Heavy Quarkonia - I (Charmonium)

Simon Eidelman

Budker Institute of Nuclear Physics
and Novosibirsk State University,
Novosibirsk, Russia

Outline

1. 1^{--} $c\bar{c}$ states
2. Other charmonium(-like) states
3. Charged charmonium-like states
4. Conclusions

Introduction

- B factories were designed to study CP violation in $B\bar{B}$ at $\Upsilon(4S)$
- From ARGUS and CLEO times it was known that much richer physics in other energy domains was accessible with special methods of analysis: $\gamma\gamma \to$ light and heavy quark mesons, τ leptons, charm, narrow Υ
- Huge statistics collected by BaBar ($\sim$500 fb^{-1}) and Belle ($\sim$1000 fb^{-1}) strengthened that and resulted in principally new studies, e.g., $\gamma\gamma \to c\bar{c}$, initial-state radiation to $q\bar{q}$ and $c\bar{c}$, and spectacular observations in $c\bar{c}$ and $b\bar{b}$ with new states found, as well as detailed studies of various mesons of light quarks
- Progress of experiment stimulated theory resulting in many models: tetraquark, hybrid, molecules, hadrocharmonium or, alternatively, effects of close thresholds, coupled channels and rescattering
- Results from hadronic colliders coming in parallel, also very important BESIII at the Beijing tau-charm factory

What Is Luminosity?

- Instantaneous luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$) – collider efficiency:

$$\mathcal{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y},$$

BEPC2 – 10^{33}, LHC (design) – 10^{34}, PEP2/KEKB – 10^{34}

- Integrated luminosity (cm^{-2}) is the instantaneous luminosity integrated over time – yield/cross section (experiment efficiency):

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

BESIII – 10 fb^{-1}, ATLAS/CMS – 300 fb^{-1}, Belle2 – 50 ab^{-1}

- For $\sigma \sim 1$ nb 1 fb^{-1} gives 10^6 events

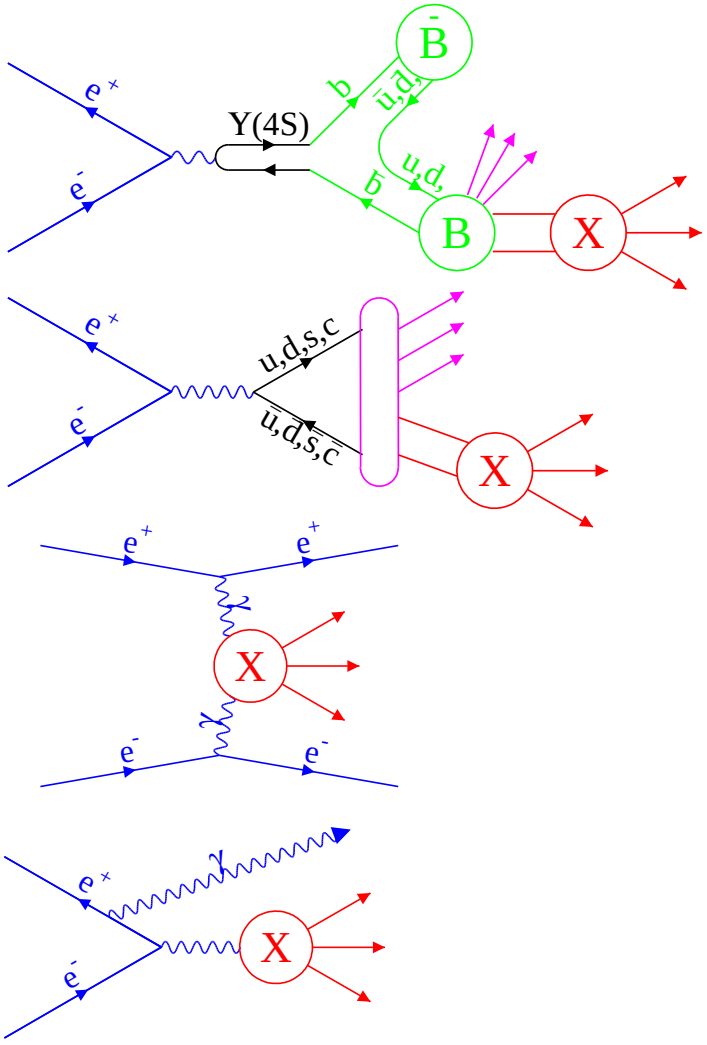
Particle Production at e^+e^- Factories

Production from B-decay
(broad D^{**}, D_{sJ}, $X(3872)$, $Y(3940)$)

Production from continuum
(D_{sJ}, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)

Two-photon production
($\eta_c(2S)$, $\chi_{c2}(2P)$, $Y(4350)$)

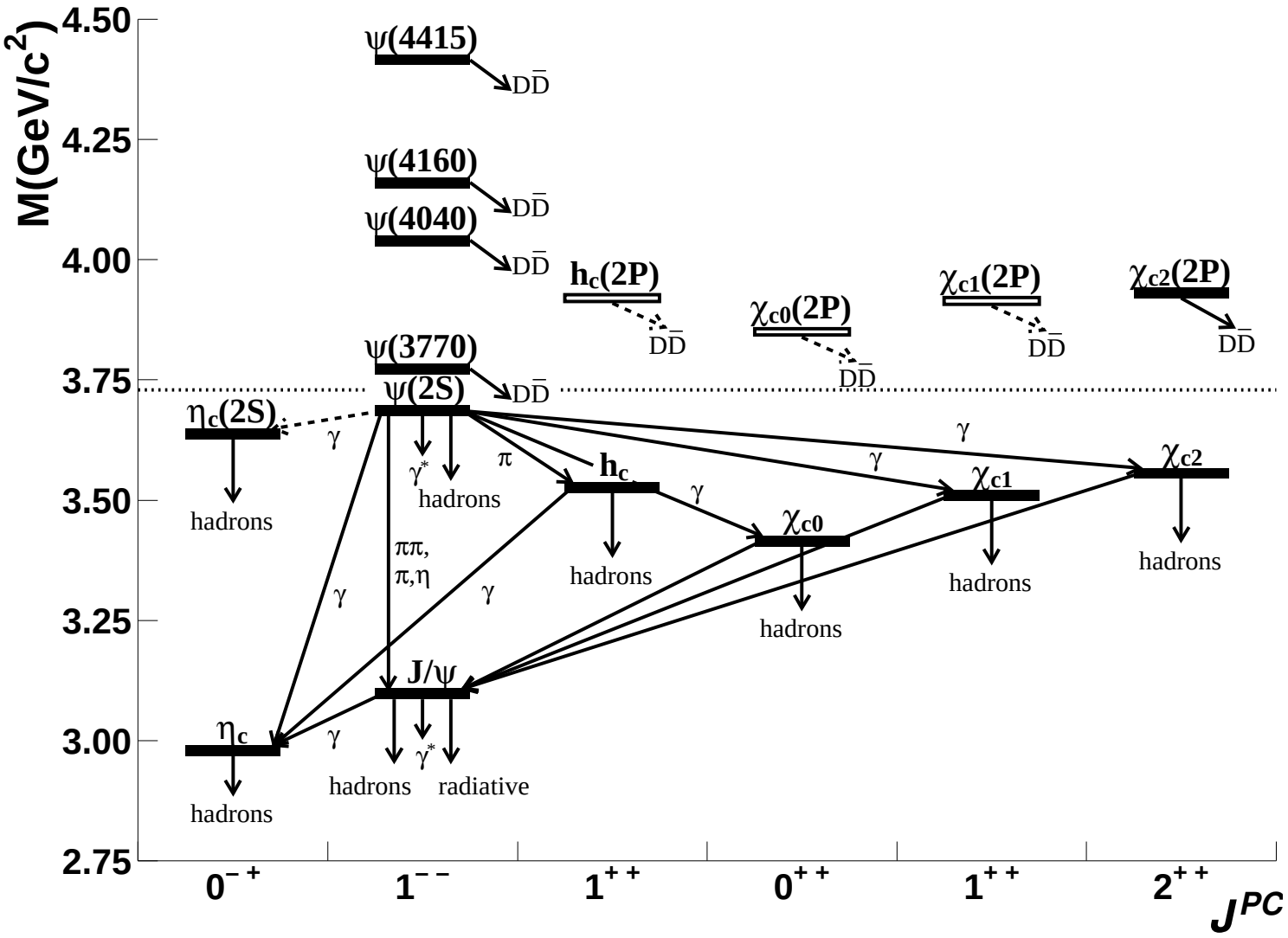
Initial state radiation
($Y(4260)$, $Y(4360)$, $X(4630)$, $Y(4660)$)



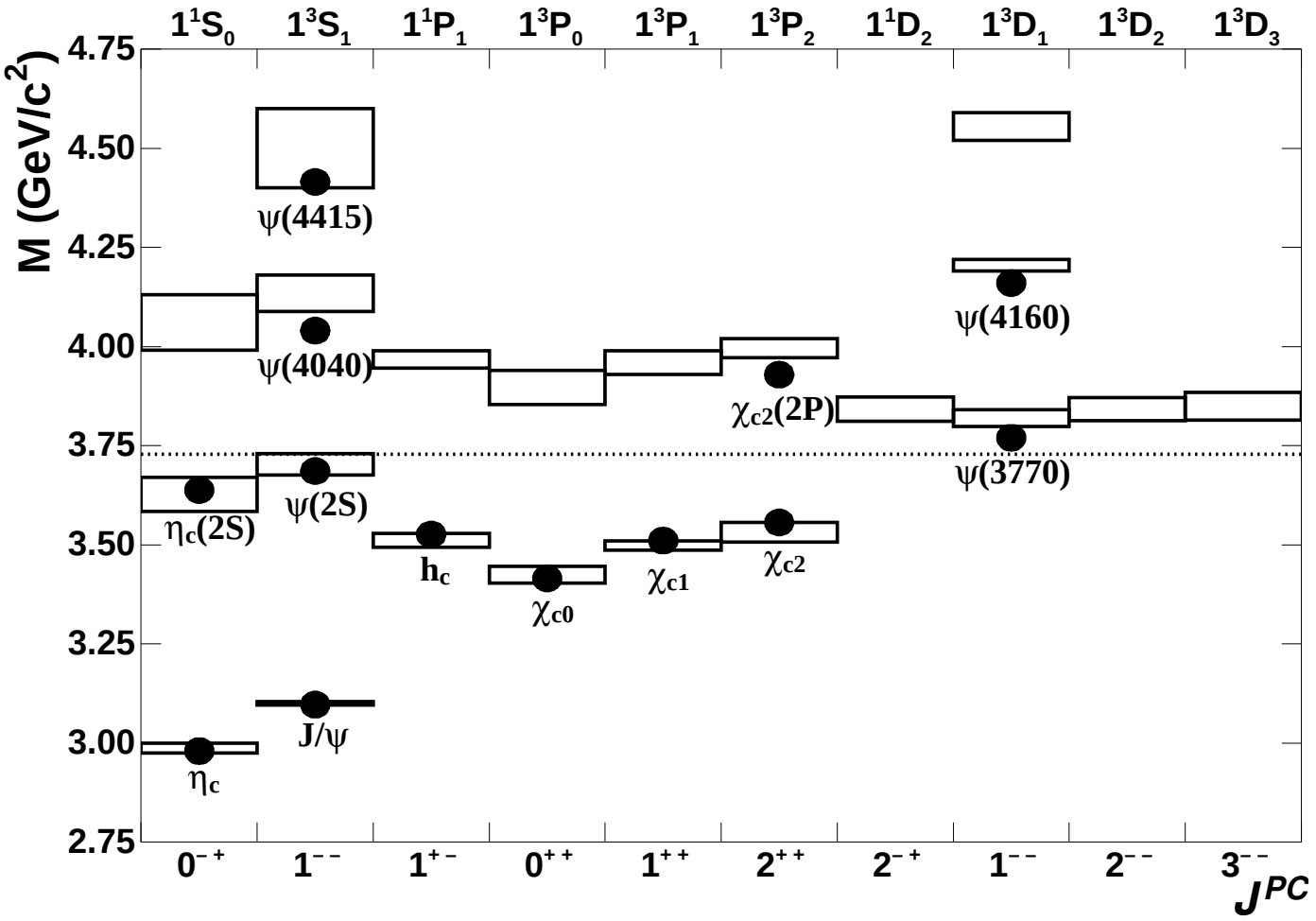
Charmonia – General Picture

- Ten $c\bar{c}$ were found in 1974-1980:
  J/ψ, $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$ below and
  $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ above the open charm threshold
- With $\eta_c(2S)$ (in 2002) and $h_c(1P)$ (in 2005)
  the $c\bar{c}$ system seemed completely understood,
  but many new $c\bar{c}$-like states decaying to $c\bar{c}X$
  rather than to open charm unexpectedly were found.
  For some of them there is no place in the $c\bar{c}$ spectrum.

The Charmonium System

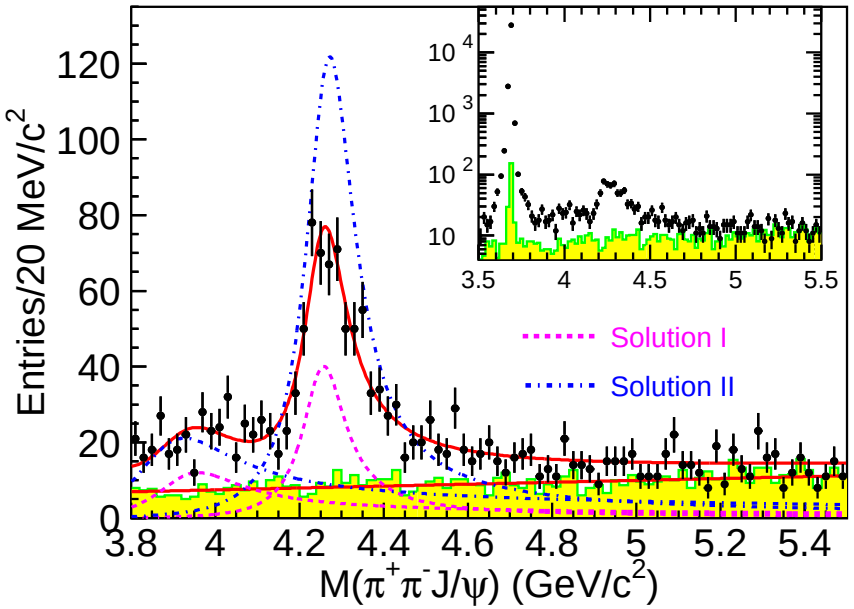


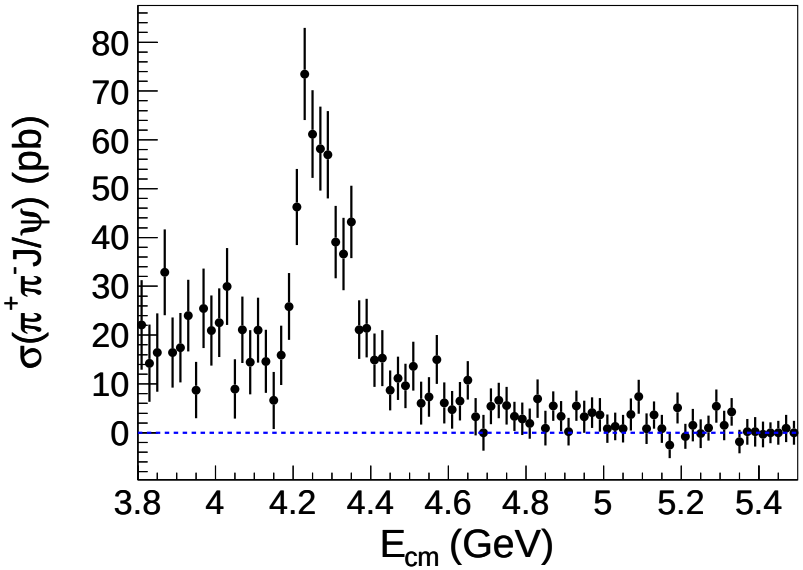
Predictions of Potential Model



Study of $e^+e^- \to \pi^+\pi^- J/\psi$ at Belle

With 967 fb^{-1} Belle confirms $Y(4260) \to J/\psi\pi^+\pi^-$ discovered with ISR by BaBar in B. Aubert et al., Phys. Rev. Lett. 95 (2005) 142001 and sees $Y(3990)$

