Charmonia and charmonium-like states in e^+e^-

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JGU Mainz

MIAPP Workshop on flavour physics with high-luminosity experiments
1st November 2016

QCD exotics

States beyond the conventional $q\bar{q}$, qqq valence quark configuration

Identify by

- Exotic quantum numbers (e.g. $\pi_1(1600)$: $J^{PC} = 1^{-+}$)
- Exotic quark contents (such as $X(5568) \sim b\bar{s}u\bar{d}$, if it exists)
- Comparison with predictions of hadron spectrum (?)

Totalitarian principle of quantum mechanics:

Everything not forbidden is compulsory

All the *XYZ*

State	M /MeV	Γ /MeV	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [95, 102], BaBar [98], LHCb [103]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [96, 104, 105, 160], D0 [97]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [107], BaBar [72, 73]
				$B \to K + (D^0 \bar{D}^0 \pi^0)$	Belle [108, 109], BaBar [110]
				$B \to K + (J/\psi\,\gamma)$	BaBar [137], Belle [138], LHCb [141]
				$B \to K + (\psi'\,\gamma)$	BaBar [137], Belle [138], LHCb [141]
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [99], CMS [100]
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [71], BaBar [72, 73]
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [74], BaBar [75]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [78], BaBar [79]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^* \bar{D})$	Belle [32]
				$e^+e^- \to J/\psi + (...)$	Belle [31]
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [163], Belle [164]
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [39]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [87, 88], CMS [90]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^* \bar{D})$	Belle [32]
$Y(4260)$	4263^{+8}_{-9}	95±14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [37, 165], CLEO [166], Belle [39]
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [167]
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [167]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [88], CMS [90]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [94]
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [38], Belle [40]
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [168]
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [40]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [49], Belle [50]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [69]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [51]
				$Y(4260) \to \pi^- + (D^* \bar{D}^*)^+$	BESIII [52]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [53], BaBar [66]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [62]
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [53], BaBar [66]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [54, 56, 57], LHCb [58]
				$B \to K + (J\psi\,\pi^+)$	Belle [62]
$Y_b(10890)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [152]
$Z_b^+(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1,2,3$	Belle [155, 158, 159]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1,2$	Belle [155]
				"$\Upsilon(5S)$" $\to \pi^- + (B\bar{B}^*)^+$, $n = 1,2$	Belle [160]
$Z_b^0(10610)$	10609± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n = 1,2,3$	Belle [157]
$Z_b^+(10650)$	10652.2±1.5	11.5±2.2	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1,2,3$	Belle [155]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n = 1,2$	Belle [155]
				"$\Upsilon(5S)$" $\to \pi^- + (B^*\bar{B}^*)^+$, $n = 1,2$	Belle [160]

S. Olsen, Front. Phys. (Beijing) **10**, 121 (2015)

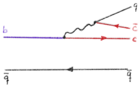
- More than 20 quarkonium-like states identified
- Only a few seen in more than one production process, or by more than one experiment
- Are we at the dawn of a new spectroscopy?

In this seminar:
personal selection of experimental results; in light of BelleII

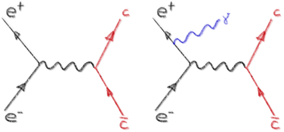
JG|U

Production mechanisms

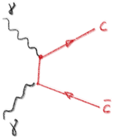
- *B* decays



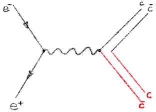
- e^+e^- direct, or via ISR



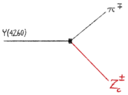
- gamma-gamma fusion



- double charmonium production



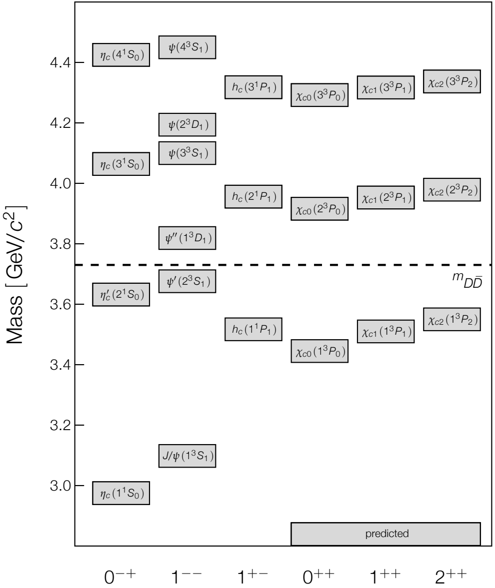
- decays of higher charmonia



- *pp* $p\bar{p}$ inclusive
- photo- / electroproduction


Charmonium Spectroscopy

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

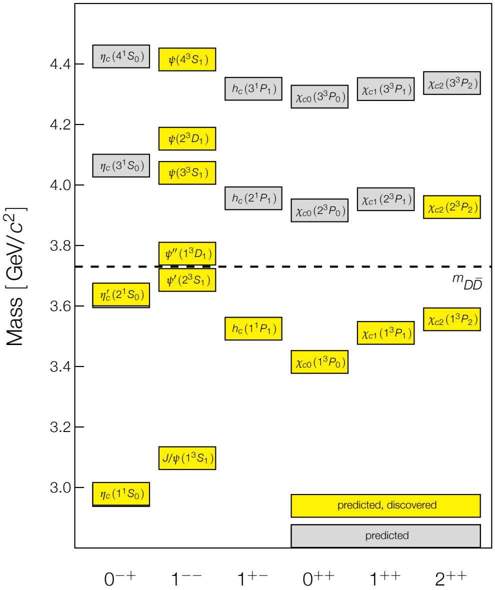
$+$ relativistic corrections!

Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson, PRD 72, 054026 (2005)

Use well-established states to fix parameters, then predict remainder of spectrum, and transitions

➡ Remarkably good description above $D\bar{D}$ threshold: some mass shifts

Charmonium spectrum



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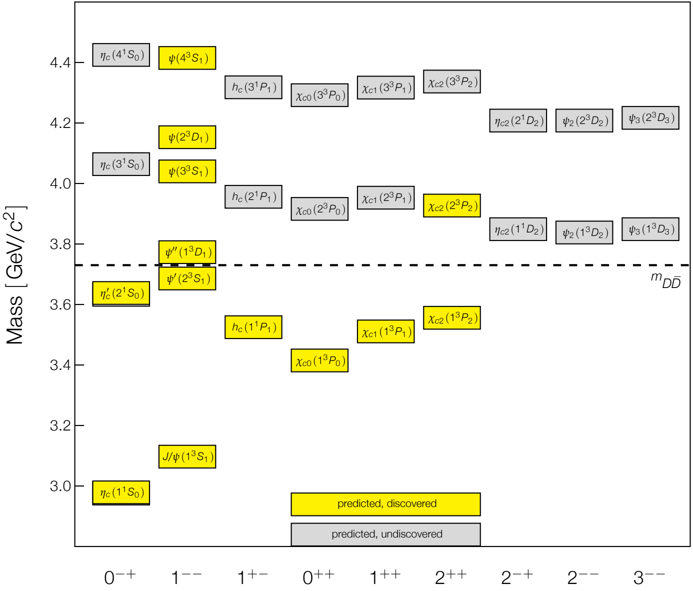
Use well-established states to fix parameters, then predict remainder of spectrum, and transitions

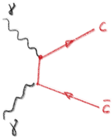
➡ Remarkably good description above $D\bar{D}$ threshold: some mass shifts

