Charged charmoniumlike states at Belle

Kirill Chilikin

ITEP, MEPhI

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Outline

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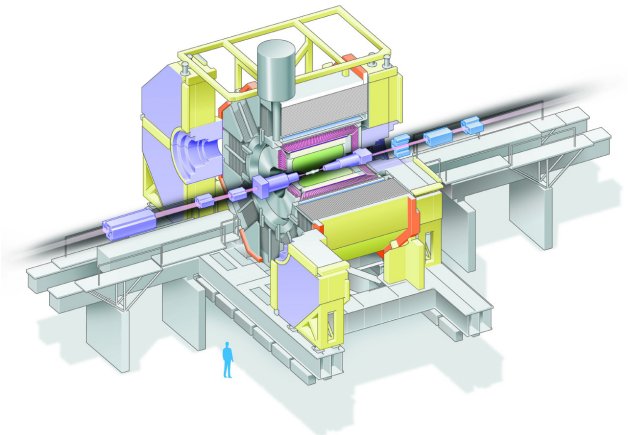
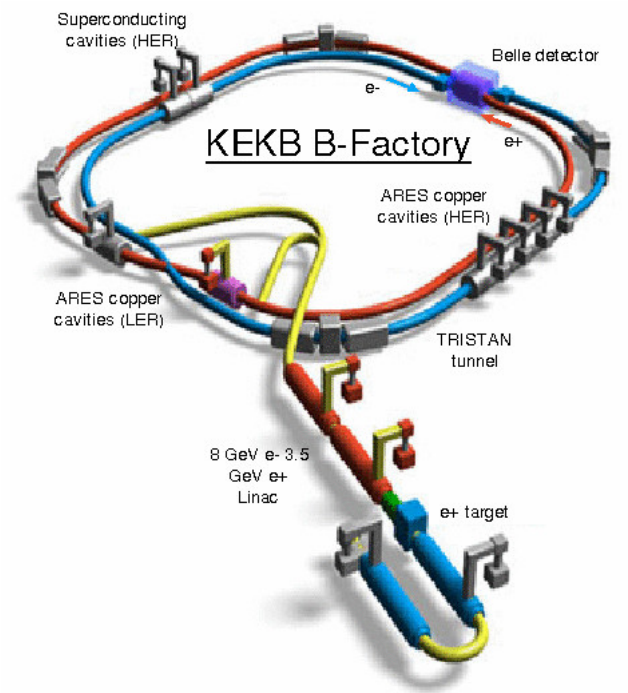
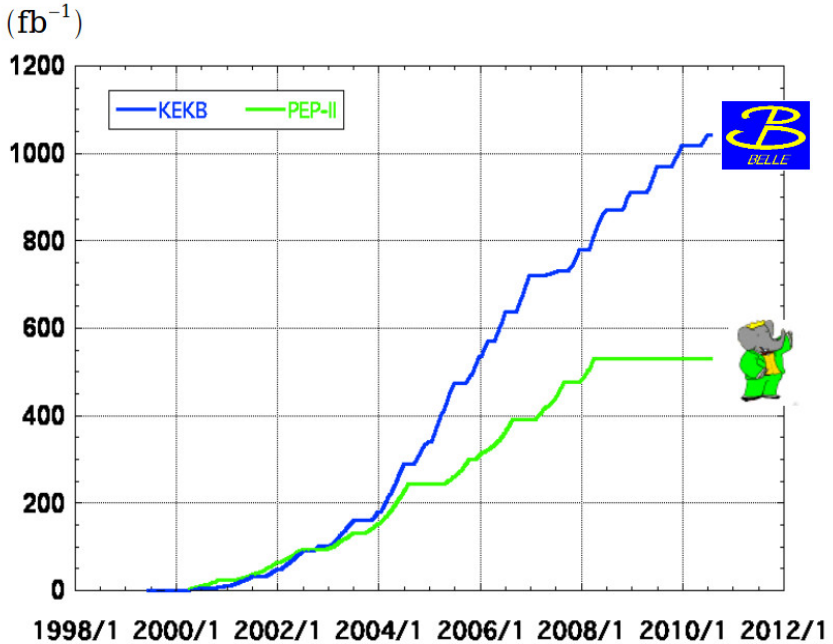
   - Old results (before 2013).
   - Measurement of the $Z_c(4430)^+$ quantum numbers.
   - Amplitude analysis of the $\bar{B}^0 \to J/\psi K^- \pi^+$.
3. Conclusion.

The Belle experiment







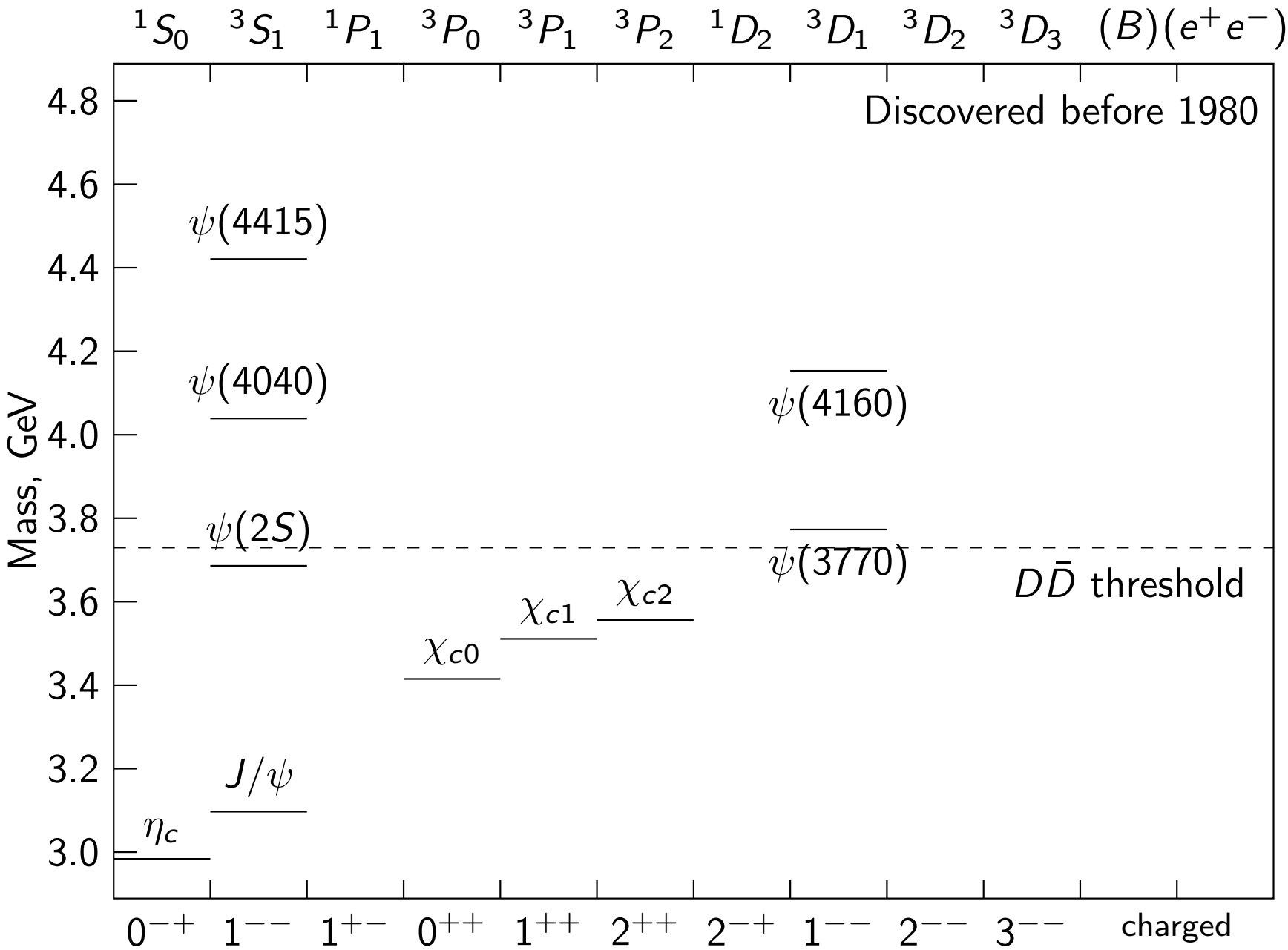
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