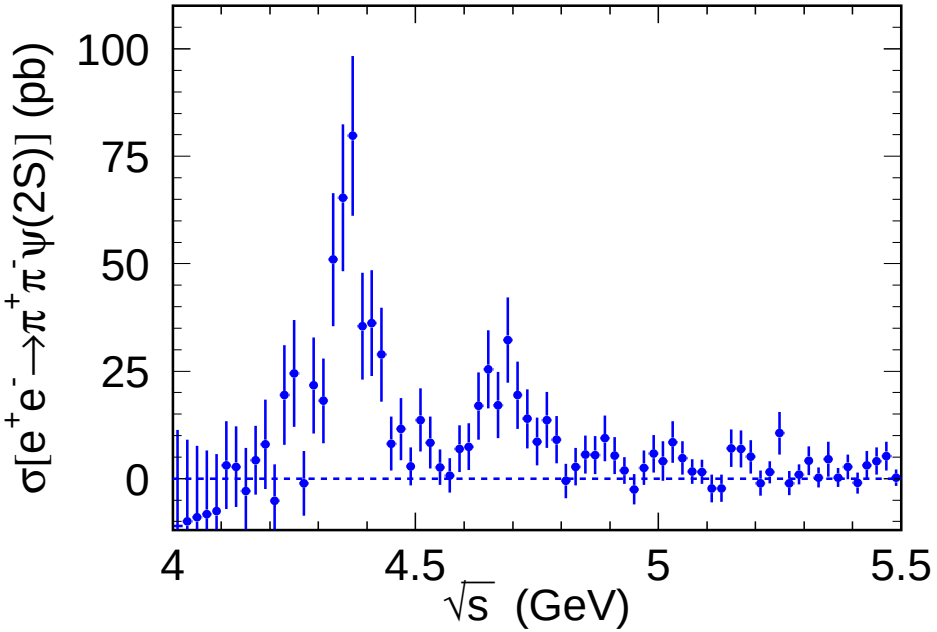




Z.Q. Liu et al., Phys. Rev. Lett. 110 (2013) 222002

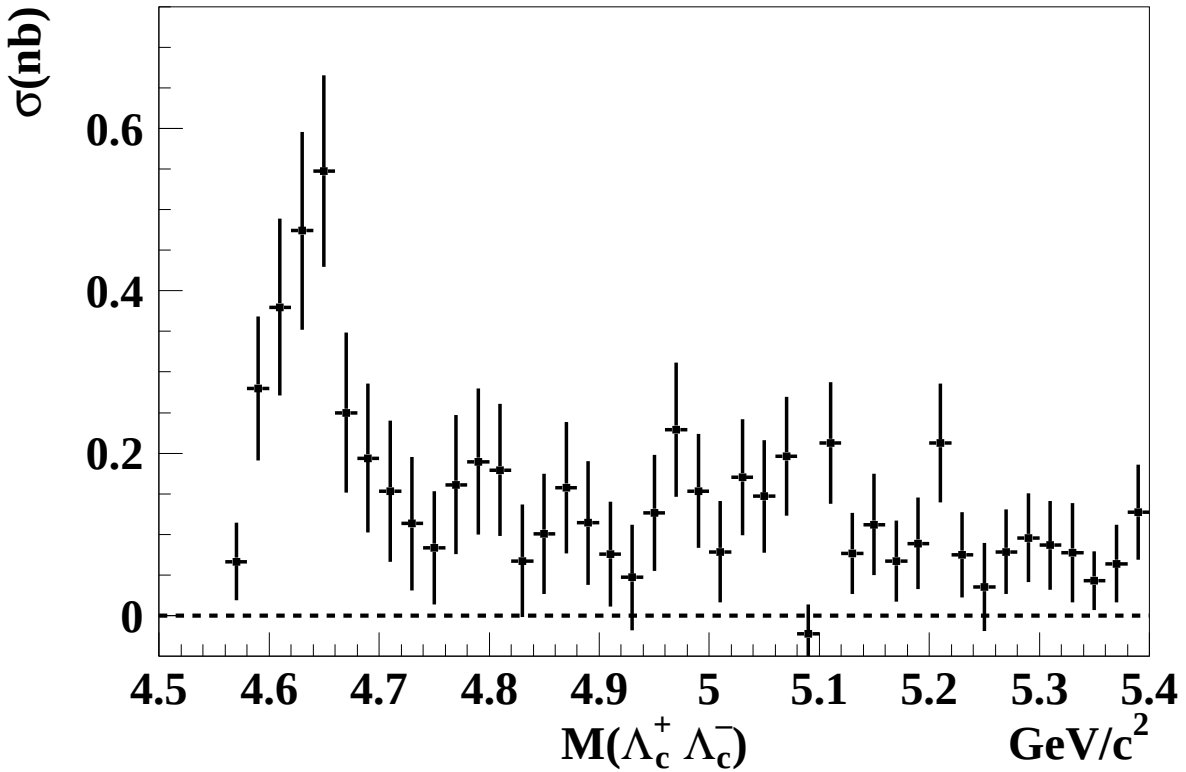
Study of $e^+e^- \to \pi^+\pi^-\psi(2S)$ at Belle

With 980 fb^{-1} Belle confirms $Y(4360) \to \psi(2S)\pi^+\pi^-$ discovered with ISR by BaBar in B. Aubert et al., Phys. Rev. Lett. 98 (2007) 212001 and $Y(4660)$ first seen by Belle in X.L.Wang et al., Phys. Rev. Lett. 99 (2007) 142002



X.L. Wang et al., Phys. Rev. D 91 (2015) 112007

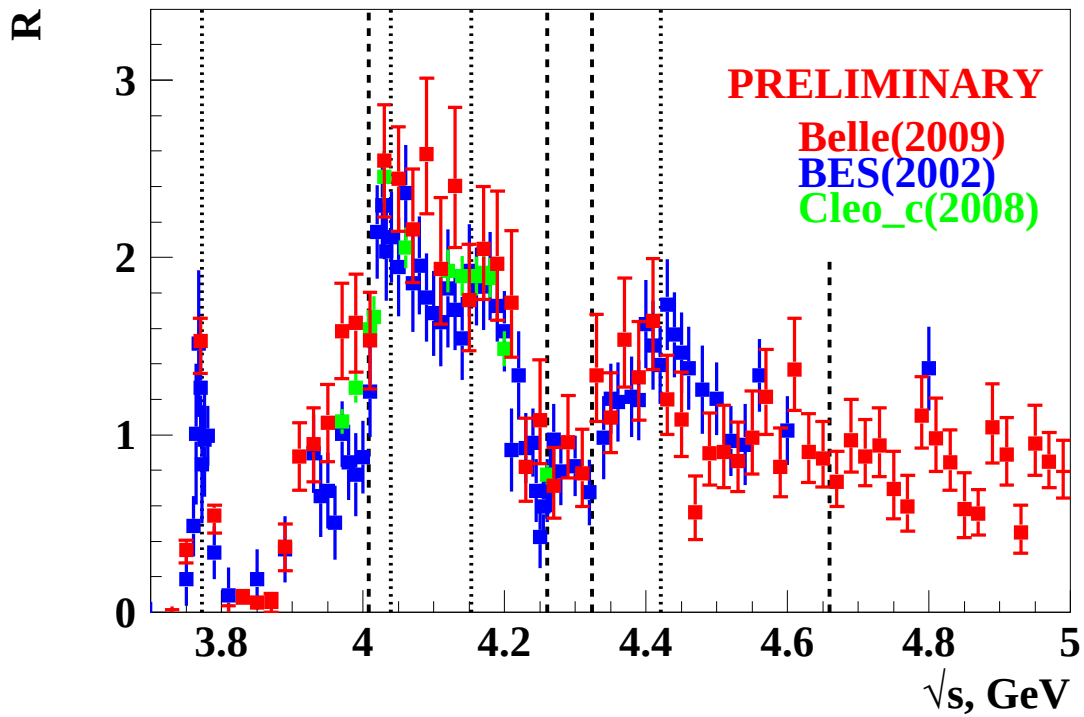
$e^+e^- \to \Lambda_c^+\Lambda_c^-$ via ISR at Belle



G. Pakhlova et al., PRL 101 (2008) 172001; Belle – 695 fb^{-1}

142^{+32}_{-28} events $(\sim 8.2\sigma)$ $M = 4634^{+8+5}_{-7-8}$ MeV $\Gamma = 92^{+40+10}_{-24-21}$ MeV

Total Exclusive Cross Section via ISR

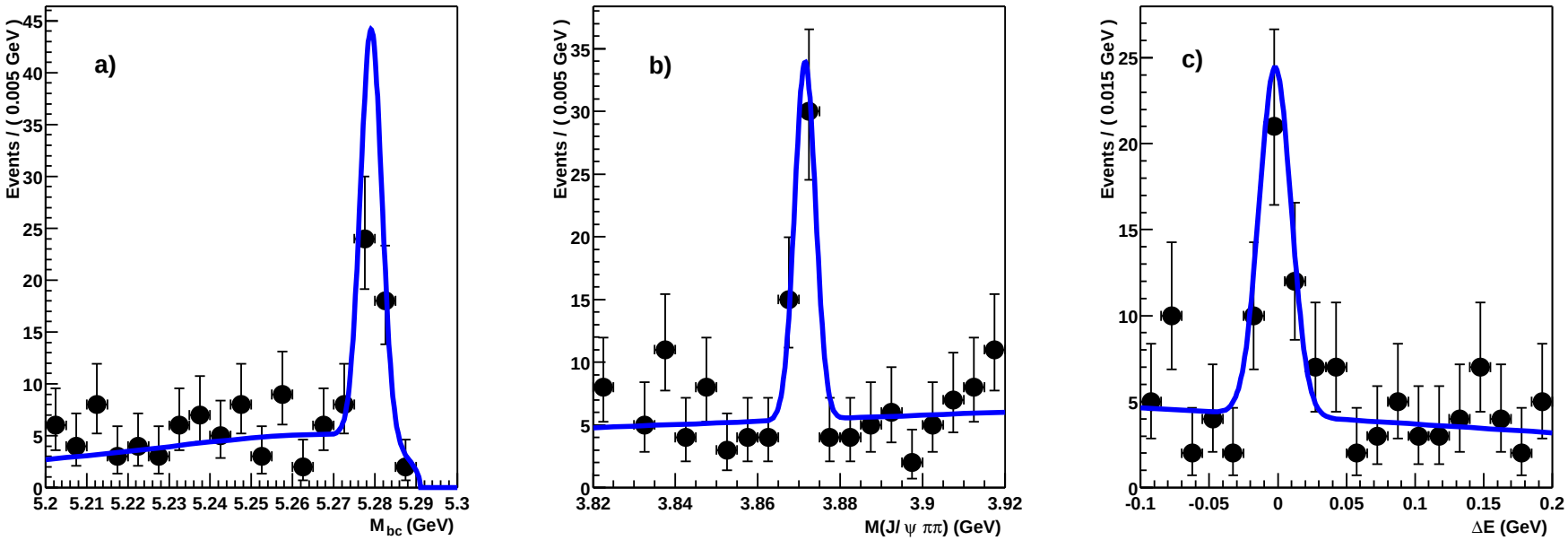


Exclusive modes seem to saturate R
after subtracting the contribution of light $(u,\ d,\ s)$ quarks.
Small room only left for states with $D_s^{(*)}$ and charmed baryons

Summary on 1^{--} States

- Four well-known excitations of the J/ψ are confirmed in exclusive channels; first steps to disentangle decay mechanisms made. Larger data samples and additional decay modes needed to perform fits in the coupled-channel model to determine their parameters.
- New vector states observed ($Y(4260)$, $Y(4360)$, $Y(4630)$, $Y(4660)$). Although well above open charm threshold, they decay to $J/\psi(\psi(2S))\pi^+\pi^-$. Energy dependence of cross sections may be affected by coupled-channel and rescattering ($D^{(*)}\bar{D}^{(*)}$) effects
- The $Y(3990)$ state of Belle is not confirmed by BaBar, but is not ruled out by them
- Are the $\psi(2S)\pi^+\pi^-$ state at 4660 MeV and $\Lambda_c^+\Lambda_c^-$ state at 4630 MeV the same?
- Interpretation is not straightforward and needs theory input.

Discovery of $X(3872)$



Belle – S.-K. Choi et al., PRL 91 (2003) 262001; 152M $B\bar{B}$ pairs; 1080 cites!

A 10.3σ $J/\psi\pi^+\pi^-$ state with $M = (3872.0 \pm 0.6 \pm 0.5)$ MeV and $\Gamma < 2.3$ MeV

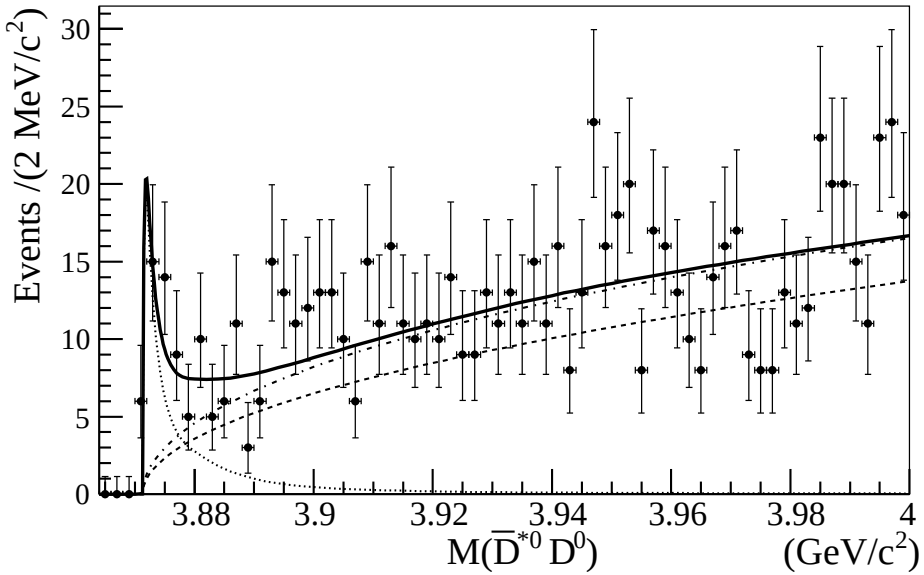
Confirmed by CDF and D0 in $p\bar{p}$ and BaBar in B decays

Seen and extensively studied at LHC

What do we know about $X(3872)$?

