Multiquarks and spectroscopy results from the B factories

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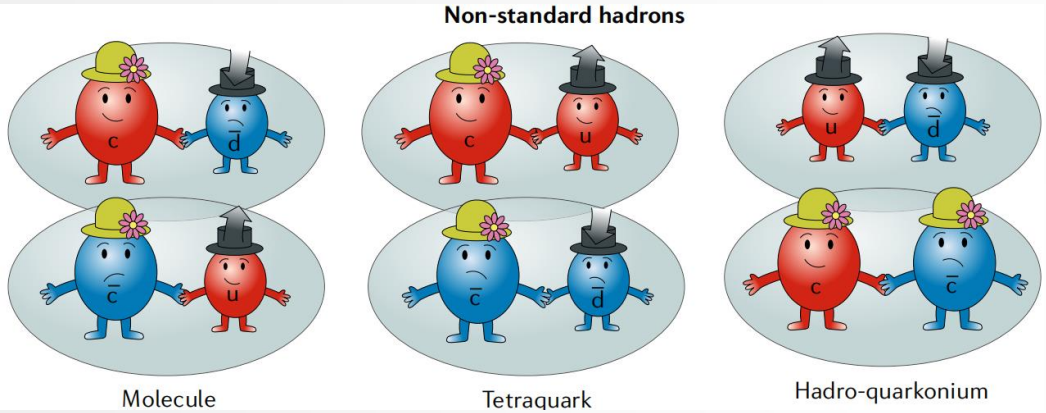
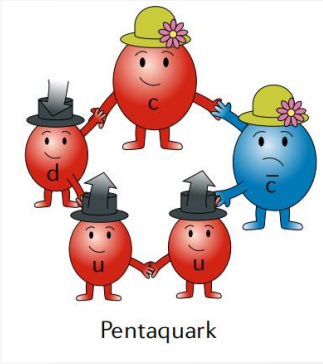
Outline

- Introduction
  - Evidence of X(3872) in $B^{\pm} \rightarrow X(3872)K^{\pm}$ from BaBar
  - X(3872) absolute BRs
  - Observation of Y(4626) in $e^+e^- \rightarrow D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^-$ from Belle
  - Observation of $Y_b(10750)$ in $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)$ from Belle
- Summary

Hadrons: normal & multiquarks (exotic)

- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks





- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, ...)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - ...

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

Where are they??

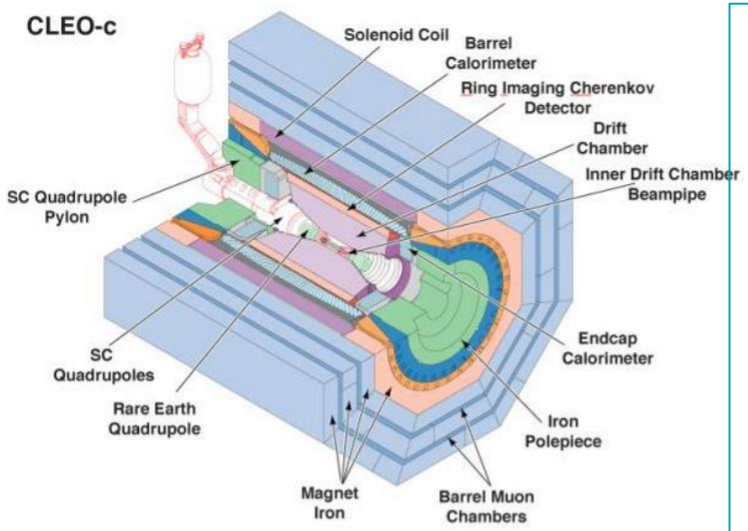
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

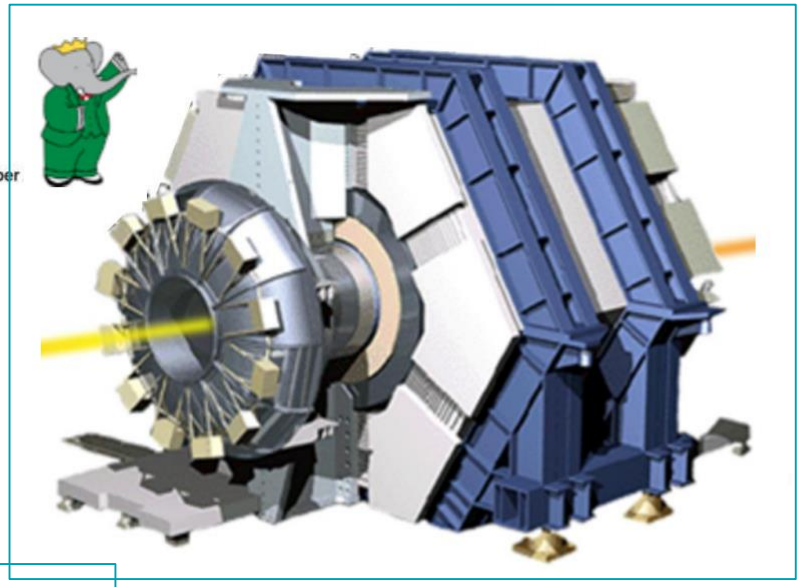
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

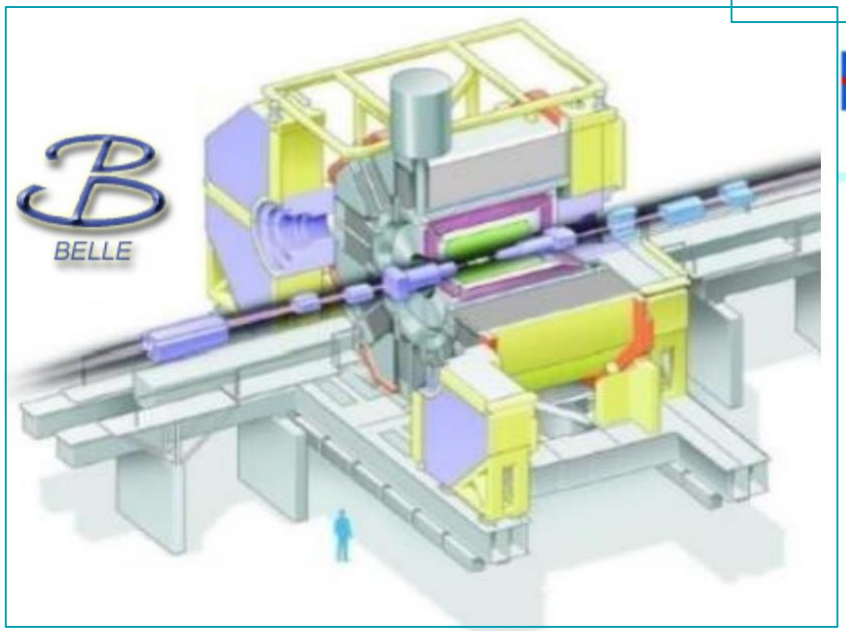
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

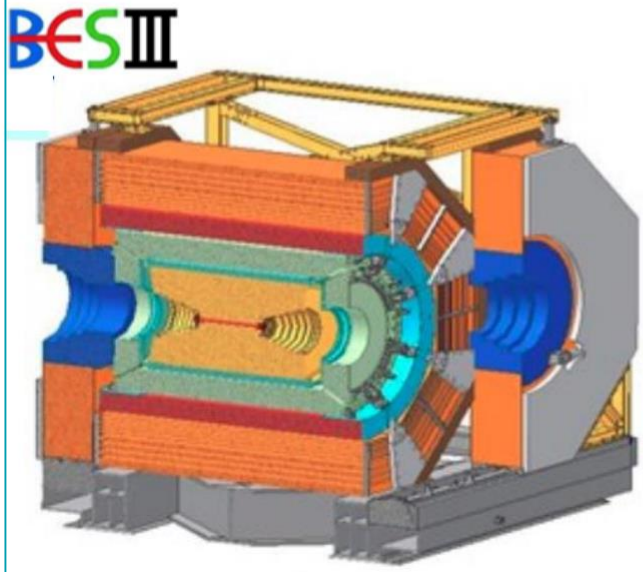
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