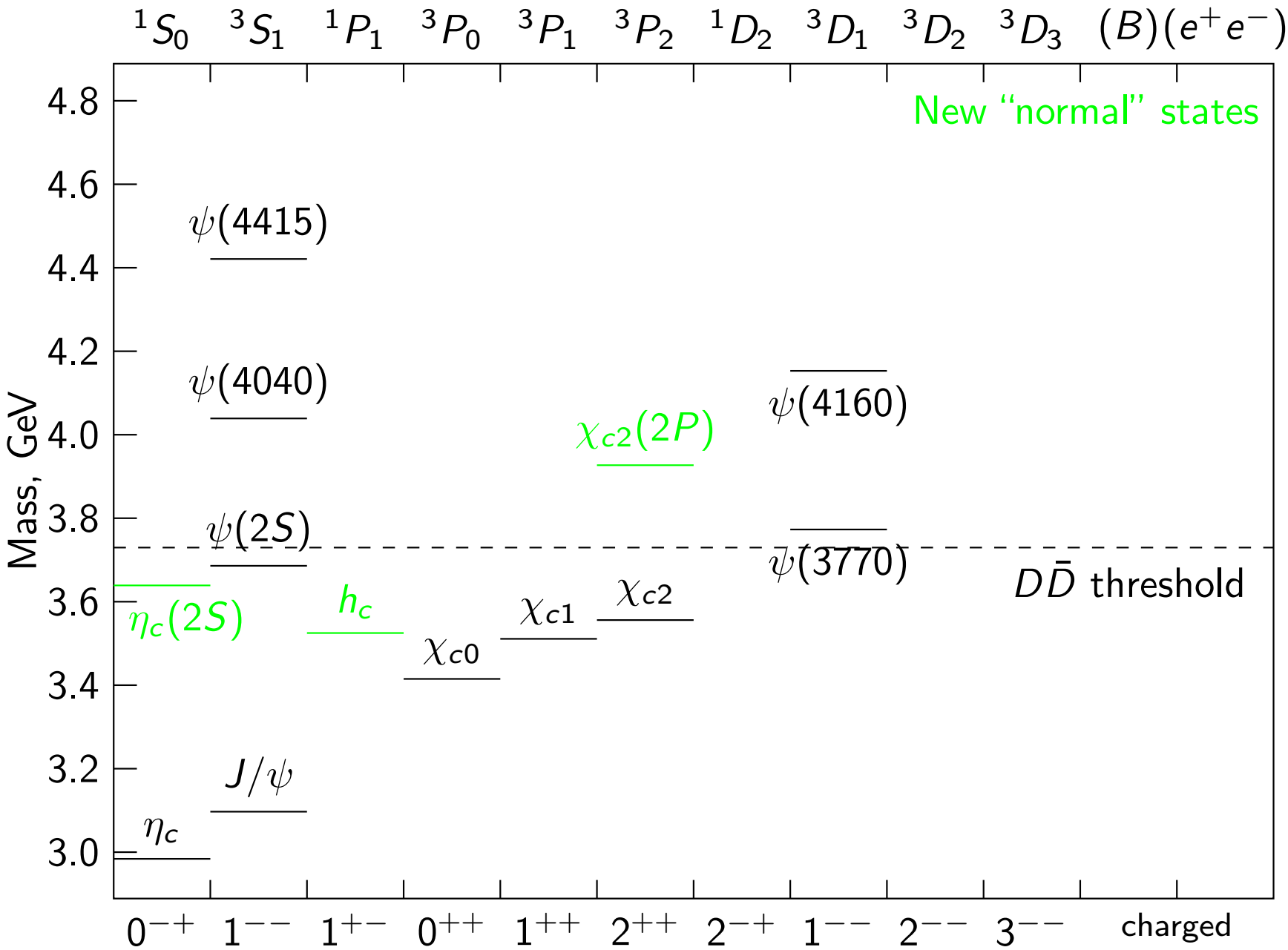
Production of charged charmoniumlike states:

- B-meson decays (772×10^6 B-meson pairs) — this talk.
- ISR (e. g., $e^+e^- \to \gamma_{\rm ISR} Z_c(3900)^+\pi^-$).