Conventional $c\bar{c}$ states

Higher charmonium states



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

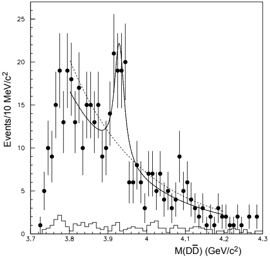


$J^P = 0^+, 2^+, \ldots$

Similar datasets, similar analyses:

- reconstruct $D^0\bar{D}^0$ and D^+D^- events in a number of exclusive hadronic final states
- select $\gamma\gamma$ events by requiring small $p_T(D\bar{D})$, large m^2_{miss}

PRL **96**, 082003 (2006); 395 fb^{-1}

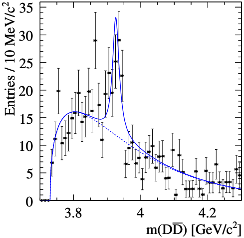


64 ± 18 events

$$M = 3929 \pm 5(\text{stat}) \pm 2(\text{sys})\,\text{MeV}/c^2$$

$$\Gamma = 29 \pm 10(\text{stat}) \pm 2(\text{sys})\,\text{MeV}$$

PRD **81**, 092003 (2010); 384 fb^{-1}



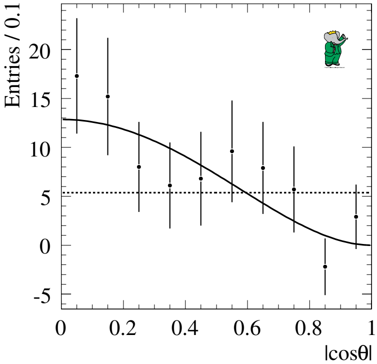
76 ± 17 events

$$M = 3926.7 \pm 2.7(\text{stat}) \pm 1.1(\text{syst})\,\text{MeV}/c^2$$

$$\Gamma = 21.3 \pm 6.8(\text{stat}) \pm 3.6(\text{syst})\,\text{MeV}$$

$\gamma\gamma \to \chi_{c2}(2P) \to D\bar{D}$

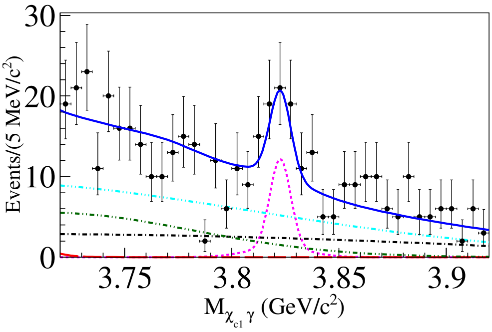
Angular distribution of signal yield:



Supports hypothesis $J = 2$, helicity 2, over $J = 0$
Preferred assignment $J^{PC} = 2^{++}$
Good candidate for $\chi'_{c2} \equiv \chi_{c2}(2^3P_2)$
More statistics: precise measurement of mass and width, other decay channels

The $X(3823)$ at Belle

PRL **111**, 032001 (2013)



Using full Belle data set of $772 \times 10^6 B\bar{B}$

$B \to K\gamma\chi_{c1}$
simultaneous fit to B^+ and B^0

3.8σ evidence

$M = 3823.1 \pm 1.8 \pm 0.7\,\text{MeV}$

very narrow

see ≈ 35 events for the decay chain

$$B \to KX(3823) \to K\gamma\chi_{c1}$$
$$\to K\gamma\gamma J/\psi$$
$$\to K\gamma\gamma\ell^+\ell^-$$

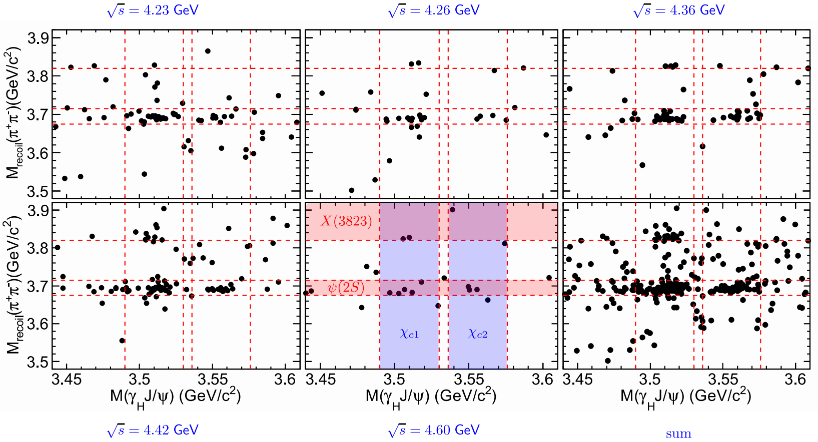
Limited statistics: no angular analysis possible

Mass (and width) compatible with $\psi_2(1^3D_2)$ state

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ PRL **115**, 011803 (2015)

reconstruct $\chi_{c1,2} \to \gamma J/\psi \to \gamma \ell^+\ell^-$
look in mass recoiling against $\pi^+\pi^-$ system, $M_{\text{recoil}}(\pi^+\pi^-)$

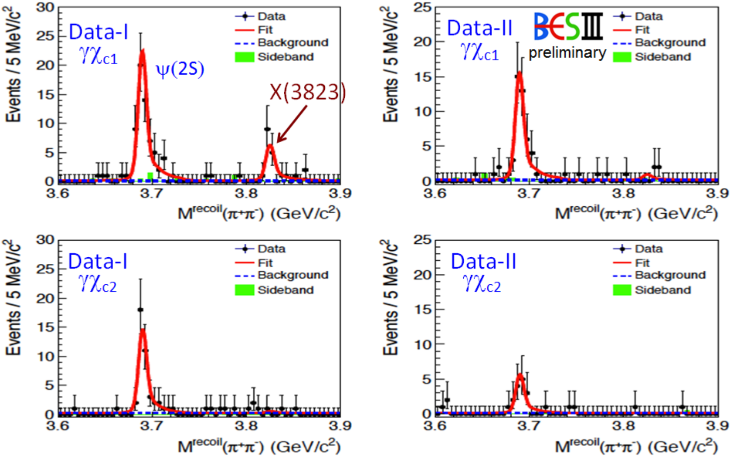
Use 5 large data sets (total luminosity $\sim 4.1\ \text{fb}^{-1}$)



$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

PRL **115**, 011803 (201

$\sqrt{s} \geq 4.36\,\text{GeV}$ $\sqrt{s} = 4.23, 4.26\,\text{GeV}$



$M = 3821.7 \pm 1.3 \pm 0.7\,\text{MeV}$, significance 6.7σ

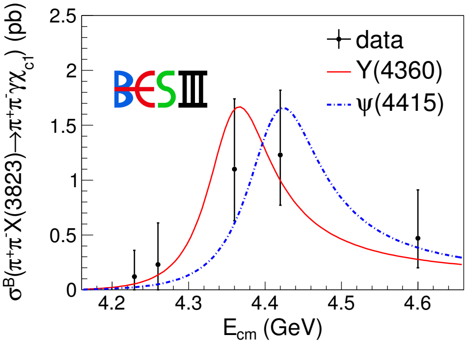
$\Gamma < 16\,\text{MeV}$ at 90% C.L.

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

PRL **115**, 011803 (2015)

Energy-dependent cross section for

$$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$$



$Y(4360)$ and $\psi(4415)$ line shapes to guide the eye

Mass and width ~ in agreement with potential model prediction for 1^3D_2

predicted to be narrow!

