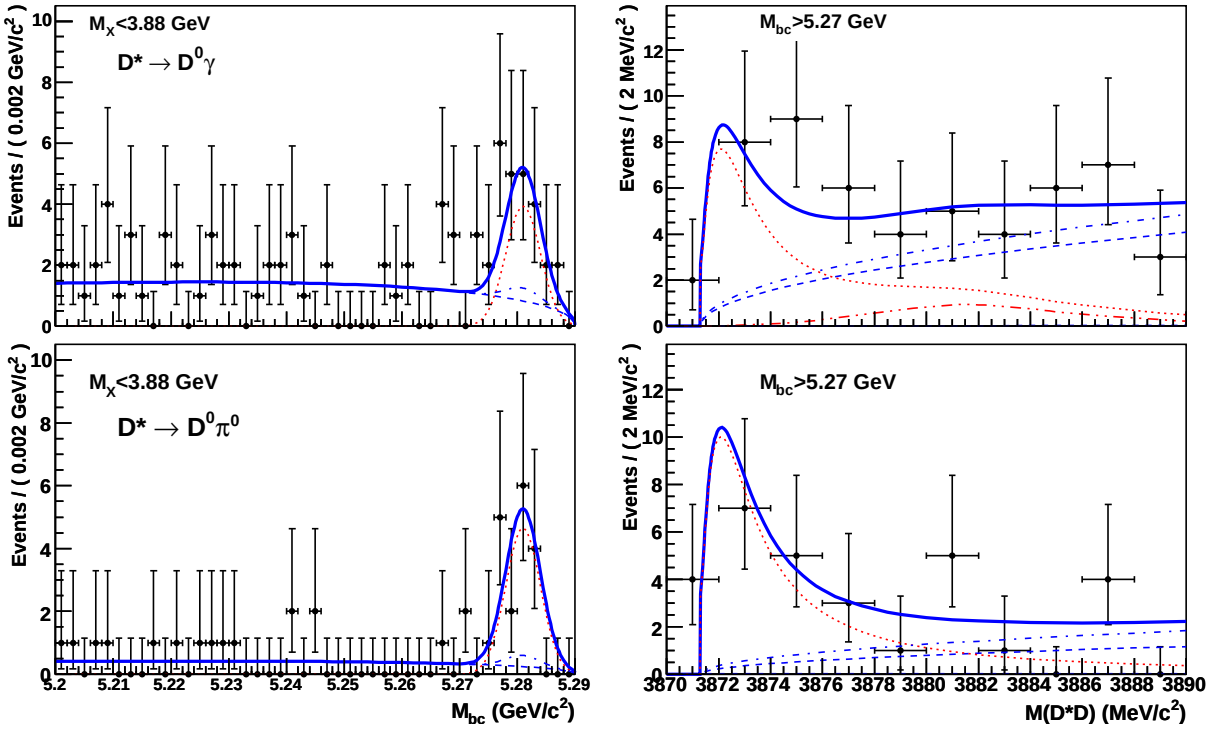
BaBar PRD77, 011102

$B \to D^0\overline{D}^{*0} K$



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

Belle [arXiv:0810.0358]: $B \to D^0\overline{D}^{*0}K$



$M = (3872.6^{+0.5}_{-0.4} \pm 0.4)$ MeV

$\Gamma(BW) = 3.9^{+2.5\,+0.8}_{-1.3\,-0.3}$ MeV

$\mathcal{B}(B \to XK) \times \mathcal{B}(X \to D^0\overline{D}^{*0}) =$

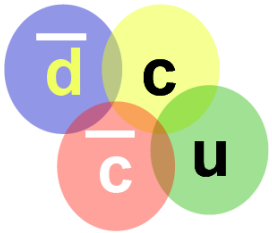
$(0.73 \pm 0.17 \pm 0.08) \times 10^{-4}$

No significant mass difference from that in $J/\psi\pi\pi$!

See also Eric Braaten's talk on properties of $X(3872)$!

This parallel session @ 15:00

Charged resonancelike states (minimal quark content $c\bar{c}u\bar{d}$)

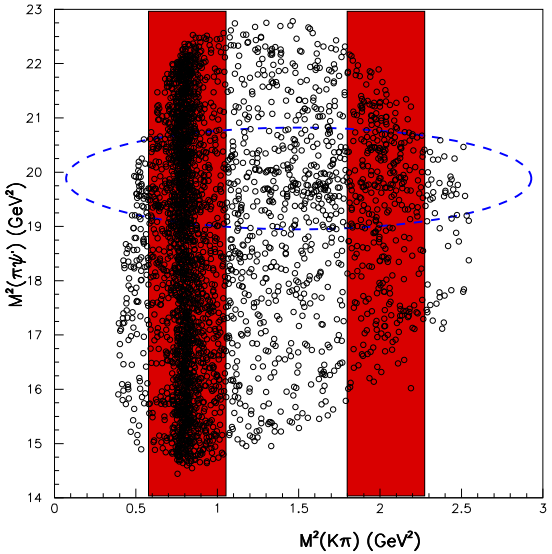


State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
Z(4050)	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^{\pm}\chi_{c1}$	$B \longrightarrow KZ^{\pm}(4050)$
Z(4250)	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^{\pm}\chi_{c1}$	$B \longrightarrow KZ^{\pm}(4250)$
Z(4430)	4433 ± 5	45^{+35}_{-18}	?	$\pi^{\pm}\psi'$	$B \longrightarrow KZ^{\pm}(4430)$

First observation of $Z^+(4430)$ @ Belle

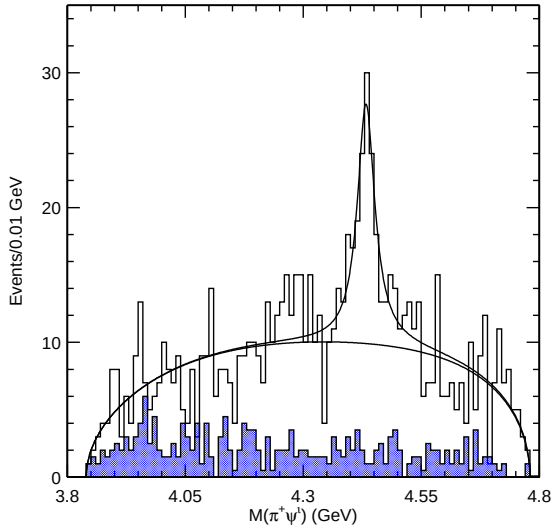
Study of $B \to K\pi^{\pm}\psi(2S)$

$K^*(890)$ and $K_2^*(1430)$ veto



S-wave Breit-Wigner

+ Background with kinematic thresholds



Belle: PRL100, 142001

Significance $= 6.5\sigma$

$M = 4433 \pm 4 \pm 1$ MeV

$\Gamma = 44^{+17\,+30}_{-13\,-11}$ MeV

$\mathcal{B}(B \to KZ(\psi(2S)\pi^+)) = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$

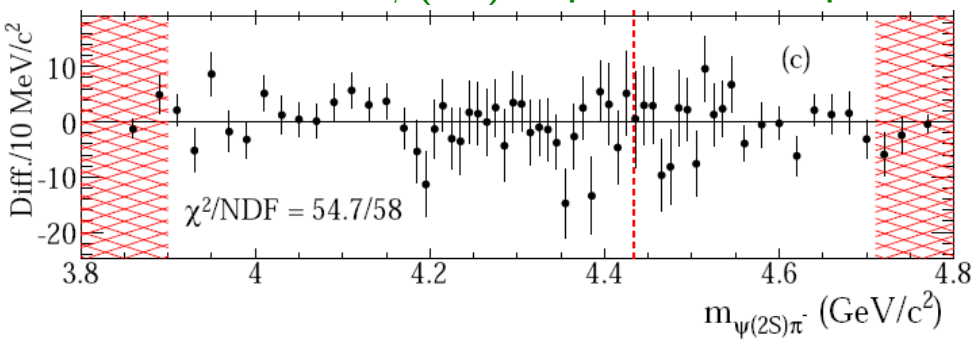
Interpretations:

- **threshold effect**
  J.L.Rosner 0708.3496, D.V.Bugg, 0709.1254
- **D^*D_1 molecular state**
  X. Liu and Y.R. Liu, 0711.0494
- **radially excited tetraquark**
  L.Maiani, A.D.Polosa, V.Riquer, 0708.3997
- **baryonium state**
  C.F.Qiao, 0709.4066
- **hadro-charmonium**
  S.Dubinskiy,M.B.Voloshin,0803.2224

BaBar observes 1.9σ signal PRD79, 112001

$\mathcal{B}(B \to KZ(\psi(2S)\pi^+)) < 3.1 \times 10^{-5}$ @ 95% C.L.

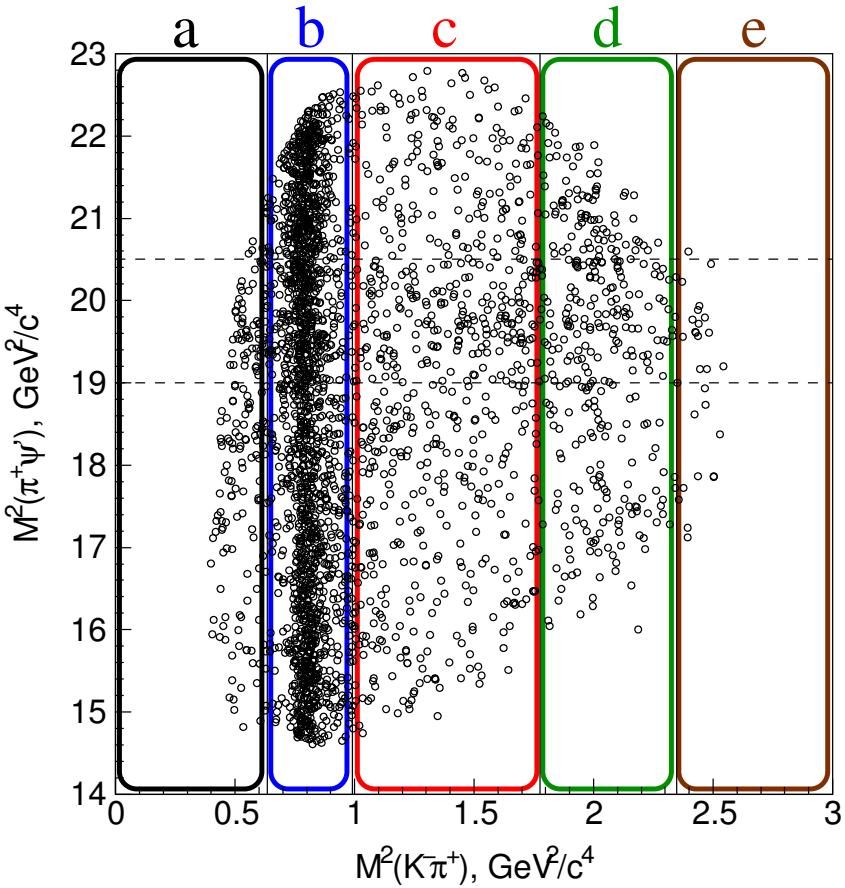
Belle and BaBar $\psi(2S)\pi$ spectrum comparison



