Charmonium(-like) states at Belle

10th particle physics workshop of China

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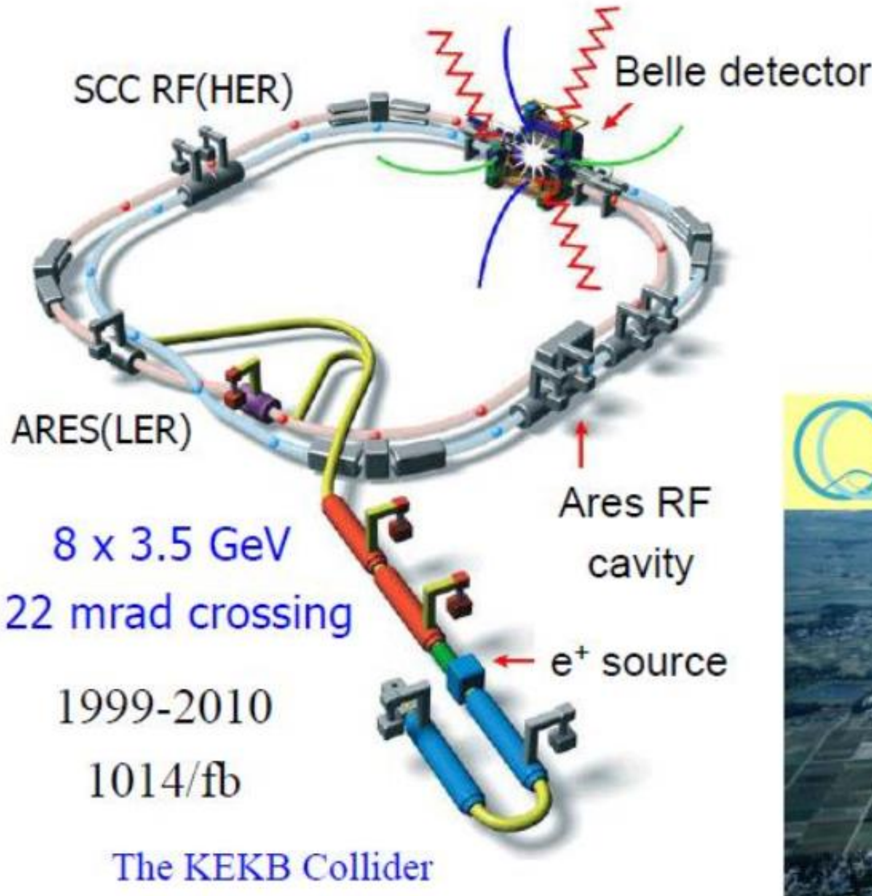
Outline

- Belle Experiment
- Introduction
- New results of Belle
- Summary

Belle Experiment

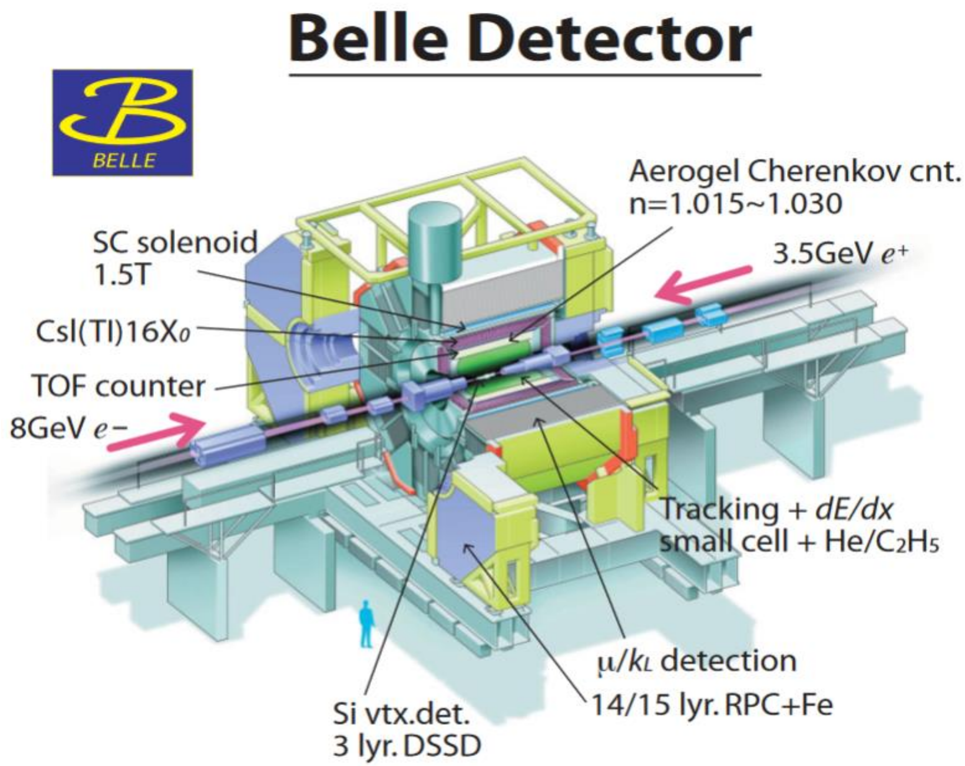
KEKB: world highest luminosity e+e− collider

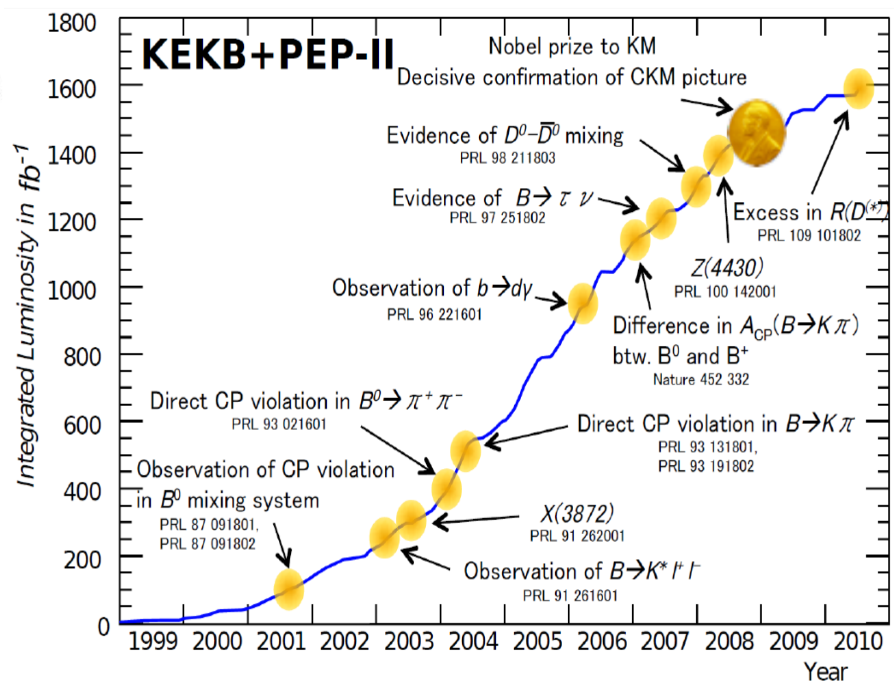


World record:

$L = 2.1 \times 10^{34}/cm^2/sec$

Belle Experiment





Charmonium production:

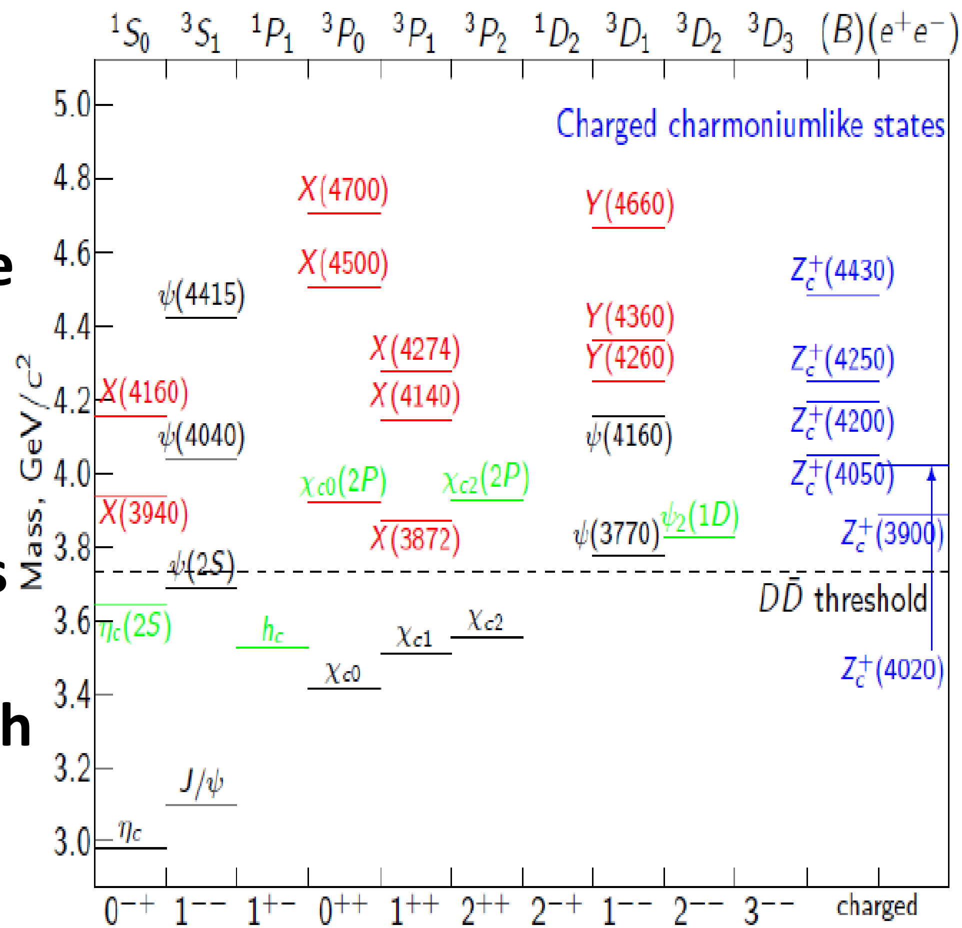
- B decay ~711 fb^{-1} Υ(4S)
- Bottomonium decay
- Double charmonium production

Charmonium(-like) states

- $c\bar{c}$ bound states described well with potential models below $D\bar{D}$ threshold.