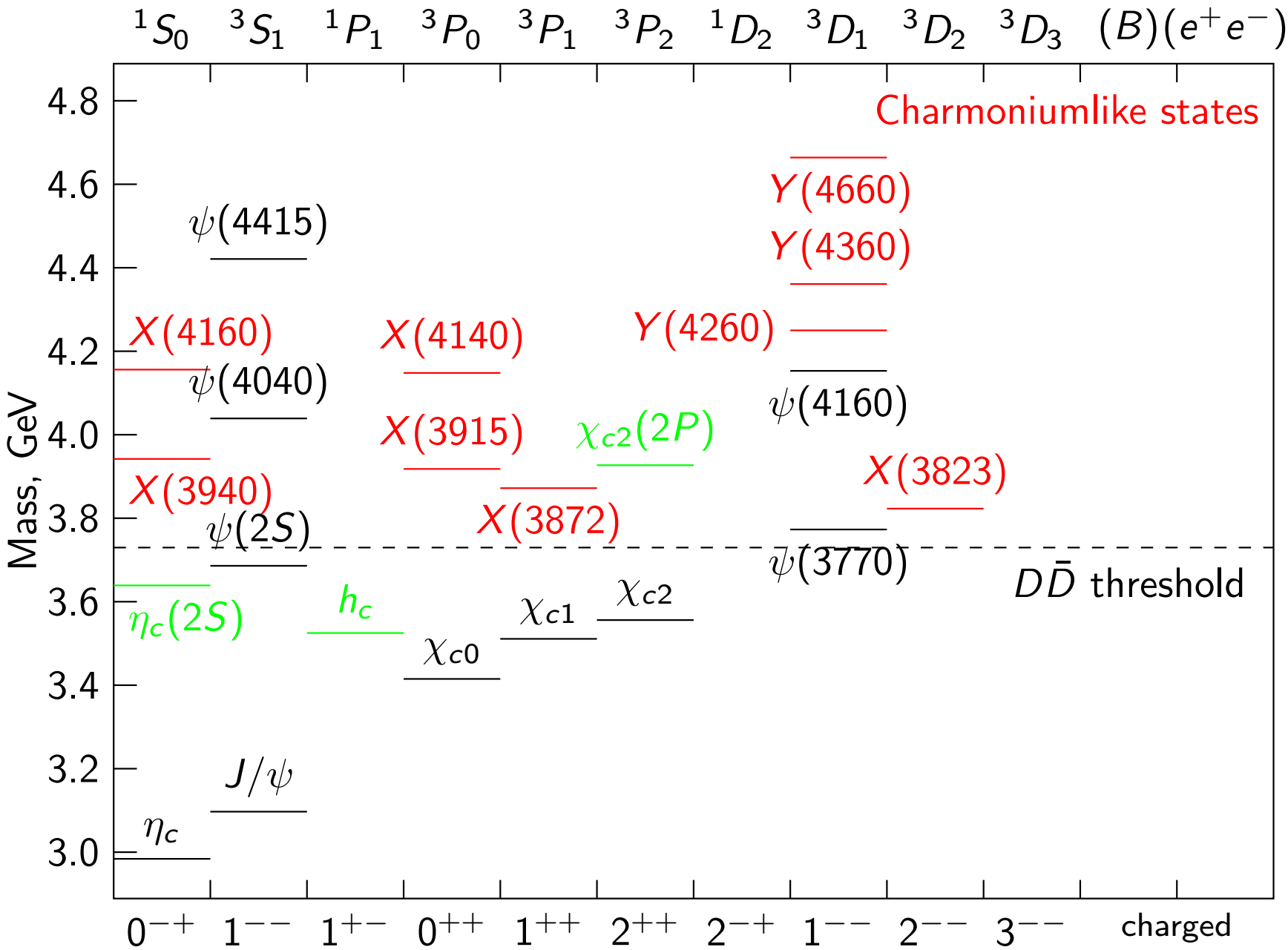
Charmonium states



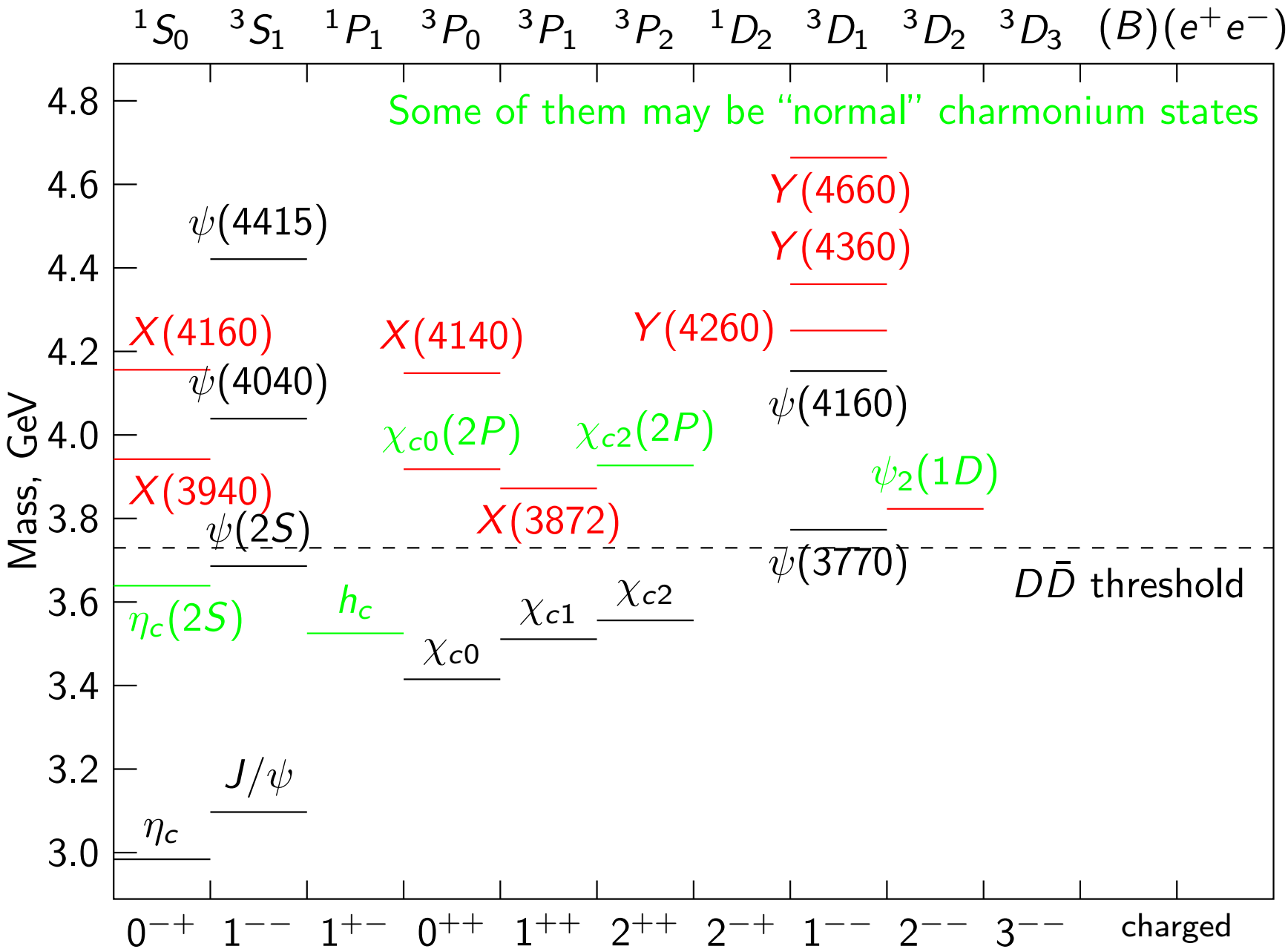
Charmonium states



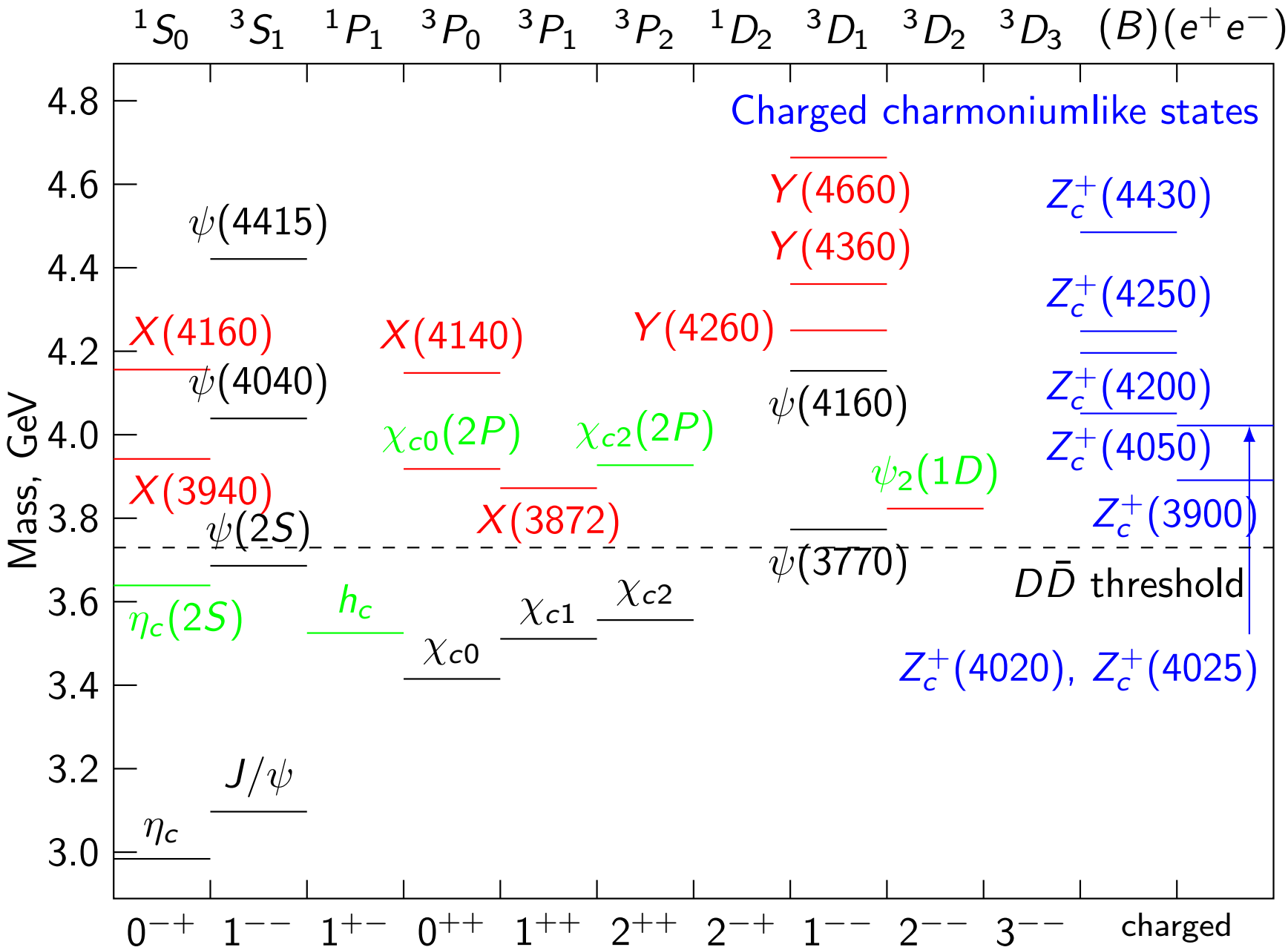
Charmonium states



Charmonium states