Full Dalitz plot analysis of $B \to K\pi^{\pm}\psi(2S)$

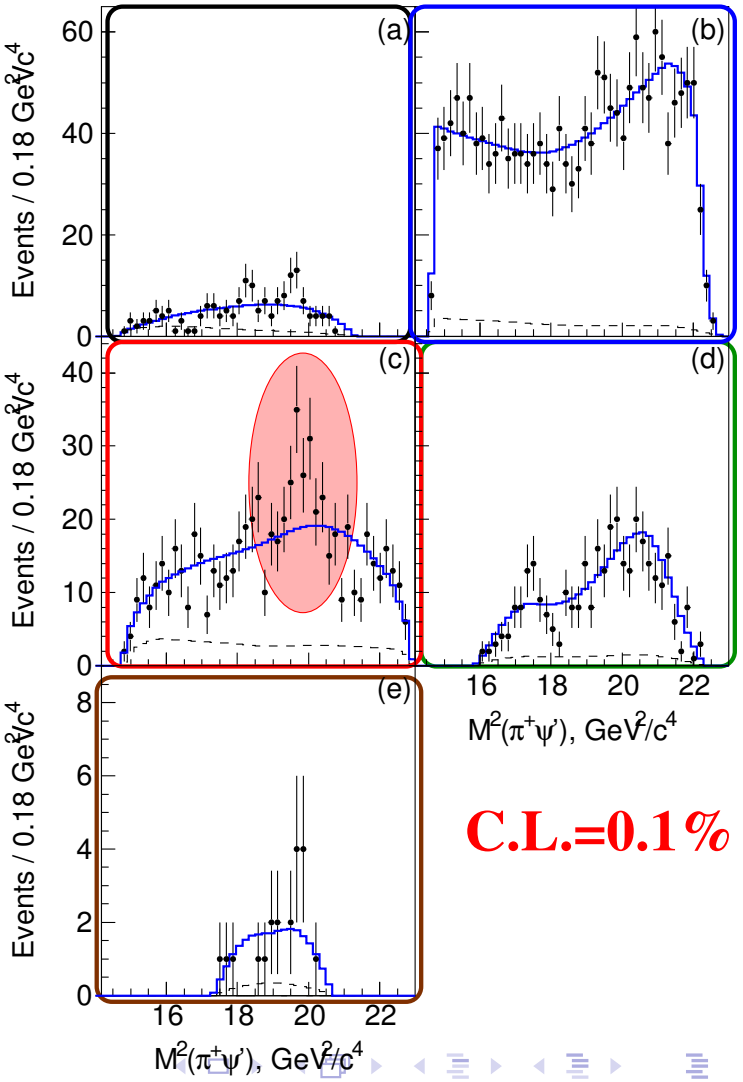
Default Dalitz model: $K^*(800)$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$

Belle: arxiv:0905.2869 (PRD)



Kπ cannot reproduce narrow peak!

Fit without $Z(4430)$

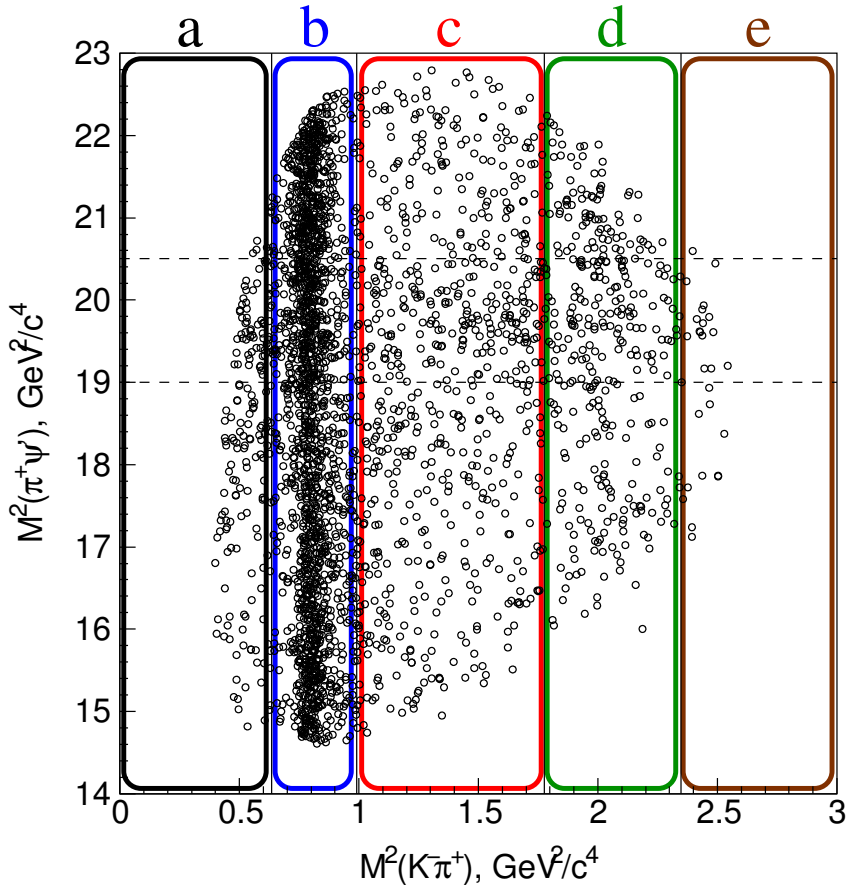


C.L.=0.1%

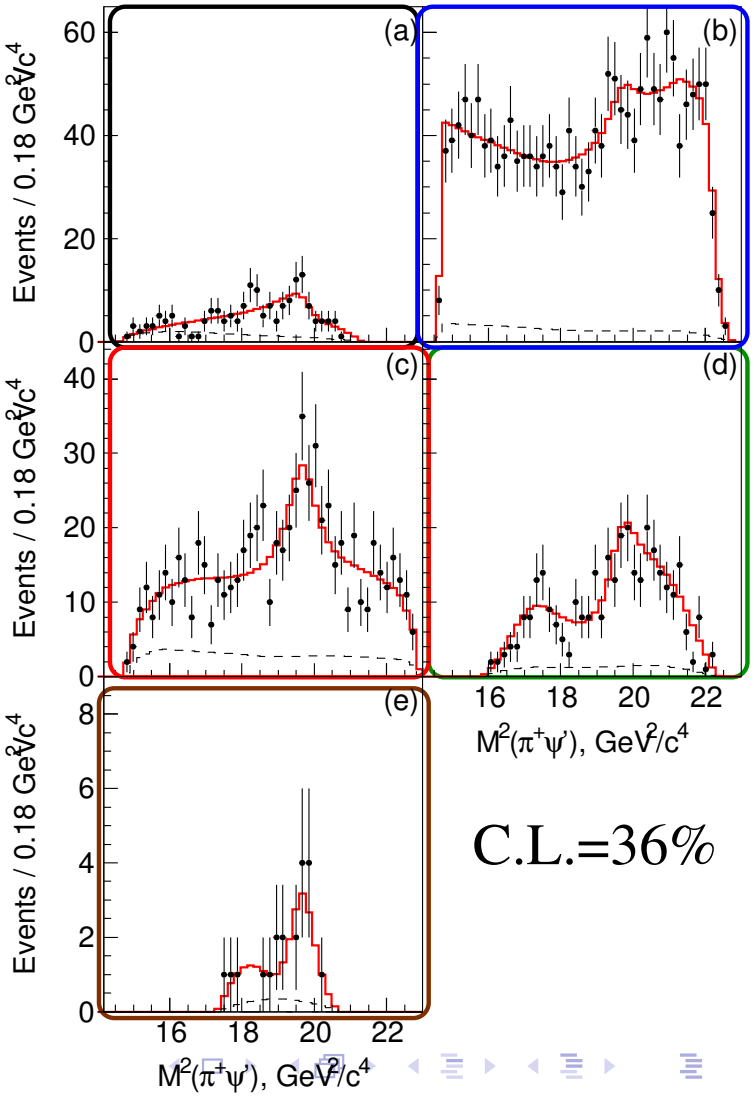
Full Dalitz plot analysis of $B \to K\pi^{\pm}\psi(2S)$

Fit with default Dalitz model + $Z(4430)$

Belle: arxiv:0905.2869 (PRD)



Fit with $Z(4430)$

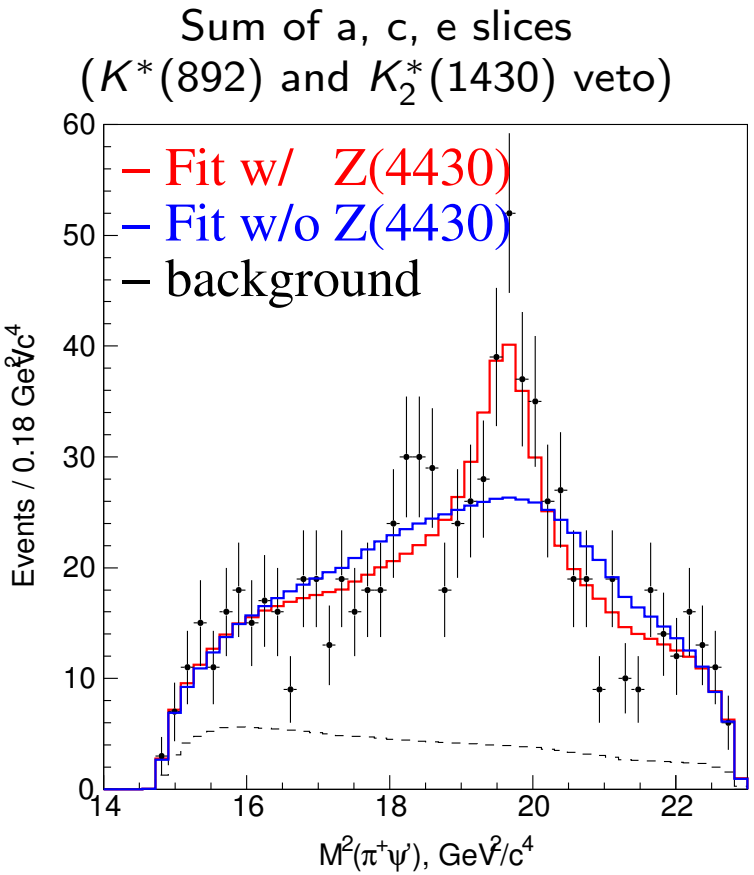


C.L.=36%

Significance of $Z(4430)$ peak is 6.4σ

Updated properties of $Z^{\pm}(4430)$

Belle confirms the original result on $Z^{\pm}(4430)$



Belle: arxiv:0905.2869 (PRD)

$$\text{Significance} = 6.4\sigma$$

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

$$\Gamma = 107^{+86+74}_{-43-56}\ \text{MeV}$$

$$\mathcal{B}(B \to KZ(\psi(2S)\pi^+)) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$$