Main Contributors of Exotics

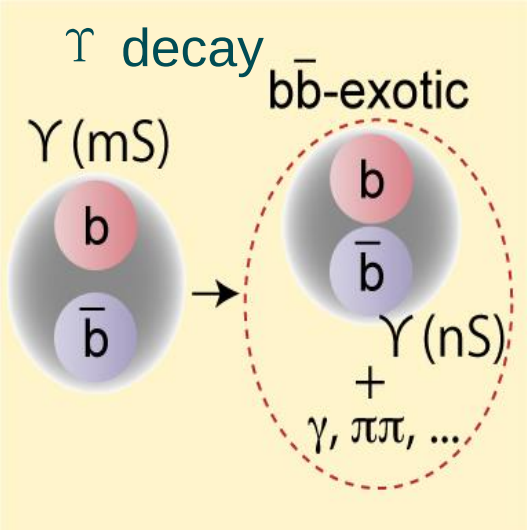


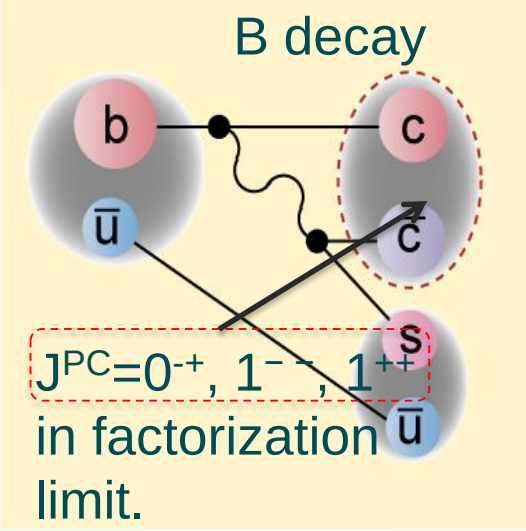


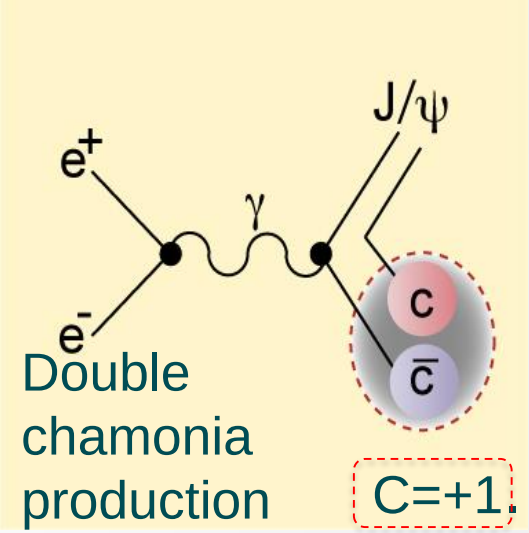


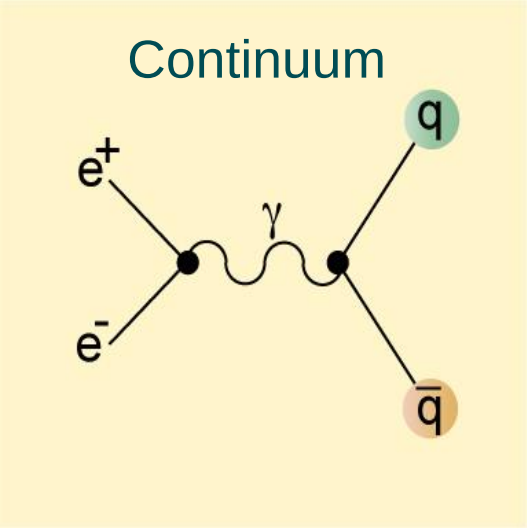


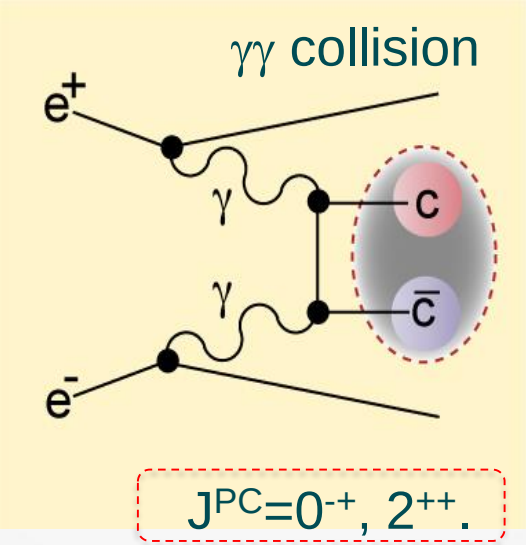
Variety of recorded reactions

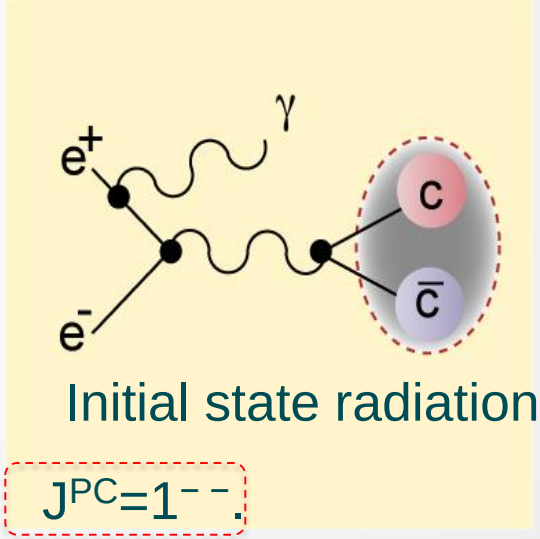




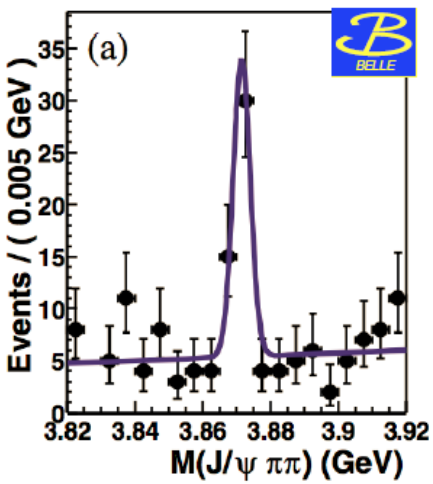


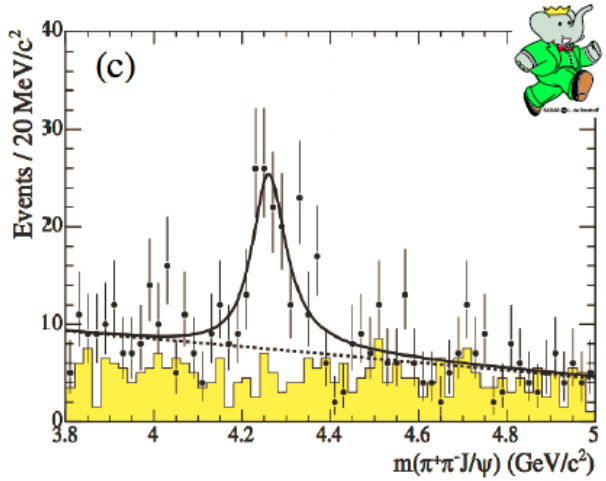


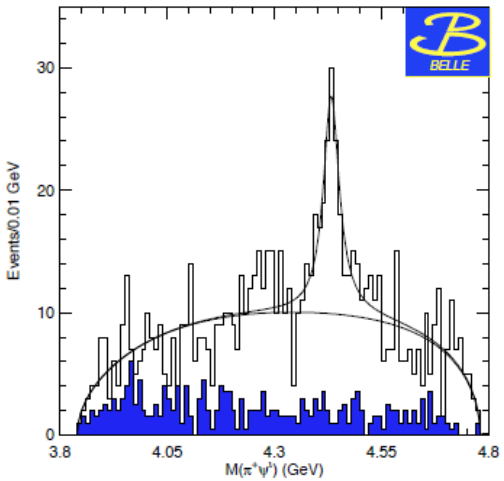




"X Y Z" – *the beginning*







$X(3872)$
PRL 91, 262001 (2003)

$Y(4260)$
PRL 95, 142001 (2005)

$Z_c(4430)^{\pm}$
PRL 100, 142001 (2008)

$B^{\pm} \to K^{\pm}[\pi^+\pi^- J/\psi]$ $\quad$ $e^+e^- \to \gamma[\pi^+\pi^- J/\psi]$ $\quad$ $B \to K[\pi^{\pm}\psi']$