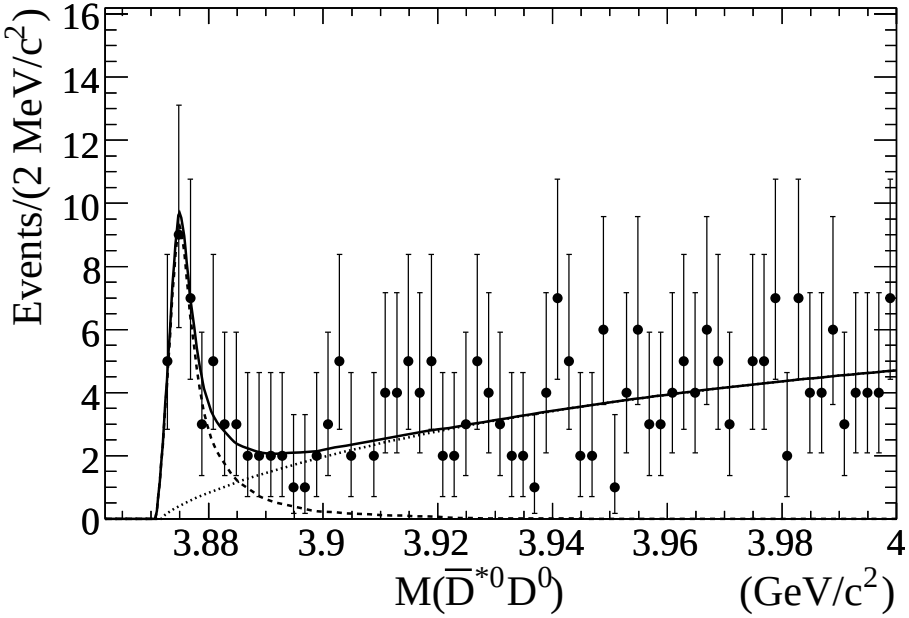
- $M_{\pi^+\pi^-} \approx M_\rho$ (violates isospin)
- Decays to $J/\psi\gamma,\ \psi(2S)\gamma \Rightarrow C = +1$
- $\mathcal{B}(\psi(2S)\gamma)/\mathcal{B}(J/\psi\gamma) = 2.46 \pm 0.64 \pm 0.29$
- Spin-parity analysis $\Rightarrow J^{PC} = 1^{++}, 2^{-+}$, finally $J^{PC} = 1^{++}$
- Doesn't decay to $\chi_{c1}\gamma,\ D\bar{D},\ \gamma\gamma,\ e^+e^-$
- No charged partner, not an isovector
- Belle (BaBar) observed decays to $D^0\bar{D}^0\pi^0 (D^0\bar{D}^{*0})$ with mass 3875 MeV, marginally OK with one state or could be two states, the rate much larger than that of $J/\psi\pi^+\pi^-$, many models suggested, but ...
- CDF: $M = 3871.61 \pm 0.16 \pm 0.19$ MeV Most precise!
  0.19 ± 0.43 MeV below the $D^0\bar{D}^{*0}$ threshold, no 2 states, $\Delta M < 3.6$ MeV at 95%CL

Study of $B \to X(3872)(D^{*0}\bar{D}^0)K$



Belle – $657 \cdot 10^6$ $B\bar{B}$ pairs;

T. Aushev et al., Phys. Rev. D 81 (2010) 031103.



BaBar – $383 \cdot 10^6$ $B\bar{B}$ pairs;

B.Aubert et al., PRD 77 (2008) 011102

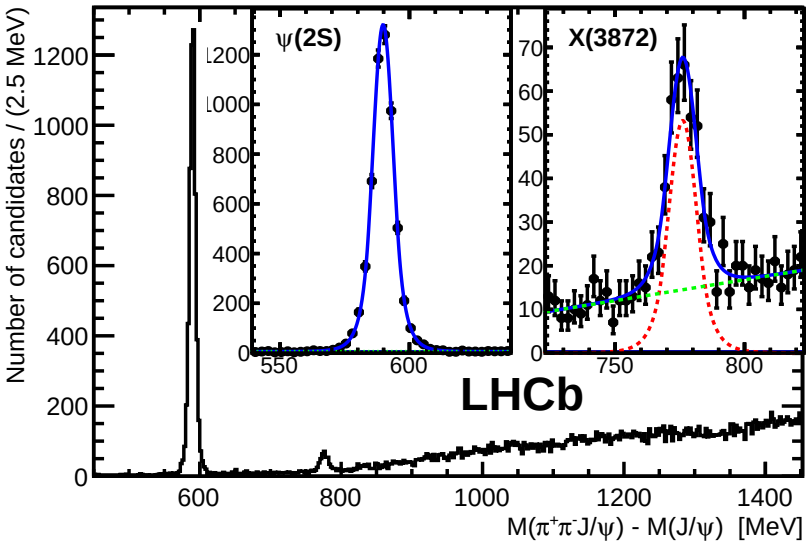
New M, Γ from Belle consistent with $J/\psi\pi^+\pi^-$, mass 2.3σ lower than in BaBar:

$$M = 3872.9^{+0.6+0.4}_{-0.4-0.5} \text{ MeV}$$

compared to the world-average $M_{J/\psi\pi\pi} = 3871.69 \pm 0.17$ MeV

Determination of X(3872) Quantum Numbers – I

A study of $B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\pi^+\pi^-,\ J/\psi \to \mu^+\mu^-$
produced in pp at $\sqrt{s} = 7$ TeV with $\int Ldt = 1$ fb^{-1}

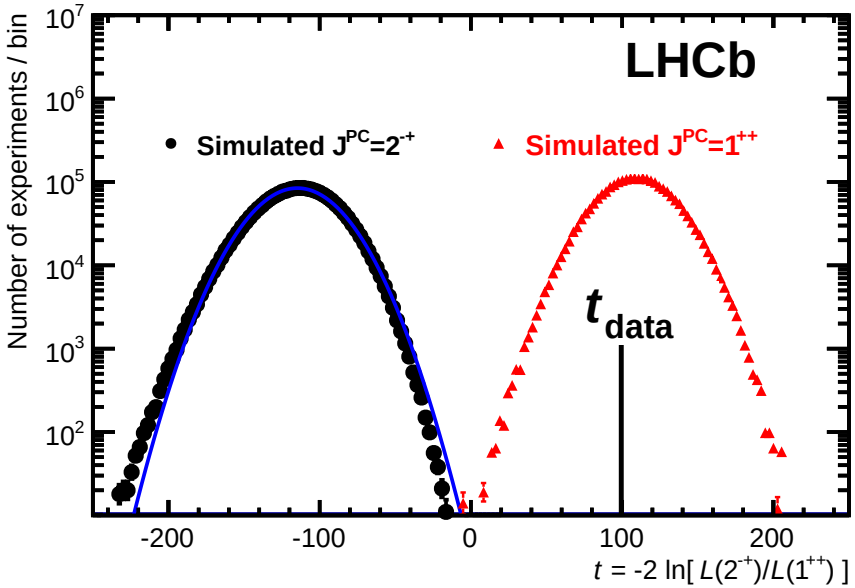


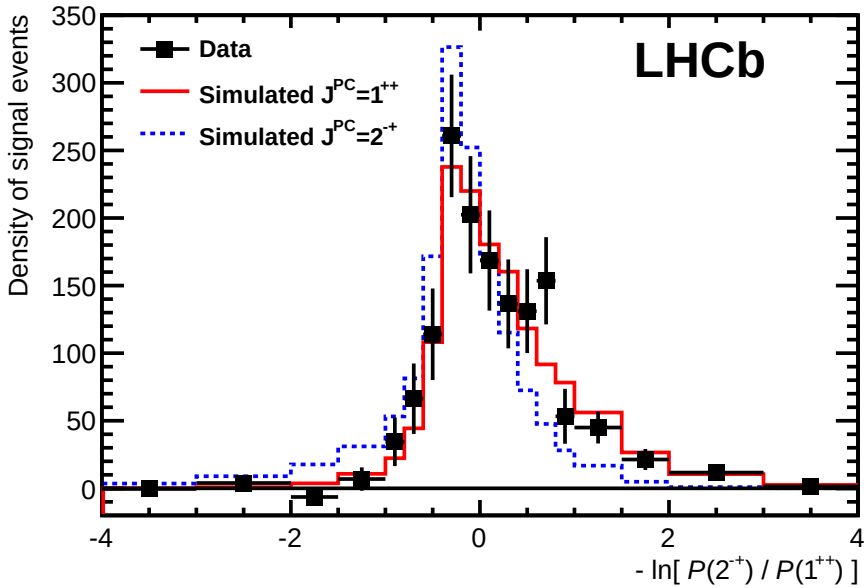
About 38000 B candidates selected in $M(J/\psi\pi^+\pi^-K^+)$ in a $\pm 2\sigma$ range,
a fit yields 5642 ± 76 $\psi(2S)$ events and 313 ± 26 $X(3872)$ (68% purity)

R. Aaij et al., Phys. Rev. Lett. 110 (2013) 222001

Determination of X(3872) Quantum Numbers – II

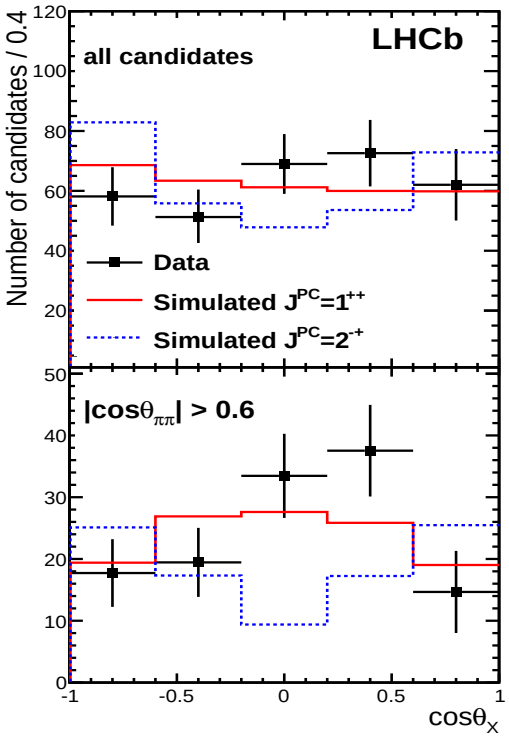
Analysis in $5D$ angular space $\Omega \equiv (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$





The 2^{-+} hypothesis is rejected with 8.4σ significance

Determination of X(3872) Quantum Numbers – III



- Projections onto five $1D$ and ten $2D$ binned distr. are all consistent with 1^{++}
- Correlations between $\cos\theta_X$ and $\cos\theta_{\pi\pi}$ increase the separation btw. 1^{++} and 2^{-+}

1^{++} rules out $X(3872)$ as a conventional $\eta_{c2}(1^1D_2)$ state,
$\chi_{c1}(2^3P_1)$ $c\bar{c}$ disfavored by $X(3872)$ mass,
Possible exotics: $D^{*0}\bar{D}^0$ molecule, 4-q state, $c\bar{c}$-molecule mixture

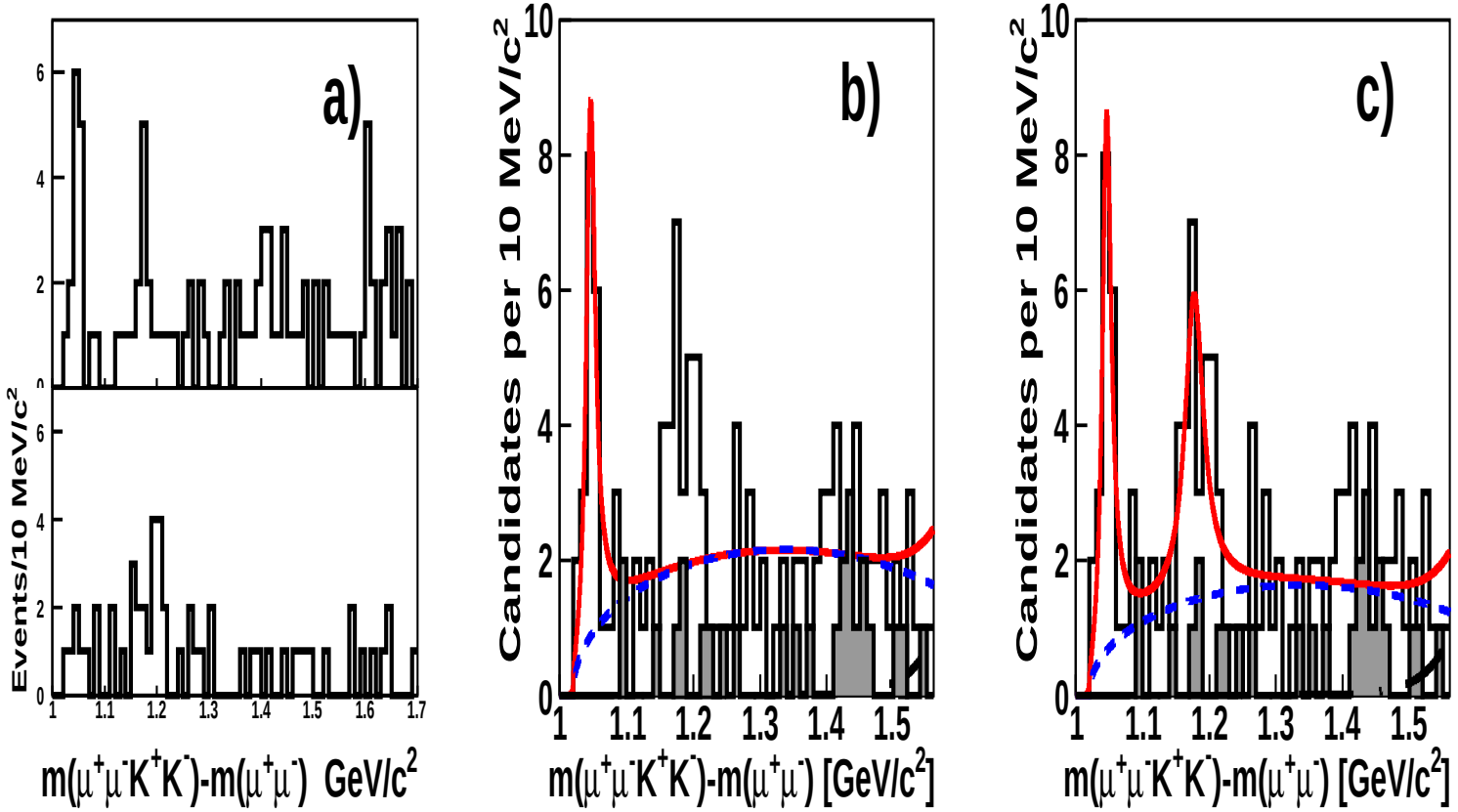
Summary on the $X(3872)$

- $J^{PC} = 1^{++}$ proved by LHCb
- $\chi_{c1}(2P)(1^{++})$ is not very likely considering the decay pattern, mass and observation of $Z(3930) = \chi_{c2}(2P)$
- Possible interpretations (in arbitrary order):
  1. an S-wave $D^0\bar{D}^{*0}$ molecule (loosely bound $[c\bar{q}][\bar{c}q]$)
  2. tetraquarks (tightly bound $[cq][\bar{c}\bar{q}]$)
  3. hybrids ($q\bar{q}$-gluon)
  4. threshold effect (cusp)
  5. a $D^0\bar{D}^{*0}$ molecule mixed with $c\bar{c}$
  6. hadrocharmonium – $c\bar{c}$ (J/ψ, ...) in the excited light-hadron matter

