Exotic states with $c\bar{c}$

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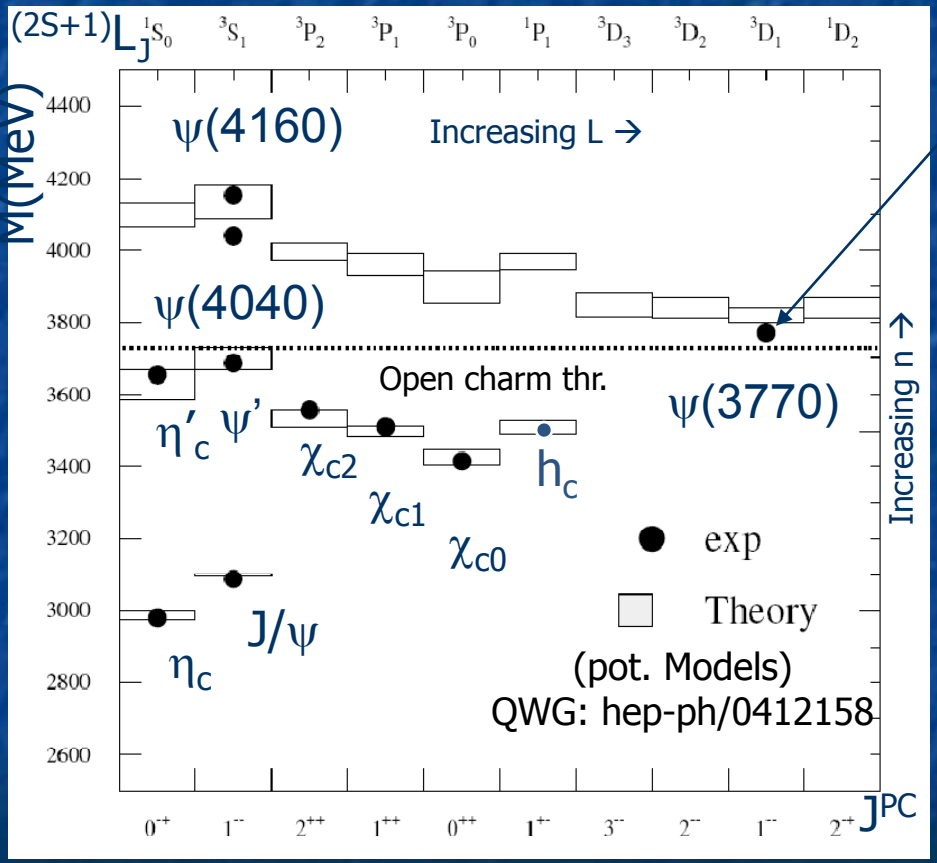
Quarkonium for Pedestrians

- Quarkonium is a bound state of a quark and an antiquark
  - Relevant quantum numbers: n,L,S,J
  - Relationship with Parity and Charge Conj:
    - $P=(-1)^{L+1}$, $C=(-1)^{L+S}$
  - ***Not all J^{PC} allowed*** (e.g. 0^{+-},0^{--},1^{-+},2^{+-} forbidden)
- Decay Properties:
  - Below open quark threshold (e.g. (cc)→DD) only electromagnetic or α_s suppressed decays allowed → mostly narrow states
  - Above open quark threshold (if DD decays allowed)→ mostly broad states

Charmonium: state of the art



same J^{PC} as J/ψ but mostly D wave !

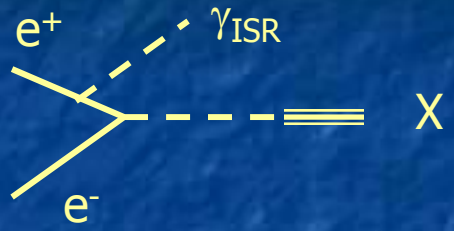
Basically all states below the open charm threshold are observed and explained

Beyond the quarkonium

- Search for states with 2 quarks+"something else"
  - New forms of aggregation
  - Expected but never identified!!!
- Hybrids: $q\bar{q}$+n gluons
  - Lowest state 1^{-+} (forbidden for quarkonium)
  - Dominant decay $H \rightarrow DD^{**}$
- Tetraquarks: $[q\bar{q}'][qq']$
  - Large amount of states
  - small widths also above threshold
- Molecules: $M[q\bar{q}]M[q'\bar{q}']$
  - Smaller number of states but still small widths also above threshold

Search for resonances:
• with non-quarkonium J^{PC}
• unnaturally small widths
• not null charge: would be clear indication of something new going on

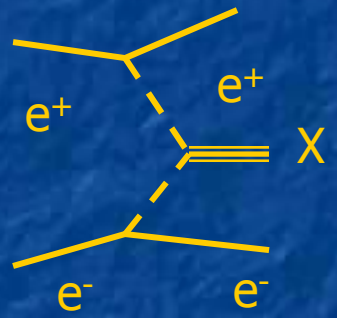
Measuring the quantum numbers



- Production:
  - ISR only produces with same quantum numbers as the photon ($J^{PC}=1^{--}$)
  - $\gamma\gamma$ only produces with C=+
  - Double charmonium production

    $e^+e^- \rightarrow \gamma^* \rightarrow X_{cc}{}^1 X_{cc}{}^2$

    Possible only if quantum numbers of the two charmonia can be combined to give a 1^{--}.



- Decay:
  - Angular distributions of decay products depend on J^P.
  - Selection rules
    - Conservation of J
    - Conservation of P,C in strong and electromagnetic decays

The new zoology

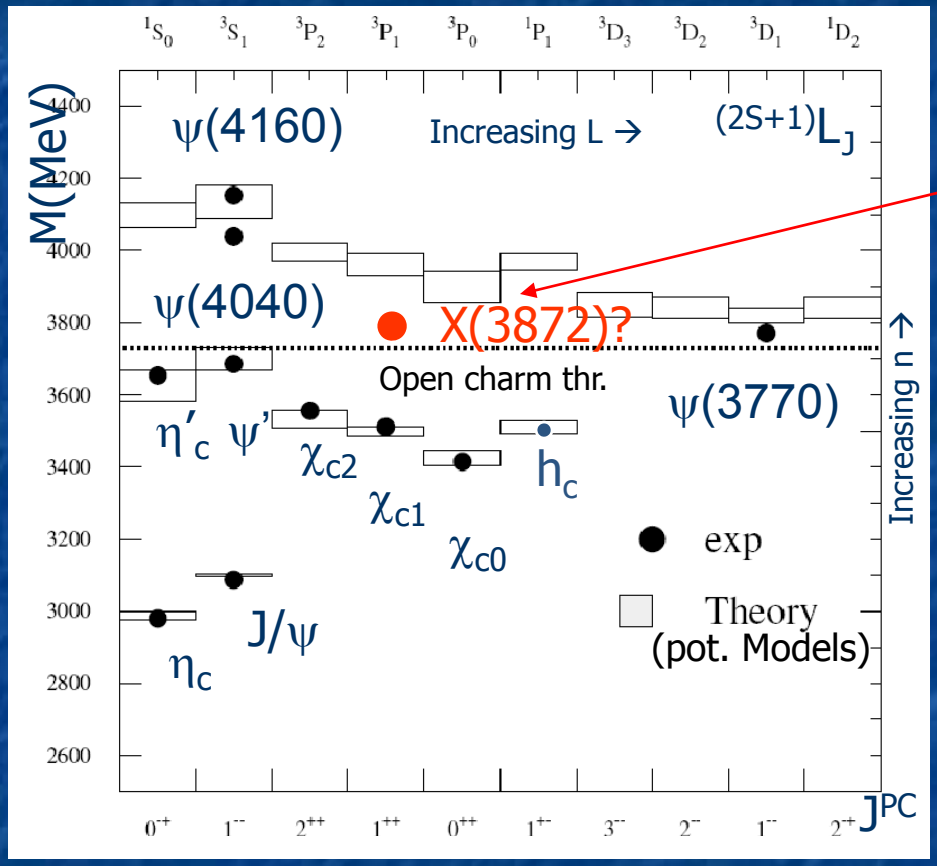
- X(3872)
- The 1-- family
- The charged states
- hot off the press

X(3872): known facts

- Decays
  - X→J/ψ ππ (original observation)
    - Maybe J/ψ ρ
  - BF(X→J/ψ ω)~ BF(X→J/ψ ρ)
  - Full angular analysis from CDF
  - X→J/ψ γ

  Implications:
    - C(X)=+1
    - C(ππ in J/ψ ππ decay)=-1
    - I(ππ)=L(ππ)=1 ➔ consistent with J/ψρ decay hypothesis
    - $J^{PC}=1^{++}$ or 2^{-+} from angular analysis
- Production
  - only B decays so far
  - No prompt e^+e^- production observed (BaBar **arXiv:0707.1633**)

The X(3872) puzzle



Not matching any predicted state!

Above DD threshold (allowed): should have large width but it is narrow

Charmonium highly suppressed decay into J/ψ ρ (isospin violation)

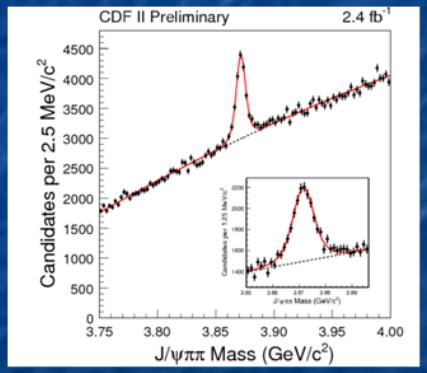
Open options

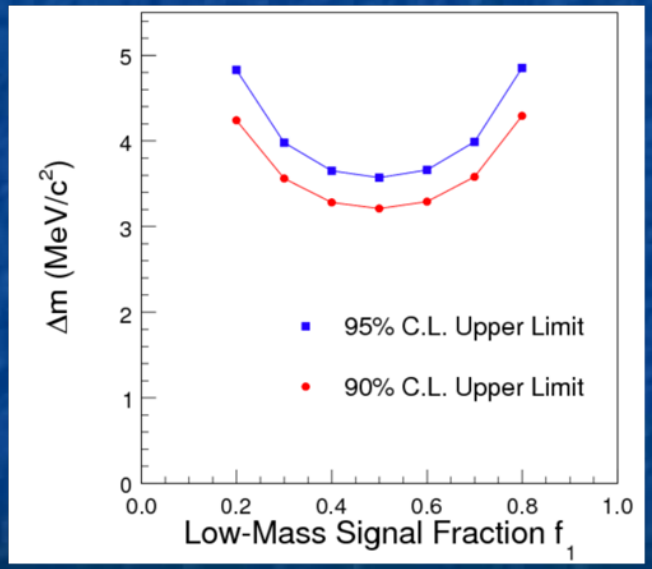
- DD* molecule
  - Right above the threshold
  - favors DD* decay over J/ψππ over J/ψγ (as observed)
- Tetraquark
  - Explains small width
  - Predicts a set of 4 states (2 charged and 2 neutral).
    - Finding these states is critical

Are there two X→J/ψππ ?

arXiv:0807.3699

- CDF with largest sample investigates the mass distribution for two resonances closeby



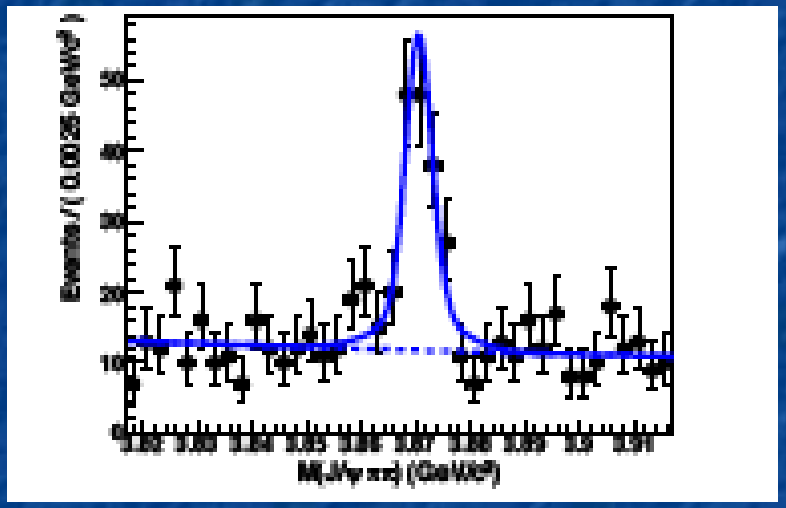


ΔM<3.2 MeV @90%C.L.

Fitted mass difference as a function of first gaussian fraction

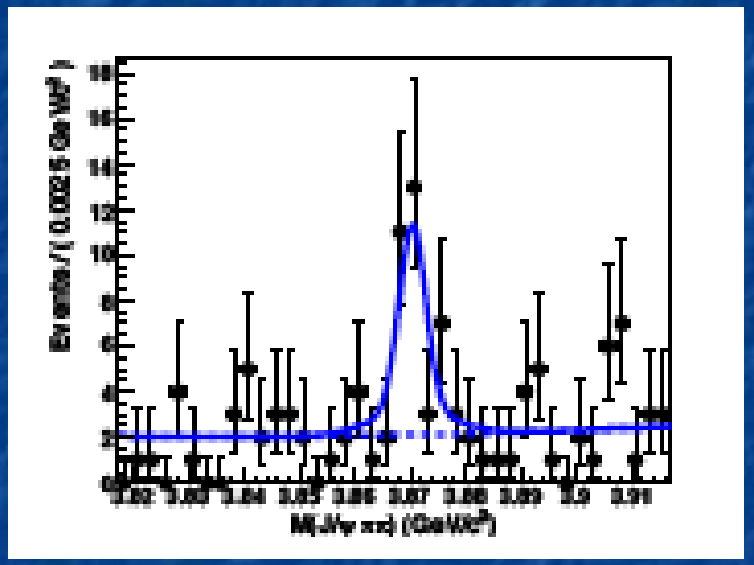
arXiv:0809.1224

Is the X in B^0 and B^+ decays the same?