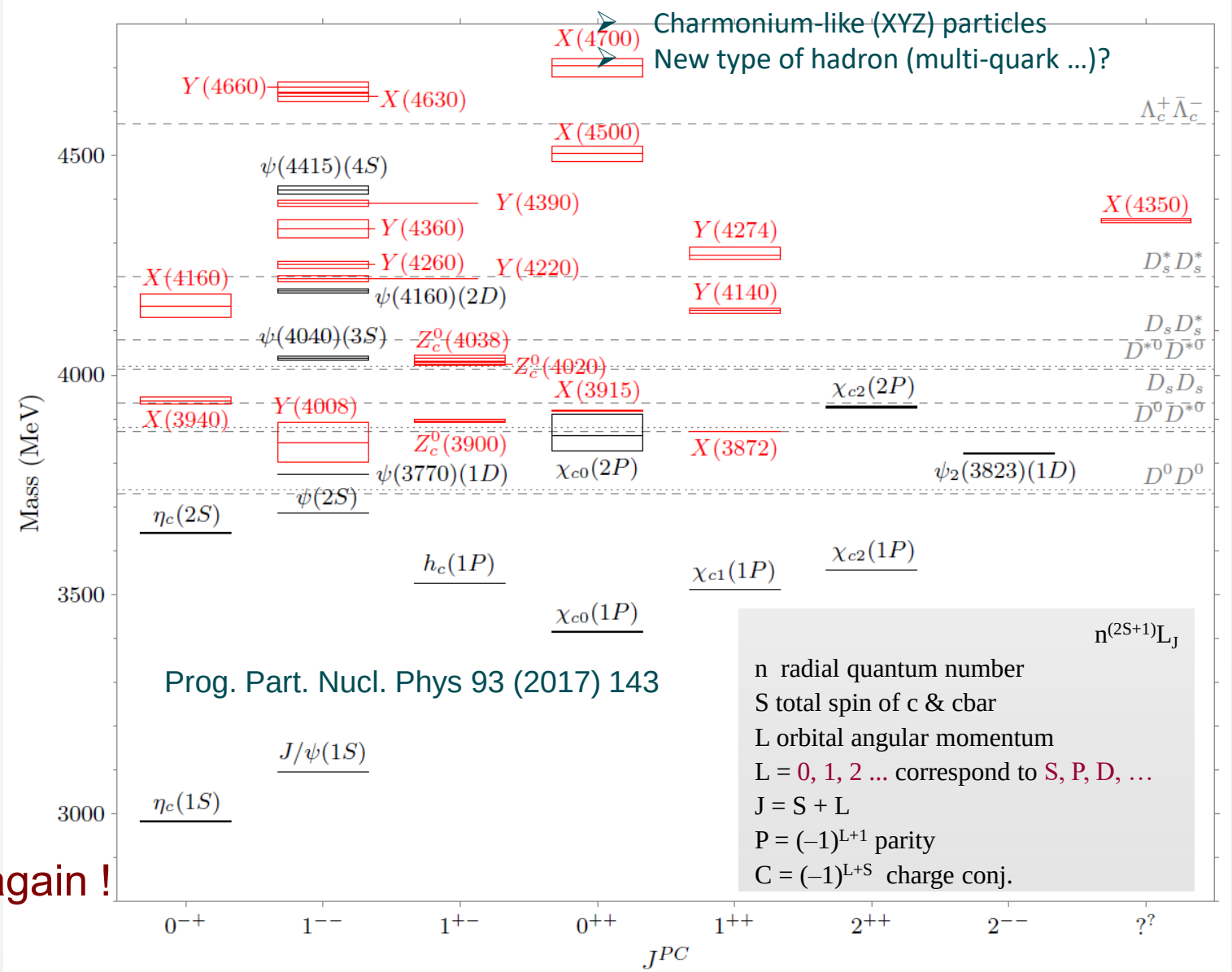
~20 multi-quark states are observed since 2003 with high significance

BES, Belle, BaBar, CDF, D0, LHCb, ATLAS, CMS

Some examples of multi-quark candidates:

X(3782)$\to J/\psi\pi^+\pi^-$, **Z^+(4430)**$\to \Psi'\pi^+$, **X(4140)**$\to J/\psi\phi$, **Z_b^+(10610)**$\to \Upsilon\pi^+$, **Z_b^+(10650)** $\to \Upsilon\pi^+$, **P_c^+(4450)** $\to J/\psi p$, **P_c^+(4380)** $\to J/\psi p$

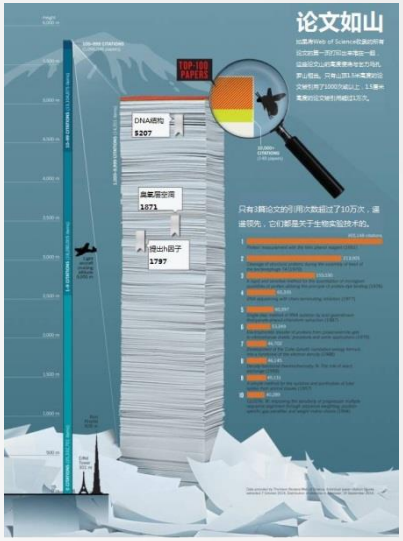
XYZ particles



Particle "Zoo" again !

If I could remember the names of all these particles, I'd be a botanist. - E. Fermi

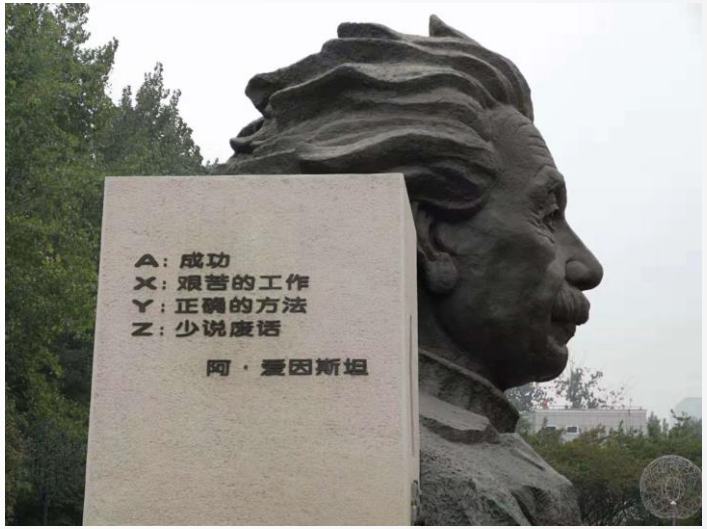
Too many models !



- Theory 1: screened potential
- Theory 2: hybrids with excited gluons
- Theory 3: tetraquark states
- Theory 4: meson molecules
- Theory 5: cusps effect
- Theory 6: final state interaction
- Theory 7: coupled-channel effect
- Theory 8: mixing of normal quarkonium and exotics
- Theory 9: mixture of all these effects
- Theories …

We need clear features to identify exotic hadronic states !

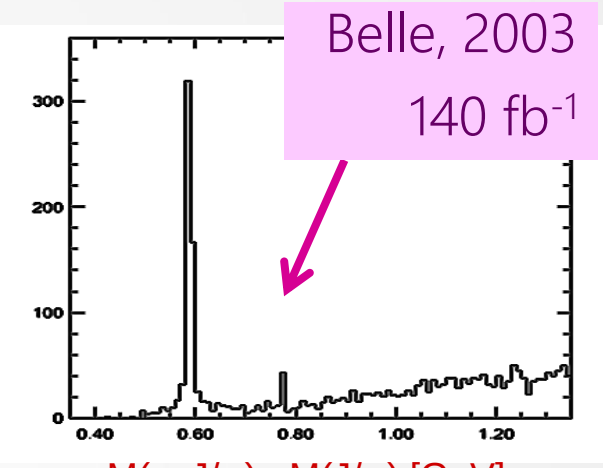
XYZ states



Success=X+Y+Z

What is the X(3872)?