- Several unpredicted states have been reported above $D\bar{D}$ threshold: **XYZ** ?

- To understand their nature, it is necessary to study their production processes along with their decay channels.



PRD.32.189

$\Upsilon(1S) \to XYZ$ + Anythings

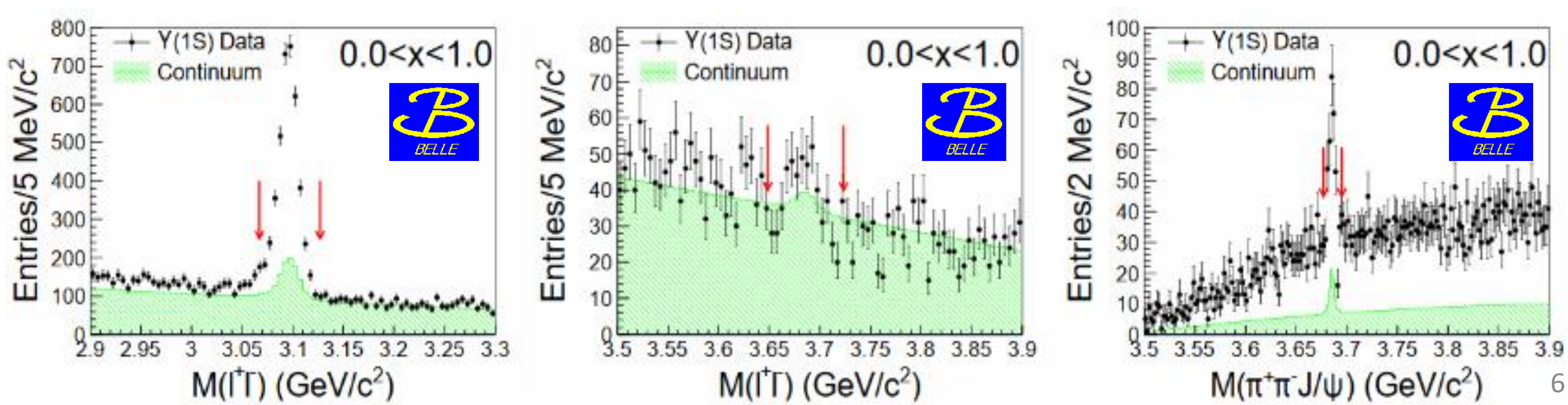
PRD 93, 112013 (2016)

- XYZ states always decay into a charmonium state such as J/ψ or $\psi(2S)$ and light hadrons.
- $\mathfrak{B}(\Upsilon(1S) \to J/\psi(\psi(2S)) + anythings) \sim 10^{-4}$
- World largest 102×10^6 $\Upsilon(1S)$ sample in Belle
- Reconstruct J/ψ or $\psi(2S)$ firstly, then combine them with K or π to search: X(3872),

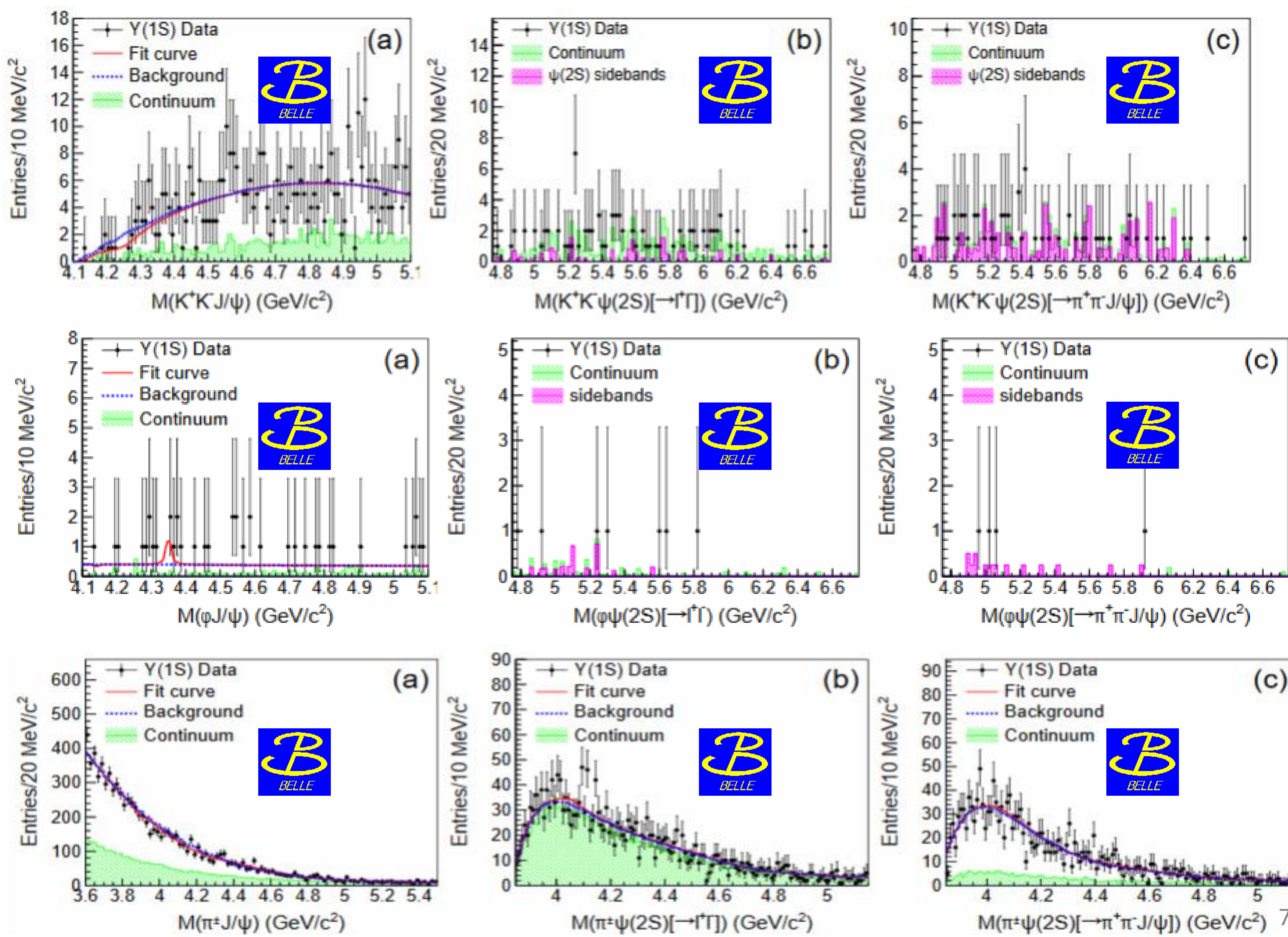
  Y(4260), Y(4360), Y(4660), Y(4140), Y(4350),

  Zc(3900),Zc(4200), Zc(4050), Zc(4430)

  Zcs



$\Upsilon(1S) \rightarrow XYZ$ + Anythings



$\Upsilon(1S) \rightarrow XYZ$ + Anythings

$$\mathfrak{B}_R^{prod} = \mathfrak{B}(\Upsilon(1S) \rightarrow XYZ + anythings)\mathfrak{B}(ZYX \rightarrow J/\psi(\psi(2S)) + hadrons)$$