$Y(4140)$ at CDF – I

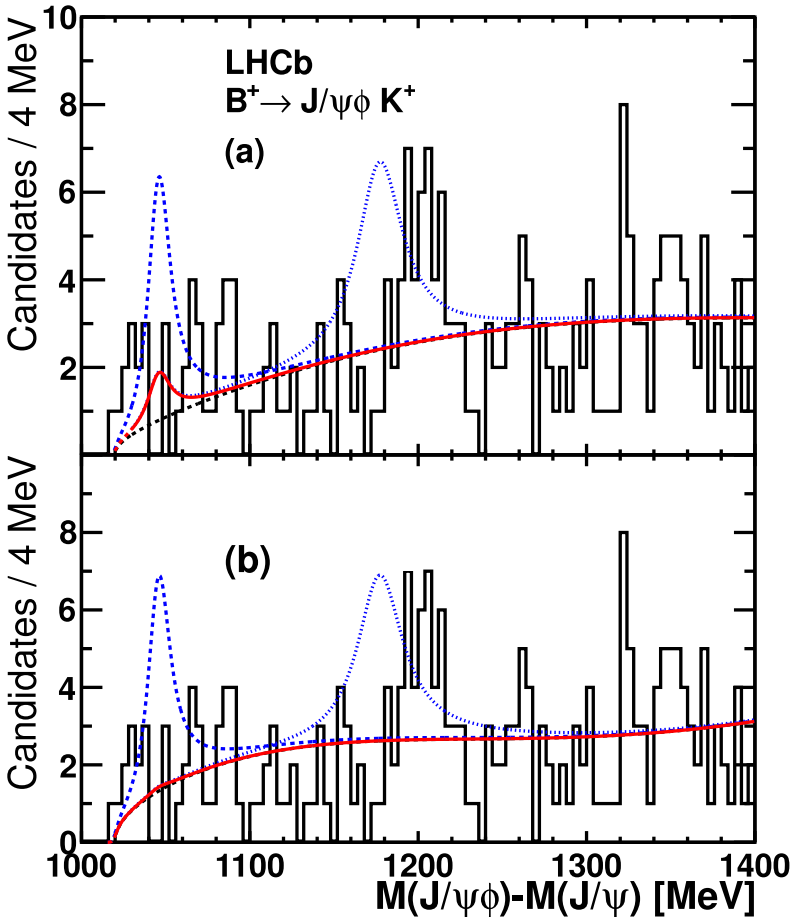
- First evidence (3.8σ) from CDF as $B^+ \to Y(4140)K^+$, $Y(4140) \to J/\psi\phi$, $N = 14 \pm 5$, $M = (4143.0 \pm 2.9 \pm 1.2)$ MeV, $\Gamma = (11.7^{+8.3}_{-5.0} \pm 3.7)$ MeV, T.Aaltonen et al., PRL 102 (2009) 242002
- Belle searched for $Y(4140)$ in B decays with a negative, but not inconsistent with CDF result, J.Brodzicka, LP-09
- Belle also didn't see $Y(4140)$ in $\gamma\gamma$, but found evidence for $Y(4350)$ with 3.2σ significance
- In 1101.0658 CDFII reports x2.2 (6 fb^{-1}) and confirms $Y(4140)$
- As before, they use $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$
- The first state of two heavy quarkonia - $c\bar{c}s\bar{s}$

$Y(4140)$ at CDF – II



Two significant structures seen: at 4143 MeV (5.0σ) and at 4274 MeV (3.1σ) with 19 ± 7 and 22 ± 8 events

Search for $Y(4140)$ at LHCb – I

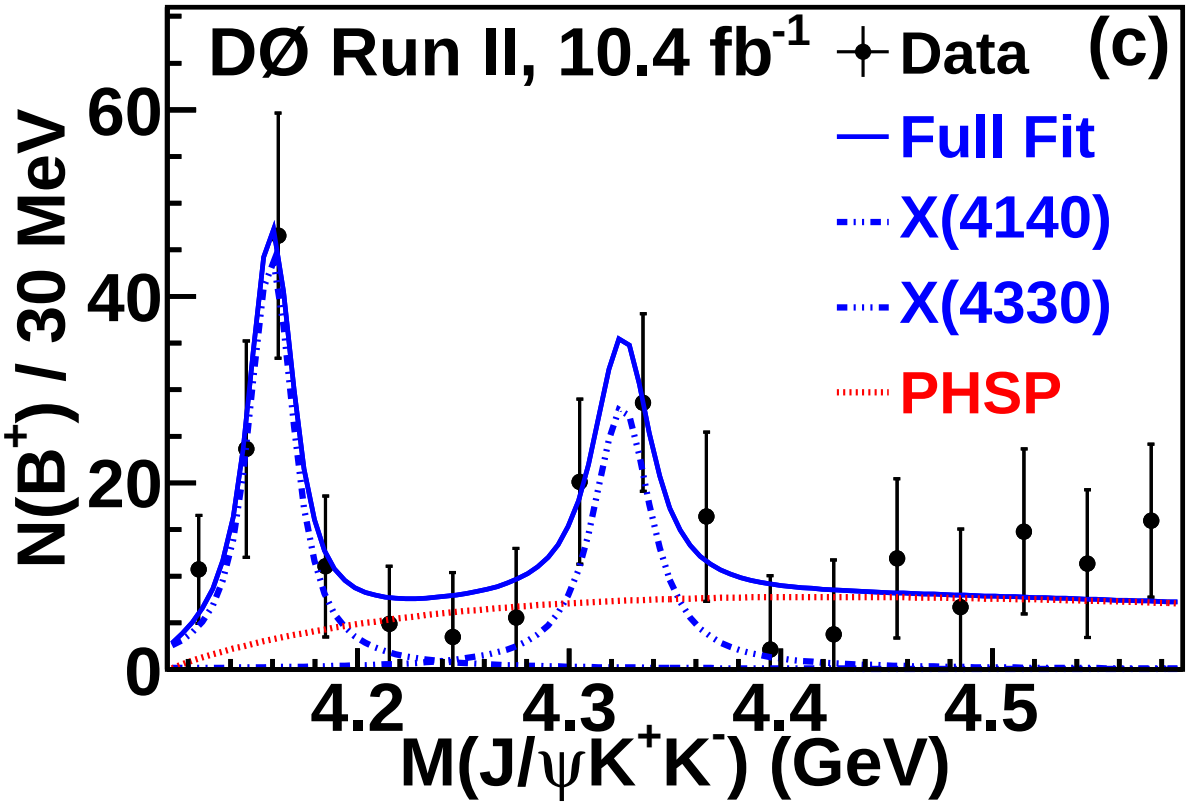


R. Aaij et al. (LHCb Collab.), Phys. Rev. D85 (2012) 091103

Search for $Y(4140)$ at LHCb – II

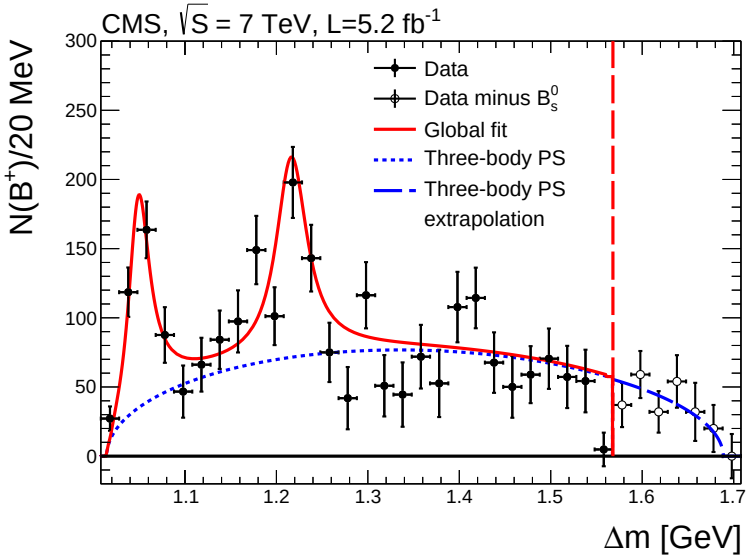
- LHCb observes 382 ± 22 events of $B^+ \to J/\psi\phi K^+$ with 115 ± 12 at CDF
- LHCb: < 16 events of $B^+ \to X(4140)K^+$ with $35 \pm 9 \pm 6$ expected from CDF, 2.4σ disagreement
- LHCb: $\frac{\mathcal{B}(B^+ \to X(4140)K^+)\mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07$ at 90%CL
- CDF: $\frac{\mathcal{B}\mathcal{B}}{\mathcal{B}} = 0.149 \pm 0.039 \pm 0.024$
- For $X(4274)$, LHCb: < 24 events, 53 ± 19 expected from CDF
- LHCb: $\frac{\mathcal{B}\mathcal{B}}{\mathcal{B}} < 0.08$, with 0.17 ± 0.06 at CDF
- Recently CMS and D0 also claimed its observation

Observation of $Y(4140)$ at D0



V.M. Abazov et al., Phys. Rev. D 89 (2014) 012004

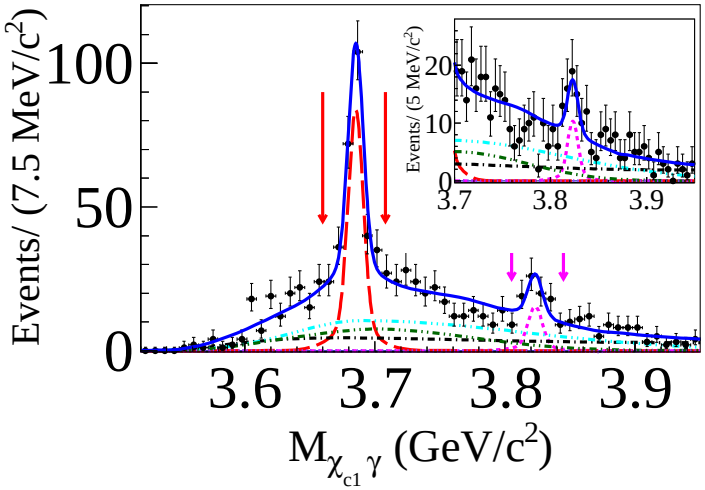
Observation of $Y(4140)$ at CMS

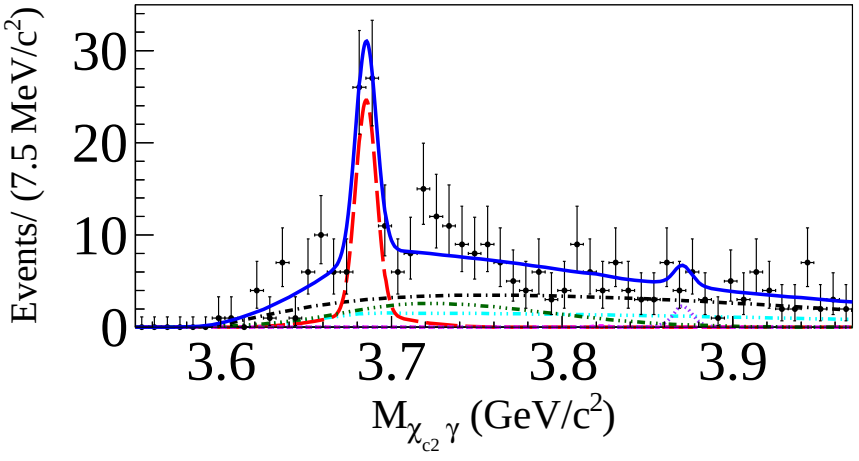


S. Chatrchyan et al., Phys. Lett. B 734 (2014) 261

New Charmonium State at Belle – I

With $772 \cdot 10^6$ $\Upsilon(4S) \to B\bar{B}$ Belle studies $B \to \chi_{c1(c2)}\gamma K$ in a broad mass range





A new state at 3820 MeV seen in $\chi_{c1}\gamma$ in addition to $\psi(2S)$!

There is no signal at 3872 MeV in both modes

B. Bhardwaj et al., Phys. Rev. Lett. 111 (2013) 032001

New Charmonium State at Belle – II

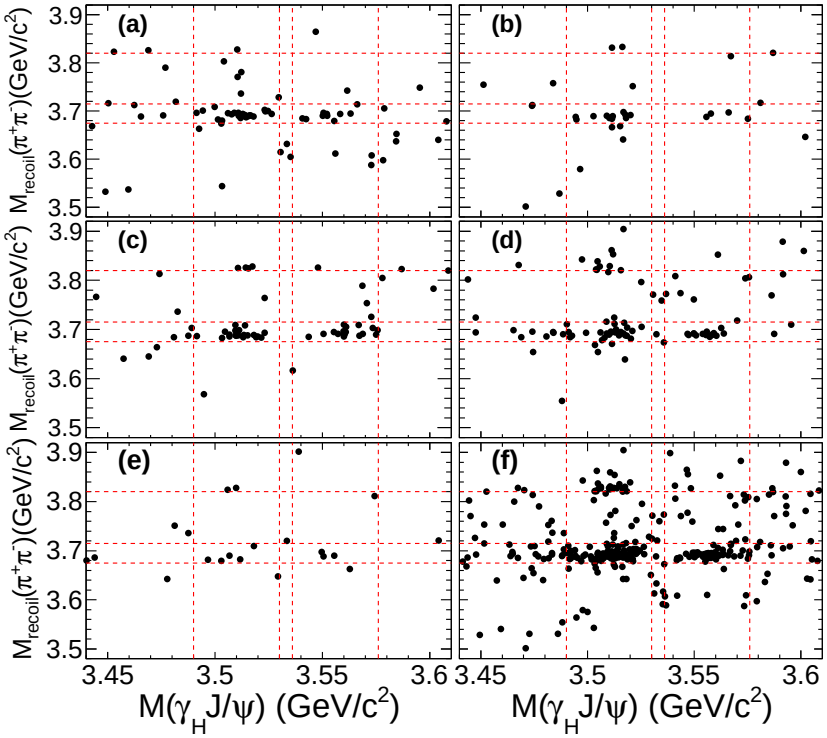
- There is 3.8σ evidence for a new state at $3823.1 \pm 1.8 \pm 0.7$ MeV
- $\mathcal{B}(B^+ \to X(3820)K^+)\mathcal{B}(X \to \chi_{c1}\gamma) = (9.7^{+2.8+1.1}_{-2.5-1.0}) \cdot 10^{-6}$
- $\mathcal{B}(\chi_{c2}\gamma)/\mathcal{B}(\chi_{c1}\gamma) < 0.41$
- It is a 1^3D_2 or $\psi(1D)$ (ψ_2) state with $J^{PC} = 2^{--}$ expected at 3810-3840 MeV, it is narrow because $M < m_D + m_{\bar{D}^*}$, $D\bar{D}$ forbidden by P
- For $X(3872)$ $\mathcal{BB} < 1.9 \cdot 10^{-6} \Rightarrow$
  $\Gamma(X(3872) \to \chi_{c1}\gamma)/\Gamma(X(3872) \to J/\psi\pi^+\pi^-) < 0.26$
  setting a constraint on the C-odd partner of $X(3872)$

