Recent Results on Heavy Quark Spectroscopy

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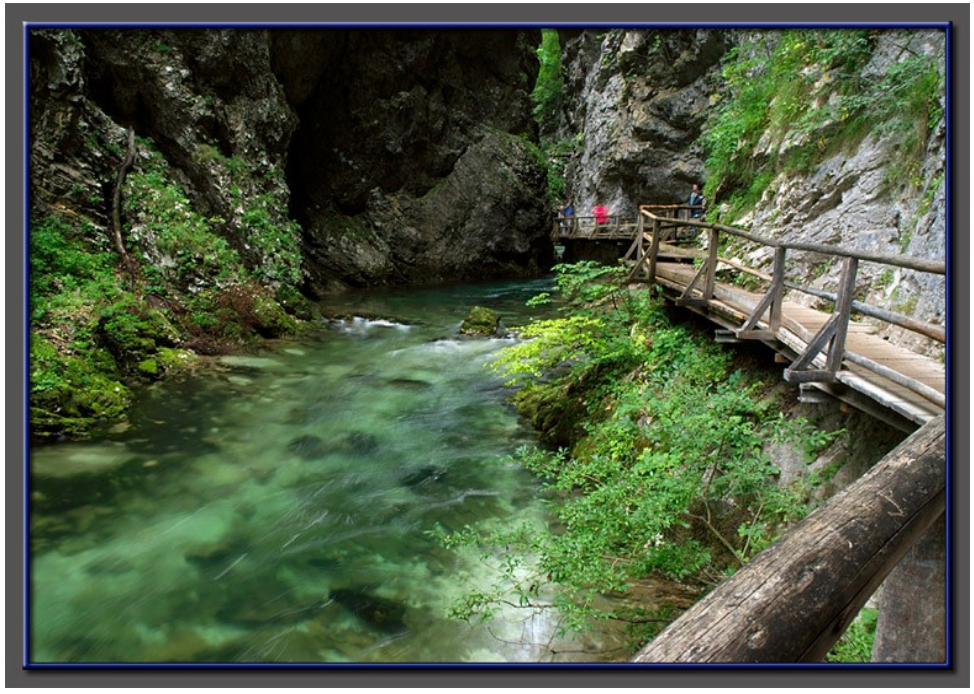
for

the Belle Collaboration

Few-quark States and the Continuum, Bled, Slovenia
15th — 22nd September 2008

List of topics

- Experimental set-up and tools
- D_{sJ} states
- Charmonium
  and charmonium-like states
- Bottomonium results:
  → will be skipped
- Summary and conclusions

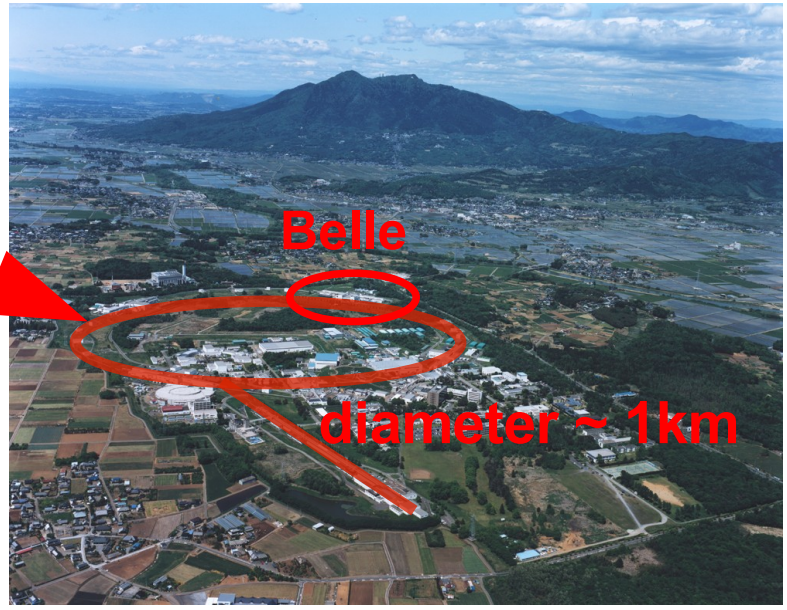


Experimental set-up & tools

The accelerator ...

KEKB
uest for CPV
kekb.jp

... an asymmetric-energy factory of B mesons



e^+ → $\Upsilon(4S)$ ← e^-

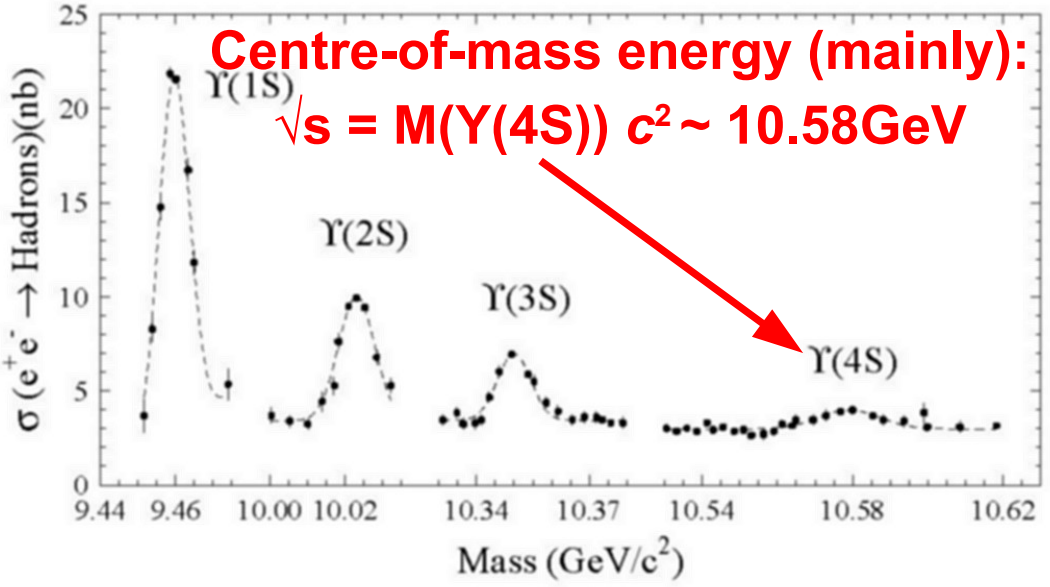
$p(e^+)$ = 3.5 GeV/c

$p(e^-)$ = 8.0 GeV/c

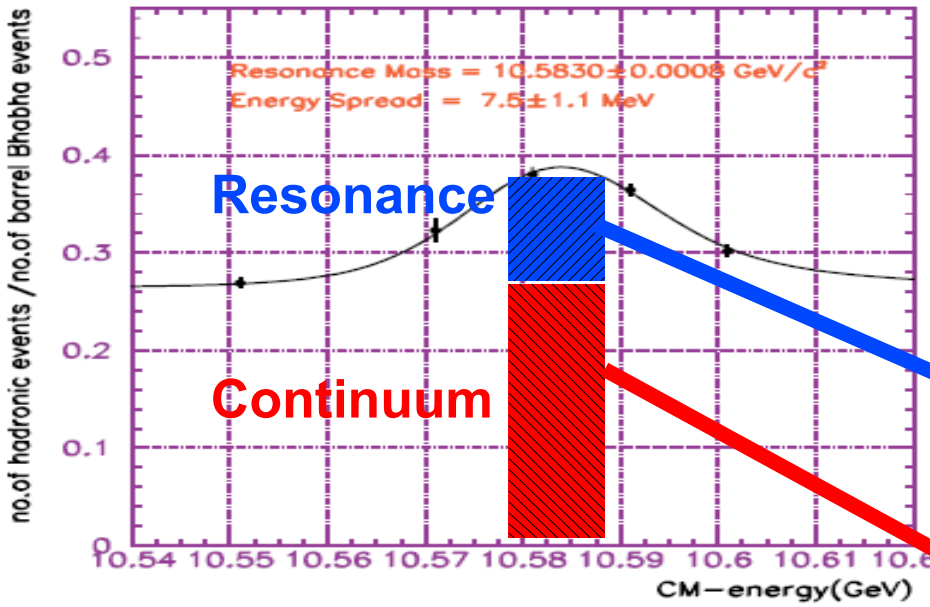
$\Upsilon(4S)$: bound state of $b\bar{b}$;
($J^{PC} = 1^{--}$, radially excited);
above the threshold for $B\bar{B}$ decays

$\Upsilon(4S) \rightarrow B\ (\bar{b}u,\ \bar{b}d)$

$\Upsilon(4S) \rightarrow \bar{B}\ (b\bar{u},\ b\bar{d})$



Experimental set-up & tools



# of events

(integrated) Luminosity

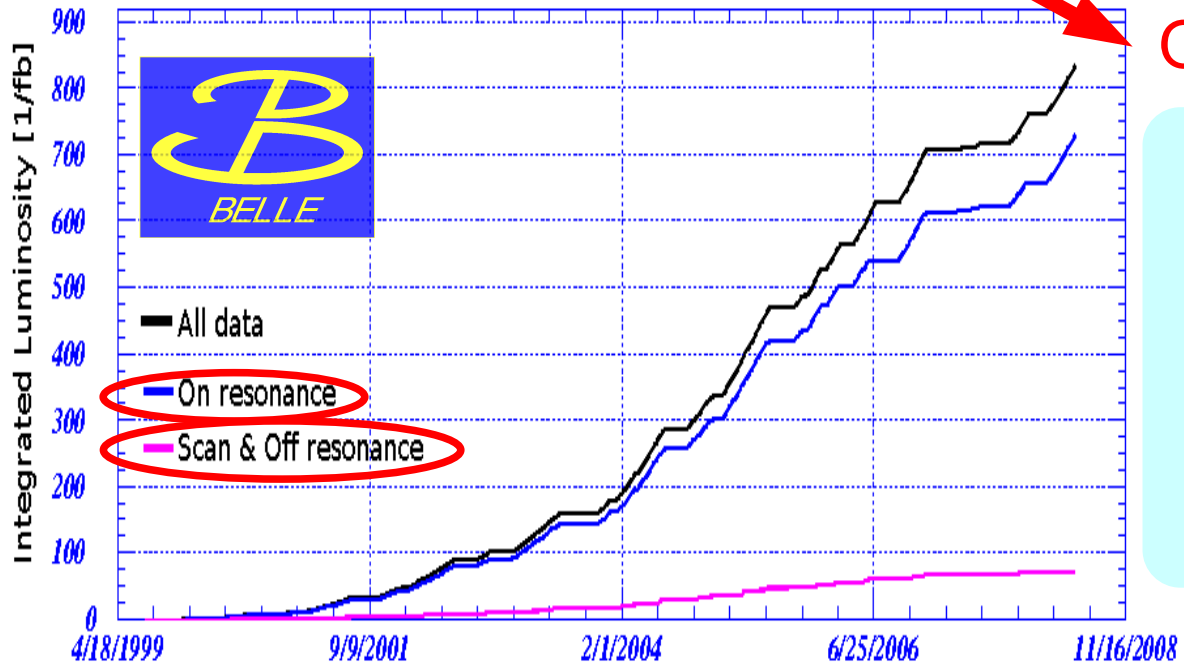
$$N = \sigma \int \mathcal{L}\, dt$$

cross-section

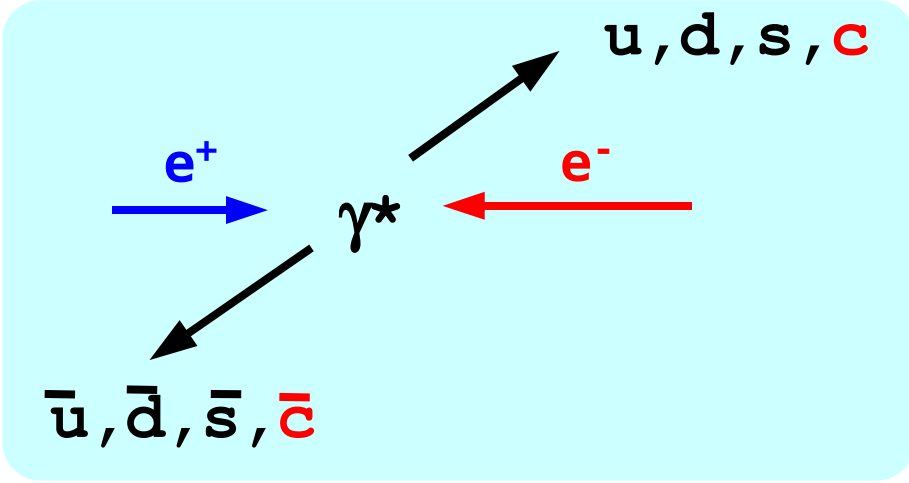
Daily!

$B\bar{B}$ pairs:

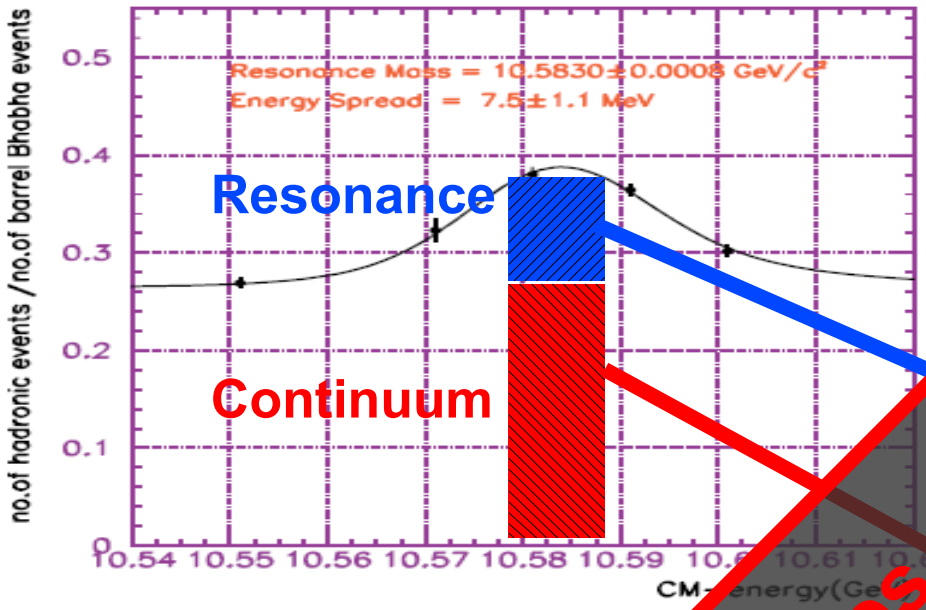
on $\Upsilon(4S)$ resonance: $1fb^{-1} \sim 1.1M\ B\bar{B}$



Other processes (continuum):



Experimental set-up & tools



# of events = cross-section · (integrated) Luminosity

$$N = \sigma \int \mathcal{L}\, dt$$

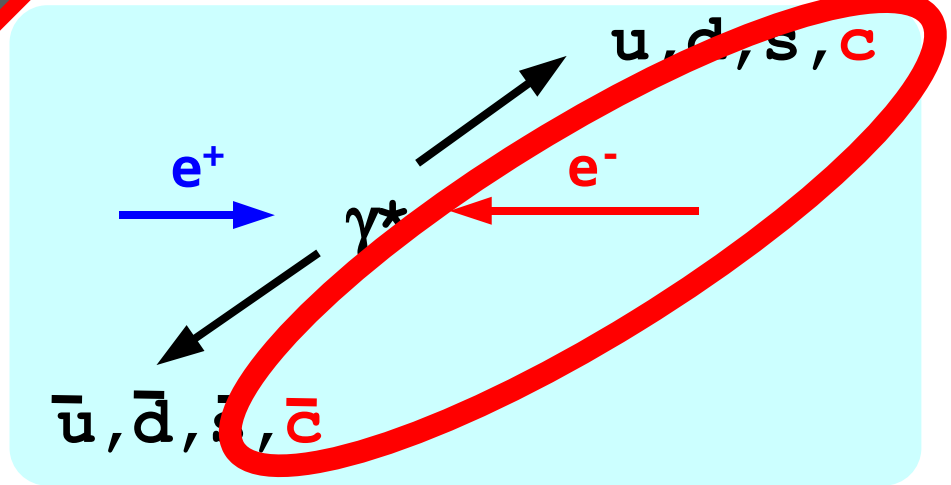
B-factories are also charm factories!

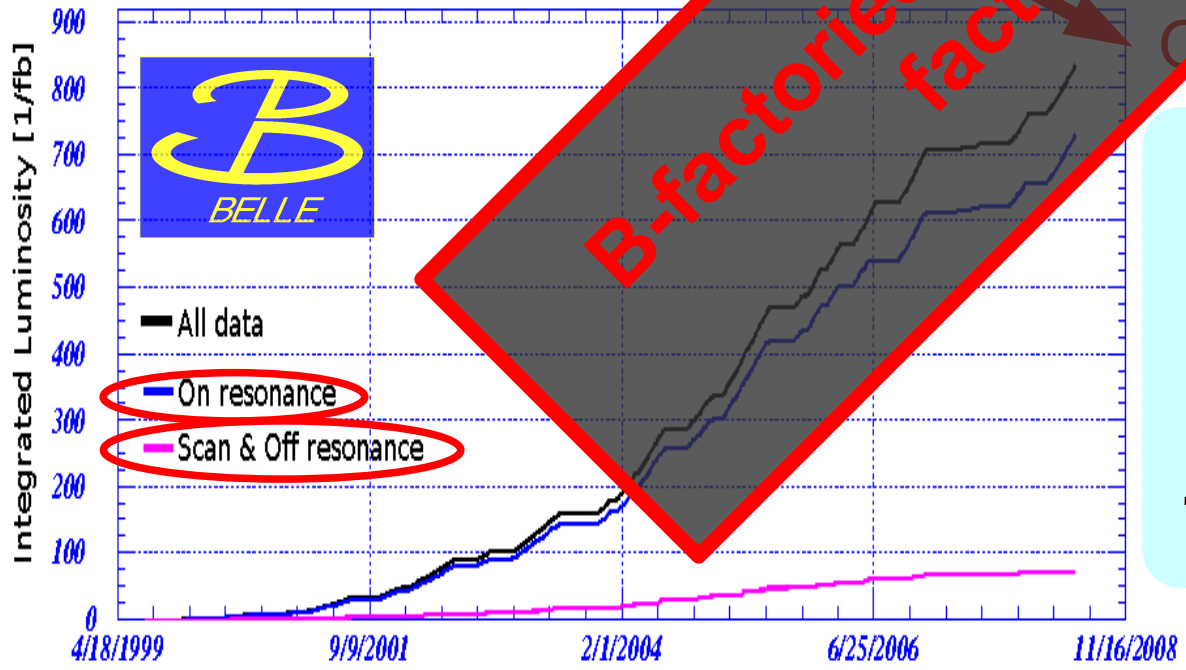
Daily!

$B\bar{B}$ pairs:

on $\Upsilon(4S)$ resonance: $1fb^{-1} \sim 1.1M\ B\bar{B}$

Other processes (continuum):





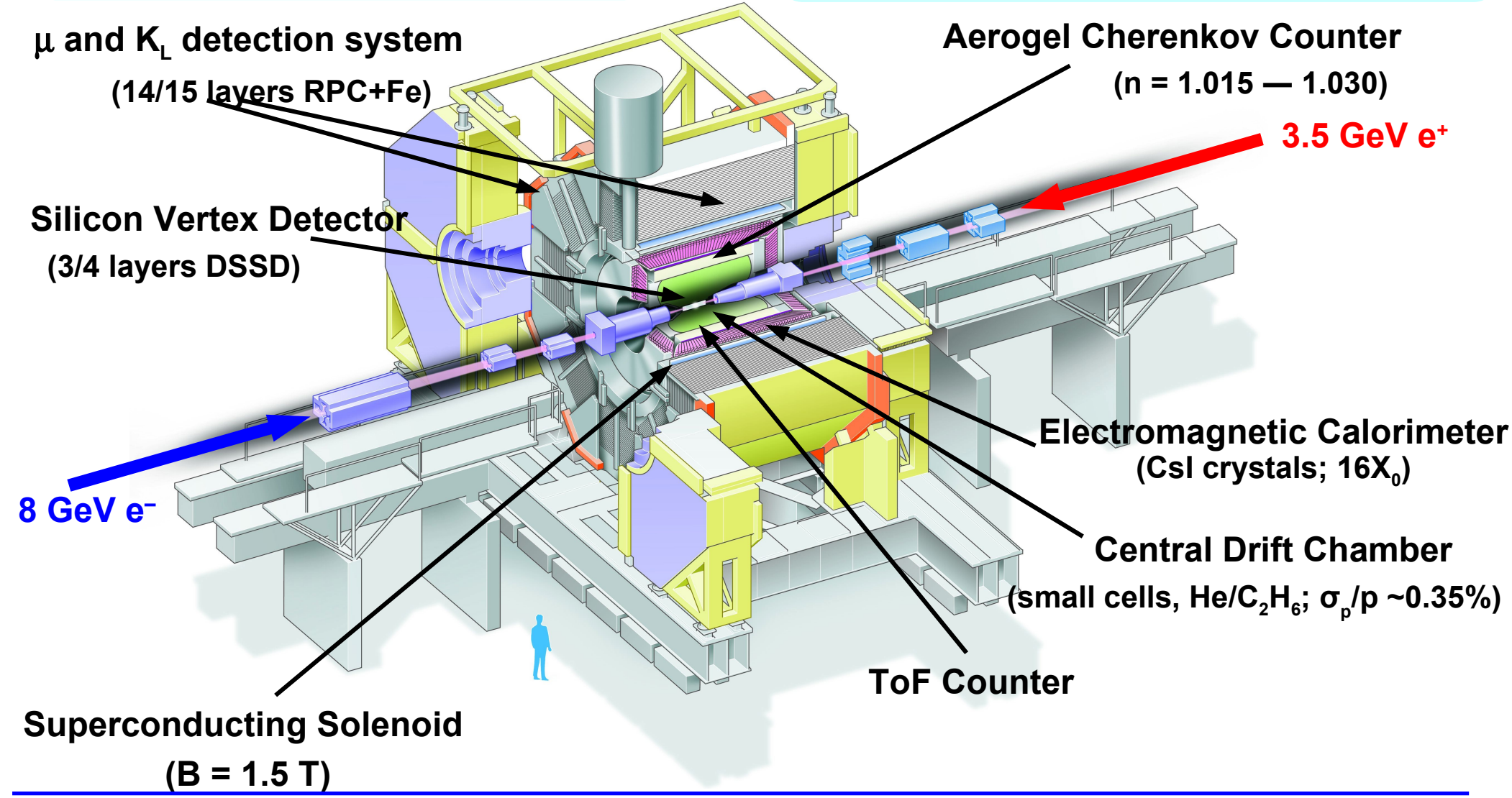
The Belle detector

Long-life particles we detect:

$e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, γ

Decaying particles we reconstruct:

$B^{\pm}$, B^0, $D^{\pm}$, D^0, π^0, Λ^0 , ...



The Belle collaboration

BINP
Chiba U.
U. of Cincinnati
Ewha Womans U.
Fu-Jen Catholic U.
U. of Giessen
Gyeongsang Nat'l U.
Hanyang U.
U. of Hawaii
Hiroshima Tech.
IHEP, Beijing
IHEP, Moscow
IHEP, Vienna
ITEP
Kanagawa U.
KEK
Korea U.
Krakow Inst. of Nucl. Phys.
Kyoto U.
Kyungpook Nat'l U.
EPF Lausanne
Jozef Stefan Inst. / U. of Ljubljana / U. of Maribor
U. of Melbourne
Nagoya U.
Nara Women's U.
National Central U.
National Taiwan U.
National United U.
Nihon Dental College
Niigata U.
Nova Gorica
Osaka U.
Osaka City U.
Panjab U.
Peking U.
Princeton U.
Riken
Saga U.
USTC
Seoul National U.
Shinshu U.
Sungkyunkwan U.
U. of Sydney
Tata Institute
Toho U.
Tohoku U.
Tohuku Gakuin U.
U. of Tokyo
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
INFN Torino
Toyama Nat'l College
VPI
Yonsei U.

14 countries, 55 institutes, ~400 collaborators

Charmed strange mesons (D_{sJ} states)

Charmed strange mesons (overview)

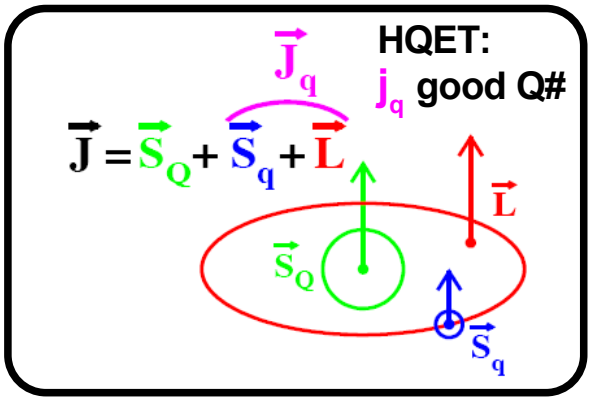
- $D_{sJ}^{*}(2317)$ and $D_{sJ}(2460)$ first observed by BABAR and CLEO in inclusive $c\bar{c}$ continuum events and by Belle also in B-decays
- Both **masses unexpectedly low**: below $D^{*}K$ and DK threshold, respectively
- Only isospin-violating or electromagnetic decays kinematically allowed ⇒ **narrow widths**

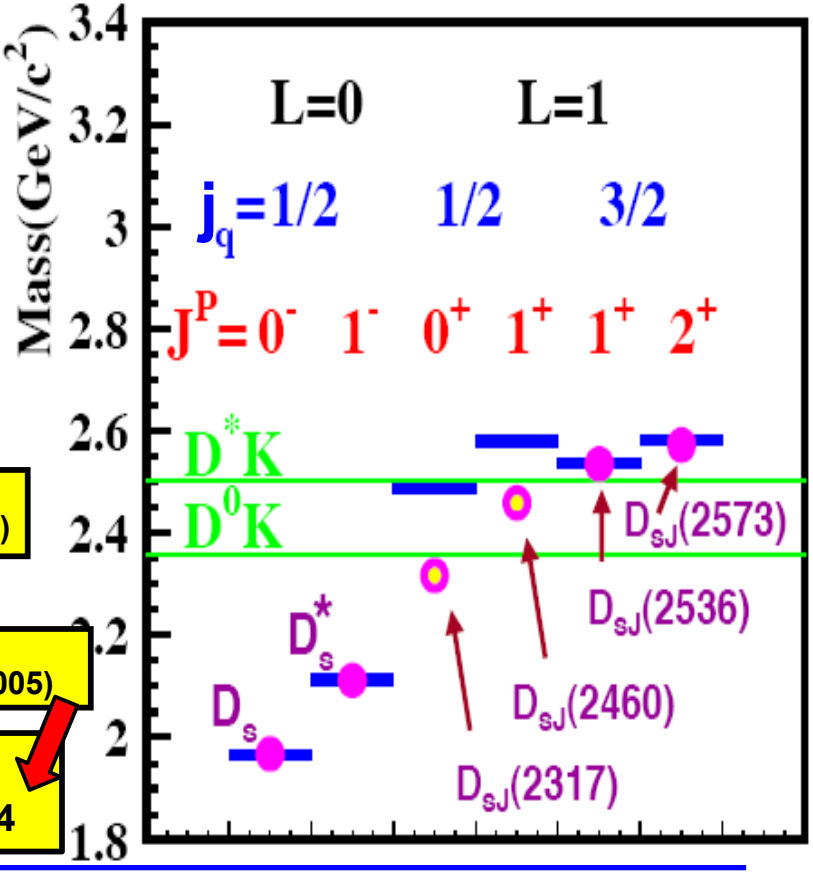
- Decay patterns and angular distributions now well established as:
  P-wave $c\bar{s}$ mesons
  with $J^P=0^+$ and $J^P=1^+$,respectively
- More B-decay production modes:
  $B^0 \to D_{sJ}^{-} K^+$ (besides $B^0 \to \bar{D} D_{sJ}$)

BABAR : 91 fb^{-1}
PRL 90, 242001 (2003)

CLEO : 13.5 fb^{-1}
PRD 68, 032002 (2003)

Belle : 124M BB
PRL 91, 262002 (2003)
Belle : 87 fb^{-1}
PRL 92, 012002 (2004)





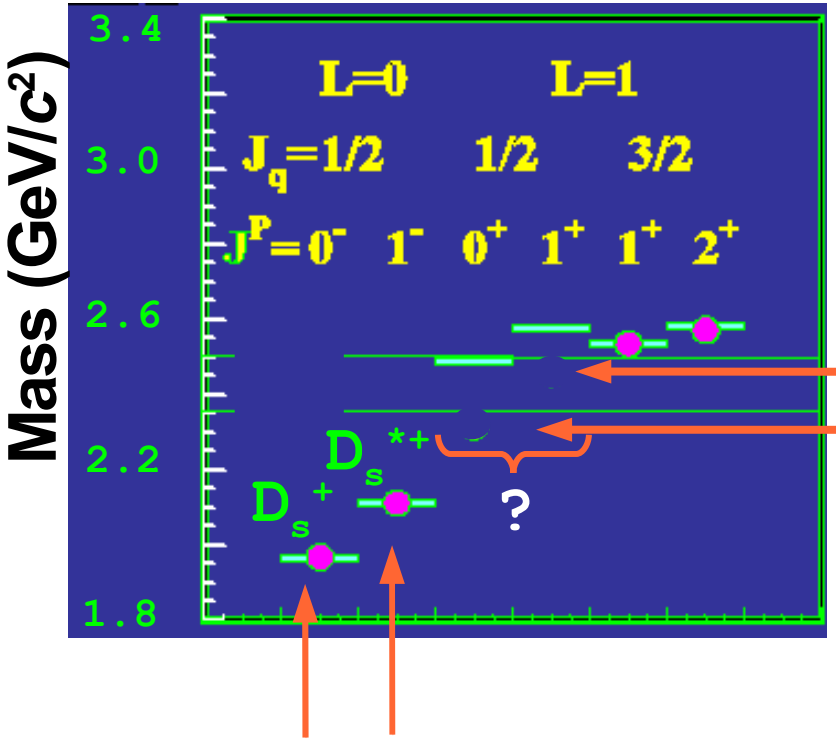
Belle : 274M BB
BELLE-CONF-0461 (2004)

Belle : 152M BB
PRL 94, 061802 (2005)

Belle : 386M BB
hep-ex/0507064

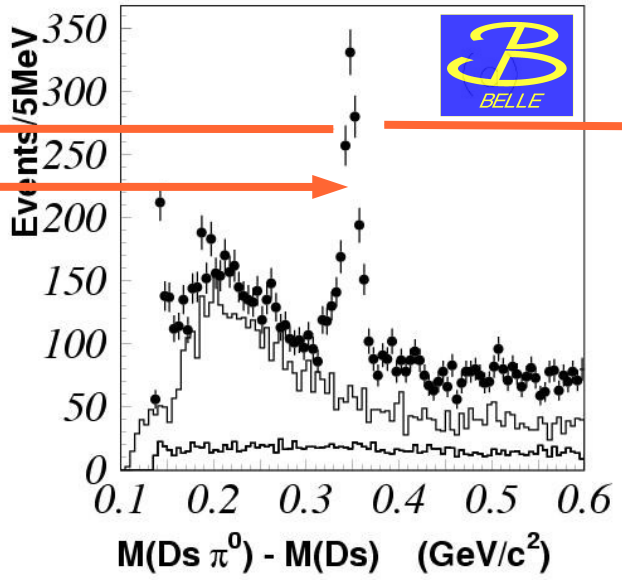
D_{sJ} – first results from $c\bar{c}$ (reminder)