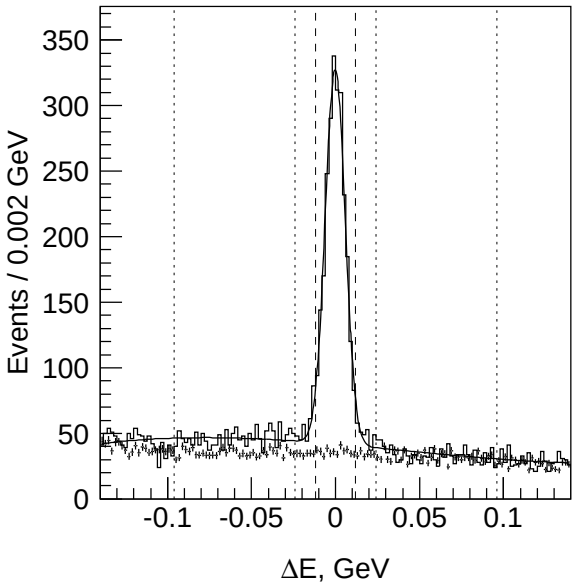
Width larger than in original analysis (45 MeV) but uncertainties are also larger.

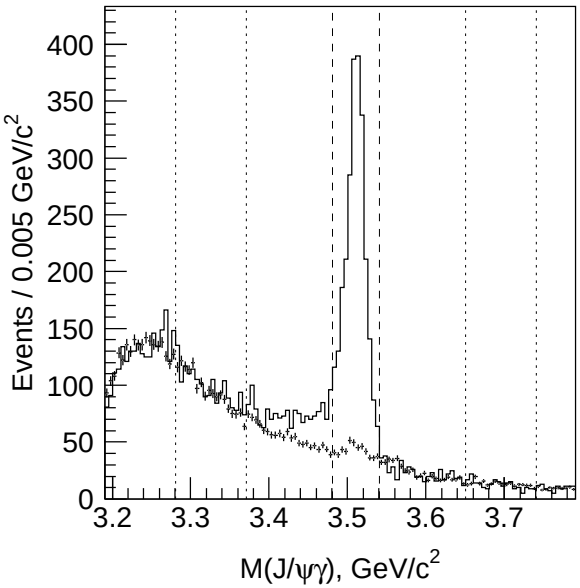
Systematic study: $Z^{\pm}(4430)$ significance in different fit models always $> 5.4\sigma$!

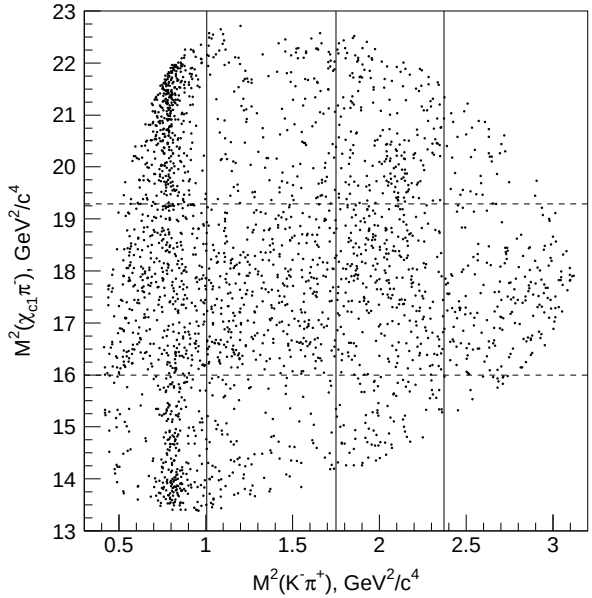
Observation of $Z^+(4050)$ and $Z^+(4250)$ @ Belle

Study of $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ decays ($\chi_{c1} \to J/\psi\gamma$) Belle PRD78, 072004

Clear signals in ΔE, M_{bc} and $M(J/\psi\gamma)$: $N(\overline{B}^0 \to K^-\pi^+\chi_{c1}) = 2126 \pm 56 \pm 42$





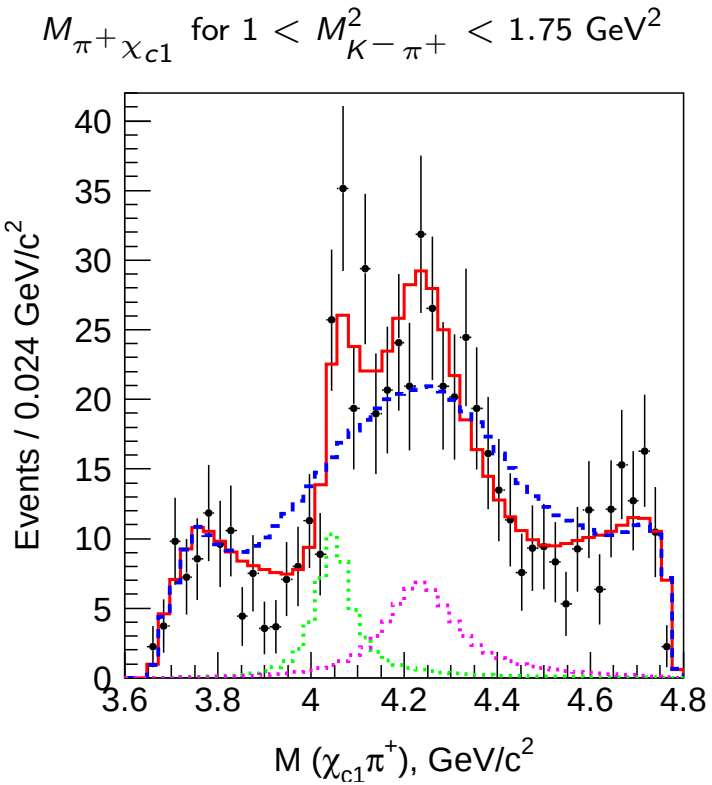


Default Dalitz model:

- $K^*(800)$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$, $K_3^*(1780)$ + $Z^+(\pi^+\chi_{c1})$
- Integrated χ_{c1} and J/ψ angular distributions
- Fit results depicted in $M^2_{K^-\pi^+}$ and $M^2_{\pi^+\chi_{c1}}$ slices

Observation of $Z^+(4050)$ and $Z^+(4250)$ @ Belle

Belle data favour fit with two new resonant structures



– only known K^* (C.L.$= 3 \times 10^{-10}$)

– $+Z(4050) + Z(4250)$ (C.L.$= 42\%$)

– $Z(4050)$ contribution

– $Z(4250)$ contribution

Belle: PRD78, 072004

	$Z(4050)^+$	$Z(4250)^+$
M [MeV]	$4051 \pm 14^{+29}_{-41}$	$4248^{+44+180}_{-29-35}$
Γ [MeV]	82^{+21+47}_{-16-22}	$177^{+54+316}_{-39-61}$
$\mathcal{B}_{\overline{B^0}} \cdot \mathcal{B}_{Z^+}$	$3.0^{+1.5+3.7}_{-0.8-1.6} \times 10^{-5}$	$4.0^{+2.3+19.7}_{-0.9-0.5} \times 10^{-5}$

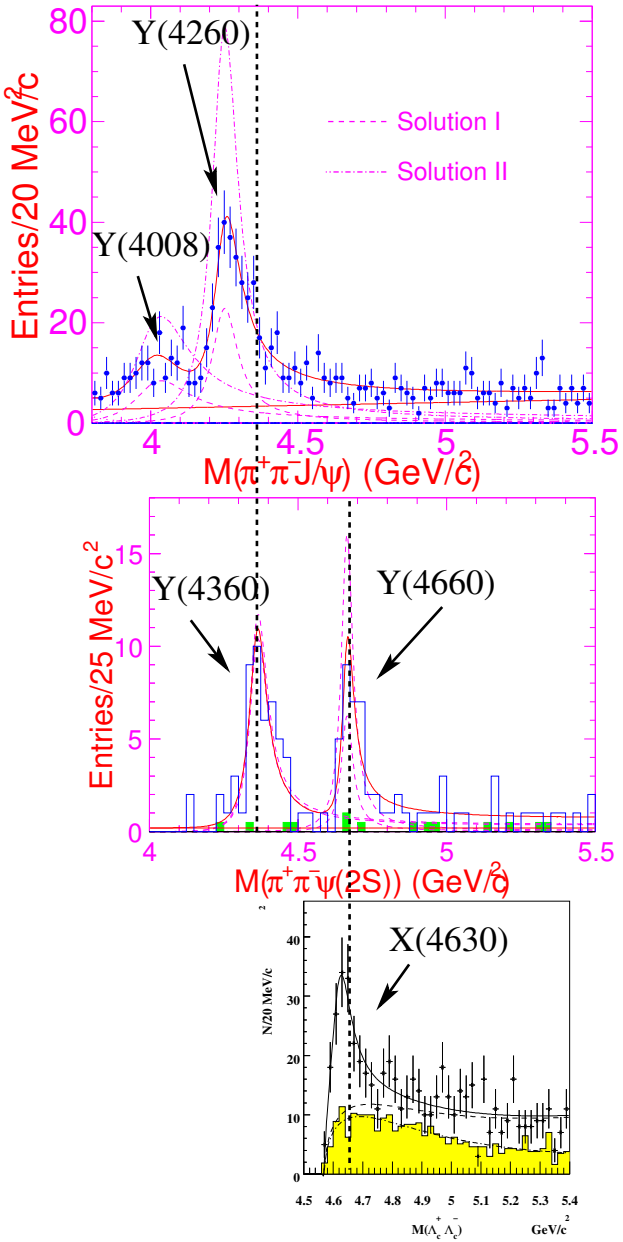
- **double resonant structure is distinctive (favoured over one res. at the 5.7σ)**
- spin of $Z_{1,2}$ not determined ($J = 0$ or 1 give comparable results)
- large syst. errors on M and Γ due to model uncertainties
- $\mathcal{B}$'s comparable to $Z^+(4430)$, $X(3872)$, ...

