Recent BESIII results on exotic charmonium-like hadrons

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Durham
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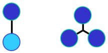
SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRiSMA+

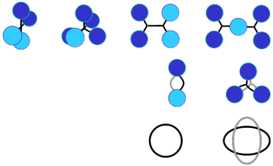
‘Exotic’ hadrons

Well-known classes of hadrons: mesons ($q\bar{q}$) and baryons (qqq)
minimal colour singlets



Already on page 1 of the quark model: other colour-neutral combinations possible

- multi-quark states (tetraquark, pentaquark, …)
- hybrids (excitation in gluonic degrees of freedom)
- glueballs



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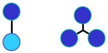

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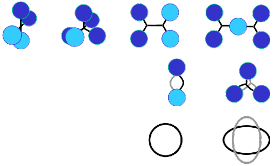


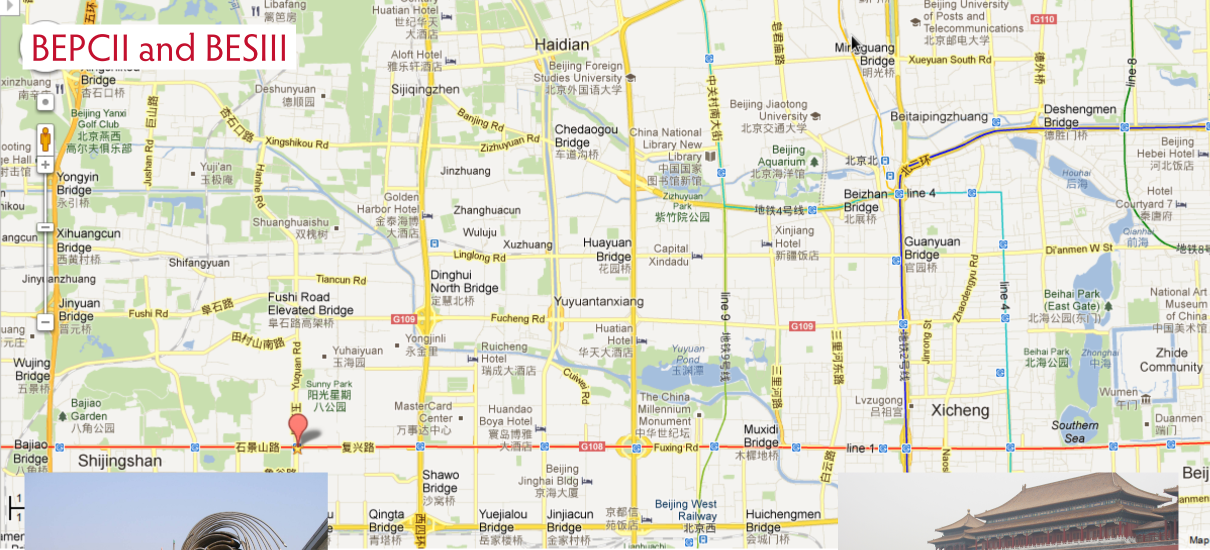
Manifestly exotic

- Quark contents requires more than $q\bar{q}$ or qqq
- Quantum numbers J^{PC} not reachable for ordinary mesons or baryons

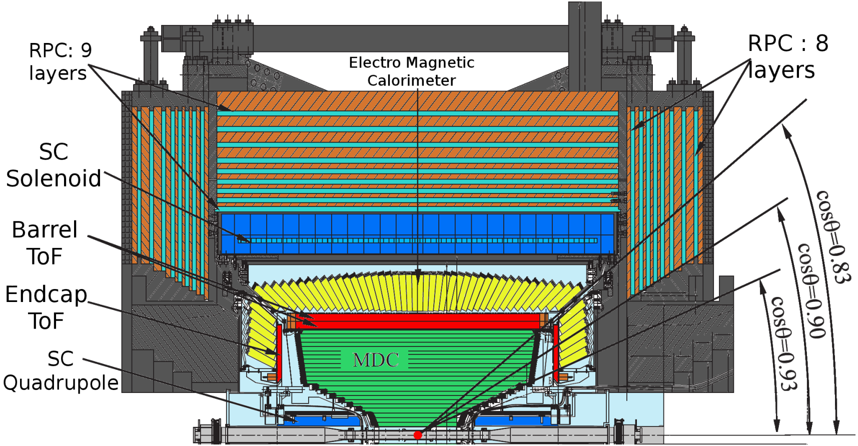
‘Cryptoexotic’

- production and/or decay patterns incompatible with standard mesons/baryons
- mass / width not fitting in spectra
- overpopulation of states

BEPCII and BESIII



BESIII

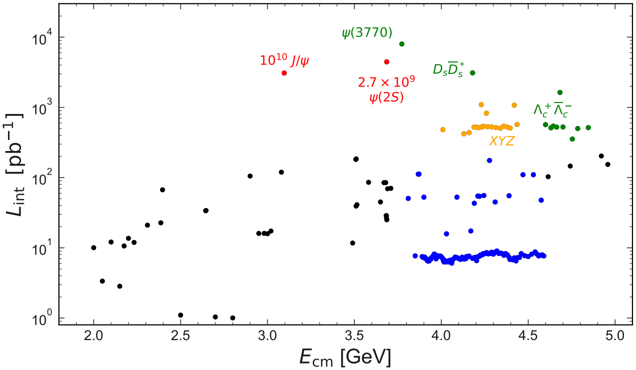


At BEPCII in Beijing: e^+e^- collisions at $\sqrt{s}$ between 2 and 5 GeV

12 years data taking at BESIII

Data sets collected so far include

- 10×10^9 J/ψ events
- 2.7×10^9 ψ' events
- $8\,\mathrm{fb}^{-1}$ on $\psi(3770)$
- scan data between 2.0 and 3.08 GeV, and above 3.735 GeV
- large datasets for *XYZ* studies: scan with $> 500\,\mathrm{pb}^{-1}$ per energy point spaced 10 – 20 MeV apart



