BESIII results on XYZ states

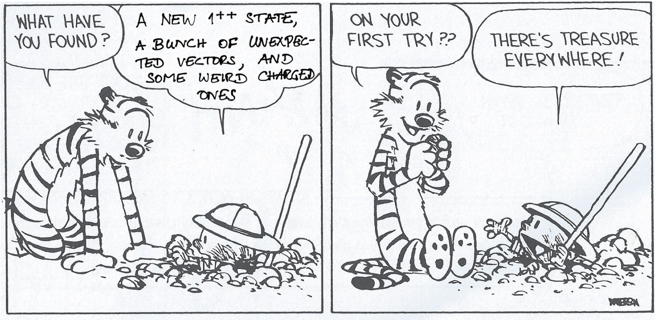
Wolfgang Gradl

JGU Mainz

HPS Seminar GSI
14th November 2018

Outline

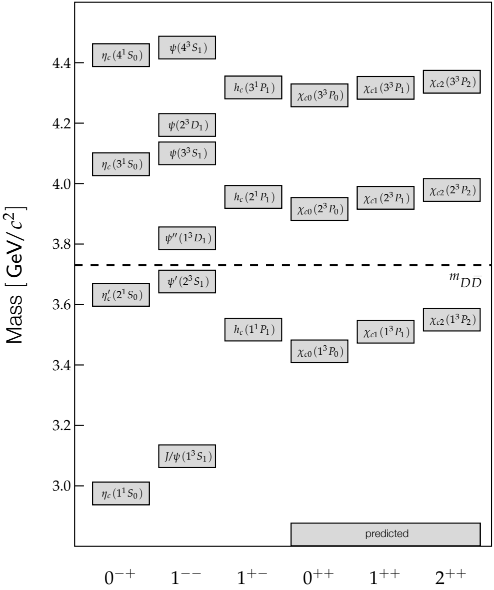
- Charmonium spectroscopy
- The $X(3872)$ and $Y(4260)$
- BESIII
- Z_c: charged charmonium-like states
- Summary and outlook



…with apologies to Bill Watterson

Charmonium Spectroscopy

Charmonium spectrum



Charmonium: $c\bar{c}$

Example potential

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

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

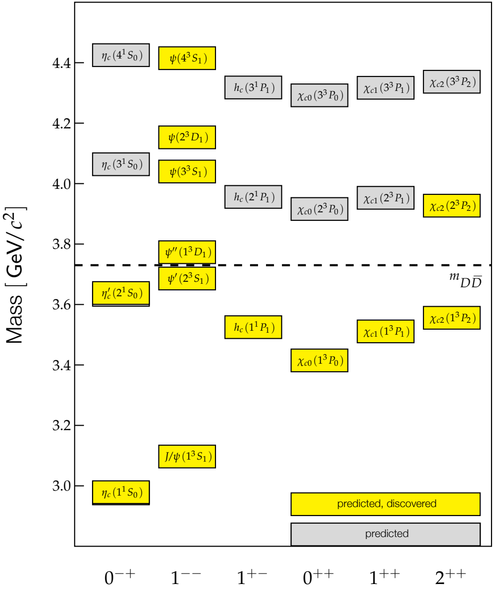
$+$ relativistic corrections!

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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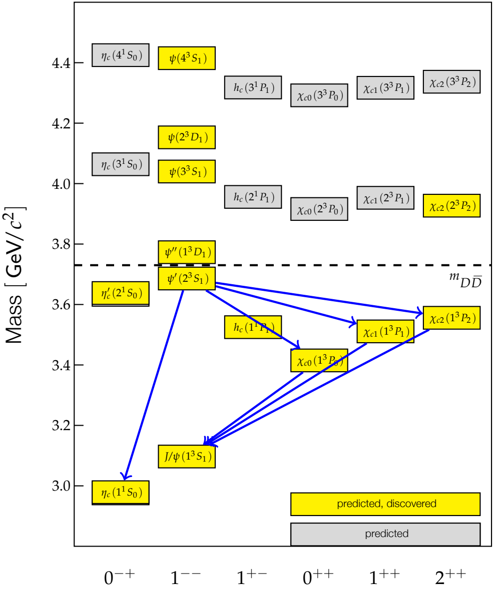

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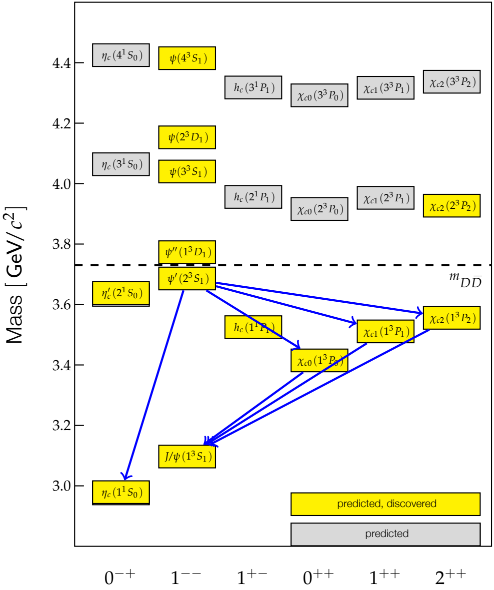
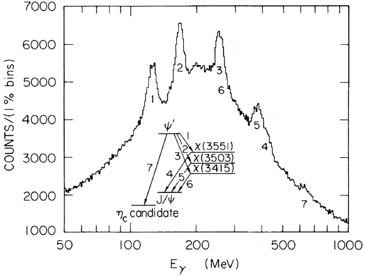


Charmonium: $c\bar{c}$

Crystal Ball at SLAC
discovery of η_c



PRL 45, 1150 (1980)

QCD exotics

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

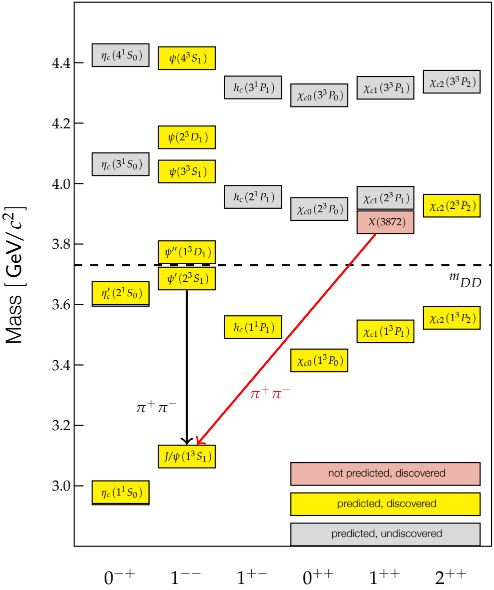
Identify by

- 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

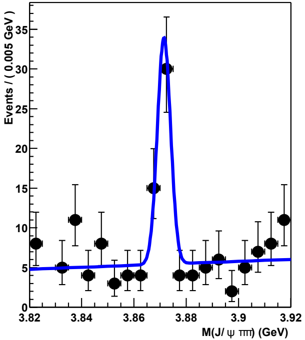
Totalitarian principle of quantum mechanics:

Everything not forbidden is compulsory

The $X(3872)$



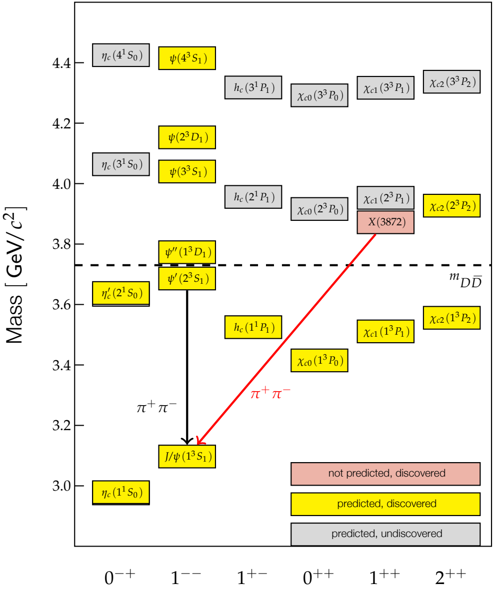
Extremely narrow, sits at or just below the DD^* threshold



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

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

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 $X(3872)$?

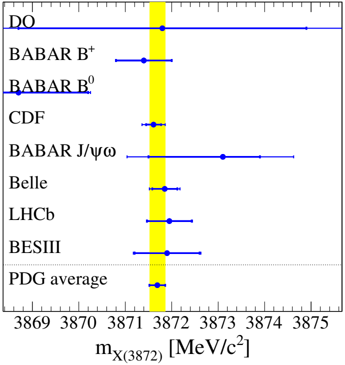
Mass

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

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

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

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



Width

Width < 1.2 MeV at 90% C.L. (detector resolution!)