$Z^+(4050)$ and $Z^+(4250)$ join $Z^+(4430)$ as charged charmonium-like exotics

1^{--} states via ISR

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
Y(4008)	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
Y(4260)	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
Y(4350)	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)
X(4630)	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)
Y(4660)	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)

1^{--} states via ISR @ Belle



$\pi^+\pi^- J/\psi$

	Belle PRL99,182004		BaBar PRL95, 142001
	Y(4008)	Y(4260)	Y(4260)
M [MeV]	$4008 \pm 40^{+114}_{-81}$	$4247 \pm 12^{+17}_{-32}$	$4259 \pm 8^{+2}_{-6}$
Γ [MeV]	$226 \pm 44 \pm 87$	$108 \pm 19 \pm 10$	$88 \pm 23^{+6}_{-9}$

Y(4008) not seen by BaBar. Y(4260) also observed by Cleo.

$\pi^+\pi^- \psi(2S)$

	Belle PRL99,142002		BaBar PRL98, 212001
	Y(4360)	Y(4660)	Y(4325)
M [MeV]	$4361 \pm 9 \pm 9$	$4664 \pm 11 \pm 5$	4324 ± 24
Γ [MeV]	$74 \pm 15 \pm 10$	$48 \pm 15 \pm 3$	172 ± 33

$\Lambda_c^+ \Lambda_c^-$

	Belle PRL101,172001
	X(4630)
M [MeV]	$4634^{+8\ +5}_{-7\ -8}$
Γ [MeV]	$92^{+40\ +10}_{-24\ -21}$

Is Y(4630) = Y(4660)? Could be a 5^3S_1 charmonium?

Too many 1^{--} states in this mass region to identify them as conventional charmonium resonances!

XY counterparts in $b\bar{b}$ and $s\bar{s}$ systems

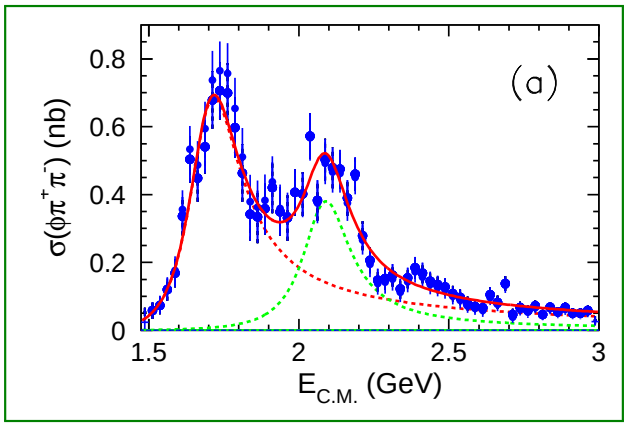
State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \longrightarrow \eta Y_s(2175)$
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^-\Upsilon(1,2,3S)$	$e^+e^- \longrightarrow Y_b$

$s\bar{s}$ system: Confirmation of $Y(2175)$ @ Belle

First observed at BaBar (PRD74, 091103) and confirmed by BESII (PRL100, 102003)

Study of $e^+e^- \to \phi\pi^+\pi^-$ and $e^+e^- \to \phi f_0(980)$ via ISR

$\sigma(\phi\pi^+\pi^-)$

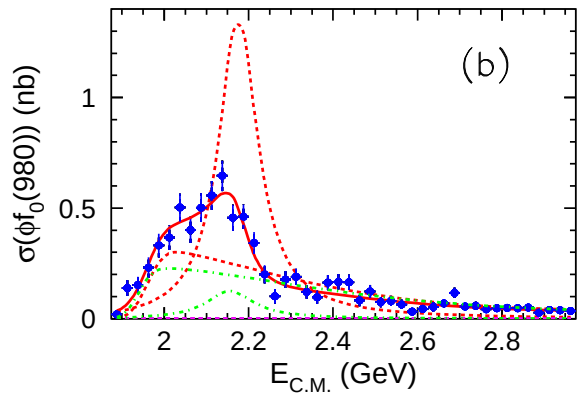


Fit with two coherent BWs

Belle arXiv:0808.0006

$\phi(1680)$
$M = 1689 \pm 7 \pm 10$ MeV
$\Gamma = 211 \pm 14 \pm 19$ MeV
$Y(2175)$
$M = 2079 \pm 13^{+79}_{-28}$ MeV
$\Gamma = 192 \pm 23^{+25}_{-61}$ MeV

$\sigma(\phi f_0(980))$

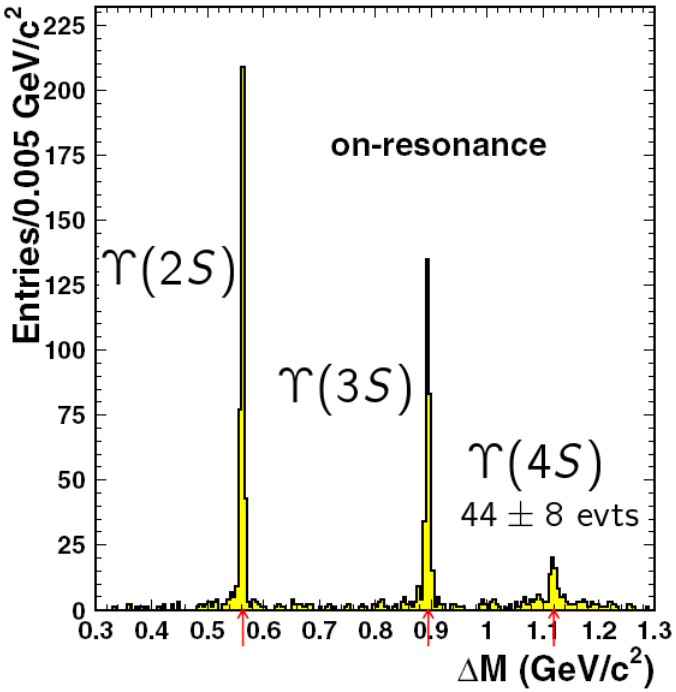


Coherent sum of one BW and nonresonant term

- Mass and width are consistnt between the two fits
- In agreement with BaBar's and BESII's measurements
- $\phi(1680)$ and $Y(2175)$ have similar width (~ 200 MeV)
  $\hookrightarrow$ suggests $Y(2175)$ is a excited ϕ ($s\bar{s}$ state)

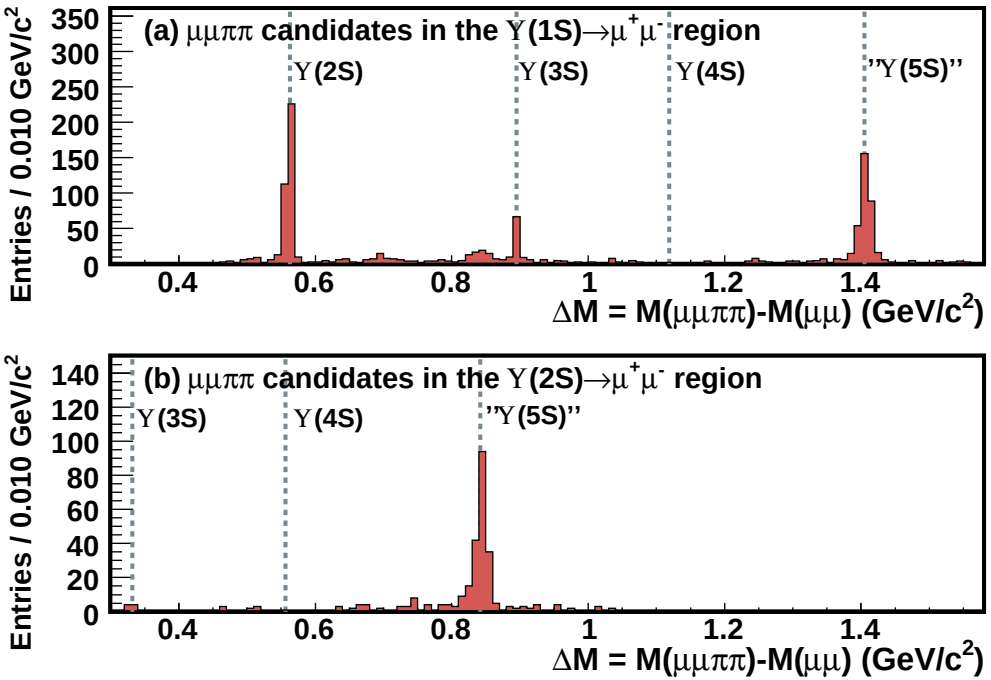
$b\bar{b}$ system: Huge $\Gamma(\Upsilon(5S) \to \pi\pi\Upsilon(1S))$

$\Upsilon(nS) \to \pi\pi\Upsilon(1S)$
with 447/fb @ $\sqrt{s} \equiv \Upsilon(4S)$



Belle: PRD75, 071103

$\Upsilon(nS) \to \pi\pi\Upsilon(1,2S)$
with 21.7/fb @ $\sqrt{s} \equiv \Upsilon(5S)$



Belle: PRL100, 112001

$b\bar{b}$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$
Γ(total)	32 keV	20 keV	20.5 MeV	110 MeV
$\Gamma(\pi\pi\Upsilon(1S))$	6 keV	0.9 keV	1.9 keV	**0.59 MeV**