Light hadrons in the decays of J/ψ, ψ' ➡ Zhu Yingchun's talk on Wed

Charmonium-like hadrons above $\sqrt{s} \approx 4.2$ GeV

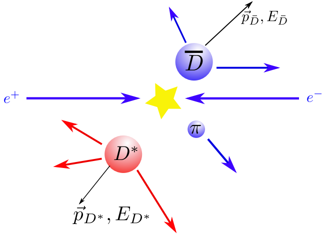
Exploit known kinematics and clean environment

Exclusive reconstruction of final states with many tracks / intermediate resonances may suffer from low efficiency

- Tracking and PID efficiencies
- Branching fractions of intermediate states
  e.g. $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = 8.98\%$

At e^+e^- collider with precisely known initial state:
can require missing track or even composite particle,
for example in the process $e^+e^- \to D^{*+}D^0\pi^-$

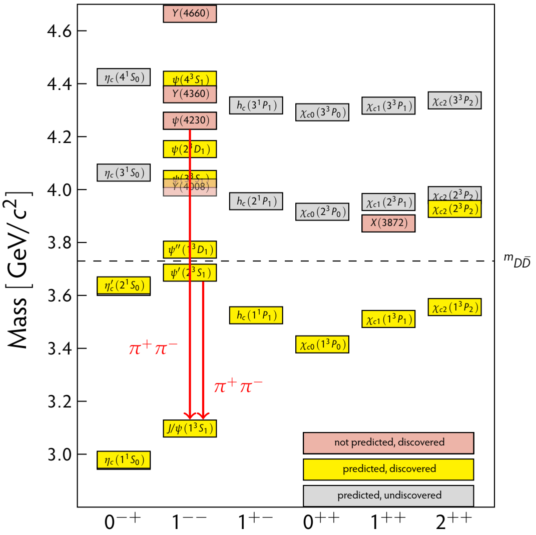
$$p^\mu_{e^+e^-} = p^\mu_D + p^\mu_\pi + p^\mu_{D^*}$$



Use *kinematic fit* with appropriate constraints to improve mass and momentum resolution

Charmonium-like vector states

$\psi(4230) \to J/\psi\,\pi^+\pi^-$



First seen in e^+e^- collisions near $\Upsilon(4S)$ in ISR production, $e^+e^- \to \gamma_{\text{ISR}} J/\psi\,\pi^+\pi^-$

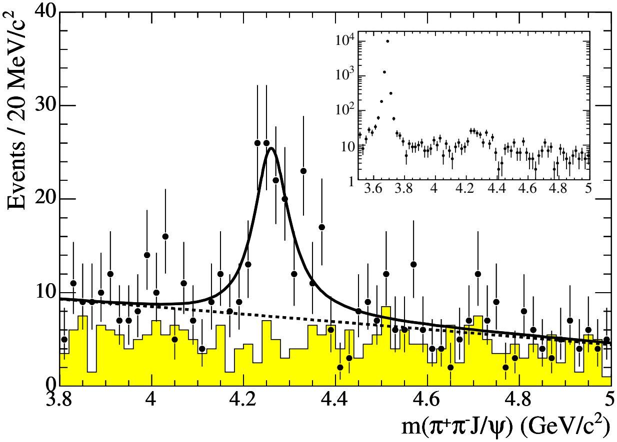
$\Rightarrow J^{PC} = 1^{--}$

Supernumerary vector state:
all 'ordinary' $c\bar{c}$ vector states already seen

$\psi(4230) \to J/\psi\,\pi^+\pi^-$

BABAR, 211 fb^{-1}, PRL 95 (2005) 142001

Discovered by *BABAR* in $e^+e^- \to \gamma_{ISR} J/\psi\,\pi^+\pi^-$



Fit with single Breit-Wigner

$$M = 4259 \pm 8^{+2}_{-6}\,\text{MeV}$$

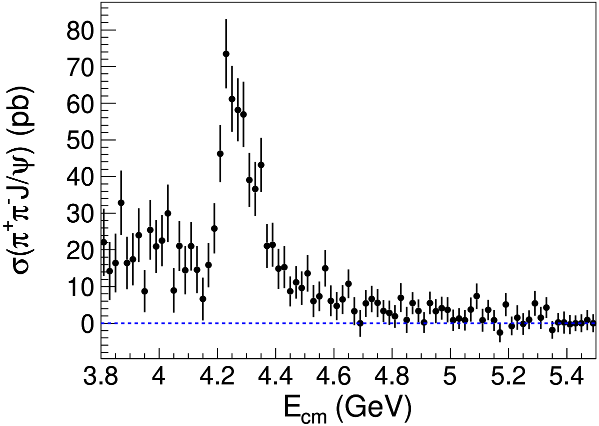
$$\Gamma = 88 \pm 23^{+6}_{-4}\,\text{MeV}$$

Call this structure $Y(4260)$

$\psi(4230) \to J/\psi\,\pi^+\pi^-$

Belle, 967 fb^{-1}, PRL 110 (2013) 252002

Belle measurement, using ISR



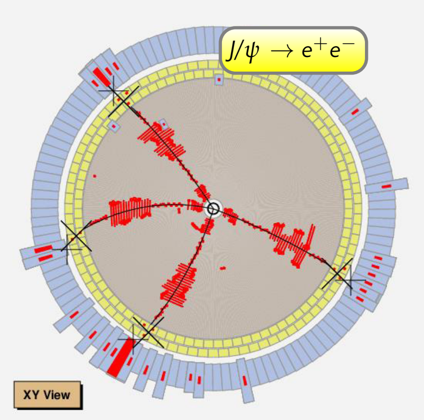
Single Breit-Wigner fit to line shape still satisfactory