B. Bhardwaj et al., Phys. Rev. Lett. 111 (2013) 032001

$X(3823)$ at BESIII – I

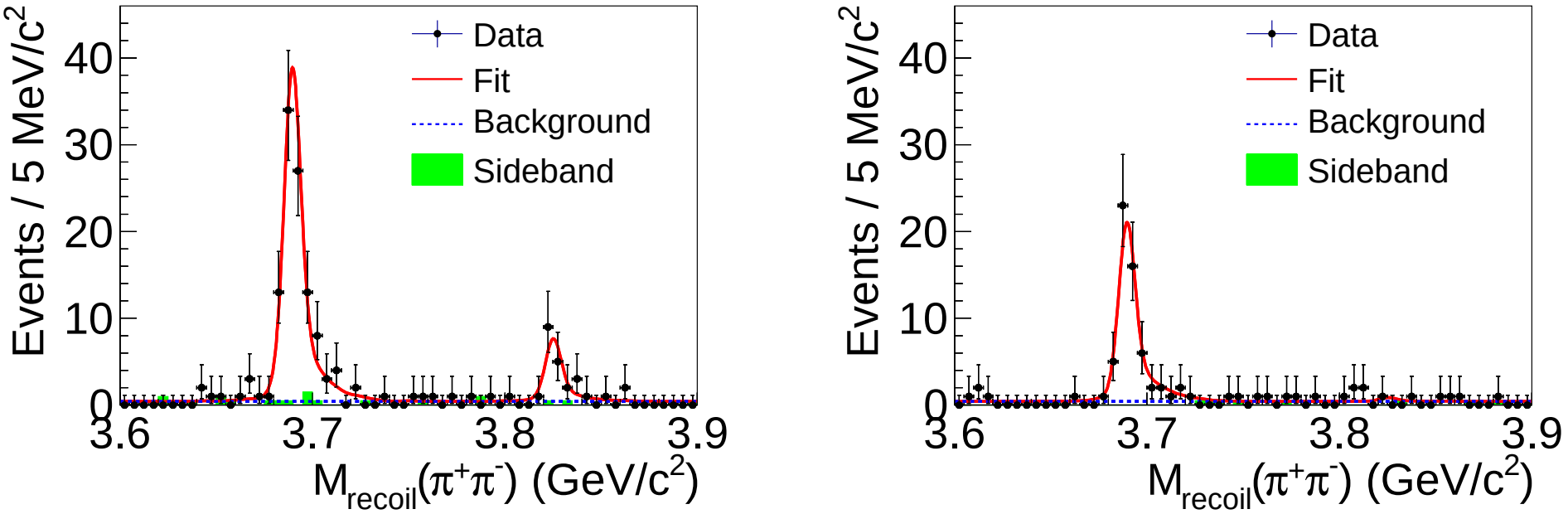
4.67 fb^{-1} from 4.19 to 4.60 GeV to search for

$e^+e^- \to \pi^+\pi^- X,\ X \to \chi_{c1(c2)}\gamma,\ \chi_{c1(c2)} \to J/\psi\gamma$



M. Ablikim et al., arXiv:1503.08203

$X(3823)$ at BESIII – II

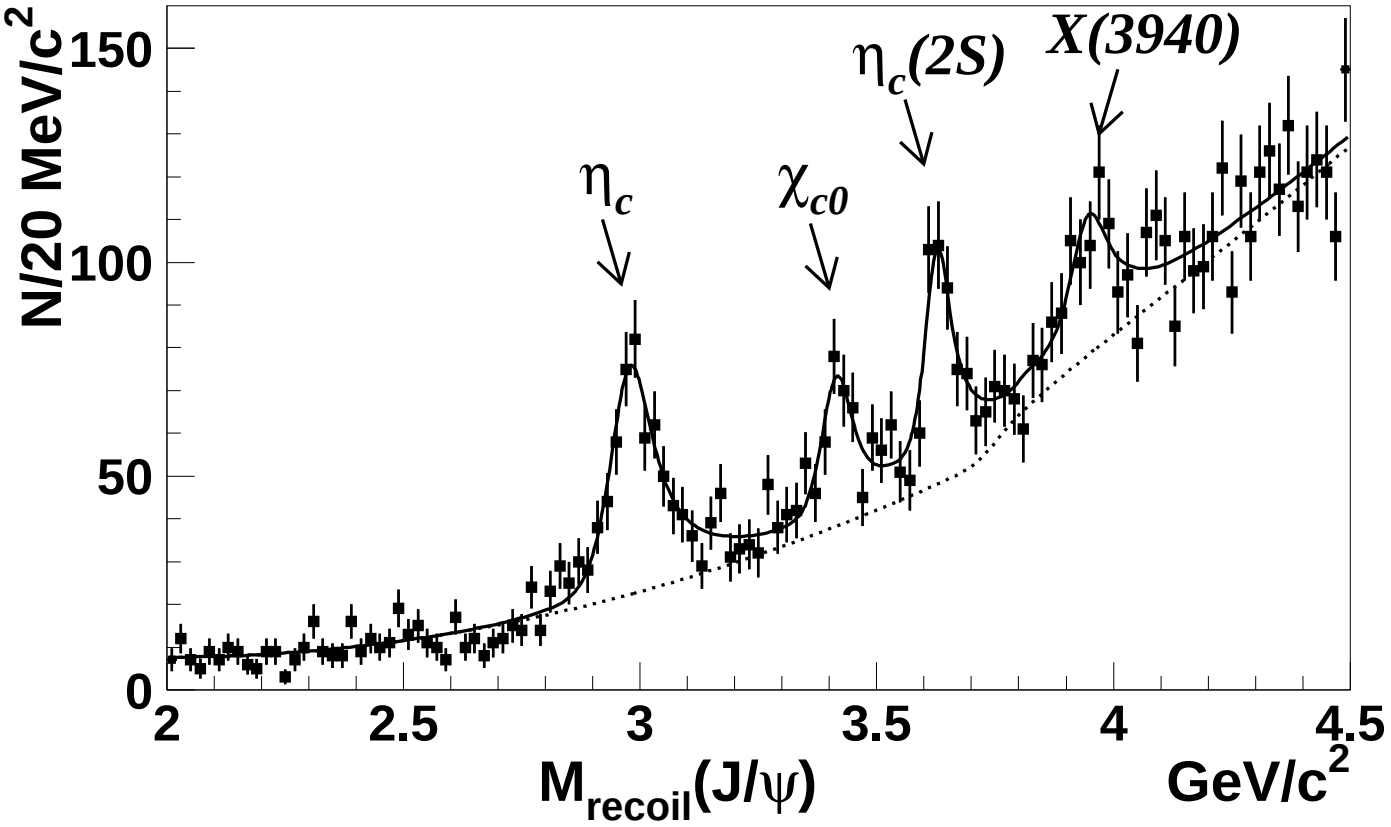


19 ± 5 events in $\gamma\chi_{c1}$, $M = 3821.7 \pm 1.3 \pm 0.7$ MeV, $\Gamma < 16$ MeV, $\sim 6\sigma$

No signal in $\gamma\chi_{c2}$, $\mathcal{B}(\chi_{c2}\gamma)/\mathcal{B}(\chi_{c1}\gamma) < 0.42$, ~ 0.2 expected

M. Ablikim et al., arXiv:1503.08203

Double Charmonium at Belle

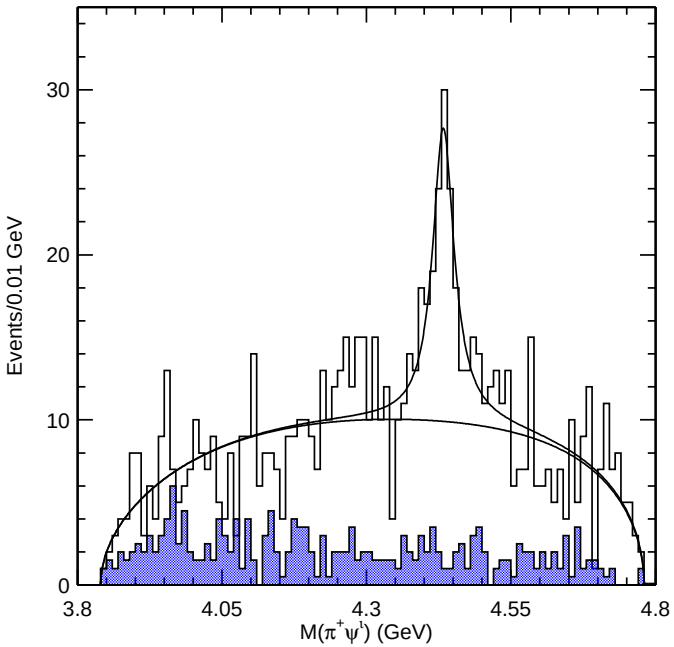


K. Abe et al., PRL 98, 082001 (2007); Belle – 357 fb^{-1}

A new state $X(3940)$ observed in the recoil to J/ψ

Observation of the $Z(4430)^{\pm}$ by Belle – I

S.-K. Choi et al., Phys. Rev. Lett. 100 (2008) 142001 observed the very first charged charmonium-like state, $B \to K\ Z(4430)^{\pm}(\psi(2S)\pi^{\pm})$, using 657M $B\bar{B}$ pairs (605 fb^{-1})



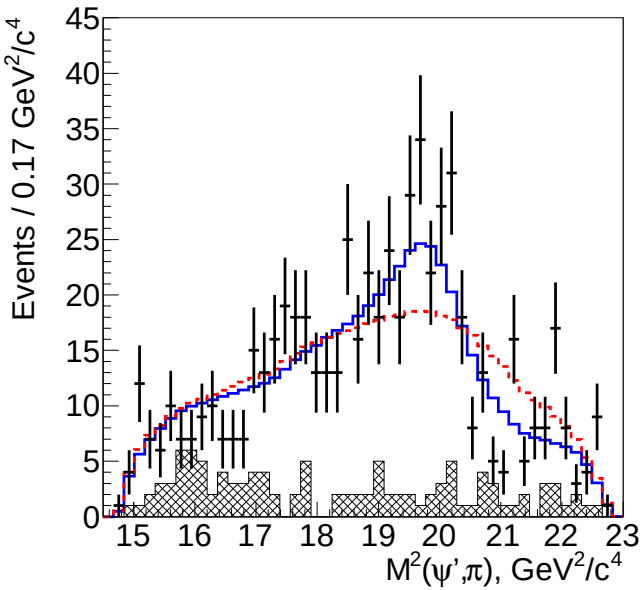
Confirmed by Dalitz plot analysis in R. Mizuk et al., Phys. Rev. D80 (2009) 031104

Not seen by BaBar with 413 fb^{1}, B. Aubert et al., Phys. Rev. D79 (2009) 112001

Observation of the $Z(4430)^{\pm}$ by Belle – II

Confirmed with full amplitude analysis and 772M $B\bar{B}$ pairs

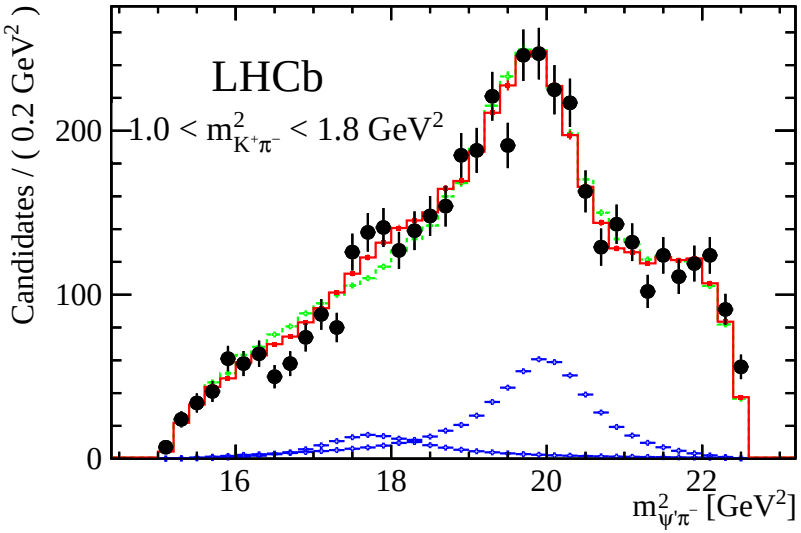
$J^P = 1^+$ is favored over the 0^-, 1^-, 2^-, 2^+ (3.4σ, 3.7σ, 4.7σ, 5.1σ)



K. Chilikin et al., Phys. Rev. D88 (2013) 074026

Confirmation of the $Z(4430)^{\pm}$ by LHCb

LHCb confirms it, $J^P = 1^+$, with $\times 10$ $B\bar{B}$ pairs

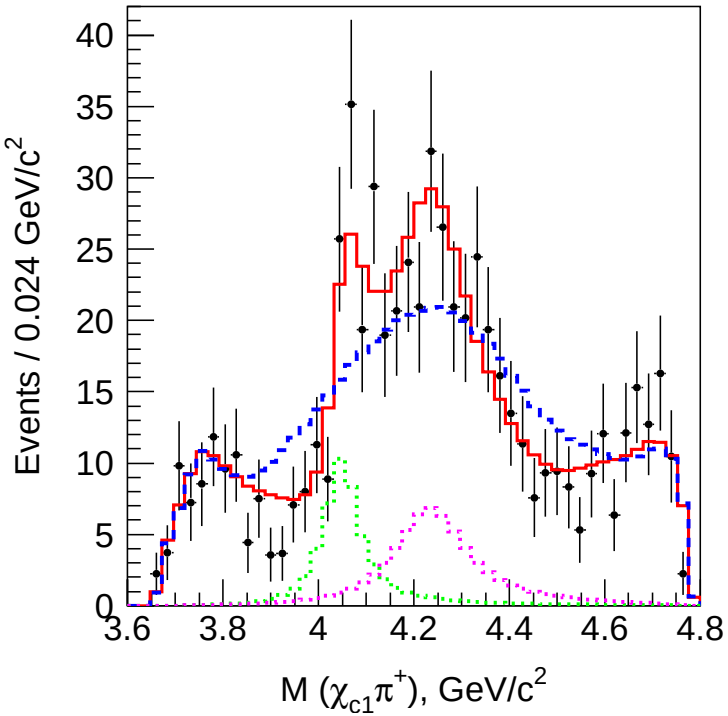


R. Aaij et al., Phys. Rev. Lett. 112 (2014) 074026

Observation of the Charged $\chi_{c1}\pi^{\pm}$ State at Belle – I

With 605 fb^{-1} Belle observes $\bar{B}^0 \to K^- X^+(\chi_{c1}\pi^+)$ with $X(4050)^+$ and $X(4250)^+$