Charmonium states

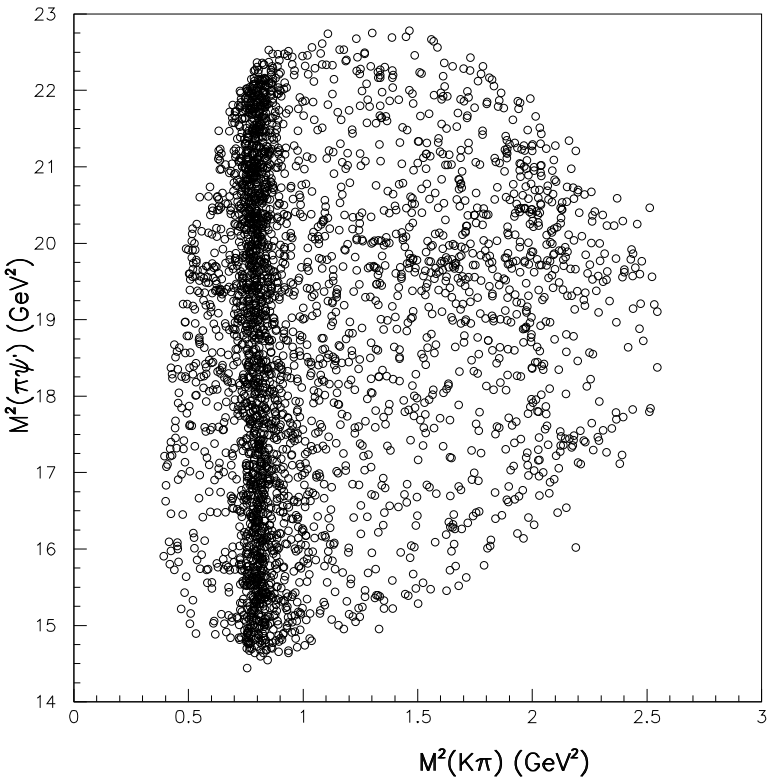


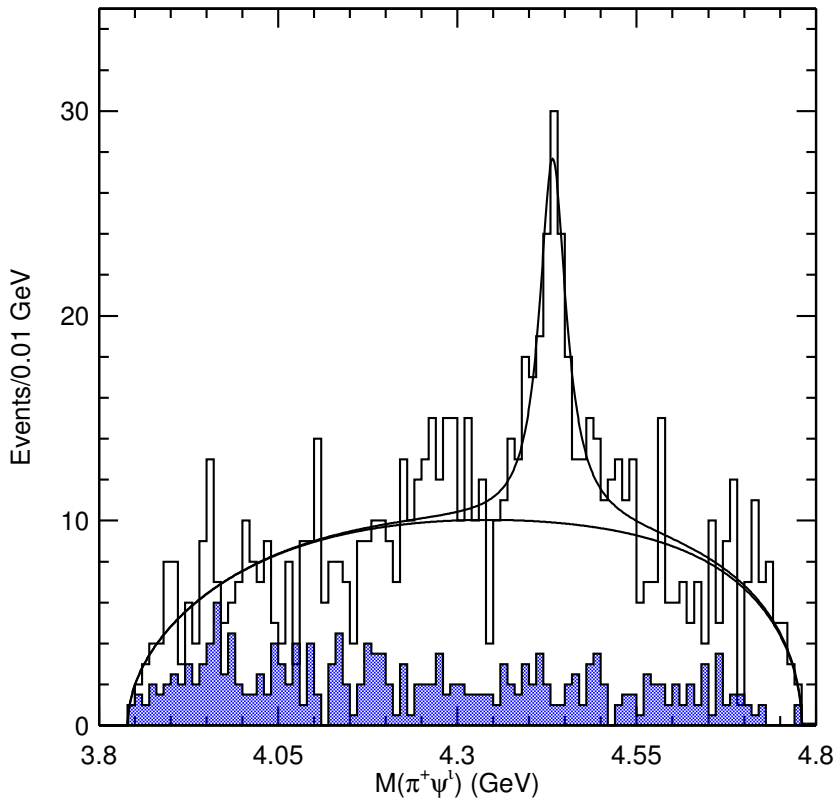
Old results

Observation of the $Z_c(4430)^+$

S.-K. Choi *et al.*, Phys. Rev. Lett. **100**, 142001 (2008).