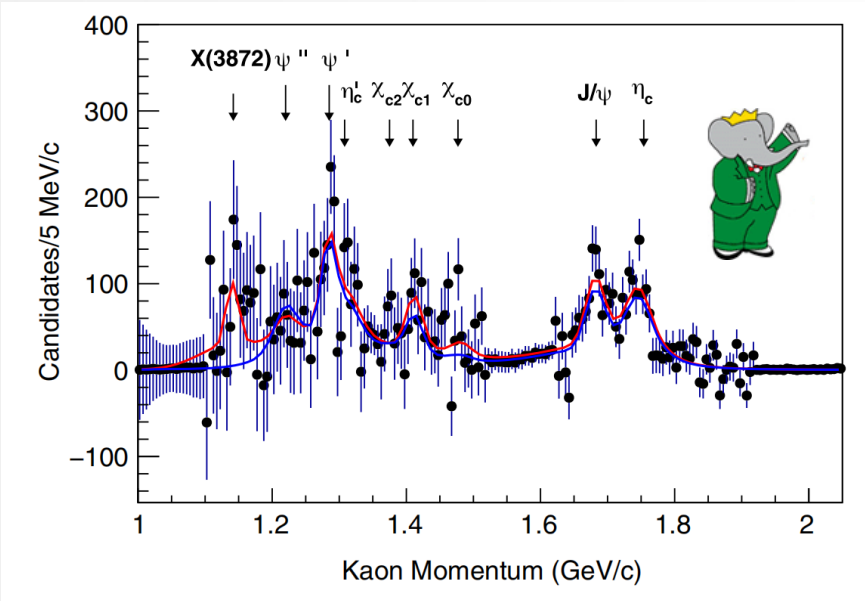
- Mass: Very close to D^0D^{*0} threshold
- Width: Very narrow, $0.96^{+0.19}_{-0.18} \pm 0.21$ MeV
  [LHCb, arXiv:2005.13422]
- $J^{PC}=1^{++}$
- Production
  - in $\bar{p}p/pp$ collision – rate similar to charmonia
  - In B decays – KX similar to $\bar{c}c$, K*X smaller than $\bar{c}c$
  - $Y(4260) \rightarrow \gamma + X(3872)$
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely $\bar{D}^0D^{*0}$ bound state (like deuteron)?
  - Mixture of excited χ_{c1} and $\bar{D}^0D^{*0}$ bound state?

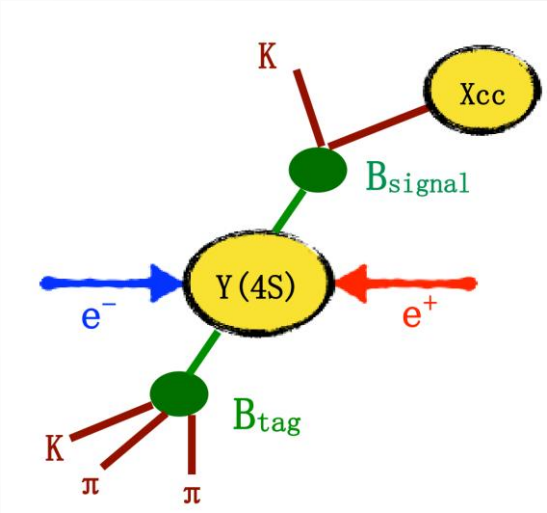


$M(\pi\pi J/\psi) - M(J/\psi)$ [GeV]

$B^{\pm}\to X(3872)K^{\pm}$

- The determination of the $B(B^{\pm}\to X(3872)K^{\pm})$ leads to $B(X(3872)\to J/\psi\pi^{+}\pi^{-})$, bringing useful information regarding the complex nature of the X(3872).
- The original tetraquark model [PRD **71**, 014028 (2005)] predicts it to be about 50%. Various molecular models [PRD **72**, 054022 (2005); PRD **69**, 054008 (2004)] predict it to be $\lesssim$10%.





BaBar, 424 fb^{-1}, PRL 124, 152001 (2020)

- Increase signal efficiency by a factor of 3 by retaining all B tag candidate instead of the best one.
- There is 3σ evidence of the decay $B^{\pm}\to X(3872)K^{\pm}$, detected for the first time using this recoil technique.
- $B(B^{\pm}\to X(3872)K^{\pm}) = (2.1\pm0.6\pm0.3)\times10^{-4}$

Absolute branching fractions of X(3872) decays

- Globally analyzing the measurements by BESIII, Belle, Babar, LHCb
- The absolute branching fractions of X(3872) is free parameters in the fitting

$$\chi^2(x) = \sum_{i=1}^{25} \frac{(x_i - x)^2}{\sigma_i^2},$$

- Statistical uncertainties are dominant for most measurements.
- Possible correlation between the systematics of different measurements in an experiments is neglected.

C.H.Li, C.Z.Yuan, Phys.Rev. D100 (2019) 094003

Index (i)	Parameters	Values	Experiments
	$X(3872) \to \pi^+\pi^- J/\psi$	$(\times 10^{-6})$	
1	$B^+ \to X(3872)K^+$	$8.61 \pm 0.82 \pm 0.52$	Belle [14]
2		$8.4 \pm 1.5 \pm 0.7$	BaBar [15]
3	$B^0 \to X(3872)K^0$	$4.3 \pm 1.2 \pm 0.4$	Belle [14]
4		$3.5 \pm 1.9 \pm 0.4$	BaBar [15]
	$X(3872) \to \gamma J/\psi$	$(\times 10^{-6})$	
5	$B^+ \to X(3872)K^+$	$1.78^{+0.48}_{-0.44} \pm 0.12$	Belle [22]
6		$2.8 \pm 0.8 \pm 0.1$	BaBar [23]
7	$B^0 \to X(3872)K^0$	$1.24^{+0.76}_{-0.61} \pm 0.11$	Belle [22]
8		$2.6 \pm 1.8 \pm 0.2$	BaBar [23]
	$X(3872) \to \gamma\psi(3686)$	$(\times 10^{-6})$	
9	$B^+ \to X(3872)K^+$	$0.83^{+1.98}_{-1.83} \pm 0.44$	Belle [22]
10		$9.5 \pm 2.7 \pm 0.6$	BaBar [23]
11	$B^0 \to X(3872)K^0$	$1.12^{+3.57}_{-2.90} \pm 0.57$	Belle [22]
12		$11.4 \pm 5.5 \pm 1.0$	BaBar [23]
	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(\times 10^{-4})$	
13	$B^+ \to X(3872)K^+$	$0.77 \pm 0.16 \pm 0.10$	Belle [16]
14		$1.67 \pm 0.36 \pm 0.47$	BaBar [17]
15	$B^0 \to X(3872)K^0$	$0.97 \pm 0.46 \pm 0.13$	Belle [16]
16		$2.22 \pm 1.05 \pm 0.42$	BaBar [17]
	$X(3872) \to \omega J/\psi$	$(\times 10^{-6})$	
17	$B^+ \to X(3872)K^+$	$6 \pm 2 \pm 1$	BaBar [18]
18	$B^0 \to X(3872)K^0$	$6 \pm 3 \pm 1$	BaBar [18]
	Ratios		
19	$\frac{\mathcal{B}(X(3872)\to\gamma J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.79 ± 0.28	BESIII [19]
20	$\frac{\mathcal{B}(X(3872)\to D^{*0}\bar{D}^0+c.c.)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	14.81 ± 3.80	BESIII [19]
21	$\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$1.6^{+0.4}_{-0.3} \pm 0.2$	BESIII [20]
22	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$0.88^{+0.33}_{-0.27} \pm 0.10$	BESIII [21]
23	$\frac{\mathcal{B}(X(3872)\to\gamma\psi(3686))}{\mathcal{B}(X(3872)\to\gamma J/\psi)}$	$2.46 \pm 0.64 \pm 0.29$	LHCb [24]
	$B^+ \to X(3872)K^+$	$(\times 10^{-4})$	
24		$2.1 \pm 0.6 \pm 0.3$	BaBar [27]
25		$1.2 \pm 1.1 \pm 0.1$	Belle [26]