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

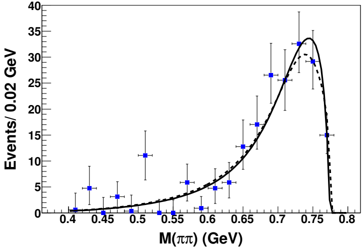
Spin and parity

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

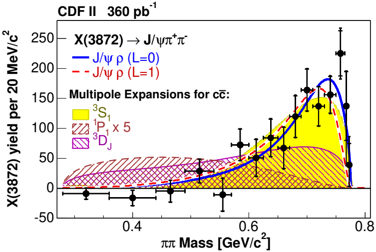
LHCb, Phys. Rev. Lett. **110**, 222001 (2013)

Isospin of $X(3872)$?

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



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



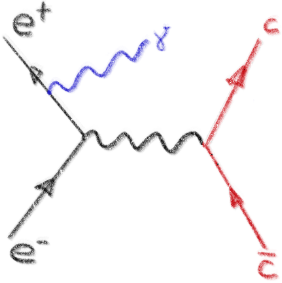
CDF, Phys. Rev. Lett. **96**, 102002

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

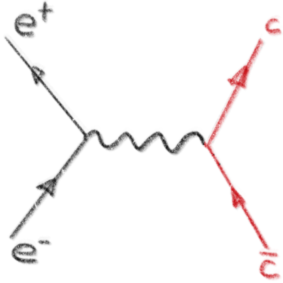
Additionally: BABAR observes $X(3872) \to \omega J/\psi$ Phys. Rev. D **82** 011101
strong kinematic suppression (low-mass tail from ω), but $\mathcal{B}$ approx. equal!
Isospin of $X(3872)$ not well defined?

Exotic vector mesons

BABAR and Belle
(running on Υ)



BESIII
(direct e^+e^-)



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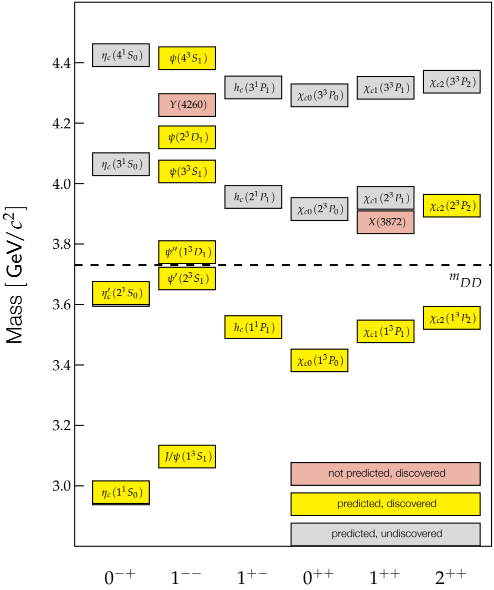
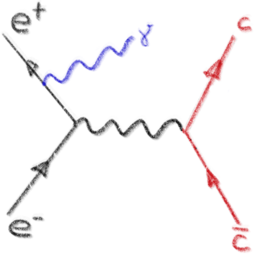


e^+e^- collisions near $\Upsilon(4S)$

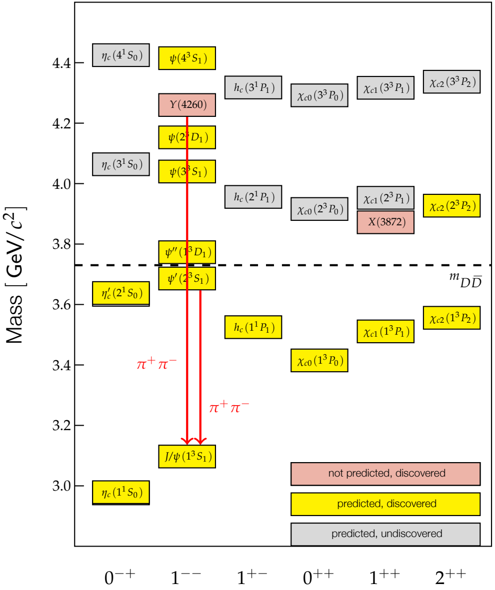
in ISR production

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

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



Exotic vector mesons



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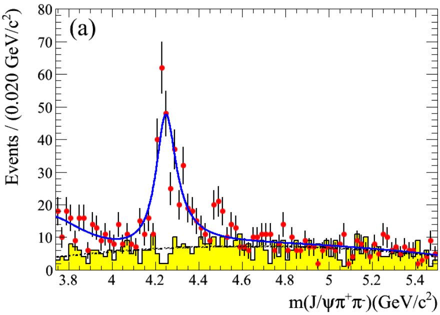
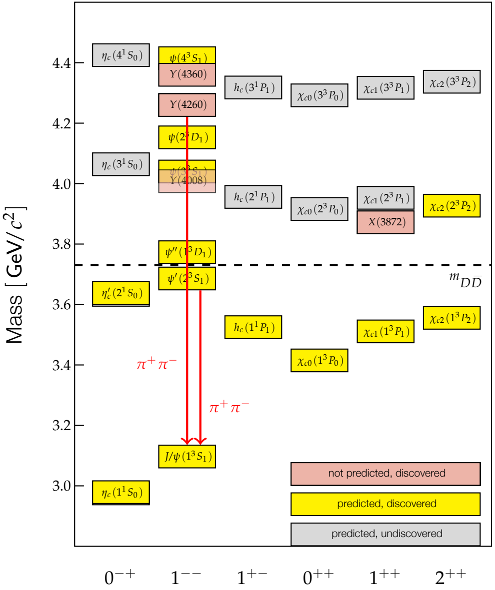


BABAR, PRD 86, 051102(R) (2012)

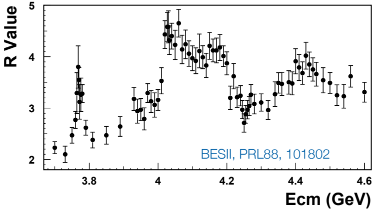
Exotic vector mesons



- $Y(4008) \to J/\psi\,\pi^+\pi^-$?
- $Y(4260) \to J/\psi\,\pi^+\pi^-$
- $Y(4360) \to \psi(2S)\pi^+\pi^-$
- $Y(4630) \to \psi(2S)\pi^+\pi^-$
- $Y(4660) \to \Lambda_c^+\overline{\Lambda}_c^-$

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

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



➡ produce them directly at BESIII!

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]
				$B\to K+(D^0D^0\pi^0)$	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?

A note on names

Confusion of names: $X(\cdots)$, $Y(\cdots)$, $Z(\cdots)$
with no clear relation between name and properties of the state

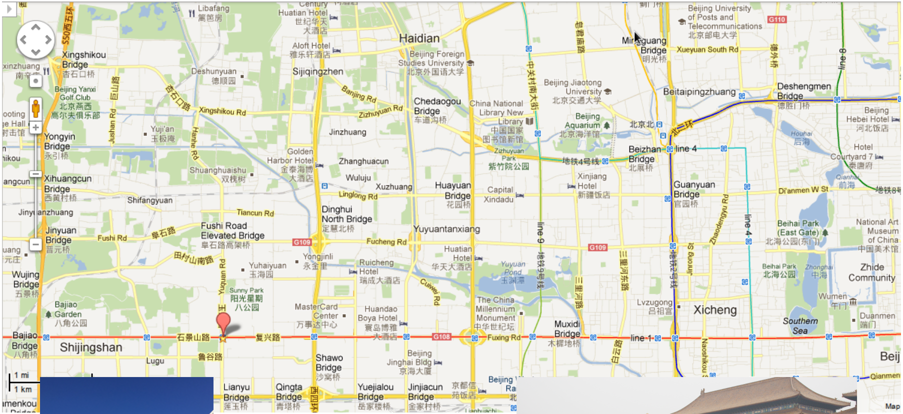
PDG'2018: reflect quantum numbers J^{PC} in name, regardless of quark configuration

J^{PC}	**Name**	**Example**
1^{--}	$\psi(\ldots)$	$\psi(4260)$ (was $Y(4260)$)
1^{++}	$\chi_{c1}(\ldots)$	$\chi_{c1}(3872)$ (was $X(3872)$)