$B^{\pm} \rightarrow XK^{\pm}$

$X \rightarrow J/\psi\pi\pi$



$B^0 \rightarrow XK_S$

$$\Delta M = (0.18 \pm 0.89 \pm 0.26)\,MeV$$

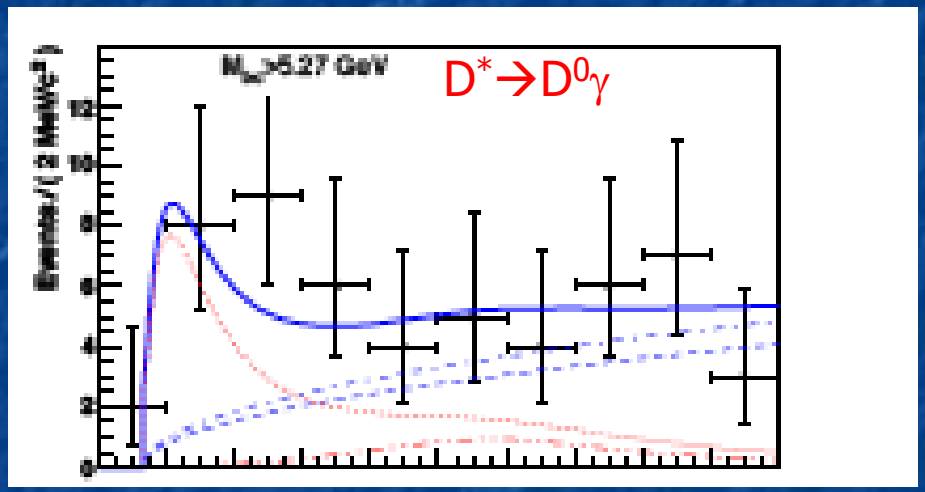
$$\frac{Br(B^0 \rightarrow XK^0; X \rightarrow J/\psi\pi\pi)}{Br(B^{\pm} \rightarrow XK^{\pm}; X \rightarrow J/\psi\pi\pi)} = 0.82 \pm 0.22 \pm 0.05$$

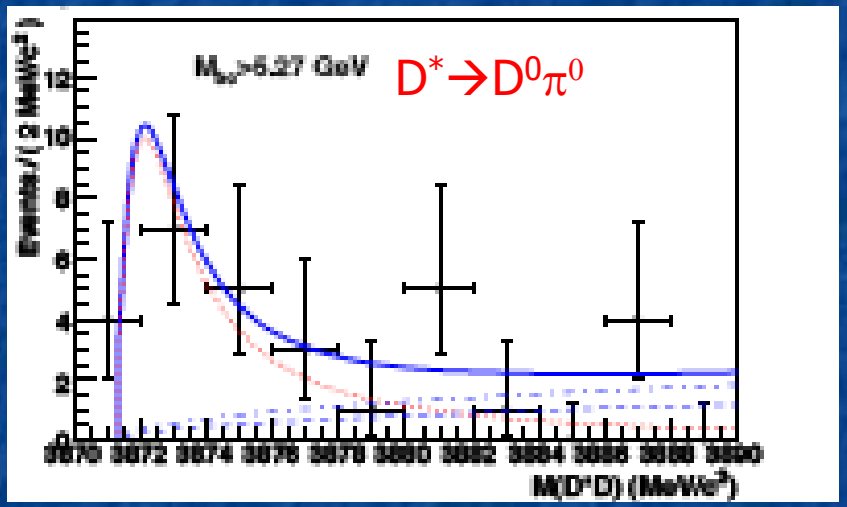
More in Phys.Rev.D77: 111101,2008

Consistent with one state, equally present in decays

X(3872)→D^0D^{*0}

- Belle [**PRL 97, 162002 (2006)**] observed X(3872)→$D^0D^0\pi^0$
- Confirmation and integration from BaBar in B→DD^*K[PRD 77, 011102(2008)]
- Most recent result from Belle





arXiv:0810.0358

$$M = (3872.6^{+0.8}_{-0.4} \pm 0.4)\,MeV$$

$$Br(B^{\pm} \to XK^{\pm}; X \to DD^*) = (0.73 \pm 0.17 \pm 0.09)10^{-4}$$

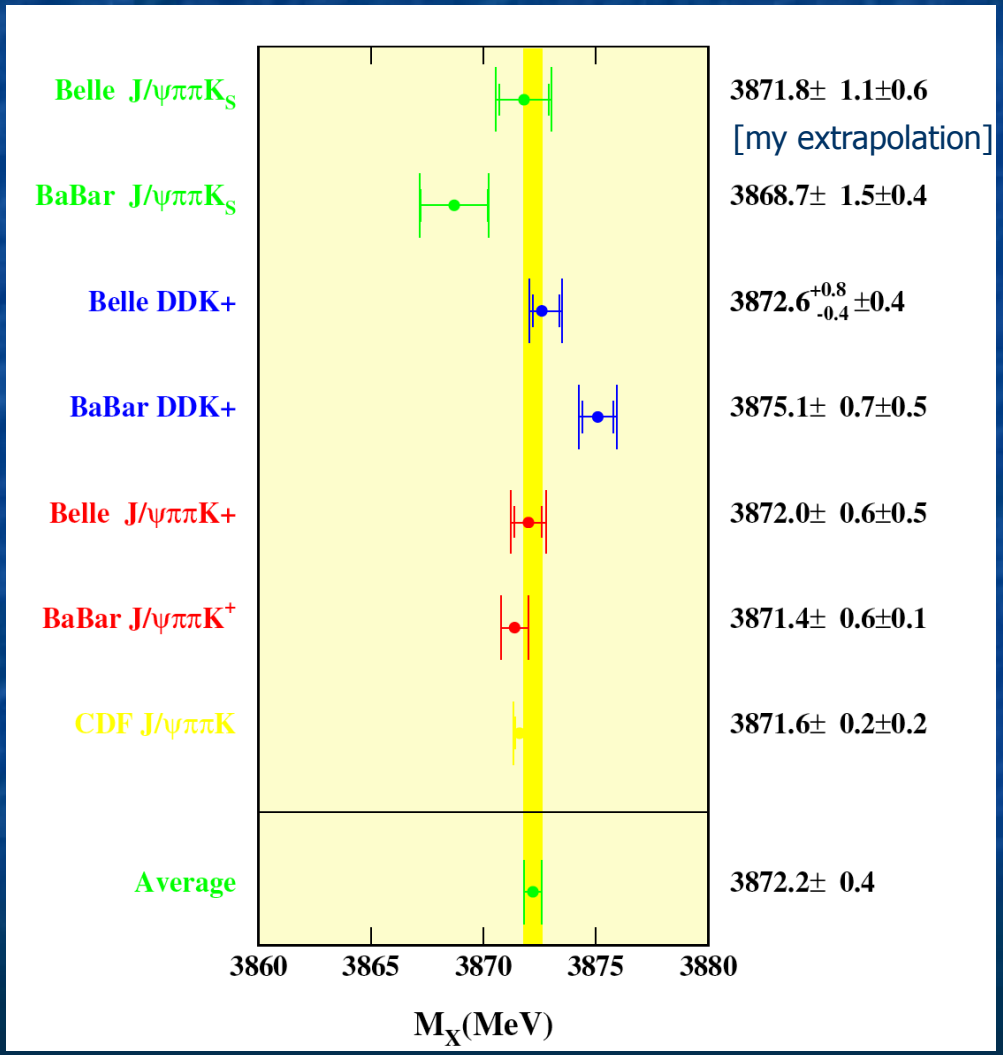
X(3872) mass

Poor agreement among mass measurements:

X→J/ψππ and X→DD(*) differ by ~3.5σ

TWO STATES? X(3872) & X(3876) ?

Predicted by tetraquark model
(but why so close to threshold?)



The new zoology

- X(3872)
- The 1-- family
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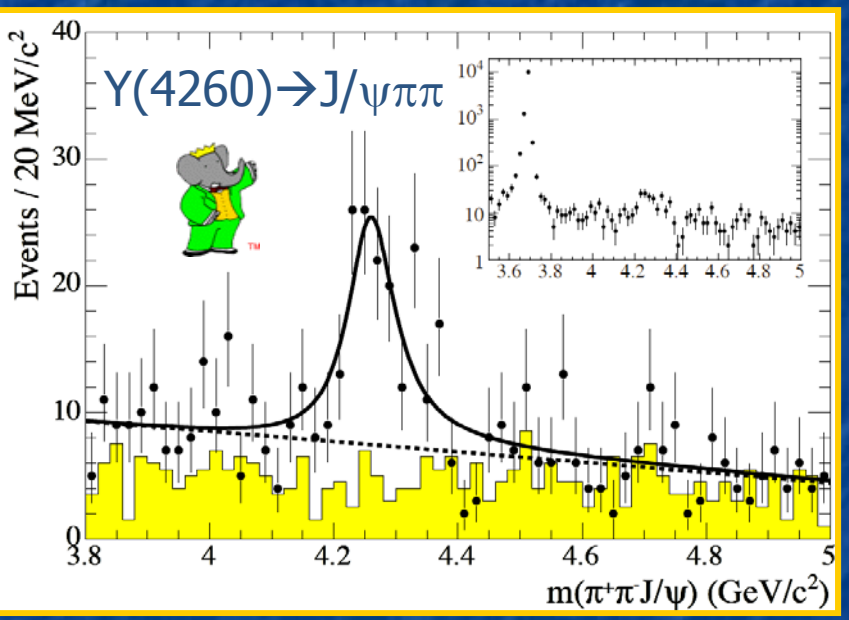
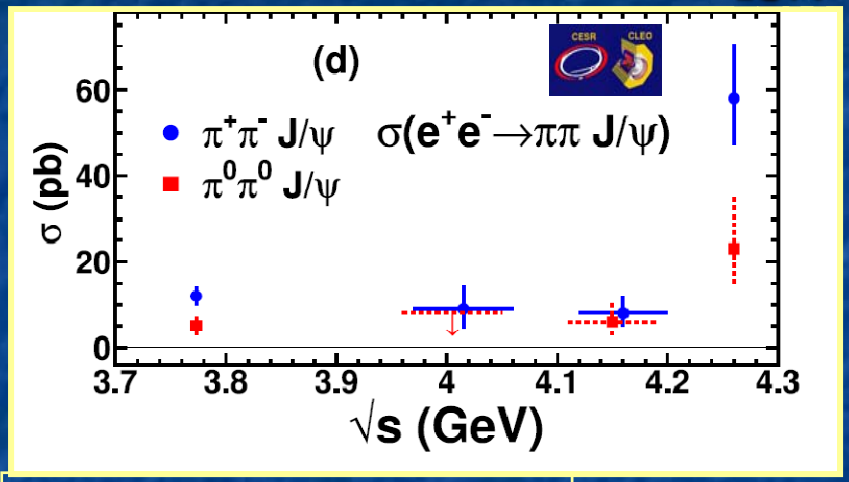
The 1^{--} family

Several resonances observed in $e^+e^- \rightarrow Y\gamma_{ISR}$

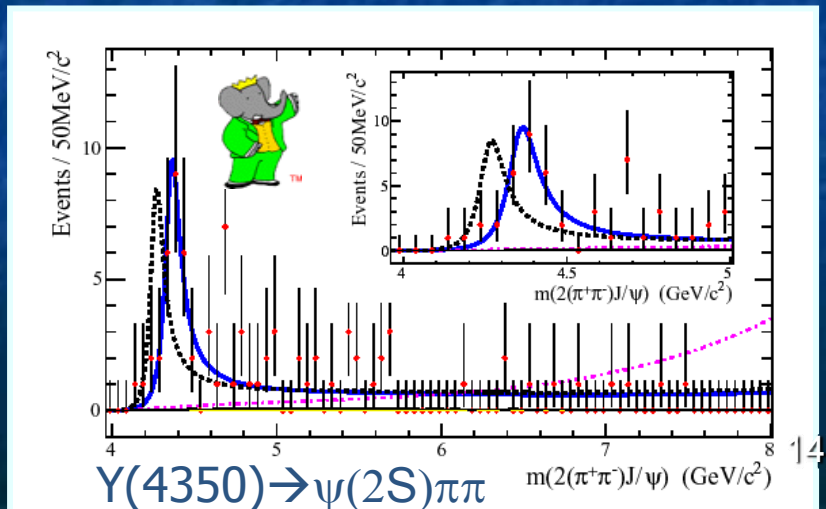
(certainly $J^{PC}=1^{--}$)



A new state: Y(4260)
PRL 95, 142001 (2005)



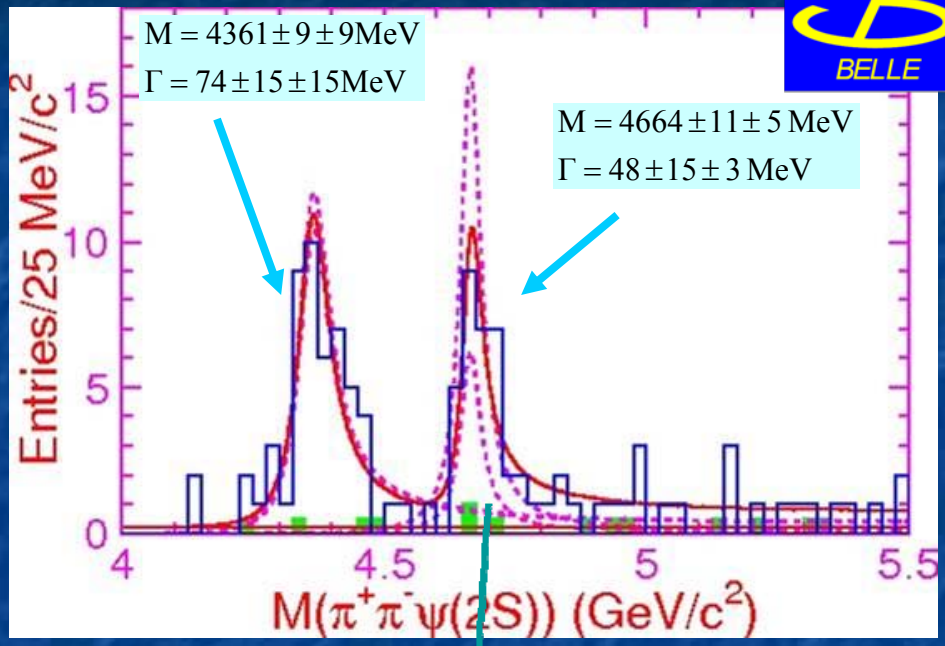
Confirmation + $J/\psi\pi^0\pi^0$:
CLEO PRD74, 091104 (2006)
CLEO-c PRL 96, 162003 (2006)