Belle : 87 fb^{-1}
PRL 92, 012002 (2004)

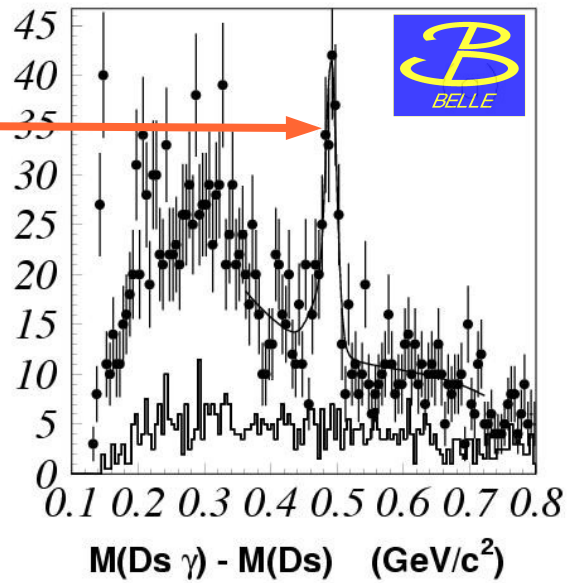


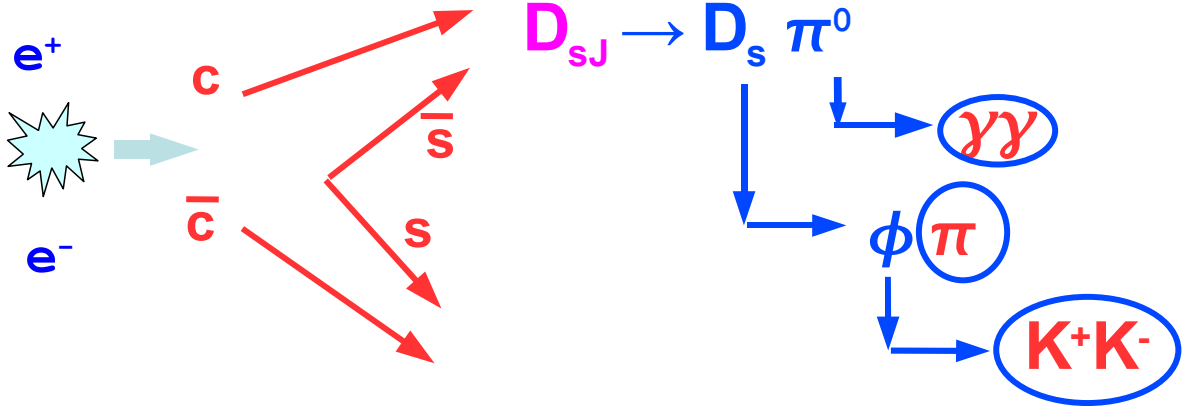
well-known D_s mesons

$D_{sJ}^*(2317)^+ \to D_s^+ \pi^0$



$D_{sJ}(2460)^+ \to D_s^+ \gamma$





$$M_{inv} = \sqrt{(\Sigma_i E_i)^2 - (\Sigma_i p_i)^2}$$

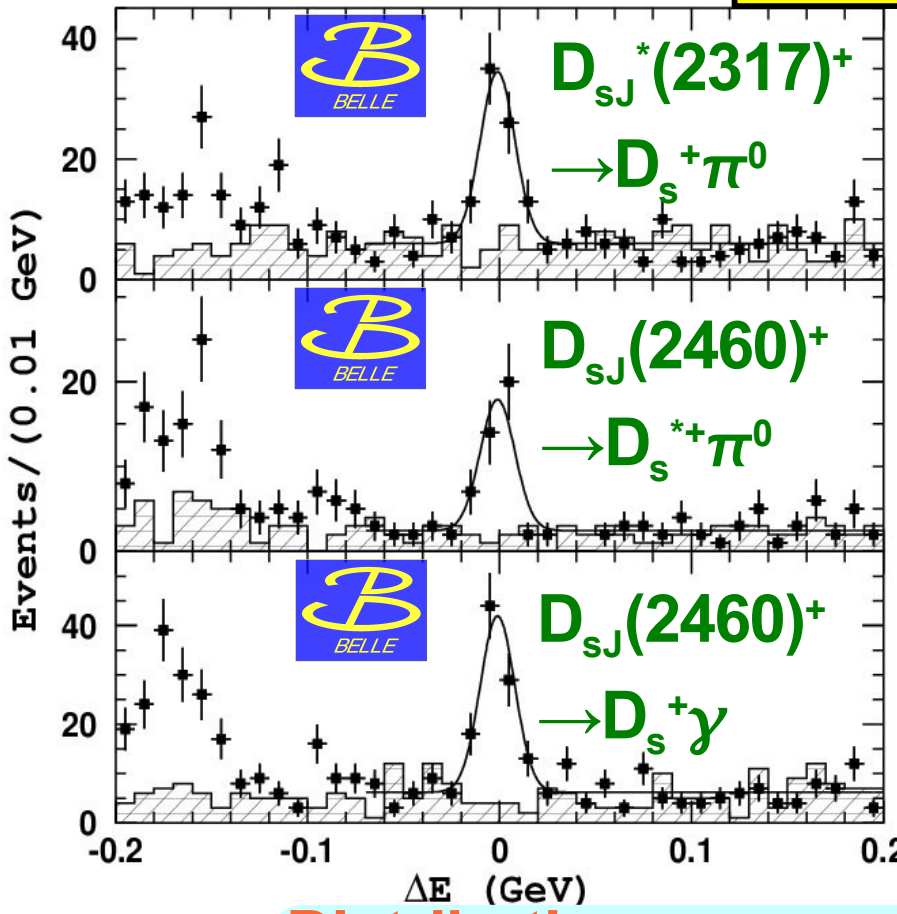
D_{sJ} – first results from B decays (rem.)

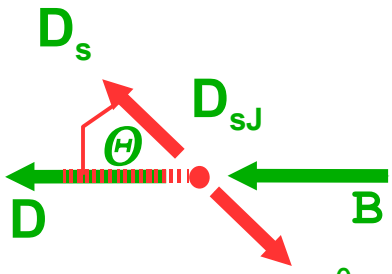
$B \to \bar{D}\, D_{sJ}$

Belle : 124M BB
PRL 91, 262002 (2003)

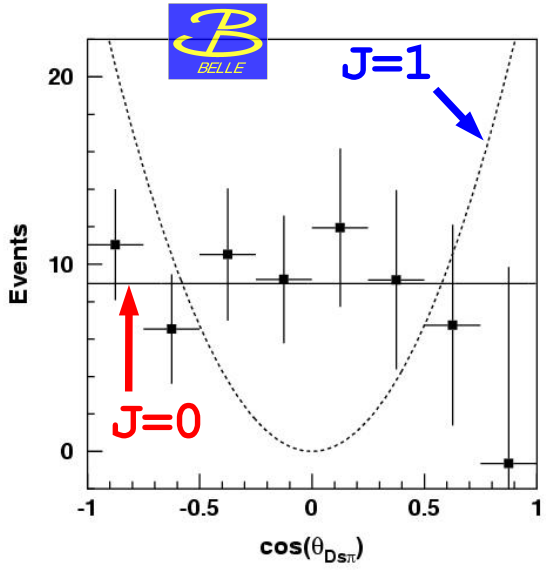
update

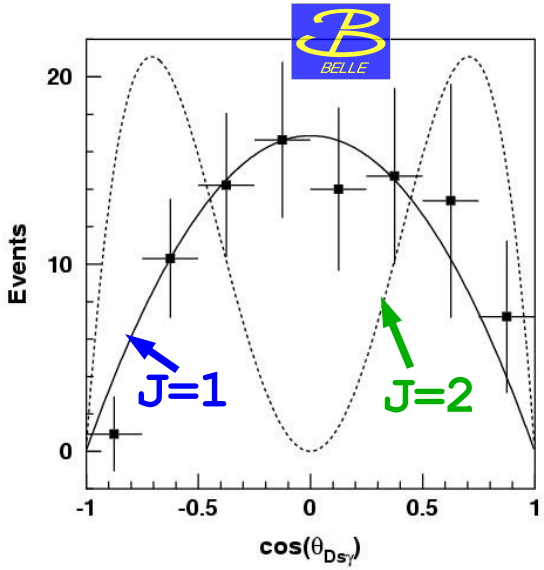
Belle : 274M BB
BELLE-CONF-0461 (2004)





Angular distribution is spin-dependent:





$D_{sJ}^*(2317)^+ \to D_s^+\pi^0$

$D_{sJ}(2460)^+ \to D_s^+\gamma$

Distributions are consistent with:

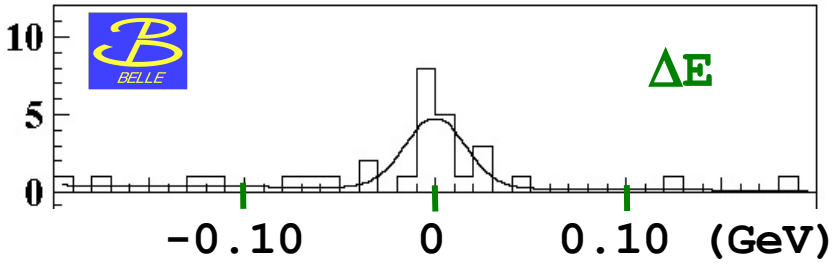
$J^P=0^+$ ($D_{sJ}^*(2317)^+$) and 1^+($D_{sJ}(2460)^+$)

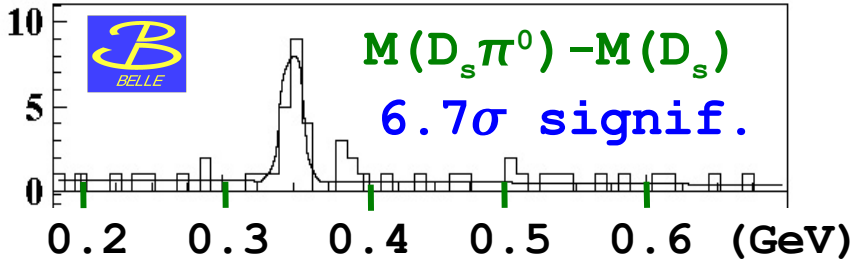
e.g. $Br(B^0 \to D^- D_{sJ}^*(2317)^+) = (10.1 \pm 1.5 \pm 3.0) \times 10^{-4}$

D_{sJ} – more results from B decays(rem.)

First time observed: $B^0 \to D_{sJ}^{*-} K^+$

Belle : 152M BB
PRL 94, 061802 (2005)



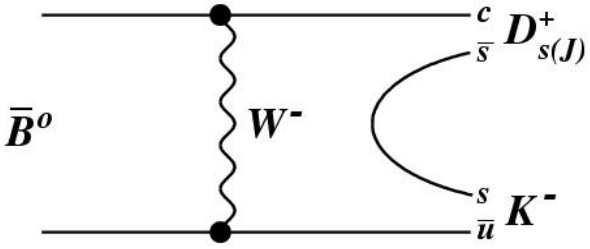


$$\frac{Br(B^0 \to D_{sJ}^{*}(2317)^{-} K^+) \cdot Br(D_{sJ}^{*}(2317)^{-} \to D_s^{-} \pi^0)}{Br(B^0 \to D_s^{-} K^+)} = 1.8 \pm 0.6$$

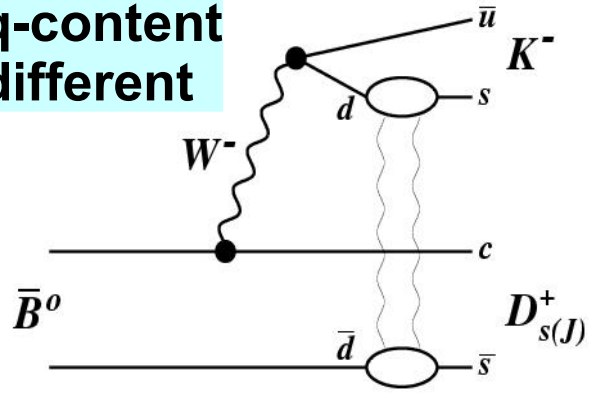
(same order of magnitude)

$$\frac{Br(B^0 \to D^{-} D_{sJ}^{*}(2317)^{+}) \cdot Br(D_{sJ}^{*}(2317)^{+} \to D_s^{+} \pi^0)}{Br(B^0 \to D^{-} D_s^{+})} = 0.13 \pm 0.05$$

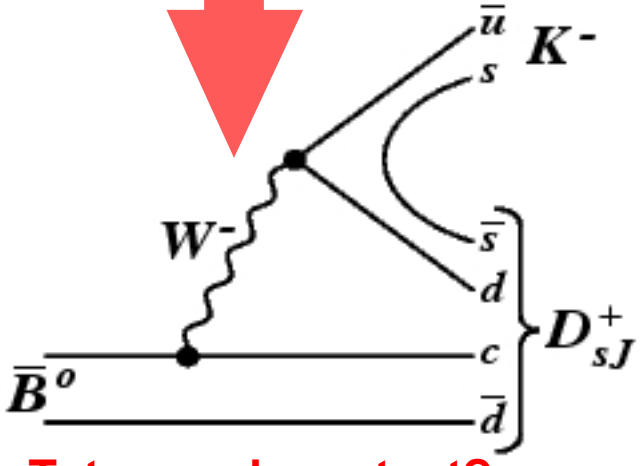
Initial and final q-content are completely different



PQCD fact. W exchange



tree with FSI



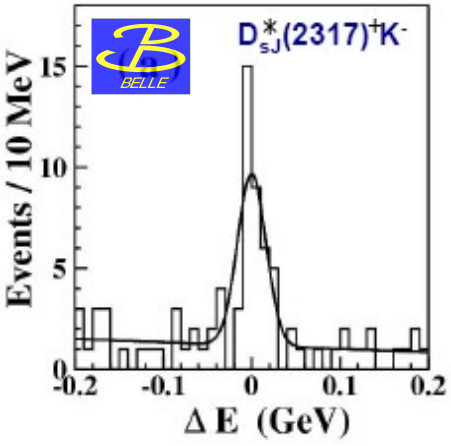
Tetraquark content?

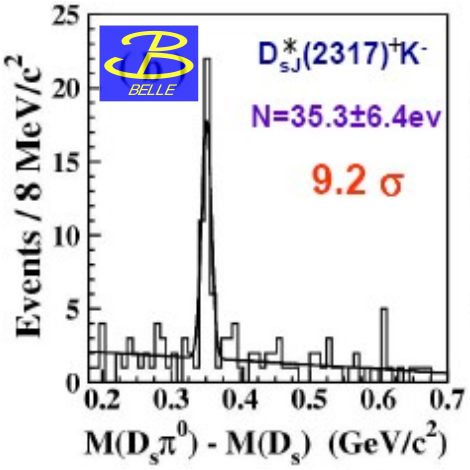
D_{sJ} states – updates from B decays

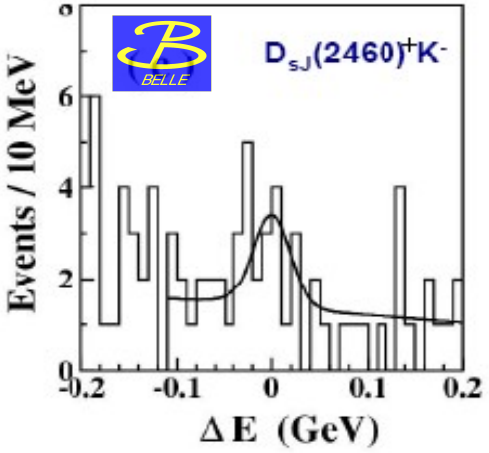
$B^0 \to D_{sJ}^{*}(2317)^{+}K^{-}$; $B^0 \to D_{sJ}(2460)^{+}K^{-}$

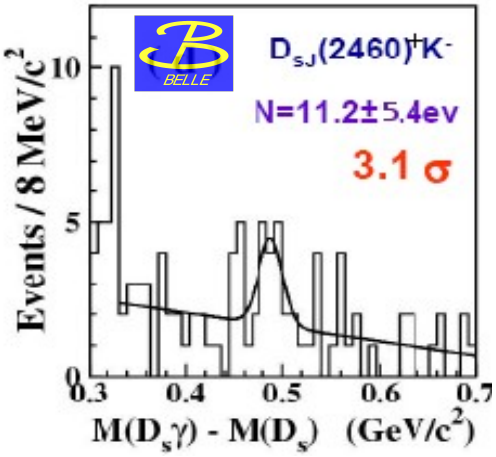
Belle : 386M BB
hep-ex/0507064

(Update with 386M $B\bar{B}$)









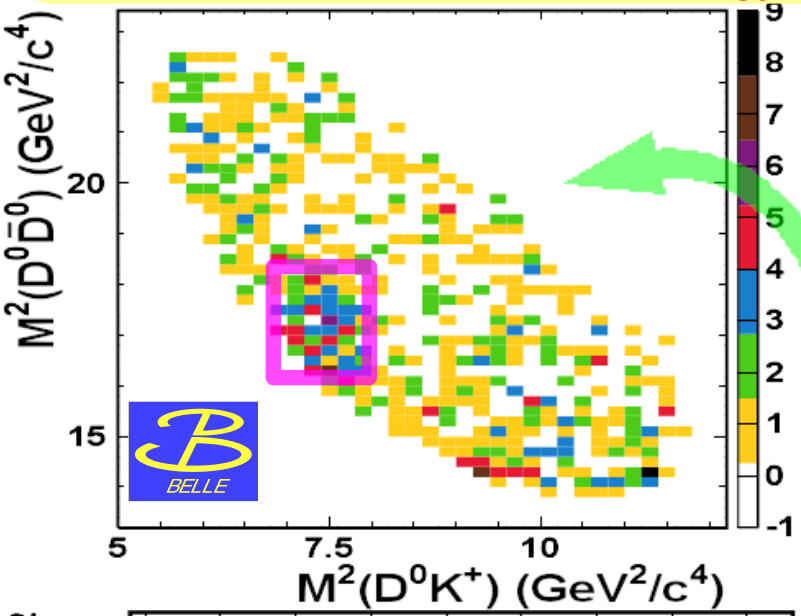
Decay mode	Yield $\Delta M(D_{sJ})$	Yield ΔE	Efficiency (10^{-4})	Product $\mathcal{B}(\overline{B}^0 \to D_{sJ}^{+}K^{-}) \times \mathcal{B}(D_{sJ} \to D_s\pi^0(\gamma))$ (10^{-5})	Signif. σ
$D_{sJ}^{*}(2317)^{+}K^{-}$	35.3 ± 6.4	34.1 ± 6.6	21.9 ± 0.6	$4.4 \pm 0.8 \pm 0.6 \pm 1.1$	9.2
$D_{sJ}(2460)^{+}K^{-}$	11.2 ± 5.4	10.2 ± 5.4	59.5 ± 1.4	$0.53 \pm 0.20^{+0.16}_{-0.15}$	3.1
				< 0.86 (90% C.L.)	

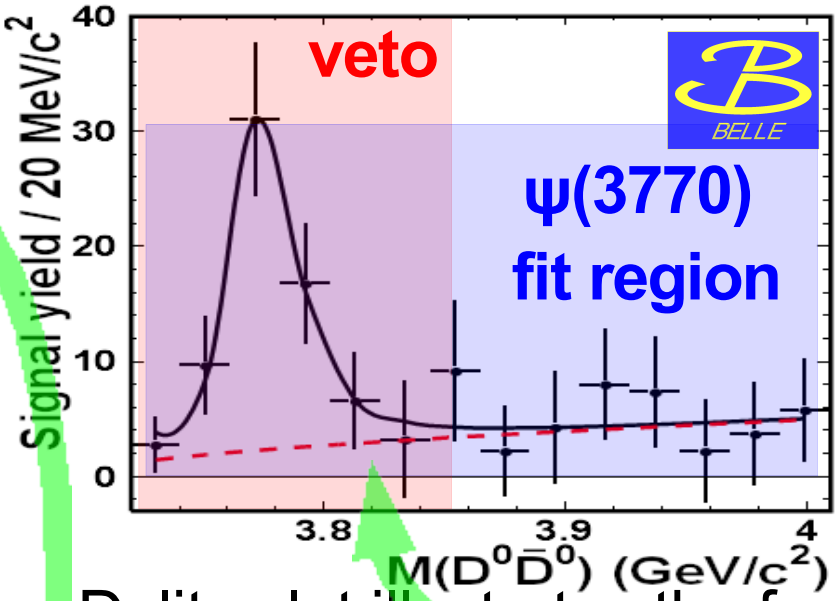
Two states are not from the same-spin doublet

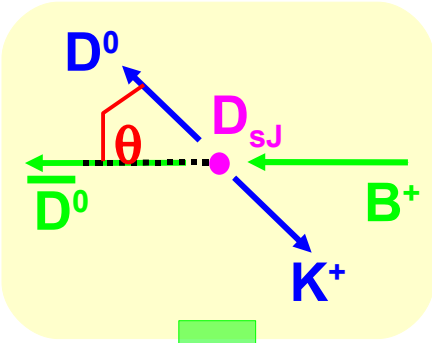
$D_{sJ}^*(2700)^+$ observed in $B^+ \to \bar{D}^0 D^0 K^+$

PRL 100, 092001(2008)
449 $B\bar{B}$

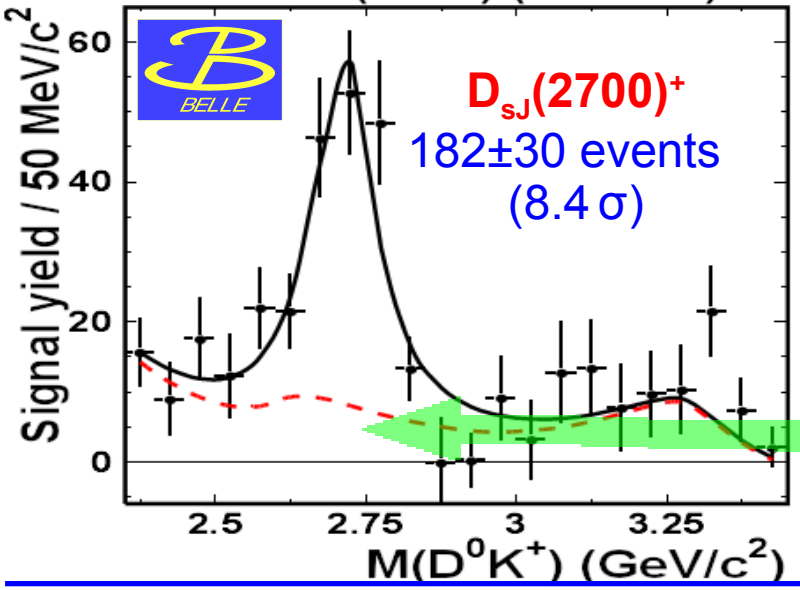
New $c\bar{s}$ state: $B^+ \to \bar{D}^0 D_{sJ}(2700)^+$, $D_{sJ}(2700)^+ \to D^0 K^+$







spin assignment



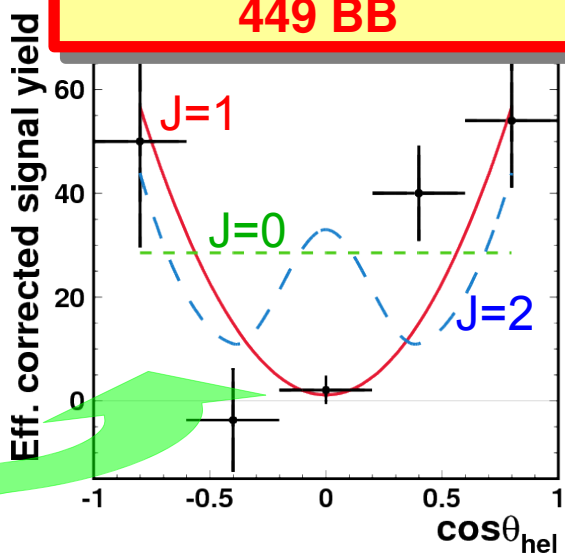
- Dalitz plot illustrates the features, while background-subtracted distributions fitted
- $\Psi(3770) \to D^0 \bar{D}^0$ veto applied
- $B^+ \to K^+ \Psi(4160)$ contribution, phase-space and threshold taken into account
- Signal yield is efficiency corrected

$D_{sJ}^{*}(2700)^{+}$ in $B^{+}\to\bar{D}^{0}D^{0}K^{+}$ cont'd

PRL 100, 092001(2008)
449 $B\bar{B}$

R	$D_{sJ}(2700)^{+}$	$\psi(3770)$
N_{sig} (significance)	182 ± 30 (8.4σ)	68 ± 15 (5.5σ)
M [MeV/c^2]	$2708 \pm 9^{+11}_{-10}$	$3776 \pm 5 \pm 4$
Γ [MeV/c^2]	$108 \pm 23^{+36}_{-31}$	$27 \pm 10 \pm 5$
Product $\mathcal{B}$ $[10^{-4}]$	$11.3 \pm 2.2^{+1.4}_{-2.8}$	$2.2 \pm 0.5 \pm 0.3$

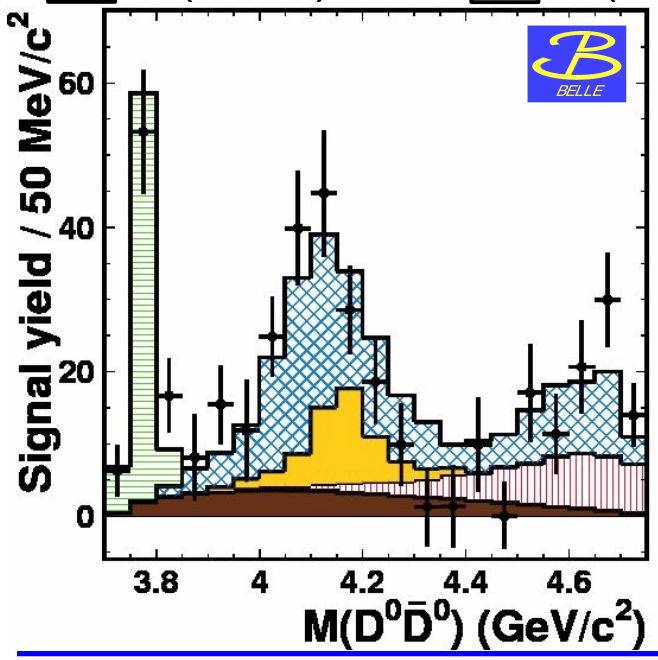
agrees with WA

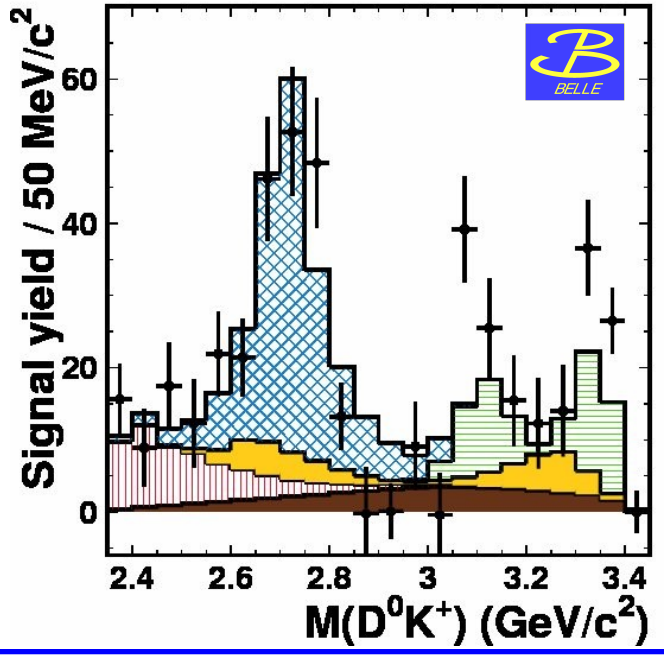


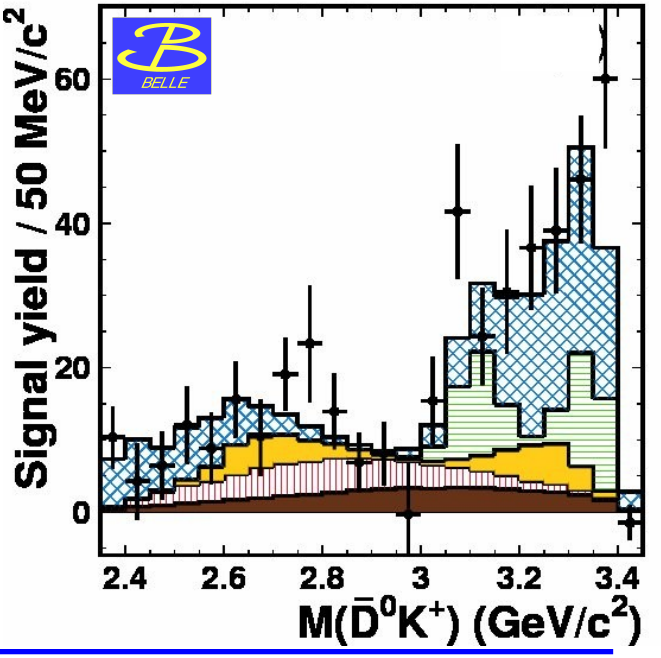
hel. & $1\to 0^{-}0^{-}$: $J^{P}=1^{-}$ favoured