BaBar does not observe them with 429 fb^{-1}



R. Mizuk et al., Phys. Rev. D78 (2008) 072004

J.P. Lees et al., Phys. Rev. D85 (2012) 052003

Observation of the Charged $\chi_{c1}\pi^{\pm}$ State at Belle – II

Quantity	Belle	BaBar
Mass, MeV	$4051 \pm 14^{+20}_{-41}$	–
Γ, MeV	82^{+21+47}_{-17-22}	–
$\mathcal{BB}, 10^{-5}$	$3.0^{+1.5+3.7}_{-0.8-1.6}$	< 1.8 at 90%CL
Mass, MeV	$4248^{+44+180}_{-29-\ 35}$	–
Γ, MeV	$177^{+54+316}_{-39-\ 61}$	–
$\mathcal{BB}, 10^{-5}$	$4.0^{+2.3+19.7}_{-0.9-\ 0.5}$	< 4.0 at 90%CL

Belle: R. Mizuk et al., Phys. Rev. D78 (2008) 072004

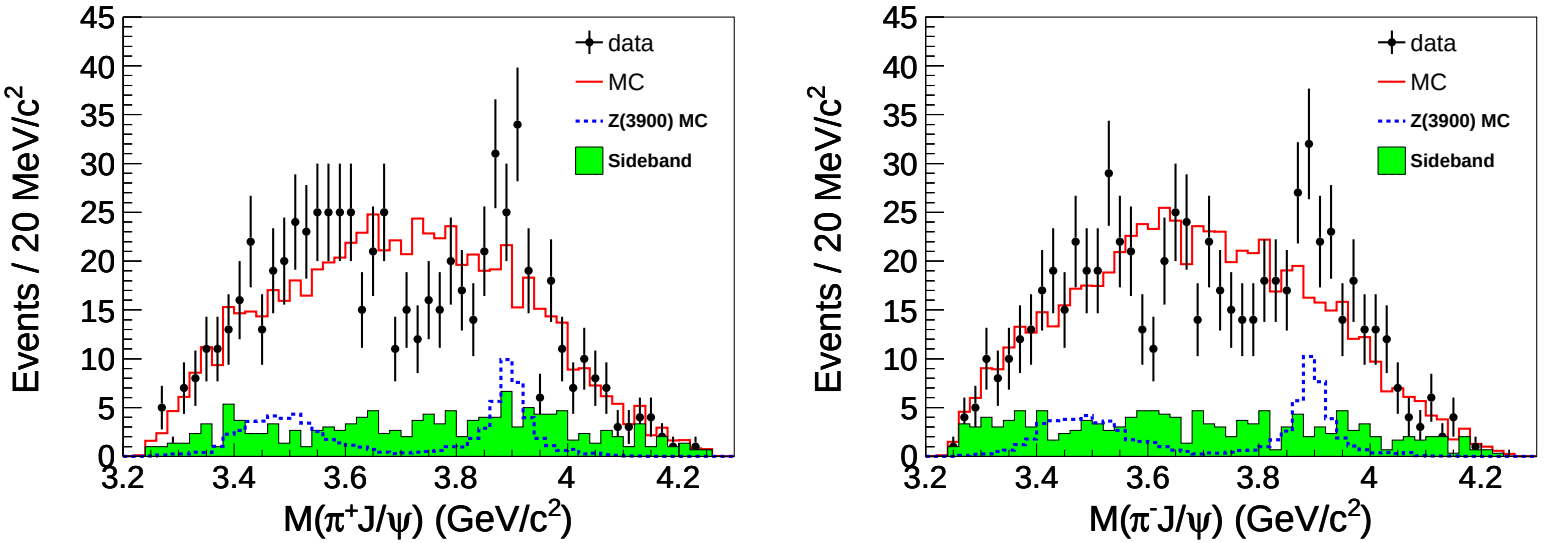
BaBar: J.P. Lees et al., Phys. Rev. D85 (2012) 052003

Observation of the Charged $J/\psi\pi^{\pm}$ State – I

From analysis of the $J/\psi\pi^{\pm}$ mass in $Y(4260) \to J/\psi\pi^{+}\pi^{-}$
both BESIII and Belle find a charged structure $-Z_c(3900)^{\pm}$

Group	BES	Belle
$\int \mathcal{L}dt$, fb^{-1}	0.525	967
Mass, MeV	$3899.0 \pm 3.6 \pm 4.9$	$3894.5 \pm 6.6 \pm 4.5$
Width, MeV	$46 \pm 10 \pm 20$	$63 \pm 24 \pm 26$
R, %	$21.5 \pm 3.3 \pm 7.5$	29.0 ± 8.9
Events	307 ± 48	159 ± 50
Ref.	PRL 110 (2013) 252001	PRL 110 (2013) 252002

Observation of the Charged $J/\psi\pi^{\pm}$ State – II

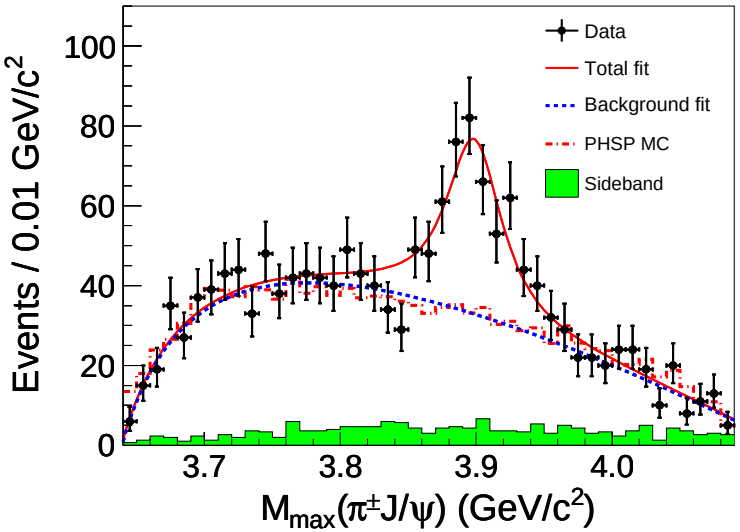


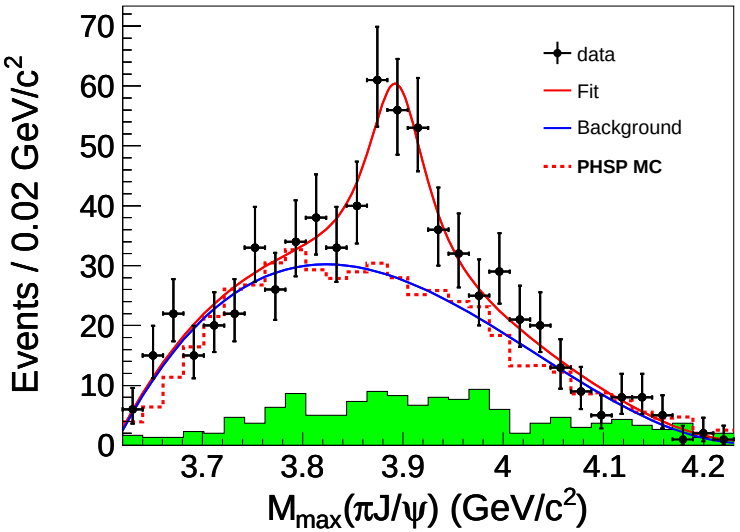
Observed in both $J/\psi\pi^{+}$ and $J/\psi\pi^{-}$

BES: M. Ablikim et al., Phys. Rev. Lett. 110 (2013) 252001

Belle: Z.Q. Liu et al., Phys. Rev. Lett. 110 (2013) 252002

Observation of the Charged $J/\psi\pi^{\pm}$ – III





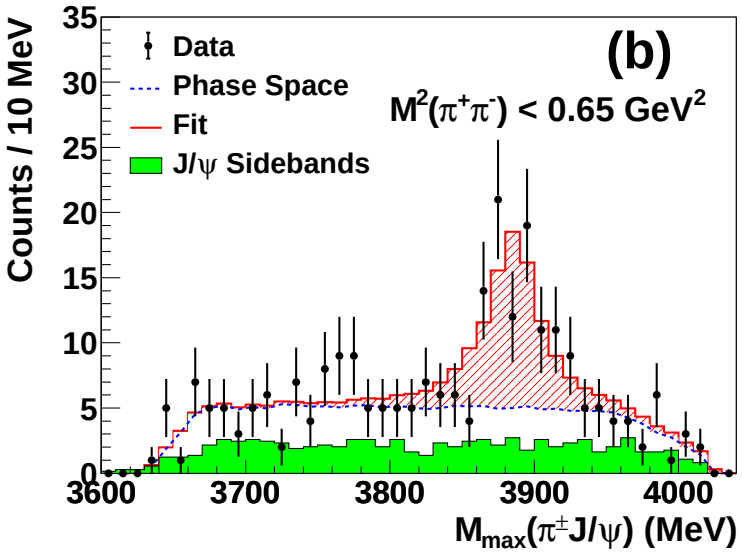
BES Belle

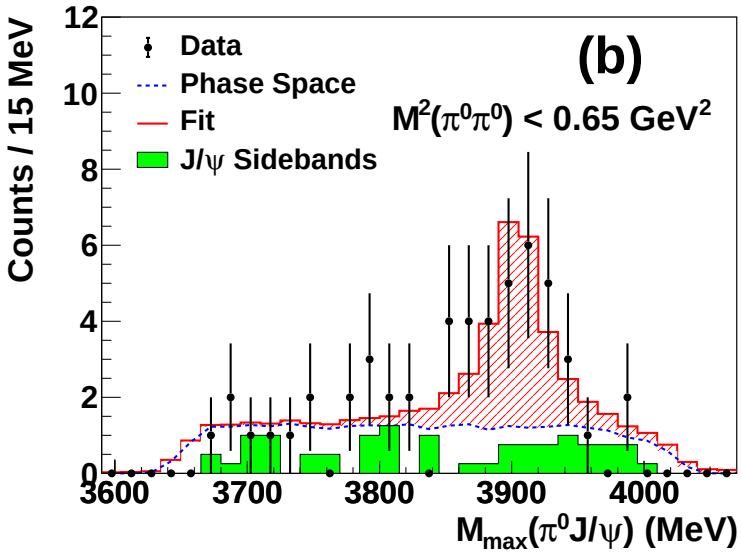
BES: M. Ablikim et al., Phys. Rev. Lett. 110 (2013) 252001

Belle: Z.Q. Liu et al., Phys. Rev. Lett. 110 (2013) 252002

Confirmation of $Z_c(3900)^{\pm}$ with CLEO Data

With 586 pb^{-1} of CLEO data at 4.17 GeV $e^+e^- \to J/\psi\pi^+\pi^-,\ J/\psi\pi^0\pi^0$ studied.
They observe the $Z_c(3900)^{\pm}$ and find evidence for the $Z_c(3900)^0$.

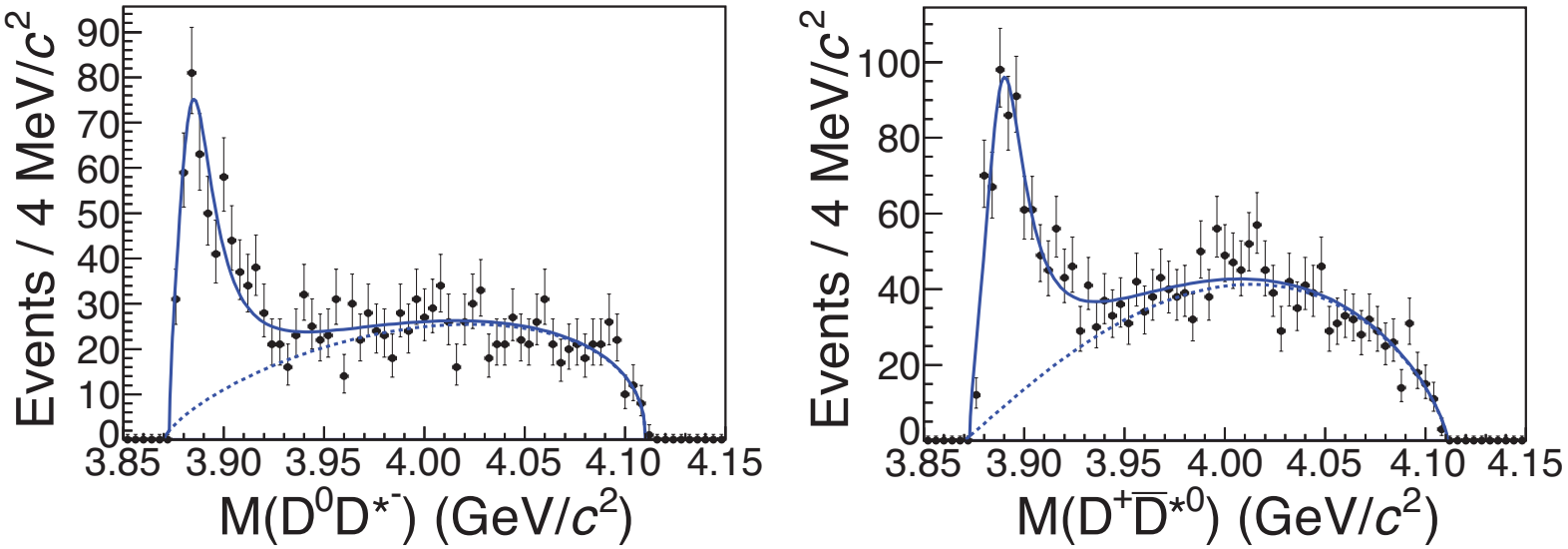




T. Xiao et al., Phys. Lett. B727 (2013) 336

Observation of $Z_c(3900)^{\pm}$ in $(D\bar{D}^*)^{\pm}$ at BESIII

A $J^P = 1^+$ structure in $(D\bar{D}^*)^{\pm}$ with mass (width) 2σ (1σ) below the $J/\psi\pi$