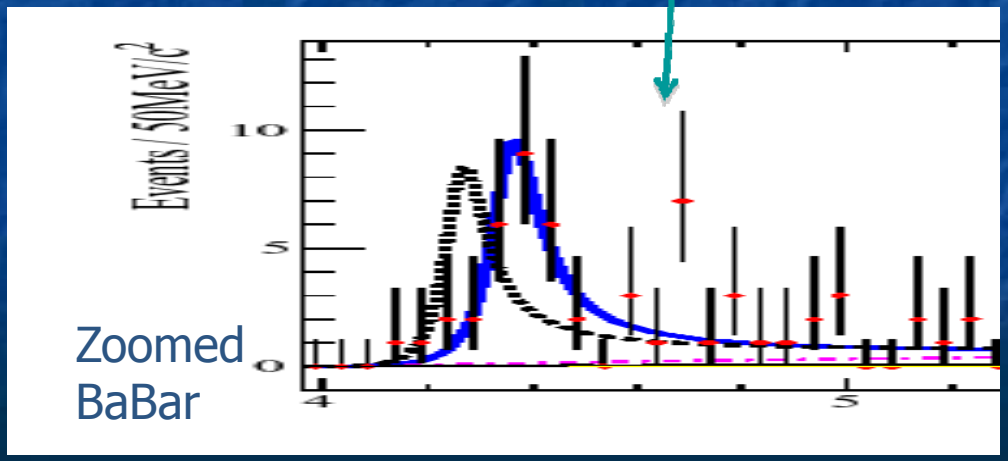


Yet another state Y(4350)
PRL 98, 212001 (2007)

The youngest of the 1^{--} family

PRL99, 142002 (2007)





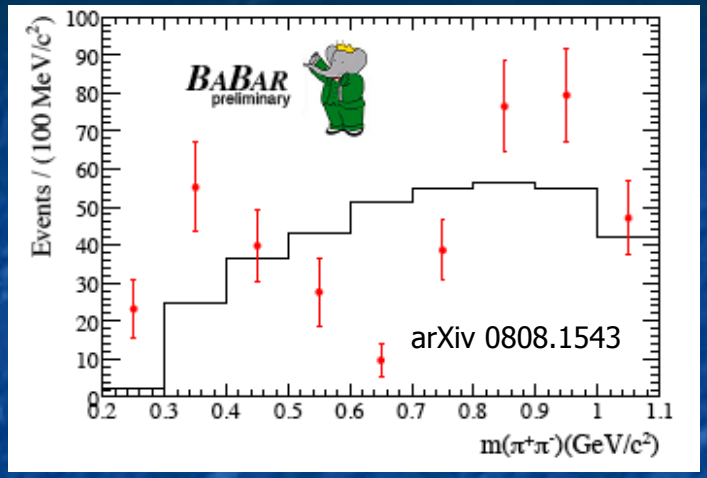
Present in low stat in BaBar's publication

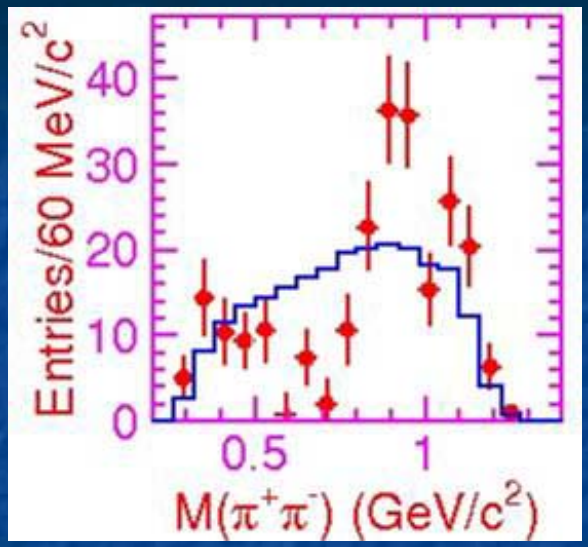
$Y \rightarrow \psi(2S)\pi\pi$

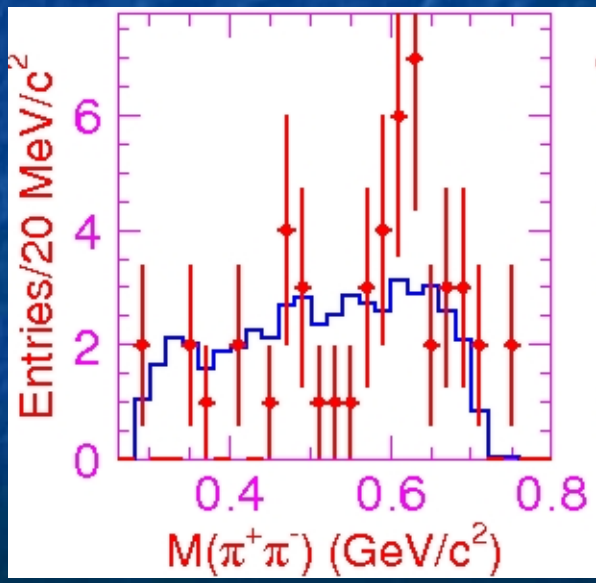
DECAY PROPERTIES

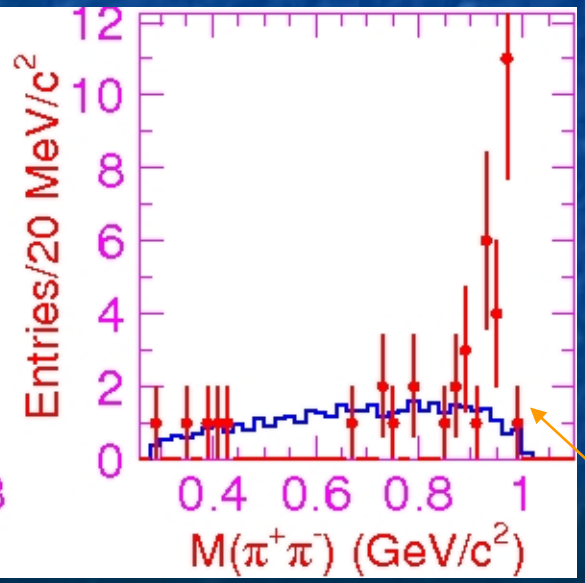
Y(4260)

PRL99, 142002 (2007)









Y(4350)

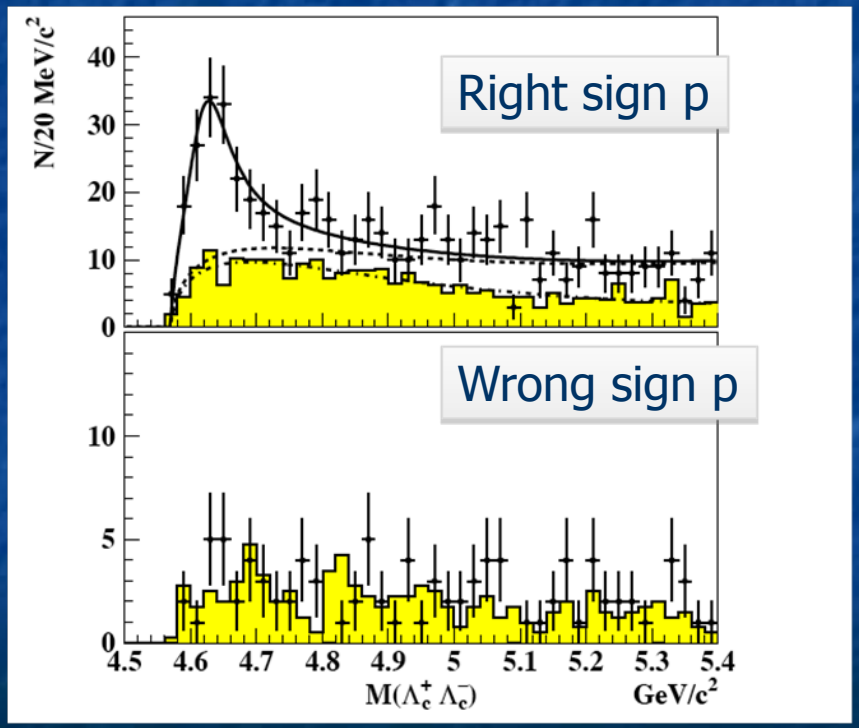
Y(4660)

f_0 dominating?
Threshold effects?

PRL101,172001 (2008)

X(4630) [or Y(4660)?]→$\Lambda_c\Lambda_c$

- Y(4660) good candidate for a $\Lambda_c\Lambda_c$ bound state
- Search for ISR e^+e^- → $\Lambda_c\Lambda_c\gamma$ events



$$M = 4634^{+8+5}_{-7-8}\ \text{MeV}$$

$$\Gamma = 92^{+40+10}_{-24-21}\ \text{MeV}$$

CFR

$$M = 4664 \pm 11 \pm 5\ \text{MeV}$$

$$\Gamma = 48 \pm 15 \pm 3\ \text{MeV}$$

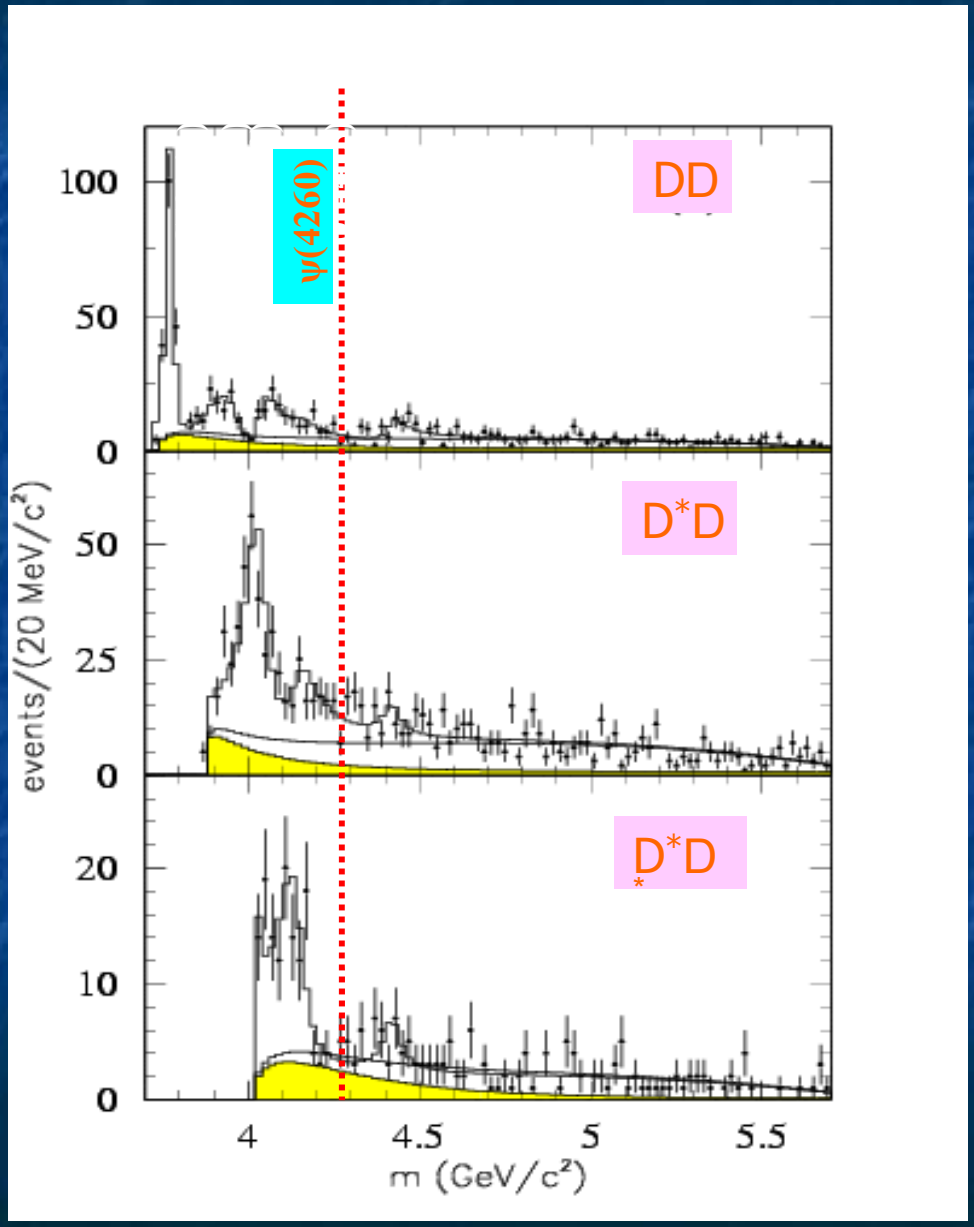
In the discovery mode

Assuming same state as $\psi(2S)\pi\pi$

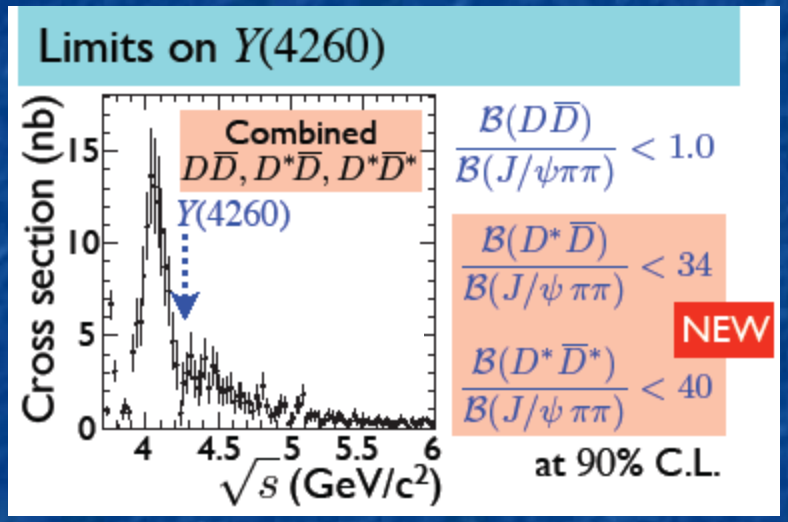
$$B_{ee}xBF = (0.68^{+0.16+0.07}_{-0.15-0.11} \pm 0.28)10^{-6}$$

$$BF(\Lambda c\Lambda c)/BF(\psi(2S)\pi\pi) \sim 12$$!