Analysis of the decays $B \to \psi' K \pi^+$.





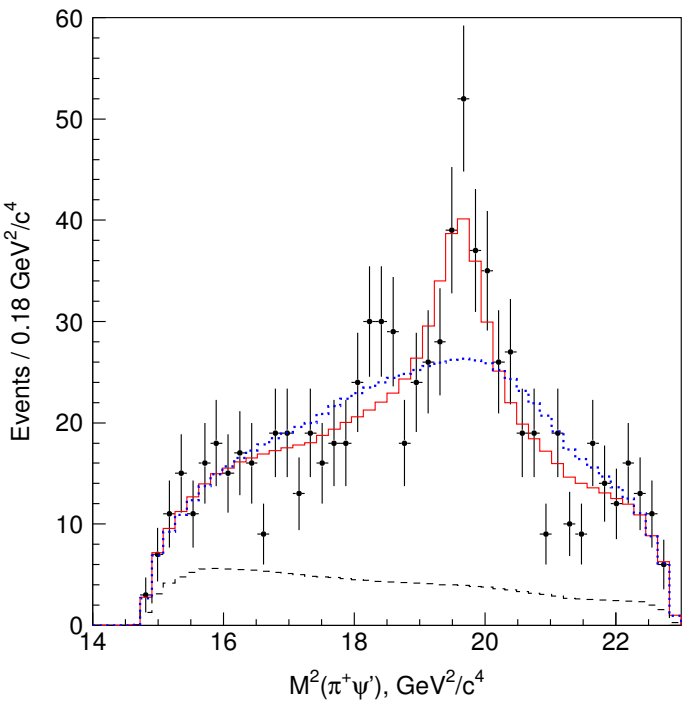
$M = 4433 \pm 4 \pm 2$ MeV/c^2, $\Gamma = 45^{+18+30}_{-13-13}$ MeV, significance: 6.5σ.

Initially was not confirmed by BABAR analysis PRD **79**, 112001 (2009).

Dalitz analysis of $B \to \psi(2S)\pi^+ K$

R. Mizuk *et al.*, Phys. Rev. D **80**, 031104(R) (2009).

Both first analyses did not take interference into account $\Rightarrow$ Dalitz analysis was performed.



The same data as for the previous Belle analysis were used.

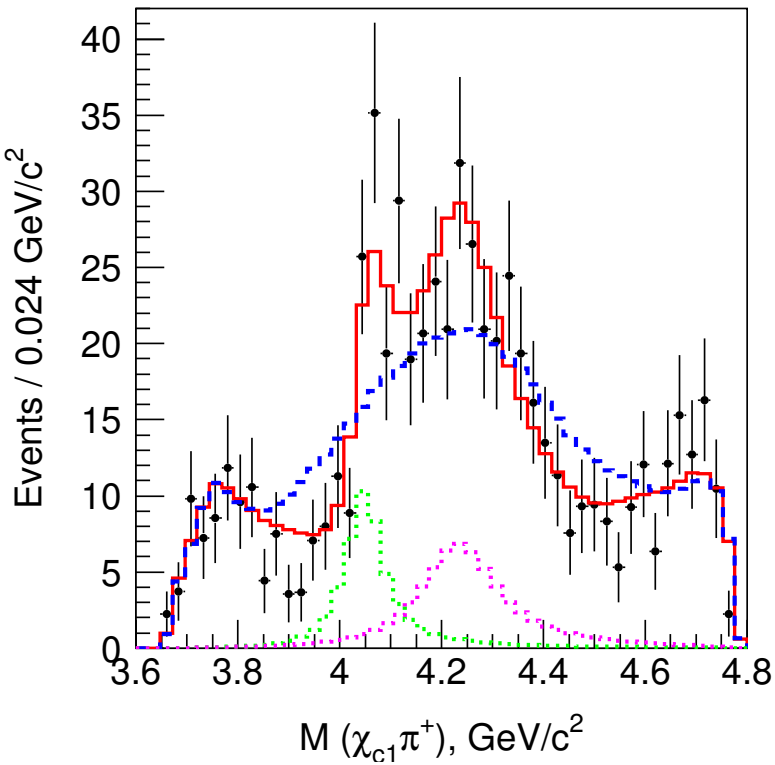
Results:

$M = 4443^{+15+19}_{-12-13}$ MeV/c^2,
$\Gamma = 107^{+86+74}_{-43-56}$ MeV,
Significance: 6.4σ.

A fit of two-dimensional distribution $(M^2_{K\pi}, M^2_{\psi(2S)\pi})$ was performed. The information is still lost due to integration over the angular variables.

Observation of $Z_c(4050)^+$ and $Z_c(4250)^+$ (Belle)

R. Mizuk *et al.*, Phys. Rev. D **78**, 072004 (2008).



Decay: $\bar{B}^0 \to \chi_{c1} K^- \pi^+$

The $Z_c(4050)^+$ parameters:

$M = 4051 \pm 14^{+20}_{-41}$ MeV/c^2,

$\Gamma = 82^{+21+47}_{-17-22}$ MeV.

The $Z_c(4250)^+$ parameters:

$M = 4248^{+44+180}_{-29-35}$ MeV/c^2,

$\Gamma = 177^{+54+316}_{-39-61}$ MeV.

Significance: $Z_c(4250)^+$: 6.2σ, $Z_c(4050)^+$: 5.0σ.

- Two-dimensional fit (Dalitz analysis).
- The $Z_c(4050)^+$ and $Z_c(4250)^+$ were not confirmed by BABAR (PRD **85**, 052003 (2012)) (but the method is less sensitive + smaller data sample) or any other experiment.

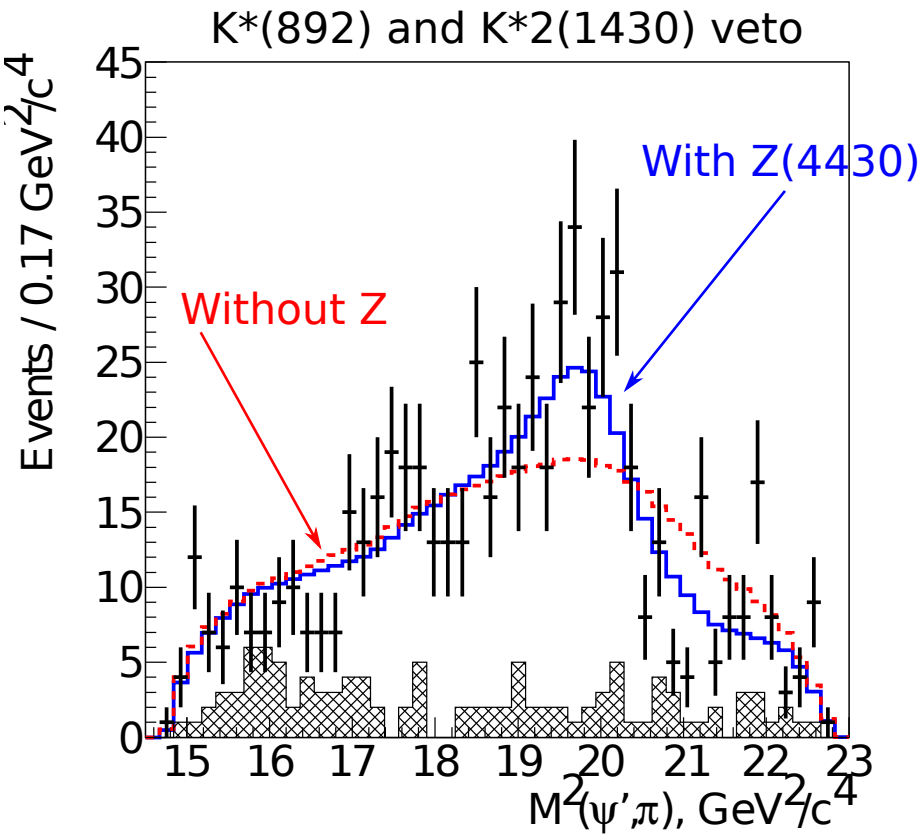
Measurement of the $Z_c(4430)^+$ quantum numbers