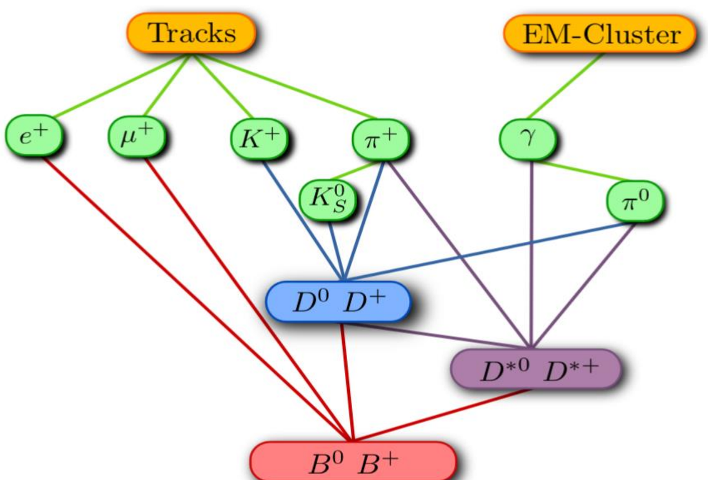
State	$N_{\rm fit}$	$N_{\rm up}$	$\varepsilon(\%)$	$\sigma_{\rm syst}(\%)$	$\Sigma(\sigma)$	$\mathcal{B}_R^{\rm prod}$
$X(3872) \rightarrow \pi^+\pi^- J/\psi$	4.8 ± 15.4	31.4	3.26	18.7	0.3	$< 9.5 \times 10^{-6}$
$Y(4260) \rightarrow \pi^+\pi^- J/\psi$	-31.1 ± 88.9	134.6	3.50	35.6	–	$< 3.8 \times 10^{-5}$
$Y(4260) \rightarrow \pi^+\pi^- \psi(2S)$	6.7 ± 29.4	56.9	0.71	35.0	0.2	$< 7.9 \times 10^{-5}$
$Y(4360) \rightarrow \pi^+\pi^- \psi(2S)$	-25.4 ± 30.1	45.6	0.86	50.0	–	$< 5.2 \times 10^{-5}$
$Y(4660) \rightarrow \pi^+\pi^- \psi(2S)$	-55.0 ± 26.2	23.1	1.06	40.7	–	$< 2.2 \times 10^{-5}$
$Y(4260) \rightarrow K^+K^- J/\psi$	-13.7 ± 10.9	14.5	1.91	45.8	–	$< 7.5 \times 10^{-6}$
$Y(4140) \rightarrow \phi J/\psi$	-0.1 ± 1.2	3.6	0.69	11.0	–	$< 5.2 \times 10^{-6}$
$X(4350) \rightarrow \phi J/\psi$	2.3 ± 2.5	7.6	0.92	10.4	1.2	$< 8.1 \times 10^{-6}$
$Z_c(3900)^\pm \rightarrow \pi^\pm J/\psi$	-26.5 ± 39.1	57.5	4.39	47.3	–	$< 1.3 \times 10^{-5}$
$Z_c(4200)^\pm \rightarrow \pi^\pm J/\psi$	-238.6 ± 154.2	235.1	3.87	48.4	–	$< 6.0 \times 10^{-5}$
$Z_c(4430)^\pm \rightarrow \pi^\pm J/\psi$	94.2 ± 71.4	195.8	3.97	34.4	1.2	$< 4.9 \times 10^{-5}$
$Z_c(4050)^\pm \rightarrow \pi^\pm \psi(2S)$	37.0 ± 47.7	112.7	1.27	46.2	0.4	$< 8.8 \times 10^{-5}$
$Z_c(4430)^\pm \rightarrow \pi^\pm \psi(2S)$	23.2 ± 42.4	92.0	1.35	47.1	0.1	$< 6.7 \times 10^{-5}$
$Z_{cs}^\pm \rightarrow K^\pm J/\psi$	-22.2 ± 17.4	22.4	3.88	48.7	–	$< 5.7 \times 10^{-6}$

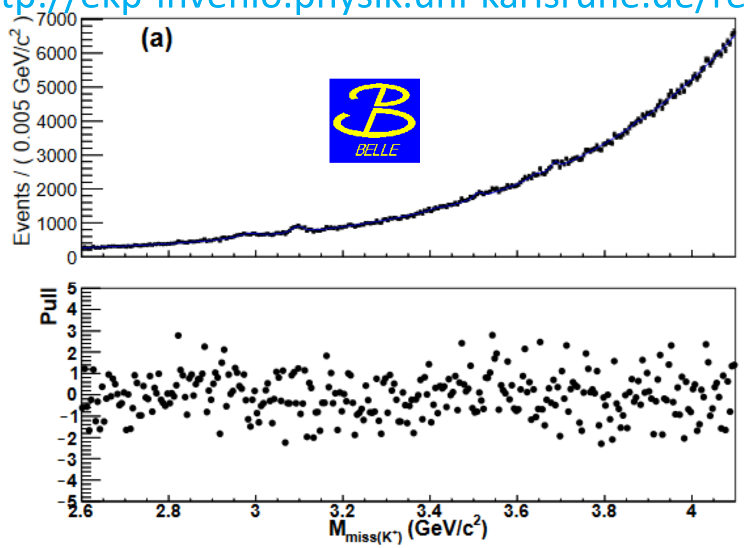
$B^+ \to X_{c\bar{c}}K^+$

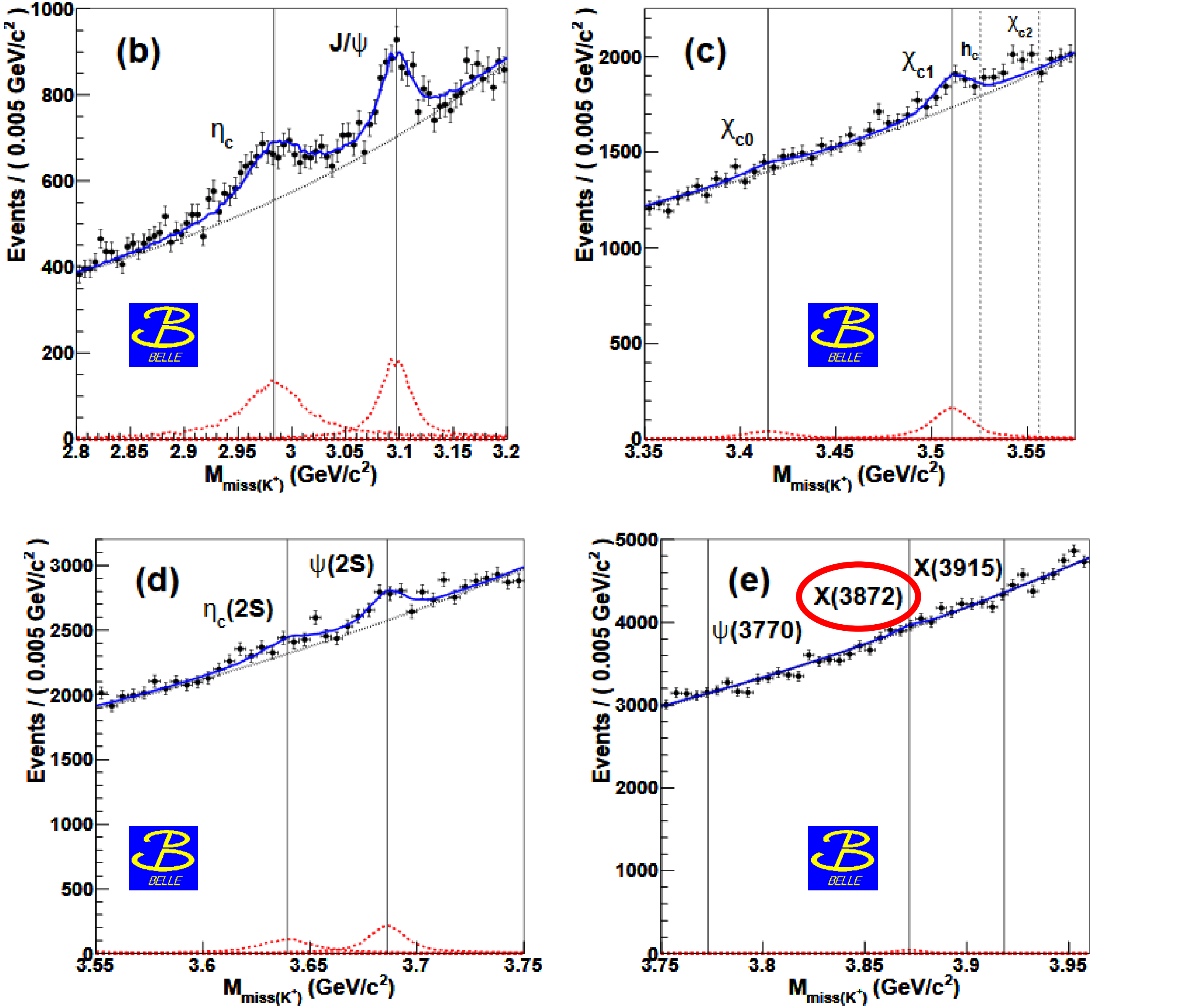
PRD 97, 012005 (2018)

- X(3872) : Admixture of a molecular state and $\chi_{c1}(2P)$? Need $\mathcal{B}(B^+ \to X(3872)K^+)$ to confirm PLB.702.359 (2011)
- World largest 772×10^6 $B\bar{B}$ pairs sample in Belle
- $X_{c\bar{c}} = \eta_c, J/\psi, \chi_{c0}, \chi_{c1}, \eta_c(2S), \psi(2S), \psi(3770)$ X(3872), X(3915)
- Neural network based hierarchical hadronic full reconstruction algorithm applied to tag a B meson.