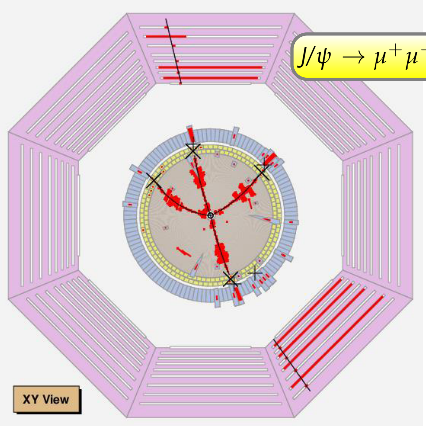
$$M = 4248.6 \pm 8.3 \pm 12.1\,\mathrm{MeV}$$

$$\Gamma = 134.1 \pm 16.4 \pm 5.5\,\mathrm{MeV}$$

but lineshape does not quite look like a Breit-Wigner

$e^+e^- \to J/\psi\,\pi^+\pi^-$ at 4.26 GeV in direct production at BESIII





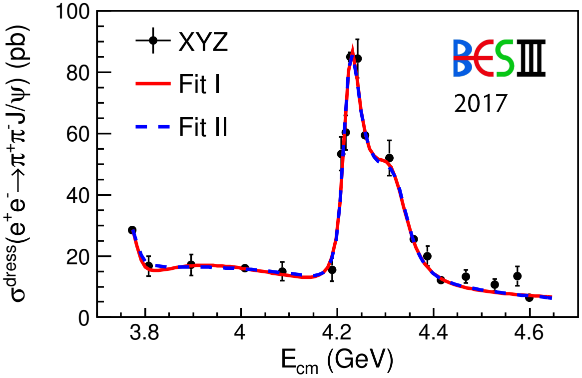
- Running at $\sqrt{s} = 4260\,\mathrm{MeV}$: simple and straightforward
- $J/\psi\,(\to \ell^+\ell^-)\pi^+\pi^-$: four charged tracks

- very clean sample, high efficiency, reliable MC simulation
- dominant background: continuum

$\psi(4230) \to J/\psi\, \pi^+\pi^-$

BESIII, PRL 118, 092001 (2017)

BESIII: make use of first batch of *XYZ* scan data set



Single Breit-Wigner not appropriate to fit line shape

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

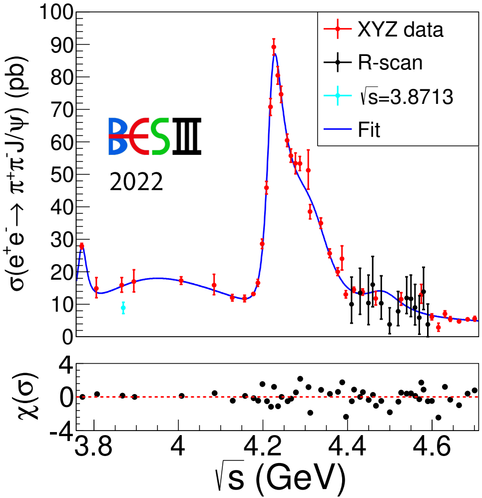
Fit 1, Fit 2: different treatment of non-resonant contribution

$Y(4260) \Rightarrow \psi(4230)$

$\psi(4230) \to J/\psi\,\pi^+\pi^-$

BESIII, Phys. Rev. D 106, 072001 (2022)

Update with fine high-statistics scan

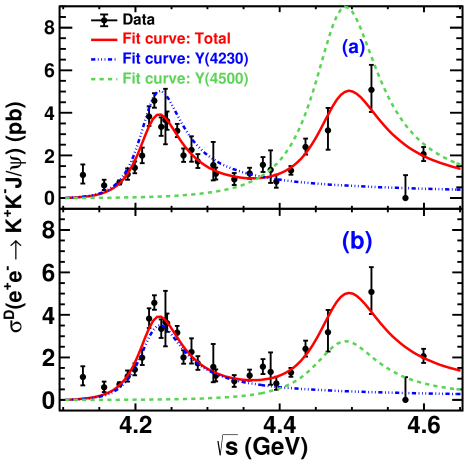


- $\psi(4220)$ and $\psi(4320)$ parameters consistent with previous measurement
- additional structure near 4.5 GeV needed — $\psi(4415)$? influences determination of $\psi(4220)$ parameters

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

Chin. Phys. C 46, 111002 (2022)

- Improve statistics by partial reconstruction: require $J/\psi \to \ell^+\ell^-$ and one $K^\pm$
- Cross section near $\psi(4230)$ about $1/20$ of $\pi^+\pi^-J/\psi$
- Fit to dressed cross section with coherent sum of 2 BW:
  parameters of low-lying structure compatible with $Y(4230)$
- $Y(4500)$: hint seen in $\pi^+\pi^-J/\psi$, but much stronger here.
  What is it? Conventional charmonium, $c\bar{c}s\bar{s}$, …?

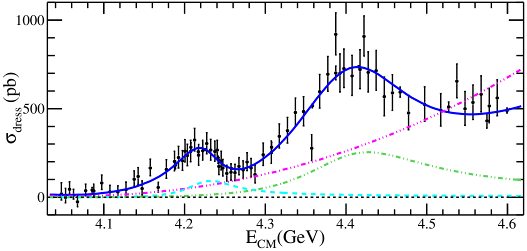


Open-charm decay channels?

Hidden-charm final states such as $\pi^+\pi^- J/\psi$, KKJ/ψ, $\pi^+\pi^-\psi(2S)$ show interesting resonant structure in the cross section

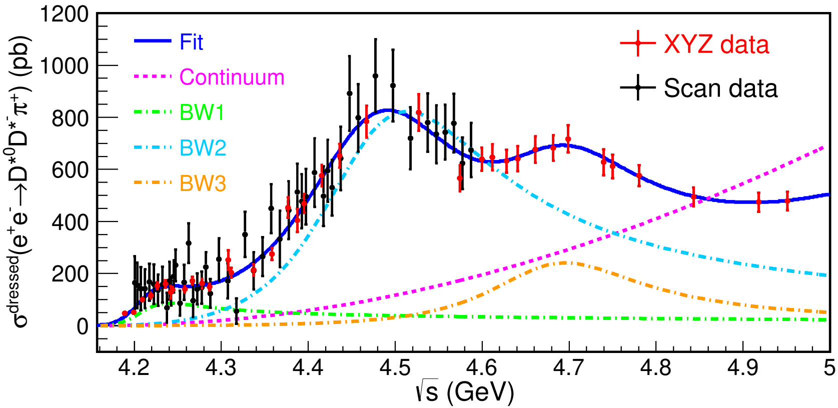
Decays of these resonances into open-charm final states?