In this talk, I'll keep using the 'old' names

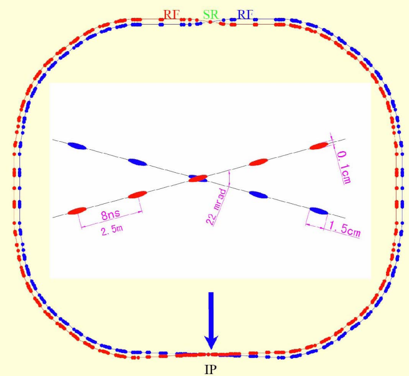

BESIII: a τ-charm factory

BEPCII and BESIII



BEPCII and BESIII

BEPCII storage rings: a τ-charm factory



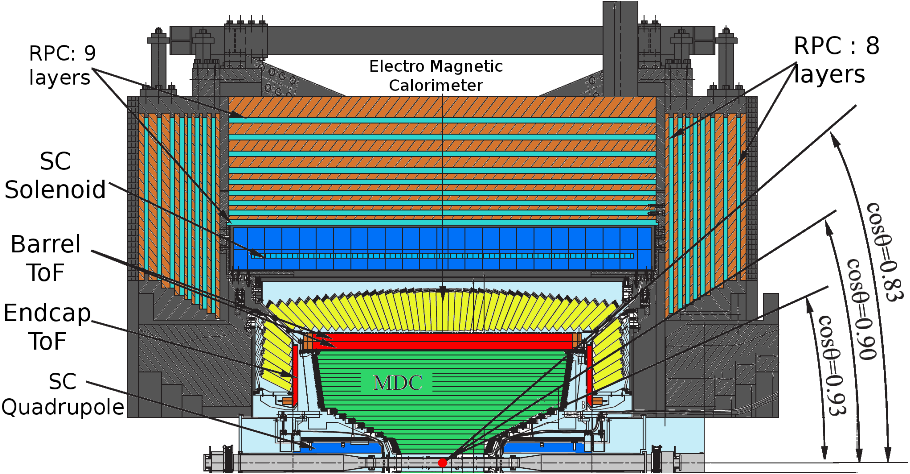
Upgrade of BEPC (started 2004,
first collisions July 2008)

Beam energy	$1 \cdots 2.3$ GeV
Optimum energy	1.89 GeV
Single beam current	0.91 A
Crossing angle	± 11 mrad

Design luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Achieved (2016)	$1.0 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Beam energy measurement:
Laser Compton backscattering
$\Delta E/E \approx 5 \times 10^{-5}$
($\approx$ 50 keV at τ threshhold)

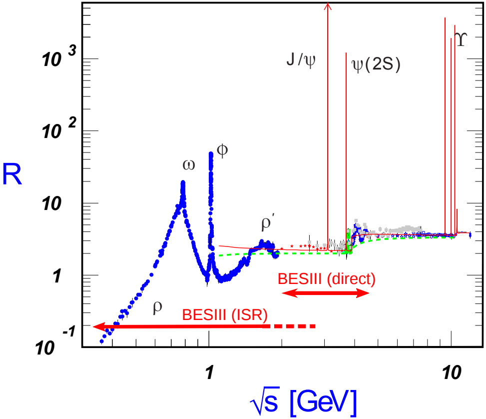
BESIII detector



Completely new detector

Design and performance comparable to CLEO-c, + muon ID

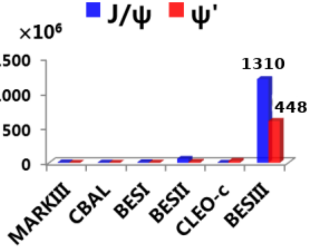
BEPC energy region

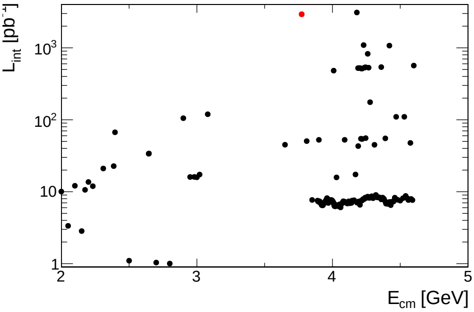


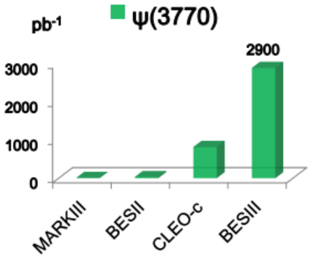
Direct production: span the interesting charmonium region

ISR: reach down to $\pi\pi$ threshold with decent statistics

Unique BESIII data set





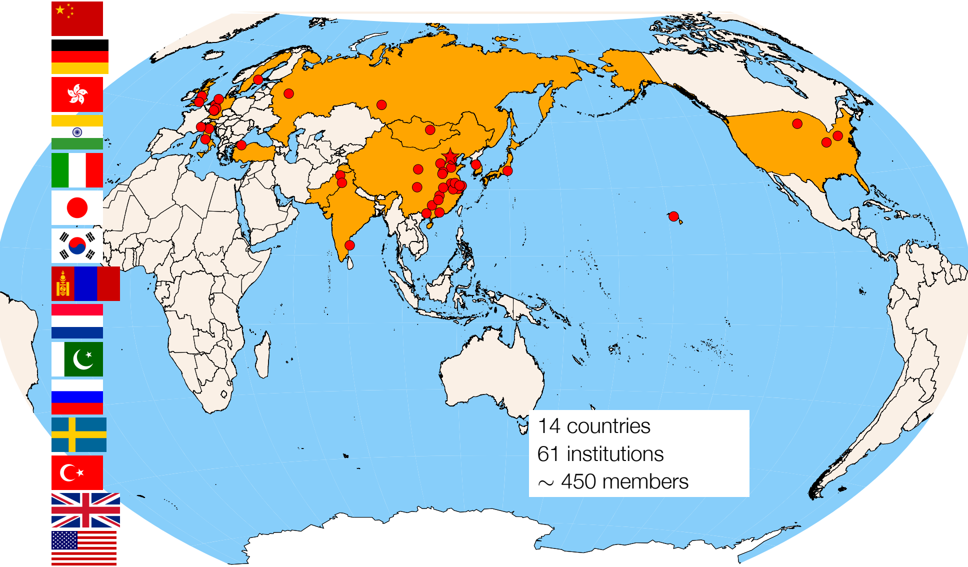


large data sets of $\approx 7\,\text{fb}^{-1}$ above 3.8 GeV for XYZ studies

$+$ 104 energy points between 3.85 and 4.59 GeV (R scan)

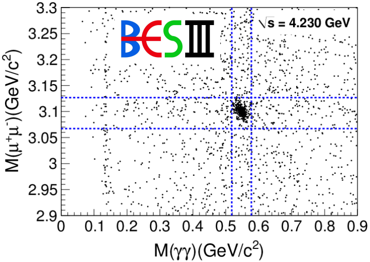
$+ \sim$ 20 energy points between 2.0 and 3.1 GeV

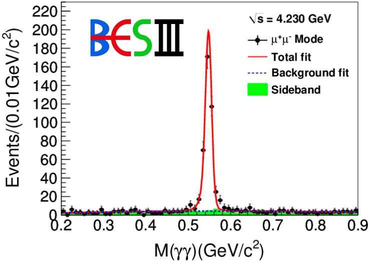
Direct production of 1^{--} states studied with world's largest scan dataset

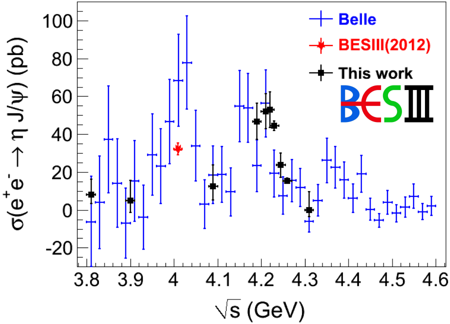

14 countries
61 institutions
∼ 450 members

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

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







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

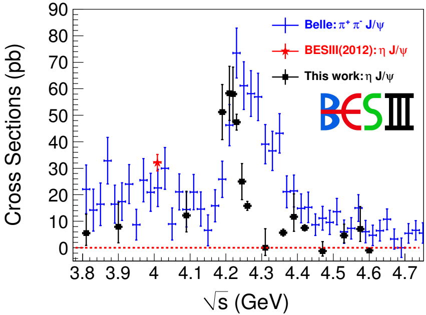
Good agreement,
significantly better precision

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

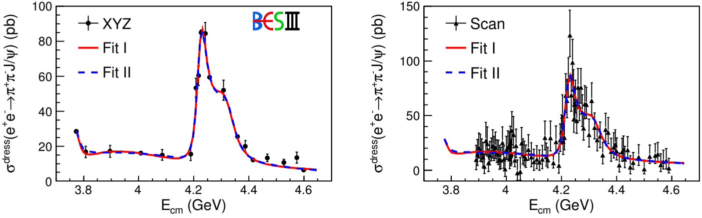
Very different line shape

➡ 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, PRL **118**, 092001 (2017)

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

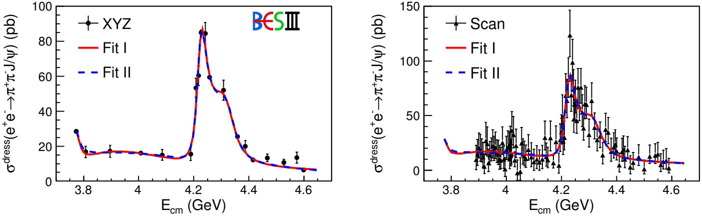
Fit 1: 3 interfering BW resonances (à la Belle)

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

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

BESIII, PRL **118**, 092001 (2017)

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



Not just one BW-like structure.