K. Chilikin *et al.* (Belle Collaboration), Phys. Rev. D **88**, 074026 (2013)

Measurement of the $Z_c(4430)^+$ quantum numbers

(four-dimensional amplitude analysis of $\bar{B}^0 \to \psi(2S)K^-\pi^+$)

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4479 ± 16	4477 ± 4	4485 ± 20	4478 ± 22	4384 ± 19
Width, MeV	110 ± 50	22 ± 14	200 ± 40	83 ± 25	52 ± 28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ



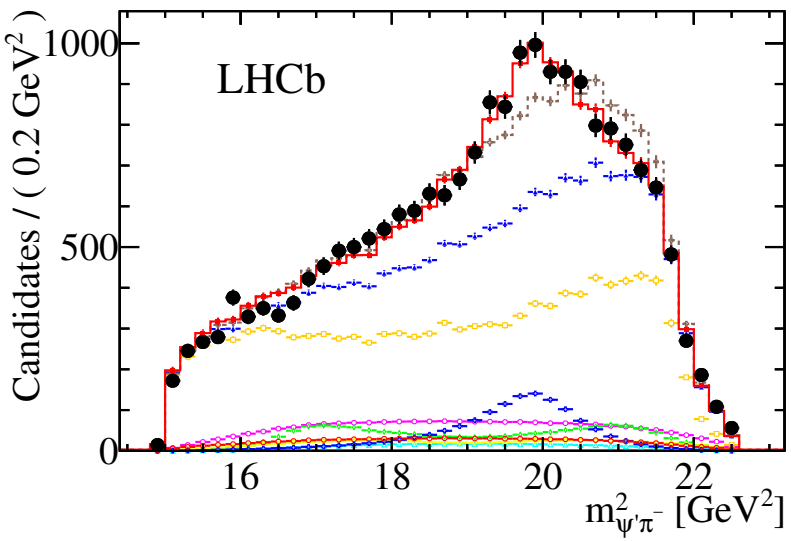
$$M = 4485^{+22+28}_{-22-11}\ \text{MeV}/c^2,$$
$$\Gamma = 200^{+41+26}_{-46-35}\ \text{MeV}.$$

Preferred hypothesis: $J^P = 1^+$.
Exclusion levels for $J^P = 0^-$, 1^-, 2^- and 2^+: 3.4σ, 3.7σ, 4.7σ and 5.1σ.

LHCb confirmation

R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **112**, 222002

The existence of the $Z_c(4430)^+$ was confirmed (significance: 13.9σ).



$M = 4475 \pm 7^{+15}_{-25}$ MeV$/c^2$,
$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV.
The mass and width of the $Z_c(4430)^+$ agree with Belle result,
The quantum numbers $J^P = 1^+$ were confirmed. Other hypotheses: 0^-, 1^-, 2^- and 2^+ were excluded at the levels of 9.7σ, 15.8σ, 16.1σ and 14.6σ, respectively.

Amplitude analysis of $\bar{B}^0 \to J/\psi K^- \pi^+$.

K. Chilikin *et al.* (Belle Collaboration), Phys. Rev. D **90**, 112009 (2014)

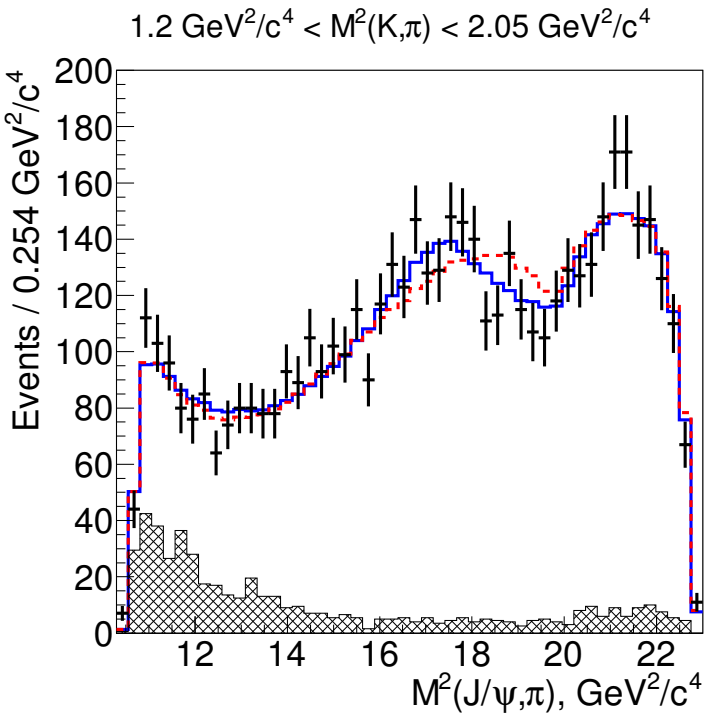
Amplitude analysis of $\bar{B}^0 \to J/\psi K^- \pi^+$

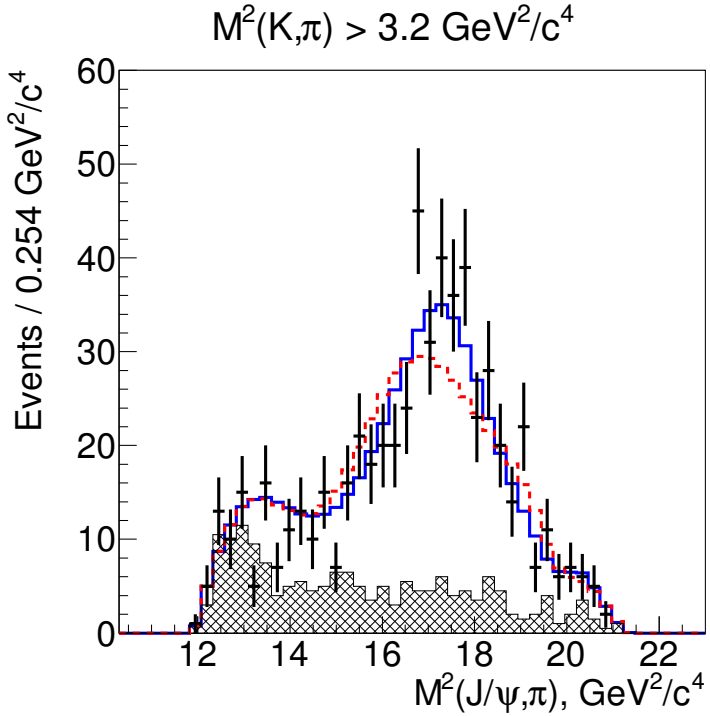
- Four-dimensional amplitude analysis similar to the measurement of the $Z_c(4430)^+$ quantum numbers.
- Resonances: all K^* (10 resonances) and $Z_c(4430)^+$.
- A search for additonal Z_c^+ was performed.