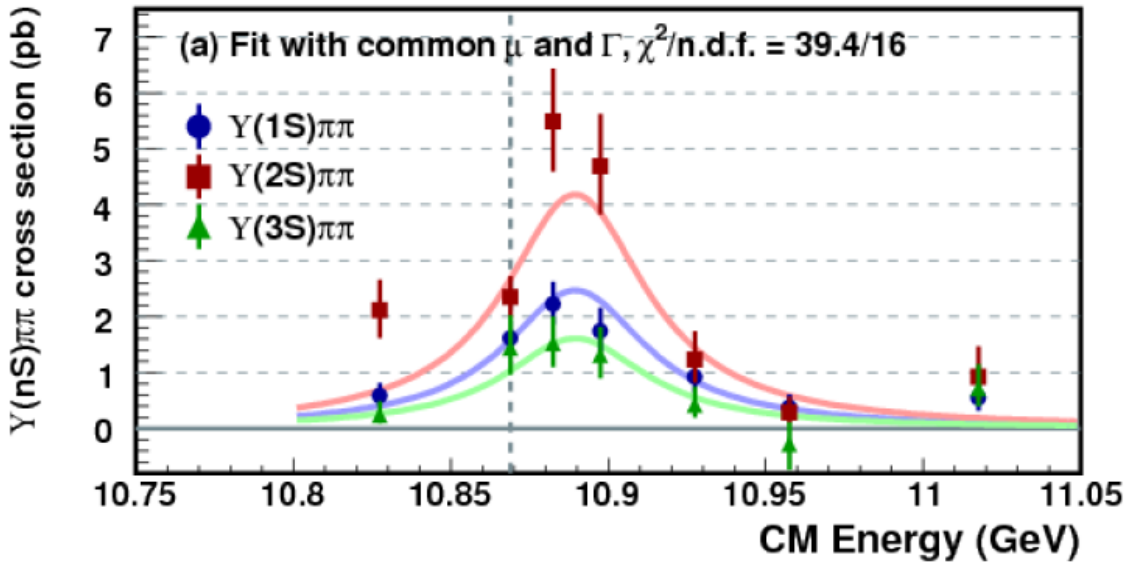
Can 1^{--} $b\bar{b}$ state have such rate? Maybe yes! (JETP Lett.87,121 & PRD77, 074033)

Is it a sign of a new particle overlaping with $\Upsilon(5S)$? Check with energy scan.

$\Upsilon(nS)\pi\pi$ production: Observation of $Y_b(10890)$

Energy scan: 7/fb collected between Υ(5S) and Υ(6S)

preliminary



arXiv:0808.2445

Fit all three cross-sections with the same BW:

	$\pi\pi\Upsilon(1S)$	$\pi\pi\Upsilon(2S)$	$\pi\pi\Upsilon(3S)$
peak [pb]	$2.46^{+0.27}_{-0.25} \pm 0.18$	$4.18^{+0.49}_{-0.46} \pm 0.55$	$1.61^{+0.31}_{-0.28} \pm 0.21$
M [MeV]	$10889.6 \pm 1.8 \pm 1.6$		
Γ [MeV]	$54.7^{+8.5}_{-7.2} \pm 2.5$		

The structure is different from known $\Upsilon(5S)$/10860

- Mean is $\sim$ 20 MeV higher
- Width is two times smaller

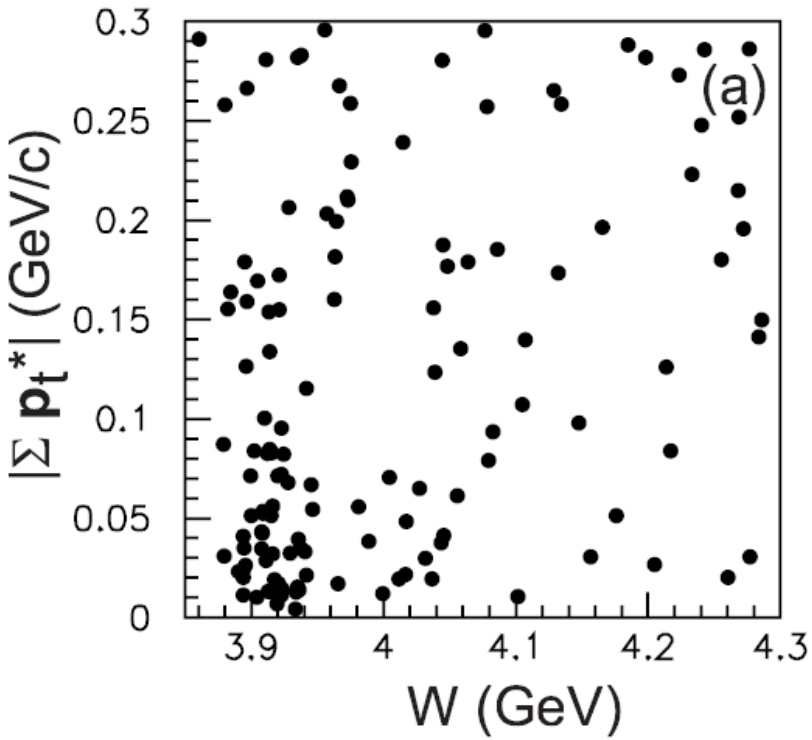
Is it a bottomonium counterpart to 1^{--} states seen in c-quarks sector?
W.S. Hou PRD74, 017504

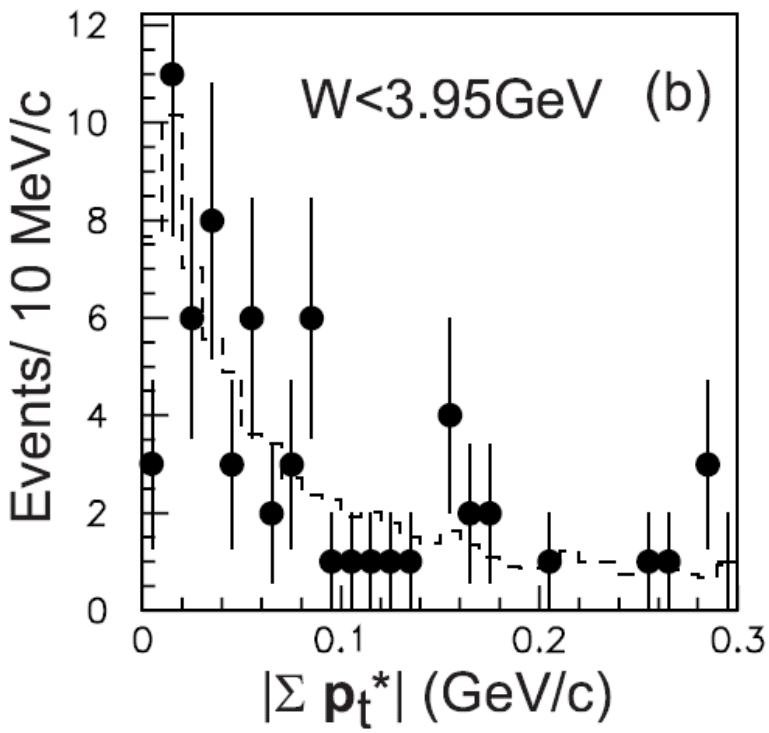
Summary

- New enhancement [**X(3915)**] observed in $\gamma\gamma \to \omega J/\psi$
  $\hookrightarrow$ if $X(3915)$ = Belle's $Y(3940)$ = BaBar's $Y(3914) \Rightarrow J^{PC} = 0^{++}$
- New on $X(3872)$
  $\hookrightarrow$ No evidence for neutral partner found
  $\hookrightarrow$ Observation of $B^0 \to X(3872)K^+\pi^-$
  $\hookrightarrow$ Latest measurement of $X(3872)$ mass in DD^* mode agrees with mass in $J/\psi\pi\pi$ mode
- No unfilled charmonium assignments are available above DD^* threshold for 1^{--} states
  $\hookrightarrow$ Except maybe $Y(4008)$
- Charged resonancelike Z states
  $\hookrightarrow$ $Z(4050)$ & $Z(4250)$ observed in $B \to K\pi\chi_{c1}$
  $\hookrightarrow$ $Z(4430)$ confirmed by Dalitz analysis of $B \to K\pi\psi(2S)$
- Possible analogue of Y states in $s\bar{s}$ and $b\bar{b}$ systems
  $\hookrightarrow$ $Y_b(10890)$ has different structure than $\Upsilon(5S)$

Backup material

$X(3915)$ in $\gamma\gamma \to \omega J/\psi$





$X(3872)$ in $D^0\overline{D}^{*0}$

Fit with Breit-Wigner

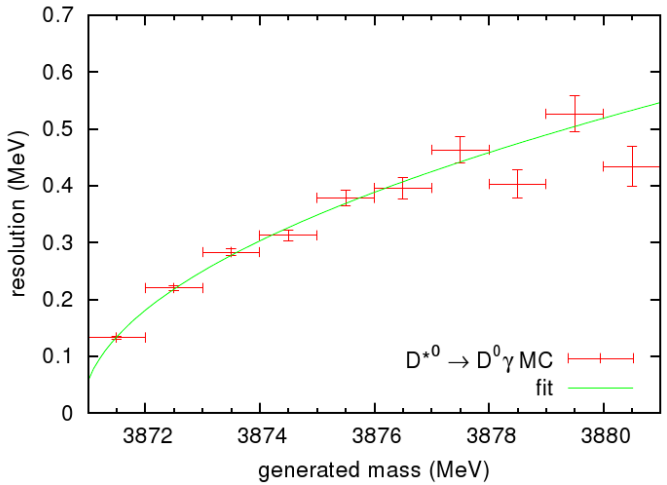
$$BW(m) = \frac{m_0 m \Gamma(m)}{(m^2 - m_0^2)^2 + m^2 \Gamma(m)^2}$$