Absolute branching fractions of X(3872) decays

- Fitting results

C.H.Li, C.Z.Yuan, Phys.Rev. D100 (2019) 094003

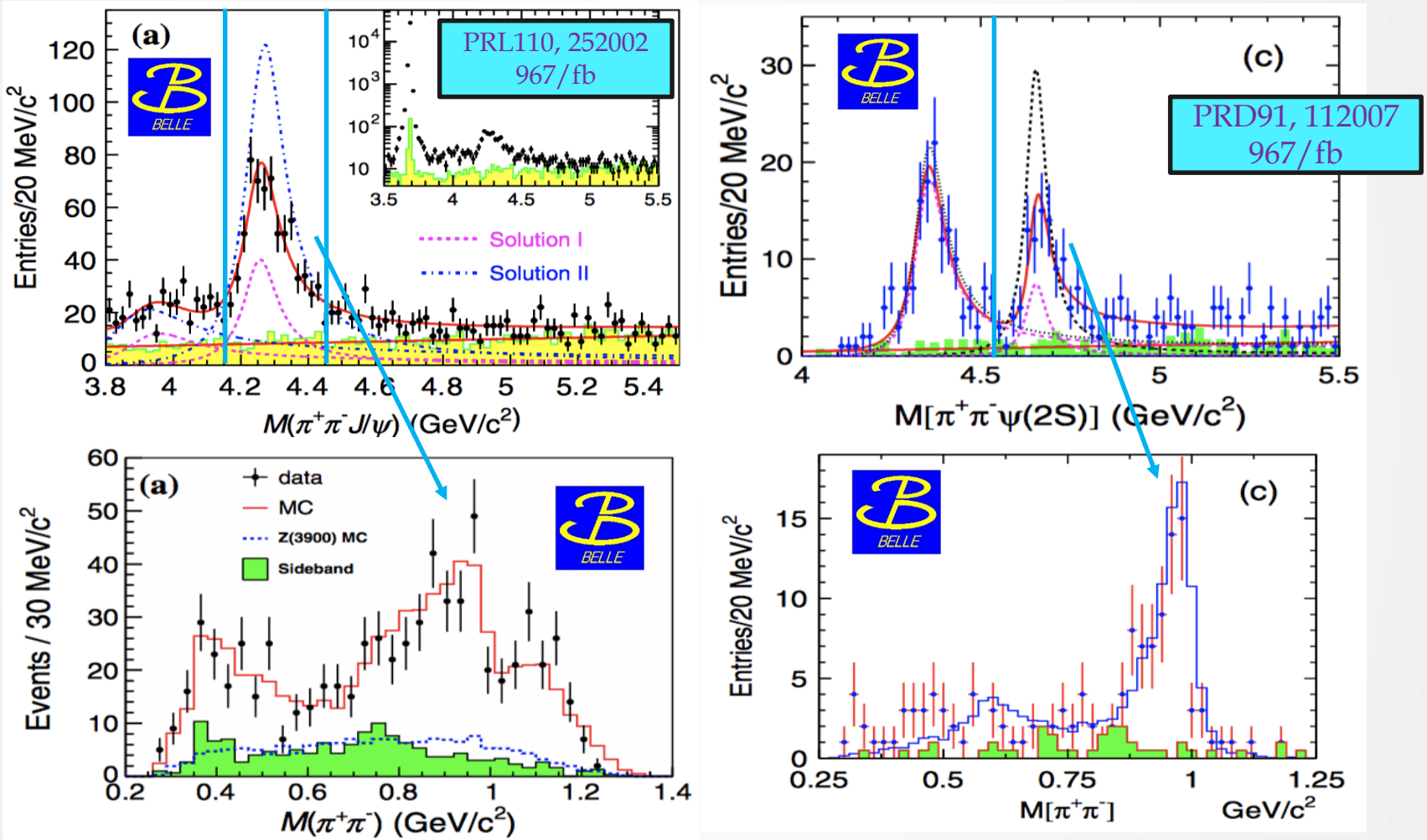
Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \to$ unknown	$(31.9^{+18.1}_{-31.5})\%$

- $X(3872) \to \pi^+\pi^- J/\psi \sim (4.1^{+1.9}_{-1.1})\%$
- $X(3872) \to D^0 D^{*0} \sim (52.4^{+25.3}_{-14.3})\%$
- Unknown decay $\sim (31.9^{+18.1}_{-31.5})\%$

- Statistical uncertainties are dominant.
- At Belle II, we need improve the measurements related with X(3872) decays

Y(4626): $e^+e^- \to D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^- + c.c.$

Motivation: Y(4260) and Y(4660) with $c\bar{c}s\bar{s}$ component



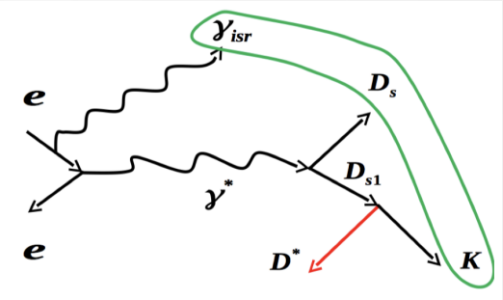
- $Y(4260) \to f_0(980)(\to \pi^+\pi^-)J/\psi$, $Y(4660) \to f_0(980)(\to \pi^+\pi^-)\psi(2S)$
  $f_0(980)$ has a $s\bar{s}$ component, and ψ has a $c\bar{c}$ component.
- **It is natural to search for such Y states with a quark component of $(c\bar{s})(\bar{c}s)$, e.g., $D_s D_{s1}(2536)$ and $D_s D_{s2}^*(2573)$.**

Analysis method

Taking $e^+e^- \to D_s^+ D_{s1}(2536)^-$ as an example

$$e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^- (\to \bar{D}^{*0} K^- / D^{*-} K_S^0)$$

We require full reconstruction of the γ_{ISR}, D_s^+ , and K^-/K_S^0.



- $D_s^+ \to \phi\pi^+, \bar{K}^{*0}K^+, K_S^0K^+, K^+K^-\pi^+\pi^0, K_S^0\pi^0K^+, K^{*+}K_S^0, \eta\pi^+$, and $\eta'\pi^+$
- For the signals, the spectrum of the mass recoiling against the $D_s^+K^-\gamma_{ISR}$ system should be accumulated at the $\bar{D}^{*0}/D^{*-}$ nominal mass.

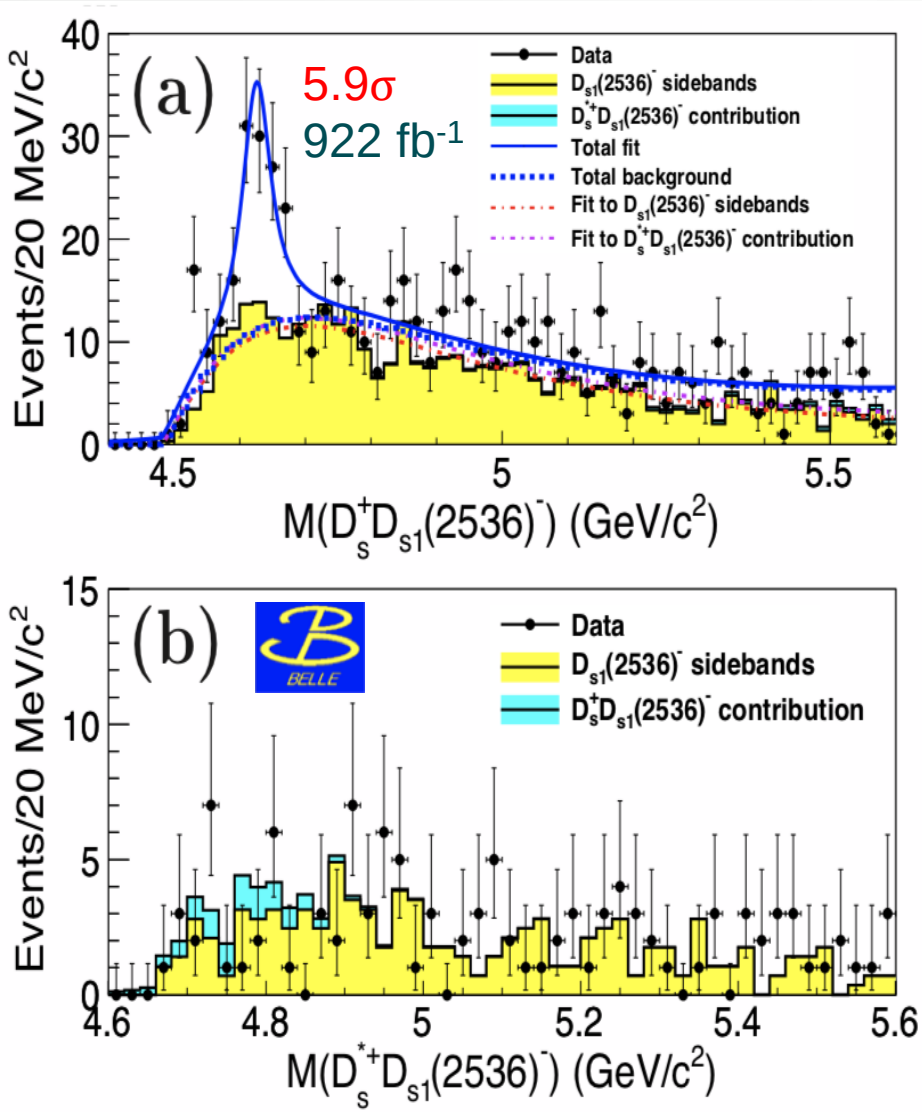
$$M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0) = \sqrt{(E^*_{c.m.} - E^*_{\gamma_{ISR}D_s^+K^-/K_S^0})^2 - \left(p^*_{\gamma_{ISR}D_s^+K^-/K_S^0}\right)^2}$$

- To improve the $M(D_s^+D_{s1}(2536)^-)$ resolution, $M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0)$ is onstrained to be the nominal mass of the $\bar{D}^{*0}/D^{*-}$.