Yes — e.g. $D^{*0}D^-\pi^+$ BESIII, PRL 122 (2019) 102002



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

BESIII, PRL 130 (2023) 121901



Fit with coherent sum of 3 rel. Breit-Wigner + continuum (phase space)

Caution: Fit to 1D projection of complicated phase space.

Multiple indistinguishable solutions (8) unavoidable, differing in rel. phases and $\mathcal{B}\Gamma_{ee}$

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

BESIII, PRL 130 (2023) 121901

Three resonant structures needed in addition to phase space:

	m [MeV/c]	Γ [MeV]
$\psi(4210)$	$4209.6 \pm 4.7 \pm 5.9$	$81.6 \pm 17.8 \pm 9.0$
$\psi(4470)$	$4469.1 \pm 26.2 \pm 3.6$	$246.3 \pm 36.7 \pm 9.4$
$\psi(4660)$	$4675.3 \pm 29.5 \pm 3.5$	$218.3 \pm 72.9 \pm 9.3$

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Implications for $Y(4230)$, assuming $\psi(4210)$ to be the same state:

- Coupling to $D^{*0}D^{*-}\pi^+$ same order of magnitude as to $D^0D^{*-}\pi^+$
- Electronic width $\Gamma_{ee}(Y(4230)) > 40$ eV
  disfavours assignment as charmonium hybrid LQCD, Y. Chen *et al.*, Chin. Phys. C 40 (2016) 8, 081002
- Coupled-channel analysis highly desirable!

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

BESIII, PRL 130 (2023) 121901

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Assume $\psi(4470)$ is the same state as $\psi(4500)$ seen in K^+K^-J/ψ:

- First observation of this state in an open-charm decay channel
- Decay rate to $D^{*0}D^{*-}\pi^+$ 2 orders of magnitude larger than to K^+K^-J/ψ: disfavours hidden-strangeness tetraquark structure

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

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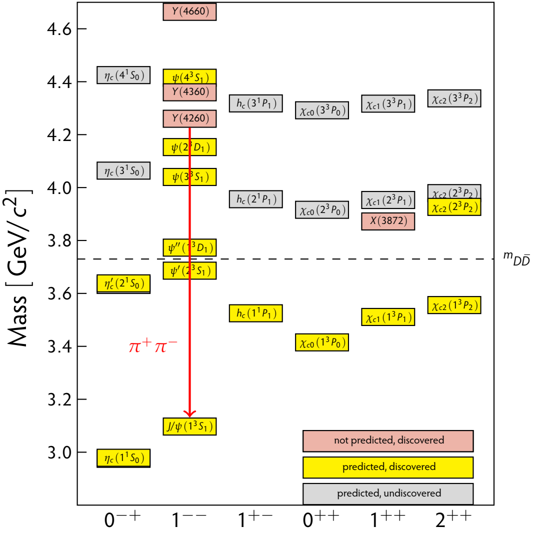
$\psi(4660)$:

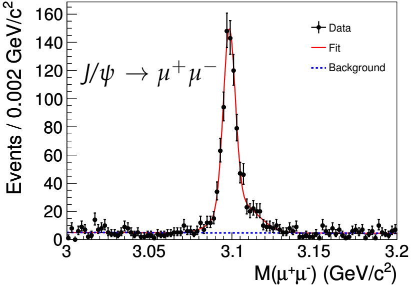
- seen in $\pi^+\pi^-\psi(2S)$ cross section by Belle (2007), BABAR (2014), and BESIII (2021)
- not seen in $D^{*-}D^0\pi^+$ Belle, PRD 80 (2009) 091101
  but in $D_s^+ D_s(2536)^-$ Belle, PRD 100 (2019) 111103
- also in $\Lambda_c^+\bar{\Lambda}_c^-$ near threshold? Belle, PRL 101 (2008) 172001
- this analysis: first non-strange open-charm decay

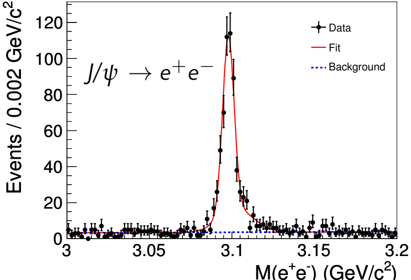
Charged charmonium-like states

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

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







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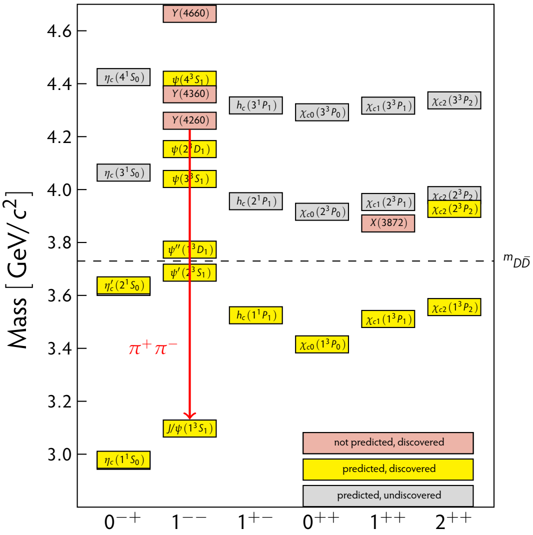