Production ratio

$$R_{21} \equiv \frac{\mathcal{B}(X(3823) \to \gamma\chi_{c2})}{\mathcal{B}(X(3823) \to \gamma\chi_{c1})}$$

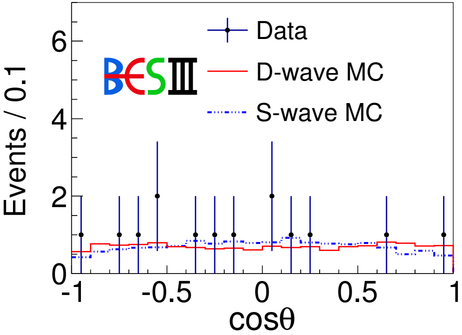
~ 0.2 prediction

< 0.43 at 90% C.L.

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

PRL **115**, 011803 (2015)

Angular distribution $\theta \equiv \angle(\pi\pi, \psi_2)$
assuming $\pi\pi$ system in S-wave: $1 + \cos^2\theta$ for spin 2



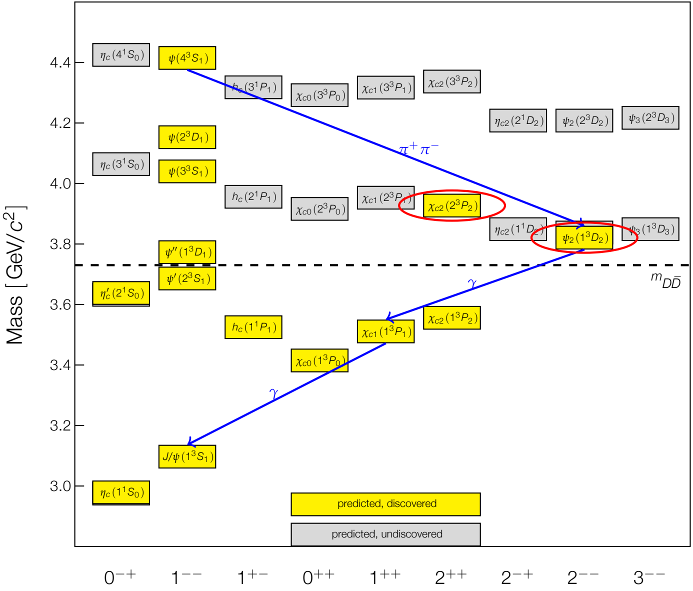
Mass and width $\sim$ in agreement with potential model prediction for 1^3D_2
predicted to be narrow!

J^P by exclusion:
$1^1D_2 \to \gamma\chi_{c1}$ forbidden
$1^3D_3 \to \gamma\chi_{c1}$ has zero amplitude

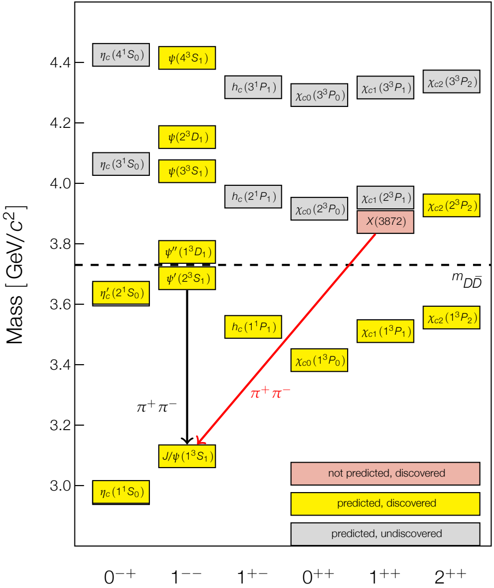
Good candidate for $\psi_2(1^3D_2)$

Not enough statistics to distinguish S and D wave from data

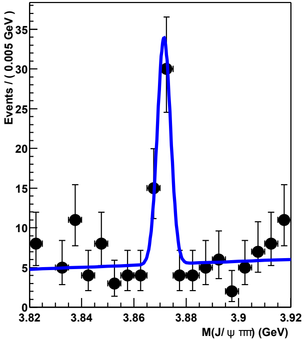
Higher charmonium states



The $X(3872)$



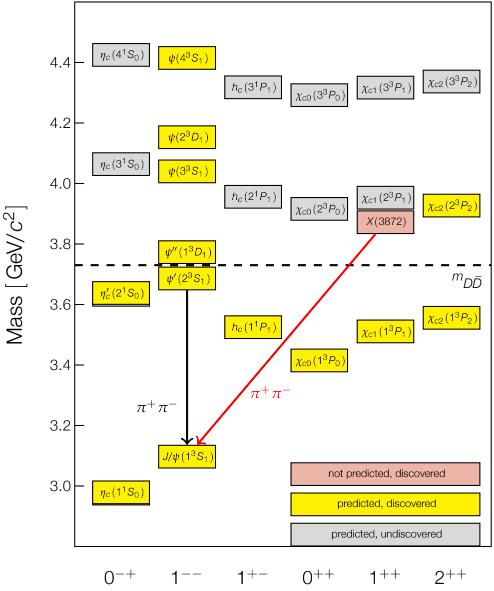
Extremely narrow, sits at or just below the DD^* threshold



$$M = 3871.69 \pm 0.17\,\text{MeV}/c^2$$

$$\Gamma < 1.2\,\text{MeV}$$

The $X(3872)$



Seen by Belle, BABAR, CDF, D0, CMS, LHCb, BESIII

Decays into $J/\psi\,\pi^+\pi^-$, $J/\psi\,\omega$, $D^0\bar{D}^0\pi^0$, $\gamma J/\psi$, $\gamma\psi(2S)$

no obvious place in spectrum
$\sim 50\,$MeV too light to be $\chi_{c1}(2P)$

What is known about the $X(3872)$?

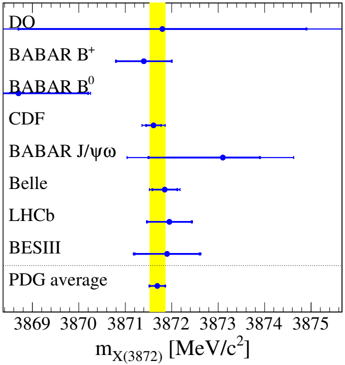
Mass

$$m_{X(3872)} = 3871.69 \quad \pm 0.17\,\text{MeV}/c^2$$
$$m_{D^0} + m_{D^{*0}} = 3871.693 \pm 0.090\,\text{MeV}/c^2$$

Near equality of $m_{X(3872)}$ and $m_{D^0} + m_{D^{*0}}$: accident, or dynamics?

"Binding energy" $= 3 \pm 192\,\text{keV}$
if molecule, then very loosely bound!

(drives ever more precise measurements of m_D and m_D^*)



Width

Width $< 1.2\,\text{MeV}$ at 90% C.L. (detector resolution!)

Belle, PRD **84**, 052004 (2011)

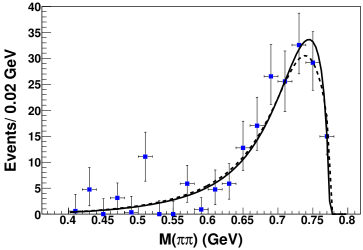
Spin and parity

Unambiguously $J^{PC} = 1^{++}$

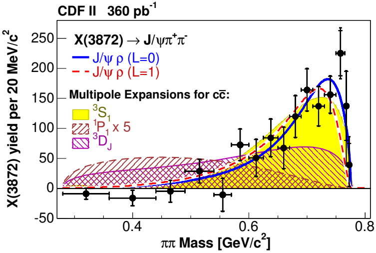
LHCb, Phys. Rev. Lett. **110**, 222001 (2013)

Isospin of $X(3872)$?