Search results:

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

New state: $Z_c(4200)^+$

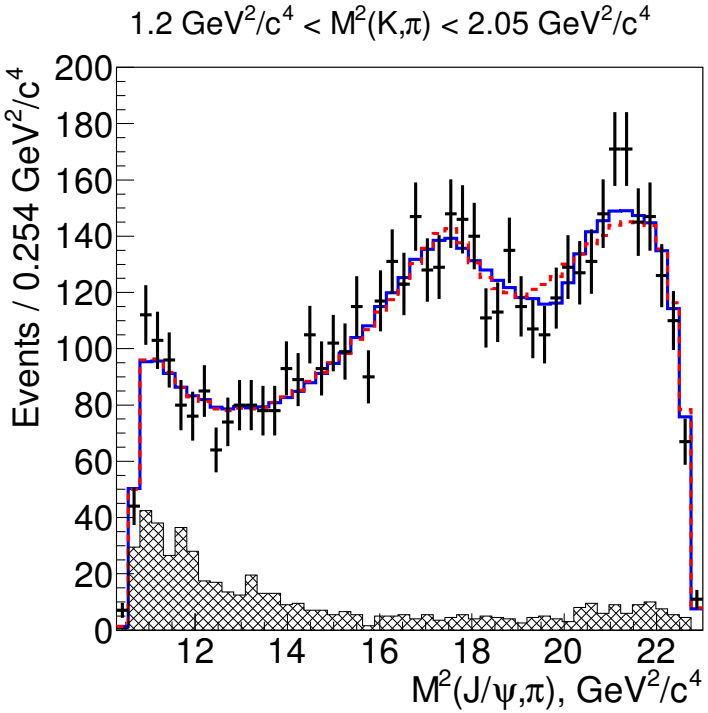


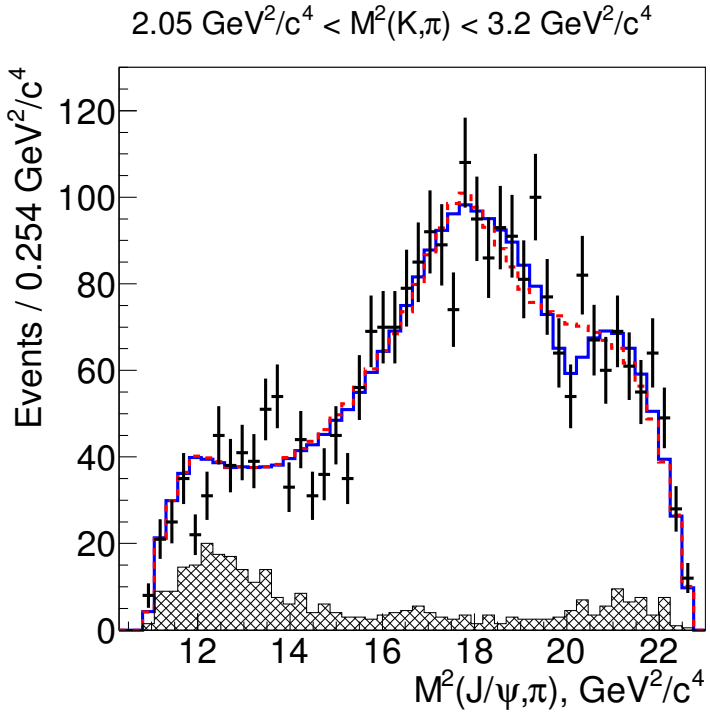


The $Z_c(4200)^+$ Wilks significance is 8.2σ for the default model and 6.6σ including the systematic error. The global significance is 6.2σ.