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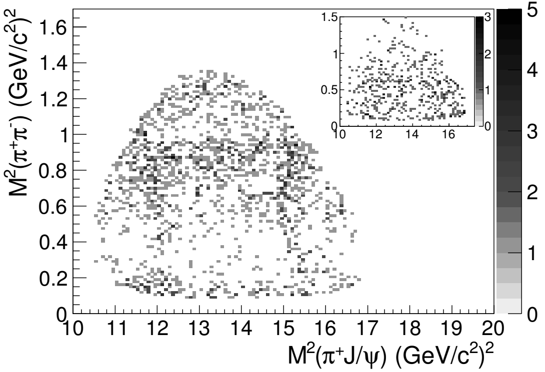
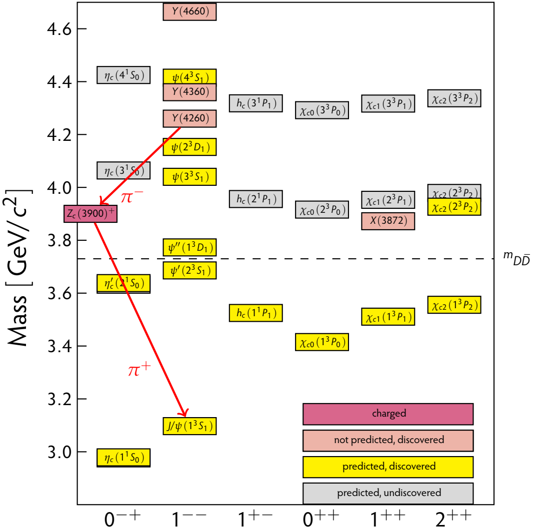


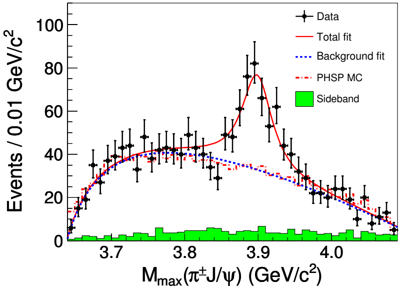
Non-trivial substructure in $J/\psi\,\pi^+\pi^-$ Dalitz plot

Resonant substructure in decay!

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

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





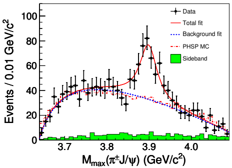
Charged charmonium-like structure

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

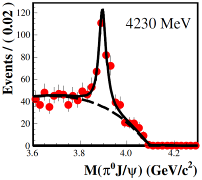
$$\Gamma = (46 \pm 10 \pm 20)\ \text{MeV}$$

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

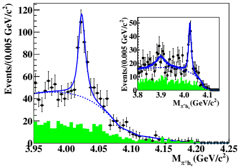
Z_c family at BESIII near $\sqrt{s} = 4.26$ GeV



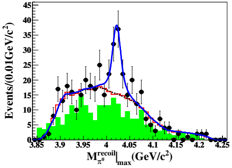
$e^+e^- \to \pi^-\pi^+J/\psi$



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



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



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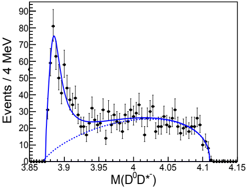
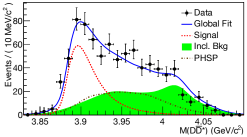
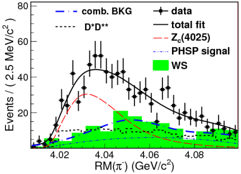


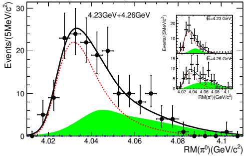
$e^+e^- \to \pi^-(D\bar{D}^*)^+$



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



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

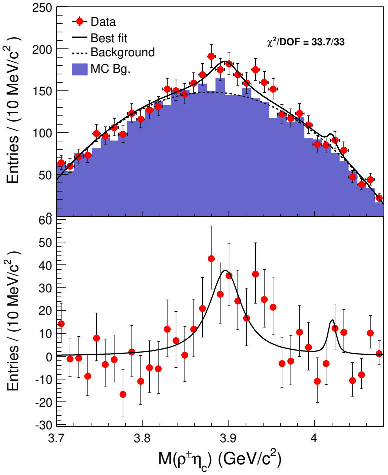


$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

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

Z_c-like states with other charmonia?

- Evidence for $Z_c(3900)^+ \to \rho^+ \eta_c$ near $\sqrt{s} = 4.26$ GeV BESIII ,PRD 100 (2019) 111102



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- No hint for $Z_c(4050)^+, Z_c(4250)^+ \to \chi_{c1}\pi^+$ BESIII, PRD 103 (2021) 052010
  in contrast to Belle in $\bar{B}^0 \to K^-\pi^+\chi_{c1}$ Belle, PRD 78 (2008) 072004
- Charged charmonium-like structure in $\psi(2S)\pi^+$ BESIII, PRD 96 (2017) 032004
  with very complicated evolution of the $\psi(2S)\pi^+\pi^-$ Dalitz plot
  but not the one seen by Belle and LHCb in $B \to K\pi\psi(2S)$ LHCb, PRL 112 (2014) 222002

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What is going on here?

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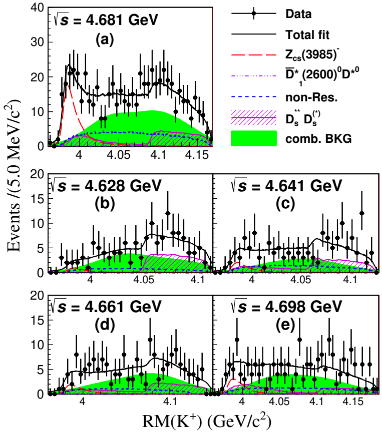
What is going on here?