$\pi^+\pi^-$ comes from $\rho^0 \to \pi^+\pi^-$:



Belle, Phys. Rev. D **84**, 052004



CDF, Phys. Rev. Lett. **96**, 102002

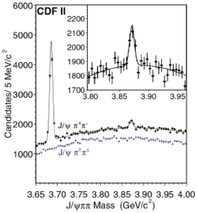
Problem: $(c\bar{c}) \to J/\psi\,\rho$ violates isospin and should be heavily suppressed.

Additionally: BABAR observes $X(3872) \to \omega J/\psi$ Phys. Rev. D **82** 011101
strong kinematic suppression (low-mass tail from ω), but $\mathcal{B}$ approx. equal!
Isospin of $X(3872)$ not well defined?

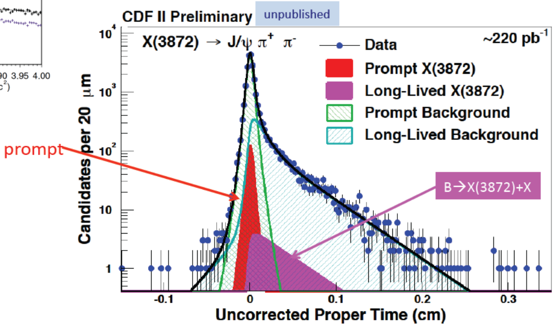
$X(3872)$ production

Production

CDF: $\approx 85\%$ of $p\bar{p} \to X(3872) + \cdots$ is prompt



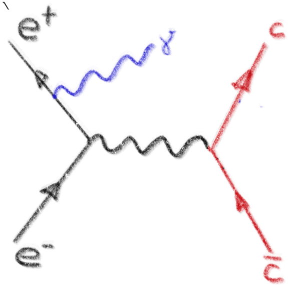
~75% @ LHC: CMS JHEP 04 (2013) 154



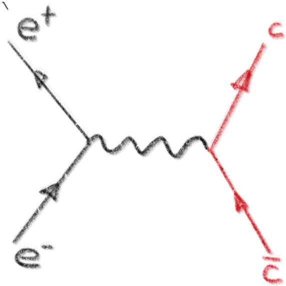
D0: $p\bar{p} \to X(3872)X \approx p\bar{p} \to \psi' X$ PRL 93, 162002

Exotic vector mesons

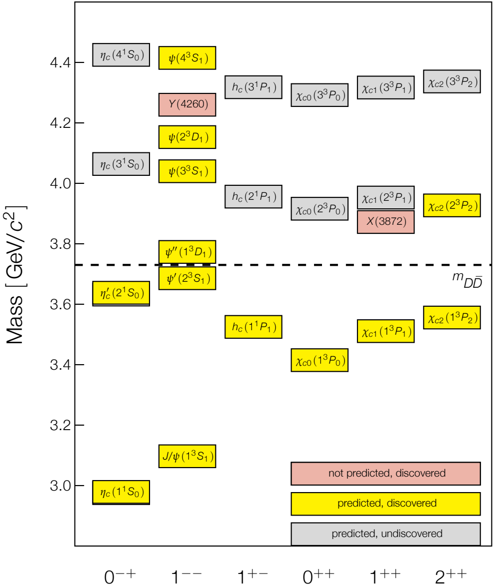
BABAR and Belle
(running on Υ)



BESIII
(direct e^+e^-)



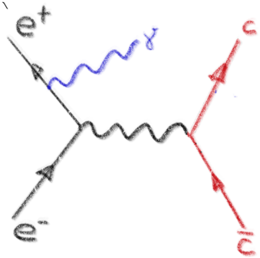
Exotic vector mesons



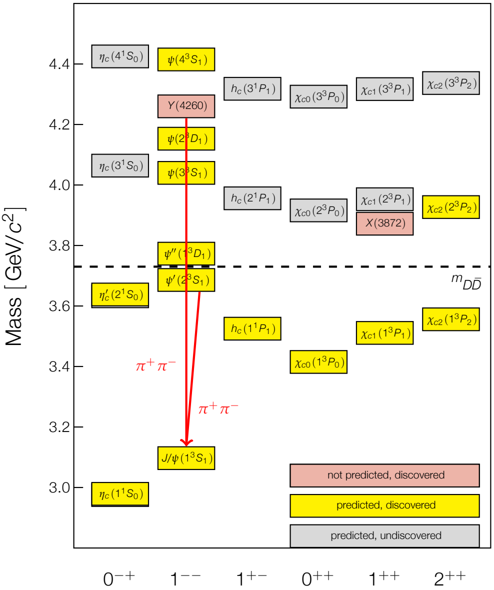
e^+e^- collisions near $\Upsilon(4S)$

in ISR production
$e^+e^- \to \gamma_{\mathrm{ISR}} J/\psi\, \pi^+\pi^-$

$\Rightarrow J^{PC} = 1^{--}$



Exotic vector mesons

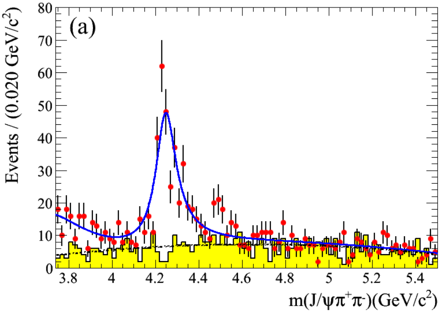


e^+e^- collisions near $\Upsilon(4S)$

in ISR production

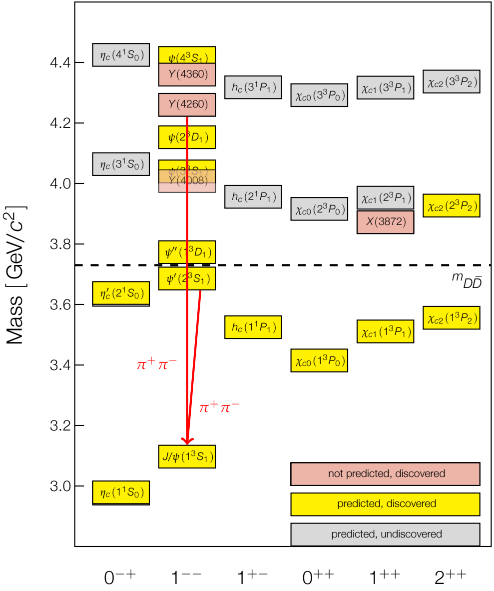
$e^+e^- \to \gamma_{ISR} J/\psi\,\pi^+\pi^-$

$\Rightarrow J^{PC} = 1^{--}$



BABAR, PRD 86, 051102(R) (2012)

Exotic vector mesons



… $Y(4008) \to J/\psi\,\pi^+\pi^-$?