ISR search for Y(4260)→ $D^{(*)}D^{(*)}$



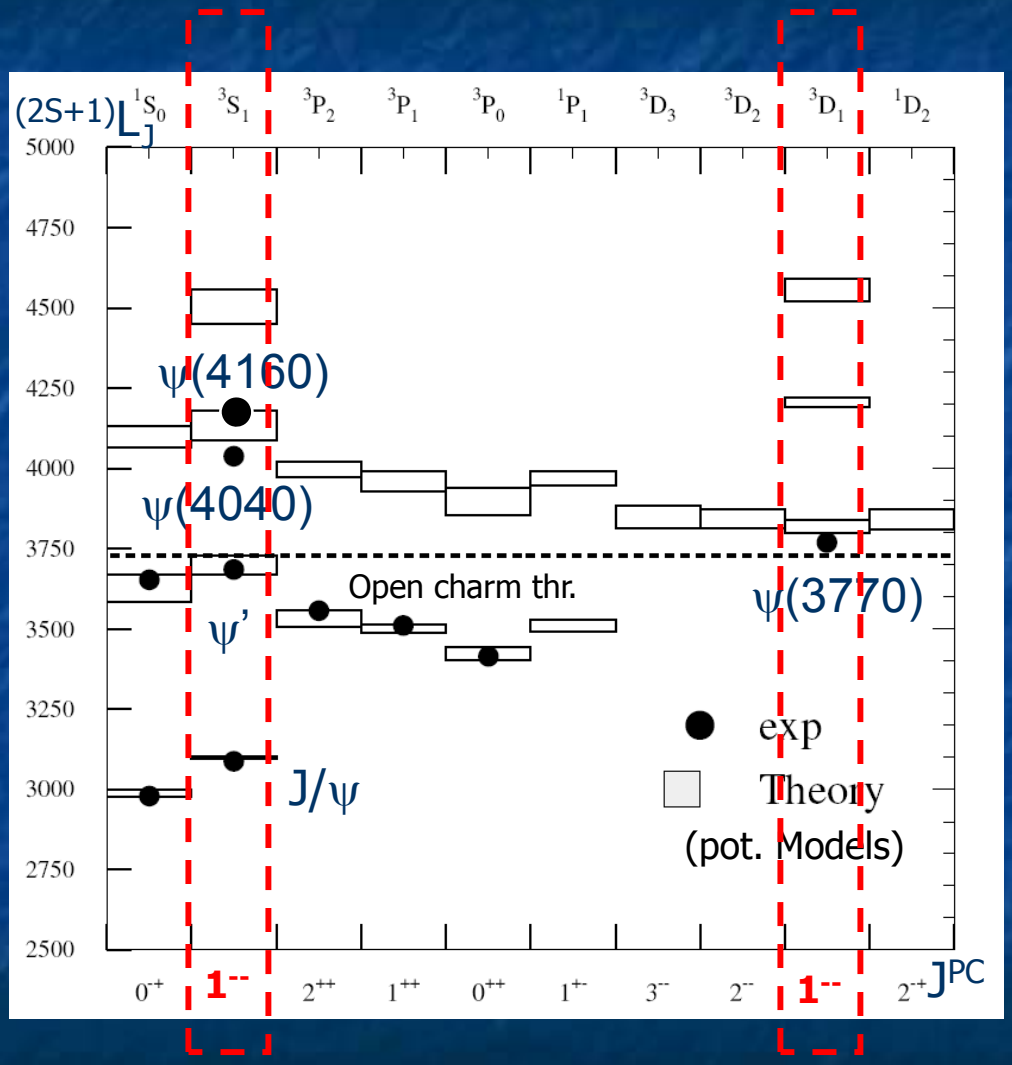
Y(4260) is 1^{--} charmonium state
➔ should decay **predominantly** to DD, D^*D, and D^*D^*



BABAR: PRD 79, 092001 (2009), 384

1^{--} family: recap

Only seen in $\psi(2S)\pi\pi$



- Not matching any potential model prediction
- Too narrow

"new physics"?

4260 can be fit by a tetraquark model (decaying into $J/\psi f_0$ …) or a hybrid (with $g \rightarrow \pi\pi$)

The new zoology

- X(3872)
- The 1-- family
- The charged states
- hot off the press

The $Z(4430)^+$

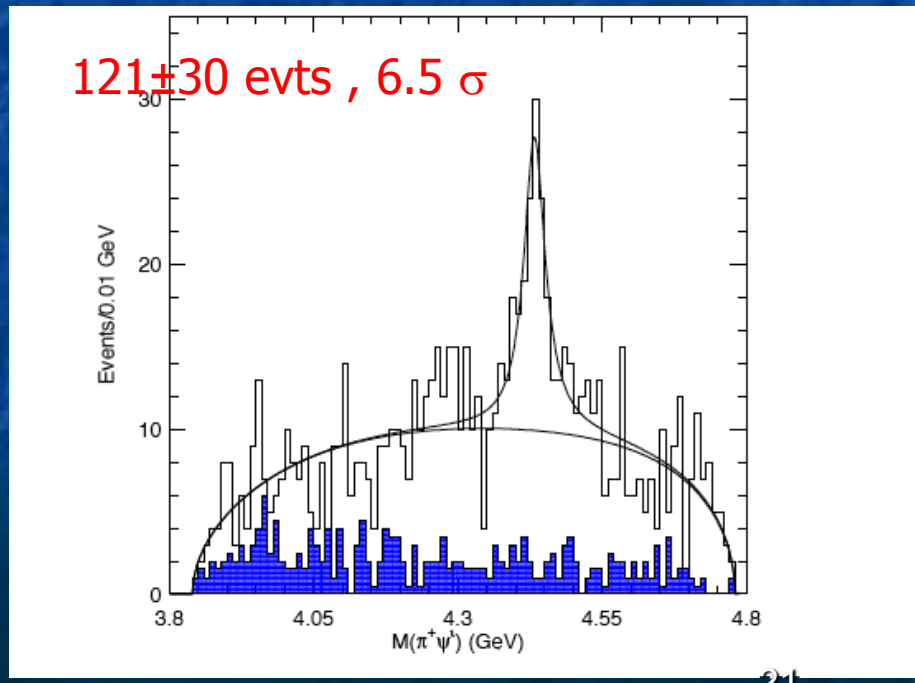
- Charged states a strong prediction of the tetra-quark model
- First observed by Belle in PRL100, 142001 (2008)
- Search for $Z^{\pm}$ →

J/ψ or $\psi(2S)$ + $\pi^{\pm}$

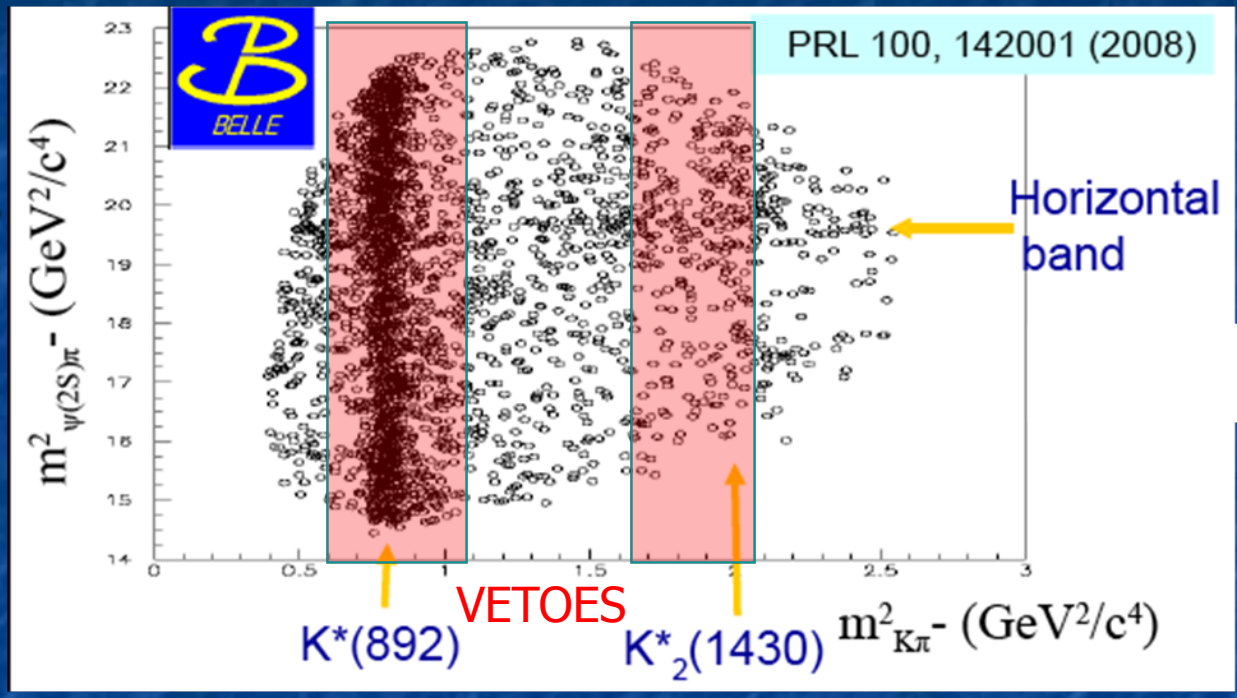
In $B \to \psi \pi^{\pm} K$ decays

$M = 4433 \pm 4 \pm 2$ MeV

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



Criticisms to "discovery analysis"

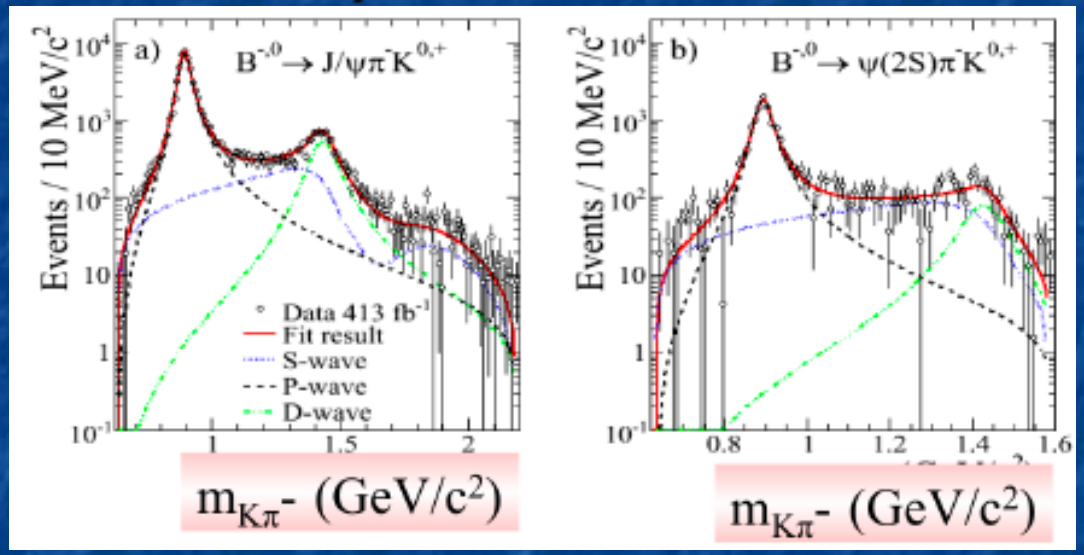


- Only "global" efficiency correction
- Poor treatment of 3-body decays (cut away dominant resonances – no interference/reflections)
- Arbitrary choice of background shape

arXiv:0811.0564

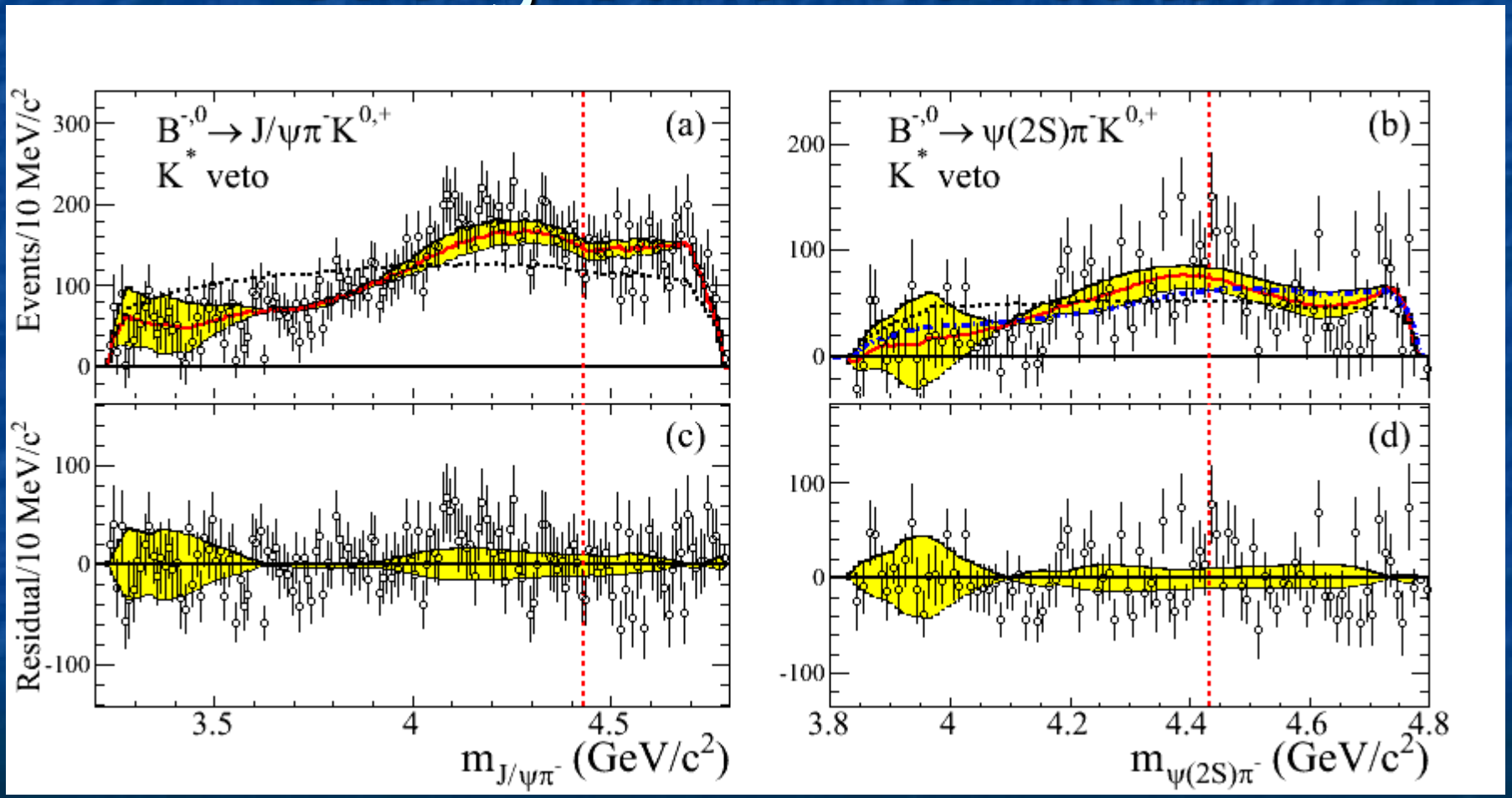
BaBar Analysis

- Event-by-event efficiency correction
- Describe the Kπ system in detail
  - Mass