$D_{sJ}(2700)^{+}$ threshold phase-space

$\Psi(3770)$ $\Psi(4160)$





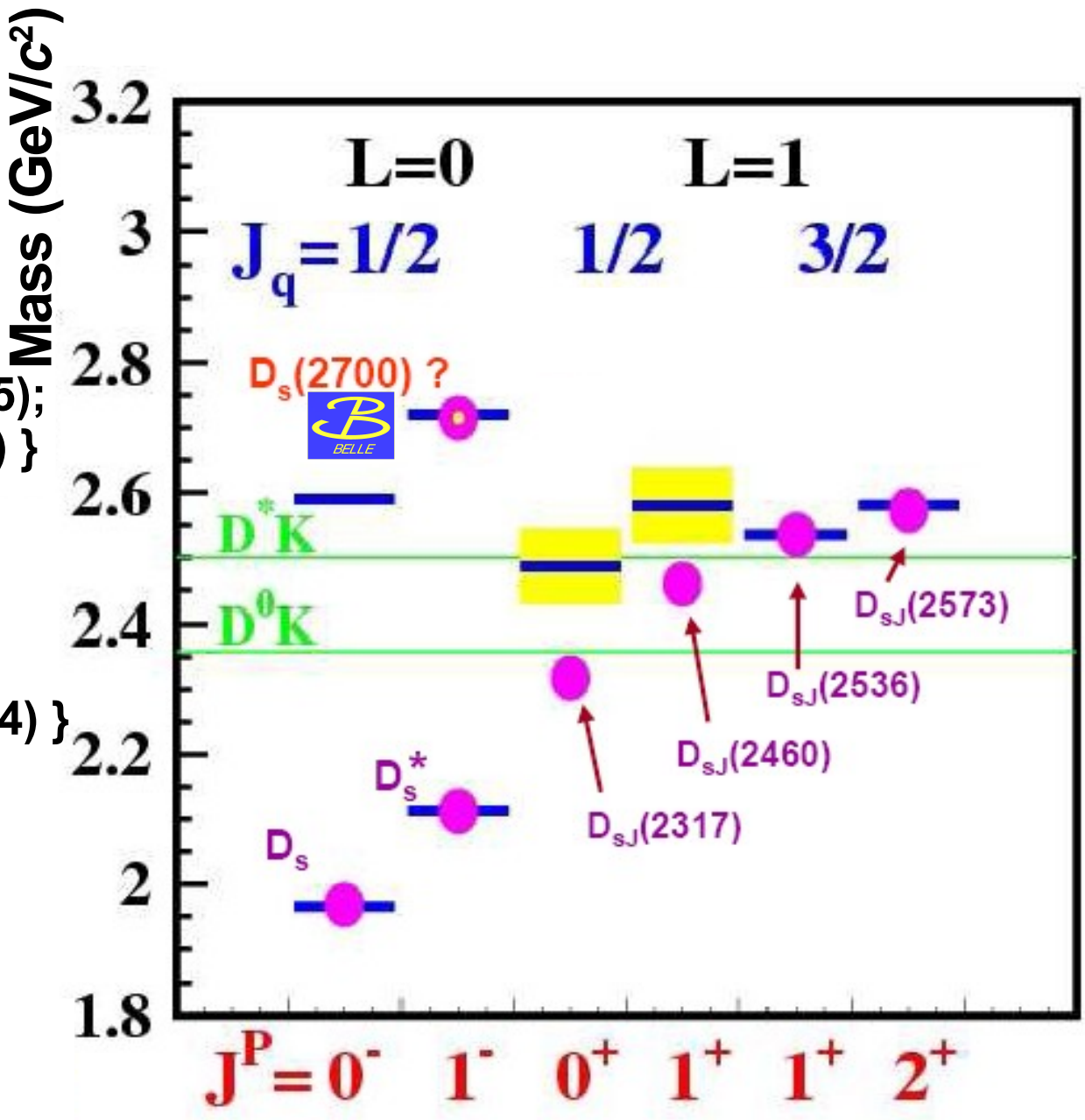


D_{sJ} meson spectroscopy update

$D_{sJ}(2700)^+ \to D^0K^+$:

- Preferred: $J^P=1^-$

- Possible interpretations:
  - ⇨ Radially excited 2^3S_1 (exc. Ds*) with mass ~2720 MeV/c^2
    { Godfrey et al. PRD 32, 189 (1985); Close et al., PLB 647, 159 (2007) }
  - ⇨ Chiral doublet 1^- state to 1^+ $D_{s1}(2536)^+$ with mass (2721 ± 10) MeV/c^2
    { Nowak et al., Acta Phys. Pol. B 35, 2377(2004) }
- Confirmation needed



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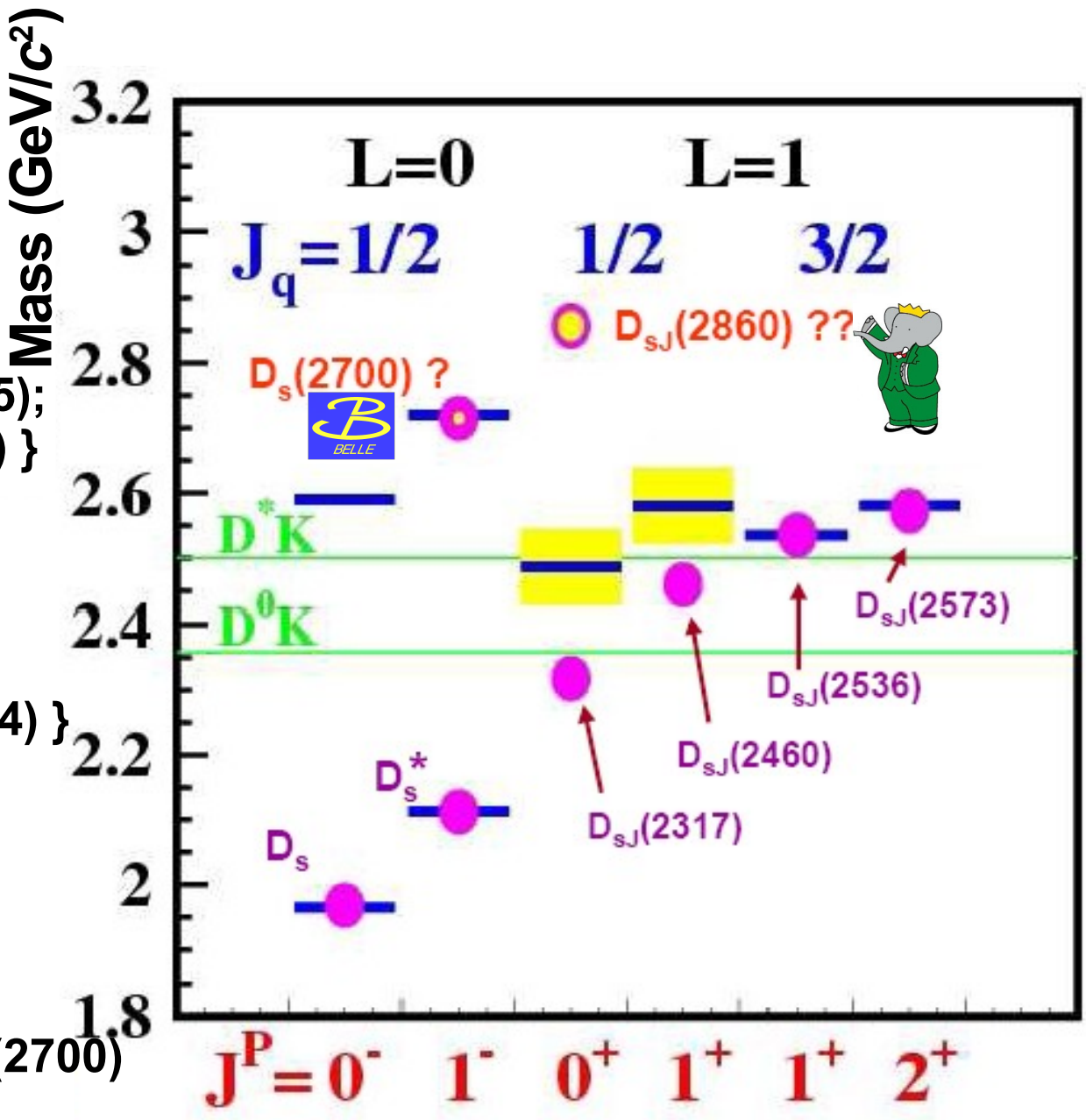
    { Nowak et al., Acta Phys. Pol. B 35, 2377(2004) }
- Confirmation needed

$D_{sJ}(2860)^+ \to D^0K^+$:

- New state from BaBar:

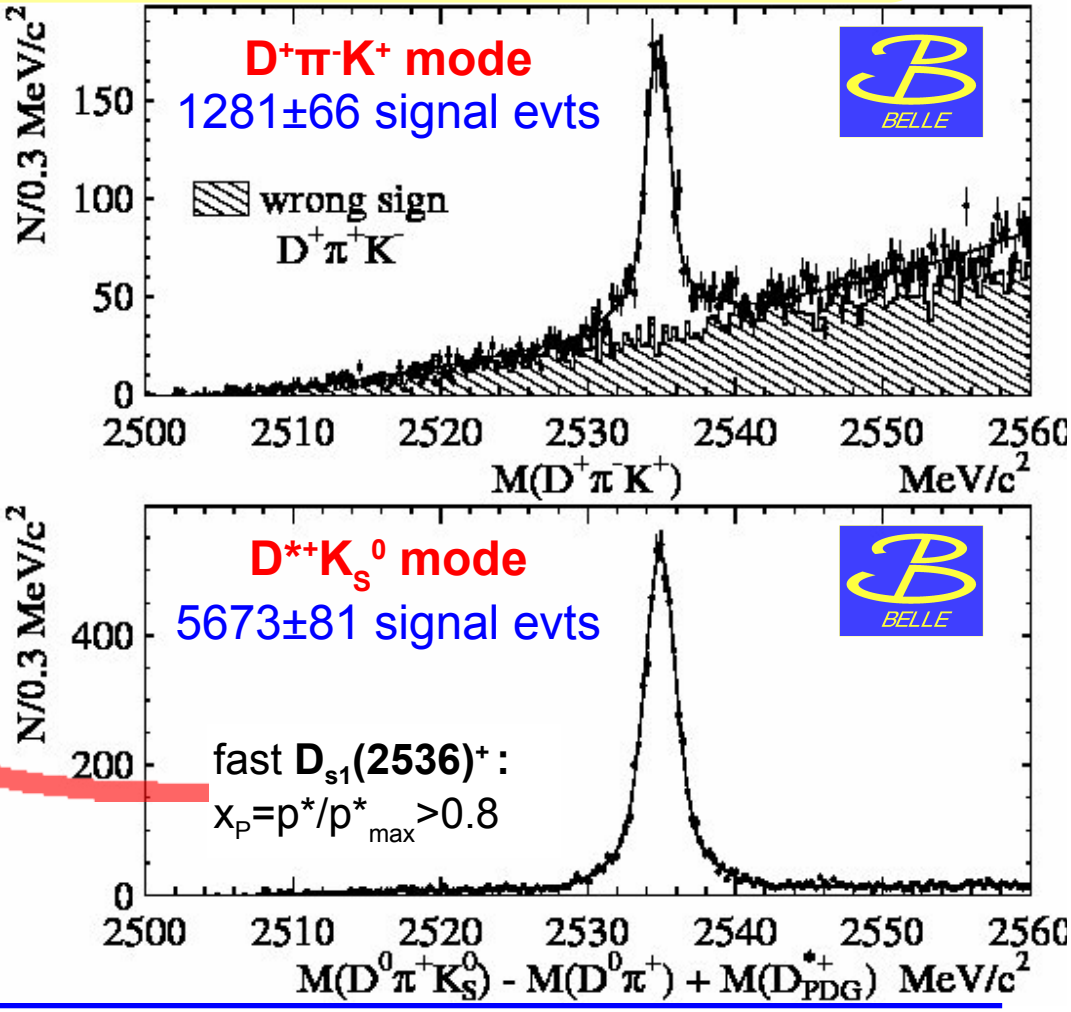
  ⇨ Seems to be different than $D_{sJ}(2700)$



$D_{s1}(2536)^+ \to D^+\pi^-K^+$, $D^{*+}K_S^0$

PRD 77, 032001 (2008)
462 fb^{-1}

- Another result of the renewed interest in measurements of charm mesons after $D_{sJ}^*(2317)$ & $D_{sJ}(2460)$ ...
- **First observation of: $D_{s1}(2536)^+ \to D^+\pi^-K^+$ (in $e^+e^- \to D_{s1}(2536)^+X$)**
  - no D^{*0} { $M(D^{*0}) < M(D^+)+M(\pi^-)$ }
  - only 2nd three-body decay mode of $D_{s1}(2536)^+$ after $D_s^+\pi^+\pi^-$
- **Also: $D_{s1}(2536)^+ \to D^{*+}K_S^0$** very clean and large sample



improves PID efficiency for $K^\pm$&$\pi^\pm$ and removes $D_{s1}(2536)^+$ from B's

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PRD 77, 032001 (2008)
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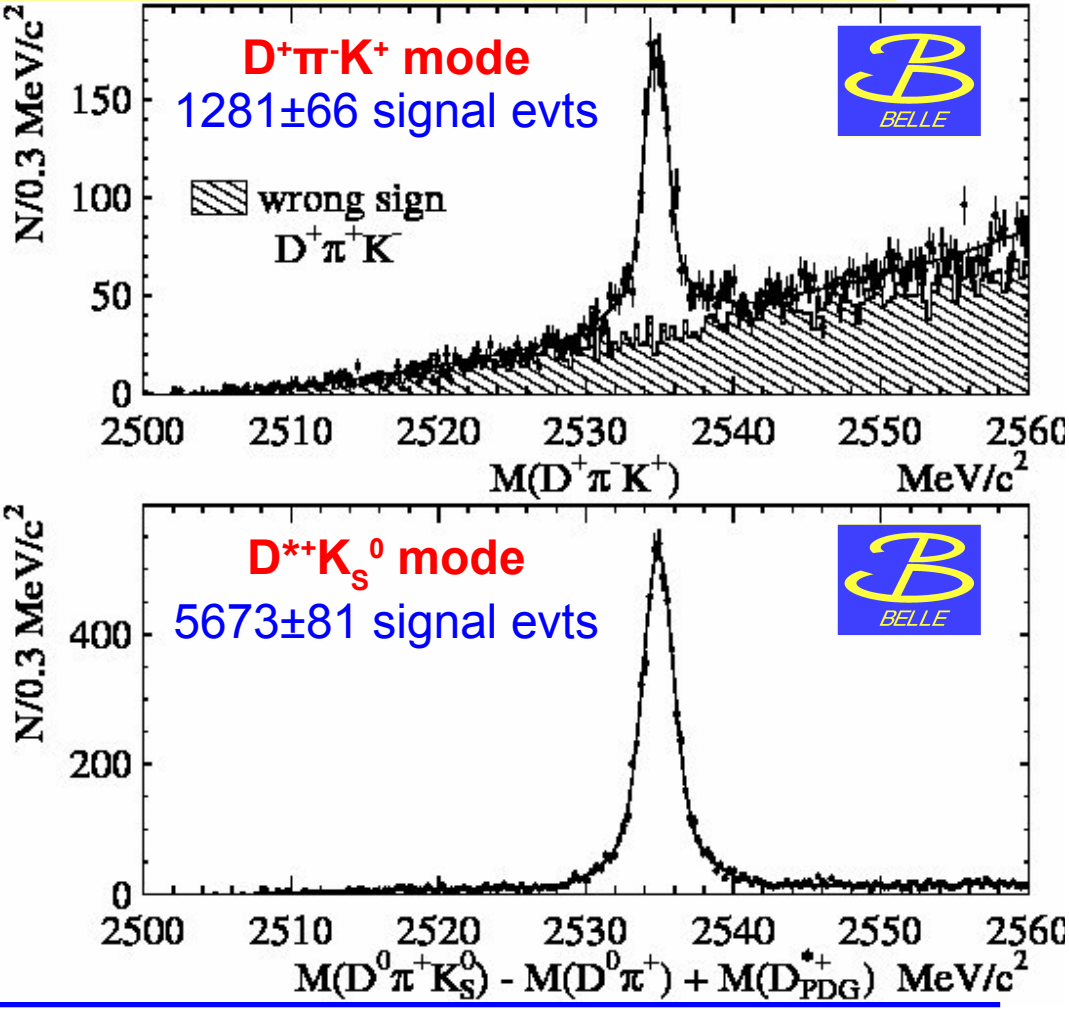
  ⇒ **partial wave analysis (PWA)**



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PRD 77, 032001 (2008)
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- **Also: $D_{s1}(2536)^+ \to D^{*+}K_S^0$**

very clean and large sample

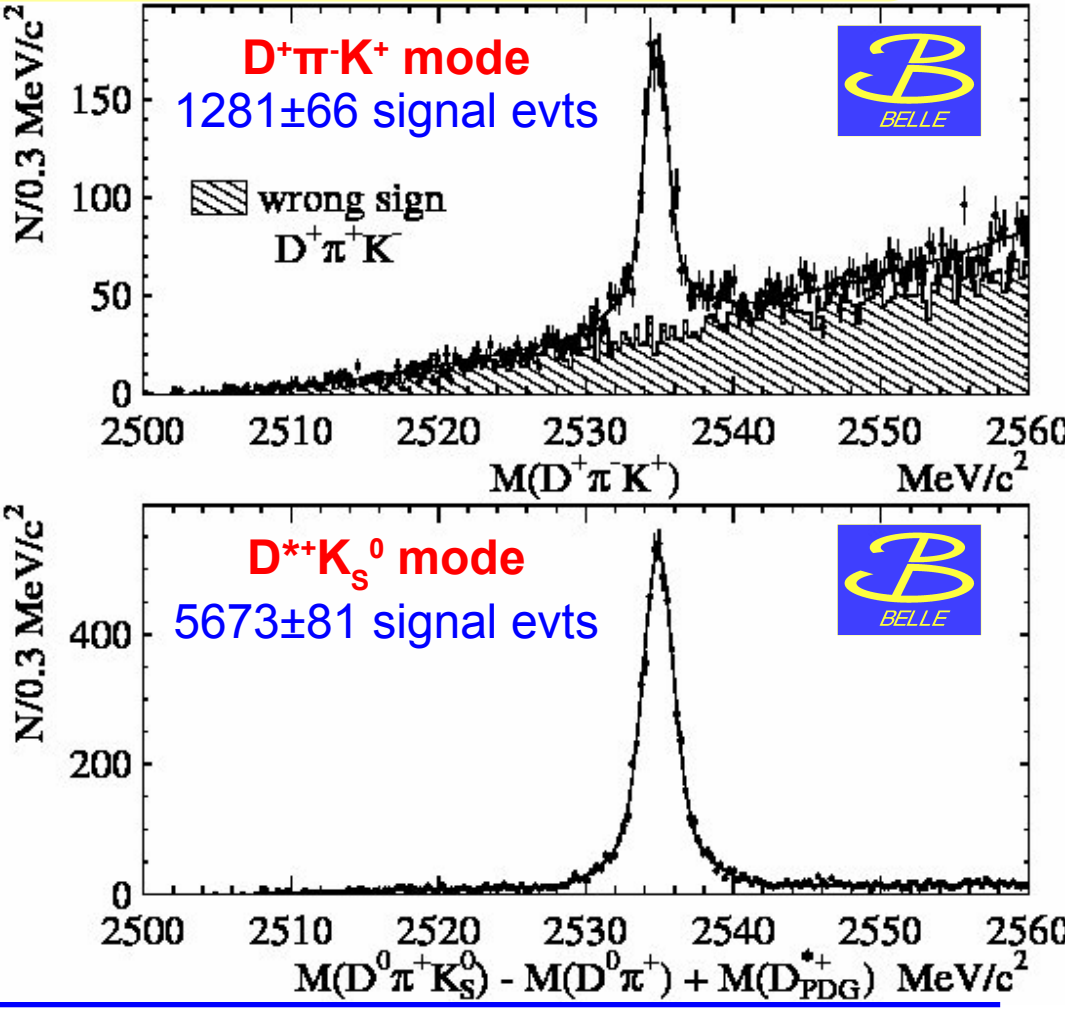
⇒ **partial wave analysis (PWA)**

Motivation:

HQET exact: D(S)-wave for j_q=3/2 (1/2)

HQET not exact:

$D_{s1}(2536)^+$ contains small admixture of j_q=1/2

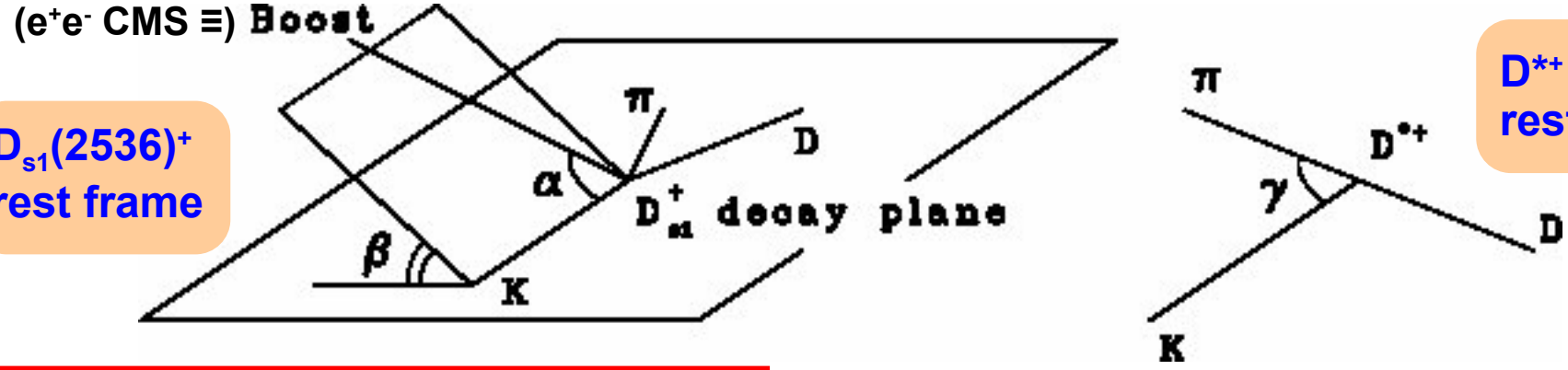


$D_{s1}(2536)^+ \to D^{*+}K_S^0$: PWA

PRD 77, 032001 (2008)
462 fb^{-1}

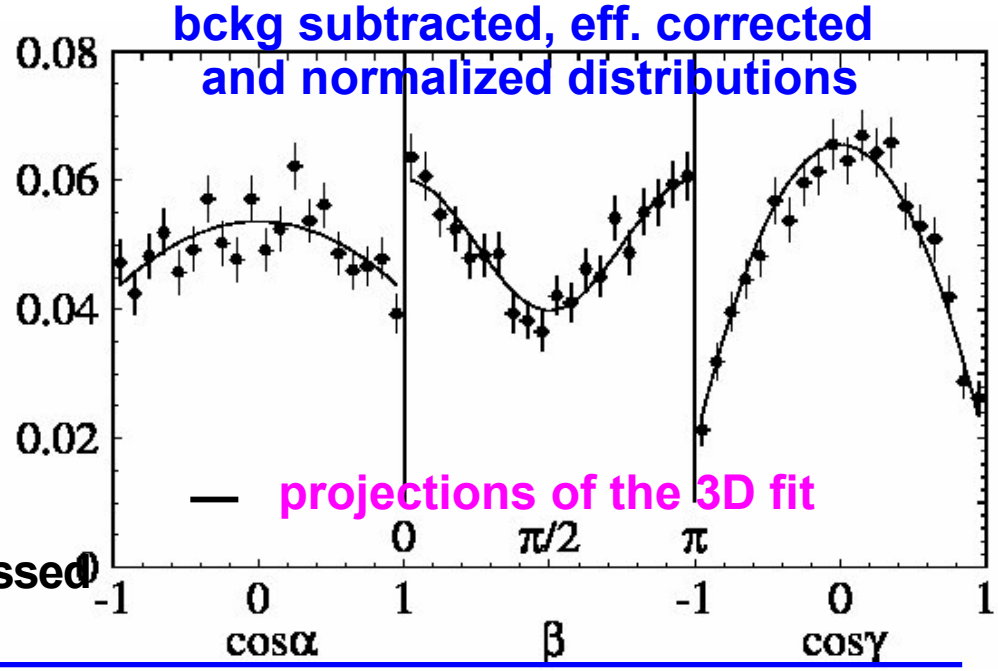
- $D_{s1}(2536)^+$ is produced in $e^+e^- \to D_{s1}(2536)^+X$ with small polarization

$\Rightarrow$ 3D angular fit performed (α,β,γ)



$$\Gamma_S / \Gamma_{total} = 1/(1 + |D/S|^2) =$$

$$0.72 \pm 0.05 \pm 0.01$$



$\Rightarrow$ S-wave dominates in

$D_{s1}(2536)^+ \to D^{*+} K_S^0$ decay

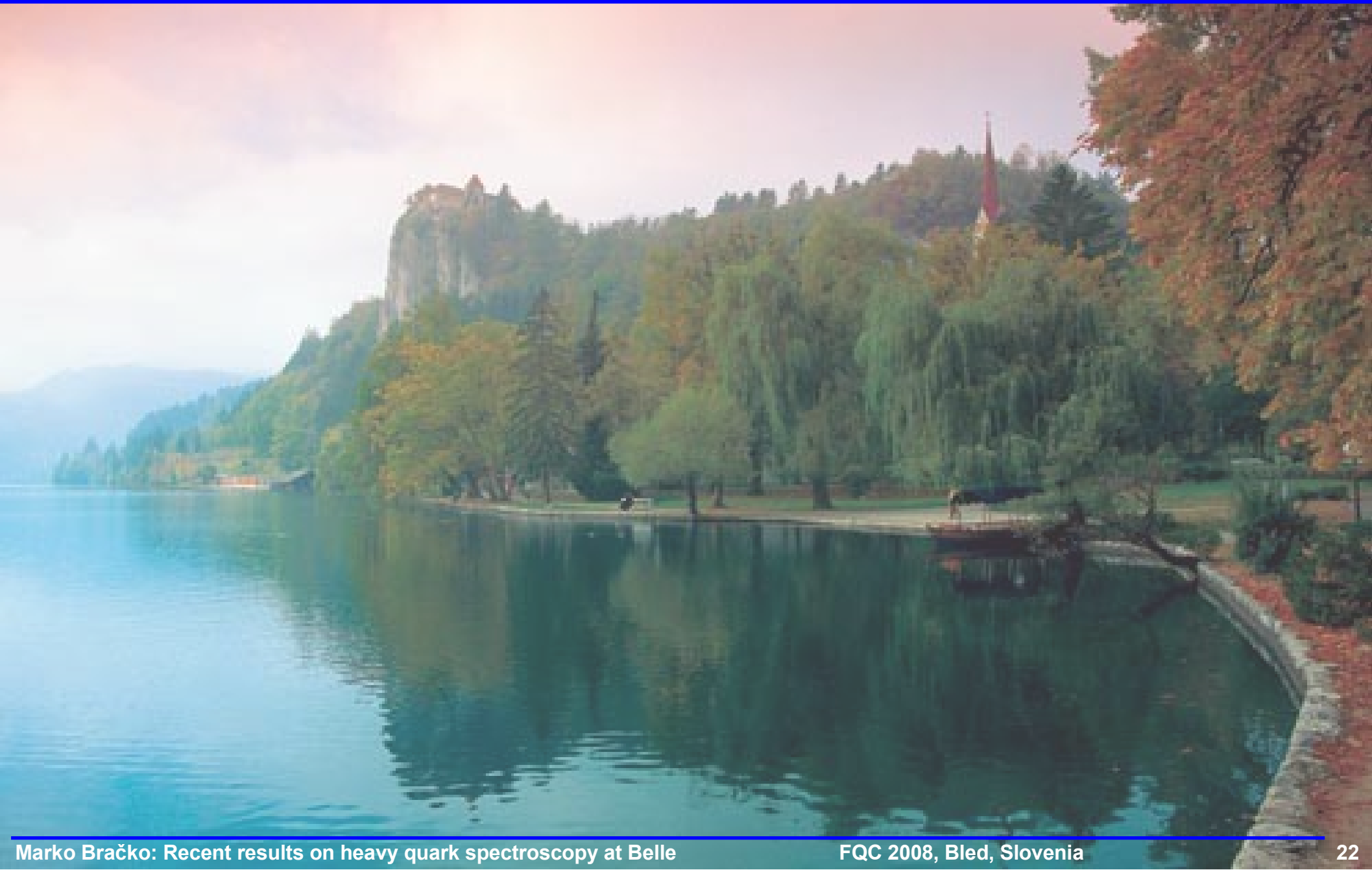
(unlike HQET expectation for pure j_q=3/2;

$D_{s1}(2536)^+$ - $D_{s1}(2460)^+$ mixing?)