See: http://ekp-invenio.physik.uni-karlsruhe.de/record/48181







(b)
J/ψ
η_c
Events / (0.005 GeV/c²)
M_miss(K+) (GeV/c²)
(c)
χ_c0
χ_c1
h_c
χ_c2
Events / (0.005 GeV/c²)
M_miss(K+) (GeV/c²)
(d)
ψ(2S)
η_c(2S)
Events / (0.005 GeV/c²)
M_miss(K+) (GeV/c²)
(e)
X(3872)
X(3915)
ψ(3770)
Events / (0.005 GeV/c²)
M_miss(K+) (GeV/c²)
BELLE

$B^+ \rightarrow X_{c\bar{c}}K^+$

Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-

Need more data or **more advanced algorithm**

Belle2

Full Event Interpretation (FEI)

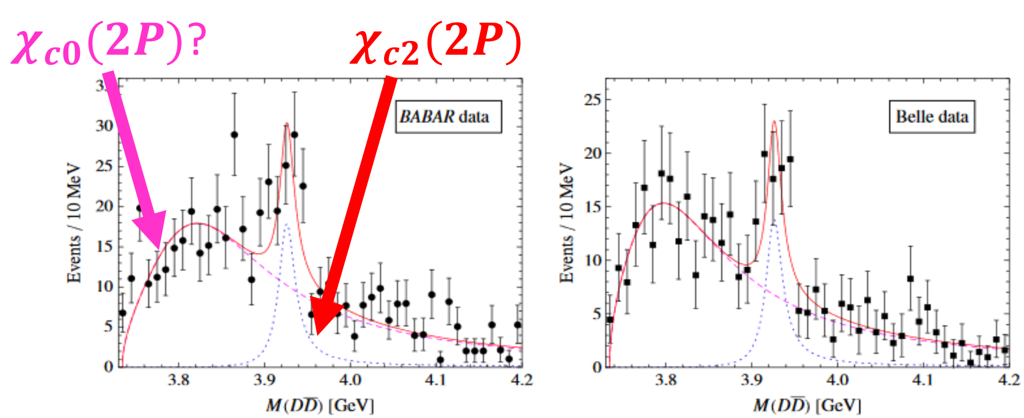
$e^+e^- \to J/\psi D\bar{D}$

PRD 95 112003 (2017)

- X(3915): find in its decay into $\omega J/\psi$, $J^{PC} = 0^{++}$
  - Was identified as $\chi_{c0}(2P)$.
  - Strong decay $\chi_{c0}(2P) \to D\bar{D}$ is expected to be the dominant decay($\Gamma \gtrsim 100MeV$).

    PRD 86, 091501 (2012),
    PRD 69, 094019 (2004)
  - But **not observed** for X(3915) ($\Gamma = 20 \pm 5MeV$)
  - $\chi_{c0}(2P) \to \omega J/\psi$ is OZI suppressed
- Where is $\chi_{c0}(2P)$? => double-charmonium production in association with the J/ψ (C = +1)

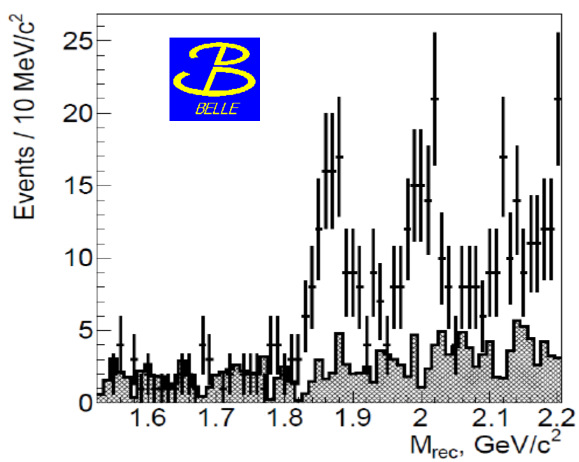
$\gamma\gamma \to D\bar{D}$

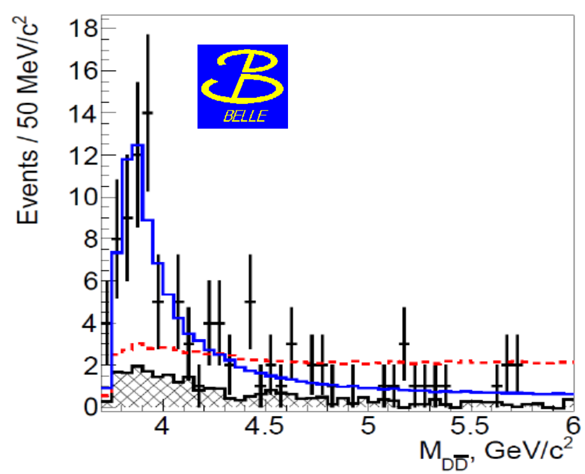


$e^+e^- \to J/\psi D\bar{D}$

PRD 95 112003 (2017)

- **Reconstruct:**
  - $J/\psi \to \ell\ell$
  - one $D^0 \to K^-\pi^+,\ K_S^0\pi^+\pi^-,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^-\pi^+$
    or $D^+ \to K_S^0\pi^+,\ K^-\pi^+\pi^+,\ K_S^0\pi^+\pi^0,\ K^-\pi^+\pi^-\pi^0$
    $K_S^0\pi^+\pi^+\pi^-$
  - require $J/\psi D$ recoil mass in D region
  - mass constraints fit for J/ψ , D
- **Multivariate analysis used: MLP mode**



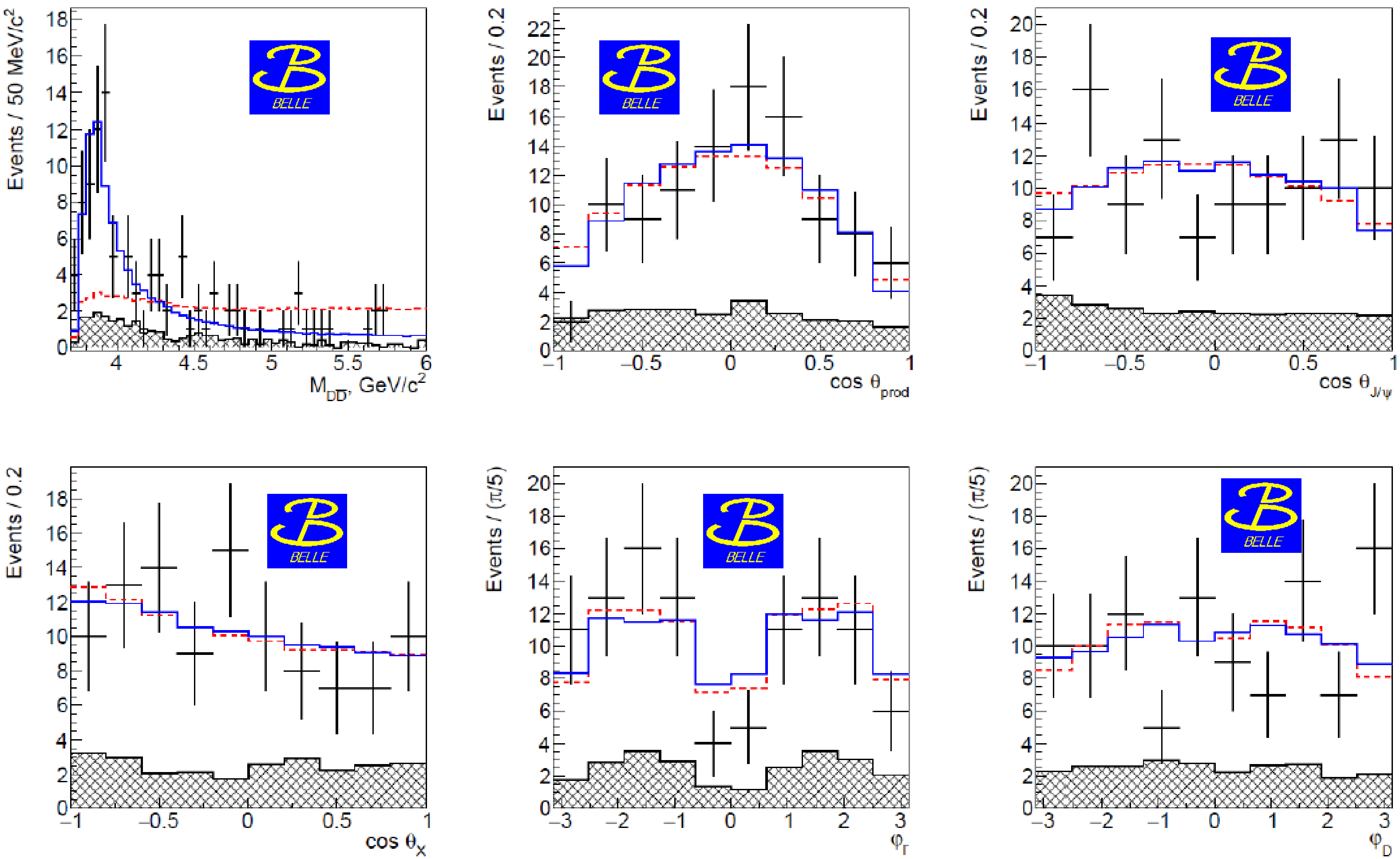


$e^+e^- \to J/\psi D\bar{D}$

PRD 95 112003 (2017)

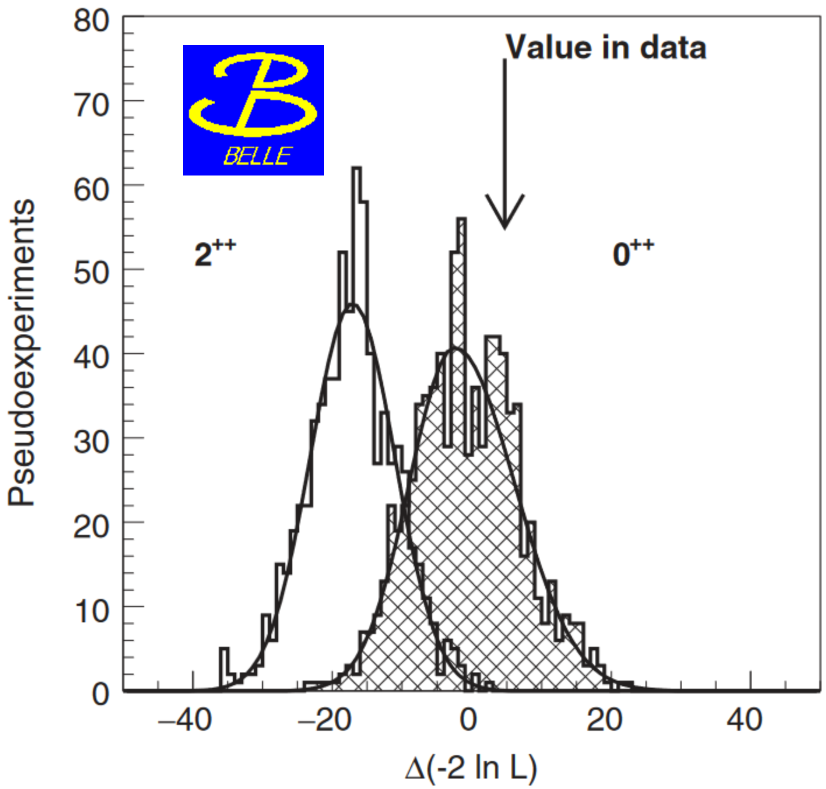
$X^*(3860)$ Or $\chi_{c0}(2P)$??