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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?

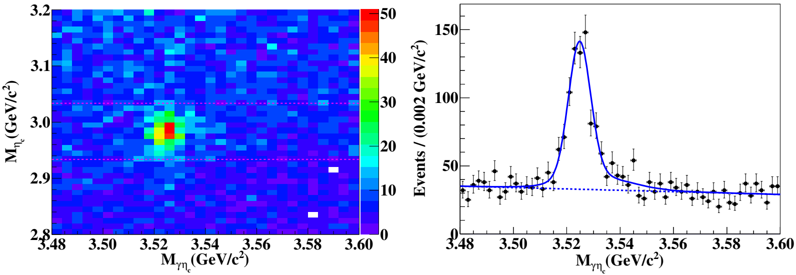
JG|U

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

BESIII, PRL **118**, 092002 (2017)

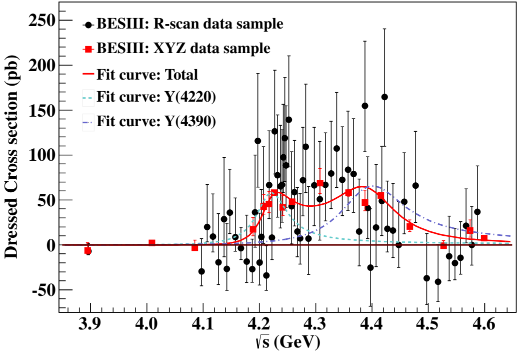
$h_c \to \gamma\eta_c$, $\eta_c \to$ 16 exclusive hadronic final states

E.g. at $\sqrt{s} = 4.42$ GeV:



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

BESIII, PRL **118**, 092002 (2017)



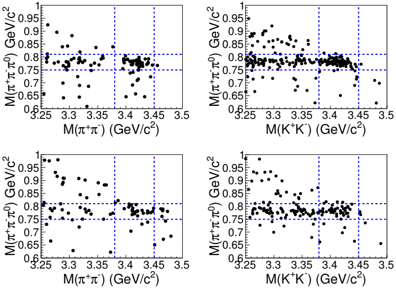
Simultaneous fit to both sets of datasets:

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

Cross section of $e^+e^- \to \omega\chi_{cJ}$

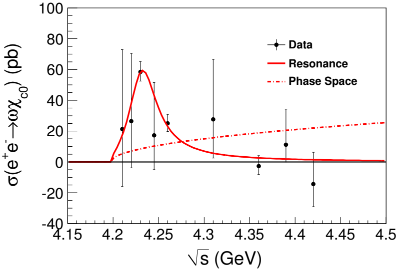
BESIII, PRL **114**, 092003 (2015)

$\omega \to 3\pi, \chi_{c0} \to \pi^+\pi^-, K^+K^-$



$\chi_{c1,2} \to \gamma J/\psi$: no signal seen

Cross section for $\omega\chi_{c0}$



Fit with phsp-modified BW:

$$M = 4230 \pm 8 \pm 6\,\text{MeV}/c^2$$

$$\Gamma = 38 \pm 12 \pm 2\,\text{MeV}$$

incompatible with single-resonance fit to $\pi^+\pi^- J/\psi$ (the "$Y(4260)$" found in PDG)

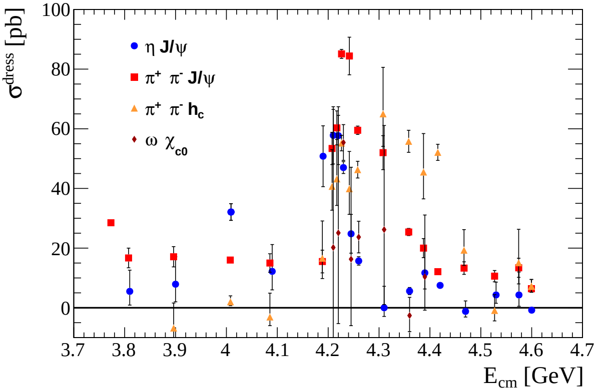
"$Y(4260)$" in different channels?

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

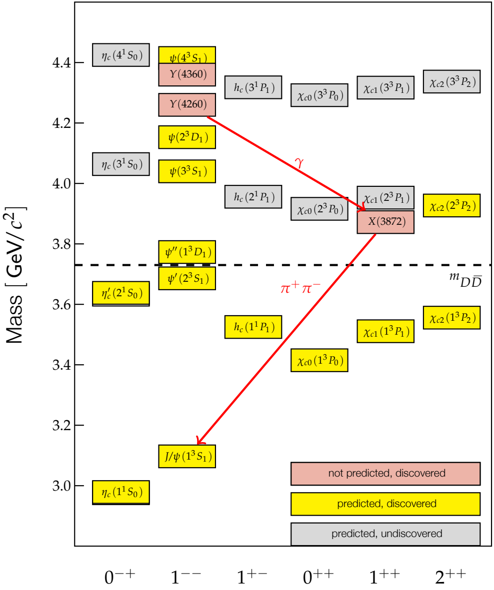
"$Y(4260)$" in different channels?

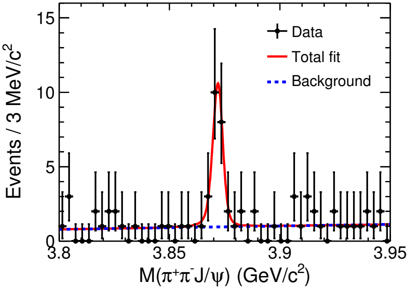
Cross-section compilation of $e^+e^- \to$ charmonium + light hadron(s) from BESIII (only energy points with large luminosities shown)



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

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





20.1 ± 4.5 events

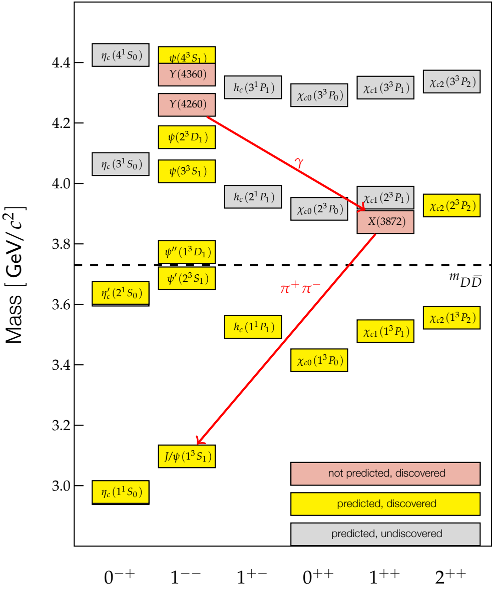
significance 6.3σ

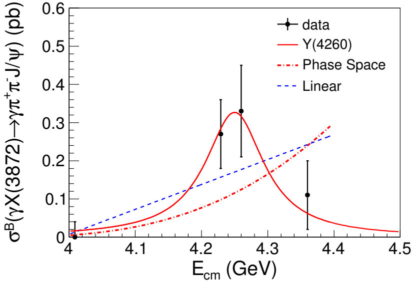
$M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c^2

[PDG2013: 3871.68 ± 0.17 MeV/c^2]

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

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





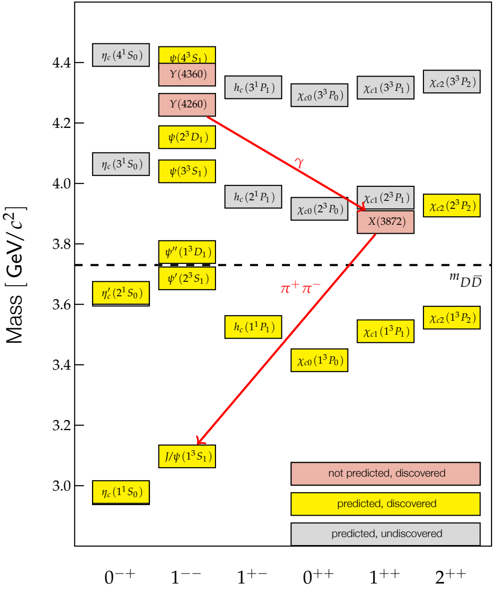
Suggestive of radiative transition
$Y(4260) \to \gamma X(3872)$

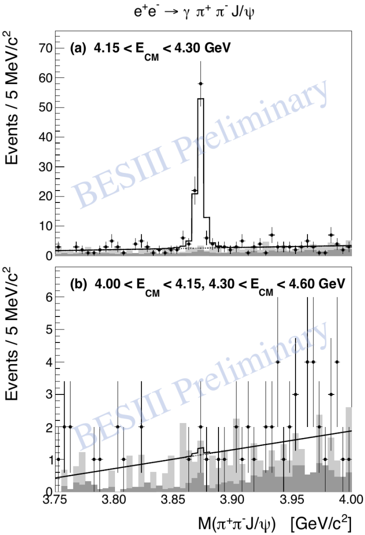
Direct connection between the two states?