However : Small energy release $\to$ D-wave suppressed

$\to$ even small S-wave component increases Γ

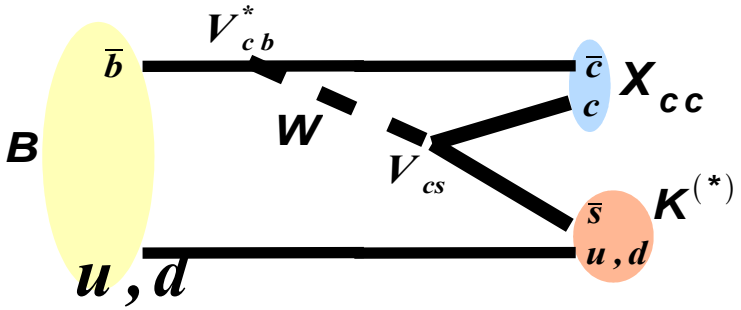
Charmonium(-like) states



B cc̄[-like] production at B-factories

- **B-meson decays:**

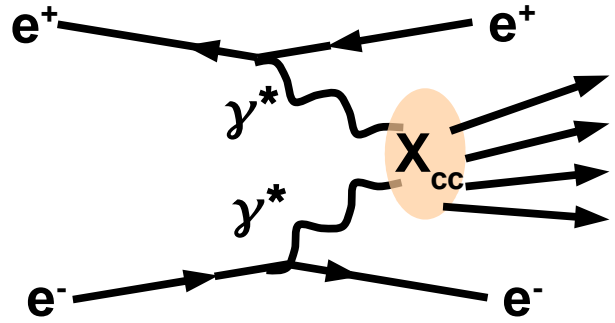
  e.g. $B \to X_{cc}\, K^{(*)}$



  $0^{-+}, 1^{--}, 1^{++}$

- **Two-photon production:**

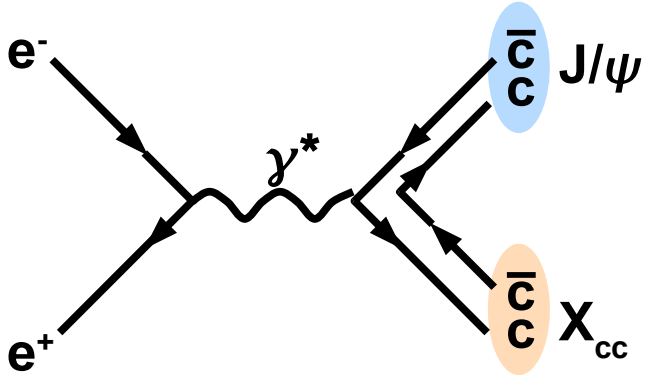
  $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X_{cc}$



  $0^{-+}, 0^{++}, 2^{++}$

- **Double cc̄ production:**

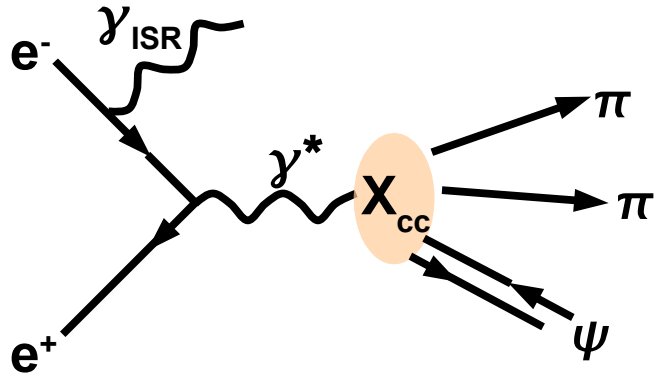
  e.g. $e^+e^- \to J/\psi\ X_{cc}$



  states with C=+

- **e^+e^- radiative return (ISR):**

  e.g. $e^+e^- \to \gamma_{ISR}\, X_{cc} \to \gamma_{ISR}\psi\pi\pi$



  1^{--} only

B $c\bar{c}$[-like] production at B-factories

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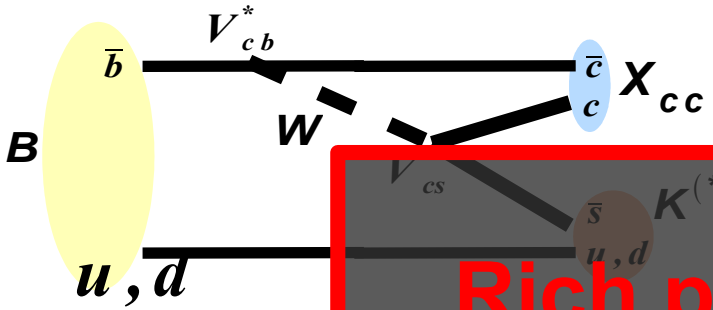
  e.g. $B \to X_{cc} K^{(*)}$



  0^{-+}, 1^{--}, 1^{++}

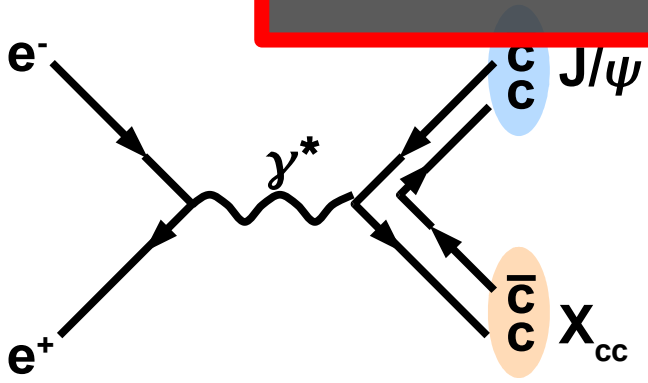
- **Two-photon production:**

  $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X_{cc}$

  0^{-+}, 0^{++}, 2^{++}

- **Double $c\bar{c}$ production:**

  e.g. $e^+e^- \to J/\psi\ X_{cc}$



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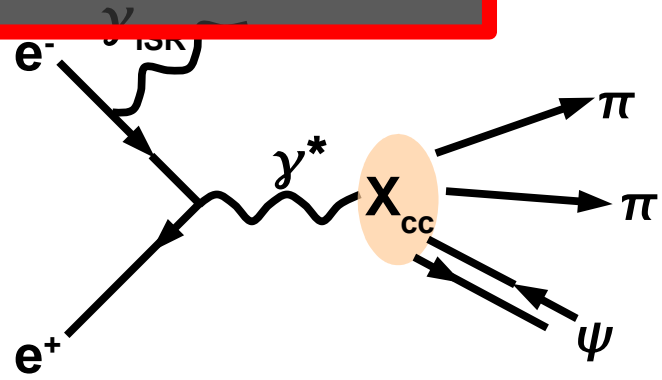
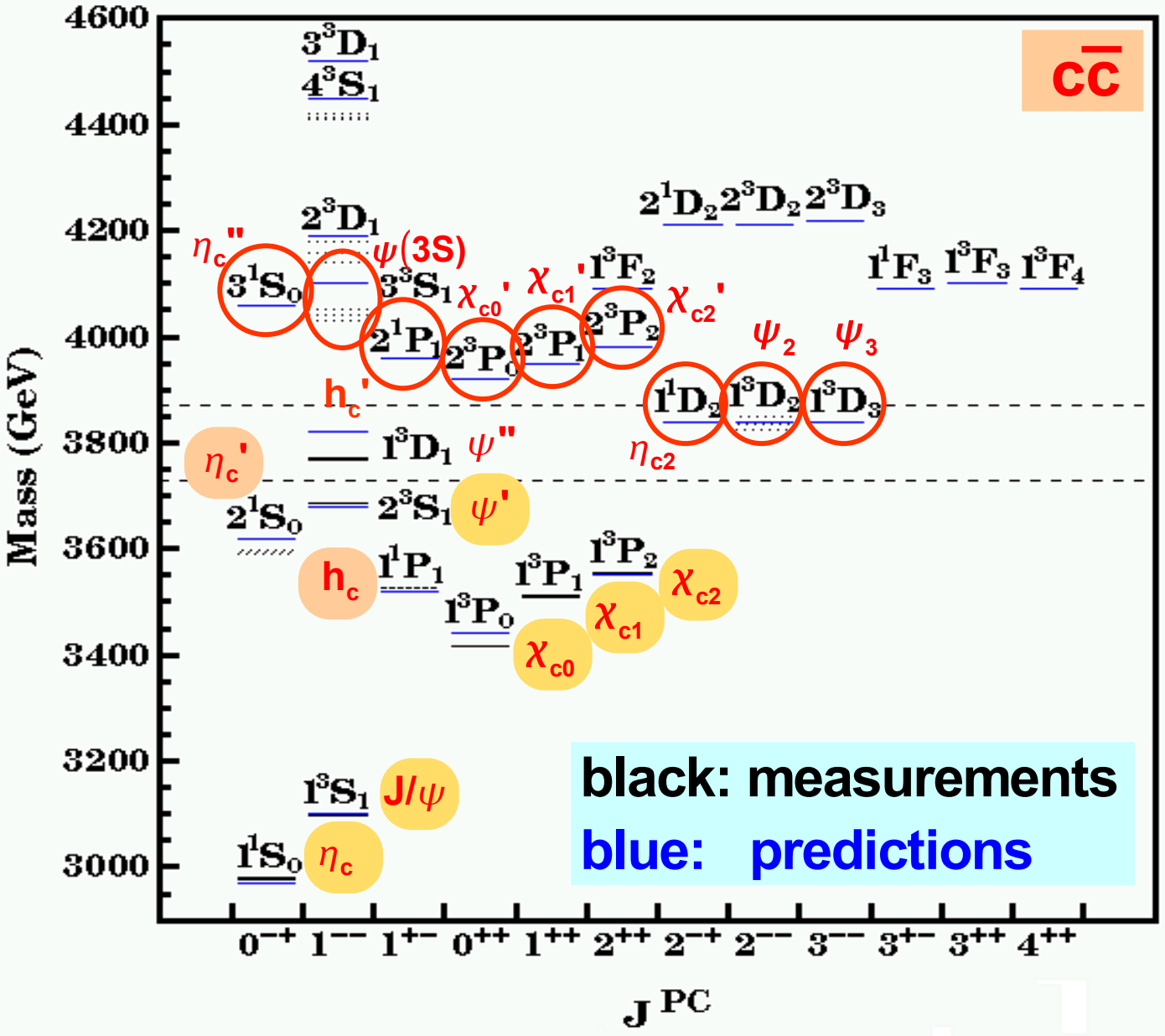


  1^{--} only

Rich possibilities to search for new states and study charmonium[-like] properties!

Charmonium spectroscopy status



$M_D+M_{D^*}=3871.3$ MeV/c^2
$2M_D$

well measured

recent

And also many new states (X, Y, Z)

State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, DO, Cleo, BaBar	3871.2±0.5 + i(<2.3)	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	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)	1^{--}	$\omega J/\psi$	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^*	B decays
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^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	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)
$Z^+(4430)$	Belle	$4433\pm4\pm1$+ $i(44^{+17}_{-13}{}^{+30}_{-11})$	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

Meson classification

Conventional mesons ($q_1\bar{q}_2$)

Exotic mesons:

- not forbidden in SM;
- exotic J^{PC} (e.g. 0^{+-}, 1^{-+}, 2^{+-},... forbidden for qq);
- exotic decay modes (not possible from qq);
- strange properties (widths,...);

- Hybrid states ($q\bar{q}$+g)
- Multiquark states ($q\bar{q}$ $q\bar{q}$ or qq $\bar{q}\bar{q}$)
- "Molecules" (loosely bound mesons: M $\bar{M}$)
- Glueballs (gg, ggg)
- Mixtures of states above
- More exotic states?

Meson classification

Conventional mesons ($q_1\bar{q}_2$)

Exotic mesons:

Important characteristic of multiquark states
(and not hybrids or charmonia):

It is possible to have charmonium-like mesons
with non-zero charge (e.g. [cucd]) ...

- Hybrid states ($q\bar{q}$+g)
- Multiquark states ($q\bar{q}$ $q\bar{q}$ or qq $\bar{q}\bar{q}$)
- "Molecules" (loosely bound mesons: M $\bar{M}$)
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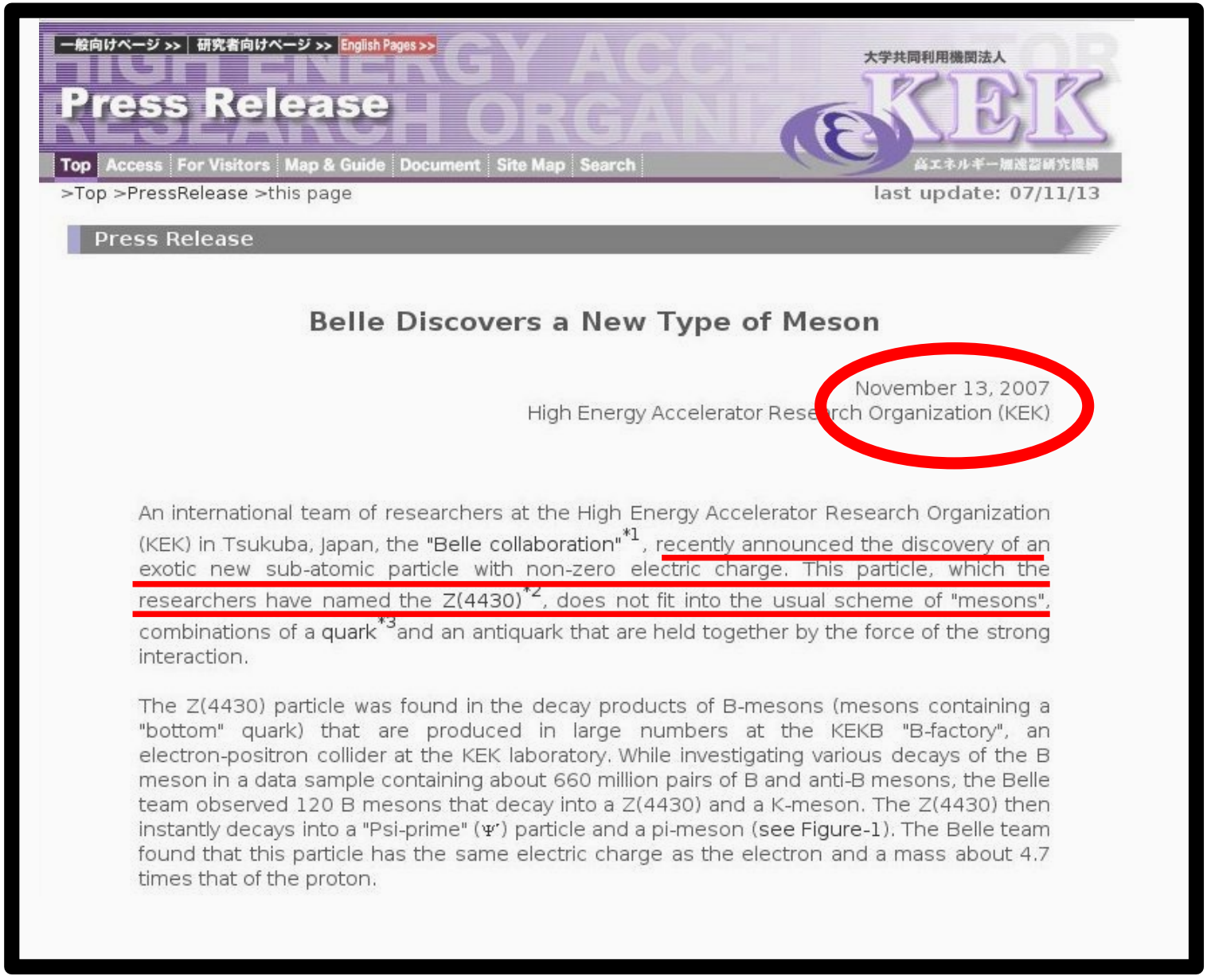
Recent hot topic: $Z(4430)^+$ state



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大学共同利用機関法人

Press Release

KEK 高エネルギー加速器研究機構

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>Top >PressRelease >this page

last update: 07/11/13

Press Release

Belle Discovers a New Type of Meson

November 13, 2007

High Energy Accelerator Research Organization (KEK)

An international team of researchers at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan, the "Belle collaboration"*1, recently announced the discovery of an exotic new sub-atomic particle with non-zero electric charge. This particle, which the researchers have named the Z(4430)*2, does not fit into the usual scheme of "mesons", combinations of a quark*3 and an antiquark that are held together by the force of the strong interaction.

The Z(4430) particle was found in the decay products of B-mesons (mesons containing a "bottom" quark) that are produced in large numbers at the KEKB "B-factory", an electron-positron collider at the KEK laboratory. While investigating various decays of the B meson in a data sample containing about 660 million pairs of B and anti-B mesons, the Belle team observed 120 B mesons that decay into a Z(4430) and a K-meson. The Z(4430) then instantly decays into a "Psi-prime" (Ψ') particle and a pi-meson (see Figure-1). The Belle team found that this particle has the same electric charge as the electron and a mass about 4.7 times that of the proton.

Recent hot topic: Z(4430)$^+$ state

PRL 100, 142001(2008)
657 $B\bar{B}$

PRL 100, 142001 (2008) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2008

Observation of a Resonancelike Structure in the $\pi^{+-}\psi'$ Mass Distribution in Exclusive $B \to K\pi^{+-}\psi'$ Decays

S.-K. Choi,[6] S. L. Olsen,[8,10] I. Adachi,[9] H. Aihara,[42] V. Aulchenko,[1] T. Aushev,[18,13] T. Aziz,[39] A. M. Bakich,[38] V. Balagura,[13] I. Bedny,[1] U. Bitenc,[14] A. Bondar,[1] A. Bozek,[27] M. Bračko,[20,14] J. Brodzicka,[9] T. E. Browder,[8] P. Chang,[26] Y. Chao,[26] A. Chen,[24] K.-F. Chen,[26] W. T. Chen,[24] B. G. Cheon,[7] R. Chistov,[13] Y. Choi,[37] J. Dalseno,[21] M. Danilov,[13] M. Dash,[46] S. Eidelman,[1] N. Gabyshev,[1] B. Golob,[19,14] J. Haba,[9] T. Hara,[32] K. Hayasaka,[22] H. Hayashii,[23] M. Hazumi,[9] D. Heffernan,[32] Y. Hoshi,[41] W.-S. Hou,[26] H. J. Hyun,[17] T. Iijima,[22] K. Inami,[22] A. Ishikawa,[34] H. Ishino,[43] R. Itoh,[9] M. Iwasaki,[42] Y. Iwasaki,[9] D. H. Kah,[17] J. H. Kang,[47] N. Katayama,[9] H. Kawai,[2] T. Kawasaki,[29] H. Kichimi,[9] H. O. Kim,[17] S. K. Kim,[36] Y. J. Kim,[5] K. Kinoshita,[3] P. Križan,[19,14] P. Krokovny,[9] R. Kumar,[33] C. C. Kuo,[24] A. Kuzmin,[1] Y.-J. Kwon,[47] J. S. Lange,[4] J. S. Lee,[37] M. J. Lee,[36] S. E. Lee,[36] T. Lesiak,[27] A. Limosani,[21] S.-W. Lin,[26] Y. Liu,[5] D. Liventsev,[13] F. Mandl,[11] A. Matyja,[27] S. McOnie,[38] T. Medvedeva,[13] W. Mitaroff,[11] K. Miyabayashi,[23] H. Miyake,[32] H. Miyata,[29] Y. Miyazaki,[22] R. Mizuk,[13] G. R. Moloney,[21] E. Nakano,[31] M. Nakao,[9] S. Nishida,[9] O. Nitoh,[45] T. Nozaki,[9] S. Ogawa,[40] T. Ohshima,[22] S. Okuno,[15] H. Ozaki,[9] P. Pakhlov,[13] G. Pakhlova,[13] C. W. Park,[37] H. Park,[17] L. S. Peak,[38] R. Pestotnik,[14] L. E. Piilonen,[46] H. Sahoo,[8] Y. Sakai,[9] O. Schneider,[18] A. J. Schwartz,[3] K. Senyo,[22] M. Shapkin,[12] C. P. Shen,[10] H. Shibuya,[40] B. Shwartz,[1] J. B. Singh,[33] A. Somov,[3] S. Stanič,[30] M. Starič,[14] T. Sumiyoshi,[44] S. Y. Suzuki,[9] F. Takasaki,[9] K. Tamai,[9] M. Tanaka,[9] Y. Teramoto,[31] I. Tikhomirov,[13] S. Uehara,[9] T. Uglov,[13] Y. Unno,[7] S. Uno,[9] P. Urquijo,[21] G. Varner,[8] K. Vervink,[18] S. Villa,[18] C. H. Wang,[25] M.-Z. Wang,[26] P. Wang,[10] X. L. Wang,[10] Y. Watanabe,[15] R. Wedd,[21] E. Won,[16] B. D. Yabsley,[38] Y. Yamashita,[28] C. Z. Yuan,[10] Z. P. Zhang,[35] V. Zhulanov,[1] A. Zupanc,[14] and O. Zyukova[1]

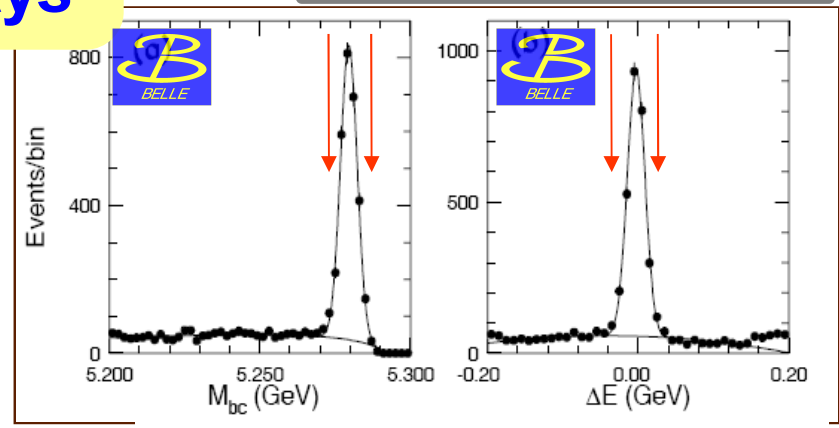
(Belle Collaboration)

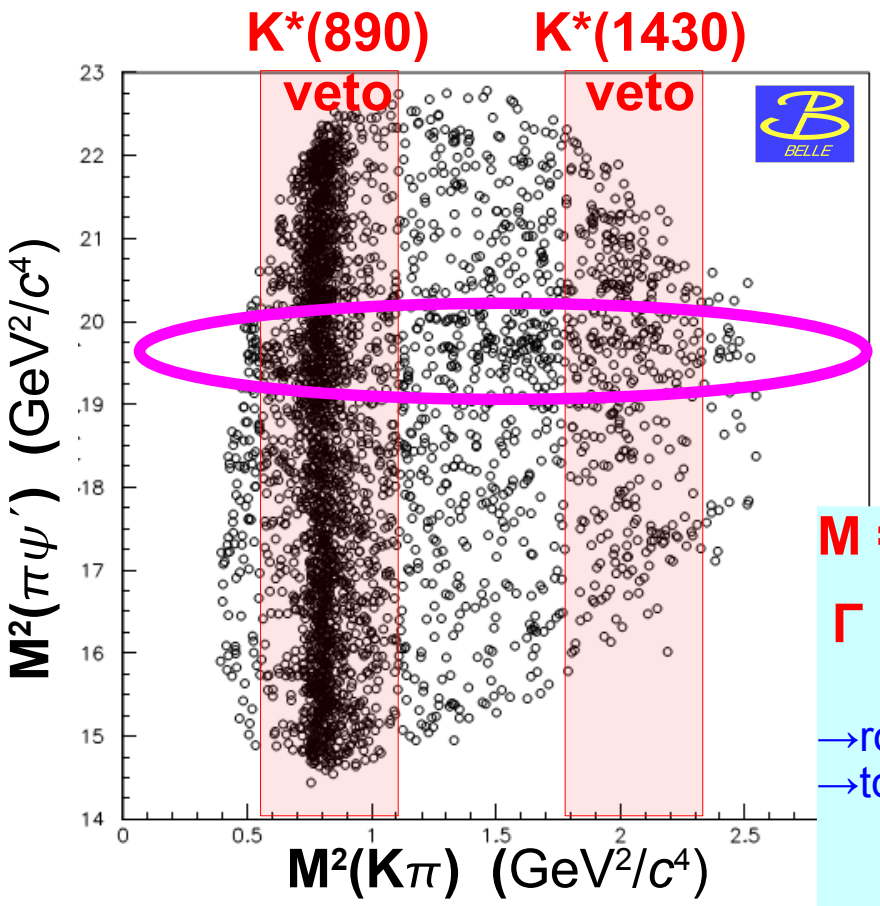
Observation of Z(4430)$^+$ state

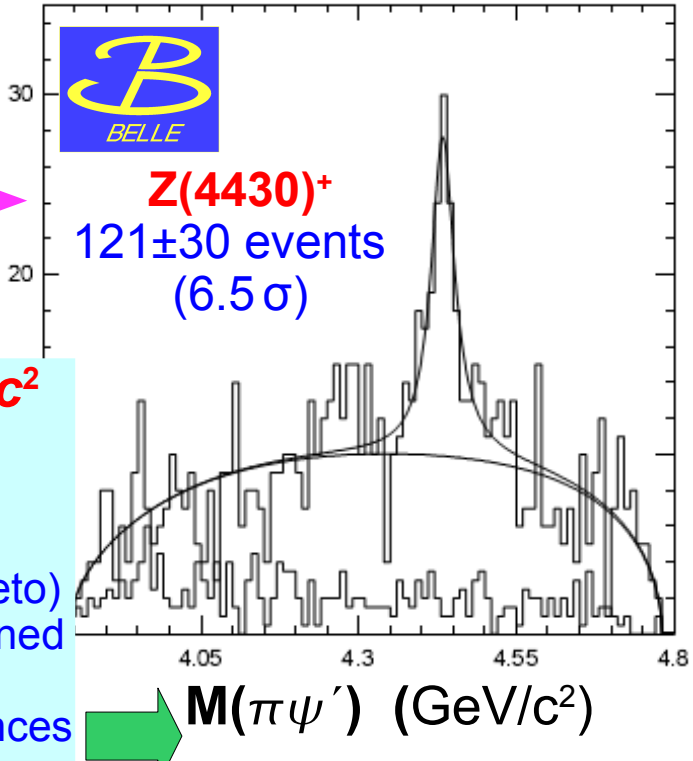
PRL 100, 142001(2008)
657 $B\bar{B}$

New state observed in $B \to K\pi^{\pm}\psi(2S)$ decays

- $B \to K\pi^{\pm}\psi'$ ($K=K^{\pm}, K_S^0$; $\psi' \to l^+l^-$ or $J/\psi\pi^+\pi^-$)
- Clear signals is both ΔE and M_{bc} seen
- Breit-Wigner and PS-like function in $M(\pi^{\pm}\psi')$ fit







$M = (4433 \pm 4 \pm 2)$ MeV/c^2

$\Gamma = (45\ ^{+18}_{-13}\ ^{+30}_{-13})$ MeV

→robust signal (subsamples;veto)
→too narrow state to be explained by interference of known S-, P- D-wave $K\pi$ resonances

$Z(4430)^+$ state cont'd

PRL 100, 142001(2008)
657 $B\bar{B}$

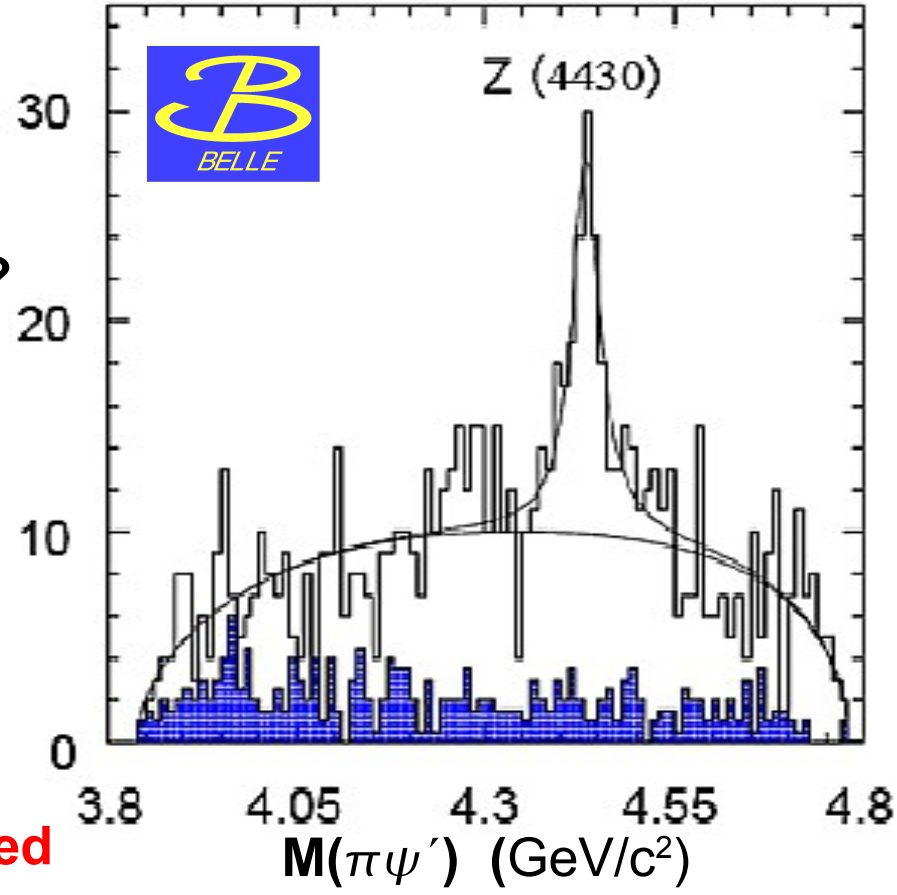
$Z(4430)^+ \to \psi(2S)\pi^+$:

- Charged state that decays like charmonium (charged charmonium-like state)

$$Br(\bar{B}^0 \to K^- Z(4430)^+) \times Br(Z(4430)^+ \to \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

- Not enough statistics to determine J^P

- Possible interpretations:
  - ⇨ $[cu][\bar{c}\bar{d}]$ tetraquark with $J^P=1^+$
    (Radial excitation of X(3872) family?)
    - Neutral partner in decays: $\psi'\pi^0/\eta$, $\eta_c'\rho^0/\omega$?
    - Charged 1S state in decays: $\psi\pi^\pm$, $\eta_c\rho^\pm$?
      { Maiani et al., arXiv:hep-ph/0708.3997 }
  - ⇨ $D^*\bar{D}_1(2420)$ threshold effect
    { Rosner, PRD 76, 114002 (2007) }
  - ⇨ $D^*\bar{D}_1(2420)$ molecule with $J^P=0^-, 1^-$
    Decay to $D^*D^*\pi$ expected.
    { Meng et al., hep-ph/0708.4222 }
  - ⇨ Further studies & confirmation needed

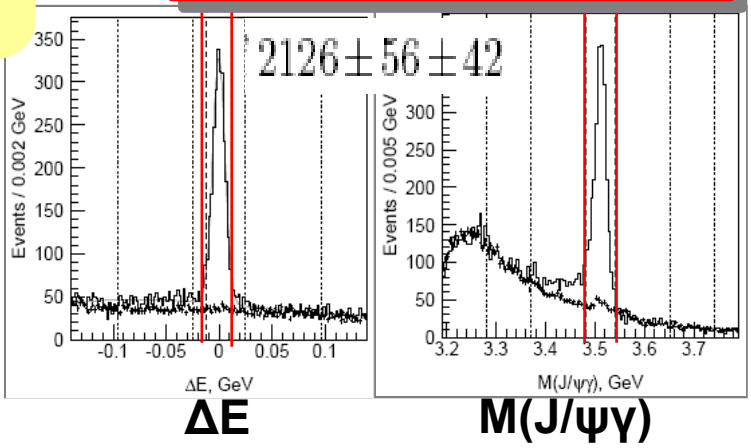


Hot topic #2: Z_1^+ and Z_2^+

arXiv:0806.4098[hep-ex]
657 $B\bar{B}$

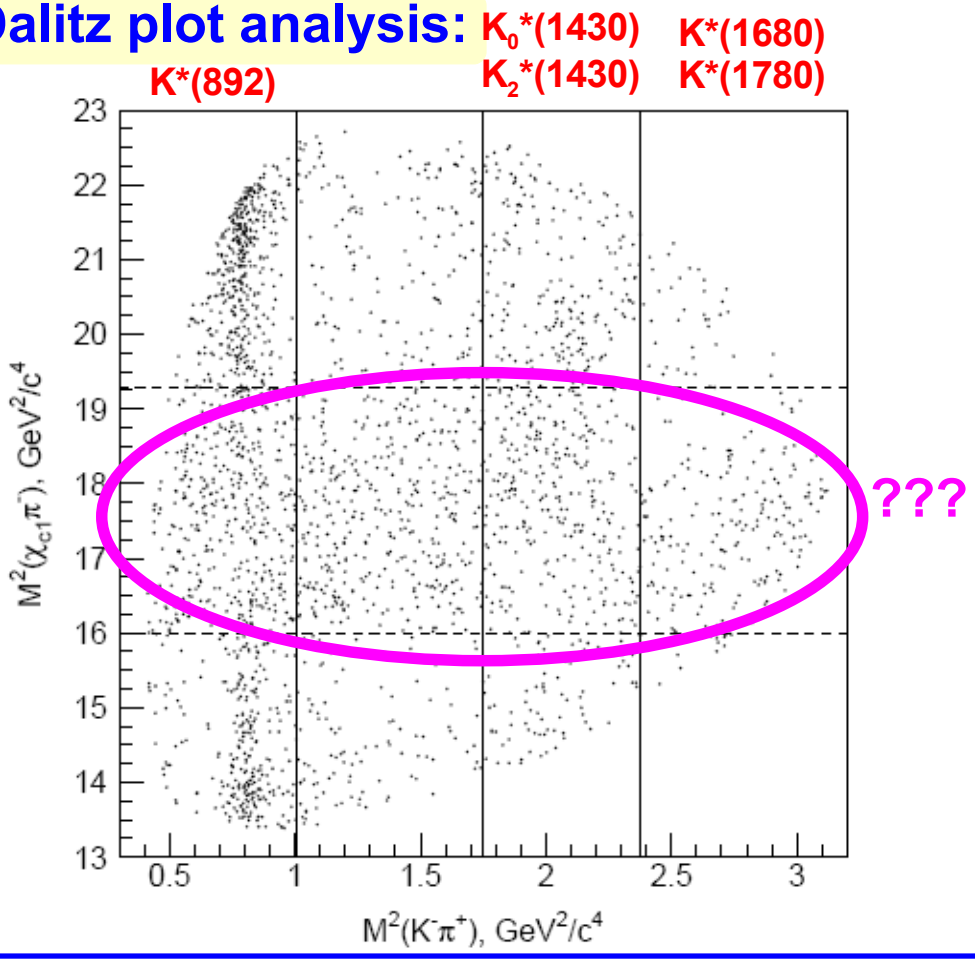
New states observed in $\bar{B}^0 \to K^-\pi^+\chi_{c1}$ decays