  - Angular distributions fitted with Legendre Polynomials

Comparison of BaBar background with data



Same "veto" definition as Belle

BaBar results

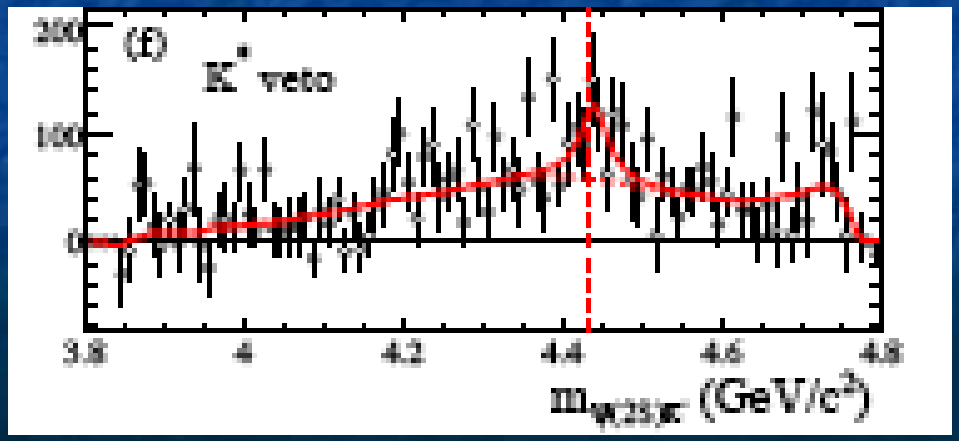
- Fitting without vetoes

  m=4476±8 MeV/c^2; Γ=32±16 MeV; signal size: 2.7σ

[offset of 43±9 MeV w.r.t. Belle]

- Same vetoes as Belle

m=4439±8 MeV/c^2; Γ=41±33 MeV; signal size 1.9σ

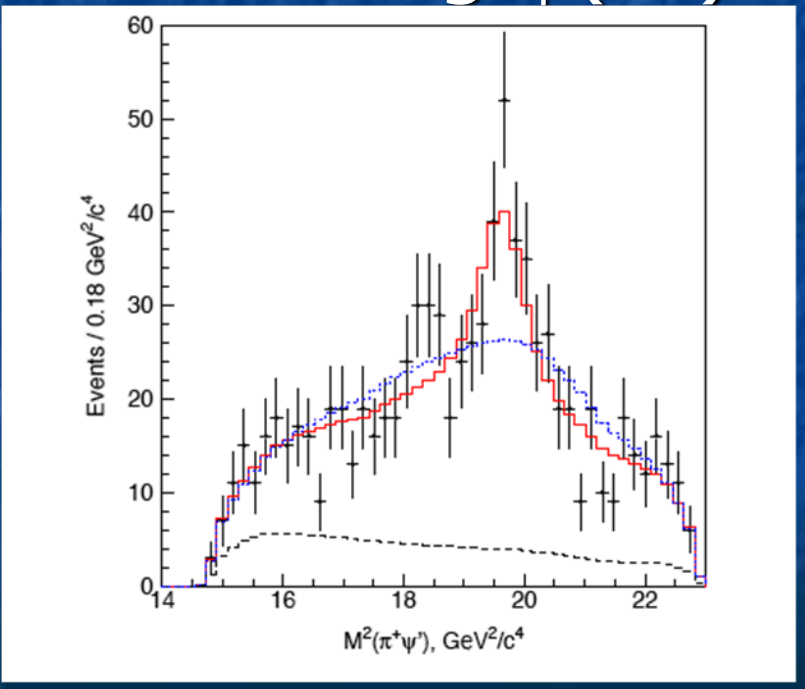


Conclusions:
• mistreatement of background might enhance significance
• veto might bias signal mass measurement

arXiv:0905.2869

Belle Dalitz Plot Analysis

- Belle's observation confirmed, but errors increase
- Including $\psi(2S)W$



W=	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	$1.3\,\sigma$
$K_2^*(1430)$	$5.5^{+1.6}_{-1.4}$	$3.1\,\sigma$
$K^*(1680)$	$2.8^{+5.8}_{-1.0}$	$1.2\,\sigma$

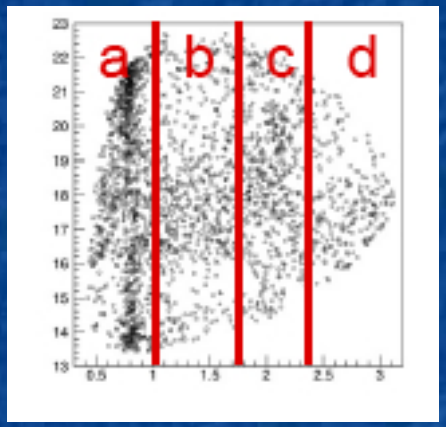
$m=4443^{+24}_{-18}$ MeV
$\Gamma=109^{+113}_{-71}$ MeV

$$\mathcal{B}(\bar{B}^0 \to K^- Z(4430)^+) \times \mathcal{B}(Z(4430)^+ \to \pi^+ \psi') = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$$

CFR. BaBar excludes 3.1 10^{-5} @90%C.L.

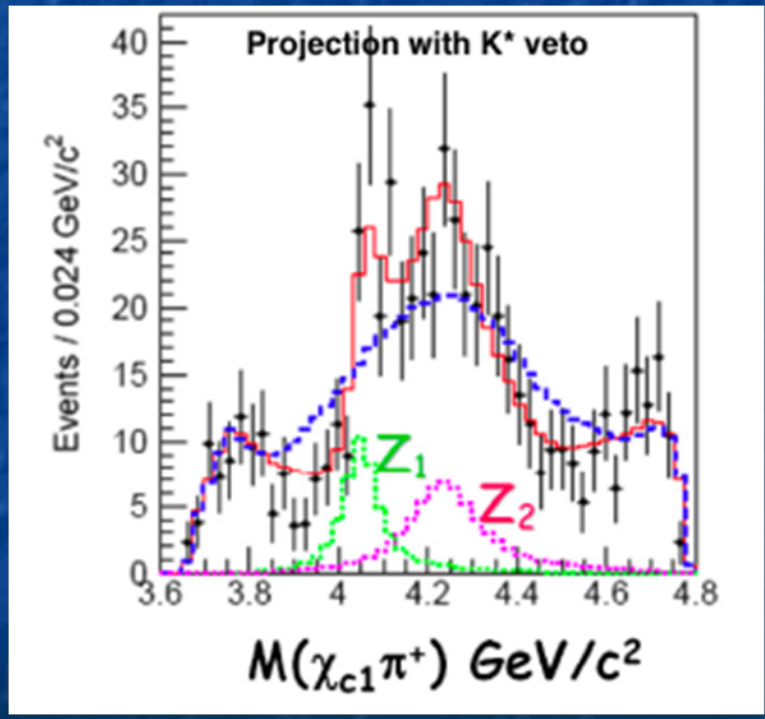
PRD 78, 072004 (2008)

Z^1 and $Z^2 \rightarrow \chi_{c1}\pi$



b+d

Same analysis strategy

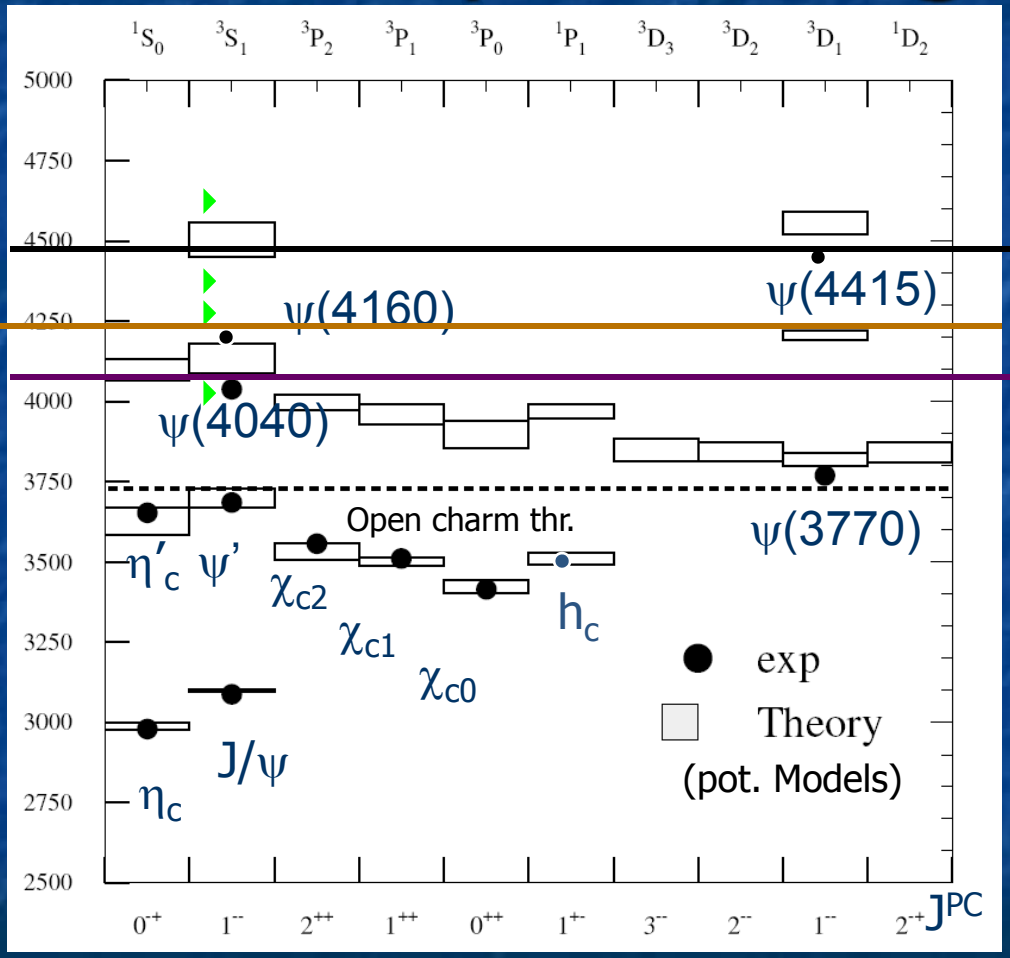


$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$

The 1^- family

Summary of charged states



Z(4430)

Z(4250)

Z(4050)

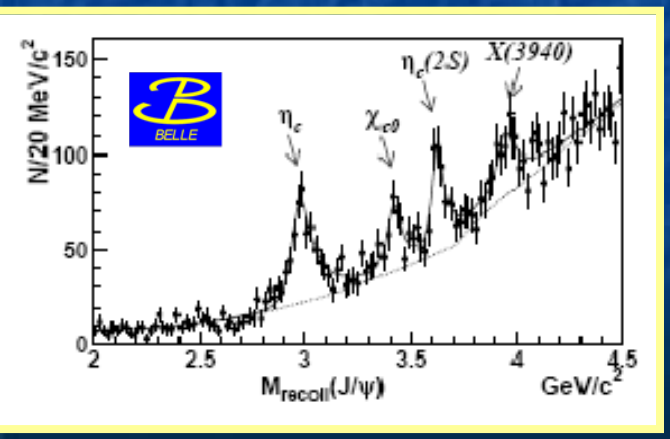
The new zoology

- X(3872)
- The 1-- family
- The charged states
- hot off the press!!