JG|U

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

BESIII preliminary





No $X(3872)$ signal outside $\sqrt{s} = 4.15\ldots4.30$ GeV

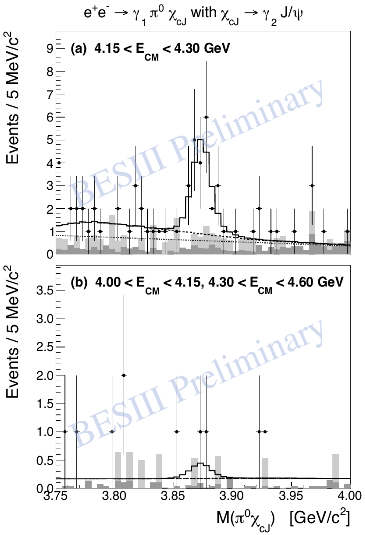
$e^+e^- \to \gamma X(3872) \to \gamma \pi^0 \chi_{cJ}$

BESIII preliminary

Search for $e^+e^- \to \gamma X(3872)$ with $X(3872) \to \pi^0 \chi_{cJ}$
with $\chi_{cJ} \to \gamma J/\psi$ and $J/\psi \to \ell^+\ell^-$

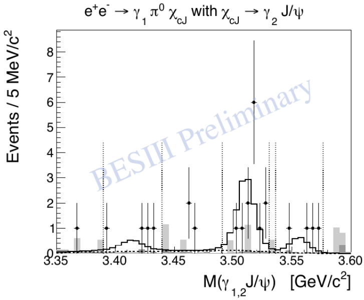
Select broad χ_{cJ} mass region using
$3.35 < m(\gamma J/\psi) < 3.60$ GeV/c^2

Using data from $\sqrt{s} = 4.15 \ldots 4.30$ GeV: see clear
$X(3872)$ signal
but none outside this $\sqrt{s}$ region



$e^+e^- \to \gamma X(3872) \to \gamma \pi^0 \chi_{cJ}$

BESIII preliminary



Using data from $\sqrt{s} = 4.15 \ldots 4.30$ GeV, separate the χ_{cJ} for $J = 0, 1, 2$

Find clear $X(3872)$ signal for $\pi^0 \chi_{c1}$ with 5.2σ and no signal for $J = 0, 2$

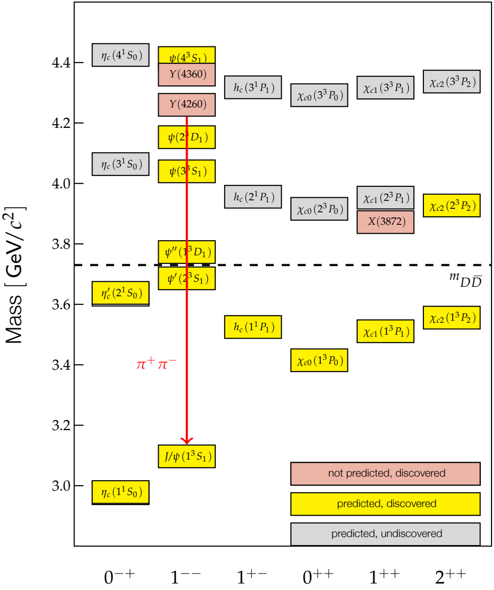
Establish existence of decay channel $X(3872) \to \pi^0 \chi_{c1}$, with branching fraction ≈ equal to $\pi^+\pi^- J/\psi$

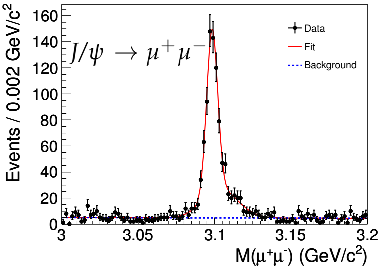
Disfavours interpretation of the $X(3872)$ as the conventional $\chi_{c1}(2P)$

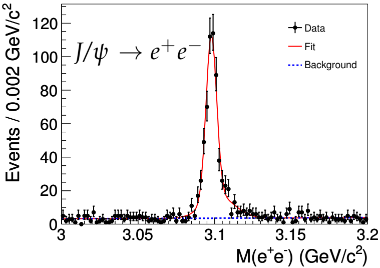
The family of Z_c states

$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

BESIII, PRL **110**, 252001 (2013)
525 pb^{-1} at 4.26 GeV



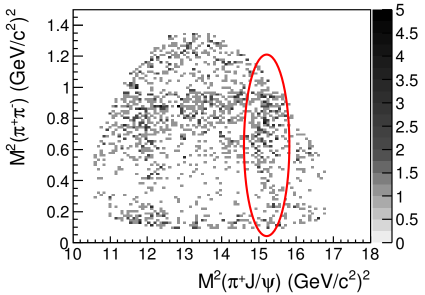


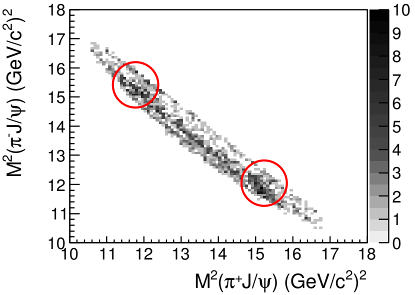


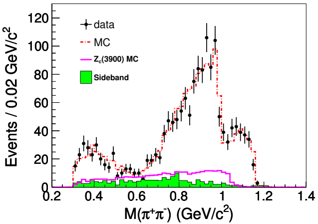
…have hundreds of events!

$J/\psi\,\pi^+\pi^-$ Dalitz plot

BESIII, PRL **110**, 252001 (2013)



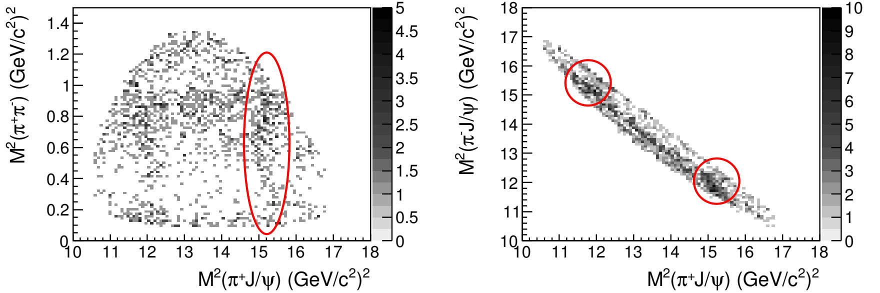


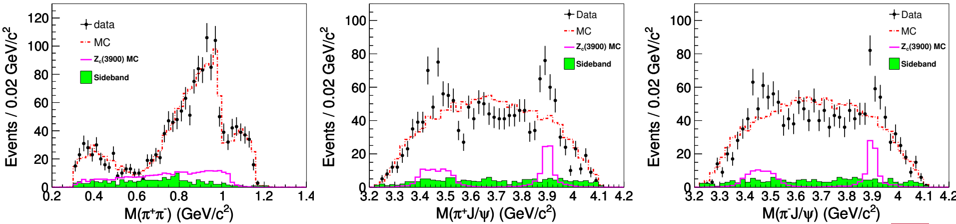


Model $\pi^+\pi^-$-system with known structure:
$f_0(500)$, $f_0(980)$, non-resonant
obtain good fit of $\pi^+\pi^-$ mass projection

$J/\psi\,\pi^+\pi^-$ Dalitz plot

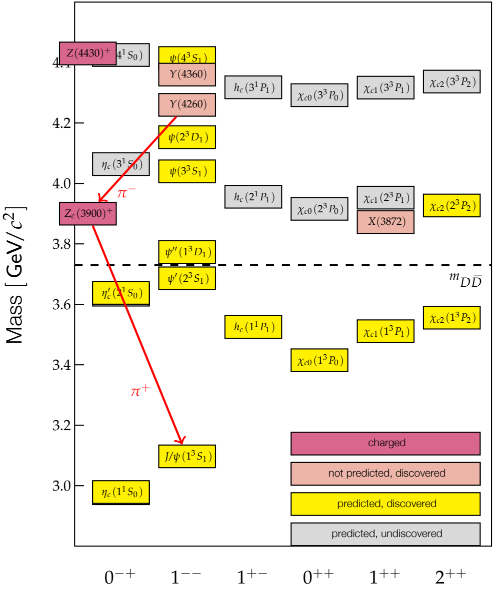
BESIII, PRL **110**, 252001 (2013)