- $B^0 \to K^-\pi^+\chi_{c1}$ ($\chi_{c1} \to J/\psi\gamma$; $J/\psi \to l^+l^-$)
- Clear signals in ΔE, M_{bc}, $M(J/\psi\gamma)$



ΔE M(J/ψγ)

Dalitz plot analysis:



- Isobar model: superposition of formfactors, Breit-Wigner amplitudes, Γ(E)
- Integrated χ_{c1}, J/ψ angular distributions (no sensitivity)
- Correction for Lorentz non-invariance of helicity
- Binned (400x400) maximum likelihood fit
- Fit results depicted in M_1^2 for M_2^2 bands

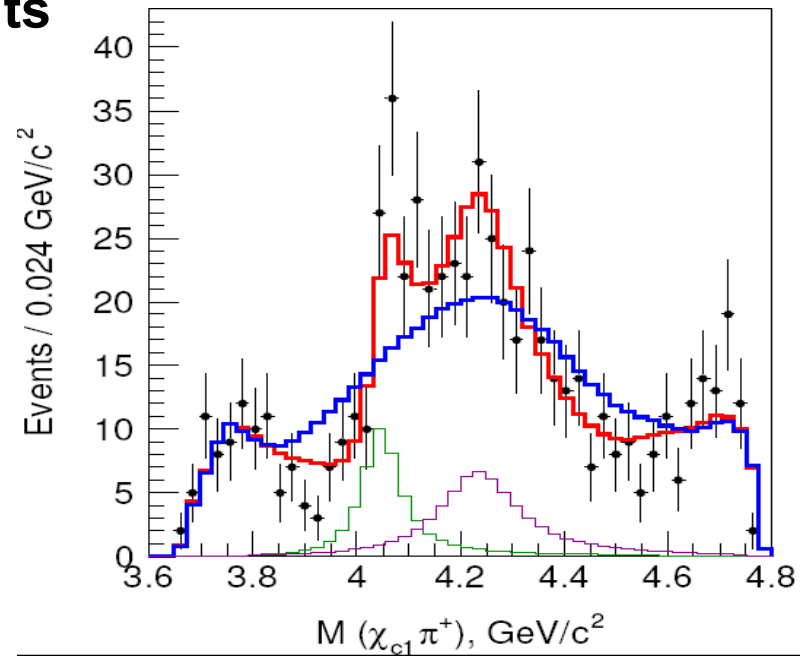
Hot topic #2: Z_1^+ and Z_2^+ continued

arXiv:0806.4098[hep-ex]
657 $B\bar{B}$

- Data favour fit with 2 resonant structures: Z_1 and Z_2
- Spin of $Z_{1,2}$ is not determined:
  J=0 and J=1 hypotheses give comparable results
- $Z_{1,2}$ parameters:
  large syst. errors due to model uncertainties

	Z_1^+	Z_2^+
M/MeV	$4051 \pm 14^{+20}_{-41}$	$4248^{+44+180}_{-29-35}$
Γ/MeV	82^{+21+47}_{-17-22}	$177^{+54+316}_{-39-61}$
$\mathcal{B}_{\overline{\mathrm{B}}^0} \times \mathcal{B}_{Z^+}$	$(3.1^{+1.5+3.7}_{-0.9-1.7}) \times 10^{-5}$	$(4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}$

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



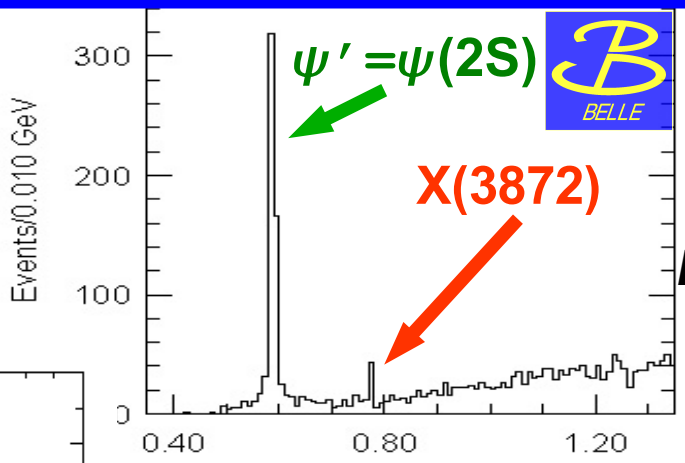
- BF product comparable to $Z^+(4430)$, $X(3872)$…

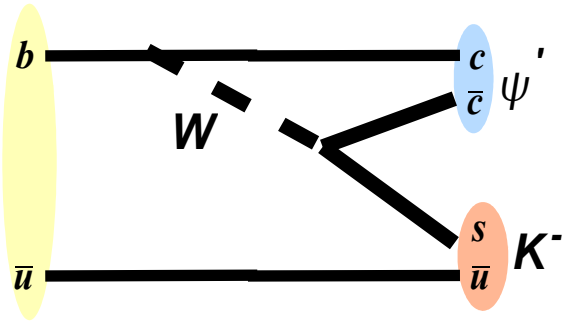
- Z_1^+, Z_2^+ join $Z^+(4430)$ as charged charmonium-like exotics → confirmation needed

X(3872): Discovery by Belle(reminder)

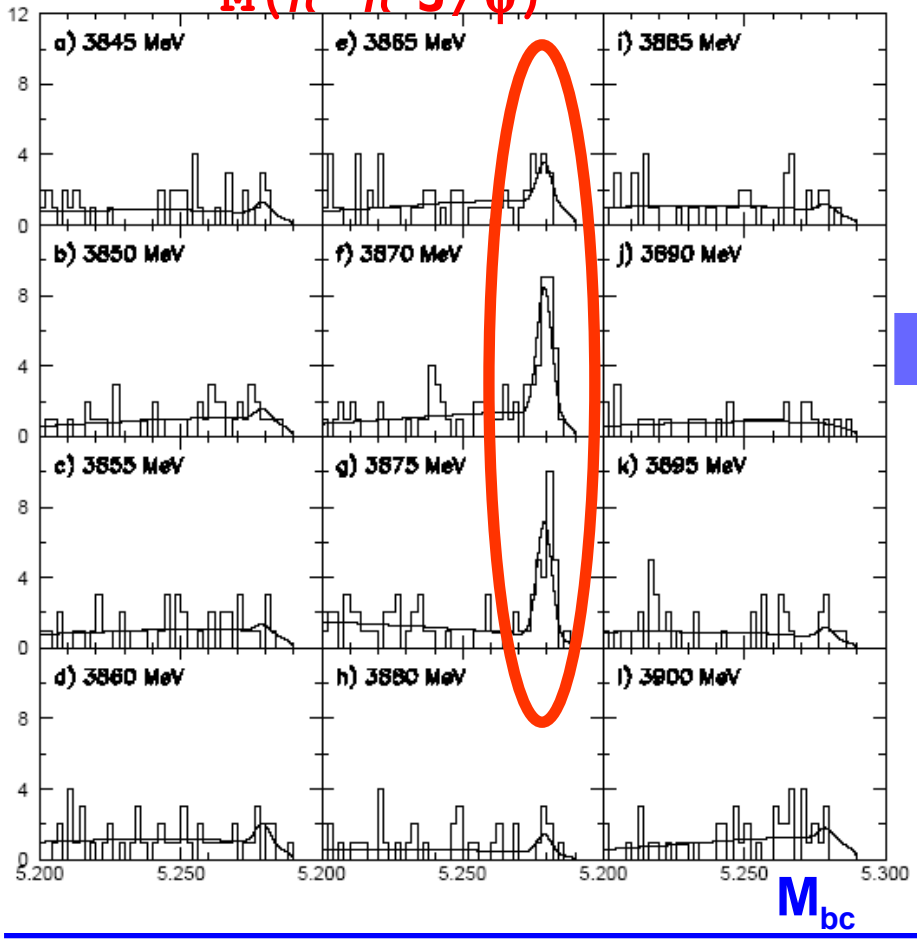
Belle : 152M BB
PRL 91, 262001 (2003)

$B^{\pm} \to K^{\pm} \pi^+ \pi^- J/\psi$ (X(3872)), $J/\psi \to \ell^+ \ell^-$





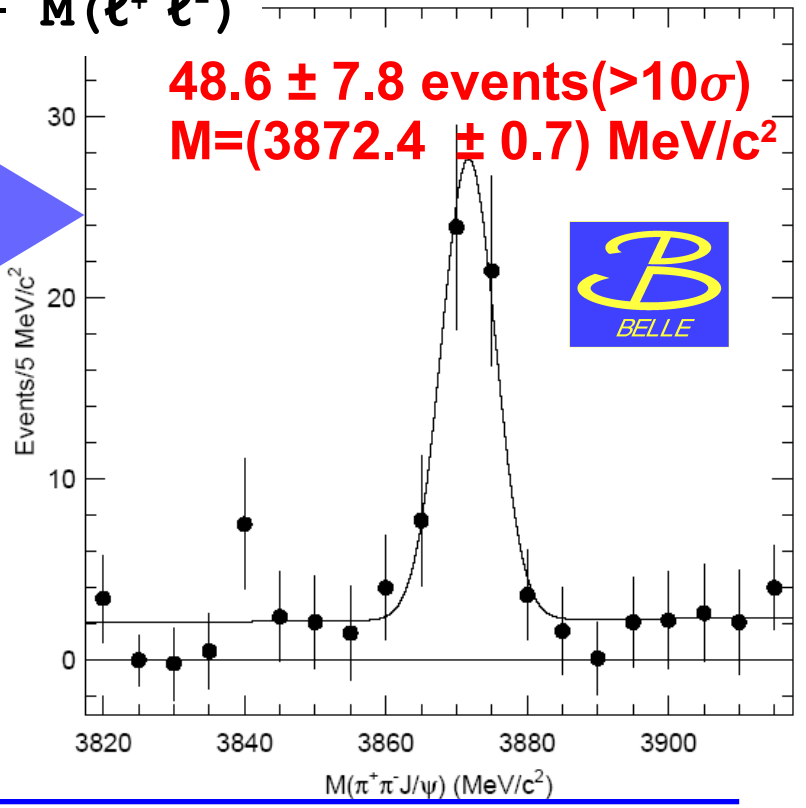
M_{bc} in 5 MeV wide intervals of $M(\pi^+ \pi^- J/\psi)$



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

Extracted # of. B decays in each interval of $M(\pi^+ \pi^- \ell^+ \ell^-)$

48.6 ± 7.8 events(>10σ)
M=(3872.4 ± 0.7) MeV/c²



X(3872) continued (reminder)

- Confirmed by BaBar, CDF, D0

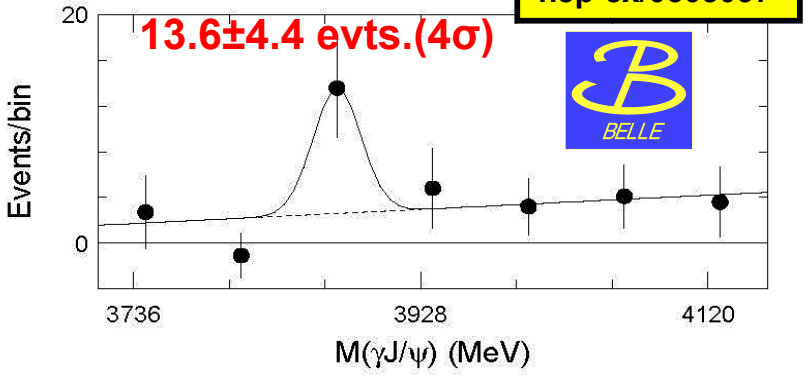
World average: $M_X = (3871.2 \pm 0.5)$ MeV/c^2

$\Gamma < 2.3$ MeV at 90% CL

- Near threshold: $M_X - m(D^0) - m(\bar{D}^{*0})$ < 1MeV

$B^\pm \to K^\pm \gamma J/\psi$

Belle : 275M BB
hep-ex/0505037



- From $M(\pi^+\pi^-)$: clustering on high end

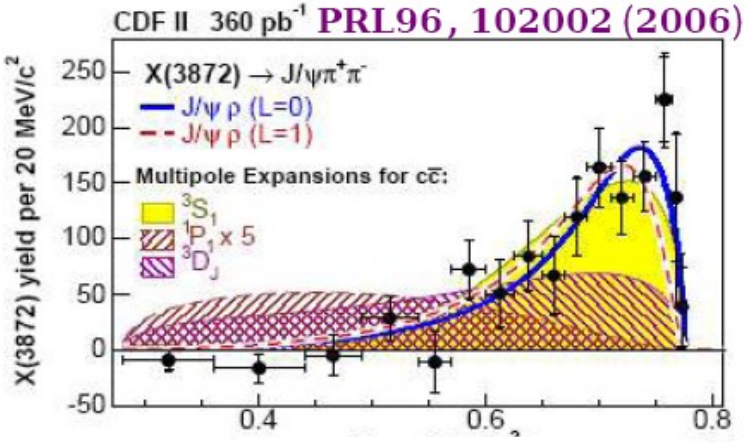
X(3872) → J/ψ ρ (S or P wave) (J = 1 or 2)

$$\frac{Br(X \to \gamma J/\psi)}{Br(X \to \pi^+ \pi^- J/\psi)} = 0.14 \pm 0.05$$

- Decay modes: J/ψγ (C=+1),

J/ψω and J/ψρ (isospin breaking)

$D\bar{D}\pi$ (but no $D\bar{D}$)



- From angular analysis, $M(\pi^+\pi^-)$,

observed decay modes:

favoured $J^{PC} = 1^{++}$ or 2^{-+} ; no $c\bar{c}$ candidate

X(3872): What is it?

- No obvious charmonium assignment ...

- Other possible interpretations:

➡ [cu][$\bar{c}\bar{u}$] or [cd][$\bar{c}\bar{d}$] tetraquark:

- Would require different mass of X produced in B^+ and B^0 decays.
- Charged X is predicted.

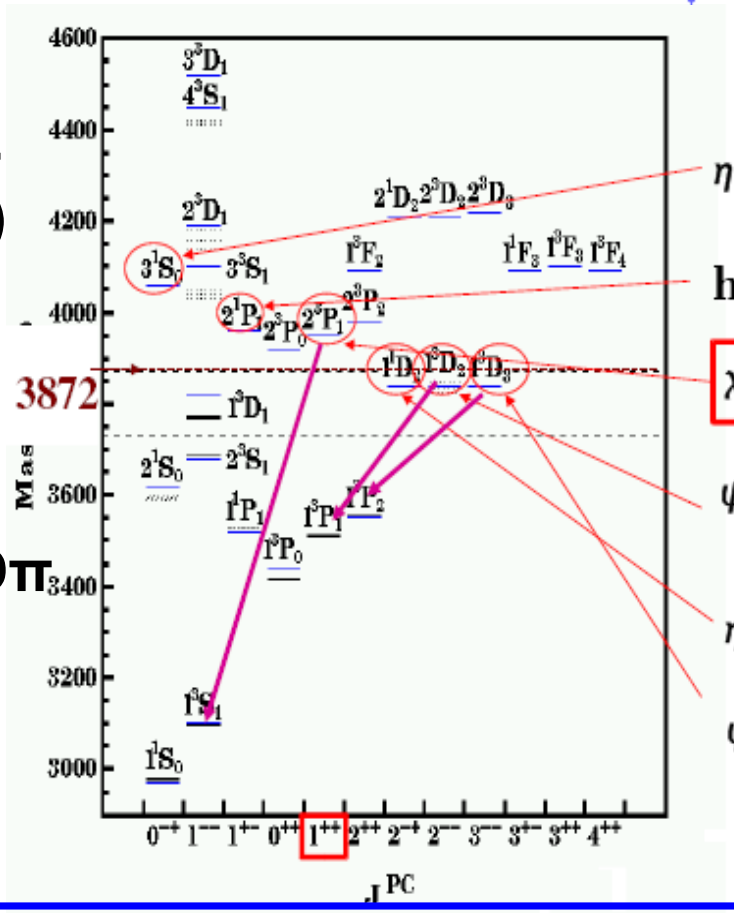
{ Maiani et al., PRD 71, 014028 (2005) }

→ So far no evidence (?)

➡ $D^{*0}\bar{D}^0$ molecule:

- $M_X \sim m(\bar{D}^0) + m(D^{*0})$
- Isospin breaking
- Favours $J/\psi\pi\pi$ over $DD\pi$
- Production in B^0 suppressed wrt. B^+

{ Braaten et al., hep-ph/0710.5482 }



hep-ex/0407033

η_c'' M too low and Γ too small

h_c' angular dist rules out 1^{+-}

χ_{c1}' $\Gamma(\gamma J/\psi)$ way too small

ψ_2 $\Gamma(\gamma\chi_{c1})$ too small
$M(\pi^+\pi^-)$ wrong

η_{c2} $\pi\pi\eta_c$ should dominate

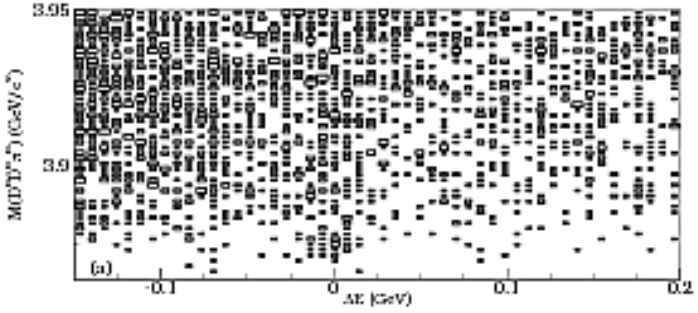
ψ_3 $\Gamma(\gamma\chi_{c2}\&\&D\bar{D})$ too small

X(3872): $D^0\bar{D}^0\pi^0$ decay mode

Belle : 447M BB
PRL 97, 162002 (2006)

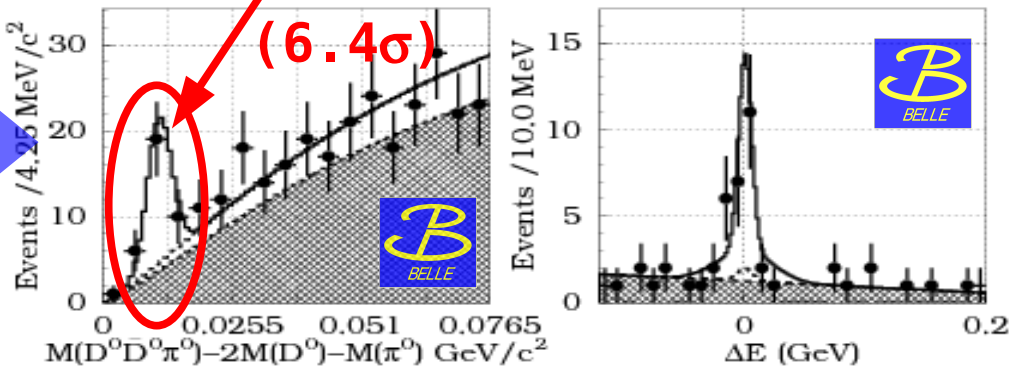
$B^+ \to K^+ D^0 \bar{D}^0 \pi^0 / B^0 \to K^0 D^0 \bar{D}^0 \pi^0$

$M(D^0\bar{D}^0\pi^0)$ and ΔE in B signal region



$M(D^0D^0\pi^0) \approx M(X)$

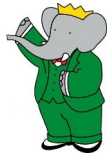
N=24.1 ± 6.1
(6.4σ)



$Br(B \to K D^0 \bar{D}^0 \pi^0) = (1.27 \pm 0.31^{+0.22}_{-0.39}) \times 10^{-4}$

$Br(X \to K D^0 \bar{D}^0 \pi^0 / Br(B^+ \to K^+ X) BR(X \to \pi^+\pi^- J/\psi) = 9.4^{+3.6}_{-4.3}$

- $M_{resonance} = (3875.4^{+1.2}_{-2.1})$ MeV/c² (Is it another X: X(3875)?)
- Supported by BaBar: $M_{resonance} = (3875.1^{+0.8}_{-0.7})$ MeV/c² (in $B \to K\bar{D}^{*0}D^0$; 383M $B\bar{B}$)



{ hep-ex/0708.1565 }

- Tetraquark interpretation {Maiani et al., hep-ph/0707.3354}:
  $[cu][\bar{c}\bar{u}] \to D^0\bar{D}^0\pi^0$ (X(3875)) ; $[cd][\bar{c}\bar{d}] \to J/\psi\pi^+\pi^-$ (X(3872))

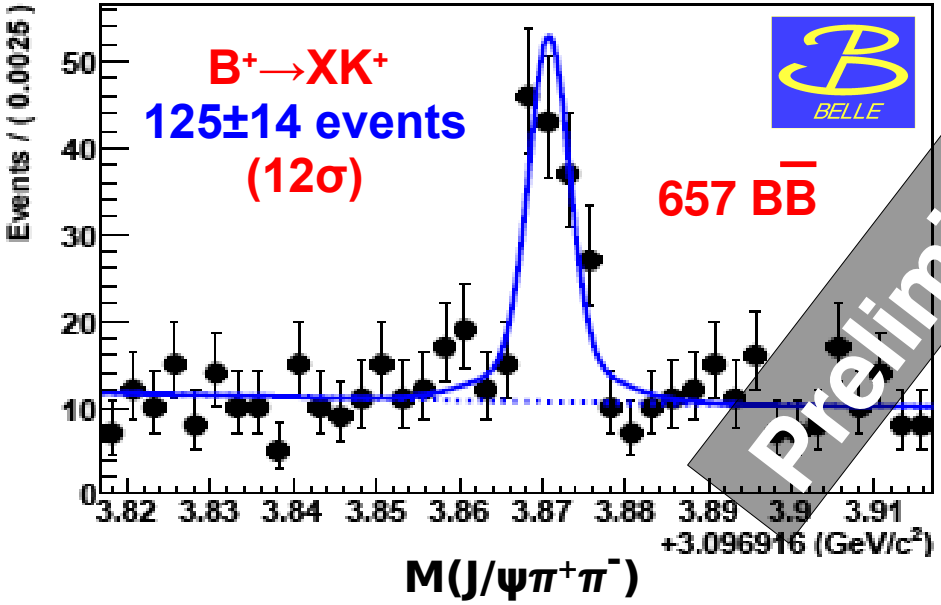
X(3872): recent news

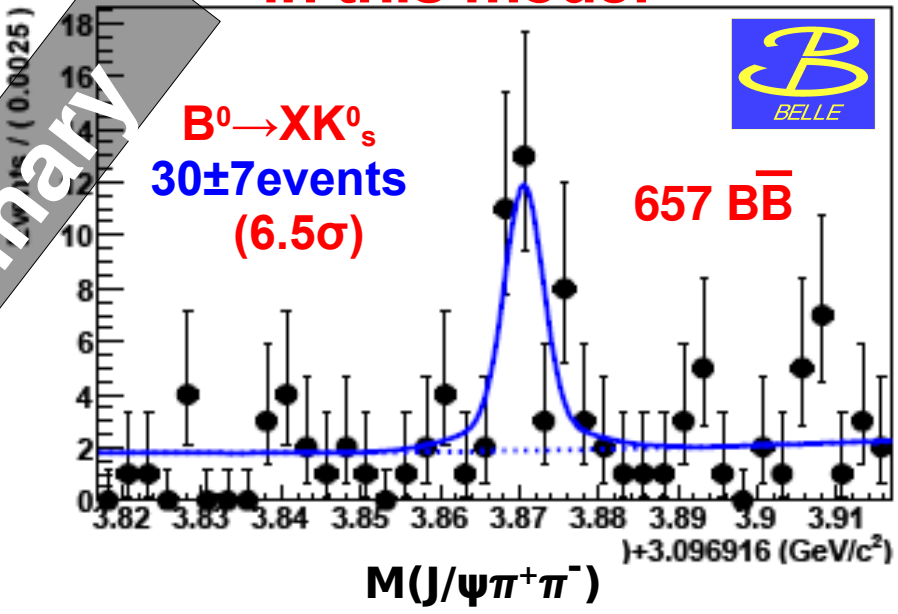
BELLE-CONF-0711
657 $B\bar{B}$

Now $X(3872)\to J/\psi\pi^+\pi^-$ is studied in $B^+\to XK^+$ and also in $B^0\to XK^0_S$

- **Applying ΔE and M_{bc} selection:**

First observation in this mode!





Preliminary

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

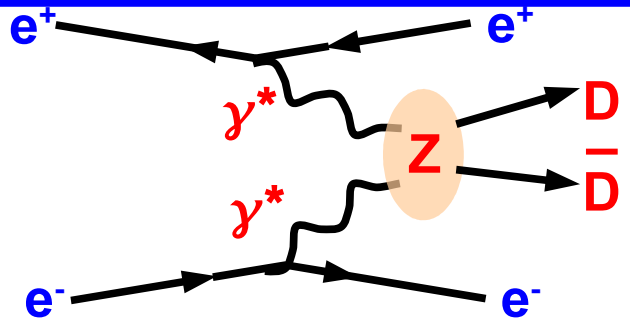
$\Delta M\sim 0$: Not really supported by the 4-q hypothesis

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

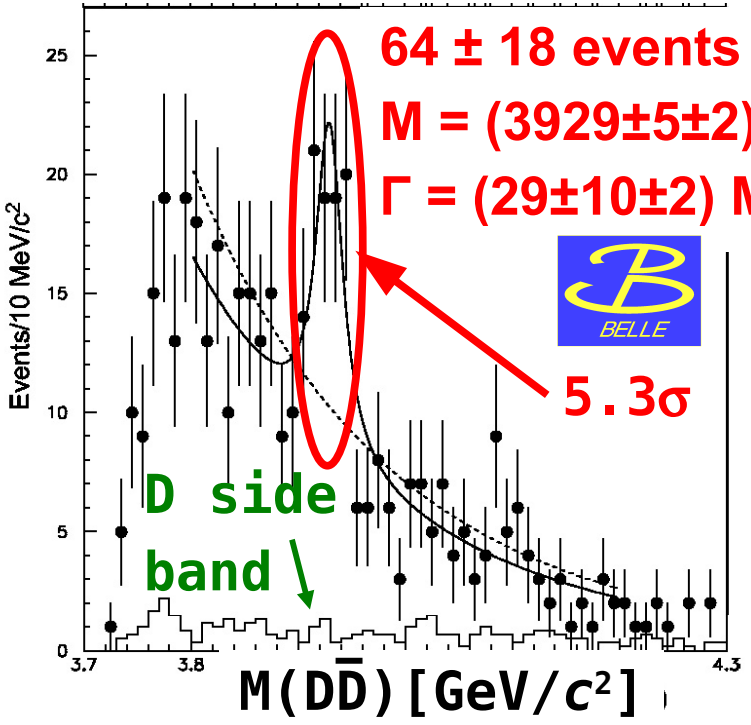
$R\sim 1$: Not really supported by the molecular interpretation

Z(3930): conventional cc (χ_{c2})

Belle : 395 fb^{-1}
PRL 96, 082003 (2006)



- un-tagged events (e^+,e^- undetected)
- $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
  $D^+ \to K^-\pi^+\pi^+$
- $p_t(D\bar{D}) < 0.05$ GeV/c

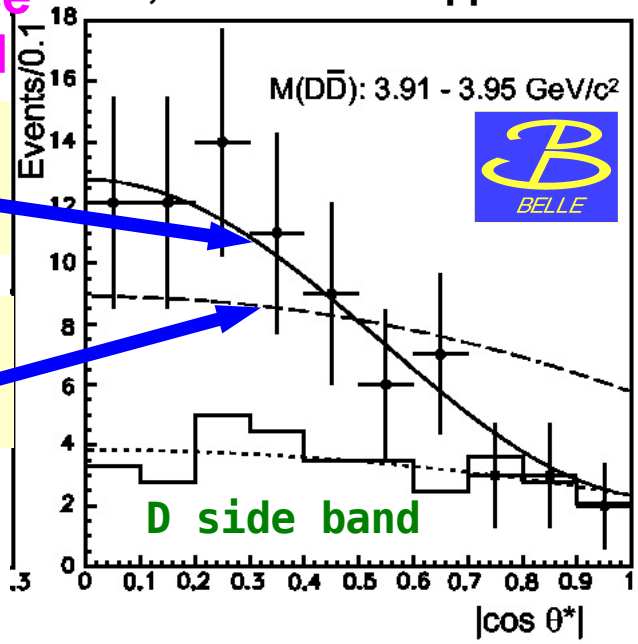


acceptance corrected

θ*: D, beam axis in γγ frame

J=2 expectation
χ^2/nof=1.9/9

J=0 expectation
χ^2/nof=23.4/9



$$\Gamma_{\gamma\gamma}(Z(3930))\,Br(Z(3930)\to D\bar{D}) = 0.18\pm0.05(stat.)\pm0.03(syst.)\ keV$$

$Z \equiv \chi_{c2}'$
2^3P_2 $c\bar{c}$

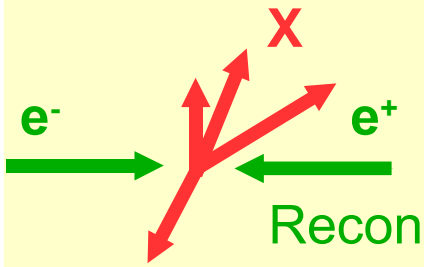
S.Godfrey,N.Isgur,PRD32,189 (1985)

C.R.Münz,Nucl.Phys.A609,364 (1996)

Double cc̄ production:J/ψ & C=+1 state

Belle : 357 fb^{-1}
PRL 98, 082001 (2007)

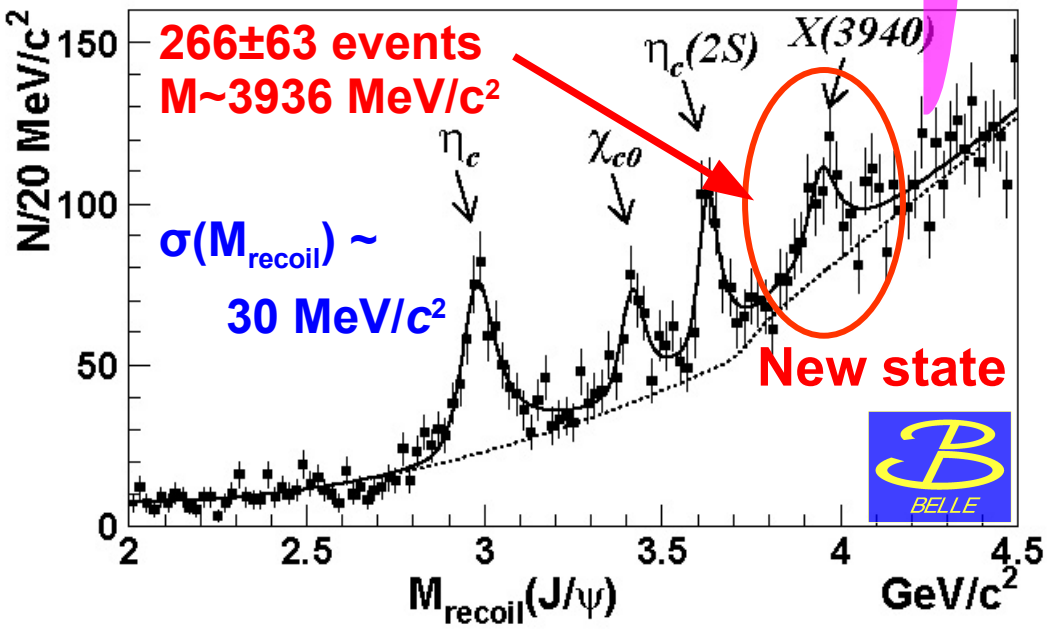
Inclusive production: charmonia factory



Reconstruct J/Ψ $\to \ell^+\ell^-$
(mass & vertex constrained fit)

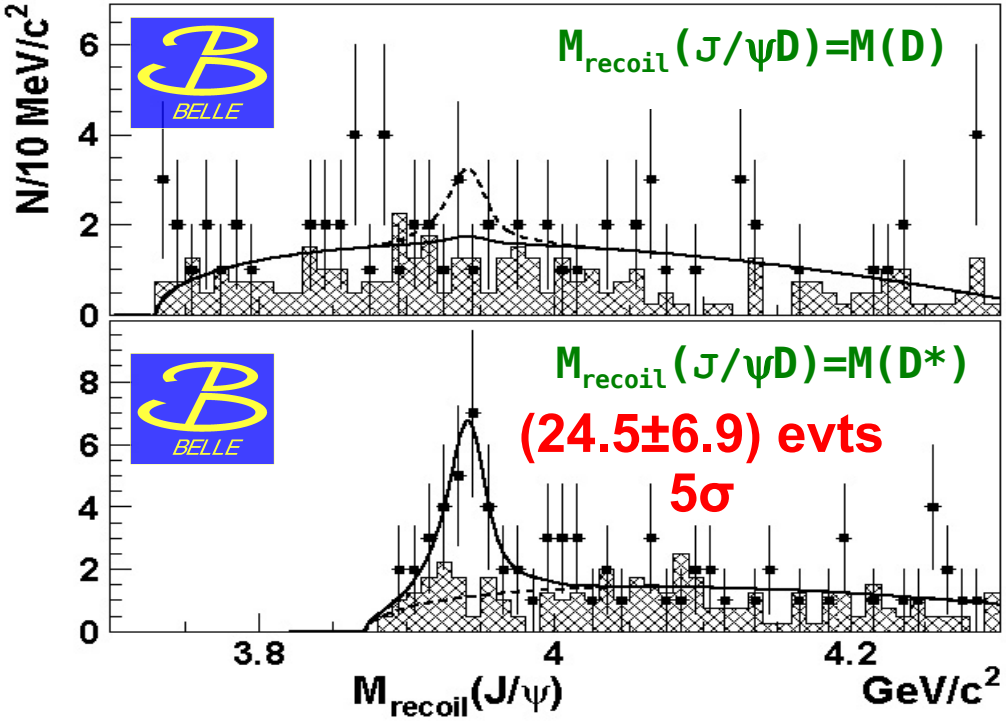
- **Recoil mass (mass of X):**

$$M_{recoil} = \sqrt{(E_{cms} - E^*_{J/\psi})^2 - p^{*2}_{J/\psi}}$$



X(3940)→D$^{(*)}$D̄ ?