The 3940 family

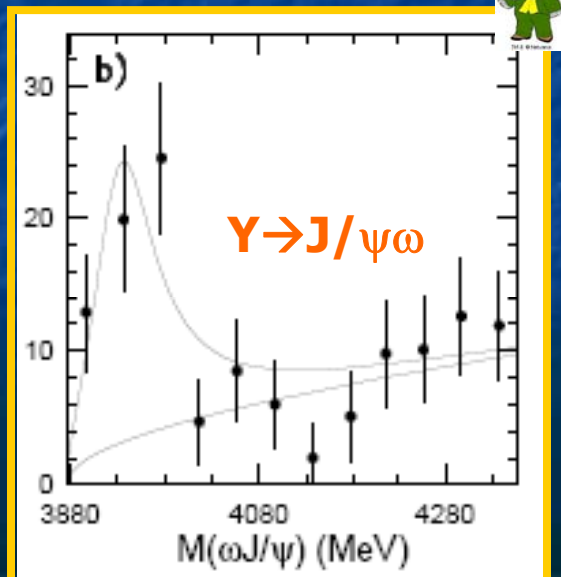
	Observed in	J^{PC}	M (MeV)	Γ (MeV)
X	$e^+e^- \to J/\psi X$ ($X \to DD^*$)	$0^{-+}, 1^{++}$	3943±8	<39
Y	$B \to YK$ ($Y \to J/\psi\omega$)	$0^{++}, 1^{-+}, \ldots$	3943±17 [Belle] 3915±4 [BaBar]	87±34 36±10
Z	$\gamma\gamma \to Z$ ($Z \to DD$)	2^{++}	3929±5	29±10

PRL 98, 082001 (2007)

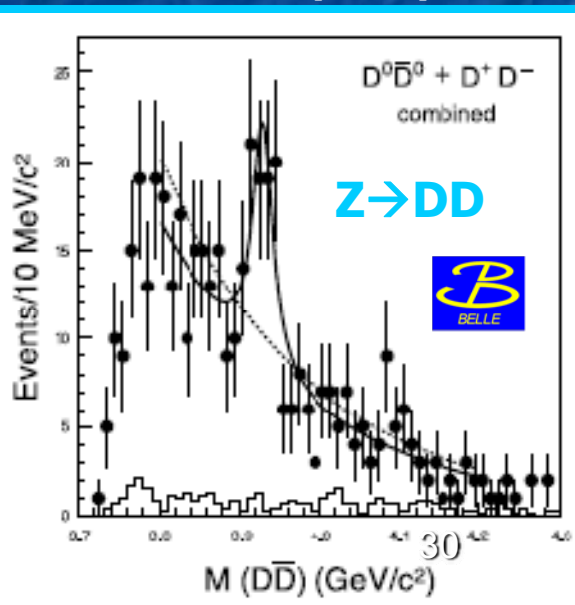


X→DD*

PRL 94, 182002 (2005)
PRL 101, 082001 (2008)

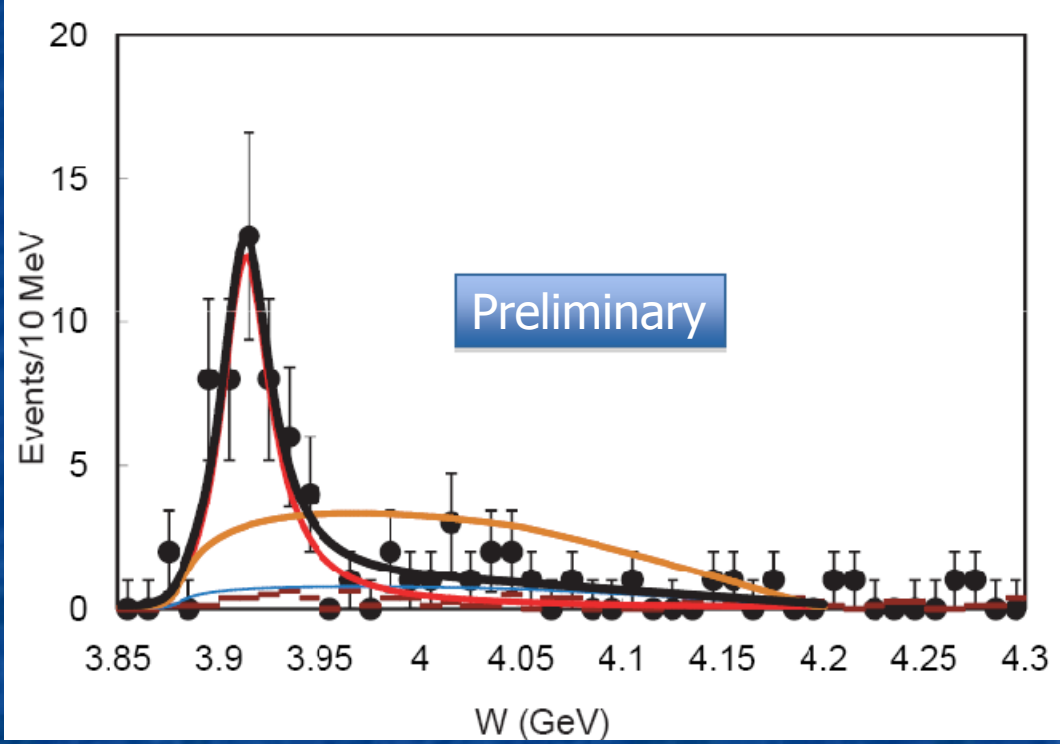


PRL 96, 082003 (2006)

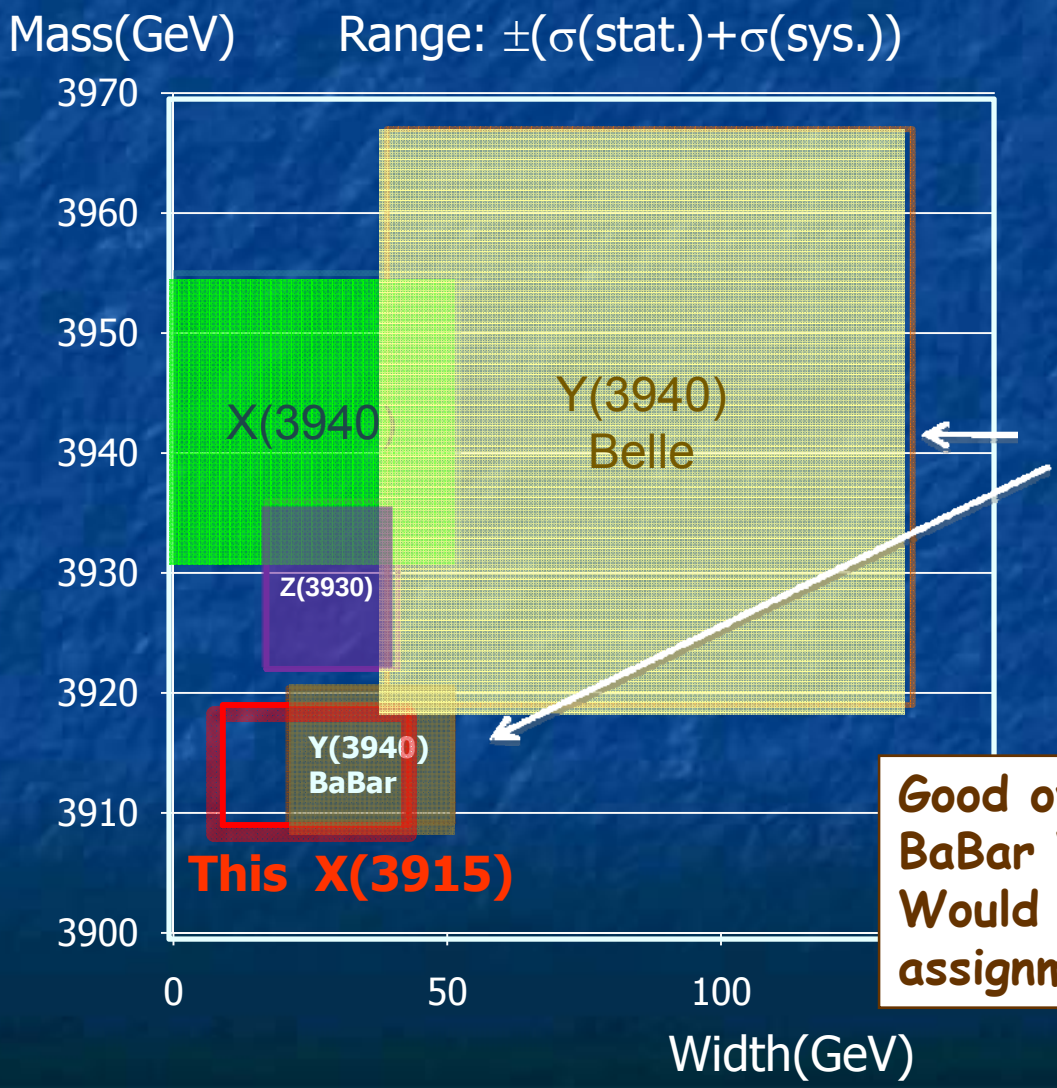


New Belle peak in $\gamma\gamma \to \omega J/\psi$

M: $3914 \pm 3 \pm 2$ MeV,
Γ: $23 \pm 10\ ^{+2}_{-8}$ MeV,
$N_{res} = 55 \pm 14\ ^{+2}_{-14}$ events
Signif. = 7.7σ



The 4 states near 3940



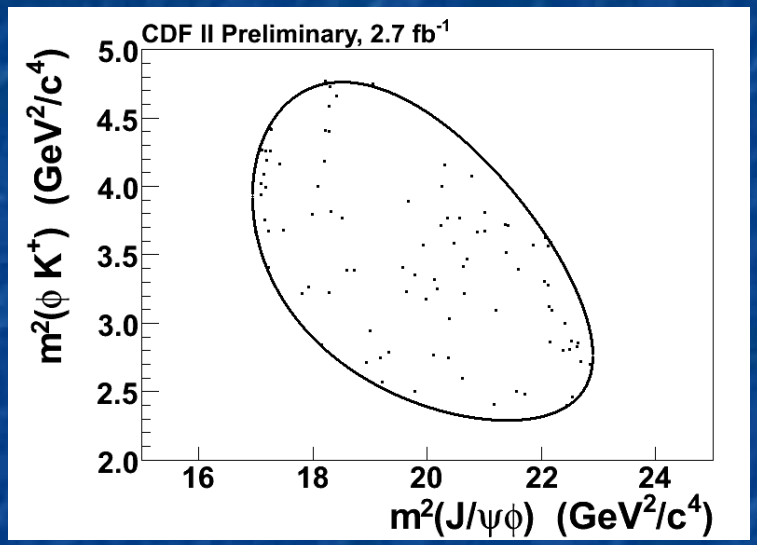
Better analysis of the J/ψ ω mass spectrum needed!!

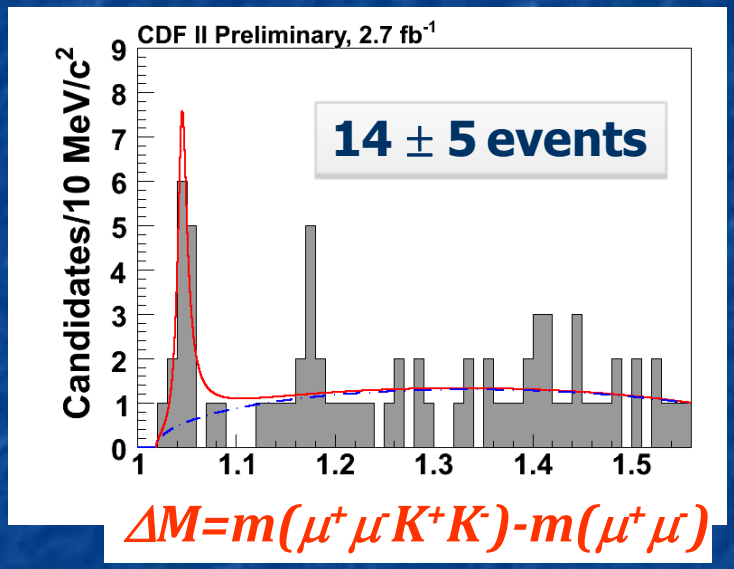
Good overlap with BaBar "Y(3940)" values
Would allow only the 0++ assignment

Y(4140) from CDF

Search for B→YK Y→J/ψφ

arXiv:0903.2229





M: 4143.0 ± 2.9 ± 1.2 MeV,
Γ: 11.7 $^{+8.3}_{-5}$ ± 3.7MeV,

Signif. > 3.8σ

Possible $J^{PC}=0^{++},1^{-+},2^{++}$

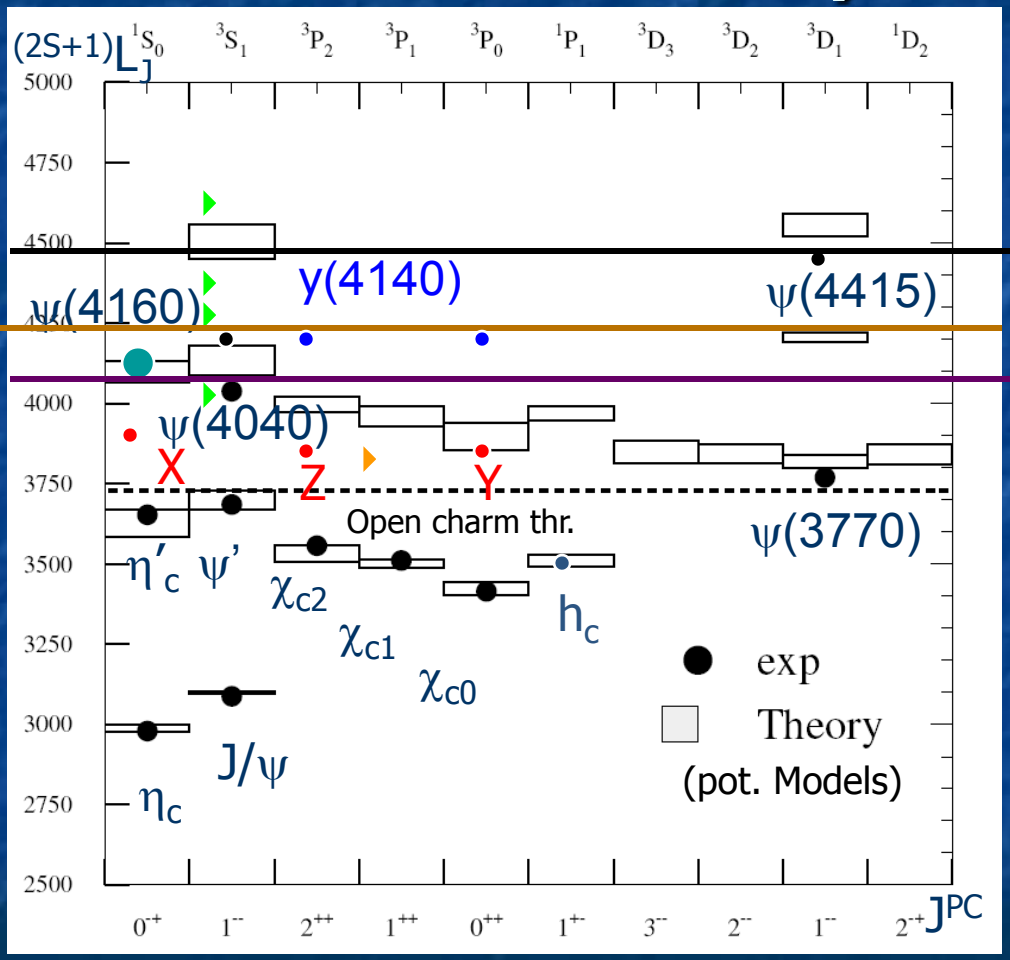
Lowest lying hybrid, expected at m~4200MeV