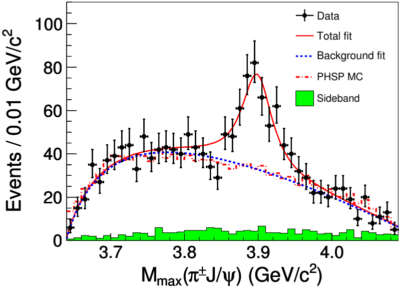




$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV

BESIII, PRL **110**, 252001 (2013)
525 pb^{-1} at 4.26 GeV





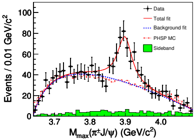
Charged charmonium-like structure

$$M = (3899.0 \pm 3.6 \pm 4.9)\ \text{MeV}/c^2$$
$$\Gamma = (46 \pm 10 \pm 20)\ \text{MeV}$$

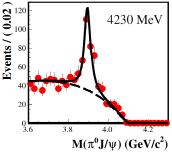
Confirmed by Belle PRL **110**, 252002
and with CLEOc data PLB 727, 366

Close to DD^* threshold
Interpretation?

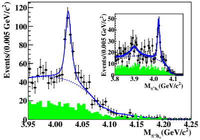
Z_c family at BESIII near 4.26 GeV



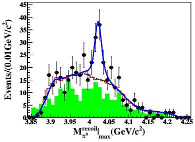
$e^+e^- \to \pi^-\pi^+ J/\psi$



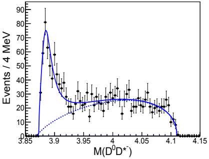
$e^+e^- \to \pi^0\pi^0 J/\psi$



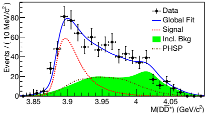
$e^+e^- \to \pi^-\pi^+ h_c$



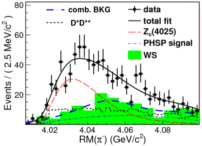
$e^+e^- \to \pi^0\pi^0 h_c$



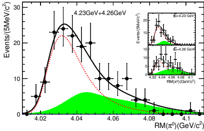
$e^+e^- \to \pi^-(D\bar{D}^*)^+$



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



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



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

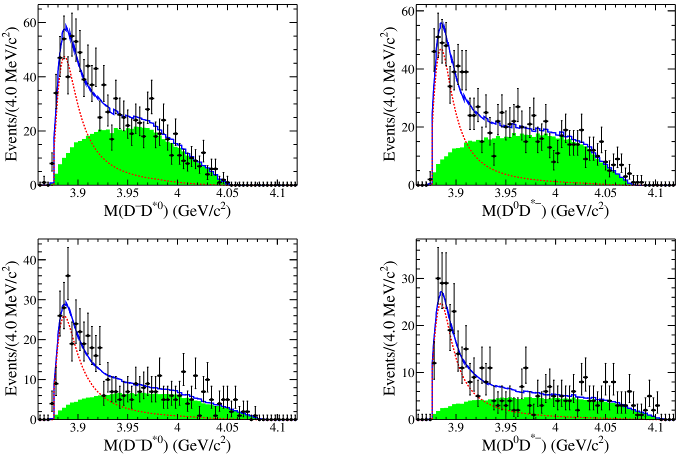
$Z_c(3900)^+$? $Z_c(3900)^0$? $Z_c(4020)^+$? $Z_c(4020)^0$?

Nature of these states? Tetraquarks, molecules, threshold effects …
Isospin triplets?
Different decay channels of the same states observed?

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

BESIII, PRD **92**, 092006 (2015)

$e^+e^- \to \pi^+ D^0 D^{*-}$ $\qquad$ $e^+e^- \to \pi^+ D^- D^{*0}$



Simultaneous fit with phase space shape + $(BW \otimes \mathcal{R}) \times \varepsilon$

Compatible with, but significantly more precise, than single-tag analysis

$e^+e^- \to \pi^+(D\bar{D}^*)^-$ with double tags: Results

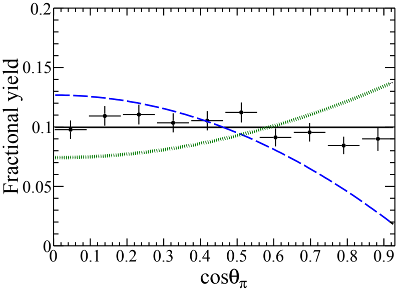
Single and double tag analyses only share $\sim 9\%$ of events: samples statistically almost independent!

	$M_{\text{pole}}\,[\text{MeV}/c^2]$	$\Gamma_{\text{pole}}\,[\text{MeV}]$
Single D tags	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
Double D tags	$3881.7 \pm 1.6 \pm 2.6$	$26.6 \pm 2.0 \pm 2.3$
Combined	$3882.3 \pm 1.1 \pm 1.9$	$26.5 \pm 1.7 \pm 2.3$

$Z_c(3885)^+$ Quantum numbers?

θ_π: angle between bachelor pion and beam axis in CMS
Know initial state is 1^-, with $J_z = \pm 1$. Depending on J^P of Z_c:

- 0^+ excluded by parity conservation
- 0^- π and $Z_c(3885)$ in P-wave, with $J_z = \pm 1$ ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1 - \cos^2\theta_\pi$
- 1^- π and $Z_c(3885)$ in P-wave ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1 + \cos^2\theta_\pi$
- 1^+ π and $Z_c(3885)$ in S or D wave.
  Assume D wave small near threshold: ➡ $\mathrm{d}N/\mathrm{d}\cos\theta_\pi \propto 1$



Efficiency corrected event yield in 10 bins in $|\cos\theta_\pi|$

data clearly favour $J^P = 1^+$ for $D\bar{D}^*$ structure

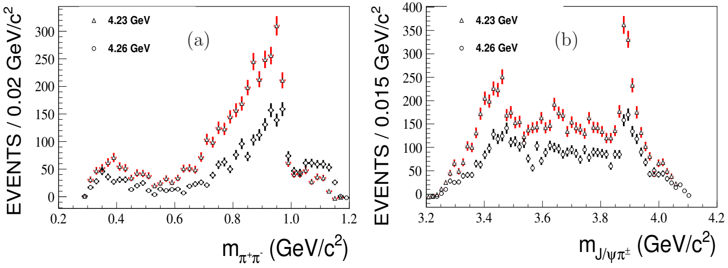
confirms J^P for $Z_c(3885)$ from single-tags

PWA of $J/\psi\,\pi^+\pi^-$

BESIII, PRL **119**, 072001 (2017)

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV ($1.92\,\text{fb}^{-1}$)

Compare signal yields:



(background subtracted)

some differences in $\pi\pi$ system;

$Z_c(3900)^+$ production cross section appears to be larger at 4.23 GeV

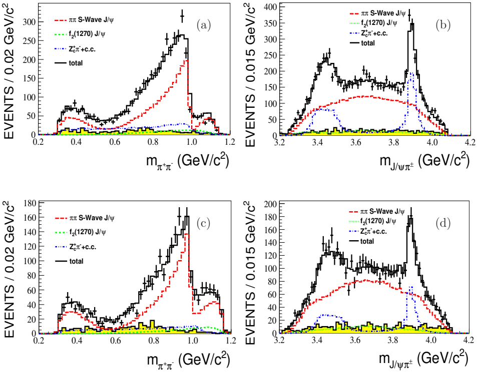
PWA of $J/\psi\,\pi^+\pi^-$

BESIII, PRL **119**, 072001 (2017)

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV ($1.92\,\text{fb}^{-1}$)

Amplitudes in the fit:

- $\pi\pi$ $\mathcal{S}$-wave: $f_0(500)$, $f_0(980)$, $f_0(1370)$
- $f_2(1270) \to \pi^+\pi^-$
- $Z_c(3900)^+ \to J/\psi\,\pi^+ + c.c.$ (Flatté-like lineshape, nominal fit: $J^P = 1^+$)
- nonresonant $J/\psi\,\pi^+\pi^-$



PWA of $J/\psi\,\pi^+\pi^-$

BESIII, PRL **119**, 072001 (2017)

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 GeV ($1.92\,\text{fb}^{-1}$)