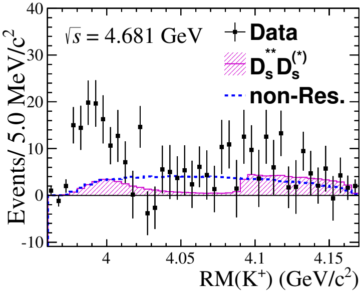
Search for strange partners to the Z_c in $D^{(*)}D_s^{(*)}$ and $J/\psi K$

Z_{cs}^{+} in $e^{+}e^{-} \to K^{+}(D_s^{-}D^{*0} + D_s^{*-}D^{0})$

BESIII, PRL 126 (2021) 102001



Threshold enhancement most prominent at $\sqrt{s} = 4.68$ GeV



Fit with rel. BW yields pole mass and width of structure at threshold

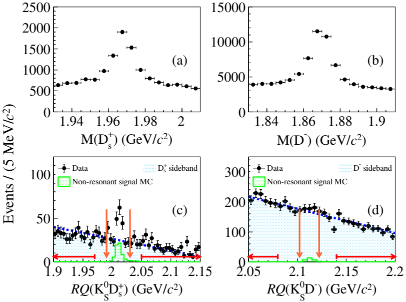
$$M_{\text{pole}} = 3982.5^{+1.8}_{-2.6} \pm 2.1\ \text{MeV}/c^2$$
$$\Gamma_{\text{pole}} = 12.8^{+5.3}_{-4.4} \pm 3.0\ \text{MeV}$$

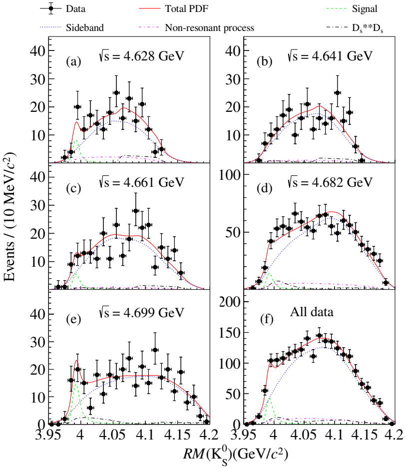
Hidden-charm open-strangeness four-quark candidate $Z_{cs}(3985)^{+}$

$e^+e^- \to K_S^0 D_s^+ D^{*-} + K_S^0 D_s^{*+} D^-$

BESIII, PRL 129 (2022) 112003

Reconstruct K_S^0 and one of D_s^{*+} or D^-, identify missing D^+ or D_s^{*-} in missing mass





See Z_{cs}^0 in system recoiling against K_S^0, with significance 4.6σ

BW parameters	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

Z_{cs} searches

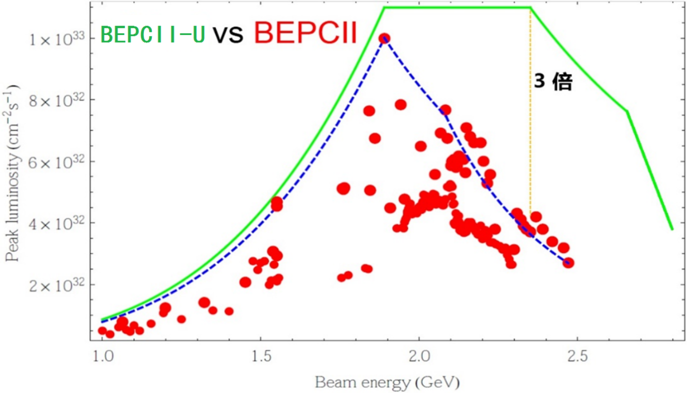
- See enhancement in the $D^* D_s$ mass in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ and $e^+e^- \to K_S^0(D_s^+ D^{*-} + D_s^{*+} D^-)$
- Consistent with two isospin partners $Z_{cs}^{\pm}$ and Z_{cs}^0
- Decay to hidden charm, i.e. study of KJ/ψ system in $e^+e^- \to KKJ/\psi$: stay tuned

Outlook for BESIII

- Currently running on $\psi(3770)$, with the goal to collect 20 fb^{-1} in total
- Upgrades to accelerator already performed
  - better feedback systems
  - automated switching from e^- to e^+, for top-up injection ($\mathcal{L}_{\mathrm{int}} + 30\%$)
  - power supplies and cooling for magnets, to allow running at higher $\sqrt{s}$
- Major upgrade to RF system in 2024 (see next slide): gain up to a factor of 3

Upgrade to accelerator: BEPCII-U project

- **Goal**: improve luminosity at large $\sqrt{s}$
- **Easiest upgrade**: install more RF power, optimize machine lattice
- **Bonus**: running above $\sqrt{s} \sim 5$ GeV becomes feasible



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- Upgrade of inner tracking system (ageing): installation of 3-layer CGEM detector (2024)

Operate BESIII for several years after upgrade (2030?)

More exciting results to come from the new larger datasets

Summary

Summary

- BESIII uniquely suited for exotics studies in the charmonium region
  large and clean data sets
- See whole families of charmonium-like unconventional states
  Sophisticated amplitude analyses needed
- **Still many open questions**
  Connection between these states?
  Can we identify the same state in different production mechanisms?
  If not, why not?
- Experimental input essential,
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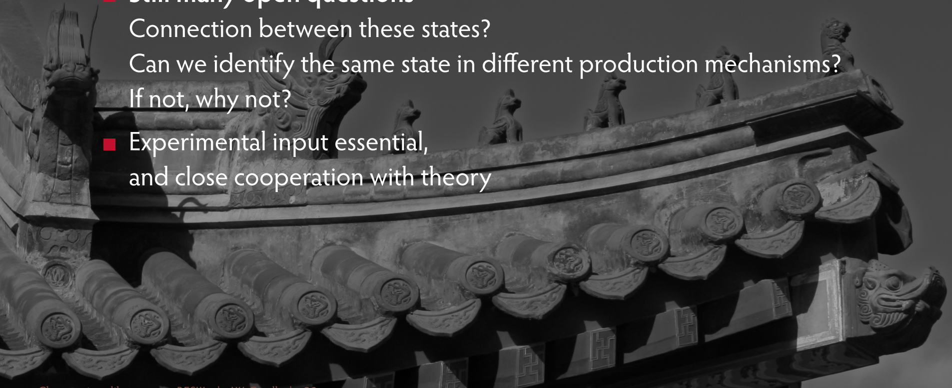


謝謝!