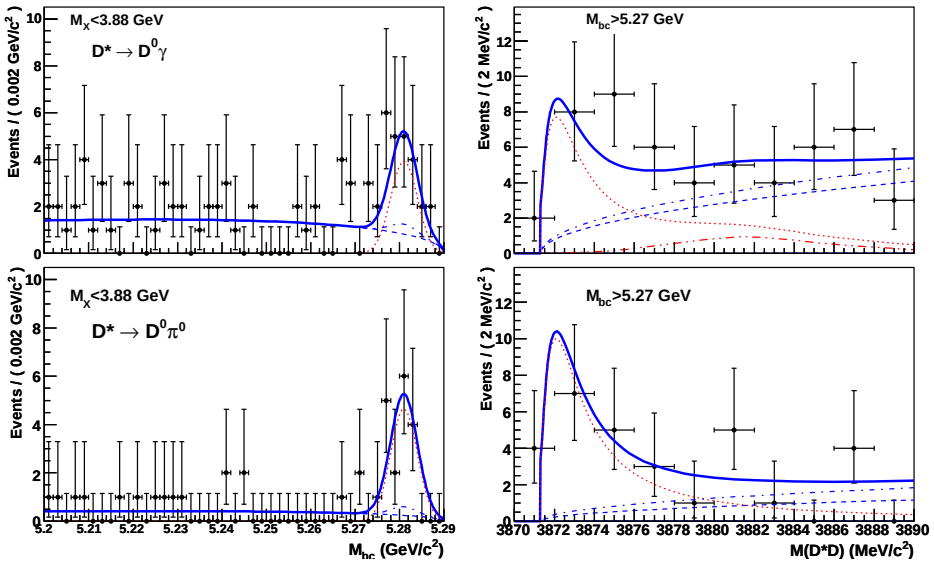
$$\Gamma(m) = \Gamma_0 \left(\frac{m_0}{m}\right) \left(\frac{p(m)}{p(m_0)}\right)^{2L+1}$$

convoluted with detector resolution

$$\sigma_X(m) = a\sqrt{m - m_0}$$

$$f(m) = \int_{-\infty}^{+\infty} BW(m-t) \cdot g(t, \sigma_X(m-t)) dt$$





$X(3872)$ in $D^0\overline{D}^{*0}$

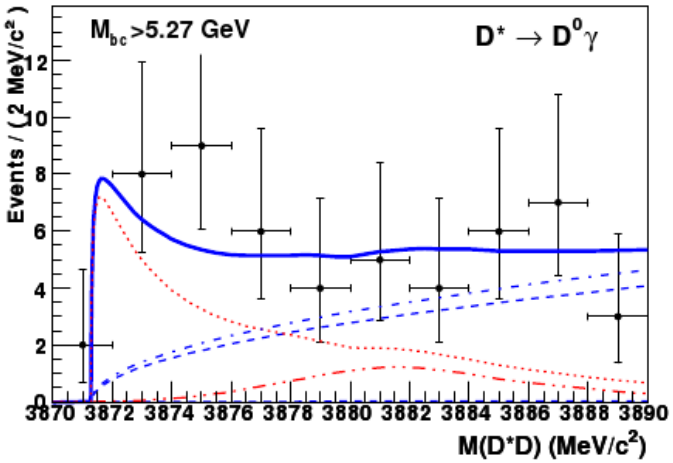
Fit with Flatte distribution (C. Hanhart et al. PRD76, 034007 (2007))

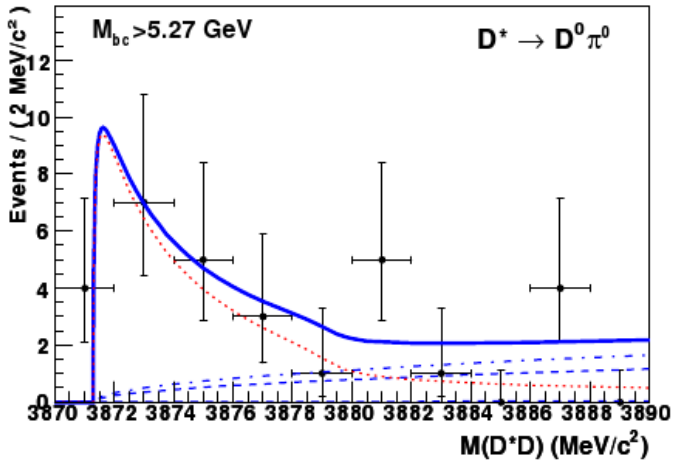
$$f(E) = \frac{gk_1}{|D(E)|^2}$$

$$D(E) = \begin{cases} E - E_f - \frac{1}{2}g\kappa + \frac{i}{2}\left(gk_1 + \Gamma(E)\right) & 0 < E < \delta \\ E - E_f + \frac{i}{2}\left(g(k_1 + k_2) + \Gamma(E)\right) & E > \delta \end{cases}$$

$$\delta = M(D^+D^{*-}) - M(D^{*0}\bar{D}^0),$$

$$k_1 = \sqrt{2\mu_1 E}, \quad k_2 = \sqrt{2\mu_2(E-\delta)}, \quad \kappa = \sqrt{2\mu_2(\delta - E)},$$





Dalitz analysis of $B \to K\pi^{\pm}\psi(2S)$ ($Z^{+}(4430)$)

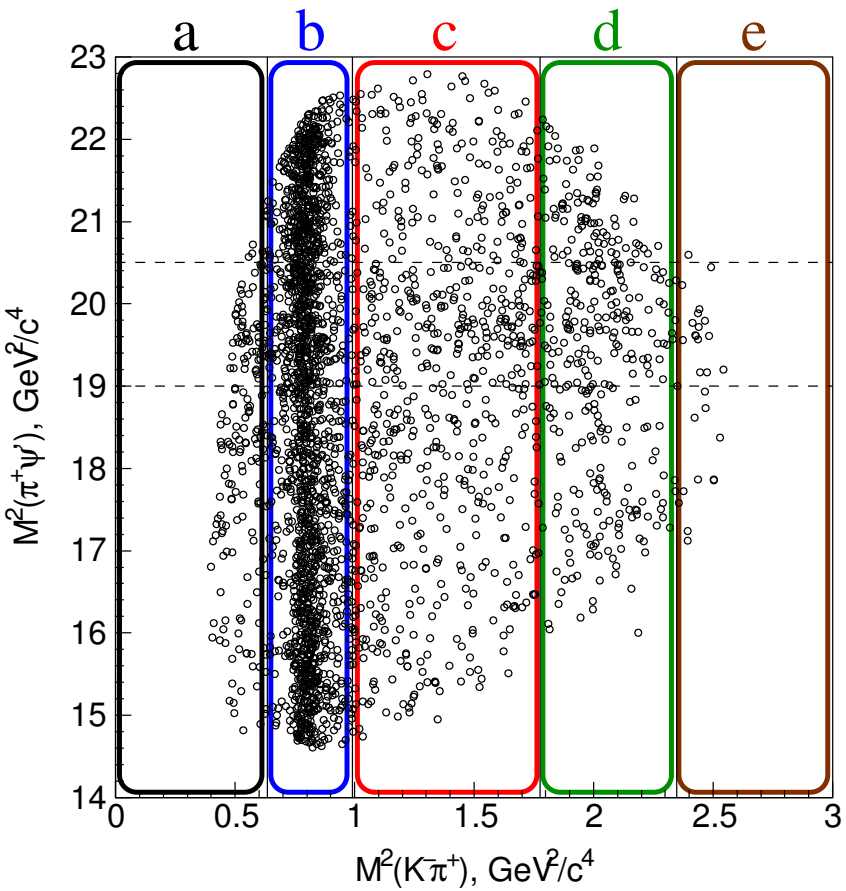
Contribution	Fit fraction (%)	Significance
$Z(4430)^{+}$	$5.7^{+3.1}_{-1.6}$	$6.4\,\sigma$
κ	$4.1^{+3.4}_{-1.1}$	$1.5\,\sigma$
$K^{*}(892)$	$64.8^{+3.8}_{-3.5}$	large
$K^{*}(1410)$	$5.5^{+8.8}_{-1.5}$	$0.5\,\sigma$
$K_0^{*}(1430)$	5.3 ± 2.6	$1.3\,\sigma$
$K_2^{*}(1430)$	$5.5^{+1.6}_{-1.4}$	$3.1\,\sigma$
$K^{*}(1680)$	$2.8^{+5.8}_{-1.0}$	$1.2\,\sigma$

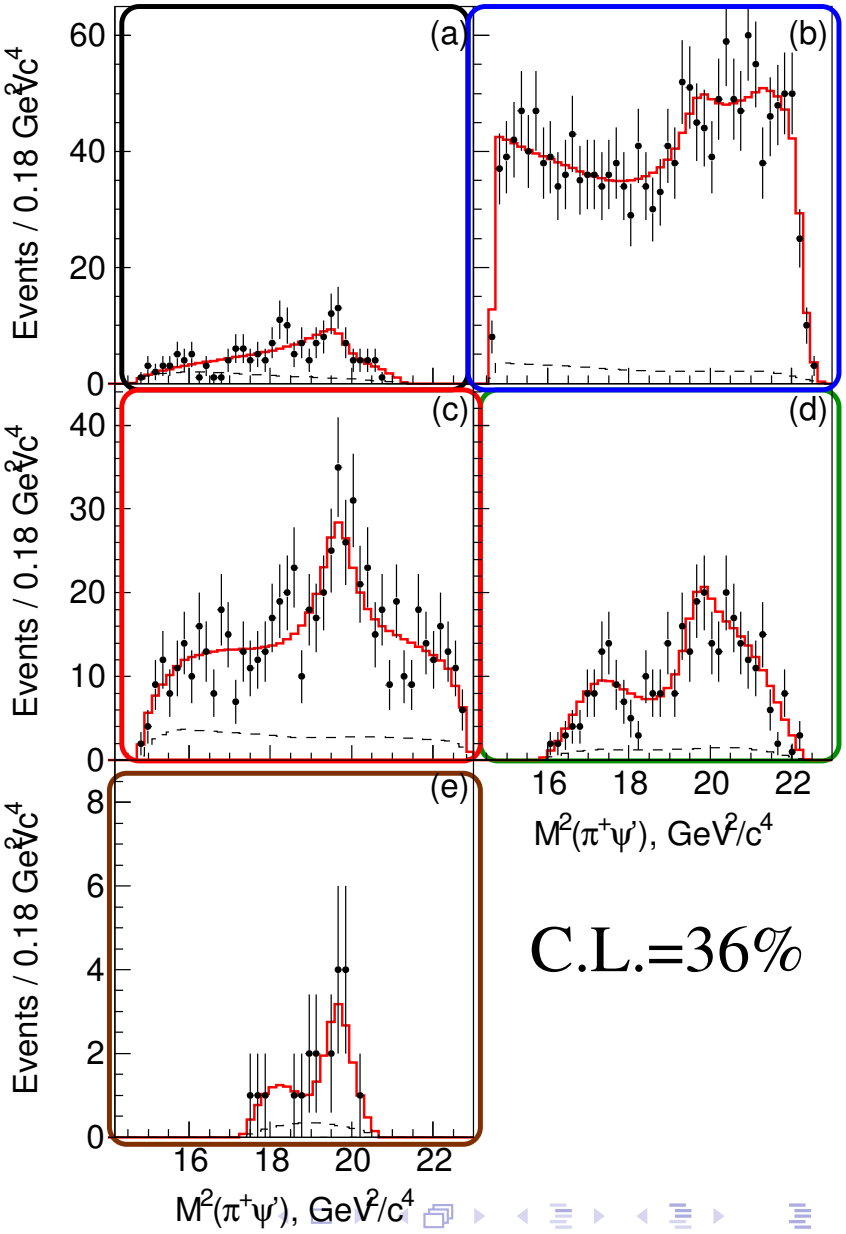
Dalitz analysis of $B \to K\pi^{\pm}\psi(2S)$ ($Z^{+}(4430)$)

TABLE II: Significance of the $Z(4430)^{+}$ for different fit models.