PWA of the data, blue lines are fit with X*



$e^+e^- \to J/\psi D\bar{D}$

PRD 95 112003 (2017)



$Mass: 3862^{+26+40}_{-32-13}\ MeV$

$width: 201^{+154+88}_{-\ 67-82}\ MeV$

$X^*(3860)$ Or $\chi_{c0}(2P)$??

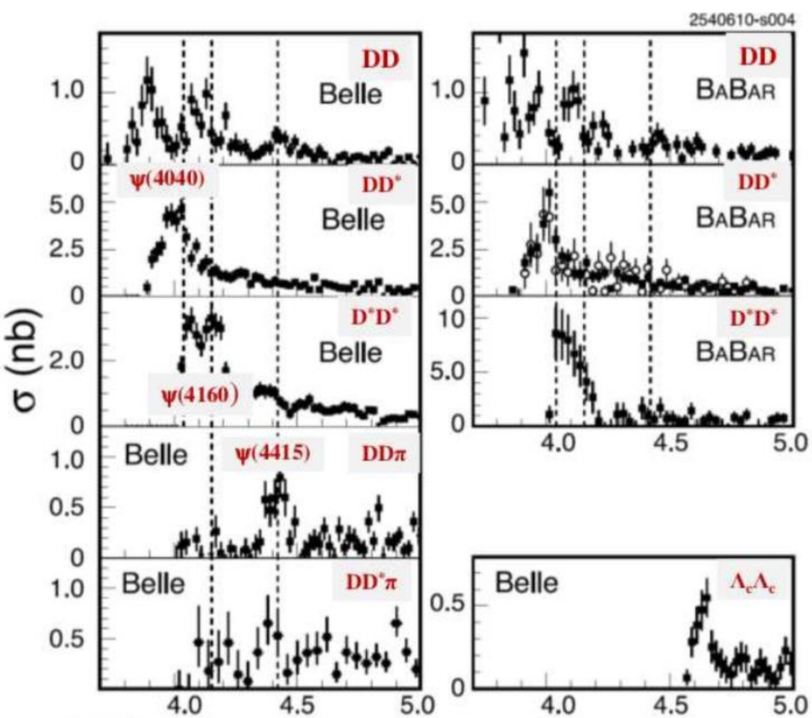
$J^{PC} = 0^{++}$ favored over the 2^{++} hypothesis at the level of 2.5σ

$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$ aka $X(3872)$	$0^+(1^{++})$
• $Z_c(3900)$ was $X(3900)$	$1^+(1^{+-})$
• $X(3915)$ was $\chi_{c0}(3915)$	$0^+(0$ or $2^{++})$

Angular analysis of $e^+e^- \to \gamma_{ISR} D^{(*)\pm} D^{*\mp}$

PRD 97, 012002 (2018)

- $\sigma(e^+e^- \to hadrons)$ **measured past are model-dependent with large uncertainties.**
- **Vector Charmonium state (ψ's) above open charm threshold are not fully understood**



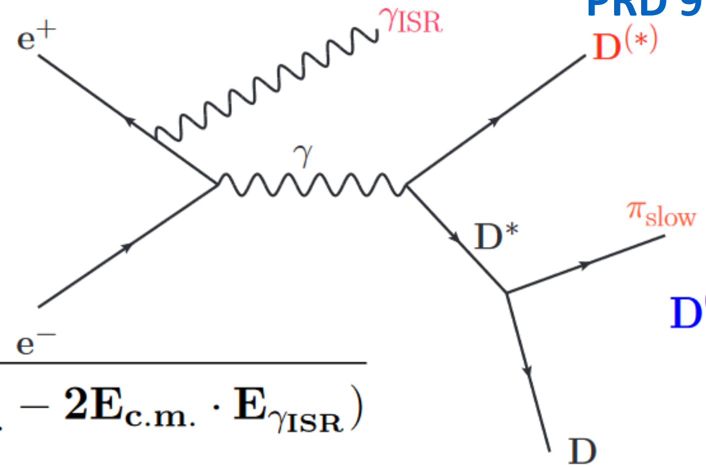
- **Belle and BaBar results agree with each other**
- **Statistics is too low to study the structure of the cross sections**
  - **More accuracy of cross section measurements**
  - **measure separately cross sections for all 3 possible** $D^{(*)\pm}D^{*\mp}$ **helicity combination**

Angular analysis of $e^+e^- \to \gamma_{ISR} D^{(*)\pm} D^{*\mp}$

PRD 97, 012002 (2018)

Method

- Partial reconstruction
- Reconstruct D^*, γ_{ISR} and π_{slow}
- $M(D^{(*)+}D^{*-}) \equiv M_{recoil}(\gamma_{ISR})$

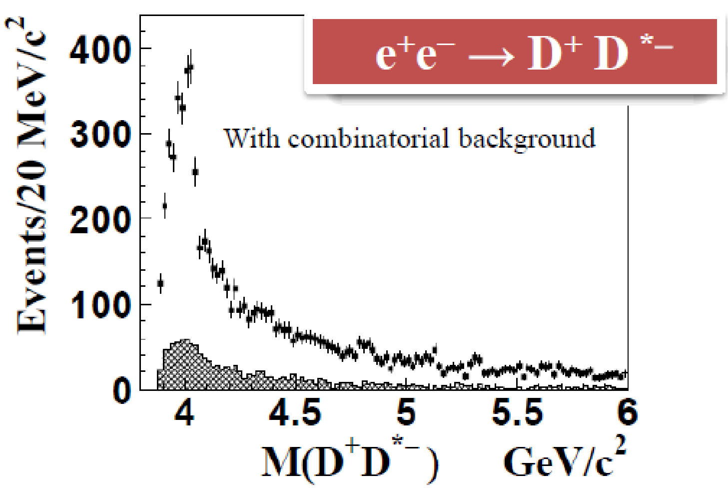


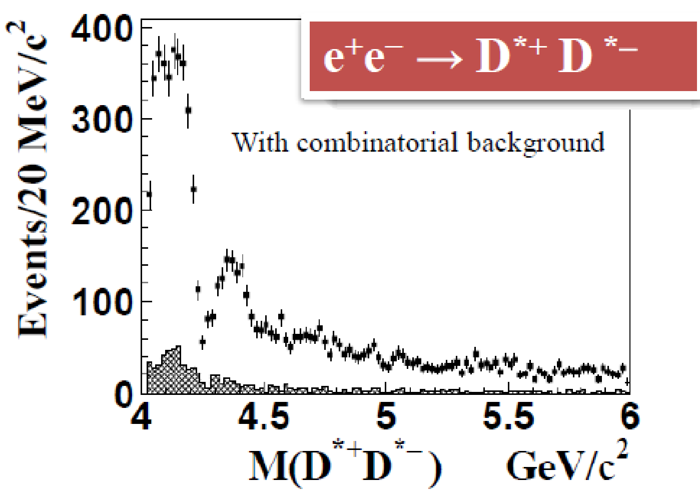
$$M_{recoil}(\gamma_{ISR}) = \sqrt{(E^2_{c.m.} - 2E_{c.m.} \cdot E_{\gamma_{ISR}})}$$

D^0 decay channels:

1. $K^-\pi^+$
2. K^-K^+
3. $K^-\pi^-\pi^+\pi^+$
4. $K^0_S\pi^+\pi^-$
5. $K^-\pi^+\pi^0$
6. $K^0_S K^+K^-$
7. $K^0_S\pi^0$
8. $K^-K^+\pi^-\pi^+$
9. $K^0_S\pi^+\pi^-\pi^0$