- **reconstruct J/Ψ + only one D**
  (to increase reconstruction efficiency)
- **constrain M $_{recoil}$(J/Ψ D)=M(D$^{(*)}$)**
  (to improve resolution: σ(M $_{recoil}$(J/ψ))~10 MeV/c²)

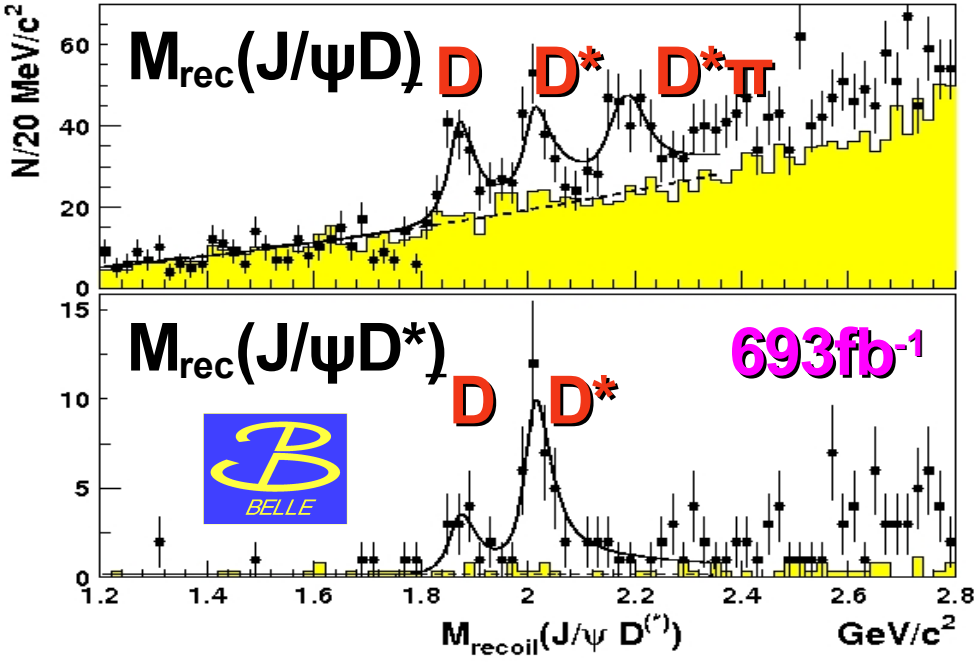


M=(3943±6±6) MeV/c²
Γ < 52 MeV @90% C.L.

Double $c\bar{c}$ production: recent update

PRL 100, 202001(2008)
693 fb^{-1}

- Used the established method to look for the $D^{(*)}\bar{D}^{(*)}$ resonances in $e^+e^- \to J/\psi\, D^{(*)}\bar{D}^{(*)}$ with larger statistics ...
- Reconstruct J/Ψ+$D^{(*)}$: Accompanying $D^{(*)}$ peaks seen in $M_{recoil}(J/\Psi\, D^{(*)})$ dist.
- Processes tagged this way: $J/\Psi DD$, $J/\Psi DD^*$, $J/\Psi D^*D^*$, $J/\Psi D^*D$,$J/\Psi D^*D^*$ (all > 5σ)

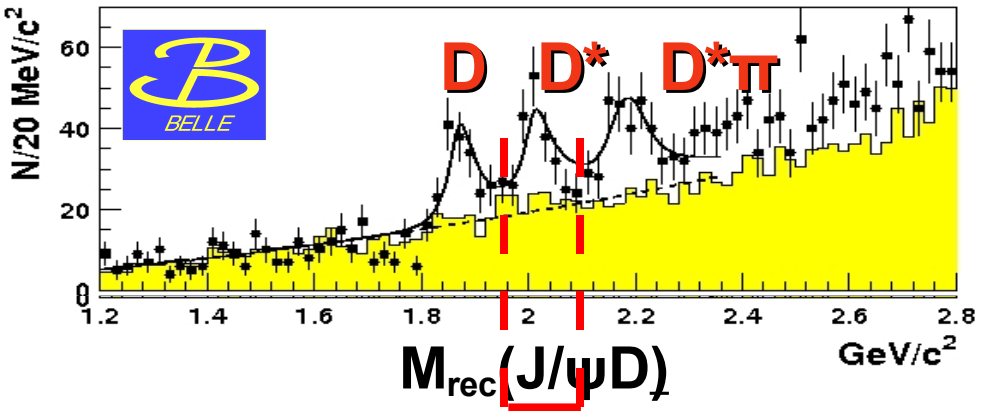


	$J/\psi D_{\rm rec}$		$J/\psi D^*_{\rm rec}$	
	N	$\mathcal{N}_\sigma$	N	$\mathcal{N}_\sigma$
$J/\psi D\bar{D}$	162 ± 25	7.6	—	—
$J/\psi D^*\bar{D}$	159 ± 28	6.5	$19.0\ ^{+6.3}_{-5.3}$	5.8
$J/\psi D^*\bar{D}^*$	173 ± 32	5.6	$47.2\ ^{+8.5}_{-7.8}$	8.4

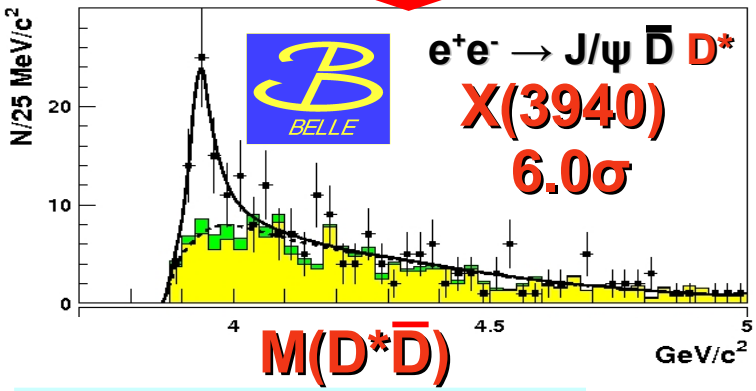
- Constrain $M_{recoil}(J/\Psi\, D^{(*)}) = M_{nominal}(D^{(*)})$ and look at $M_{recoil}(J/\Psi) = M_{recoil}(D^{(*)}\bar{D}^{(*)})$ distributions ...

Double cc̄ prod.: X(3940) and X(4160)

PRL 100, 202001(2008)
693 fb^{-1}



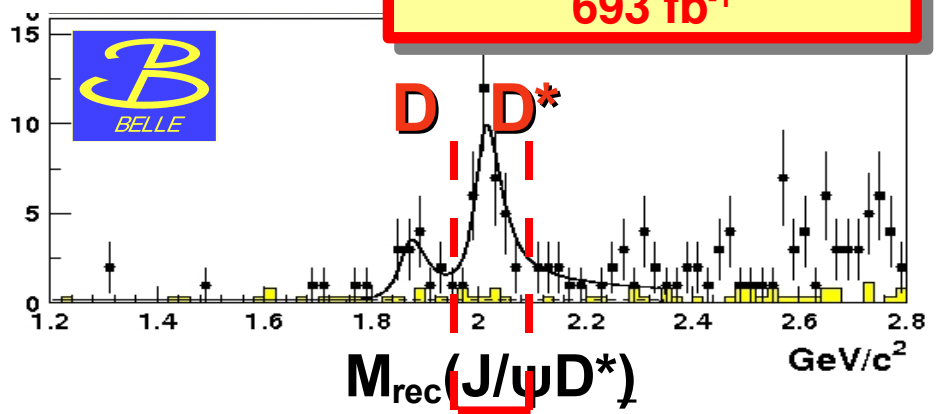
$M_{rec}(J/\psi D)$



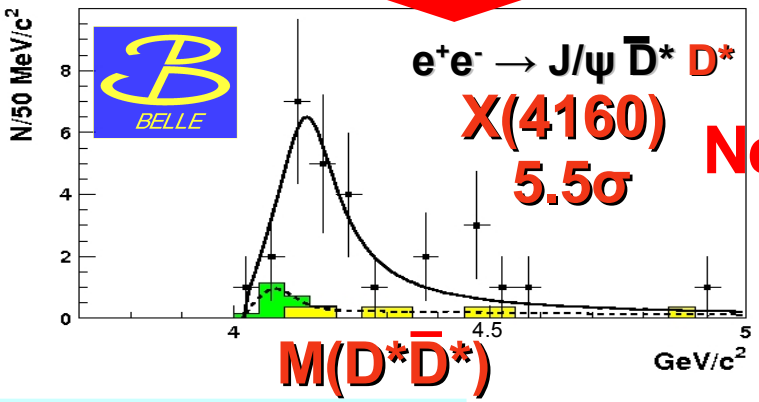
$M(D^*\bar{D})$

$M=(3942\ ^{+7}_{-6}\pm6)$MeV

$\Gamma=(37^{+26}_{-15}\pm12)$MeV



$M_{rec}(J/\psi D^*)$



$M(D^*\bar{D}^*)$

$M=(4156\ ^{+25}_{-20}\pm15)$MeV

$\Gamma=(139^{+111}_{-61}\pm21)$MeV

C_x=+1:
X(4160)≠ψ(4160)

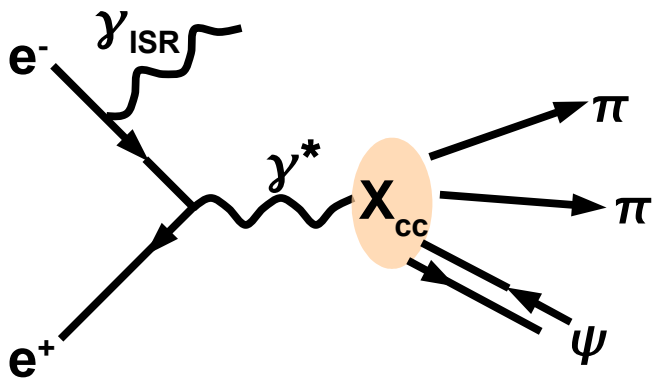
- **Possible assignments:** $\eta_c(3S)$, $\eta_c(4S)$, $\chi_{c0}(3P)$ (but masses 100-150 MeV too large)
- **Needed to be done:** angular analysis; search in $\gamma\gamma\rightarrow DD^*$, D^*D^*

Study of 1^{--} states with ISR

- ISR gives access to $J^{PC} = 1^{--}$ states
- Information on 1^{--} charmonia above the open-charm threshold
- Exclusive hadronic cross sections at $\sqrt{s} < E_{cms}$ can be successfully performed at B-factories:

  ISR enables wide energy range,

  high luminosity "compensates" for the emission of hard photons
- Y(4260) observed via ISR by BaBar, later confirmed by CLEO



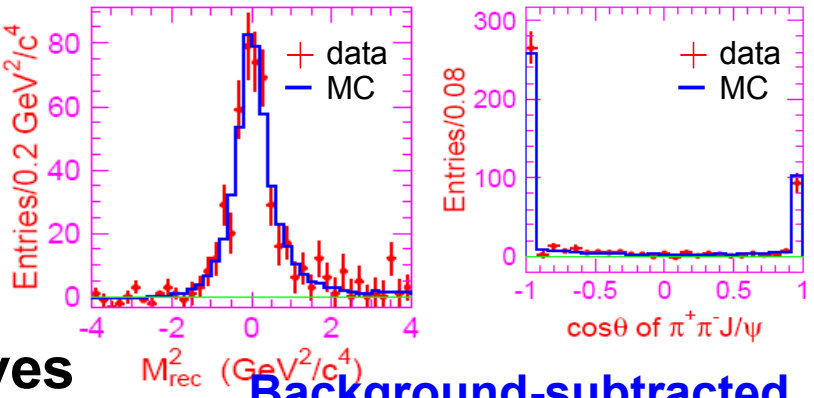
➡ Using BaBar's approach and large collected statistics Belle reports new results for these 1^{--} mesons

Study of 1^{--} states in $e^+e^- \to \gamma_{ISR} J/\psi\pi^+\pi^-$

PRL 99, 182004 (2007)
548 fb-1

- Study of $e^+e^- \to \gamma_{ISR} J/\psi\pi^+\pi^-$
- Reconstruction: $\pi^+\pi^-$ & $J/\psi(\to e^+e^-, \mu^+\mu^-)$
  (no extra tracks allowed; γ_{ISR} not detected)
- Missing(rec.) mass identifies ISR process:

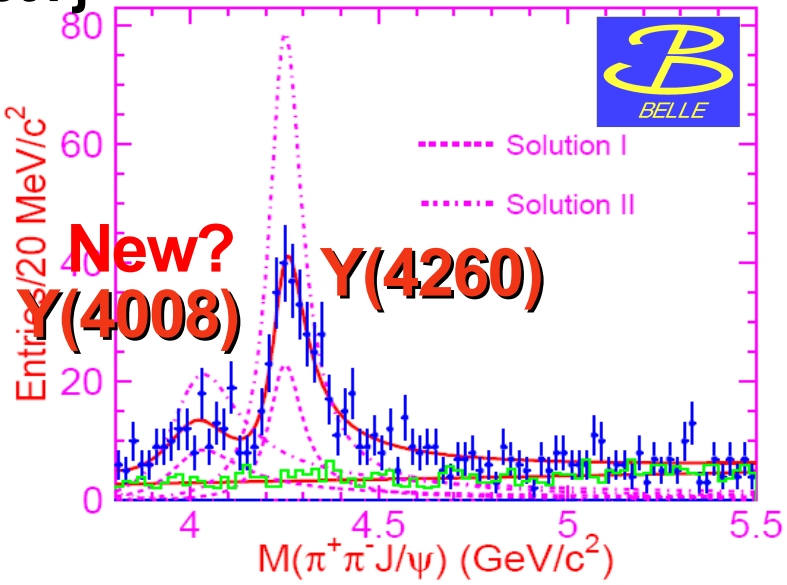
$$M_{rec} = \sqrt{(E_{cms} - E^*_{J/\psi\pi^+\pi^-})^2 - p^{*\,2}_{J/\psi\pi^+\pi^-}}$$



Background-subtracted distributions (MC check)

- Fit to M(J/ψπ⁺π⁻) with two coherent BW curves
- Y(4260) confirmed (discovered by BaBar)
- New Y(4008) resonance? { Might be: 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	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$



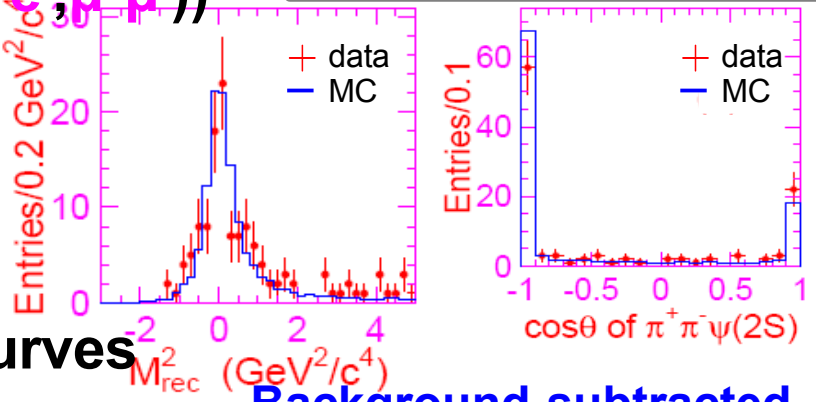
Study of 1^{--} states in $e^+e^- \to \gamma_{ISR} \psi' \pi^+\pi^-$

PRL 99, 142002 (2007)
673 fb-1

- Study of $e^+e^- \to \gamma_{ISR}\, \psi(2S)\pi^+\pi^-$
- Reconstruction: $\pi^+\pi^-$ & $\psi(2S)(\to \pi^+\pi^- J/\psi(\to e^+e^-, \mu^+\mu^-))$
  (no extra tracks allowed; γ_{ISR} not detected)
- Missing(rec.) mass identifies ISR process:

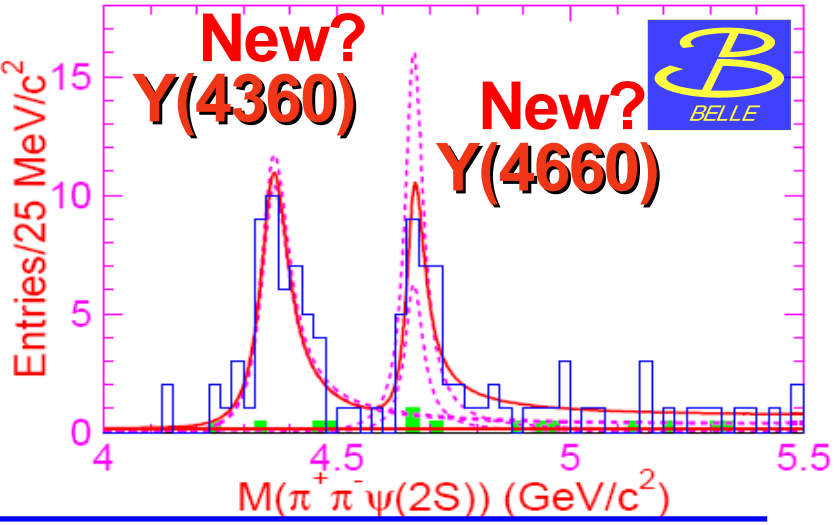
$$M_{rec} = \sqrt{(E_{cms} - E^*_{\psi(2S)\pi^+\pi^-})^2 - p^{*\,2}_{\psi(2S)\pi^+\pi^-}}$$

- Fit to M(ψ(2S)$\pi^+\pi^-$) with two coherent BW curves
- Y(4360) resonance:
  close to BaBar's (4324±24)MeV/c²), but narrower
- New Y(4660) resonance?



Background-subtracted distributions (MC check)

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



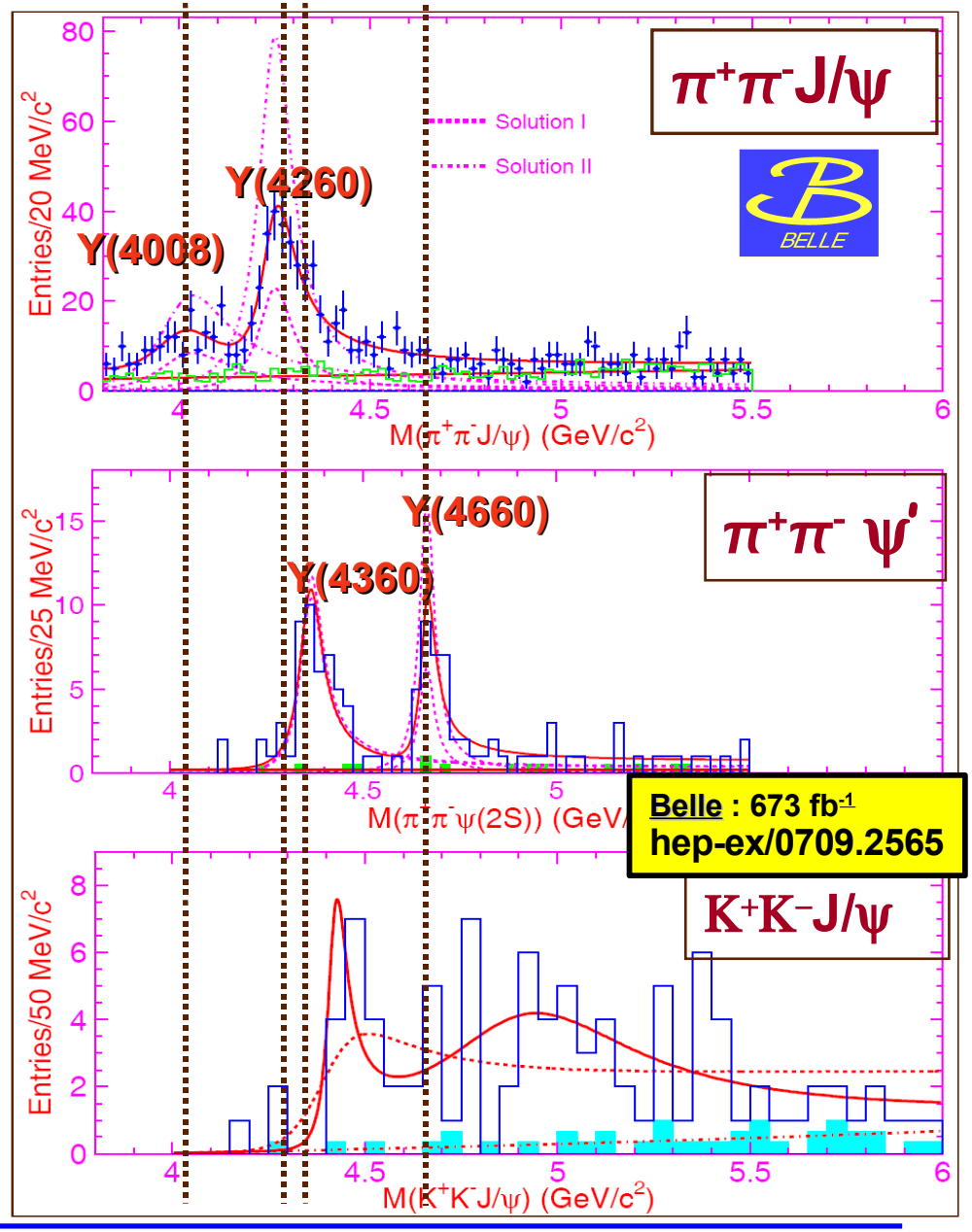
1^{--} Y states with ISR: What are they?

Charmonium options:

- Y states above $D\bar{D}$ threshold but don't match well the peaks in $D^{(*)}\bar{D}^{(*)}$ cross-sections
- Large widths for $\psi\pi\pi$ transition: not likely for conventional $c\bar{c}$
- No $c\bar{c}$ assignments available in this mass region (there are too many 1^{--} states)

Other options:

- Charm-meson threshold effects
- $D\bar{D}_1$ or $D^*\bar{D}_0$ molecules
- $cq\bar{c}q$ tetraquarks
- $c\bar{c}g$ hybrids predicted@4.2-5GeV $D\bar{D}_1$ mode should dominate
- Coupled-channel effects



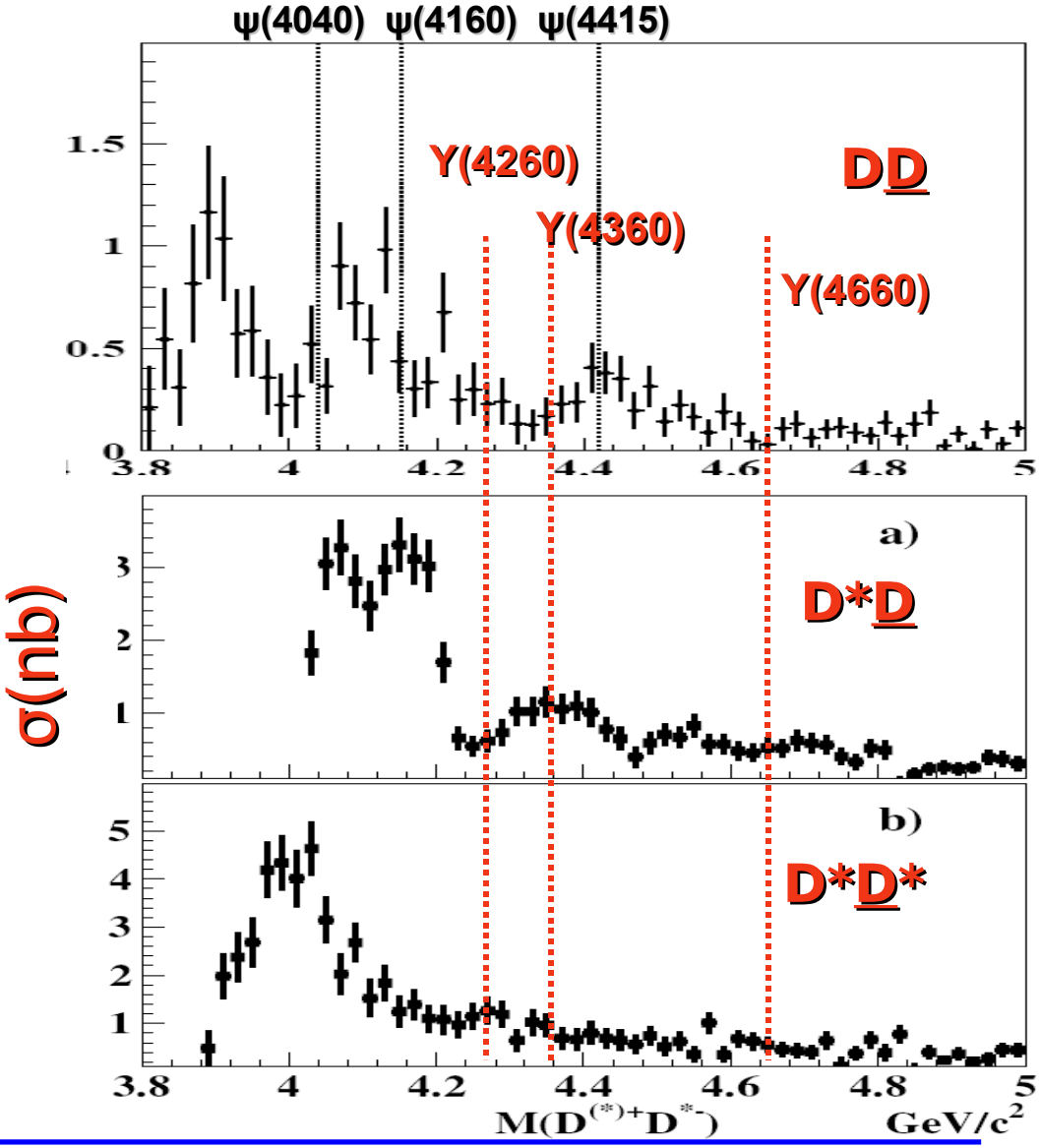
Exclusive $D^{(*)}D^{(*)}$ cross sections w. ISR

PRL 98, 092001 (2007) 548 fb-1

PRD 77, 011103 (2008) 673 fb-1

- $e^+e^- \to D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ cross sections measured with ISR
- $D\bar{D}^*$, $D^*\bar{D}^*$: using partial reconstruction; γ_{ISR} detected

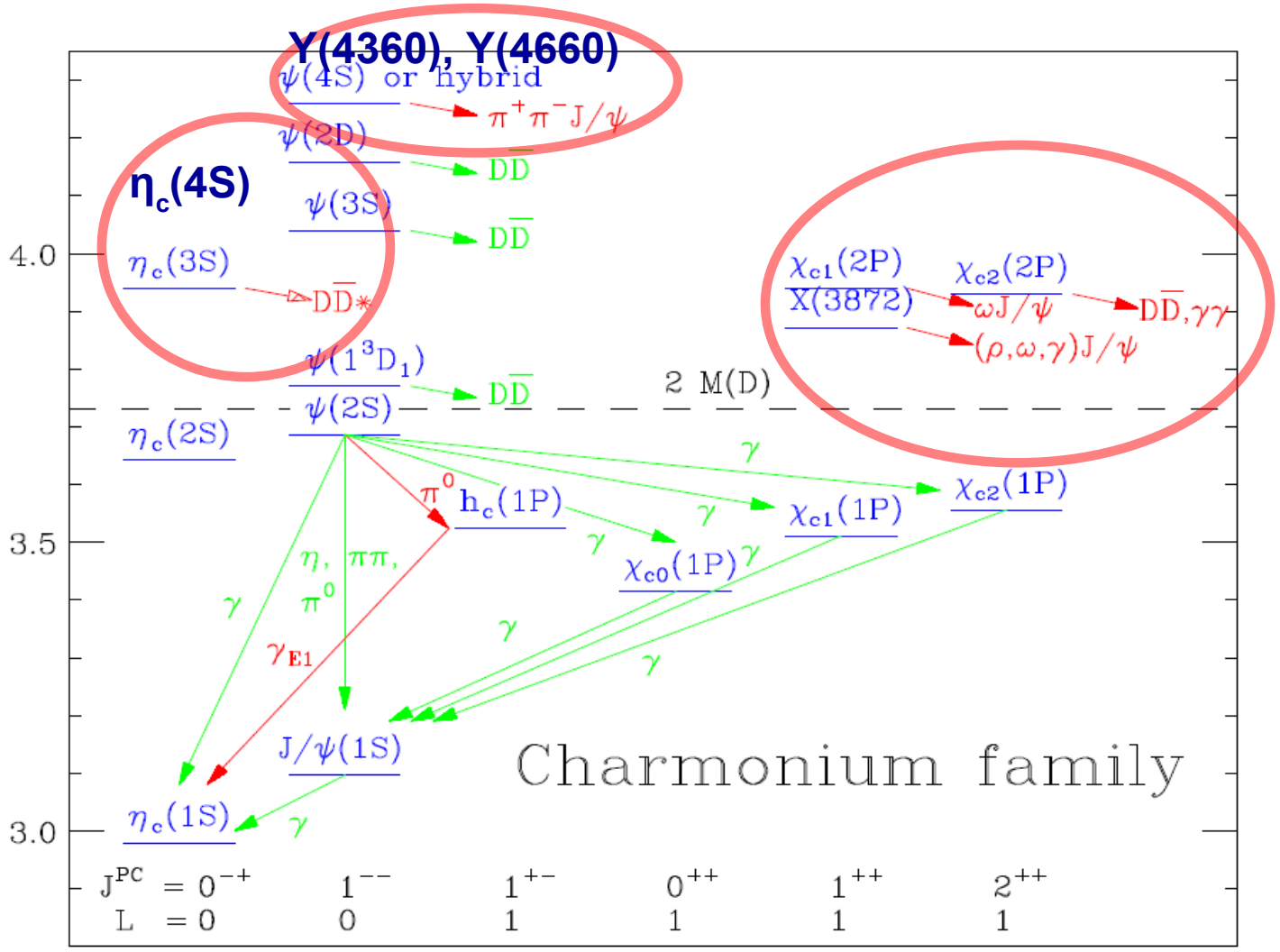
  $D\bar{D}$: fully reconstructed; γ_{ISR} used if detected
- Recoil mass is again used to identify ISR events
- Method is well established
- Difficult interpretation in terms of resonances (there are many maxima/minima, model dependent coupled-chann and threshold effects…)



Charmonium spectroscopy update

Few new states added...