… $Y(4260) \to J/\psi\,\pi^+\pi^-$

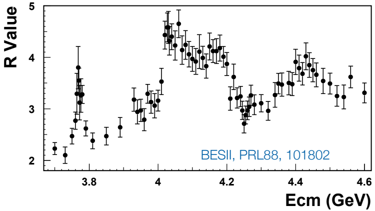
… $Y(4360) \to \psi(2S)\pi^+\pi^-$

… $Y(4630) \to \psi(2S)\pi^+\pi^-$

… $Y(4660) \to \Lambda_c^+\overline{\Lambda}_c^-$

- supernumerary states: all 1^{--} slots already taken

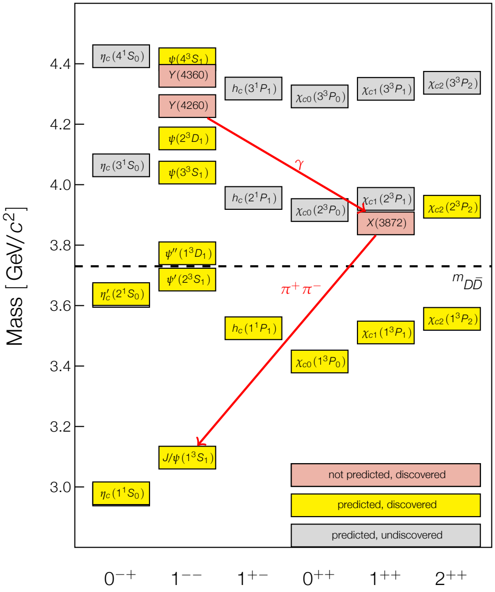
➡ do not correspond to peaks in $\sigma(e^+e^- \to \text{hadrons})$

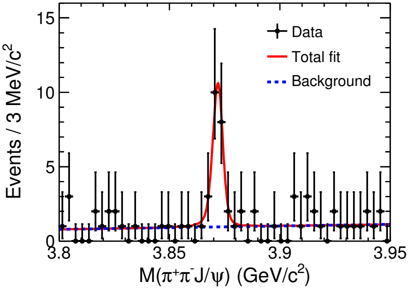


➡ produce them directly at BESIII!

$e^+e^- \to \gamma X(3872) \to \gamma J/\psi\, \pi^+\pi^-$

BESIII, PRL **112**, 092001 (2014)





20.1 ± 4.5 events

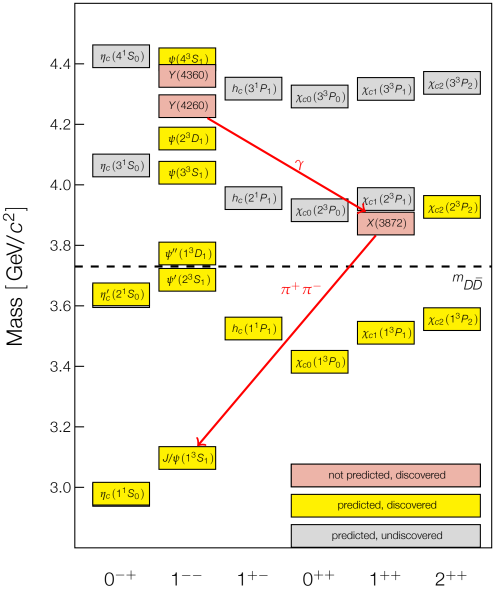
significance 6.3σ

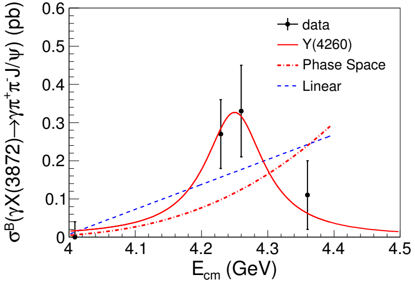
$M = 3871.9 \pm 0.7 \pm 0.2\,\mathrm{MeV}/c^2$

[PDG2013:
$3871.68 \pm 0.17\,\mathrm{MeV}/c^2$]

$e^+e^- \to \gamma X(3872) \to \gamma J/\psi\, \pi^+\pi^-$

BESIII, PRL **112**, 092001 (2014)





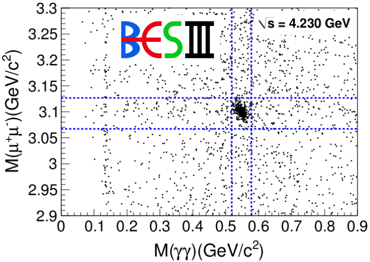
Suggestive of radiative transition
$Y(4260) \to \gamma X(3872)$

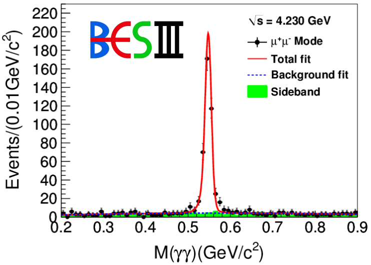
Direct connection between the two states?

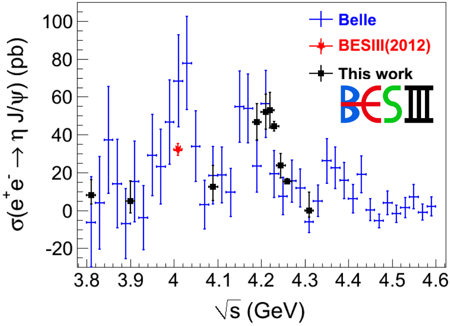
Data at 4.6 GeV to be analysed

$e^+e^- \to \eta J/\psi$

BESIII, PRD **91**, 112005 (2015)







Compare to $e^+e^- \to \gamma_{\rm ISR}\eta J/\psi$ from
Belle, PRD **87**, 051101(R) (2013)

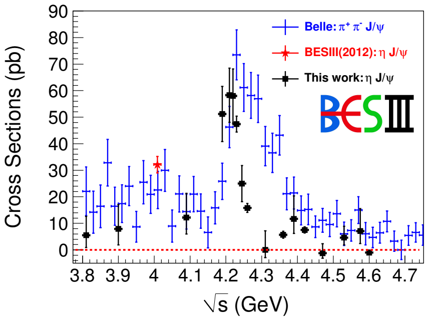
Good agreement,
significantly better precision

Cross section peaks around 4.2 GeV

Also searched for $e^+e^- \to \pi^0 J/\psi$:
no significant signal found

$e^+e^- \to \eta J/\psi$ vs $e^+e^- \to \pi^+\pi^- J/\psi$

BESIII, PRD **91**, 112005 (2015)



Compare to $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ from Belle, PRL **110**, 252002 (2013)

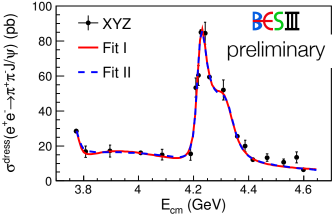
Very different line shape

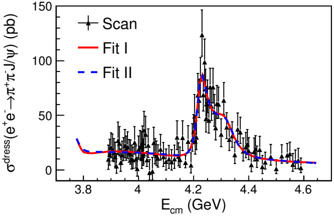
➡ Different dynamics at work in $e^+e^- \to \eta J/\psi$ compared to $e^+e^- \to \pi^+\pi^- J/\psi$

A closer look at $e^+e^- \to J/\psi\,\pi^+\pi^-$

BESIII preliminary,
to be submitted to PRL

Use full available dataset above 3.8 GeV, measure dressed cross section σ^{dress}:





Not just one BW-like structure.