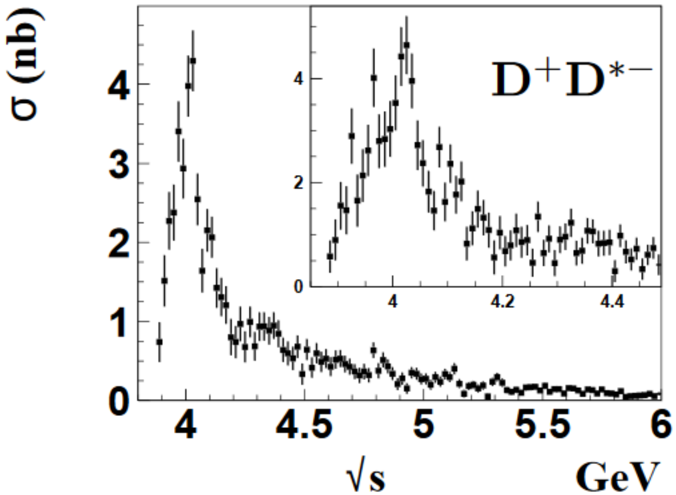
951 fb^{-1} data

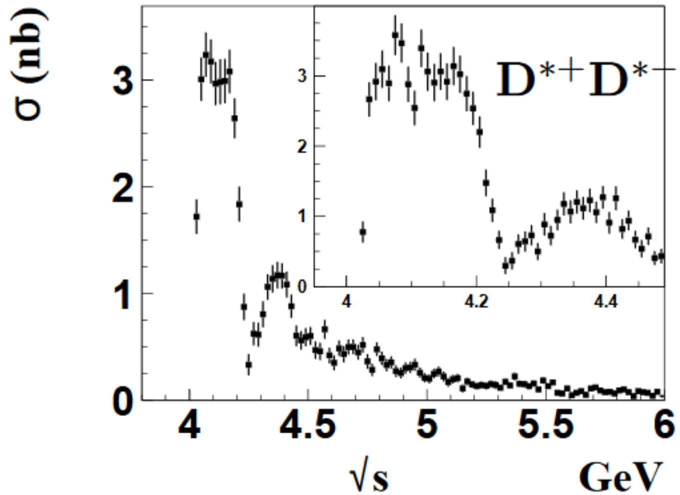




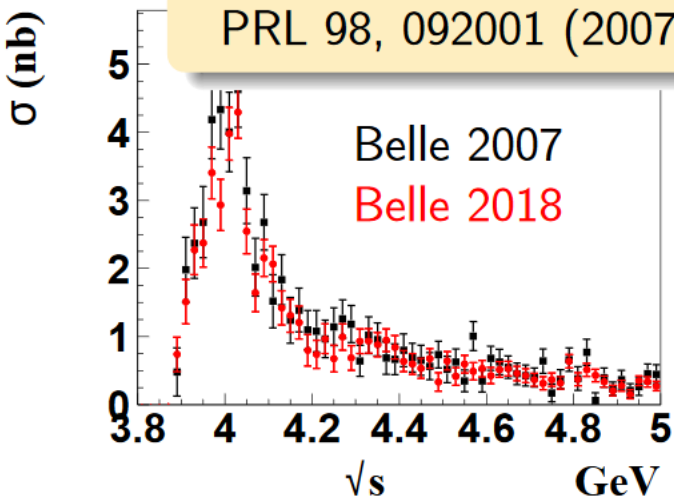
Angular analysis of $e^+e^- \to \gamma_{ISR} D^{(*)\pm} D^{*\mp}$

PRD 97, 012002 (2018)

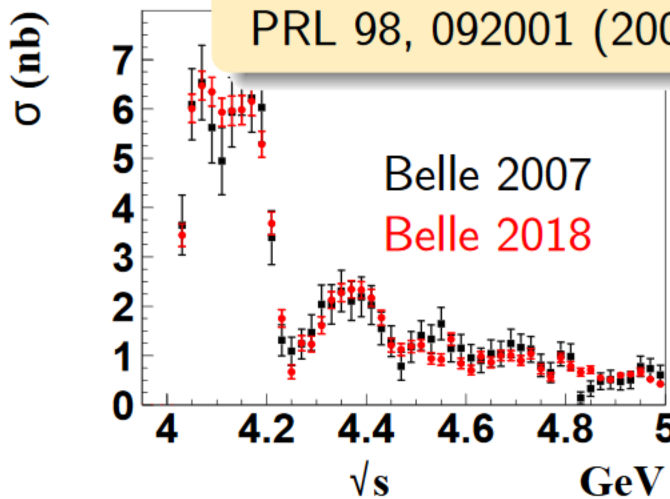




PRL 98, 092001 (2007)



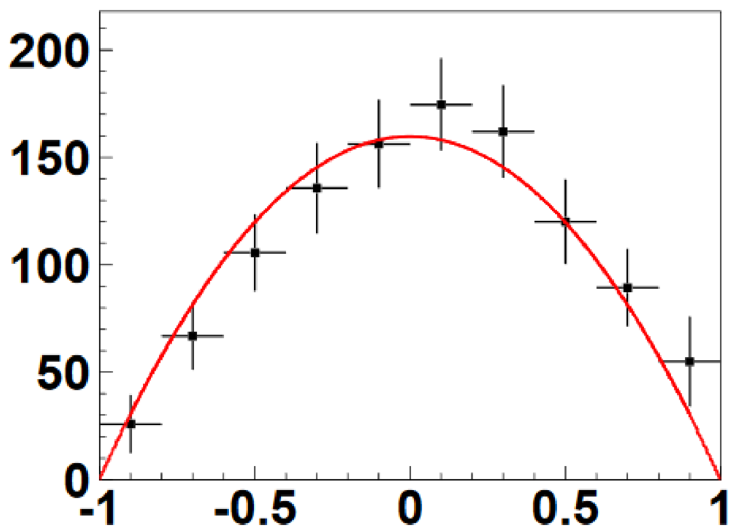
PRL 98, 092001 (2007)

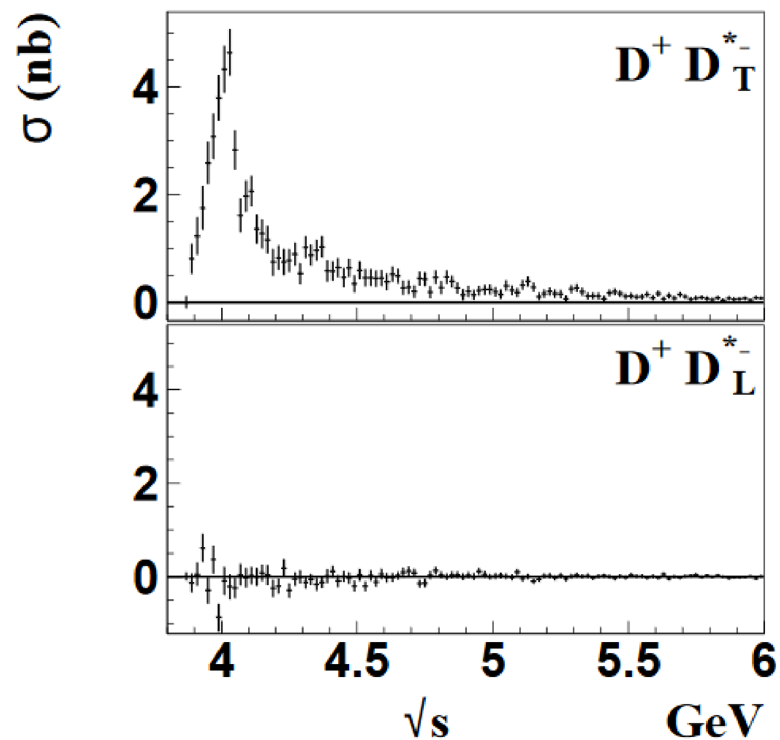


Angular analysis of the process $e^+e^- \to D^+D^{*-}$

- Study D^* helicity angle distribution in each bin of $M(D^+D^{*-})$
- D^* are transversely polarized
  $\Longrightarrow$ Check method

$4.05 < M(D^+D^{*-}) < 4.3\text{GeV}/c^2$



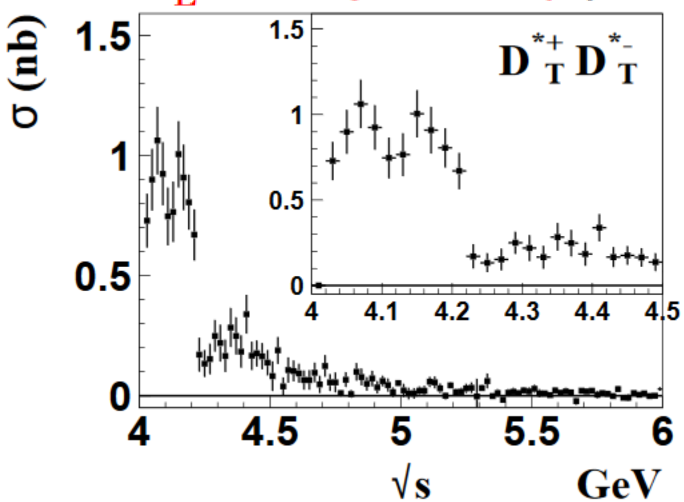


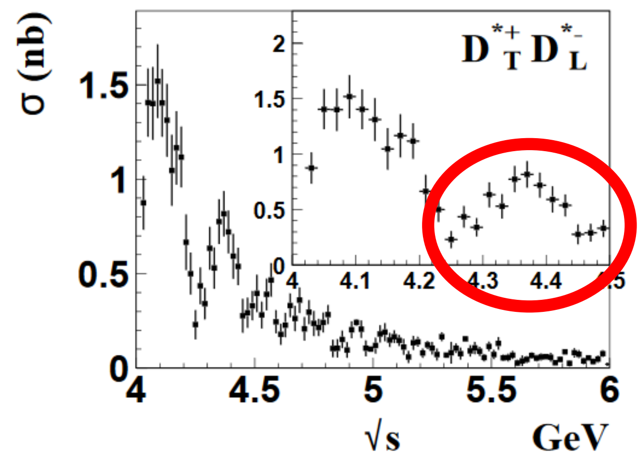
Angular analysis of the process $e^+e^- \to D^{*+}D^{*-}$