	Model	Significance
1	default	$6.4\,\sigma$
2	no $K_0^*(1430)$	$6.6\,\sigma$
3	no $K^*(1680)$	$6.6\,\sigma$
4	release constraints on κ mass & width	$6.3\,\sigma$
5	new K^* $(J = 1)$	$6.0\,\sigma$
6	new K^* $(J = 2)$	$5.5\,\sigma$
7	add non-resonant $\psi' K^-$ term	$6.3\,\sigma$
8	add non-resonant $\psi' K^-$ term, release constraints on κ mass & width	$5.8\,\sigma$
9	add non-resonant $\psi' K^-$ term, new K^* $(J = 1)$	$5.5\,\sigma$
10	add non-resonant $\psi' K^-$ term, new K^* $(J = 2)$	$5.4\,\sigma$
11	add non-resonant $\psi' K^-$ term, no $K^*(1410)$	$6.3\,\sigma$
12	add non-resonant $\psi' K^-$ term, no $K^*(1680)$	$6.6\,\sigma$
13	LASS parameterization of S-wave component	$6.5\,\sigma$

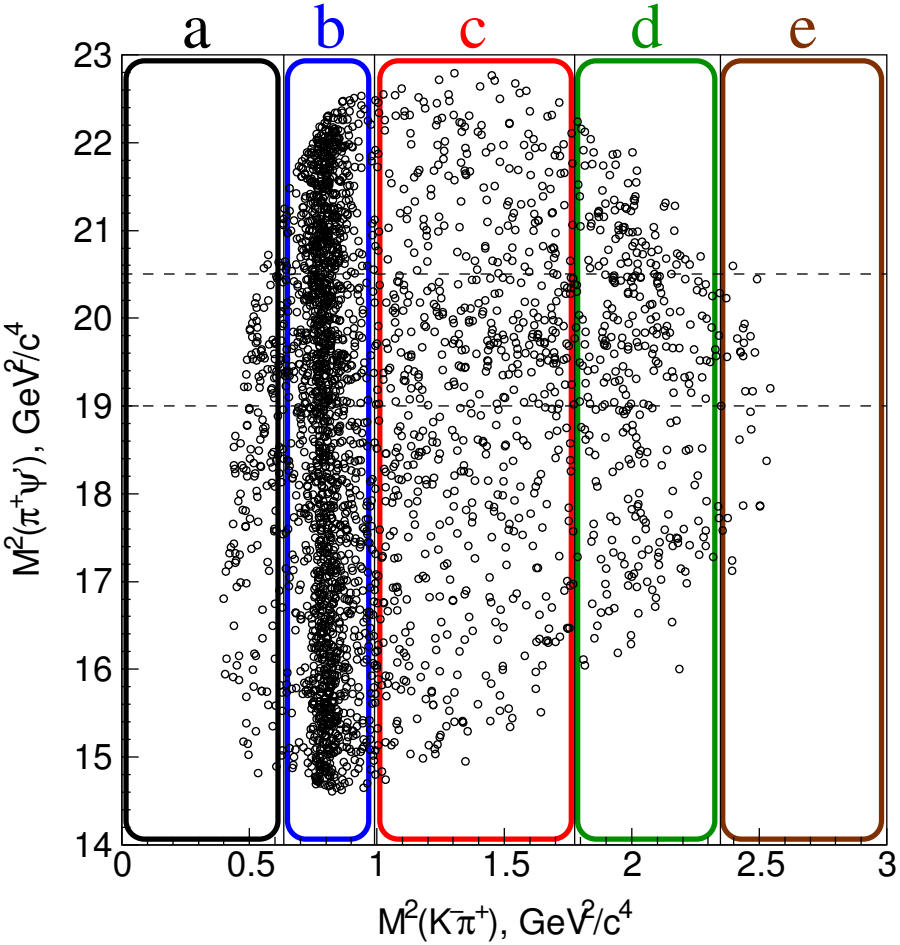
Dalitz analysis of $B \to K\pi^{\pm}\psi(2S)$ ($Z^{+}(4430)$)

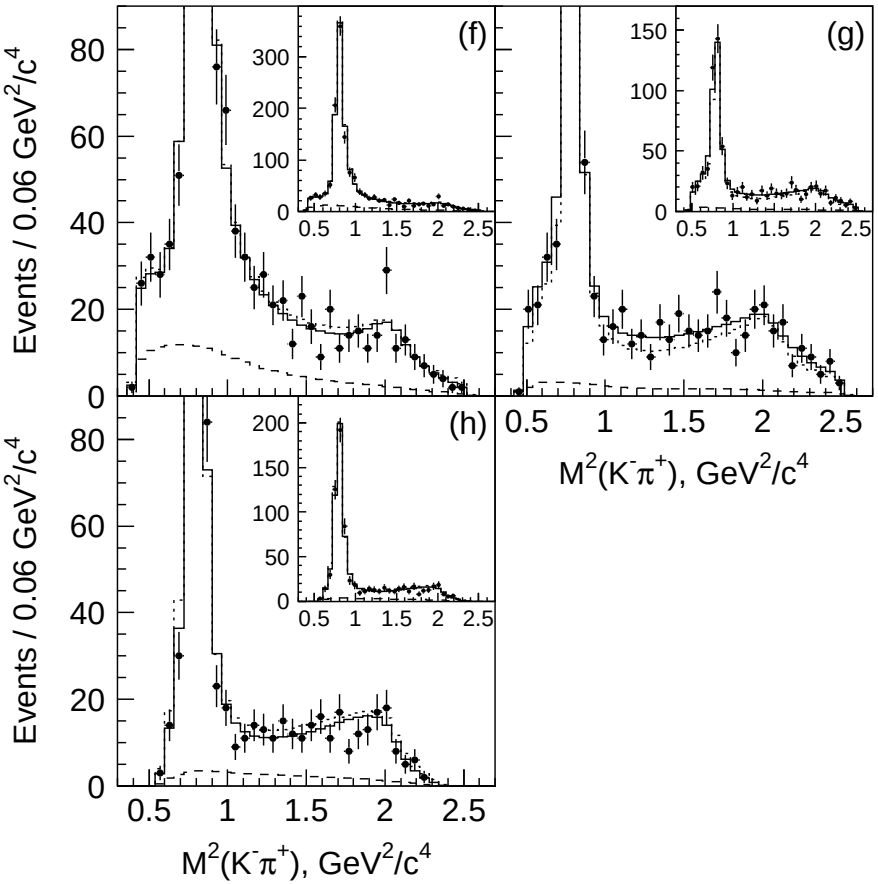




C.L.=36%

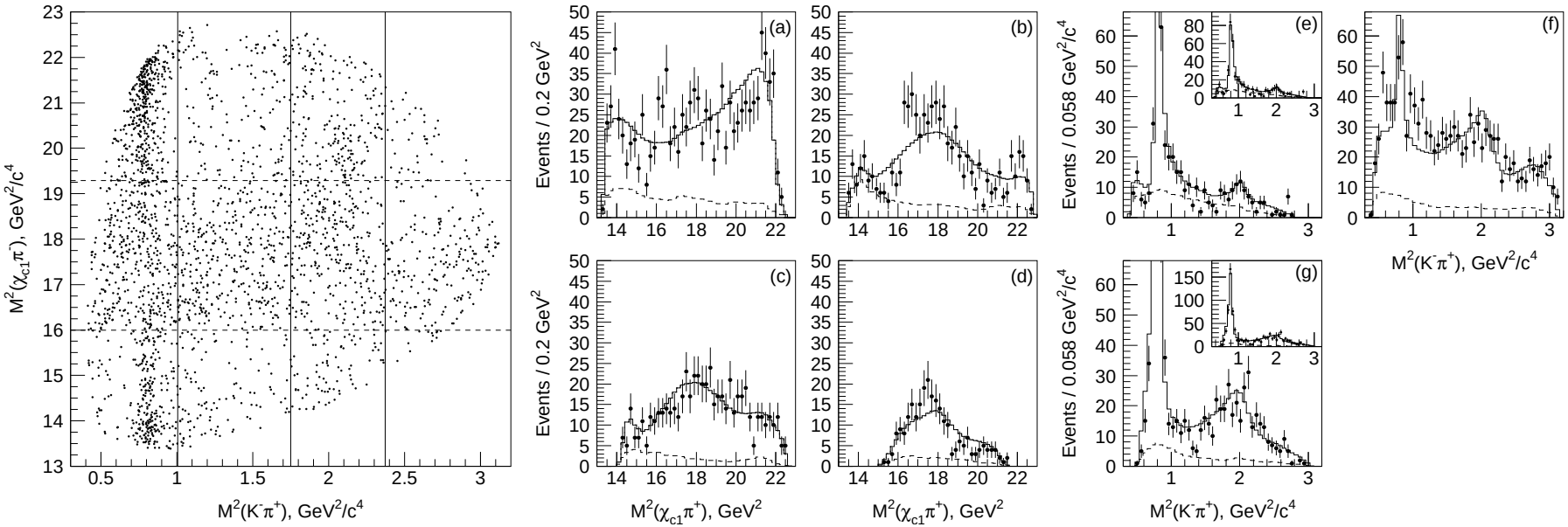
Dalitz analysis of $B \to K\pi^{\pm}\psi(2S)$ ($Z^{+}(4430)$)





Dalitz analysis of $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ ($Z^+(4050)$ & $Z^+(4250)$)