$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$$

$Z_c(4430)^+$

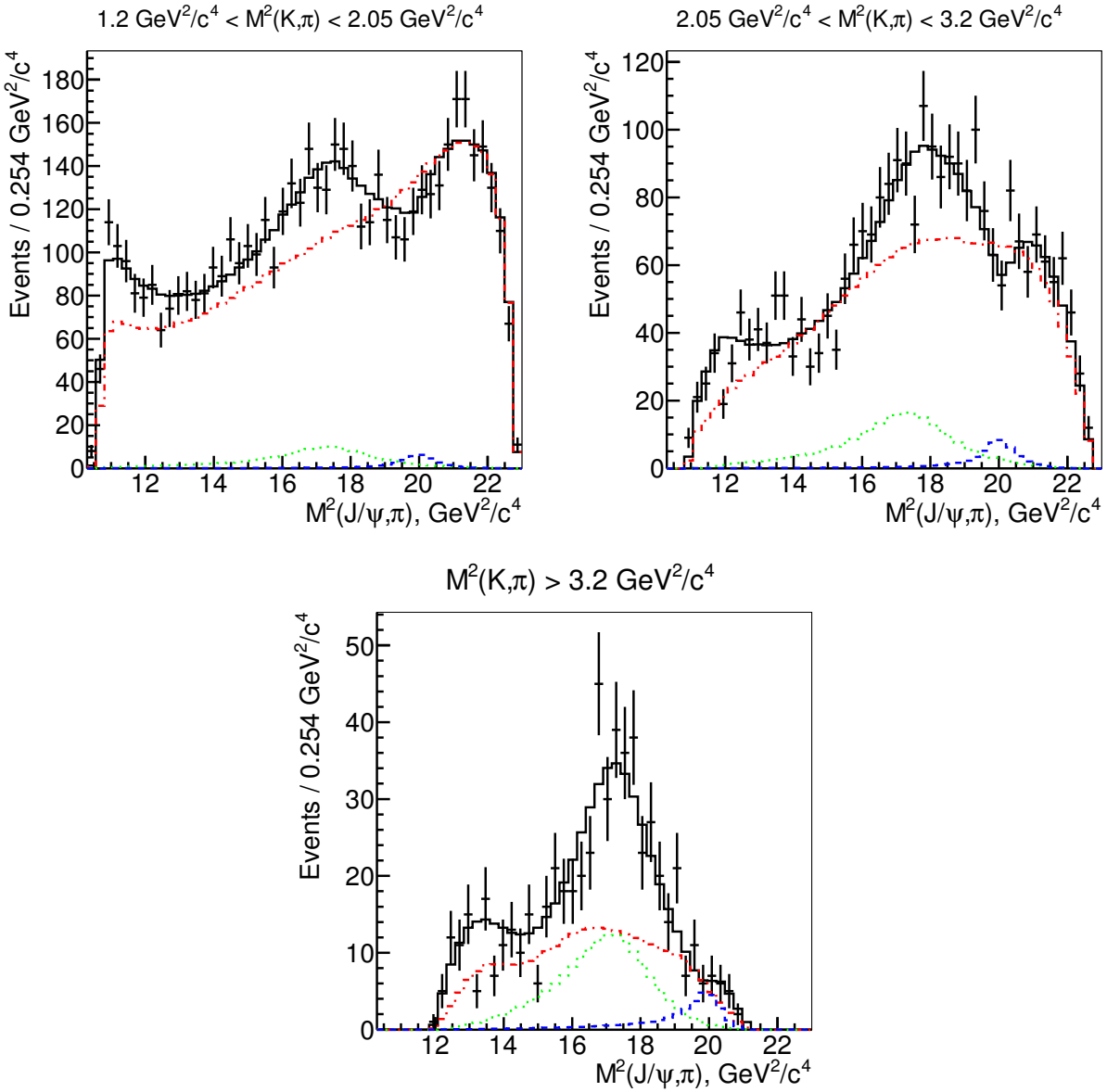




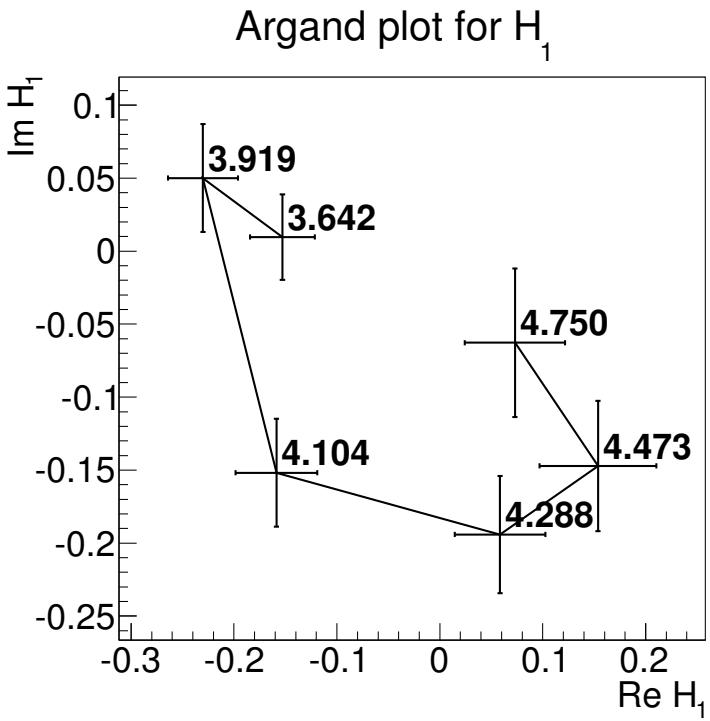
The $Z_c(4430)^+$ significance is 5.1σ for the default model and 4.0σ including the systematic error.

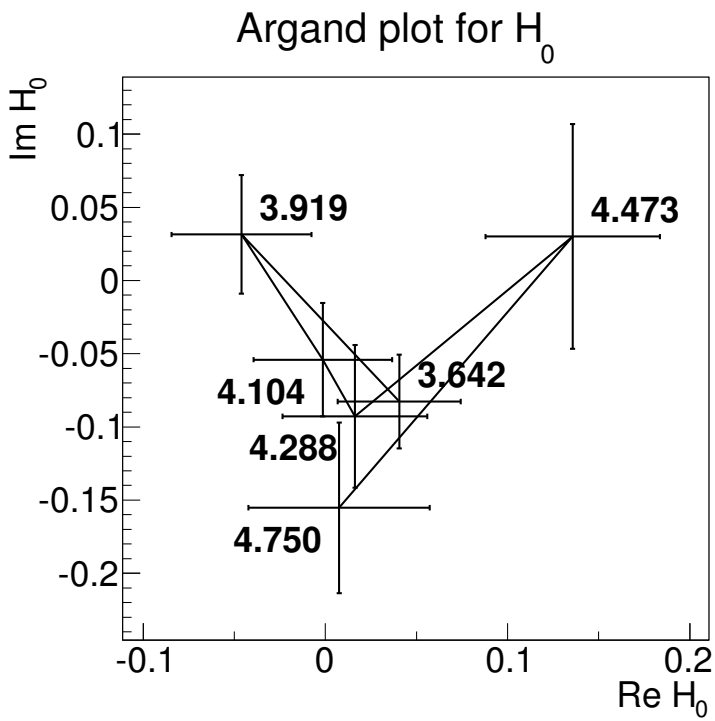
$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

Contributions of the $Z_c(4200)^+$ and $Z_c(4430)^+$



Argand plots for the $Z_c(4200)^+$





H_1 absolute value and phase change as for a resonance.

H_0 has too large errors to draw any conclusions.

Search for the $Z_c(3900)^+$

$Z_c(3900)^+$ parameters:

$$M_0 = 3891.2 \pm 3.3 \text{ MeV}/c^2, \ \Gamma_0 = 39.5 \pm 8.1 \text{ MeV}.$$

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	3889.8 ± 3.3	3890.3 ± 3.1	3890.6 ± 3.3	3891.1 ± 3.2	3891.5 ± 3.3
Width, MeV	43.2 ± 6.5	37.8 ± 7.9	39.2 ± 8.1	39.4 ± 8.5	41.2 ± 7.7
Significance	2.4σ	1.1σ	0.1σ	$< 0.1\sigma$	0.2σ

No significant signal was observed. For $J^P = 1^+$ (the quantum numbers are measured by BESIII)

$$\mathcal{B}(\bar{B}^0 \to Z_c(3900)^+ K^-) \times \mathcal{B}(Z_c(3900)^+ \to J/\psi\pi^+) < 9 \times 10^{-7} \text{ (90\% CL)}.$$

$\bar{B}^0 \to J/\psi K^- \pi^+$: other results

- The $Z_c(4200)^+$ quantum number hypotheses $J^P = 0^-$, 1^-, 2^-, 2^+ are excluded at the levels of 6.1σ, 7.4σ, 4.4σ and 7.0σ, respectively.
- Branching fractions:

$$\mathcal{B}(\bar{B}^0 \to J/\psi K^- \pi^+) = (1.15 \pm 0.01 \pm 0.05) \times 10^{-3},$$
$$\mathcal{B}(\bar{B}^0 \to J/\psi K^*(892)) = (1.19 \pm 0.01 \pm 0.08) \times 10^{-3},$$

Conclusions

- The $Z_c(4430)^+$ quantum numbers were measured: $J^P = 1^+$. This result is confirmed by the LHCb collaboration.
- A new charged charmoniumlike state $Z_c(4200)^+$ with $J^P = 1^+$ was observed in the decays $\bar{B}^0 \to J/\psi K^- \pi^+$, evidence for $Z_c(4430)^+ \to J/\psi \pi^+$ was found.