$\psi(4230)$ in different decay channels

pdgLive Home > $c\bar{c}$ MESONS > $\psi(4230)$ > $\psi(4230)$ MASS

$\psi(4230)$ MASS

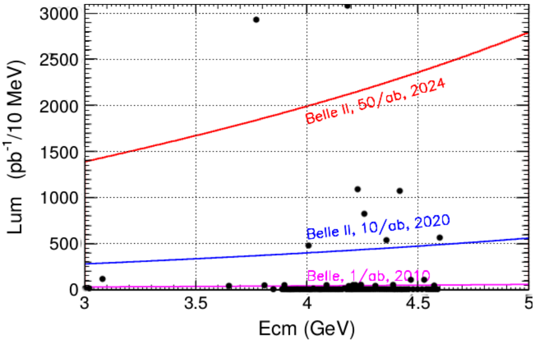
INSPIRE search

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4222.7 ± 2.6	**OUR AVERAGE** Error includes scale factor of 1.7. See the ideogram below.				
4234.4 ±3.2 ±0.2		[1] ABLIKIM	2021AJ	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
4216.7 ±8.9 ±4.1		[2] ABLIKIM	2020AG	BES3	$e^+ e^- \to \mu^+\mu^-$
4220.4 ±2.4 ±2.3		[3] ABLIKIM	2020N	BES3	$e^+ e^- \to \pi^0\pi^0 J/\psi$
4218.6 ±3.8 ±2.5		[3] ABLIKIM	2020O	BES3	$e^+ e^- \to \eta J/\psi$
4218.5 ±1.6 ±4.0		[4] ABLIKIM	2019AI	BES3	$e^+ e^- \to \omega\chi_{c0}$
4228.6 ±4.1 ±6.3		ABLIKIM	2019R	BES3	$e^+ e^- \to \pi^+ D^0 D^{*-}$ + c.c.
4200.6 $^{+7.9}_{-13.3}$ ±3.0		[5] ABLIKIM	2019V	BES3	$e^+ e^- \to \gamma\chi_{c1}(3872)$
4222.0 ±3.1 ±1.4		[6] ABLIKIM	2017B	BES3	$e^+ e^- \to \pi^+\pi^- J/\psi$
4218 $^{+5.5}_{-4.5}$ ±0.9		ABLIKIM	2017G	BES3	$e^+ e^- \to \pi^+\pi^- h_c$

PDG now calls the narrow structure $\psi(4230)$ — seen in many different decay modes, mainly charmonium + light meson(s)

Luminosity expectation Belle II (ISR) vs BESIII (direct)

B2TiP WG7



Note: old luminosity projection for Belle II; current $\mathcal{L}_{\text{int}} = 428\,\text{fb}^{-1}$, target is $4\,\text{ab}^{-1}$ by 4/2026

BESIII datasets relevant for years to come!

Upgrade of inner tracking detector with CGEM

CGEM: replace inner drift chamber
three layers of cylindrical GEM detectors.

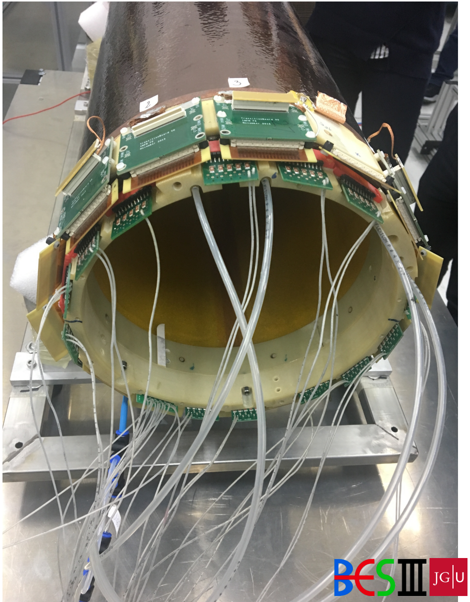
Radiation hard, efficient, fast, better hit resolution along beam direction.

Italy, with strong support of IHEP,
Germany, and Sweden.

Improvements w.r.t. KLOE CGEM detector:

- Improved anode design
- Analogue readout (new ASIC, designed in Torino)
- Micro-TPC reconstruction: get coordinates and direction

Detector on track for installation in 2024



$X(3872)$ in a nutshell

Belle's discovery (2003) in $B \to KJ/\psi\,\pi^+\pi^-$: extremely narrow resonance

Observed in B decays, prompt production in pp, $p\bar{p}$, heavy-ion collisions, and in $\psi(4230) \to \gamma X(3872)$

Mass sits extremely close to $D^0\bar{D}^{*0}$ threshold

No charged partner: isospin singlet
but large isospin violation in its decays $J/\psi\,\rho^0$ and $J/\psi\,\omega$

LHCb: $J^P = 1^+$ without any doubt

does not fit into $c\bar{c}$ spectrum as 2^3P_1 state: too light
nevertheless, PDG labels this state now as $\chi_{c1}(3872)$

$D^0\,\bar{D}^{*0}$ molecule? Four-quark state?

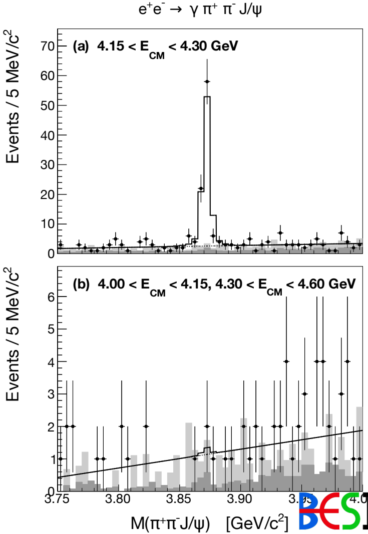
$X(3872) \to \pi^0 \chi_{c1}$

BESIII, Phys. Rev. Lett. 122 (2019) 202001

$X(3872)$ discovered in $J/\psi\,\pi^+\pi^-$, also seen in $J/\psi\,\omega$.
other decay modes, with other charmonia?