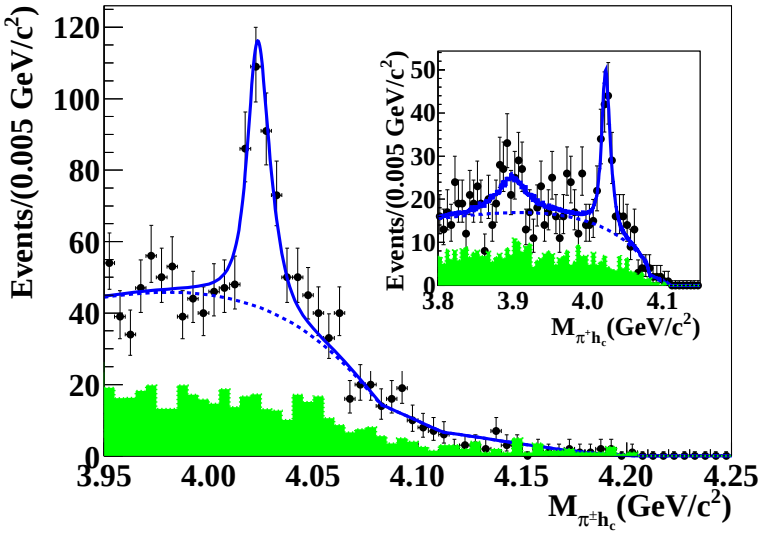


$$\Gamma(D\bar{D}^*)/\Gamma(J/\psi\pi) = 6.2 \pm 1.1 \pm 2.7$$

M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 022001

Observation of $Z_c(4020)^{\pm}$ in $e^+e^- \to h_c\pi^+\pi^-$

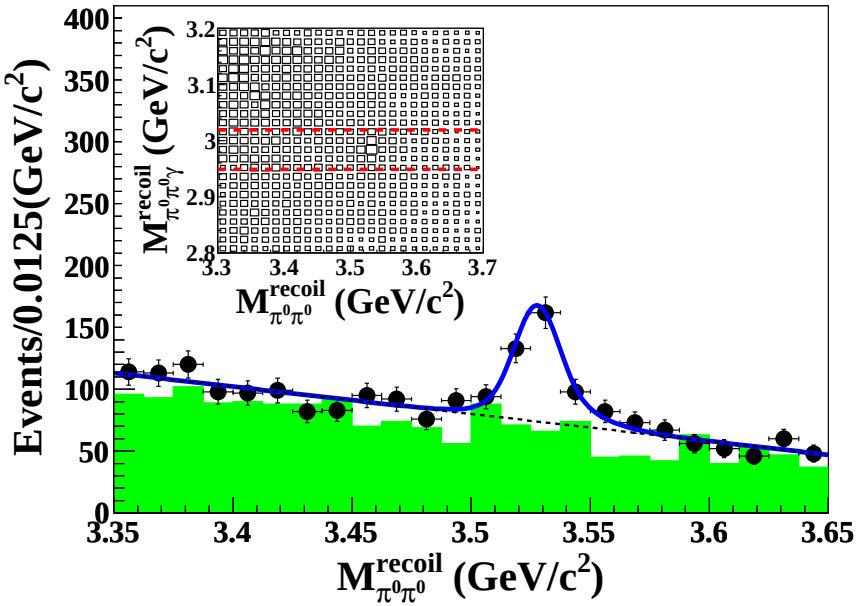
In $e^+e^- \to h_c\pi^+\pi^-$ a charged structure in $h_c\pi^{\pm}$ seen
with mass $4022.9 \pm 0.8 \pm 2.7$ MeV and width $7.9 \pm 2.7 \pm 2.6$ MeV

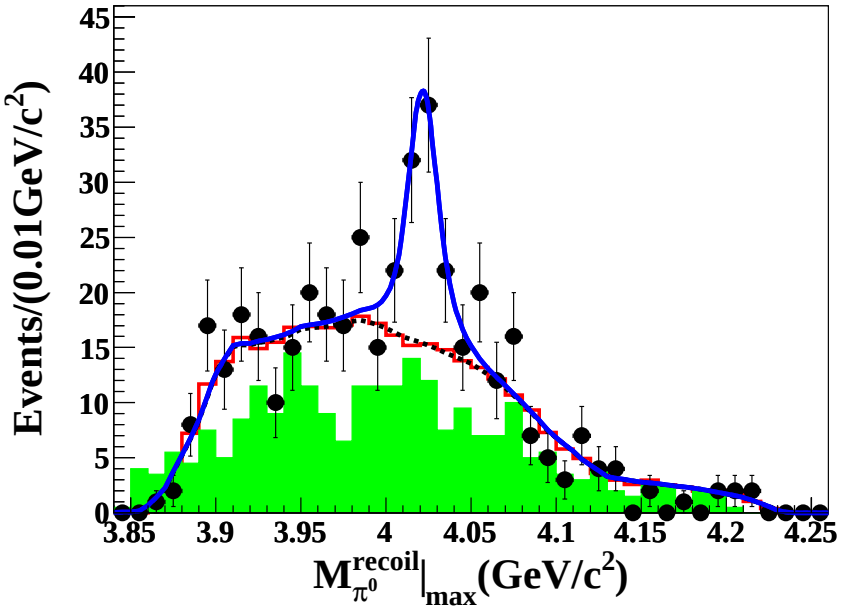


M. Ablikim et al., Phys. Rev. Lett. 111 (2013) 242001

Observation of $Z_c(4020)^0$ in $e^+e^- \to h_c\pi^0\pi^0$ at BESIII

BESIII: $\sigma(e^+e^- \to h_c\pi^0\pi^0) \approx 0.5\sigma(e^+e^- \to h_c\pi^+\pi^-)$ at 4.23, 4.26 and 4.36 GeV,
$h_c \to \eta_c(1S)\gamma$, $\eta_c \to X$ full recon., h_c in recoil to $\pi^0\pi^0$, η_c in recoil to $\pi^0\pi^0\gamma$



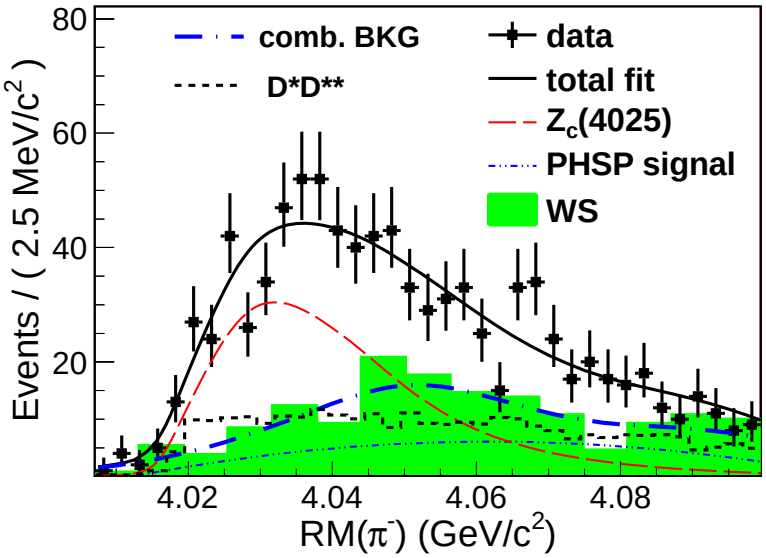


Narrow $Z_c(4020)^0$ is observed at $4023.9 \pm 2.2 \pm 3.8$ MeV

M. Ablikim et al., Phys. Rev. Lett. 113 (2014) 212002

Observation of $Z_c(4020)^{\pm}$ in $e^+e^- \to D^*\bar{D}^*\pi$

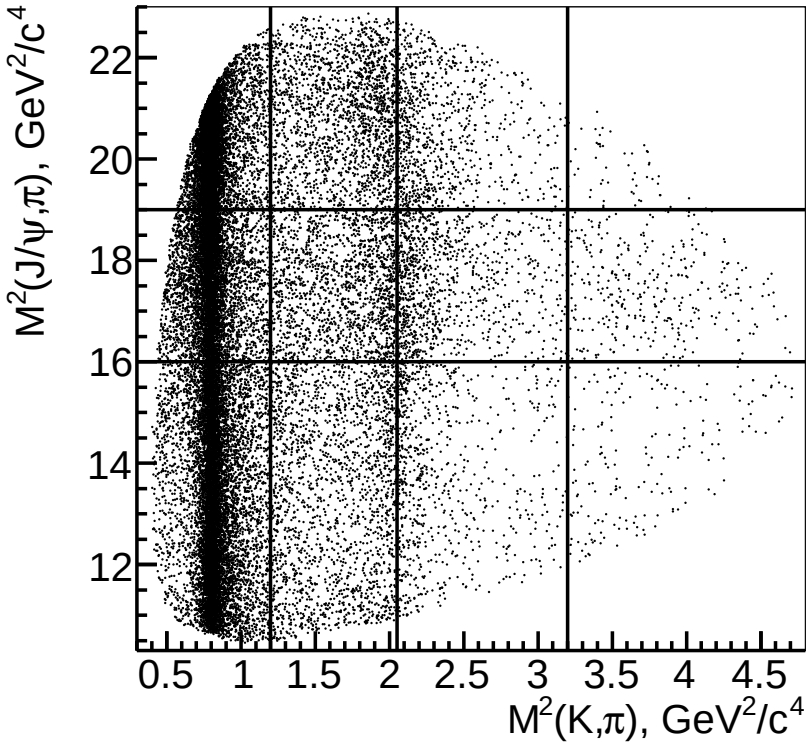
In $e^+e^- \to D^*\bar{D}^*\pi$ at 4.26 GeV a charged structure seen in $D^*\bar{D}^*$ with mass $4026.3 \pm 2.6 \pm 3.7$ MeV and width $24.8 \pm 5.6 \pm 7.7$ MeV



M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 132001

Charged $J/\psi\pi^+$ States in $\bar{B}^0 \to J/\psi K^-\pi^+$ at Belle – I

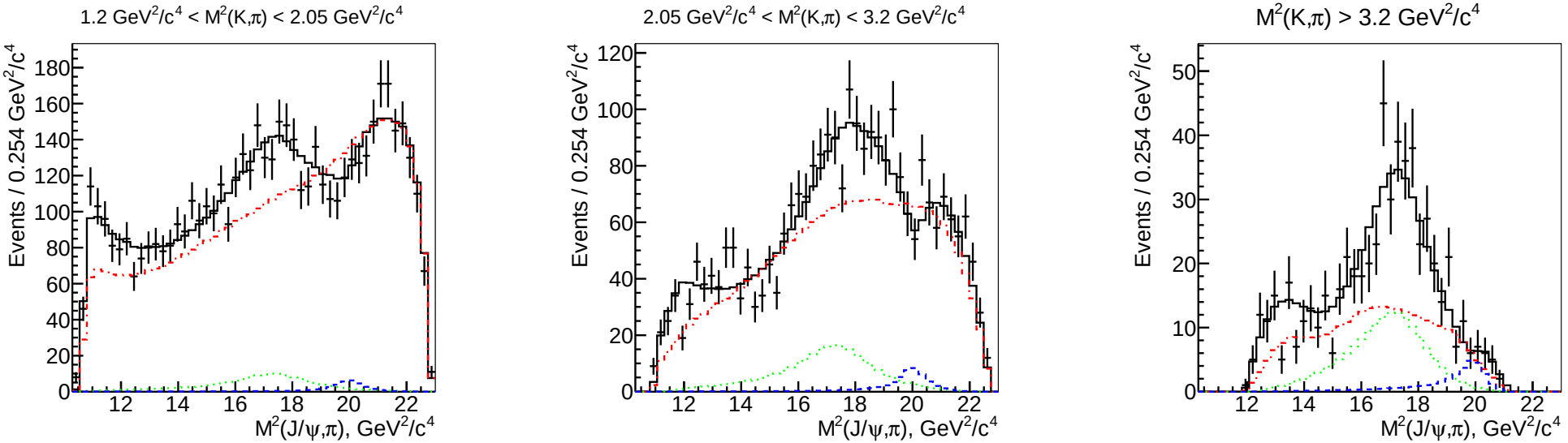
A study of $\bar{B}^0 \to J/\psi K^-\pi^+$ decays with 772M $B\bar{B}$ pairs at $\Upsilon(4S)$ (711 fb^{-1})



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

Charged $J/\psi\pi^+$ States in $\bar{B}^0 \to J/\psi K^-\pi^+$ at Belle – II

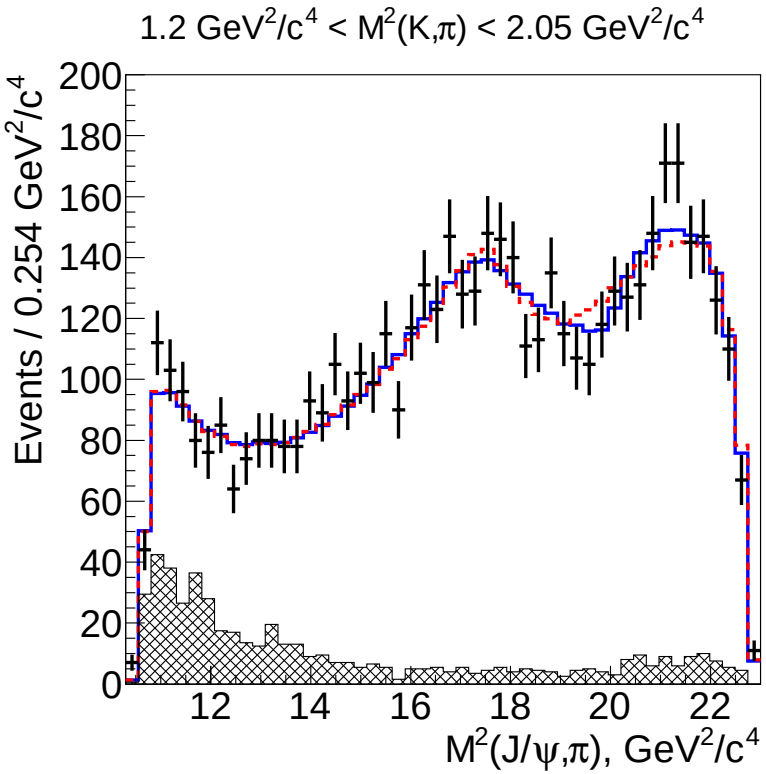
$Z_c(4200)^+ \to J/\psi\pi^+$ with mass 4196^{+31+17}_{-29-13} MeV and width $370^{+70+\ 70}_{-70-132}$ MeV seen

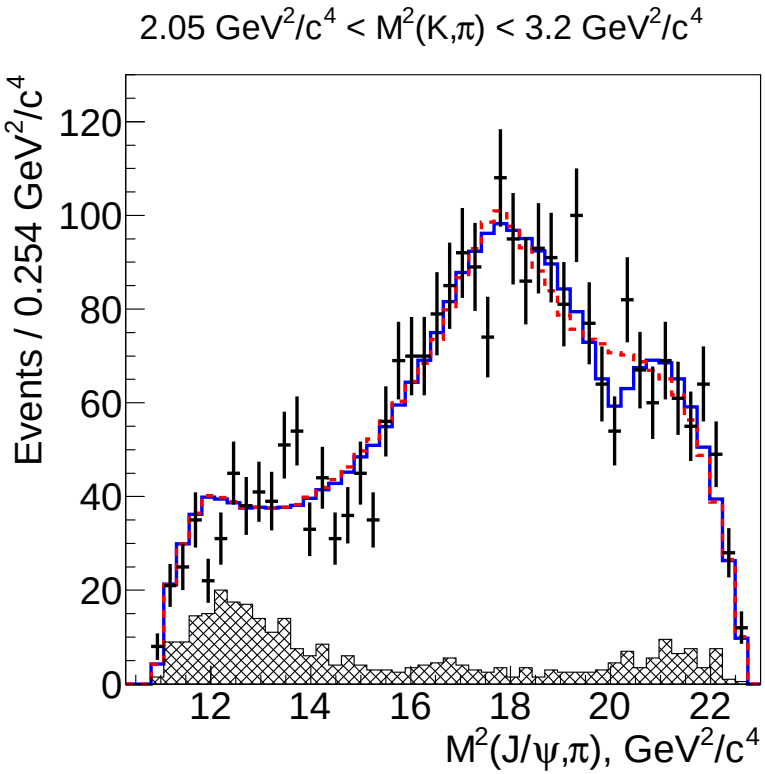


K. Chilikin et al., Phys. Rev. D 90 (2014) 112009

Charged $J/\psi\pi^+$ States in $\bar{B}^0 \to J/\psi K^-\pi^+$ at Belle – III

They also find evidence for $Z(4430)^+ \to J/\psi\pi^+$
and do not see $\bar{B}^0 \to Z_c(3900)^+ K^-$, $Z_c(3900)^+ \to J/\psi\pi^+$