Simultaneous fit to energy-dependent cross section for two sets of datasets:

Parameter	Fit 1 / MeV	Fit 2 / MeV
$M(R_1)$	$3812.6^{+61.9}_{-96.6}$	$\cdots$
$\Gamma_{\text{tot}}(R_1)$	$476.9^{+78.4}_{-64.8}$	$\cdots$
$M(R_2)$	4222.0 ± 3.1	4220.9 ± 2.9
$\Gamma_{\text{tot}}(R_2)$	44.1 ± 4.3	44.1 ± 3.8
$M(R_3)$	4320.0 ± 10.4	4326.8 ± 10.0
$\Gamma_{\text{tot}}(R_3)$	$101.4^{+25.3}_{-19.7}$	$98.2^{+25.4}_{-19.6}$

stat. errors only

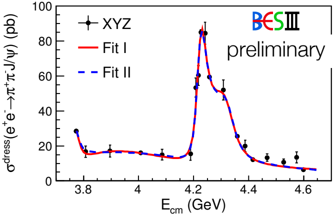
Fit 1: 3 interfering BW resonances
(à la Belle)

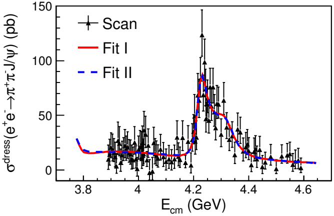
Fit 2: smooth shape for continuum, 2 BW
(à la *BABAR*)

A closer look at $e^+e^- \to J/\psi\,\pi^+\pi^-$

BESIII preliminary,
to be submitted to PRL

Use full available dataset above 3.8 GeV, measure dressed cross section σ^{dress}:





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$\Gamma_{\text{tot}}(R_3)$	$101.4^{+25.3}_{-19.7}$	$98.2^{+25.4}_{-19.6}$

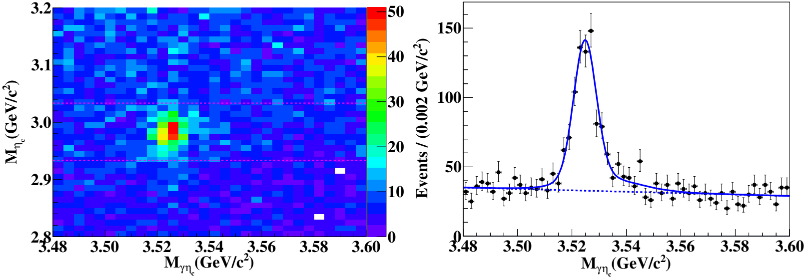
stat. errors only

- Lineshape more complicated than just a single resonance / structure
- $Y(4008)$ not needed to describe data
- Significances for R_2 and $R_3 > 7\sigma$
- $Y(4360) \to J/\psi\,\pi^+\pi^-$ seen?

Cross section of $e^+e^- \to h_c\pi^+\pi^-$

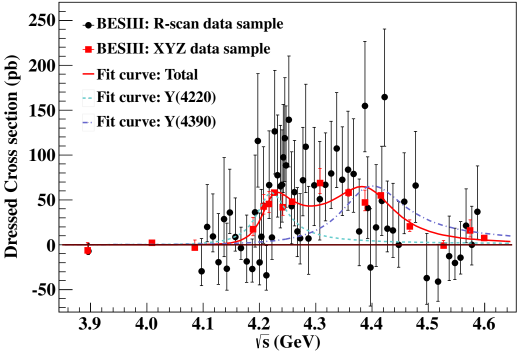
BESIII preliminary, 1610.07044

$h_c \to \gamma\eta_c$, $\eta_c \to$ 16 exclusive hadronic final states
E.g. at $\sqrt{s} = 4.42$ GeV:



Cross section of $e^+e^- \to h_c\pi^+\pi^-$

BESIII preliminary, 1610.07044



Simultaneous fit to both sets of datasets:

Parameter	Fit / MeV
$M(R_1)$	$4218.4 \pm 4.0 \pm 0.9$
$\Gamma(R_1)$	$66.0 \pm 9.0 \pm 0.4$
$M(R_2)$	$4391.6 \pm 6.3 \pm 1.0$
$\Gamma(R_2)$	$139.5 \pm 16.1 \pm 0.6$

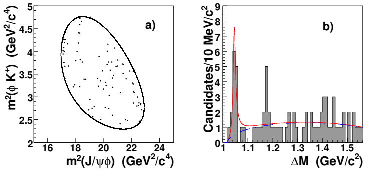
“$Y(4260)$” in different channels?

Channel	Mass $M\,[\mathrm{MeV}/c^2]$	Width $\Gamma\,[\mathrm{MeV}]$
PDG	4251 ± 9	120 ± 12
$J/\psi\,\eta$	narrow structure seen	
$J/\psi\,\pi^0$	not seen (UL on σ)	
$J/\psi\,\pi^+\pi^-$	$4220.9 \pm 2.9 \pm 1.4$	$44.1 \pm 3.8 \pm 2.0$
$h_c\pi^+\pi^-$	$4218.4 \pm 4.0 \pm 0.9$	$66.0 \pm 9.0 \pm 0.4$
$\chi_{c0}\omega$ $^{(*)}$	$4230 \pm 8 \pm 6$	$38 \pm 12 \pm 2$

PDG value from $e^+e^- \to \gamma J/\psi\,\pi^+\pi^-$ at Belle, *BABAR*, CLEO

$^{(*)}$: BESIII, PRL **114**, 092003 (2015), called $X(4230)$ by PDG

Search for $Y(4140) \to J/\psi\,\phi$



CDF first reported evidence for
$Y(4140) \to J/\psi\,\phi$ in $B^+ \to J/\psi\,\phi K^+$,
also claimed by D0 and CMS

CDF, PRL **102**, 242002, (2009)

Not seen by LHCb (0.37 fb^{-1}), Belle (B decays and $\gamma\gamma$ events), or BABAR
Belle sees $X(4350)$ in $\gamma\gamma \to J/\psi\,\phi$ PRL **104**, 112004 (2010)

$J/\psi\,\phi$ system has $C = +1$: search in radiative transitions of charmonium or $Y(4260)$

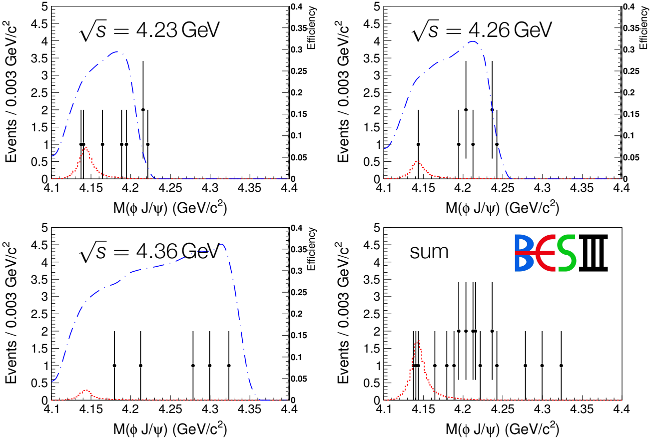
If both $Y(4260)$ and $Y(4140)$ are *charmonium hybrids*:
partial width of $Y(4260) \to \gamma Y(4140)$ may be up to several tens of keV
N. Mahajan, PLB **679**, 228 (2009)

Search for $Y(4140) \to J/\psi\,\phi$

BESIII, PRD **91**, 032002 (2015)

Use BESIII's large data samples from 4.23 – 4.36 GeV (2.47 fb^{-1} in total)

$$e^+e^- \to \gamma J/\psi\,\phi$$
$$J/\psi \to e^+e^-, \mu^+\mu^-,$$
$$\phi \to K^+K^-, K^0_S K^0_L, \pi^+\pi^-\pi^0$$



Search for $Y(4140) \to J/\psi\,\phi$

BESIII, PRD **91**, 032002 (2015)

No significant signal found; place upper limits on
$\sigma(e^+e^- \to \gamma Y(4140)) \times \mathcal{B}(Y(4140) \to J/\psi\,\phi)$

Compare sensitivity to $e^+e^- \to \gamma X(3872) \times \mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)$

$\sqrt{s}$ / GeV	4.23	4.26	4.36
$\sigma \times \mathcal{B}(X(3872))$/pb	0.27 ± 0.09	0.33 ± 0.12	0.11 ± 0.09
$\sigma \times \mathcal{B}(Y(4140))$/pb	< 0.35	< 0.28	< 0.33

Assuming $\mathcal{B}(Y(4140) \to J/\psi\,\phi) \sim 30\%$ and $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) \sim 5\%$:

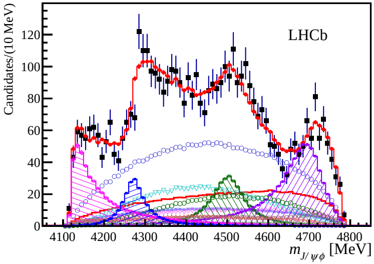
$$\frac{\sigma[e^+e^- \to \gamma Y(4140)]}{\sigma[e^+e^- \to \gamma X(3872)]} < 0.1 \quad \text{at 4.23, 4.26 GeV}$$

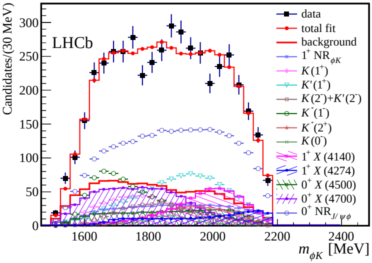
JG|U

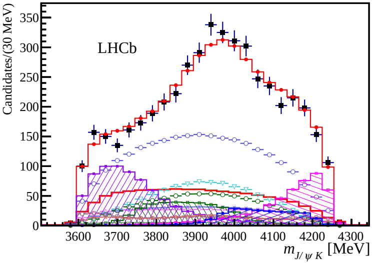
$B^+ \to J/\psi\,\phi K^+$ amplitude analysis at LHCb

1606.07895, 1606.07898

- In $3\,\text{fb}^{-1}$, see 4289 ± 151 $B^+ \to J/\psi\,\phi K^+$ candidates
- 7 K^* resonances, non-res. ϕK amplitude
- 4 exotic $J/\psi\,\phi$ resonances
- No $J/\psi K$ resonance needed







JG|U

$B^+ \to J/\psi\,\phi K^+$ amplitude analysis at LHCb

1606.07895, 1606.07898

Results of amplitude analysis:

State	σ	$M_0\,[\mathrm{MeV}/c^2]$	$\Gamma_0\,[\mathrm{MeV}]$
$X(4140)$	8.4σ	$4146.5 \pm 4.5\,^{+4.6}_{-2.8}$	$83 \pm 21\,^{+21}_{-14}$
$X(4274)$	6.0σ	$4273.3 \pm 8.3\,^{+17.2}_{-\ \ 3.6}$	$56 \pm 11\,^{+\ 8}_{-11}$
$X(4500)$	6.1σ	$4506 \pm 11\,^{+12}_{-15}$	$92 \pm 21\,^{+21}_{-20}$
$X(4700)$	5.6σ	$4704 \pm 10\,^{+14}_{-24}$	$120 \pm 31\,^{+42}_{-33}$

$X(4140), X(4274)$: $J^P = 1^+$
$X(4500), X(4700)$: $J^P = 0^+$

- $X(4140)$ and $X(4274)$ confirmed
- much larger width than previous analyses
- two new states: $X(4500), X(4700)$

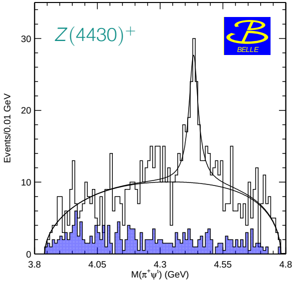
The family of Z_c states

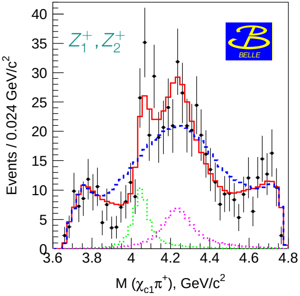
Charged charmonium-like states: a Z^+ family?

Belle observes broad, **charged** charmonium-like states in $(c\bar{c})K\pi$ Dalitz plots

- $Z(4430)^+$ in $B \to \psi(2S)\pi^+K$ — Phys. Rev. Lett. **100**, 142001 (2008)
- $Z_1(4050)^+$ and $Z_2(4250)^+$ in $B \to \chi_{c1}\pi^+K$ — Phys. Rev. D **78**, 072004 (2008)

Quark content at least $|c\bar{c}u\bar{d}\rangle$ ➠ No simple $q\bar{q}$ meson!





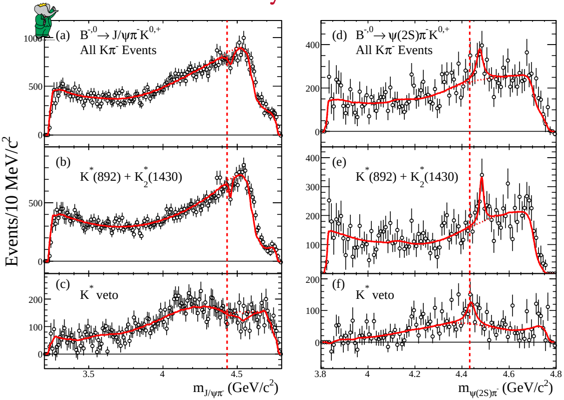
- 2-Z^+ favoured over 1-Z^+
- most clearly seen in $1.0 < m^2_{K\pi} < 1.75\,\text{GeV}^2$

Charged charmonium-like states: a Z^+ family?

BABAR:

Phys. Rev. D **79**, 112001 (2009)

- No significant evidence for $Z(4430)$ found in $B \to \psi(2S)\pi^+K$
- No resonant behaviour in $J/\psi\,\pi^+$ seen in $B \to J/\psi\,\pi^+K$



Phys. Rev. D **85** 052003 (2011)

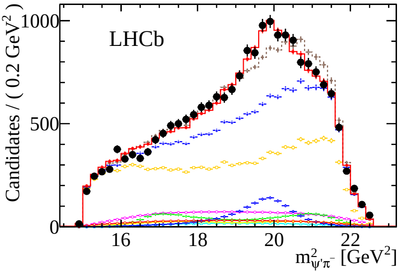
- No significant need for Z_1 or Z_2 in $B \to K\pi\chi_{c1}$
- but not fully incompatible with Belle result

$Z_c(4430)^-$ in $B \to K\pi^-\psi'$ at LHCb

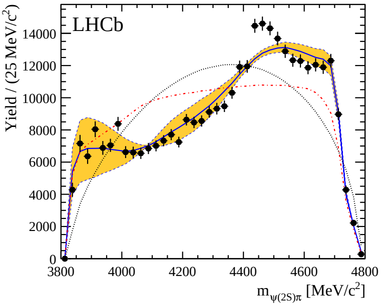
$\approx 25\,000$ candidates for $B \to K\pi^-\psi'$ in $3\,\text{fb}^{-1}$

Two analysis methods

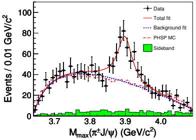
- 4D amplitude analysis à la Belle
  extract phase motion
  establish $J^P = 1^+$
  PRL **112** 222002 (2014)



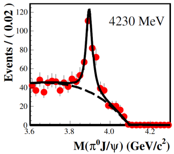
- Moments analysis à la *BABAR*
  reflections from K^* not enough;
  confirms existence of $Z_c(4430)$
  PRD **92** 112009 (2015)



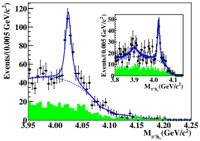
Z_c family at BESIII



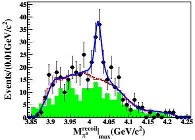
$e^+e^- \to \pi^-\pi^+J/\psi$



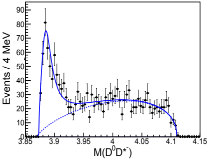
$e^+e^- \to \pi^0\pi^0J/\psi$



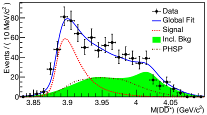
$e^+e^- \to \pi^-\pi^+h_c$



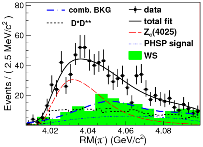
$e^+e^- \to \pi^0\pi^0h_c$



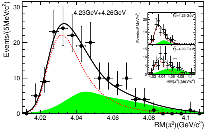
$e^+e^- \to \pi^-(D\bar{D}^*)^+$



$e^+e^- \to \pi^0(D\bar{D}^*)^0$



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

$Z_c(3900)^+$?