Another 'edge' state, better candidate molecule

More on the 1^{--} family

Summary

The charged candidates



Z(4430)

Z(4250)

Z(4050)

X(3872) never ending story

One more member of the 3940 family

X(4160)

New state from CDF
Good Hybrid candidate

Outlook

	$J/\psi\pi^+\pi^-$	$D^{(*)}D^{(*)}$	$J/\psi\omega$	$J/\psi\pi^+\pi^0$	$\psi(2S)\pi$	$J/\psi K,\pi$	$\Psi(2S)\pi\pi$	$J/\psi\phi,\eta$	$J/\psi\gamma$
X(3872)	Seen	Seen	Not seen	Not seen	Not seen	No search	N/A	Not seen	Seen
Y(3940)	No Fit	X(3940)?	Seen	No search	Not seen	No search	No search	No Fit	No fit
Y(4260)	Seen	Not Seen	No fit	No search	No search	No search	Not seen	No fit	N/A
Y(4350)	Not seen	No fit	No fit	No search	No search	No search	Seen	No fit	N/A
Z(4430)	No search	No search	No fit	No search	Seen	Not Seen	No search	No Fit	N/A
Y(4660)	Not seen	No fit	No fit	No search	No search	No search	Seen	No Fit	N/A

Plenty of states seen with low stat and in only one channel

➔ next generation [SuperB(elle)?] needed

backup

G. Cibinetto, talk at this conference

Confirmation of Y(3940) ($B \to K \underbrace{\omega J/\psi}_{\pi^+\pi^-\pi^0}$)

New result, based on 350 fb^{-1}:

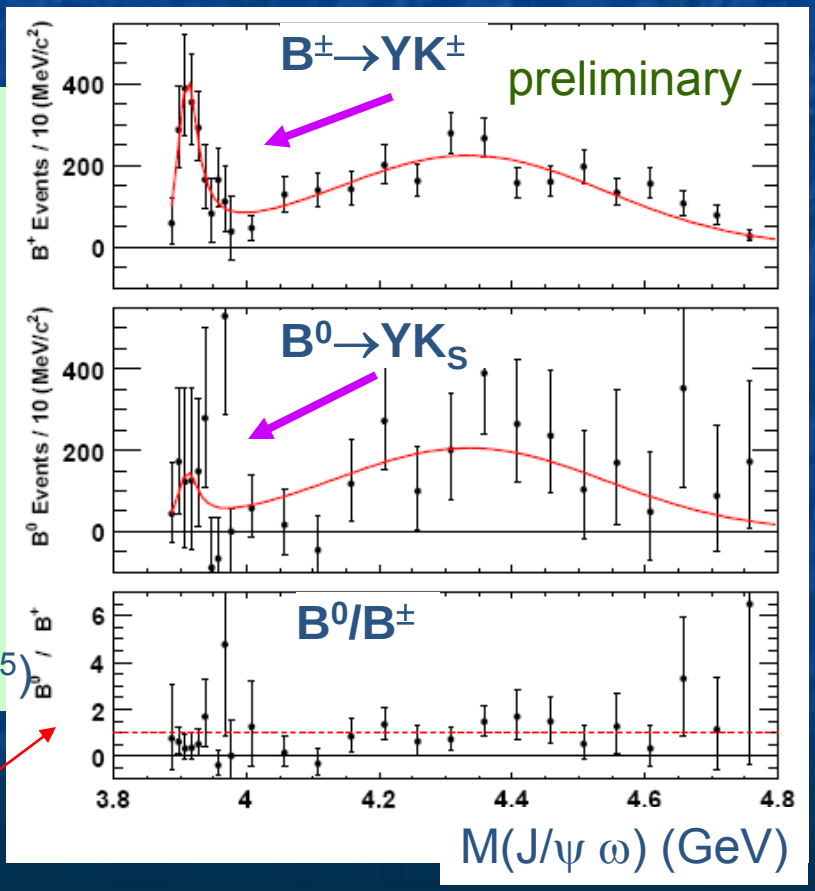
$$M(Y) = (3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst))\ \mathrm{MeV}/c^2\,,$$
$$\Gamma(Y) = (33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst))\ \mathrm{MeV}\,.$$

Belle's evidence for $B \to YK$, $Y \to J/\psi\omega$ confirmed

- ~30MeV lower mass than Belle's
- Narrower width
- Clear demonstration of decay into ω
- Preliminary BF estimate similar to Belle's (~10^{-5})

Y(3940) closer to X(3940)
Can they be the same state?

Isospin cons.



X(4160)→ D*D*

Obtain J/ψD(*)D(*) samples through kinematic separation, look at m(D(*)D(*)) after background subtraction:

$e^+ e^- \rightarrow J/\psi\, D^{(*)}D^{(*)}$

reconstructed

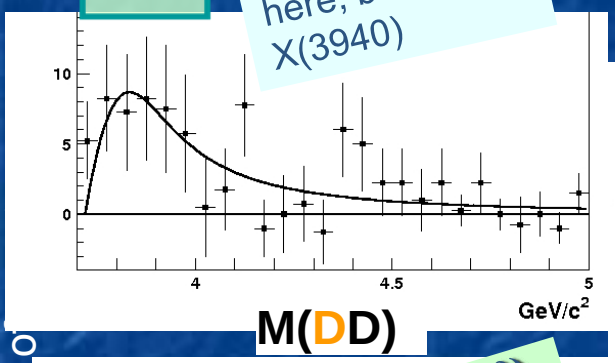
Inferred (Recoil mass)

BELLE-CONF-0705

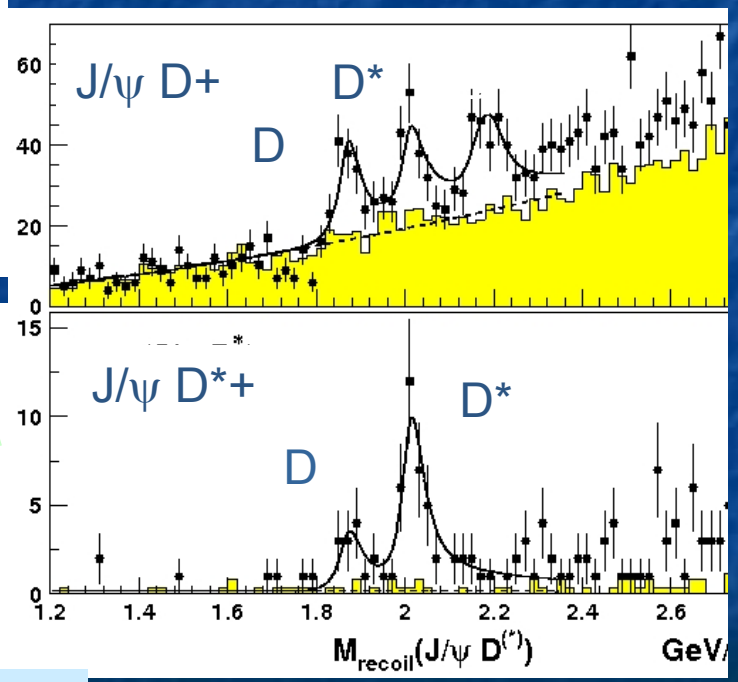
M = 3942 ±6 MeV
Γ_{tot} =37 ±12 MeV
N_{ev}= 52 ±11

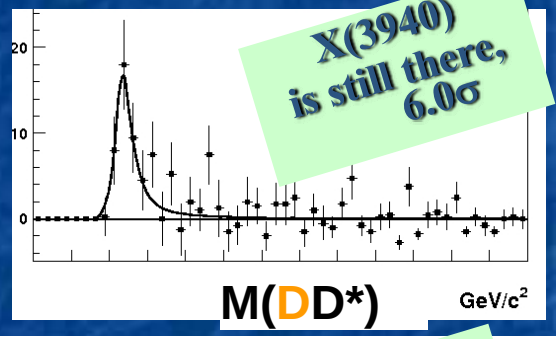
3.8 σ

Something's here, but it's not X(3940)



M(DD)

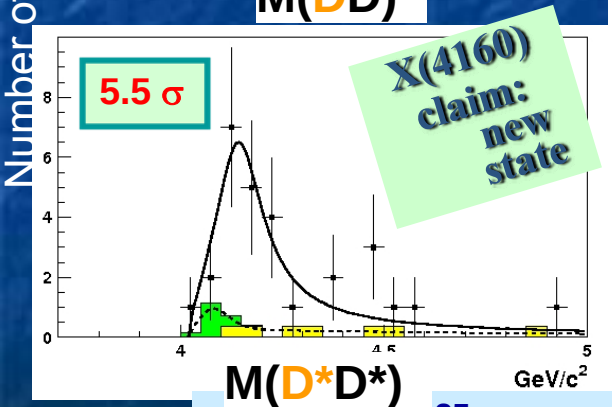




M(DD*)

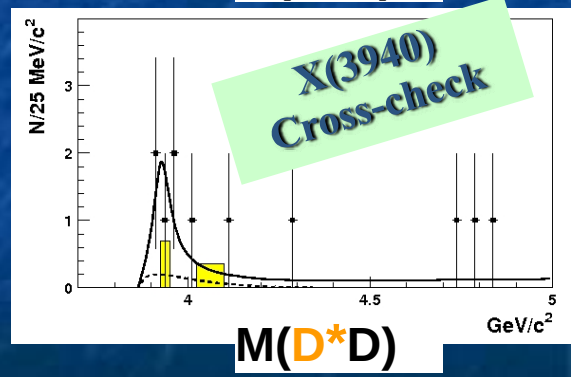
5.5 σ

X(4160) claim: new state



M(D*D*)

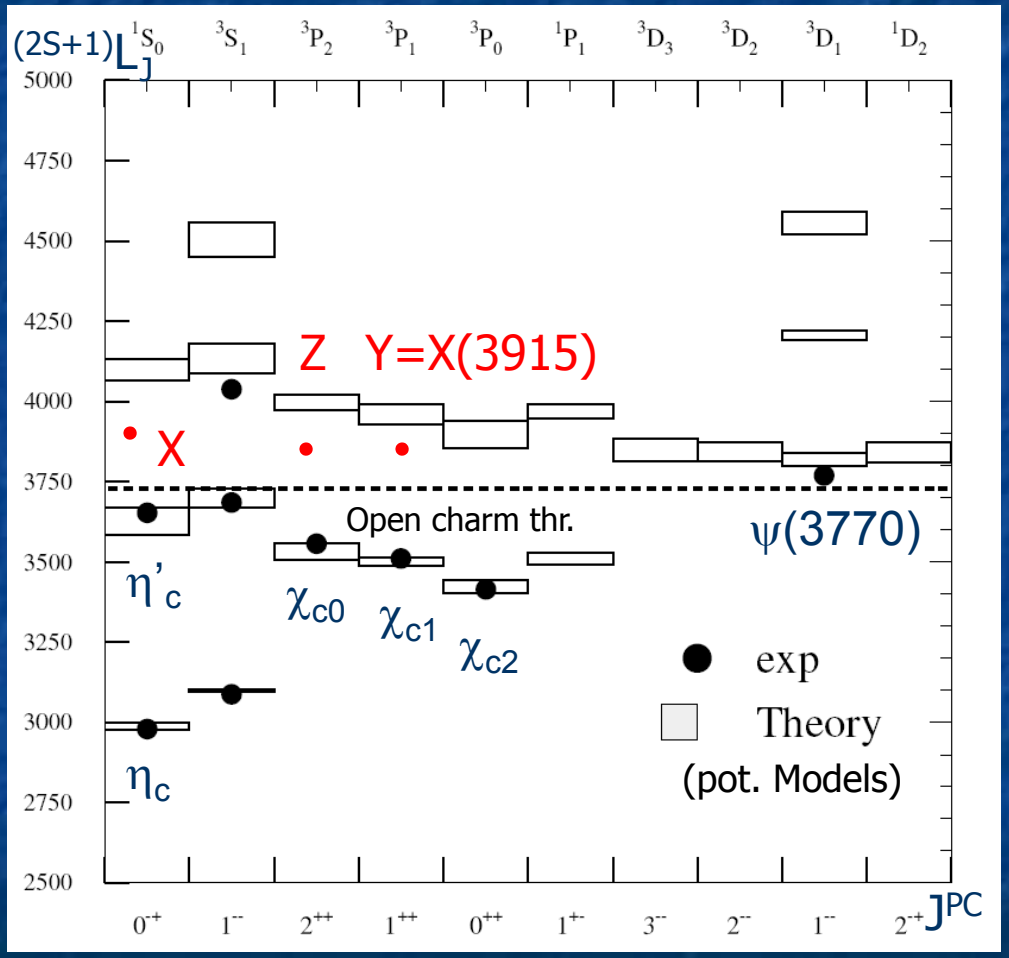
M = 4156 $^{+25}_{-20}$ ±15MeV
Γ_{tot} = 37 $^{+111}_{-61}$ ±21MeV
N_{ev}= 24 $^{+12}_{-8}$



M(D*D)

One more particle to explain …
$J^{CP}=0^{-+}$ not excluded ($\eta_c(3S)$)

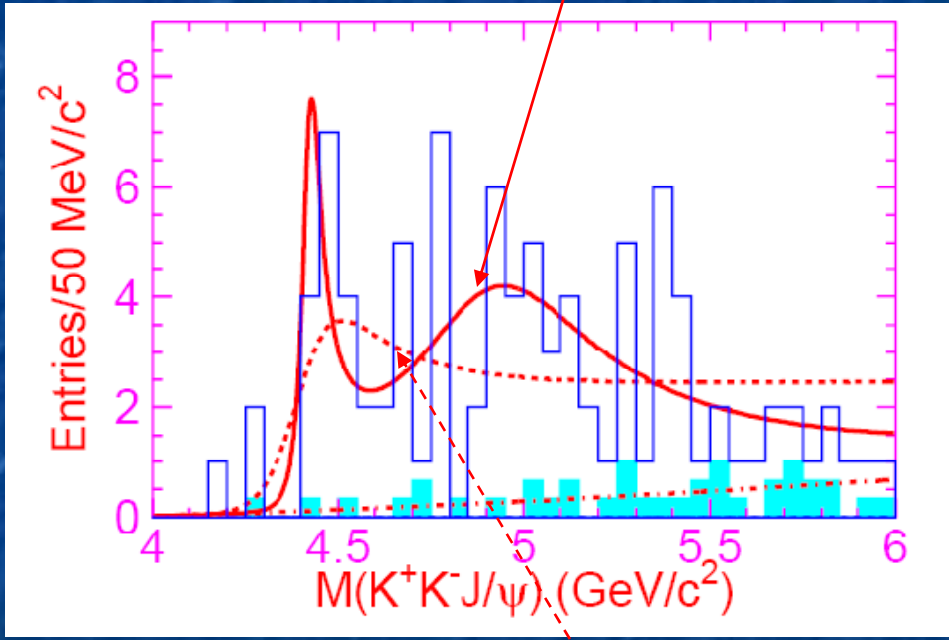
"Just" charmonium states?