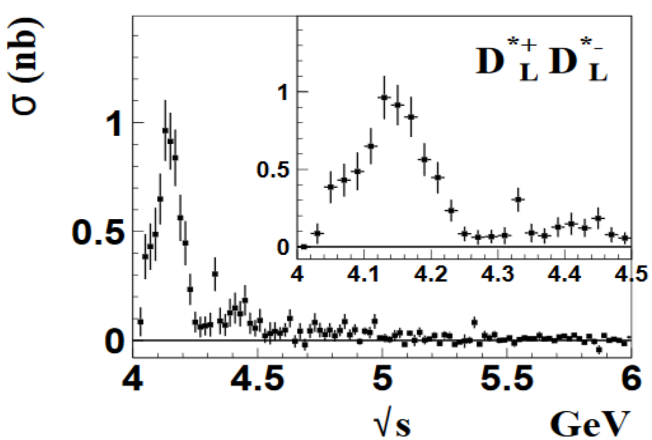
- Study of the D^* helicity angle distribution in each bin of $M(D^{*+}D^{*-})$
- Helicity composition of the $D^{*+}D^{*-}$ final state:

$$D_T^{*+}D_T^{*-},\ D_T^{*+}D_L^{*-}\ \text{and}\ D_L^{*+}D_L^{*-}$$

  - $D_T^* \equiv$ transversely polarized D^* meson
  - $D_L^* \equiv$ longitudinally polarized D^* meson







- not trivial too fit the cross section because of the threshold and coupled-channels effects
- Only TL Helicity of $e^+e^- \to \gamma_{ISR} D^{*\pm} D^{*\mp}$ have the component at higher energy

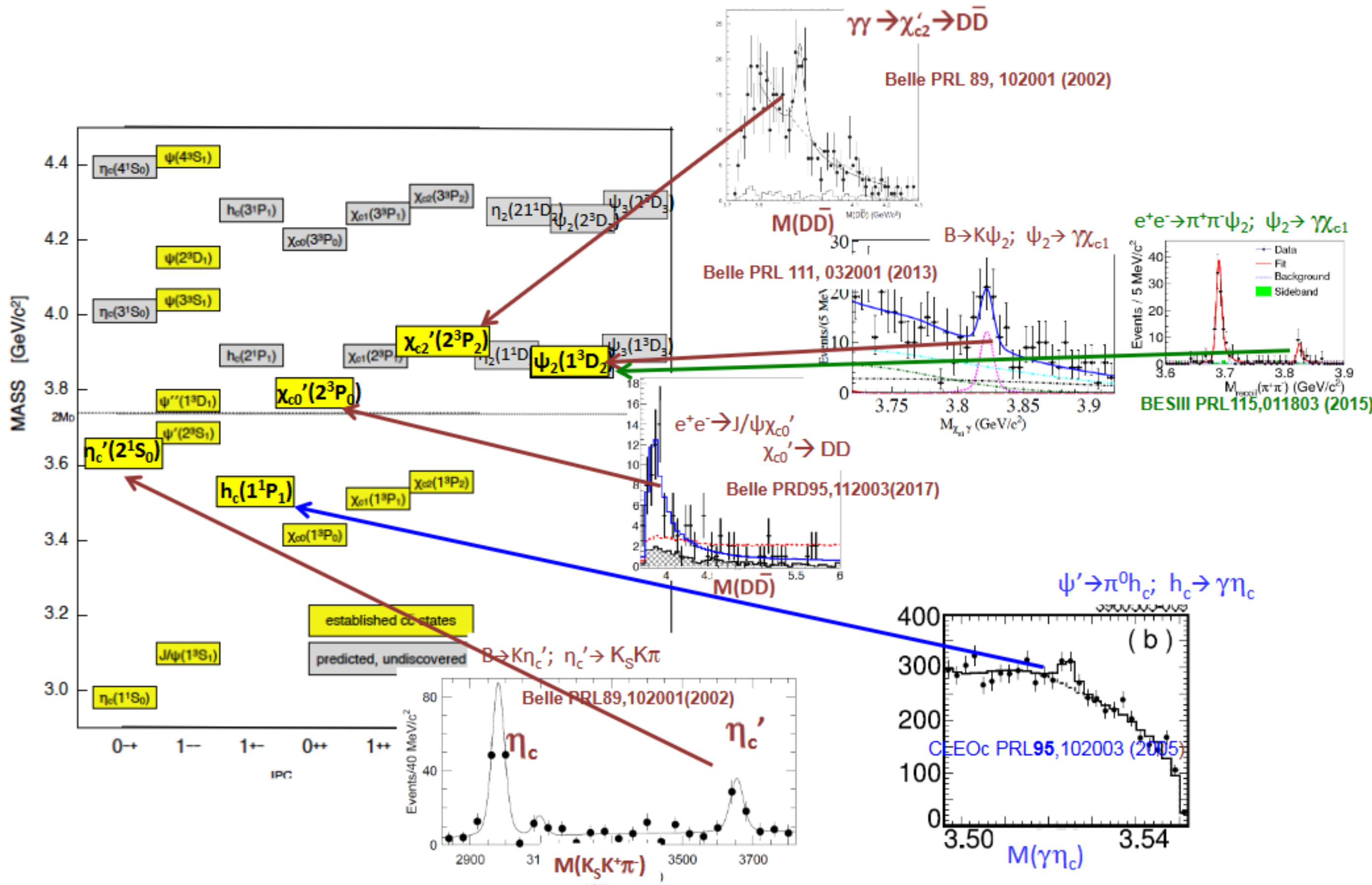
Summary

- ◆$\Upsilon(1S)$ →XYZ + Anythings
  No XYZ was found
- ◆$B^+ \rightarrow X_{c\bar{c}}K^+$
  No X(3872) signal
- ◆$e^+e^- \rightarrow J/\psi D\bar{D}$
  observation of $X^*(3860)$ Or $\chi_{c0}(2P)$
- ◆*Angular analysis of* $e^+e^- \rightarrow \gamma_{ISR}D^{(*)\pm}D^{*\mp}$
  Helicity-dependent structure?

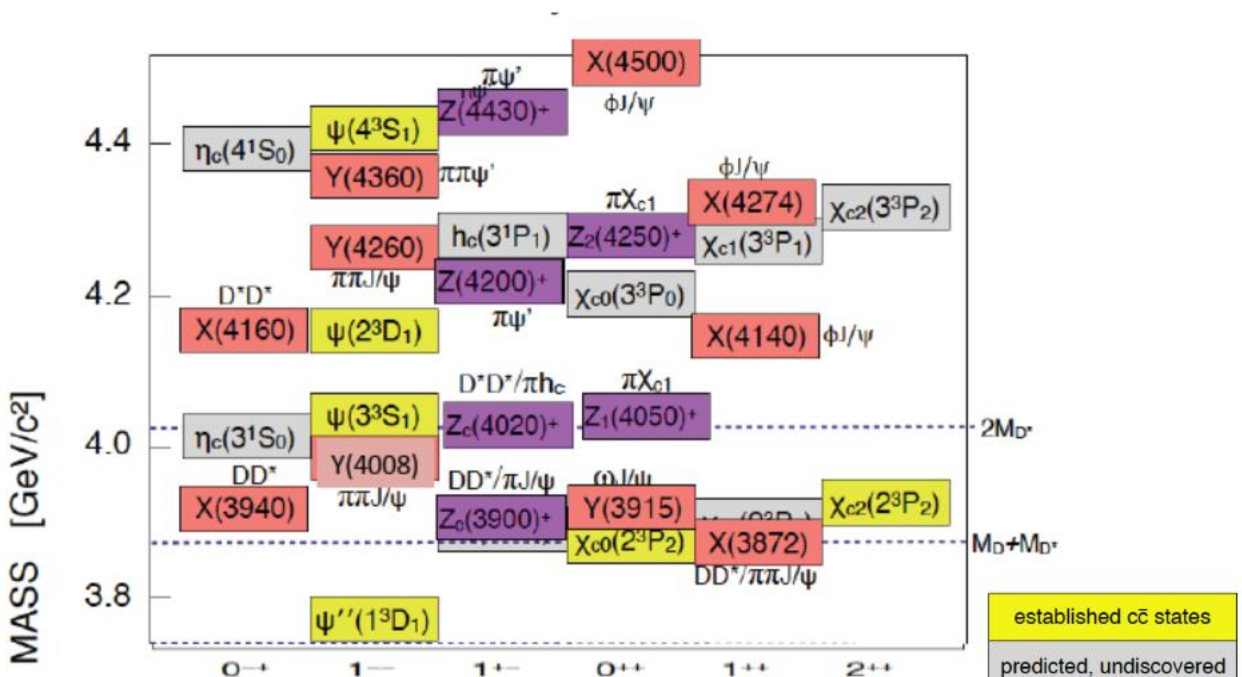
Thanks!

Backup

charmonium: post B-factory era



Backup



>15 charmonium-like states found that ***do not*** fit into any of the unassigned charmonium levels

Backup

If X(3915) ≠ χ'_{c0}, what is it?