$M(D_s^+ D_{s1}(2536)^-)$

Belle, PRD100, 111103(R) (2019)

After applying the $\bar{D}^{*0}/D^{*-}$ mass constraint



An unbinned simultaneous likelihood fit:

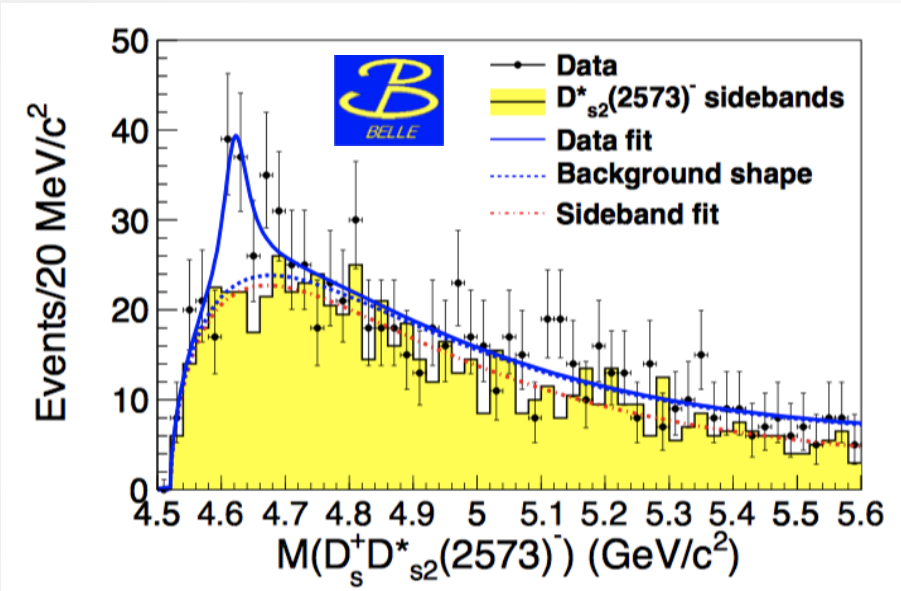
- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s1}(2536)^-$ mass sidebands: a threshold function
- $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background contribution: a threshold function
- A non-resonant contribution: a two-body phase space form

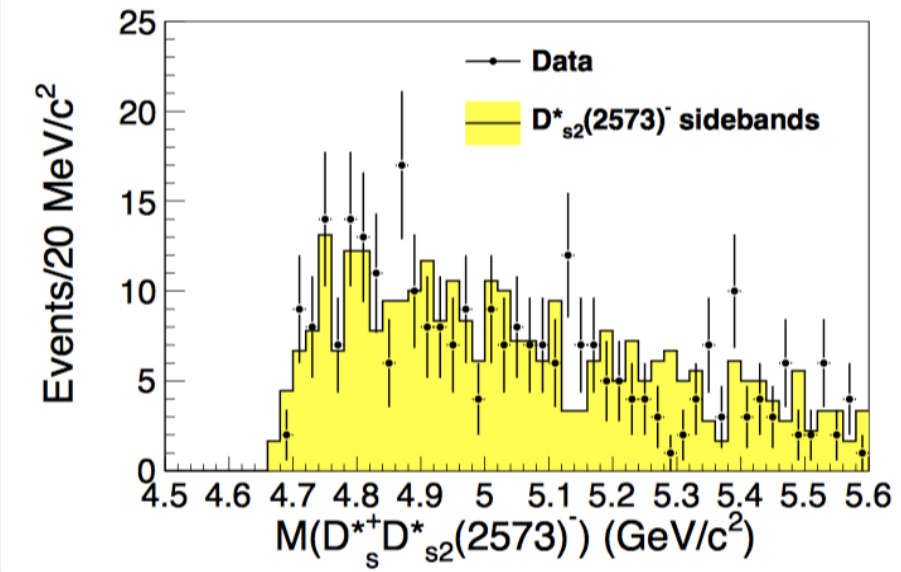
$M=(4625.9^{+6.2}_{-6.0}(\text{stat.}) \pm 0.4(\text{syst.}))\ \text{MeV}/c^2$
$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat.}) \pm 4.0(\text{syst.}))\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-) = (14.3^{+2.8}_{-2.6}(\text{stat.}) \pm 1.5(\text{syst.}))\ \text{eV}$

One possible background is from $e^+e^- \to D_s^{*+}(\to D_s^+\gamma)D_{s1}(2536)^-$.
No obvious structure is observed in the $e^+e^- \to D_s^{*+}(\to D_s^+\gamma)D_{s1}(2536)^-$.

$e^+e^- \to D_s^+ D_{s2}^*(2573)^-(\to \bar{D}^0 K^-) + c.c.$ via ISR at Belle

To improve the $M_{rec}(\gamma_{ISR})$ resolution, $M_{rec}(\gamma_{ISR} D_s^+ K^-)$ is constrained to the nominal mass of the $\bar{D}^0$.





Belle, PRD101, 091101(R) (2020)

An unbinned simultaneous likelihood fit:

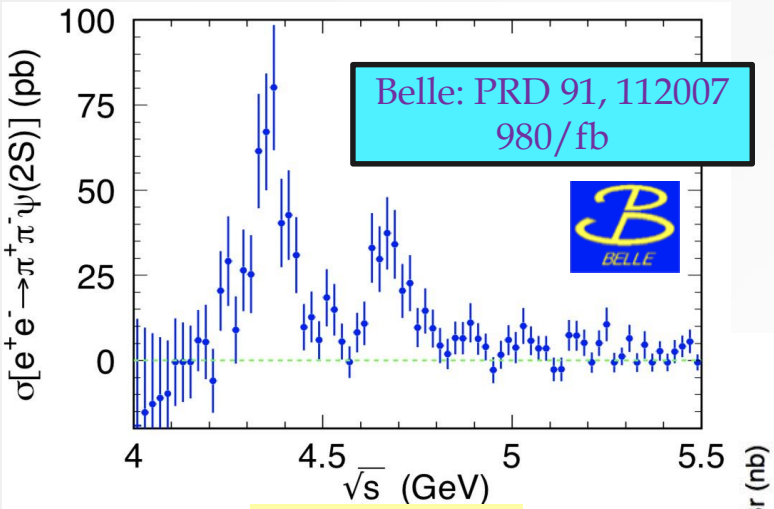
- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s2}^*(2573)^-$ mass sidebands: a threshold function
- A non-resonant contribution: a two-body phase space form

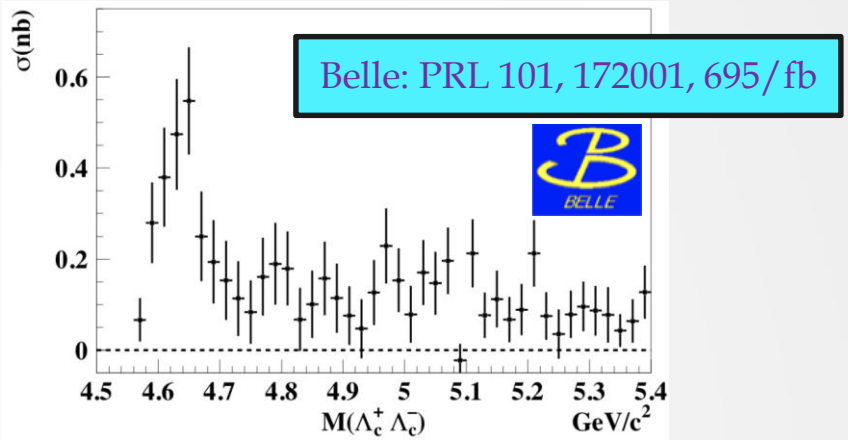
$M=(4619.8^{+8.9}_{-8.0}(\text{stat.}) \pm 2.3(\text{syst.}))\ \text{MeV}/c^2$
$\Gamma = (47.0^{+31.3}_{-14.8}(\text{stat.}) \pm 4.6(\text{syst.}))\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s2}^*(2573)^-) \times \mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-) = (14.7^{+5.9}_{-4.5}(\text{stat.}) \pm 3.6(\text{syst.}))\ \text{eV}$