Observed signal yields and cross section
$\sigma \times \mathcal{B} \equiv \sigma(e^+e^- \to Z_c(3900)^\pm \pi^\mp \to J/\psi\,\pi^+\pi^-)$ from the PWA fit:

$\sqrt{s}$	N_{sig}	$\sigma \times \mathcal{B}$ [pb]
4.23 GeV	952.3 ± 93.3	$22.0 \pm 1.0 \pm 4.8$
4.26 GeV	343.3 ± 23.3	$11.0 \pm 1.2 \pm 5.4$

PWA of $J/\psi\,\pi^+\pi^-$

BESIII, PRL **119**, 072001 (2017)

PWA of $e^+e^- \to J/\psi\,\pi^+\pi^-$ with full datasets at 4.23 and 4.26 **GeV** ($1.92\,\mathrm{fb}^{-1}$)

Test different J^P assignments for $Z_c(3900)^+$: Replace $Z_c(3900)^+(1^+)$ with $Z_c(3900)^+(J^P)$ in the fit,
add $Z_c(3900)^+(1^+)$,
observe change in likelihood for given Δ(ndf)

J^P	$\Delta(-2\ln L)$	significance
1^+ over 0^-	94	$12\,\sigma$
1^+ over 1^-	158	$> 16\,\sigma$
1^+ over 2^-	152	$> 15\,\sigma$
1^+ over 2^+	96	$> 12\,\sigma$

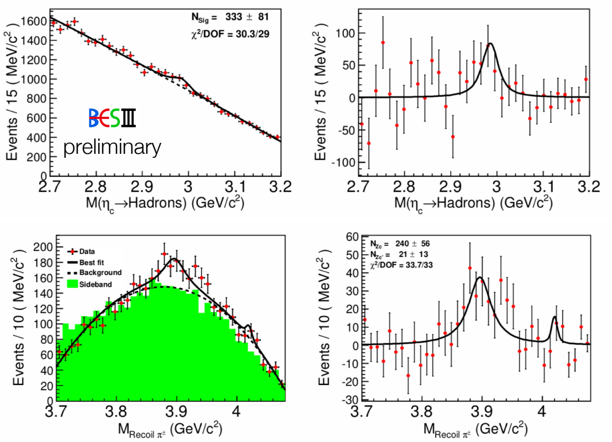
Data clearly favours $J^P = 1^+$ over all tested hypotheses
consistent with $Z_c(3885)^+ \to (D\bar{D}^*)^+$

JG|U

$Z_c(3900)^+ \to \eta_c \rho^+$

BESIII preliminary

- Select $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$, reconstructing η_c in 9 hadronic decay modes
- Select $\rho^\pm \to \pi^\pm\pi^0$, η_c by invariant mass
- Look in mass recoiling against $\pi^\mp$



- Strong evidence for $e^+e^- \to \pi Z_c$, $Z_c(3900)^+ \to \eta_c \rho^+$ 3.9σ significance, including systematics

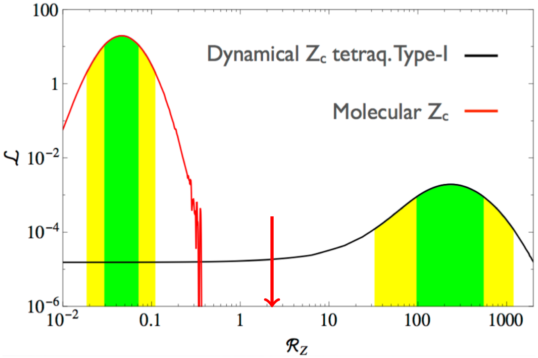
$Z_c(3900)^+ \to \eta_c \rho^+$

BESIII preliminary

- Select $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$, reconstructing η_c in 9 hadronic decay modes
- Select $\rho^\pm \to \pi^\pm\pi^0$, η_c by invariant mass
- Look in mass recoiling against $\pi^\mp$
- Strong evidence for $e^+e^- \to \pi Z_c$, $Z_c(3900)^+ \to \eta_c\rho^+$ 3.9σ significance, including systematics

Discriminate between molecular and tetraquark interpretation
Phys. Lett. B 746, 194 (2015)

$$R_z \equiv \frac{\mathcal{B}(Z_c \to \eta_c\rho)}{\mathcal{B}(Z_c \to J/\psi\,\pi)} = 2.1 \pm 0.8 \quad \text{at 4.23 GeV}$$



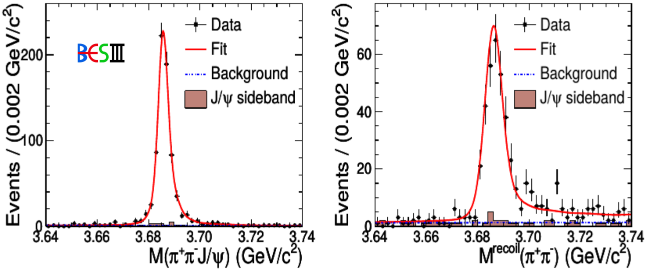
JG|U

$e^+e^- \to \pi^+\pi^-\psi(2S)$

BESIII, PRD **96**, 032004 (2017)

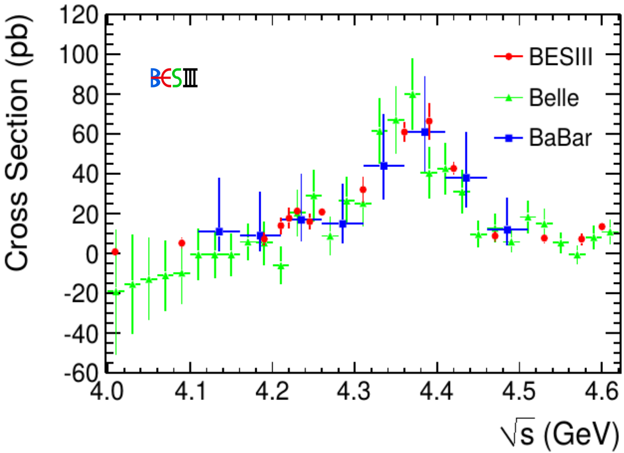
Consider process $e^+e^- \to \pi^+\pi^-\psi(2S)$
Reconstruct $\psi(2S)$ in two decay modes:

- $\psi(2S) \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\ell^+\ell^-$:
  direct reconstruction
- $\psi(2S) \to J/\psi$ + neutrals $\to \ell^+\ell^-$ + neutrals:
  identify J/ψ, look at mass recoiling against $\pi^+\pi^-$



$e^+e^- \to \pi^+\pi^-\psi(2S)$: cross section

BESIII, PRD **96**, 032004 (2017)

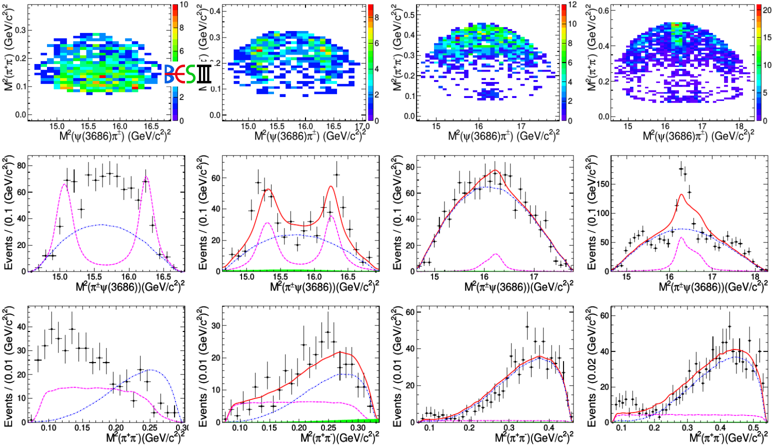


Compatible with ISR measurements from B factories,
significantly more precise
completely different shape than $\pi^+\pi^- J/\psi$

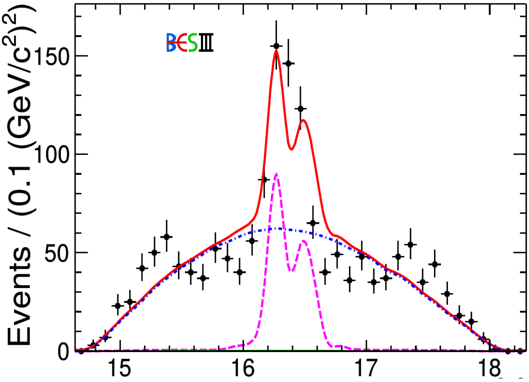
$e^+e^- \to \pi^+\pi^-\psi(2S)$: Dalitz plots

BESIII, PRD **96**, 032004 (2017)