- Poor match with predictions
  - Above threshold?
- If X≠Y, difficult to explain absence of Y→open charm
  - Hybrid?

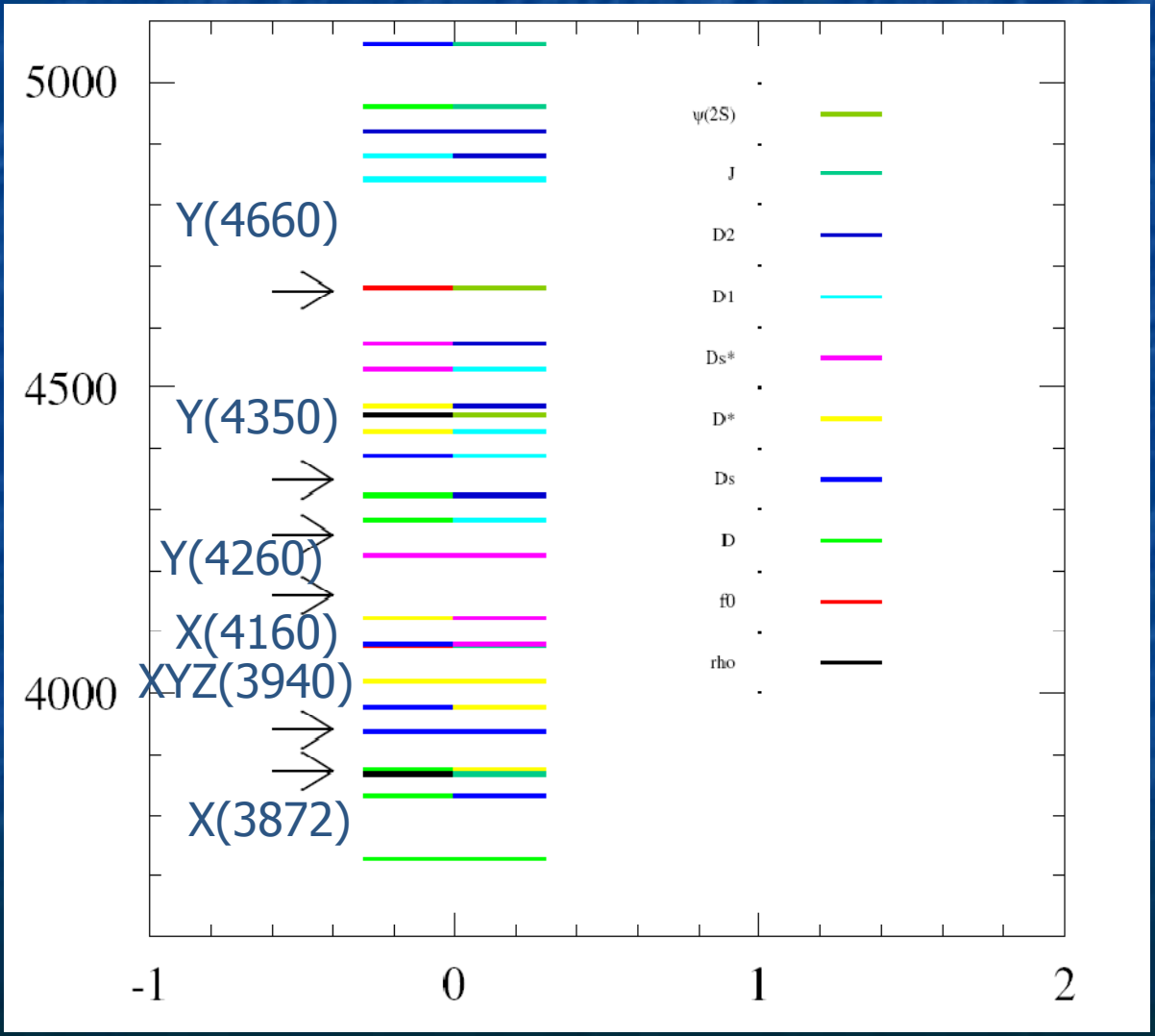
Fits to J/ψ KK invariant mass

'Standard ' y(4415) + 1 BW:
M = (4875±132) MeV
Γ = (630±126) MeV

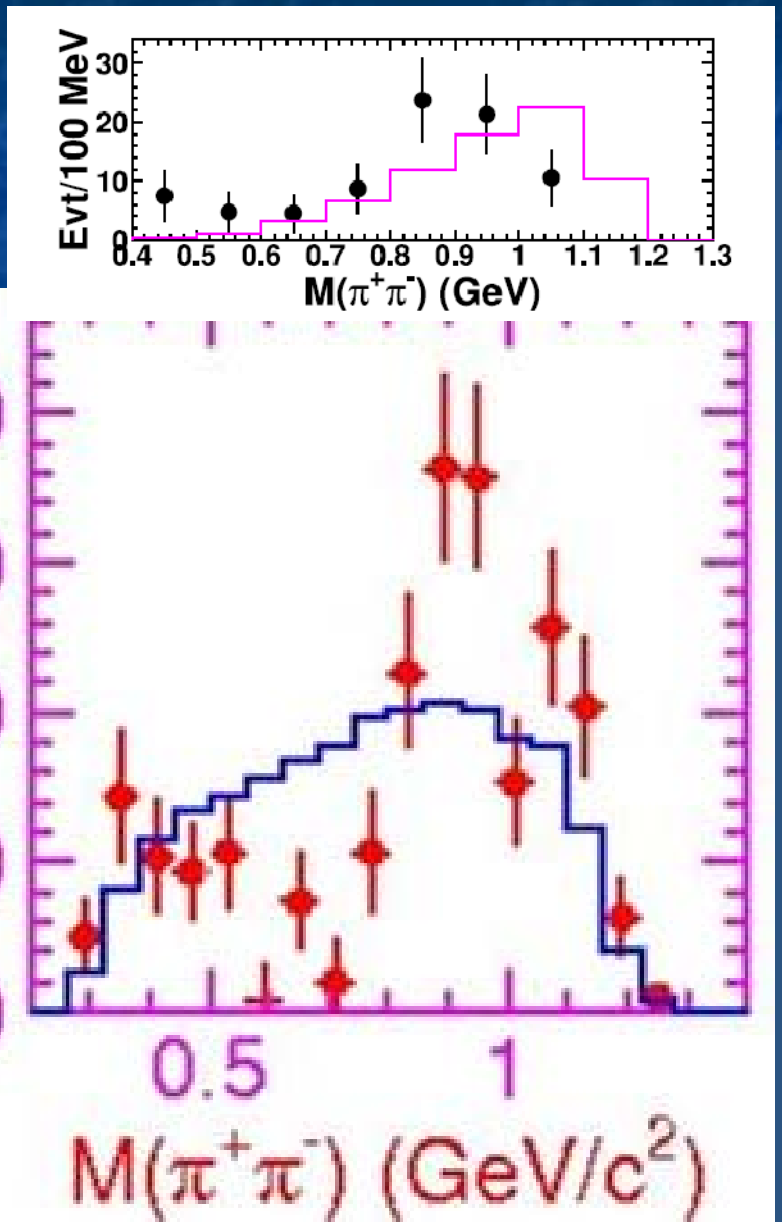


single BW:
M = (4430±38) MeV
Γ = (254±49) MeV

Thresholds and new states



CLEO and Belle on 4260

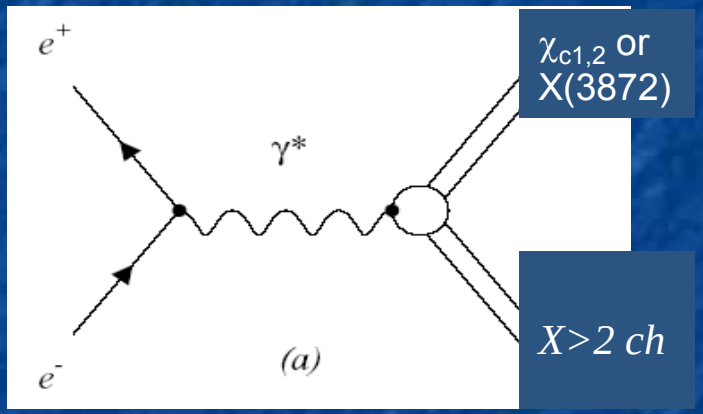


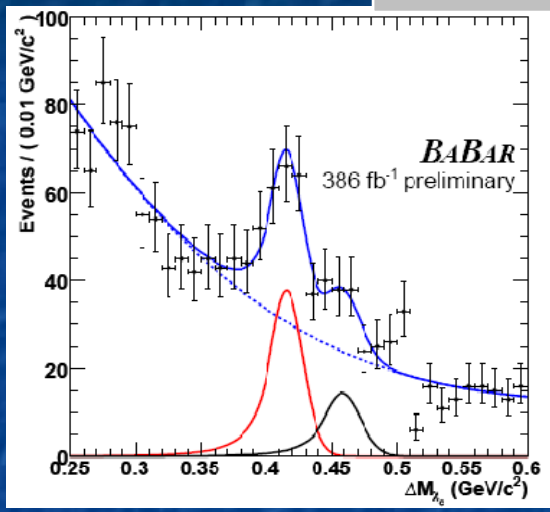
Search for $X(3872) \to J/\psi\,\gamma$ in continuum

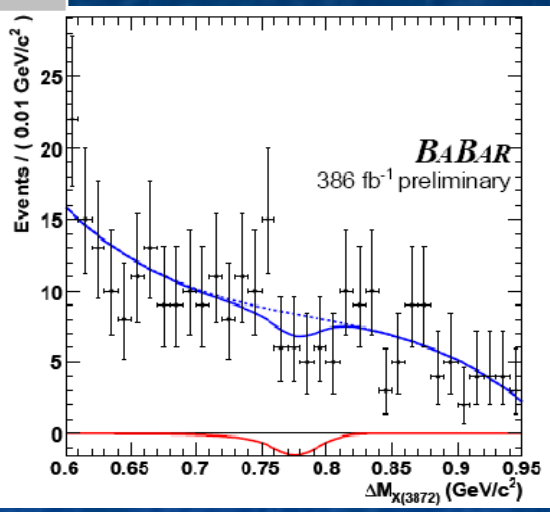
386fb^{-1}

arXiv:0707.1633

J/ψ production observed in continuum while no evidence of χ_c states.







χ_c production is consistent with the expected contributions from prompt $\psi(2S)$ production feed-down to χ_c: no evidence of prompt $\chi_{c1,2}$

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

$$\sigma(e^+e^- \to \chi_{c1,direct}X)\cdot\mathcal{B}(X \to (N_{ch}>2)) = (41.1 \pm 18.0 \pm 20.6)\ \text{fb}$$
$$(< 77\ \text{fb}\ @90\%\ C.L.),$$
$$\sigma(e^+e^- \to \chi_{c2,direct}X)\cdot\mathcal{B}(X \to (N_{ch}>2)) = (23.2 \pm 27.7 \pm 26.1)\ \text{fb}$$
$$(< 79\ \text{fb}\ @90\%\ C.L.).$$

$$\sigma(e^+e^- \to X(3872)X)\cdot\mathcal{B}(X(3872) \to \gamma J/\psi)\cdot\mathcal{B}(X \to (N_{ch}>2))$$
$$= (-2.7 \pm 3.7 \pm 1.0)\ \text{fb} \quad (< 5.1\ \text{fb}\ @90\%\ C.L.).$$

Samples used in results

Experiments

58MJ/ψ, 14M ψ(2S)

- e^+e^- →Charmonium (CLEO-c, BES-II)

3M ψ(2S), 1.8 M ψ(3770)

  - $L\sim10^{33}/cm^2/s$
  - E=3.0-4.3 GeV

657M Y(4S)

- e^+e^- → Y(4S): (BaBar, Belle, CLEO)

383M Y(4S) 1.5M Y(1S),1.9M Y(2S), 1.7M Y(3S),9M Y(4S)

  - $L\sim10^{34}/cm^2/s$
  - Charmonium in B decays, ISR and γγ production
    - Capability to measure J^{PC} also in production
- $p\bar{p}$ colliders (CDF, D0)

1.3 fb^{-1}

2.4bf-1

  - High Xsection → copious production
  - Extremely high backgrounds

Disclamers:
- time is very short
  → could not cover everything
- theory statements are indicative