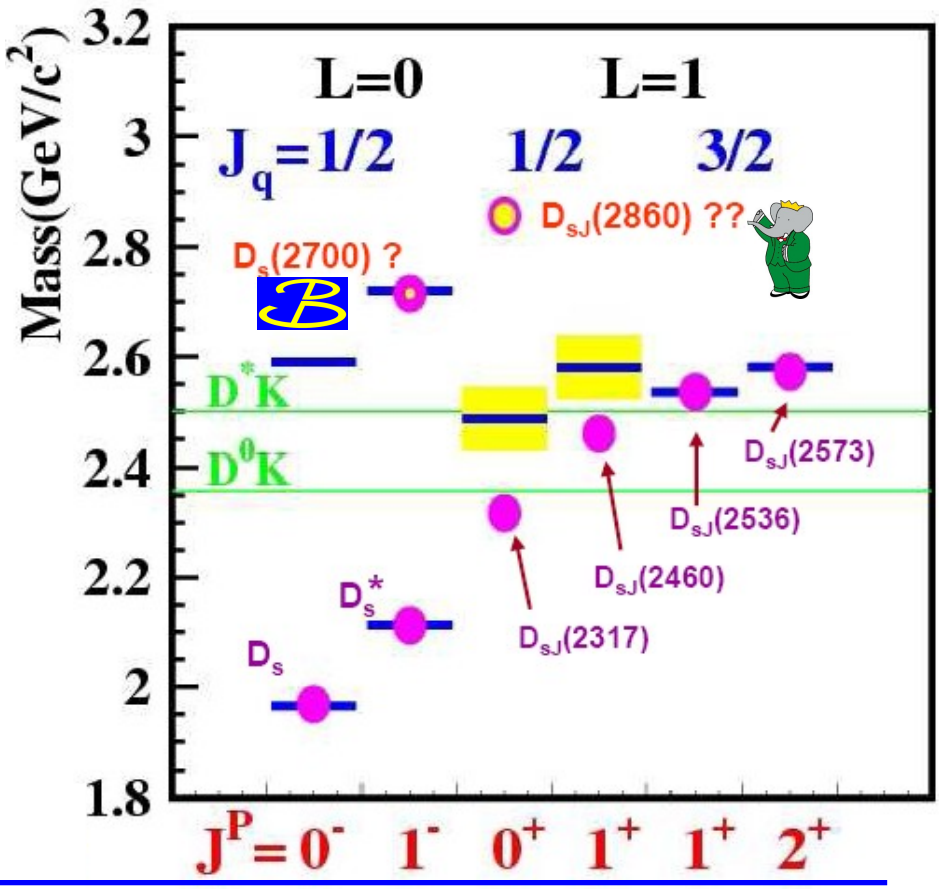
... but we still do not understand them ...



Summary and conclusions

Summary and conclusions

- D_{sJ} states :
  - ➡ $D_{s0}^{*}(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$ better understood, but mass shift not clear yet ...
  - ➡ New D_{sJ} state observed in $B \to \bar{D}^0 D^0 K^+$: $D_{sJ}(2700)^+ \to D^0 K^+$
  - ➡ $D_{s1}(2460)^{\pm}$ - $D_{s1}(2536)^{\pm}$ mixing? (HQET not so good ...)
  - ➡ New results eagerly awaited ...



Summary and conclusions

- **Charmonium(-like) states :**
  - ➡ Two radially excited conventional states: η_c' , χ_{c2}'
  - ➡ Following the X(3872) "tradition" of discoveries ...
    - ... New exotic state observed in $B \to \psi(2S)\pi^{\pm}K$ decays:
      $Z(4430)^+$ (charged charmonium-like state)
    - ... also Z_1^+ and Z_2^+ in $B^0 \to K^-\pi^+\chi_{c1}$ decays
  - ➡ New charmonium spectroscopy established at 4GeV?
    Good candidates for molecular states, multiquarks; hybrids; ...
    X(3872), $Z(4430)^+$, Z_1^+ and Z_2^+; Y(4260); ...
  - ➡ Same type of XYZ spectroscopy in b(s)-quark sector?
  - ➡ Many interesting results and new states come from Belle ...
    ... it is important that a lot of studies are still ongoing,
    so expect more exciting news soon ...

Supplementary material

Asymmetric-energy e^+e^- colliders

$E_{CMS} \sim m_{\Upsilon(4S)} c^2 = 10.58\ GeV$

$1.71 \times 10^{34}\ cm^{-2}s^{-1}$ (WR!)

9.0 GeV e^- (HER)

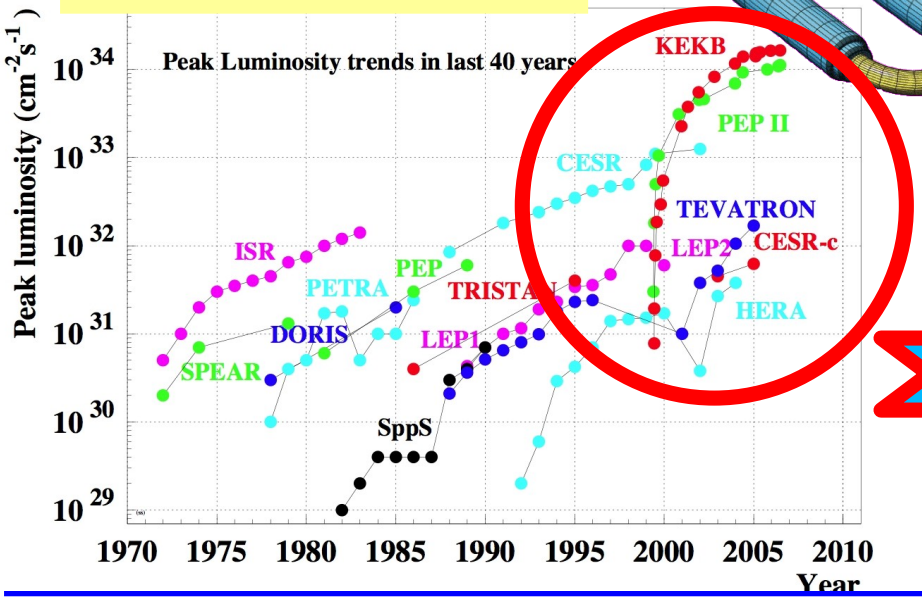
3.1 GeV e^+ (LER)

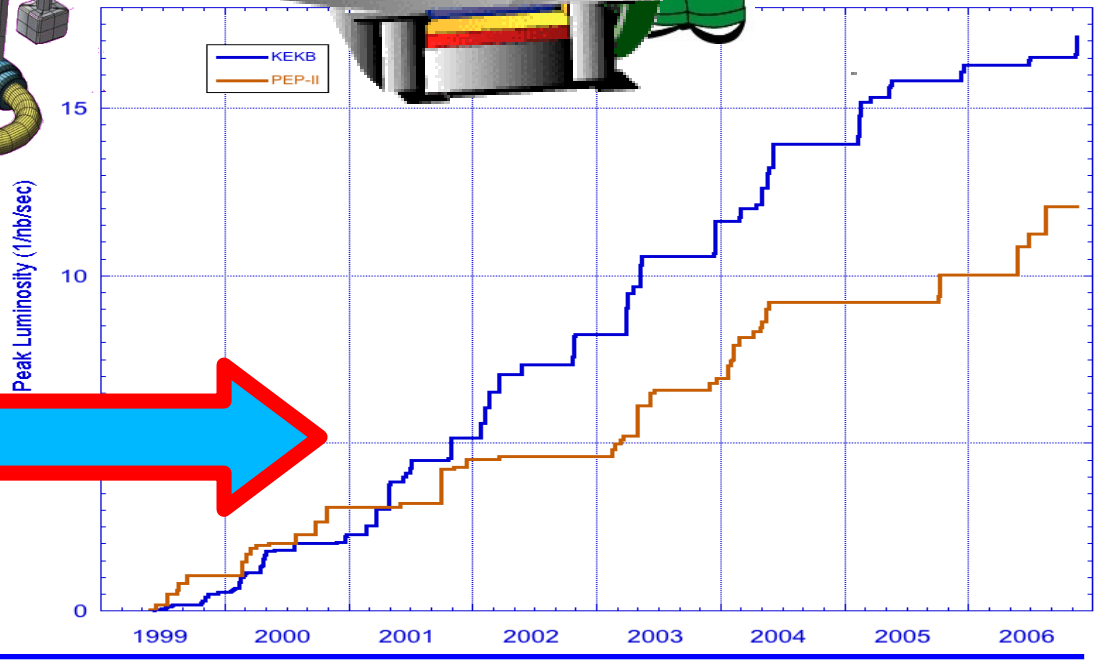
8.5 GeV e^- (HER)

3.5 GeV e^+ (LER)

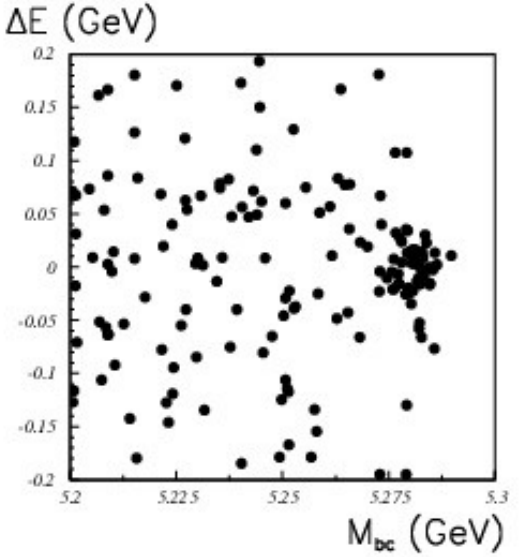
$1.21 \times 10^{34}\ cm^{-2}s^{-1}$

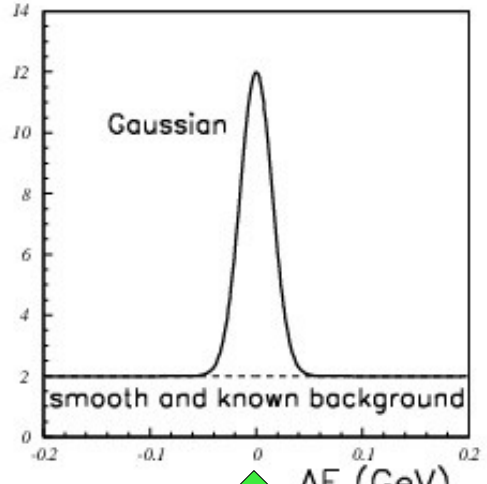
$Rate_i = Lumi. \times \sigma_i$

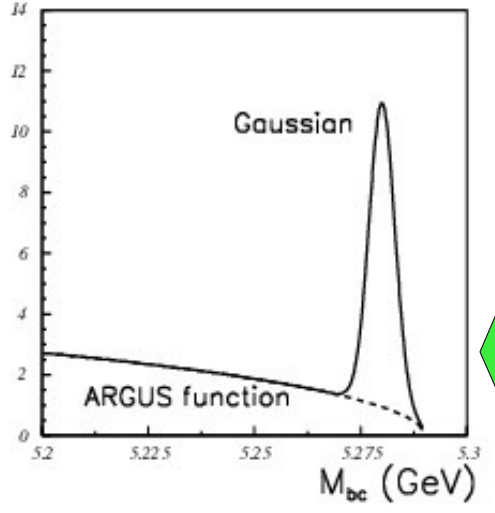


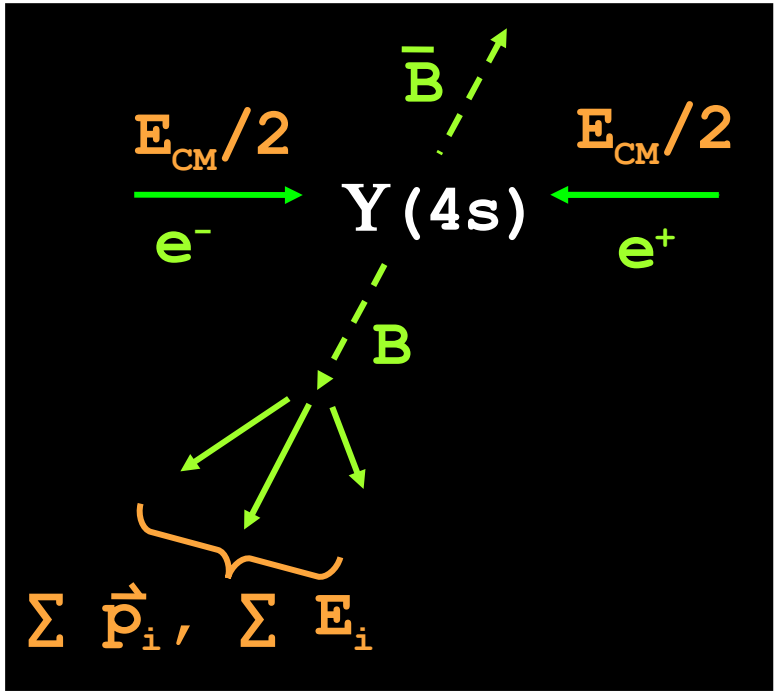


Analysis tools: B reconstruction









$$\Delta E \equiv \sum E_i - E_{CM}/2$$

$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

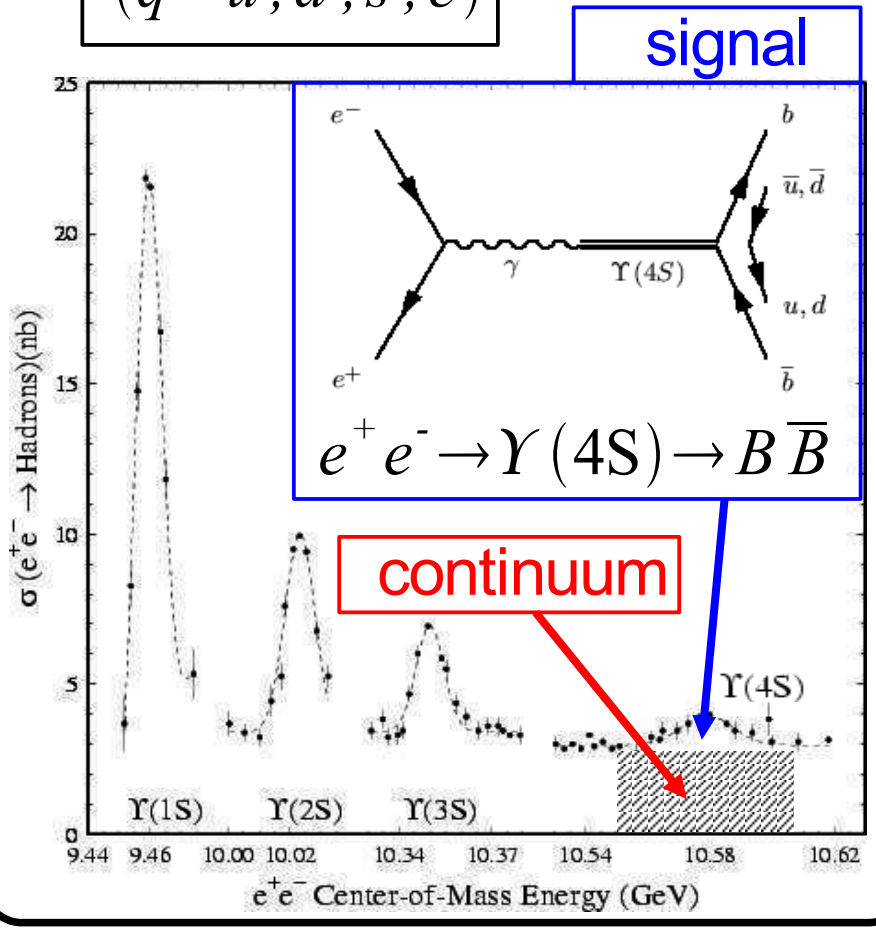
Reconstructing B meson decays at Y(4S):
use two variables,
beam constrained mass M_{bc}
and
energy difference ΔE

Continuum background suppresion

- **The background : ~ 3 x $B\overline{B}$**

"continuum"

$$e^+e^- \to q\bar{q}$$
$$(q = u, d, s, c)$$



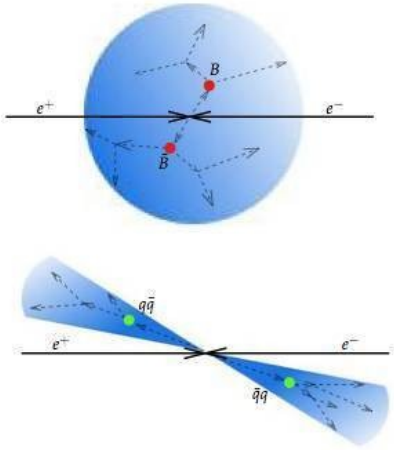
- **The event topology**

Spherical $B\overline{B}$

versus

Jet-like continuum

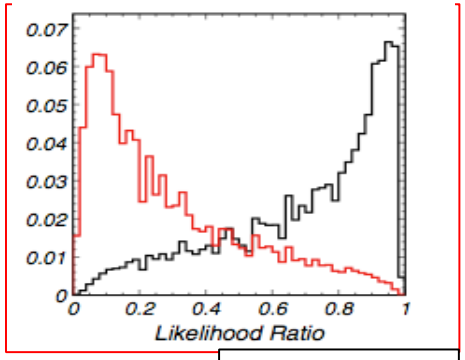
→ Fisher variable



- **B flight direction**

→ $\cos\theta_B$

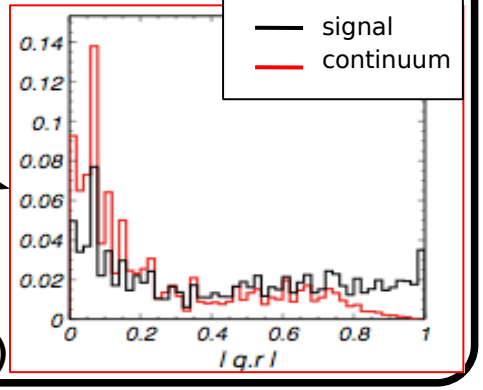
(**$B\overline{B}$: ~$\sin^2\theta_B$;cont. : flat**)



- **B-flavour tagging**

→ tag-quality parameter ***r***

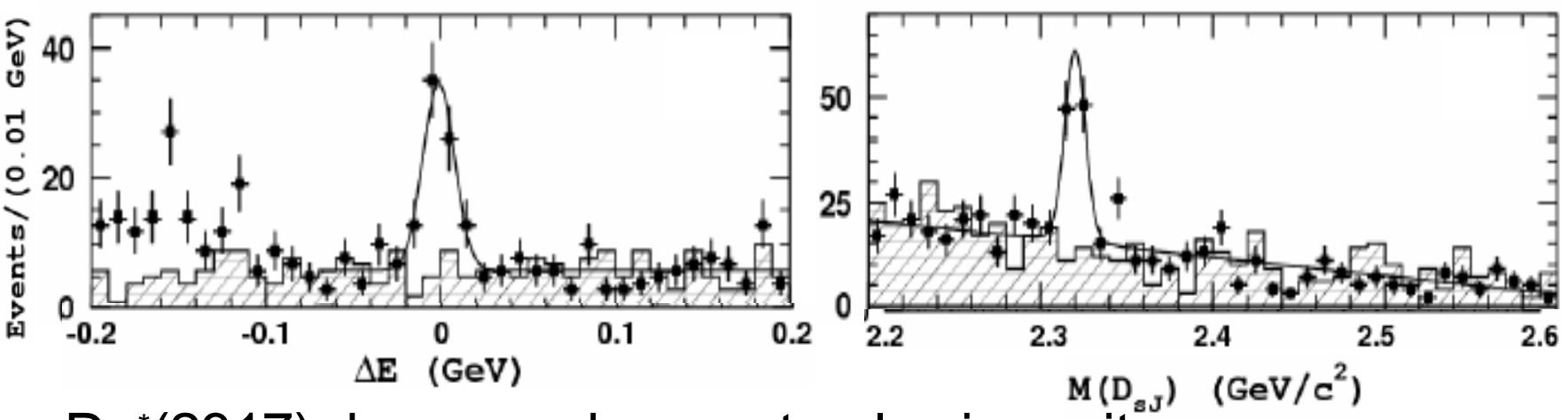
(≡ confidence that the other B meson's flavour *q* is correctly tagged)



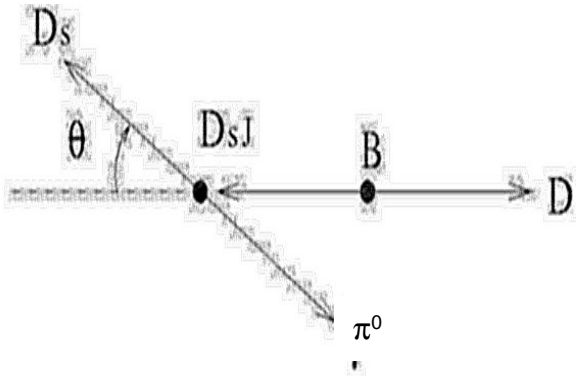
D_{sJ} states – updates from B decays

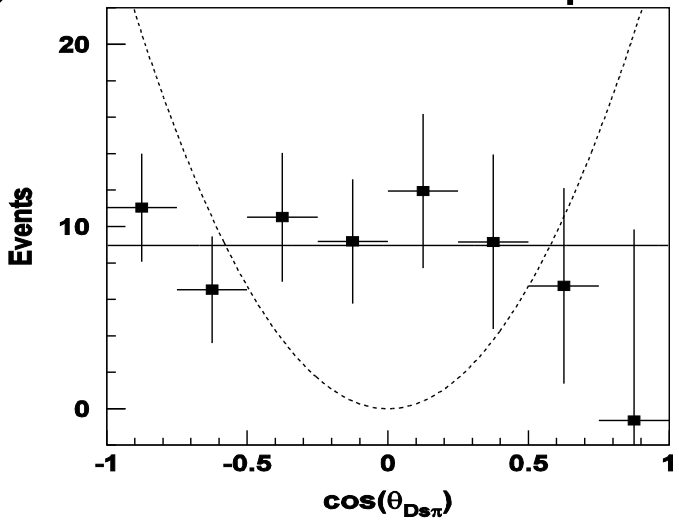
$B \to \bar{D}\ D_{sJ}^{*}(2317)^{+}$, $D_{sJ}^{*}(2317)^{+} \to \bar{D}_s^{+}\pi^0$

Belle: 274M BB
BELLE-CONF-0461 (2004)



- $D_{sJ}^{*}(2317)$ decay mode → natural spin-parity
- $D_{sJ}^{*}(2317)$ decay angular distribution → spin 0





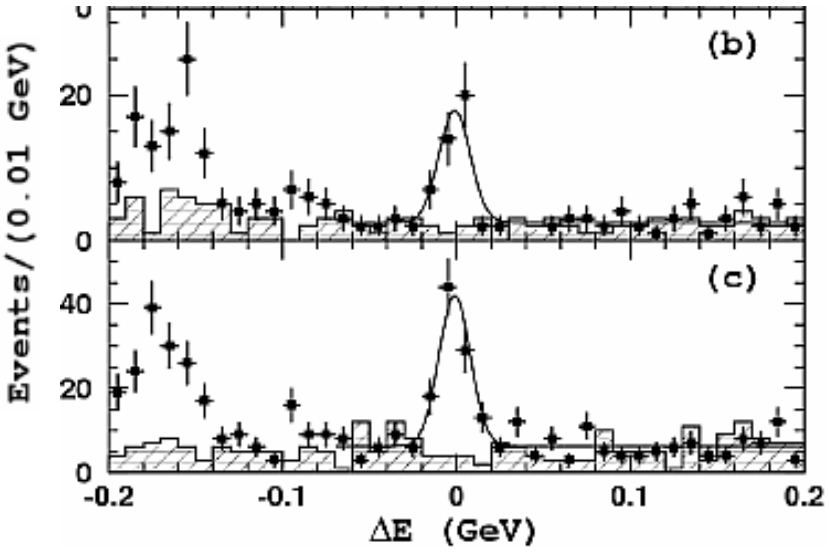
Dotted line:
J = 1
$\chi^2/_{d.o.f} = 38/8$

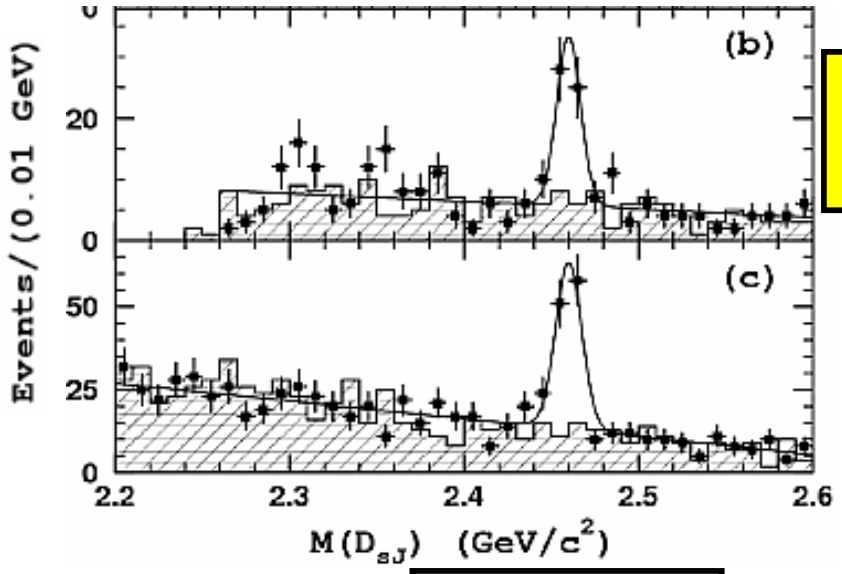
Solid line:
J = 0
$\chi^2/_{d.o.f} = 3/8$

Natural spin-parity
→ $\mathbf{J^P = 0^+}$

D_{sJ} states – updates from B decays

$B \to \overline{D}\, D_{sJ}(2460)^+$; (b)$D_{sJ}(2460)^+ \to D_s^+ \gamma$; (c)$D_{sJ}(2460)^+ \to D_s^{*}(2112)^+ \pi^0$, $D_s^{*+} \to D_s^+ \gamma$

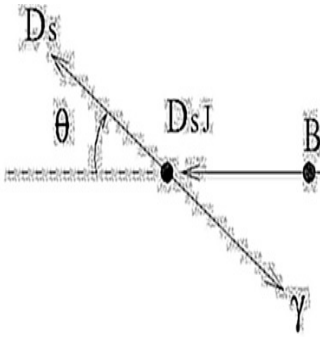




Belle: 274M $B\overline{B}$
BELLE-CONF-0461 (2004)