Interpretations of Y(4626)

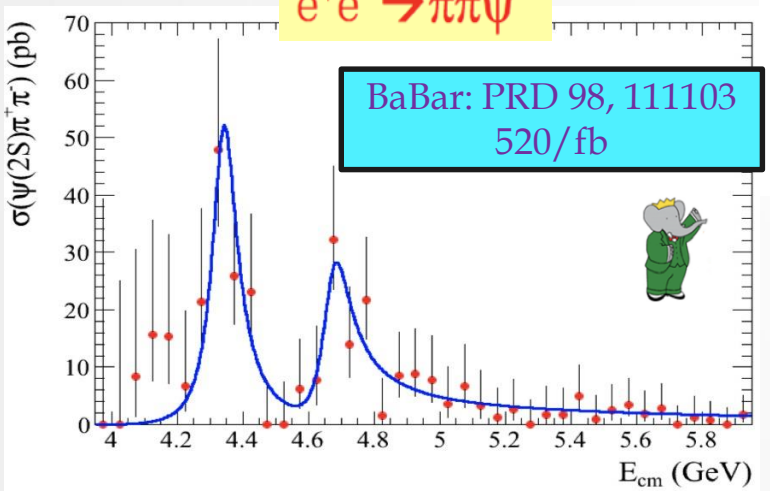
- A tetraquark state in a chiral constituent quark model with a scaling method [Y.Tan and J. L. Ping, PRD101, 054010 (2020)].
- A P-wave tetraquark state $[cs][\bar{c}\bar{s}]$ with 1^{--} in the multiquark color flux-tube model [C. R. Deng, H. Cheng and J.L. Ping, PRD 101, 054039 (2020)].
- A hidden-strange molecular state from $\Lambda_c^+\Lambda_c^-$ interaction [J. T. Zhu, Y. Liu, D. Y. Chen, L. Y. Jiang, and J. He, arXiv:1911.03706 (2020)].
- A molecular state from interaction $D_s^*\bar{D}_{s1}(2536)$ - $D_s\bar{D}_{s1}(2536)$ [J. He, J. T. Zhu, and D. Y. Chen, EPJC 80, 246 (2020)].
- A tetraquark and etc instead of $D_s^*\bar{D}_{s1}(2536)$ molecular within the Bethe-Salpeter framework [H.W.Ke, X.H.Liu, and X.Q.Li, arXiv:2004.03167 (2020)].
- A higher charmonium [J.Z.Wang, R.Q.Qian, X. Liu, and T. Matsuki, PRD 101, 034001 (2020)].
- A hidden-charm exotic mesons in the diquark model [Z. G. He, B. A. Kniehl, and X.P.Wang, PRD 101, 074032 (2020); J.F.Giron, R.F.Lebed arxiv:2005.07100].

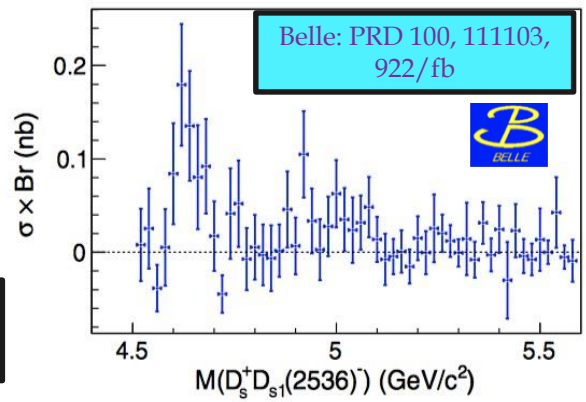
Y(4630) = Y(4660)?

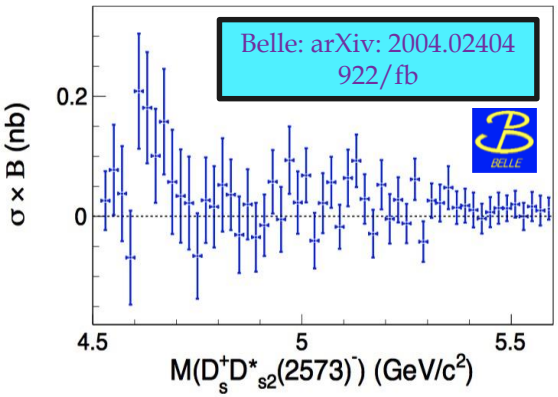




$e^+e^- \rightarrow \pi\pi\psi'$







Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8\ +5}_{-7\ -8}$	$92^{+40\ +10}_{-24\ -21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669\pm21\pm3$	$104\pm48\pm10$
Belle, $D_s^+D_{s1}(2536)^-$	$4626^{+7}_{-7}\pm1$	$49.8^{+14}_{-12}\pm4$
Belle, $D_s^+D_{s2}^*(2573)^-$	$4620^{+9}_{-8}\pm3$	$47.0^{+32}_{-15}\pm5$

- These states may be the same
- Need improved precision

$\Upsilon(5S)$ and $\Upsilon(6S)$ in $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

- tag $\Upsilon(nS) \to \mu^+\mu^-$ and select $\pi^+\pi^-$

$\Upsilon(5S)$:
Mass = $(10891.9 \pm 3.2 \pm^{0.6}_{1.5})$ MeV
Width = $(53.7 \pm^{7.1}_{5.6} \pm^{0.9}_{5.4})$ MeV

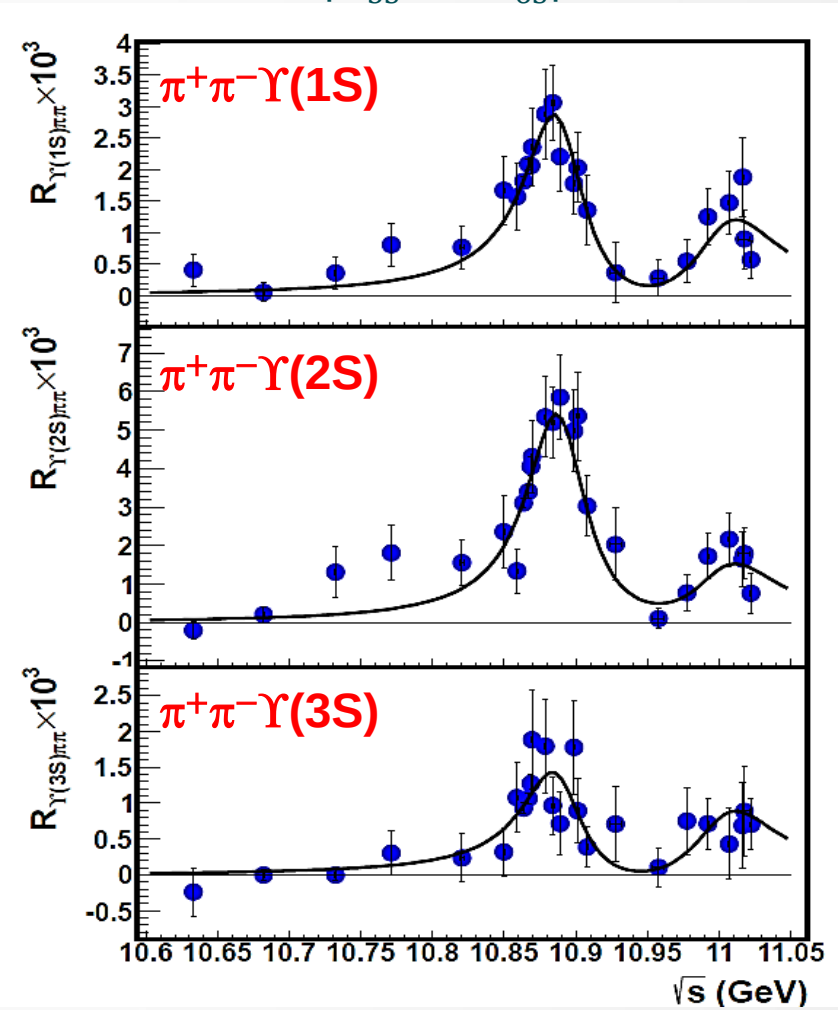
$\Upsilon(6S)$:
Mass = $(10987.5 \pm^{6.4}_{2.5} \pm^{2.2}_{2.1})$ MeV
Width = $(61 \pm^{9}_{19} \pm^{2}_{20})$ MeV

$\phi = -1.0 \pm 0.4 \pm^{1.0}_{0.1}$ rad

- Results agree with previous measurements
- State at 10.75 GeV?