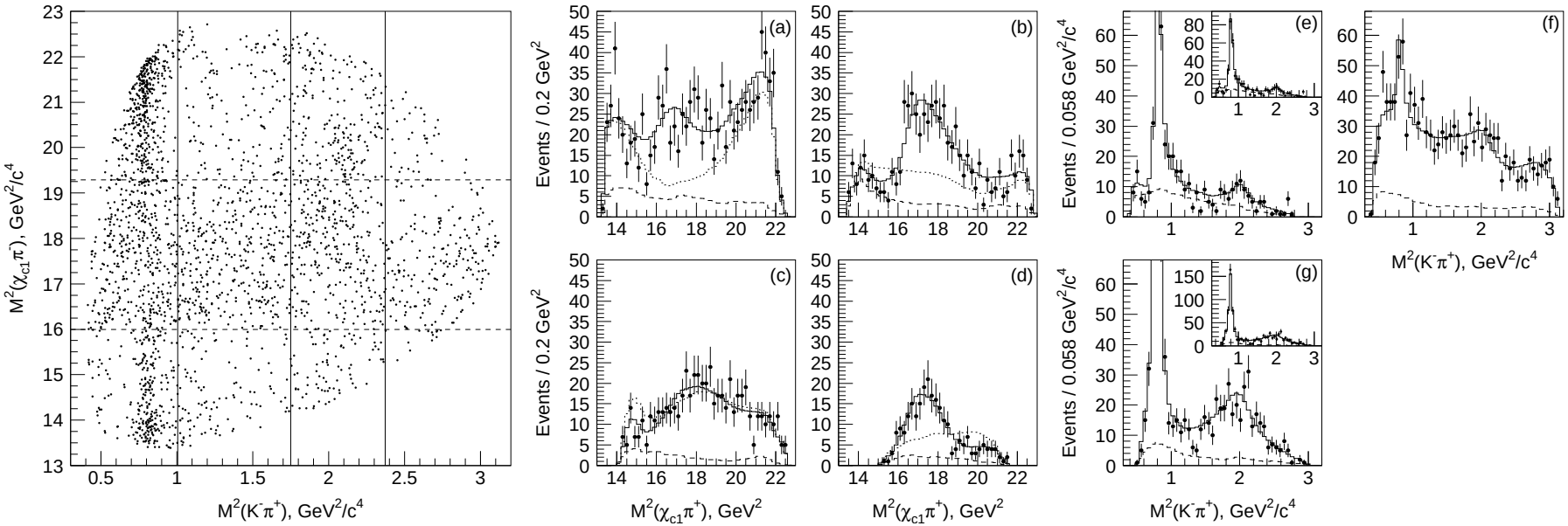
Fit without $\pi\chi_{c1}$ resonance



$$C.L. = 3 \times 10^{-10}$$

Dalitz analysis of $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ ($Z^+(4050)$ & $Z^+(4250)$)

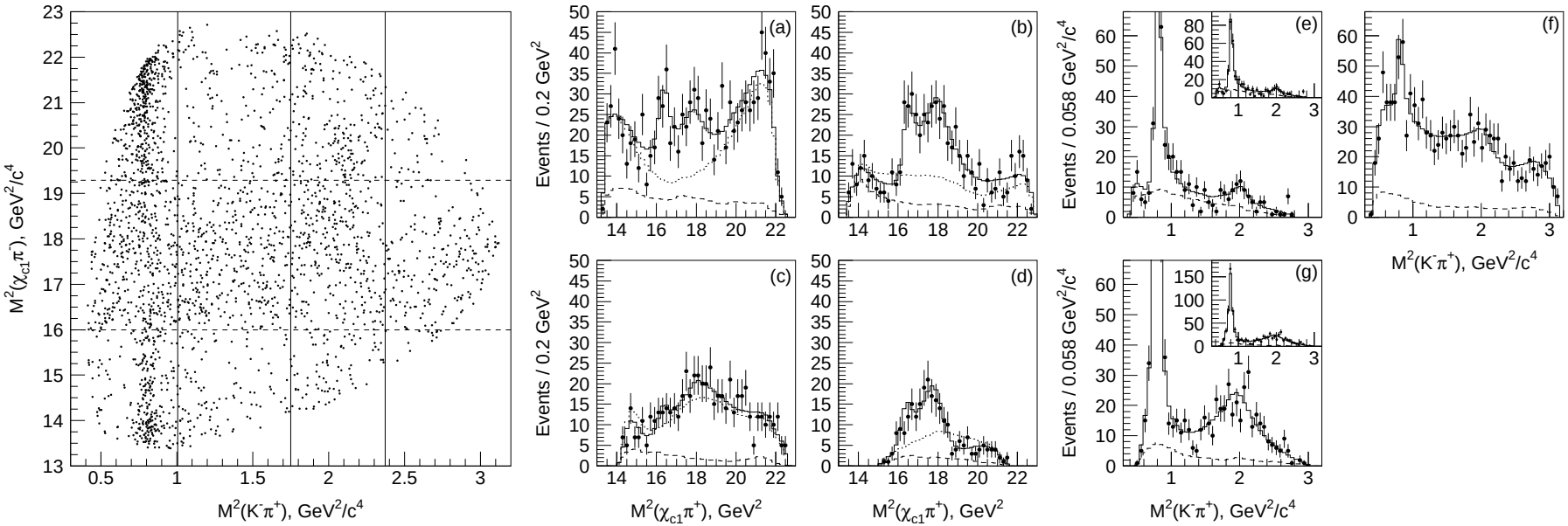
Fit with one $\pi\chi_{c1}$ resonance



$$M = 4150^{+31}_{-16}\ \text{MeV}$$
$$\Gamma = 352^{+99}_{-43}\ \text{MeV}$$
$$\text{Significance} = 10.7\sigma$$
$$C.L. = 0.1\%$$

Dalitz analysis of $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ ($Z^+(4050)$ & $Z^+(4250)$)

Fit with two $\pi\chi_{c1}$ resonances



$M = 4051 \pm 14^{+29}_{-41}$ MeV	$M = 4248 \pm^{+44}_{-29}\ ^{+180}_{-35}$ MeV
$\Gamma = 82^{+21}_{-16}{}^{+47}_{-22}$ MeV	$\Gamma = 177^{+54}_{-39}{}^{+316}_{-61}$ MeV
Significance $= 5.7\sigma$	Significance $= 5.7\sigma$

$C.L. = 42\%$

Dalitz analysis of $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ ($Z^+(4050)$ & $Z^+(4250)$)

TABLE II: Different fit models that are used to study systematic uncertainties and the significances of the single- and double-Z^+ hypotheses.

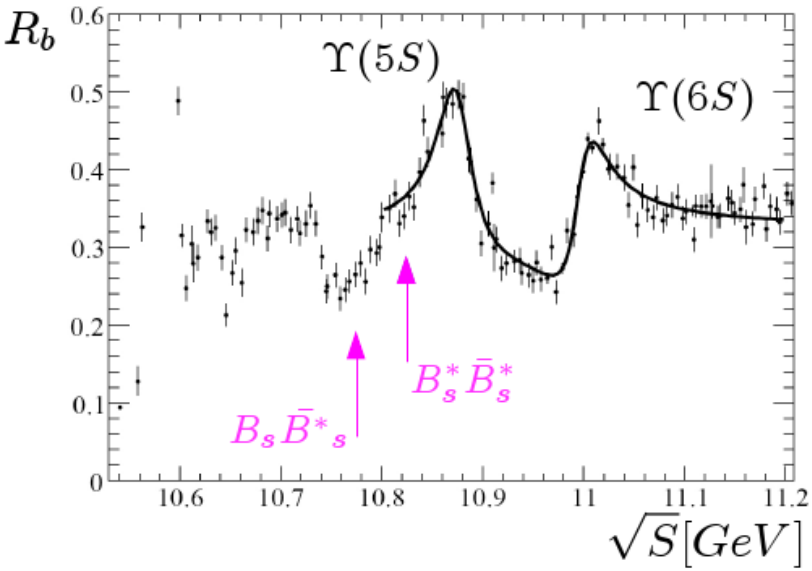
	Model	Significance of one Z^+	One Z^+ vs. two Z^+	Significance of two Z^+
1	default (see text)	$10.7\,\sigma$	$5.7\,\sigma$	$13.2\,\sigma$
2	no κ	$15.6\,\sigma$	$5.0\,\sigma$	$16.6\,\sigma$
3	no $K^*(1410)$	$13.4\,\sigma$	$5.4\,\sigma$	$14.8\,\sigma$
4	no $K_0^*(1430)$	$10.4\,\sigma$	$5.2\,\sigma$	$14.4\,\sigma$
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-resonant $\chi_{c1}K^-$ term	$9.0\,\sigma$	$5.3\,\sigma$	$10.3\,\sigma$
8	add non-resonant $\chi_{c1}K^-$ term, no $K^*(1410)$	$11.3\,\sigma$	$5.1\,\sigma$	$13.5\,\sigma$
9	add non-resonant $\chi_{c1}K^-$ term, no $K^*(1680)$	$11.4\,\sigma$	$5.3\,\sigma$	$13.7\,\sigma$
10	add non-resonant $\chi_{c1}K^-$ term, no $K_3^*(1780)$	$10.8\,\sigma$	$5.4\,\sigma$	$13.2\,\sigma$
11	add non-resonant $\chi_{c1}K^-$ term, release constraints on κ mass & width	$9.5\,\sigma$	$5.3\,\sigma$	$10.7\,\sigma$
12	add non-resonant $\chi_{c1}K^-$ term, new K^* $(J=1)$	$7.7\,\sigma$	$5.4\,\sigma$	$9.2\,\sigma$
13	add non-resonant $\chi_{c1}K^-$ term, new K^* $(J=2)$	$6.2\,\sigma$	$5.6\,\sigma$	$8.1\,\sigma$
14	LASS parameterization of S-wave component	$12.4\,\sigma$	$5.3\,\sigma$	$13.8\,\sigma$

Energy scan @ BaBar [PRL102, 012001]

- **Extract parameters for $\Upsilon(5S)$ and $\Upsilon(6S)$**

  Fit a simple model with

$$\sigma = \underbrace{|A_{nr}|^2}_{b\bar{b}\text{-continuum}} + \underbrace{|B_r + A_{5S}e^{i\phi_{5S}}BW(M_{5S},\Gamma_{5S}) + A_{6S}e^{i\phi_{6S}}BW(M_{6S},\Gamma_{6S})|^2}_{\text{Flat component interfering with 2 relativistic Breit-Wigner resonances}}$$



	$\Upsilon(5S)$	$\Upsilon(6S)$
$M[MeV]$	10876 ± 2	10960 ± 2
$\Gamma[MeV]$	43 ± 4	37 ± 3
$\phi[rad]$	2.11 ± 0.12	0.12 ± 0.07
$M_{PDG}[MeV]$	10865 ± 8	11019 ± 8
$\Gamma_{PDG}[MeV]$	110 ± 13	79 ± 16

Measure differences to PDG values