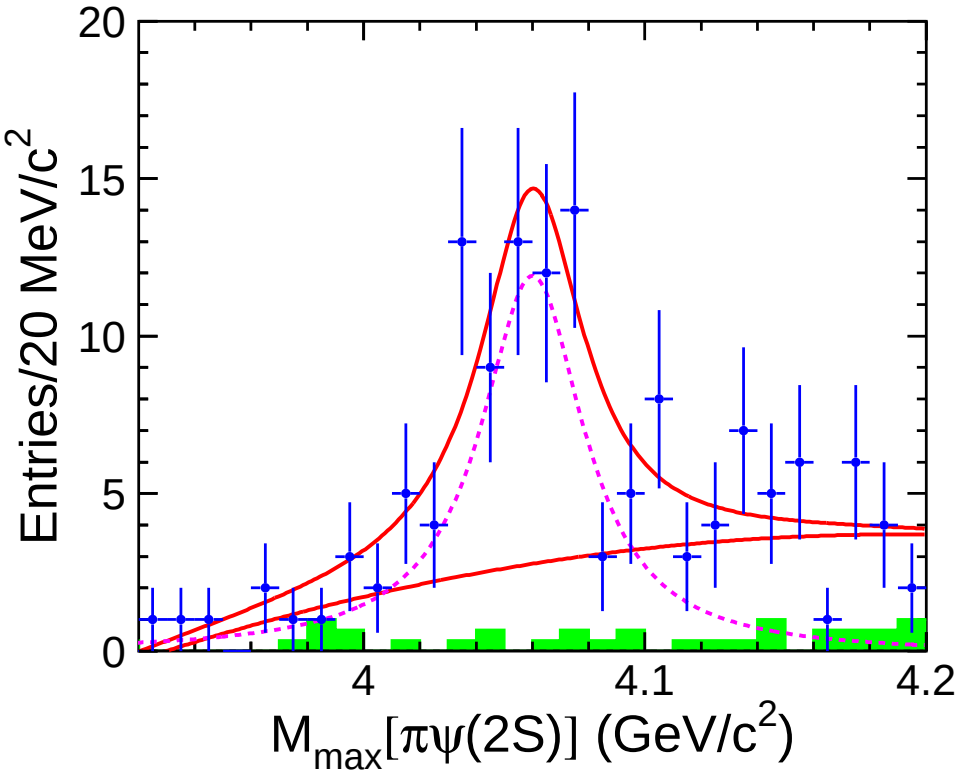




K. Chilikin et al., Phys. Rev. D 90 (2014) 112009

Observation of the $\psi(2S)\pi^{\pm}$ at 4050 MeV at Belle

In a study of $e^+e^- \to \pi^+\pi^-\psi(2S)$ Belle finds a 3.5σ charged $\psi(2S)\pi^{\pm}$ structure in $Y(4360)$ decay with mass of $4054 \pm 3 \pm 1$ MeV and width of $45 \pm 11 \pm 6$ MeV



X.L. Wang et al., Phys. Rev. D 91 (2015) 112007

New Charmonium(like) States – I

State	J^{PC}	Process
$\eta_c(2S, 3639)$	0^{-+}	$B \to K(K_S K\pi)$
$\psi(3820)$	2^{--}	$B \to \chi_{c1}\gamma K$
$X(3872)$	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$
$X(3915)$	$0/2^{?+}$	$B \to K(J/\psi\omega)$
$\chi_{c2}(2P, 3927)$	2^{++}	$\gamma\gamma \to D\bar{D}$
$X(3940)$	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Y(3990)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$Y(4140)$	$?^{?+}$	$B \to K(J/\psi\phi)$
$X(4160)$	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$
$Y(4260)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$X(4350)$	$0/2^{++}$	$\gamma\gamma \to J/\psi\phi$

New Charmonium(like) States – II

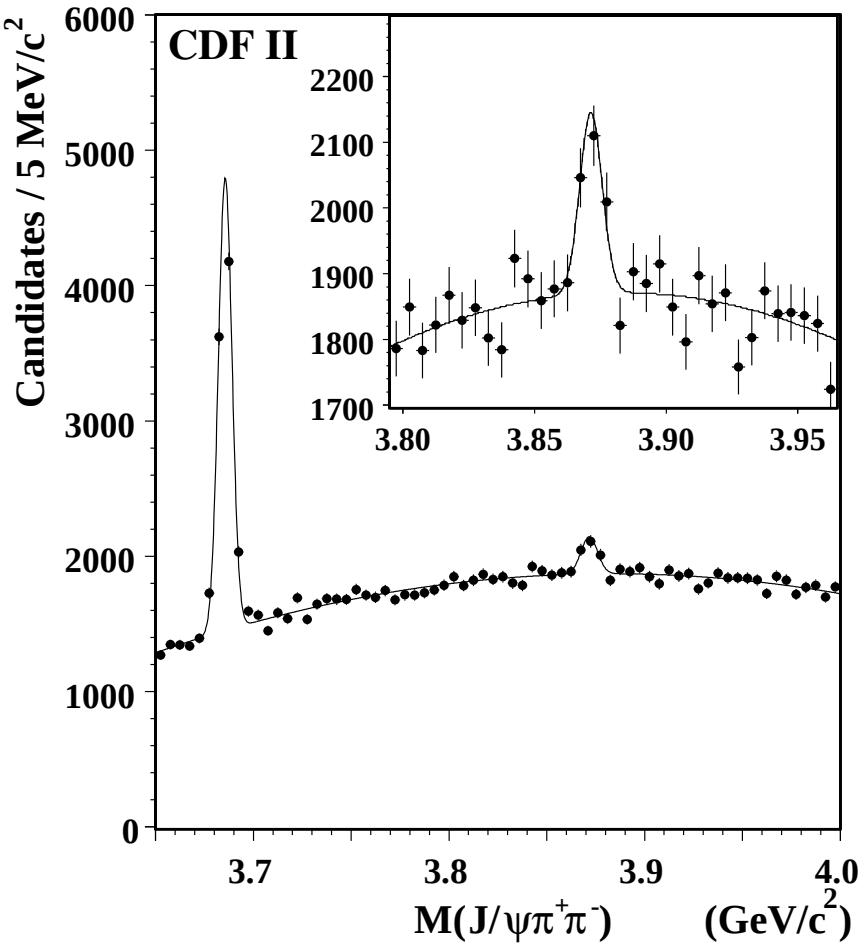
State	J^{PC}	Process
$Y(4360)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$
$Y(4630)$	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$
$Z_c(3900)^+$	1^+	$e^+e^- \to J/\psi\pi\pi,\ D\bar{D}^*$
$Z_c(4020)^+$	1^+	$e^+e^- \to h_c\pi\pi,\ D^*\bar{D}^*$
$Z_1(4050)^+$	$?^?$	$B \to K(\chi_{c1}(1P)\pi^+)$
$Z_c(4050)^+$	$?^?$	$e^+e^- \to \psi(2S)\pi\pi$
$Z_c(4200)^+$	1^+	$B \to K(J/\psi\pi^+)$
$Z_2(4250)^+$	$?^?$	$B \to K(\chi_{c1}(1P)\pi^+)$
$Z(4430)^+$	1^+	$B \to K(\psi(2S)\pi^+),\ K(J/\psi\pi^+)$

Conclusions and Future

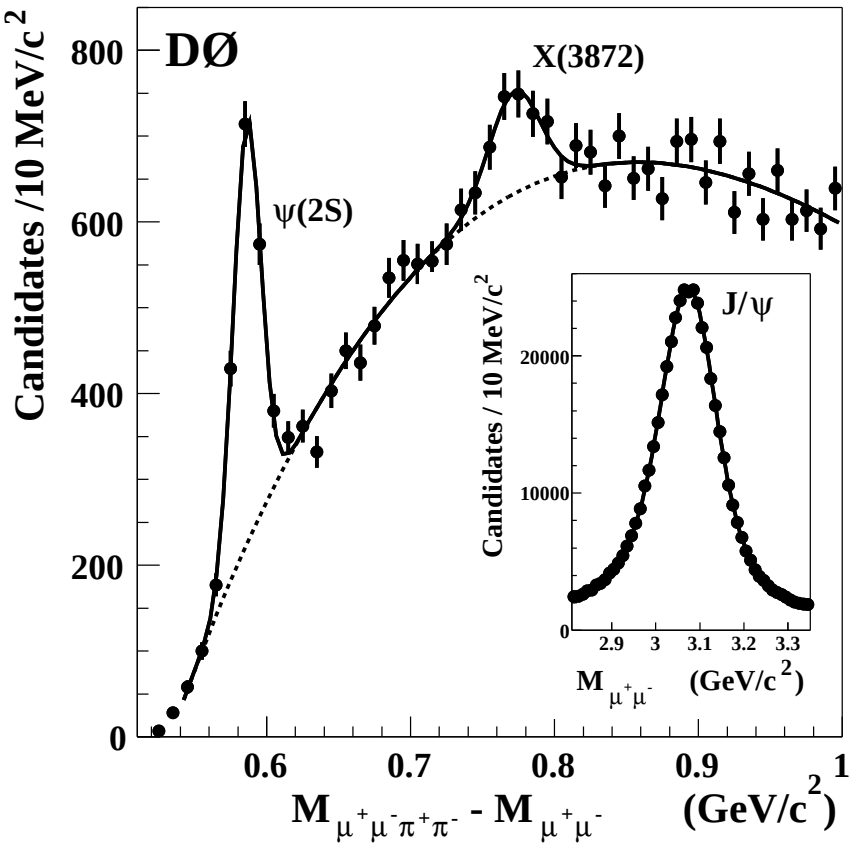
- A large Zoo of new charmonium-like states has been discovered due to high statistics measurements and sophisticated analysis methods
- Some fit the $c\bar{c}$ family, some not and the family is not yet complete
- Nature of many states is still unclear (glueball, hybrid, tetraquark, molecule, hadrocharmonium, rescattering, ...)
- Charged states not fitting the quark model exist
- More theoretical efforts needed
- A lot of work for BESIII and LHCb as well as for future experiments – PANDA, BelleII and Super tau-charm factory
- Bottomonium analogues are very likely

Backup Slides

$X(3872)$ at the Tevatron

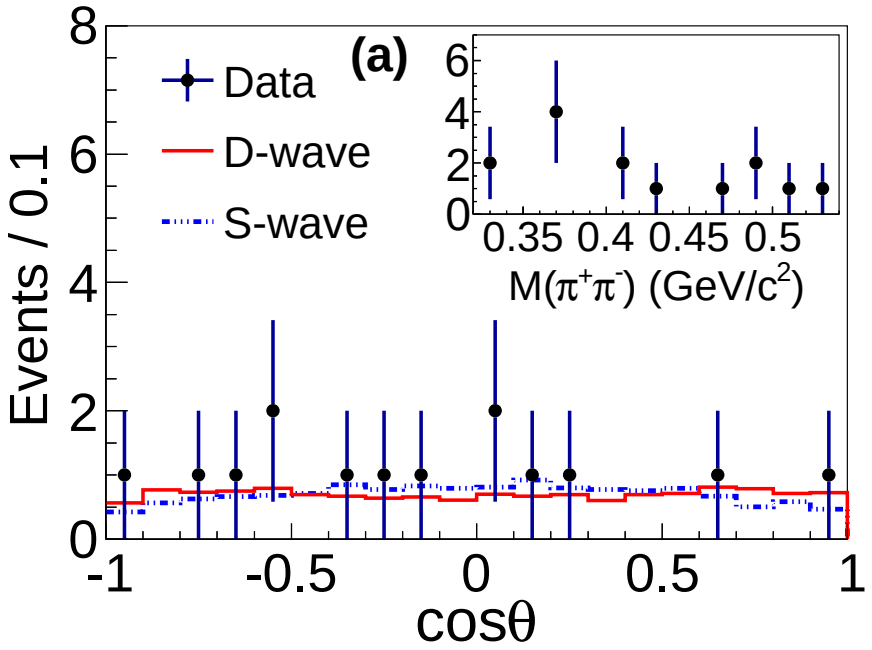


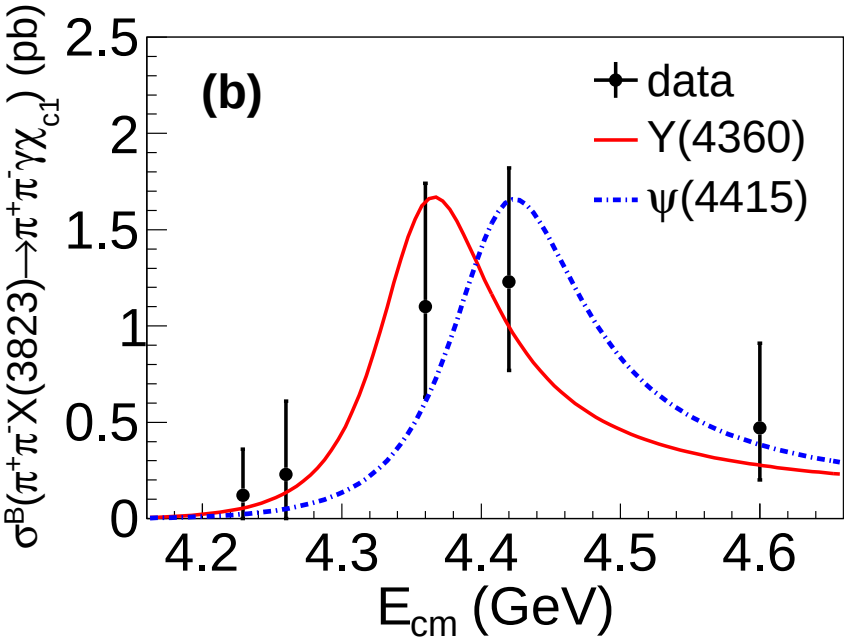
CDF



D0

$X(3823)$ at BESIII – III





$X(3823)$ is $\psi(1^3D_2)$ or ψ_2 state with $J^{PC} = 2^{--}$

It is narrow because $M < m_D + m_{\bar{D}^*}$, $D\bar{D}$ forbidden by P

M. Ablikim et al., arXiv:1503.08203

Charged $J/\psi\pi^+$ States in $\bar{B}^0 \to J/\psi K^-\pi^+$ at Belle

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

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