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

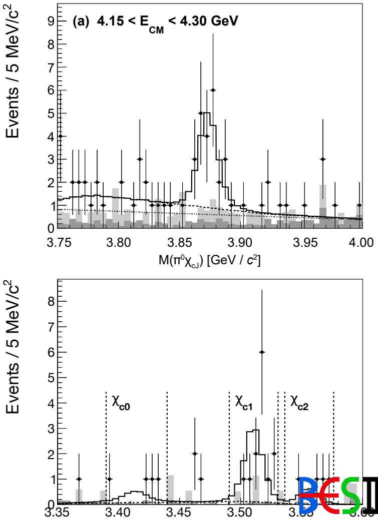
- $X(3872)$ production happens in $\sqrt{s} \sim$4.15 GeV to 4.30 GeV,
  but not outside
- Suggestive of very strong connection between $X(3872)$ and $Y(4230)$



$X(3872) \rightarrow \pi^0 \chi_{c1}$

BESIII, Phys. Rev. Lett. 122 (2019) 202001

- Search for $X(3872) \rightarrow \pi^0 \chi_{cJ} \rightarrow \pi^0 \gamma J/\psi$ in $e^+e^- \rightarrow \gamma X(3872)$
- Select events with $e^+e^- \rightarrow \gamma \pi^0 \gamma J/\psi$ with $M(\gamma J/\psi)$ near χ_{cJ} mass: clear signal near $X(3872)$ mass
- $M(\gamma J/\psi)$ in signal region: indication of χ_{c1}, χ_{c2}

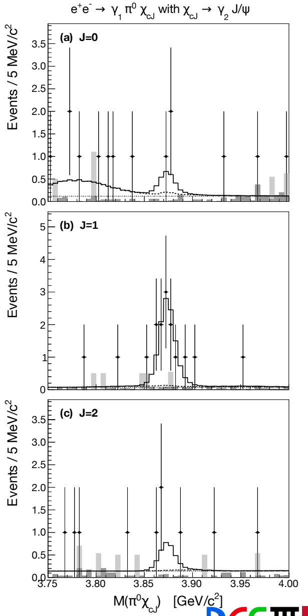


$X(3872) \to \pi^0 \chi_{c1}$

- Clear $X(3872) \to \pi^0 \chi_{c1}$ signal seen, stat. significance more than 5σ
- Normalise to 'discovery mode'

$$\frac{\mathcal{B}(X(3872) \to \pi^0 \chi_{c1})}{\mathcal{B}(X(3872) \to \pi^+ \pi^- J/\psi)} = 0.88^{+0.33}_{-0.27} \pm 0.10$$

- Estimate $\mathcal{B}(X(3872) \to \pi^0 \chi_{c1}) \sim 3 - 6\%$
- 'ordinary $c\bar{c}$': $\Gamma(2^3P_1 \to \pi^0 \chi_{c1}) \sim 0.06$ keV
  Dubynskiy and Voloshin, Phys. Rev. D **77** (2008) 014013,
  implying an extremely narrow $X(3872)$
- Disfavour pure $c\bar{c}$ interpretation of $X(3872)$



Radiative and open-charm decay modes of $X(3872)$

BESIII, PRL 124 (2020) 242001

Ratio of branching fractions

$$R_{\gamma\psi} = \frac{\mathcal{B}(X(3872) \to \gamma\psi')}{\mathcal{B}(X(3872) \to \gamma J/\psi)}$$

- Predicted to be in the range
  - $(3 \text{ to } 4) \times 10^{-4}$ if $X(3872)$ is $D^{*0}\bar{D}^0$ molecule,
  - 1.2 to 15 if pure $c\bar{c}$ state
  - 0.5 to 5 if mixture
- Experimental situation:

$$R_{\gamma\psi} = \begin{cases} 2.46 \pm 0.64 \pm 0.29 & \text{LHCb} \\ 3.4 \pm 1.4 & \text{BABAR} \\ < 2.1 & \text{Belle} \end{cases}$$

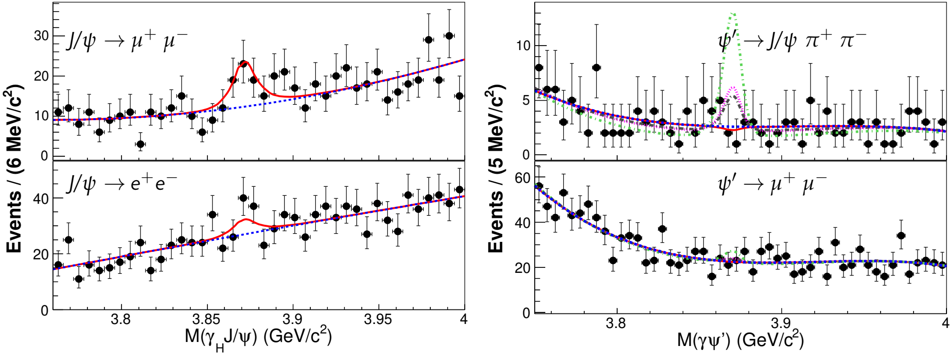
Nucl. Phys. B 886 (2014) 665

Phys. Rev. Lett. 102 (2009) 132001

Phys. Rev. Lett. 107 (2011) 091803

Radiative decay modes of $X(3872)$

BESIII, PRL 124 (2020) 242001



Simultaneous fits to $M(\gamma J/\psi)$ or $M(\gamma\psi')$.
See clear $X(3872) \to \gamma J/\psi$, at 3.5σ, but no hint for $\gamma\psi'$ (contradicts BABAR).

Upper limit at the 90% C.L.: $R_{\gamma\psi} < 0.59$

Somewhat in tension ($\sim 2\sigma$) with LHCb and BABAR, but in agreement with Belle.