$Z_c(3900)^0$?

$Z_c(4020)^+$?

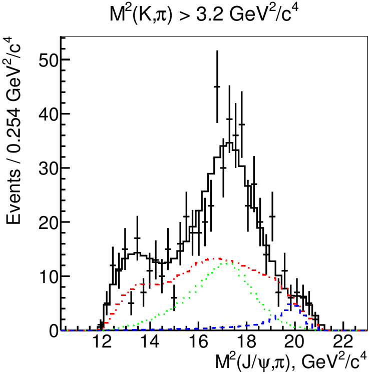
$Z_c(4020)^0$?

Nature of these states? Isospin triplets?
Different decay channels of the same states observed?
Other decay modes?
Other similar states (e.g. isospin singlets; with strangeness contents …)?

$Z_c(3900)$ in B decays?

PRD **90**, 112009 (2014)

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



- See $Z_c(4430)^+ \to J/\psi\, \pi^+$
- No $Z_c(3900)^+$ needed
- Instead: $Z_c(4200)^+$

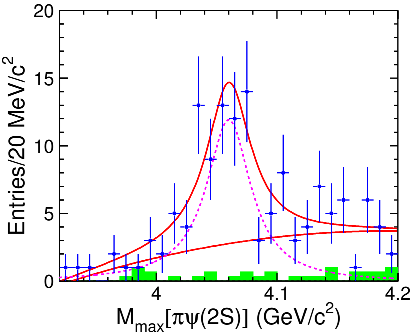
$$M = 4196^{+31+17}_{-29-13}\ \text{MeV}/c^2,$$

$$\Gamma = 370^{+70+70}_{-70-132}\ \text{MeV}.$$

$Z_c(4055)^+ \to \psi' \pi^+$

PRD **91**, 112007 (2015)

In $e^+e^- \to \gamma\psi'\pi^+\pi^-$, for events near $Y(4360)$



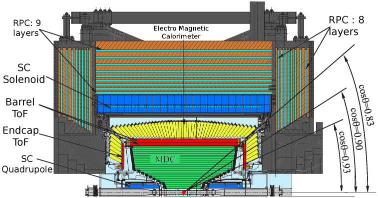
- Yet another charged, charmonium-like resonance
- Not seen in B decays, either by Belle or LHCb
- Don't see Z_c from B decays here …

Open questions

- More such states to be found, with other charmonia?
- Dependence on production mechanism?
- Can we observe more connections between these states such as possibly $Y(4260) \to \gamma X(3872)$?
- Are these all resonances? Or threshold effects? ‘true nature’? How can we distinguish?
- $\cdots$

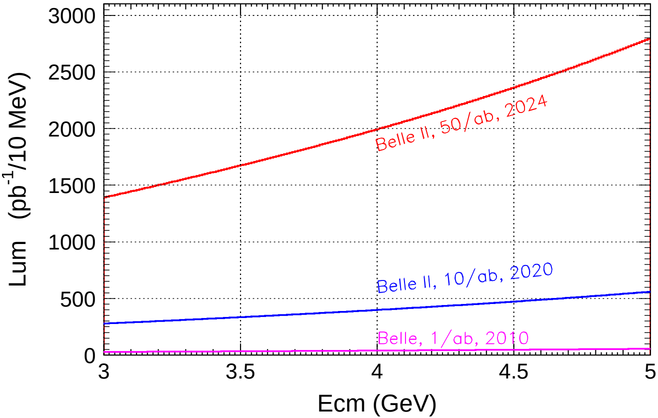
Future: BESIII

- Set to run for $\gtrsim 8$ more years
- If running near 'sweet spot' of accelerator ($\sqrt{s} = 3.77\,\text{GeV}$):
  collect $\sim 5\,\text{fb}^{-1}$ / year
- Accelerator upgrades:
  - Increase beam energy
    currently, $\sqrt{s} < 4.6\,\text{GeV}$
  - Top-up injection
  - Major luminosity upgrade? (crabbed waist)
- Plan for 2016/17:
  add 6–8 points of $500\,\text{pb}^{-1}$ around $4.3\,\text{GeV}$
- Further plans under discussion

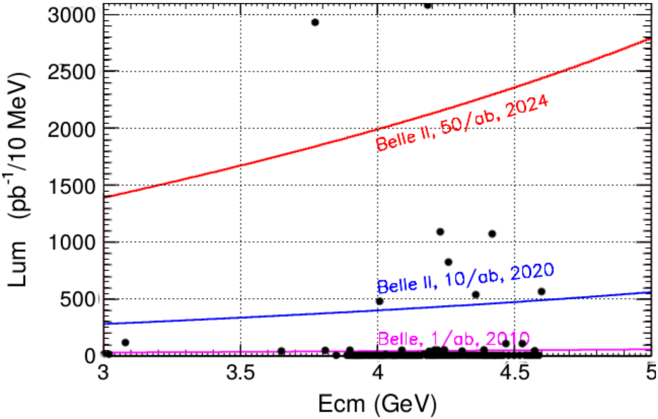


Luminosity expectation BelleII (ISR) vs BESIII (direct)

B2TiP WG7



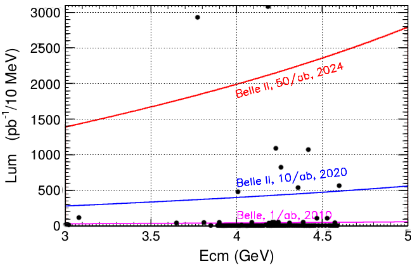
Luminosity expectation BelleII (ISR) vs BESIII (direct)



Typical mass resolution for charged states in ISR physics: $\lesssim 5\,\mathrm{MeV}/c^2$

Spacing of BESIII R-scan points: 5 MeV (beam-energy spread $\sim$ 1.3 MeV)

Belle-II ISR vs BESIII

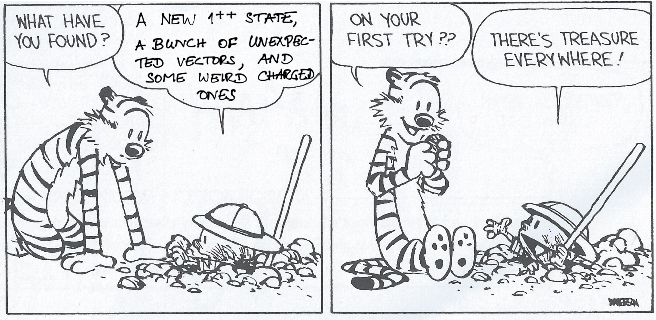


Direct scan

- (very) high luminosity at a few selected $\sqrt{s}$
- better resolution in $\sqrt{s}$ — relevant for direct production of 1^{--} states

ISR

- ISR: many $\sqrt{s}$ simultaneously
- reduced point-to-point systematics
- mass resolution limited by detector res.
- boost of hadronic system vs. γ_{ISR} may actually help efficiency



…with apologies to Bill Watterson