$\sqrt{s}$ / GeV 4.226 4.258 4.358 4.416



$e^+e^- \to \pi^+\pi^-\psi(2S)$: Structure at $\sqrt{s} = 4.416$ GeV



Fit part of Dalitz plot with $M^2(\pi^+\pi^-) > 0.3$ (GeV/c^2)^2, 1^+ S-wave BW:

$$M = 4030.3 \pm 0.1\,\text{MeV}/c^2$$

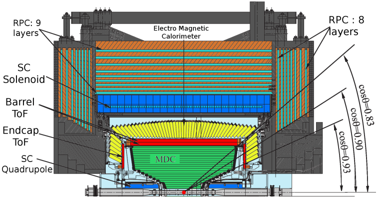
$$\Gamma = 5.1 \pm 0.2\,\text{MeV}$$

Open questions on XYZ states

- Other decay modes (e.g. into light mesons)?
- Other similar states (e.g. isospin singlets; with strangeness contents …)?
- More such states to be found, with other charmonia? — yes, e.g. $Z_c(4430)$, Z_b
- Dependence on production mechanism?
  Connection to states found in B decays (Belle, LHCb)?
- 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?
- $\cdots$

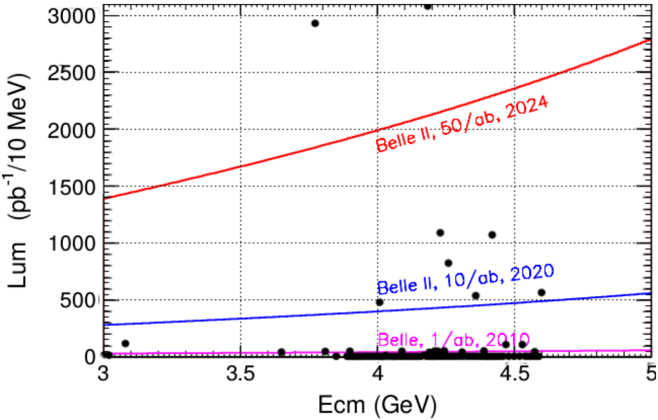
Future for BESIII

- Set to run for $\gtrsim 8$ more years
- If running near 'sweet spot' of accelerator ($\sqrt{s} = 3.77$ GeV): collect $\sim 5\,\text{fb}^{-1}$ / year
- Accelerator upgrades:
  - Increase beam energy
    currently, $\sqrt{s} \leq 4.60$ GeV
    increase by **300 MeV** with moderate effort
    upgrade ongoing
  - Top-up injection



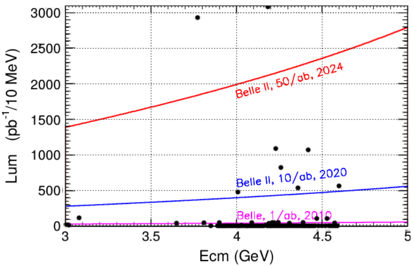
Luminosity expectation BelleII (ISR) vs BESIII (direct)

B2TiP WG7



Typical mass resolution for charged states in ISR physics: $\lesssim 5\,\text{MeV}/c^2$
Spacing of BESIII R-scan points: $5\,\text{MeV}$ (beam-energy spread $\sim 1.3\,\text{MeV}$)

Belle-II ISR vs BESIII



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

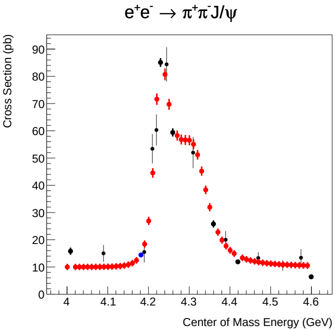
Direct scan

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

Future running at BESIII

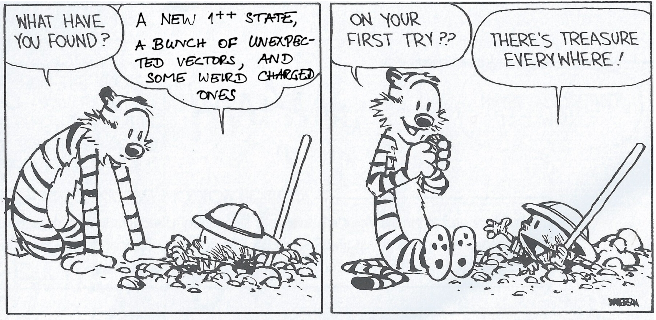
Not a time-ordered list!

- 10^{10} J/ψ (almost done!)
- continue XYZ scan with $500\,\text{pb}^{-1}$ / energy point
- $\geq 10\,\text{fb}^{-1}$ at $\psi(3770)$
- more $\Lambda_c^+\overline{\Lambda}_c^-$ data, after energy upgrade
- threshold runs for $\Lambda\overline{\Lambda}$, …
- …



Exciting times ahead!

謝謝！



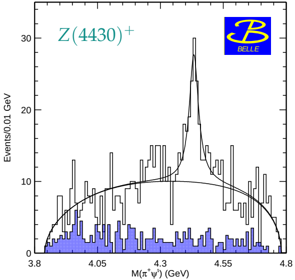
…with apologies to Bill Watterson

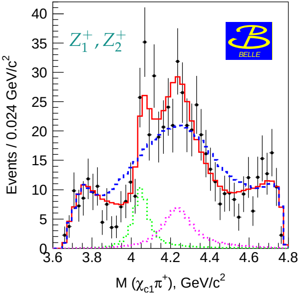
Charged charmonium-like states: a Z^+ family?

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?

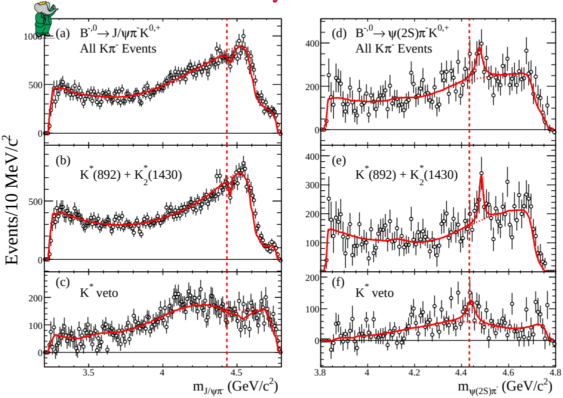
BABAR:

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

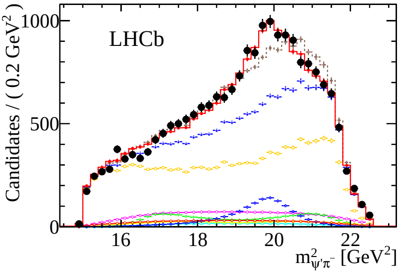


$Z_c(4430)^-$ in $B \to K\pi^-\psi'$ at LHCb

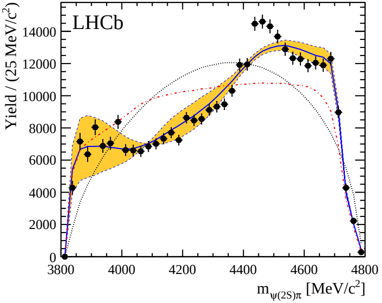
$\approx 25\,000$ candidates for $B \to K\pi^-\psi'$ in $3\,\text{fb}^{-1}$

Two analysis methods

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

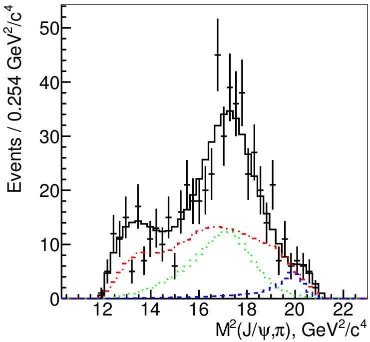


- Moments analysis à la *BABAR*
  reflections from K^* not enough;
  confirms existence of $Z_c(4430)$
  PRD **92** 112009 (2015)



$Z_c(3900)$ in B decays?

PRD **90**, 112009 (2014)



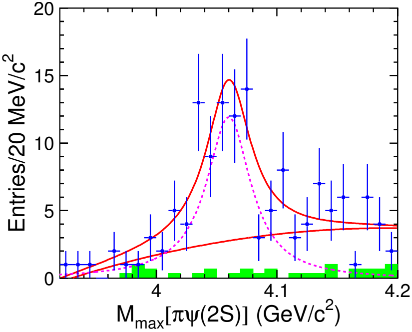
- See $Z_c(4430)^+ \to J/\psi\, \pi^+$
- No $Z_c(3900)^+$ needed
- Instead: $Z_c(4200)^+$

$$M = 4196^{+31+17}_{-29-13} \text{ MeV}/c^2,$$
$$\Gamma = 370^{+70+70}_{-70-132} \text{ MeV}.$$

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

PRD **91**, 112007 (2015)

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



- 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 …