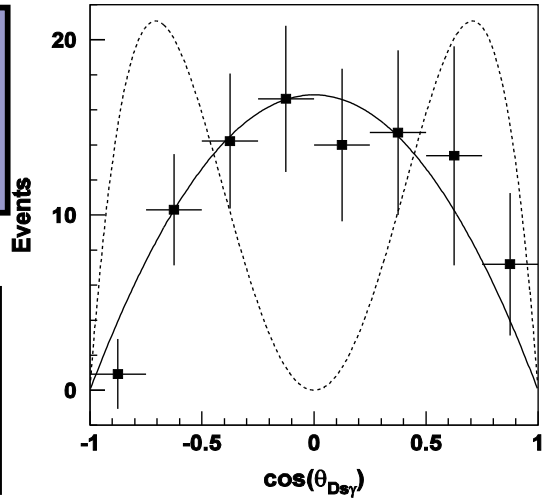
$D_s \gamma$ mode: absent, if J=0

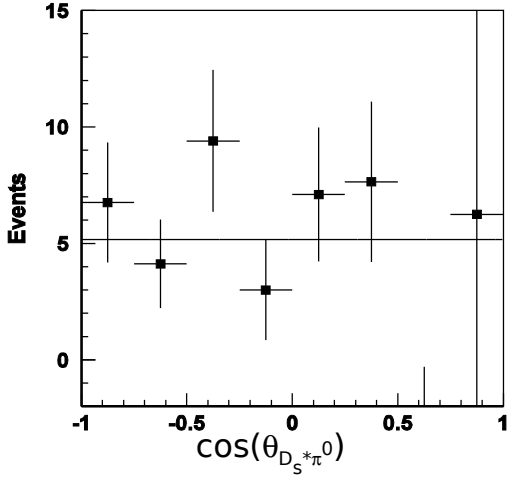
$D_s^{*}\pi^0$ mode



Dashed line:
J = 2
$\chi^2/_{d.o.f} = 89/8$

Solid line:
J = 1
$\chi^2/_{d.o.f} = 4/8$





Solid line:
J = 1
S-wave

$\to J^P = 1^+$

Z(4430)+ state: more info

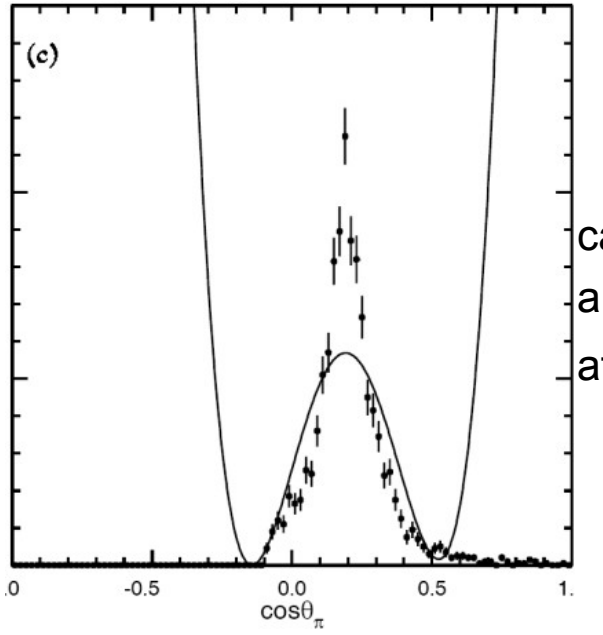
$Z^+(4430)$

S-, P-, D-wave interference:

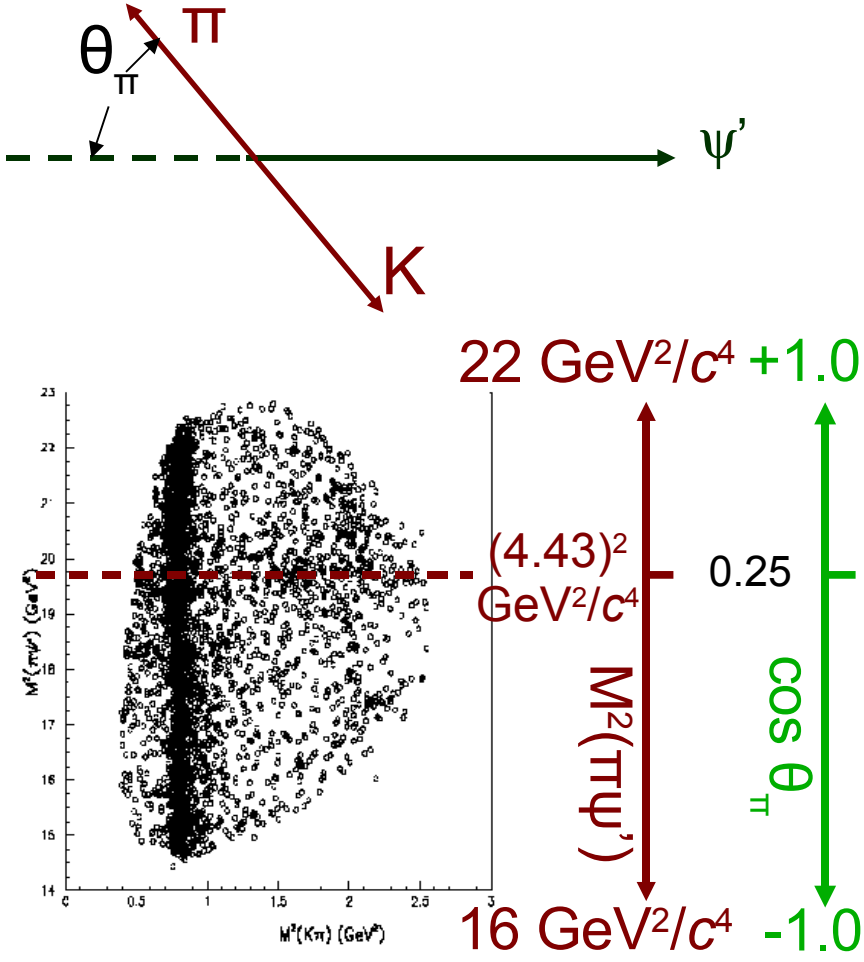
resonance	Longitudinal ψ'	Transverse ψ'
κ	constant	$--$
$K^*(890)$	$\cos\theta_\pi$	$\frac{1}{\sqrt{2}}\sin\theta_\pi$
$K_2^*(1430)$	$\frac{3}{2}\cos\theta_\pi^2 - \frac{1}{2}$	$\sqrt{\frac{3}{2}}\sin\theta_\pi\cos\theta_\pi$

interference

incoherent



cannot produce
a single narow peak
at $\cos\theta_\pi \sim 0.25$



Z_1^+ and Z_2^+ in $\bar{B}^0 \to K^- \pi^+ \chi_{c1}$ decays: fit

- data
- - - background
—— fit function
..... fit function without Z

Fit results: $M^2(\chi_{c1}\pi^+)$ projections in 4 $M^2(K^-\pi^+)$ bands

Null hypothesis:

all known K*'s;

poor fit :

C.L. $\leq 2*10^{-4}$

Add $Z \to \chi_{c1}\pi^+$:

signif. 10.7σ

$(\sqrt{(-2\ln L/L_0)})$,

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

$M_Z = (4150^{+31}_{-16})$ MeV/c^2

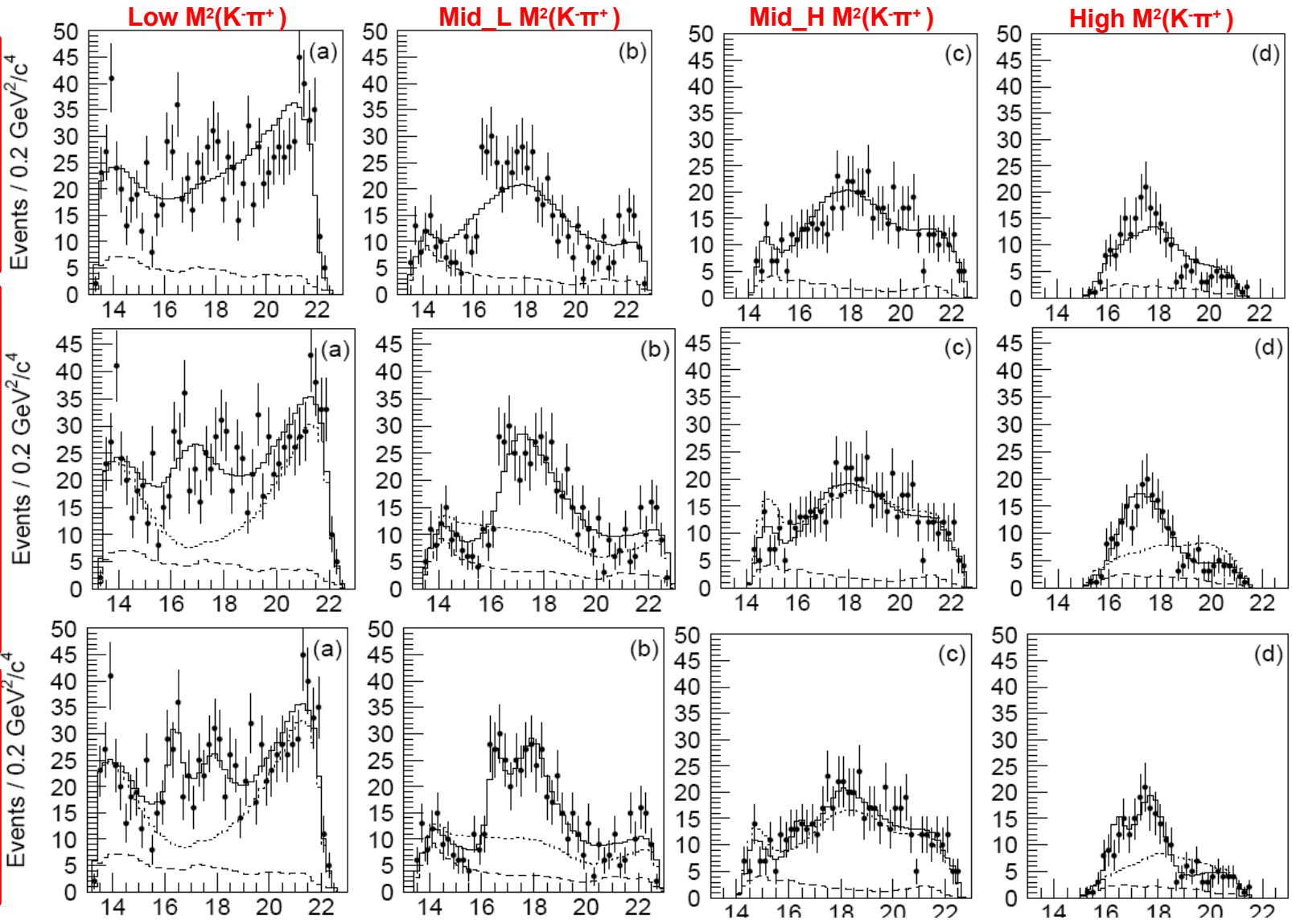
$\Gamma_Z = (352^{+99}_{-43})$ MeV

Two $Z \to \chi_{c1}\pi^+$:

signif. wrt 1 Z:

5.7σ,

C.L. = 0.4



Z_1^+ and Z_2^+ : fit fractions

	One Z^+		Two Z^+	
Contribution	Fit fraction	Signif.	Fit fraction	Signif.
$Z^+_{(1)}$	$(33.1^{+8.7}_{-5.8})\%$	$10.7\,\sigma$	$(8.0^{+3.8}_{-2.2})\%$	$5.7\,\sigma$
Z^+_2	–	–	$(10.4^{+6.1}_{-2.3})\%$	$5.7\,\sigma$
κ	$(1.9 \pm 1.8)\%$	$2.1\,\sigma$	$(3.6 \pm 2.6)\%$	$3.5\,\sigma$
$K^*(892)$	$(28.5 \pm 2.1)\%$	$10.6\,\sigma$	$(30.1 \pm 2.3)\%$	$9.8\,\sigma$
$K^*(1410)$	$(3.6 \pm 4.4)\%$	$1.3\,\sigma$	$(4.4 \pm 4.3)\%$	$2.0\,\sigma$
$K^*_0(1430)$	$(22.4 \pm 5.8)\%$	$3.4\,\sigma$	$(18.6 \pm 5.0)\%$	$4.5\,\sigma$
$K^*_2(1430)$	$(8.4 \pm 2.7)\%$	$5.2\,\sigma$	$(6.1 \pm 2.9)\%$	$5.4\,\sigma$
$K^*(1680)$	$(5.2 \pm 3.7)\%$	$2.2\,\sigma$	$(4.4 \pm 3.1)\%$	$2.4\,\sigma$
$K^*_3(1780)$	$(7.4 \pm 3.0)\%$	$3.6\,\sigma$	$(7.2 \pm 2.9)\%$	$3.8\,\sigma$
	110.5%		92.8%	

There is small net interference effect

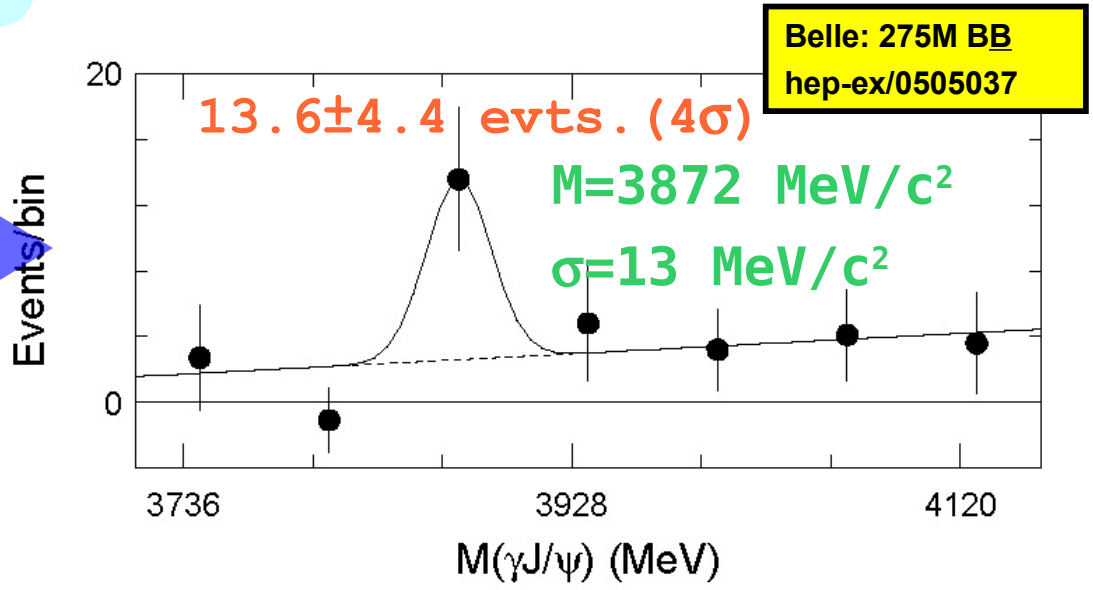
X(3872): properties (by Belle)

World average: M = (3871.2 ± 0.5) MeV/c^2
(PDG 2006) Γ < 2.3 MeV at 90% CL

$B^{\pm} \to K^{\pm} \gamma J/\psi$

$B^{\pm} \to K^{\pm} \chi_{c1}(\gamma J/\psi)$ as calibration mode, π^0 veto

Extracted # of B's in bins of $M(\gamma J/\psi)$



Belle: 275M BB
hep-ex/0505038

Br(B→XK) Br(X→ $\pi^+\pi^- J/\psi$) = (1.31 ± 0.24 ± 0.13) x 10^{-5}

charmonium, DD*, tetraquarks...?

$$\frac{Br(X \to \gamma J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 0.14 \pm 0.05$$

C(X(3872))=+1

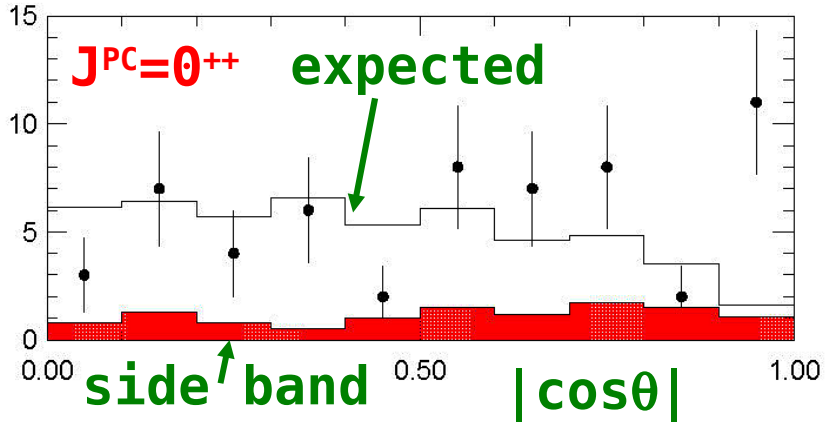
E.S.Swanson,PLB588,189(2004)
L.Maiani et al.,PRD71,014028(2005)

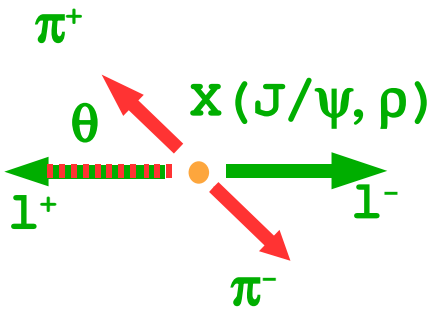
X(3872): properties (by Belle)

Angular distributions in $B^{\pm} \to K^{\pm} X(\pi^+\pi^- J/\psi)$

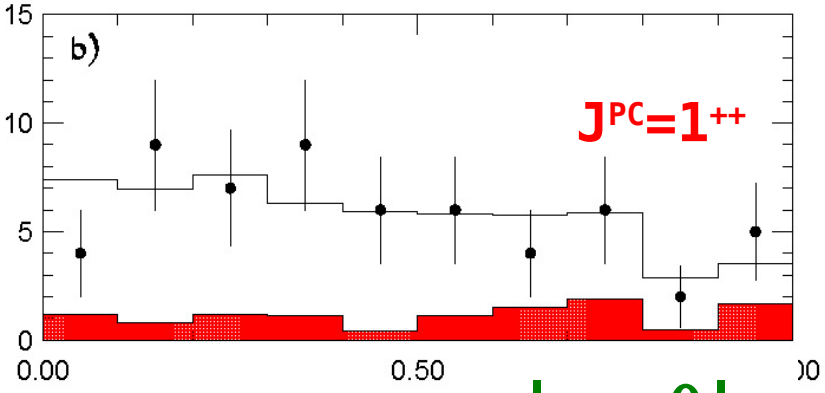
Belle: 275M BB̄
hep-ex/0505038

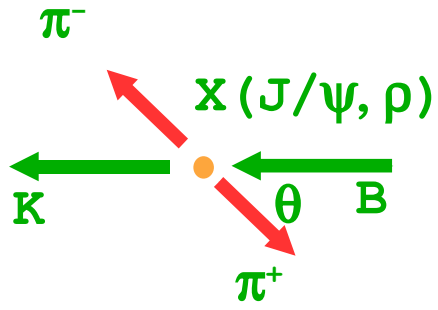
Examples:





$\chi^2/nof=31/9$





$\chi^2/nof=5/9$

X(3872)→ J/ψ ρ, S-wave

- X(3872)→γ J/ψ
- angular distribution
- M($\pi^+\pi^-$) in X(3872)→$\pi^+\pi^-$J/ψ

disfavour all of J=0,1,2 $c\bar{c}$ states

except

1^{++}, 2^{++}

X(3872)→$D^0\bar{D}^0\pi^0$??

1^{++} → DD* S-wave

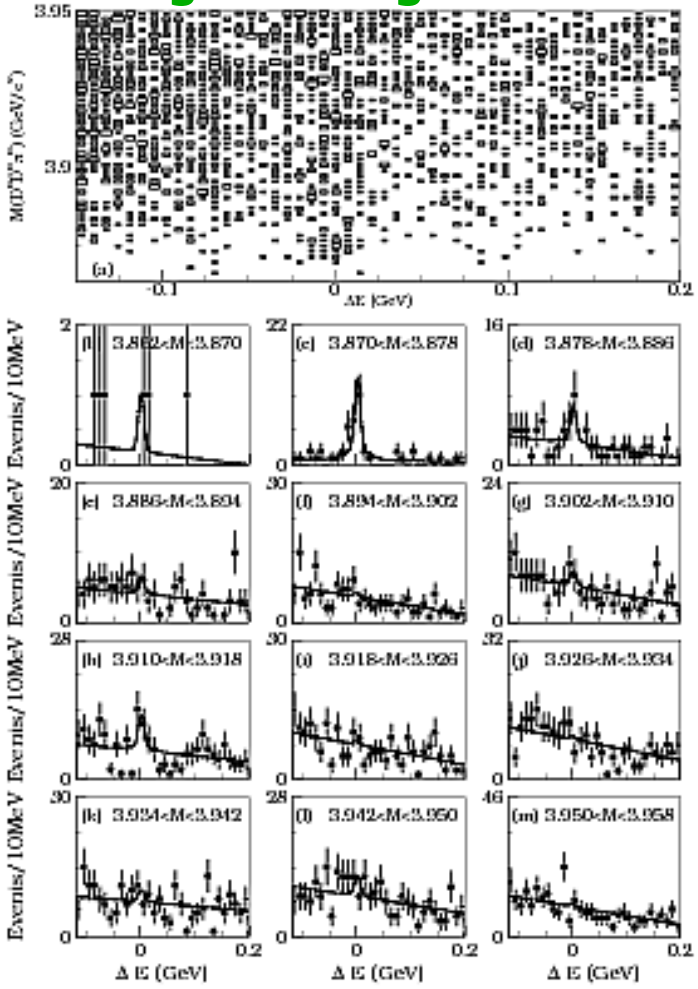
2^{++} → DD* D-wave, suppressed by $(q^*)^{2L+1}$

X(3872): properties (by Belle)

$B^+ \to K^+ D^0 \bar{D}^0 \pi^0 / B^0 \to K^0 D^0 \bar{D}^0 \pi^0$

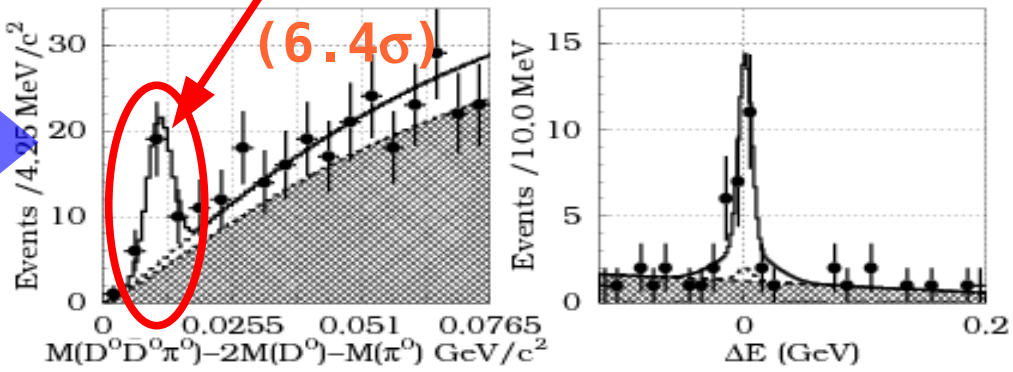
Belle: 447M $B\bar{B}$
hep-ex/0606055
(submitted to PRL)

$M(D^0\bar{D}^0\pi^0)$ and ΔE in B signal region



$M(D^0D^0\pi^0) \approx M(X)$

N=24.1 ± 6.1
(6.4σ)



$Br(B \to K D^0 \bar{D}^0 \pi^0) = (1.27 \pm 0.31^{+0.22}_{-0.39}) \times 10^{-4}$

$Br(X \to K D^0 \bar{D}^0 \pi^0 / Br(B^+ \to K^+ X) BR(X \to \pi^+\pi^- J/\psi) = 9.4^{+3.6}_{-4.3}$

This is hard to accomodate with a 2^{++} state, but $M_{resonance} = (3875.4^{+1.2}_{-2.1}) MeV/c^2$ (Is it X?)

However, if the resonance = X(3872), then:

$J^{PC}(X(3872)) = 1^{++}$

X(3872): interpretation

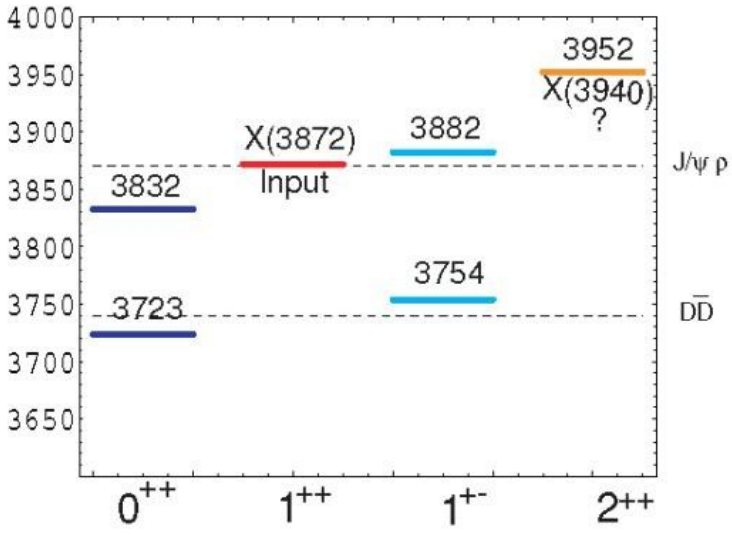
Tetraquarks:

L. Maiani et al., PRD71, 014028 (2005)

- predicted spectrum
- mass difference:

$$M(X_h) - M(X_l) = \frac{7 \pm 2}{\cos\theta}\ MeV$$

θ: mixing angle



DD* molecule:

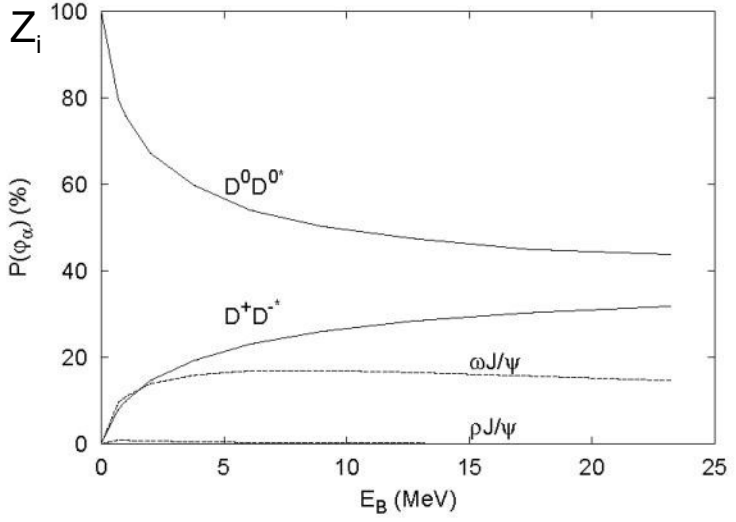
E.S.Swanson, PLB588, 189 (2004)

- wave function fractions

$$\frac{Br(B^0 \to K^0 X)}{Br(B^+ \to K^+ X)} = \frac{|4Z_{+-}^{1/2} + Z_{00}^{1/2}|^2}{|4Z_{00}^{1/2} + Z_{+-}^{1/2}|^2}$$

$$R = \frac{2Z_{00}\Gamma(D^{*0})}{Z_{\rho\psi}\Gamma(\rho)}.$$

$$R = \frac{Br(X \to D^0 D^0 \pi^0)}{Br(X \to J/\psi\, \pi^+ \pi^-)} = 10 \pm 4$$

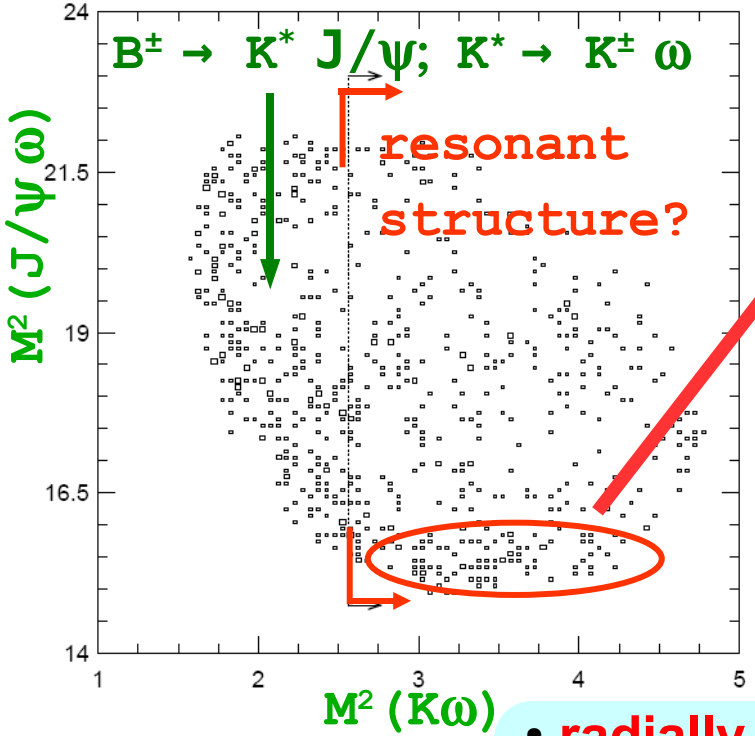


binding energy

Y(3940)

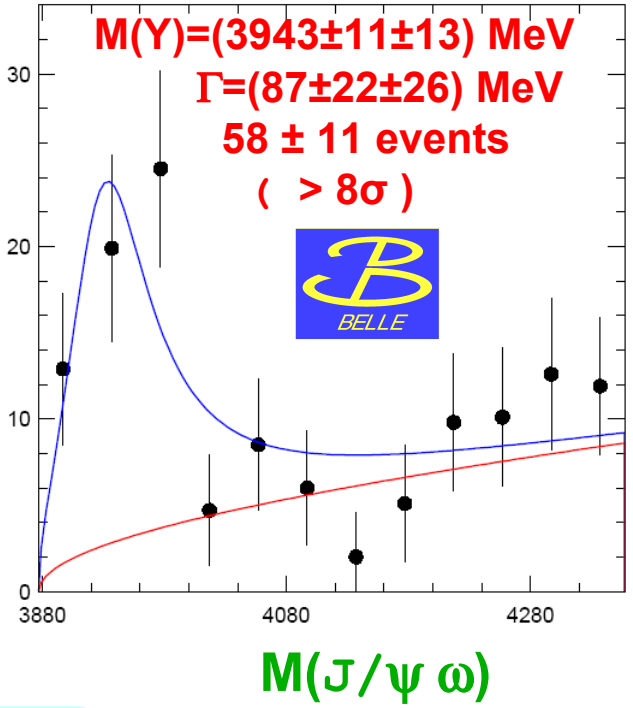
Belle : 275 BB
PRL 94, 182002 (2005)

Dalitz plot for
$B \to K \omega J/\psi$; $\omega \to \pi^+ \pi^- \pi^0$



No. of B's in bins of $M(\omega J/\psi)$

$Br(B \to Y(3940)K) \times Br(Y \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$



F.E.Close,P.R.Page,
Nucl.Phys.B443,233(1995)
C.Banner et al.,
PRD56,7039(1997)

- **radially excited P-wave $\bar{c}c$?**
  ... but it has large $Br(Y \to \omega J/\psi)$
- **$c\bar{c}$-gluon hybrid?**
  Has suppressed $D^{(*)}D^{(*)}$ decays
  ... but hybrids predicted at M>4.3 GeV

Mass/widths need further study...
(discrepancy with BaBar: hep-ex/0711.2047)

X(3940): Interpretation (at 357 fb^{-1})

Belle : 357 fb^{-1}
PRL 98, 082001 (2007)

- There is no evidence for X(3940)→J/ψ ω : X(3940) ≠ Y(3940)
- Combine inclusive/D*$\bar{D}$ tagged samples,
  common events removed, corrections for tagging & veto efficiencies,
  assume equal fractions of X(3940)→D*^{0} $\bar{D}^0$ and X(3940)→D*$^+$ D$^-$

For more than 2 charged tracks

$Br_{>2}$(X(3940→D*$\bar{D}$) > 45% @90% C.L.

Br (X(3940)→D $\bar{D}$) < 41% @90% C.L.

Br (X(3940)→J/ψ ω) < 26% @90% C.L.

There are several speculations on X(3940) nature, all with pro's and con's

→ further experimental study needed (angular distributions)