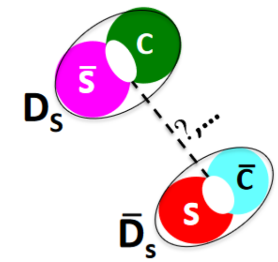
$X(3915) \to \omega J/\psi$ violates OZI-rule unless it's a 4-quark state

Mass is near $2m_{D_s}$ threshold: $M(X(3915)) = 2m_{D_s}$ -18 MeV

$X(3915) \to D\bar{D}$ decays are suppressed: $\Gamma(X(3915) \to D\bar{D}) < 1$ MeV

X(3915) as a D_s-$\bar{D}_s$ molecule?

Li & Voloshin, PRD 91, 114014

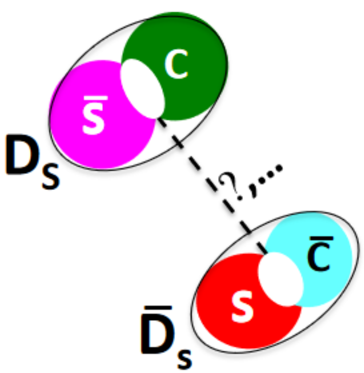


what binds it?

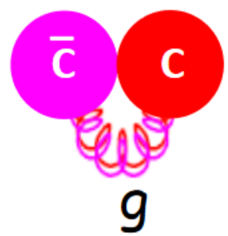
"BE"=$2m_{Ds} - M_{X3915}$=18 MeV

D_s-$\bar{D}_s$ molecule?

Li & Voloshin, PRD 91, 114014

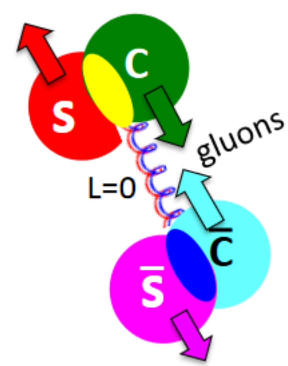


$c\bar{c}$-gluon hybrid?



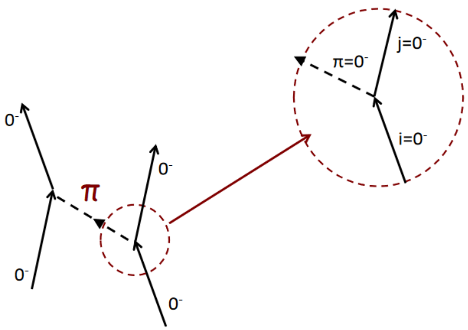
[cs][$\bar{c}\bar{s}$] tetraquark?

Lebed & Polosa, PRD 93, 094024



Backup

$0^- \leftrightarrow 0^-$ π-exchange violates Parity



i → *j* + π

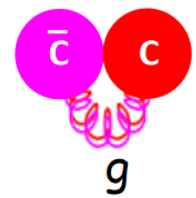
initial state

P=-1; *J*=0

to conserve *P, j* & π should be in a P-wave & not conserve *J*

0^- 0^- 0^- vertices must be 0

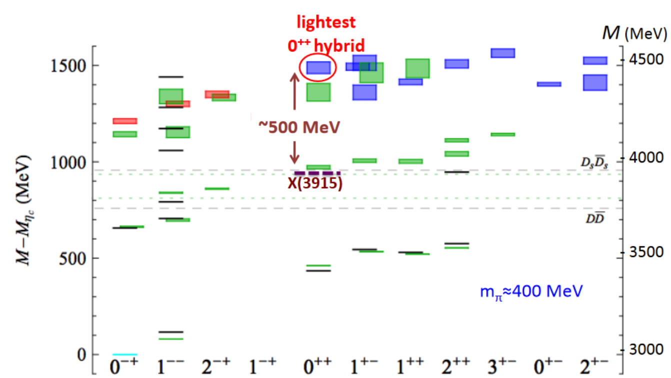
X(3915) as a $c\bar{c}$-*gluon* hybrid?



too light for 0^{++} $c\bar{c}$-hybrid?

3915 MeV is too light for a 0^{++} hybrid

-- Lattice QCD calculation --



Liu, *et al* (Had Spec Collab) JHEP07,126

Backup

What is the X(3915)?

It is ***not*** the χ'_{c0} charmonium state

Belle recently found a much better χ'_{c0} candidate

It is ***not*** a threshold effect

18 MeV away from the nearest threshold (& a benign one at that)

It is ***not*** a good candidate for a $D_s\bar{D}_s$ molecule:

B.E. ≈ 18 MeV; ← needs a binding mechanism to produce this;

standard nuclear-physics-type forces do not work

It is ***not*** a $c\bar{c}$-gluon hybrid:

unless current (m_π≈400 MeV) LQCD mass calcs are wrong by ≈500 MeV

If it is a $[cs][\bar{c}\bar{s}]$ QCD tetraquark:

the X(3915)→$\eta\eta_c$ decay mode should be seen soon

Backup

Search for $\Upsilon(1S, 2S) \to Z_c^+ Z_c^-$ and $e^+ e^- \to Z_c^+ Z_c^-$ at $\sqrt{s}$ = 10.52, 10.58 and 10.867 GeV

- No clear signals are observed in the studied modes.
- Determined upper limits on product of branching fraction and cross section (90 % C.L.).

arXiv:1805.02308v1 [hep-ex] Accepted by PRD

Data Sample

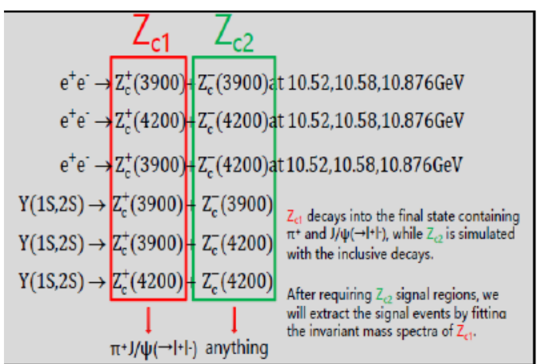
5.74 fb^{-1} at $\Upsilon(1S)$ peak
24.91 fb^{-1} at $\Upsilon(2S)$ peak
89.5 fb^{-1} at $\sqrt{s}$ = 10.52 GeV,
711fb^{-1}at $\sqrt{s}$ = 10.58 GeV (Υ (4S) peak)
121.4 fb^{-1} at $\sqrt{s}$ = 10.867GeV (Υ (5S) peak)

Analysis Method

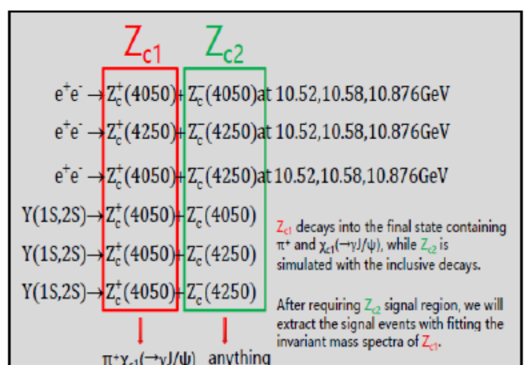
- Z_{c1} decays into $\pi^+ J/\psi$, $\pi^+\chi_{c1}$, $\pi^+\psi(2S)$. Z_{c2} is simulated with inclusive decays. ($e^+e^- \to u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}$)
- After requiring Z_{c2} signal regions, we will extract the signal events by fitting the invariant mass spectra of Z_{c1}.

Decay Modes

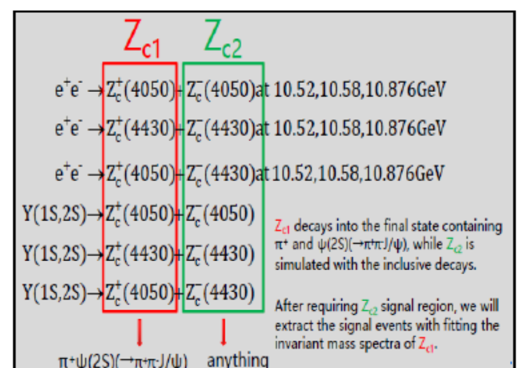
$Z_{c1} \to \pi^+ J/\psi$



$Z_{c1} \to \pi^+ \chi_{c1}$



$Z_{c1} \to \pi^+ \psi$ (2S)



Backup

Observation of $\Xi_c(2930)^0$ and Updated Measurements of $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$

- ➢ Ξ_c $(2930)^0$ is observed with a statistical significance greater than 5σ.
- ➢ Precise Results M = 2928.9±3.0 +0.8/-12.0 MeV, Γ=19.5±8.4+5.4/-7.9 MeV
  B.F. $(B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c) = (4.80 \pm 0.43 \pm 0.60) \times 10^{-4}$ (consistent with **PDG 2016, 2017**).
- ➢ B.F. $(B^- \to K^- Y(4660)) \times$ B.F. $(Y(4660) \to \Lambda_c^+ \bar{\Lambda}_c^-) < 1.2 \times 10^{-4}$ (90% C. L).
  B.F. $(B^- \to K^- Y_\eta) \times$ B.F. $(Y_\eta \to \Lambda_c^+ \bar{\Lambda}_c^-) < 2.0 \times 10^{-4}$ (90% C. L).

Eur. Phys. J. C 78, 252 (2018)

Fit including Y_η **Fit including Y(4660)**