Belle, PRD 93, 011101(R) (2016)

fit to $|A_{5S} + e^{i\phi} A_{6S}|^2$



Update cross sections of $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

- Same data samples, but with improved analysis

Previous analysis

- tag $\Upsilon(nS) \to \mu^+\mu^-$ and select $\pi^+\pi^-$
- Count numbers of events in signal and sideband regions
- Reported visible cross section

New analysis

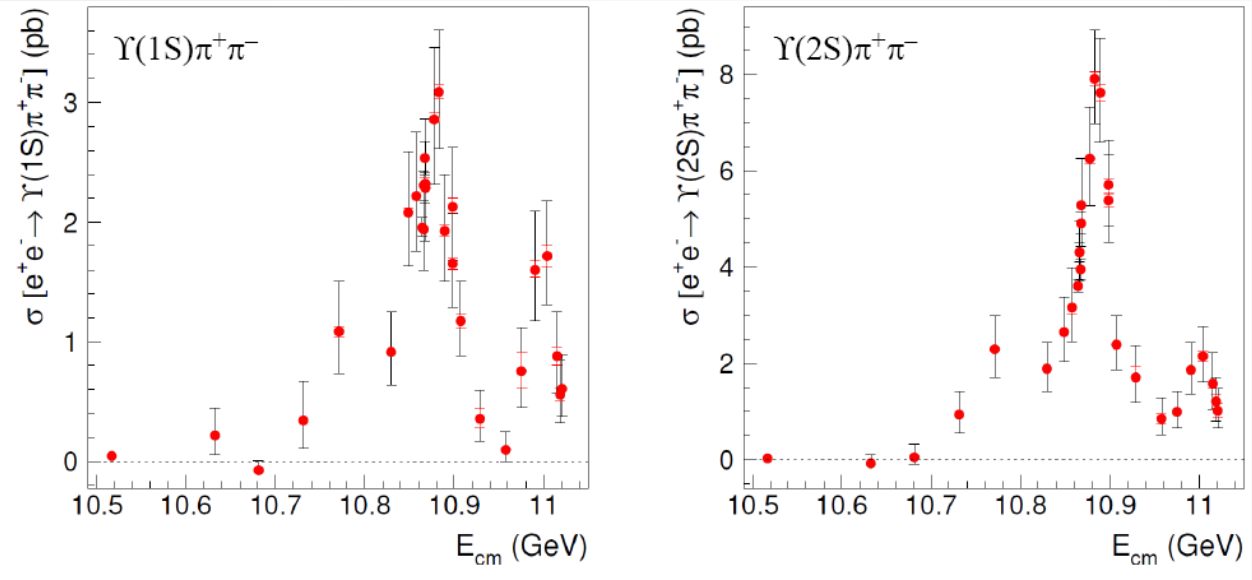
- tag $\Upsilon(nS) \to \mu^+\mu^-/e^+e^-$ and select $\pi^+\pi^-$
- Fit with well constrained signal and background shapes
- Initial state radiation correction is considered, and ISR of $\Upsilon(5S)$ peak data supply useful information on the cross section line shapes

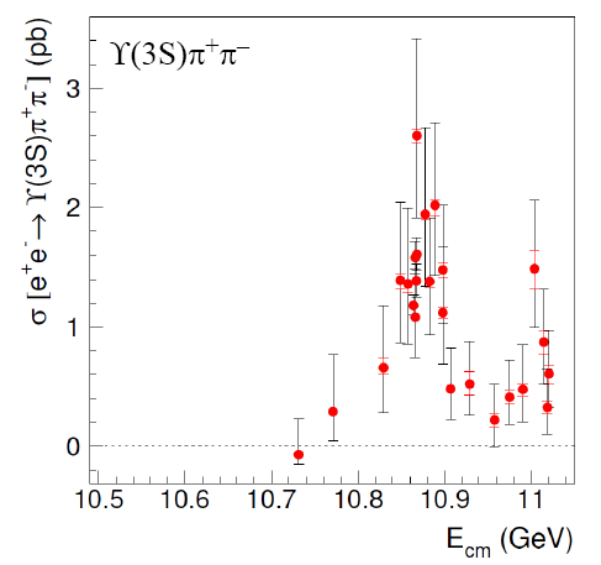
Precision improves by 30% + observation of Y(10750)!

Belle, JHEP 1910, 220 (2019)

Update cross sections of $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

Belle, JHEP 1910, 220 (2019)





Black error bars: statistical

Red error bars: uncorrelated systematic errors

Structure at 10.75 GeV is more significant

Fits to energy dependent cross sections

$$|\mathrm{BW}^{(n)}_{\Upsilon(5S)} + e^{i\alpha_n}\,\mathrm{BW}^{(n)}_{\Upsilon(6S)} + e^{i\beta_n}\,\mathrm{BW}^{(n)}_{\mathrm{new}} + e^{i\gamma_n}\,\mathrm{BW}^{(n)}_{\Upsilon((n+1)S)}|^2 \otimes \mathrm{Gaussian}$$

$$F_{BW}(s, M, \Gamma, \Gamma^0_{ee} \times \mathcal{B}_f) = \frac{\sqrt{12\pi\,\Gamma\,\Gamma^0_{ee} \times \mathcal{B}_f}}{s - M^2 + iM\Gamma}\sqrt{\frac{\Gamma_f(s)}{\Gamma_f(M^2)}}$$

Simultaneous fit to three channels with some common parameters.

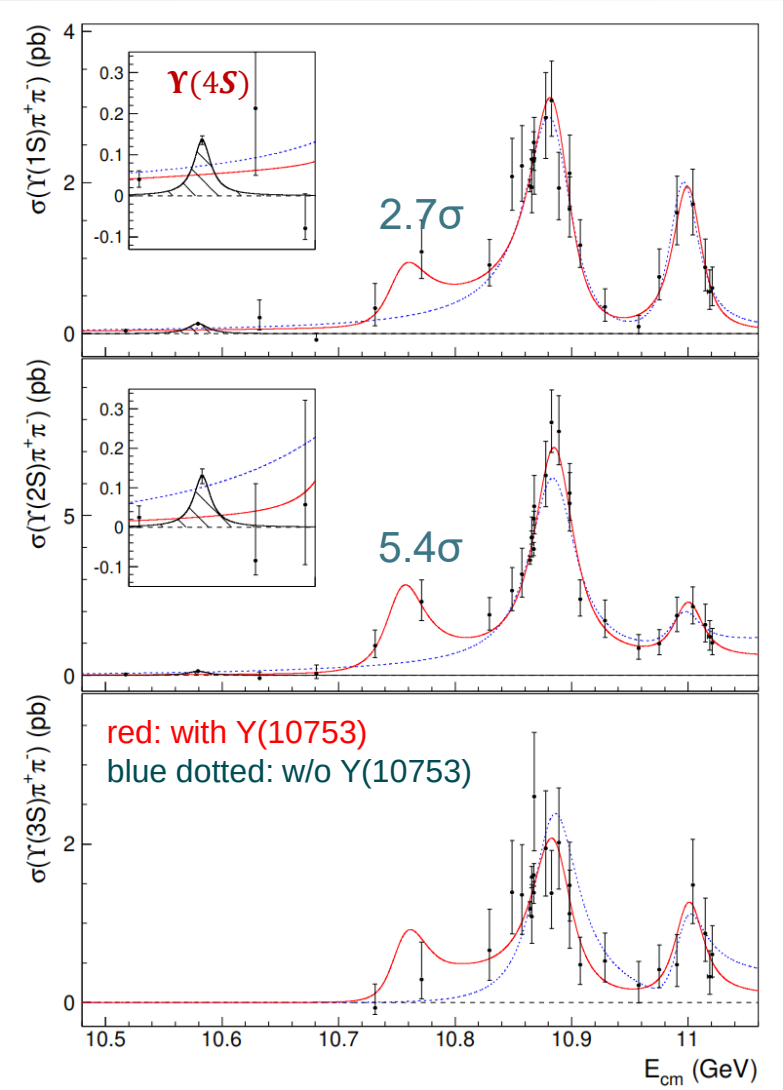
Free parameters: Mass M, width Γ, product of partial width and branching fraction $\Gamma_{ee}B(\pi\pi\Upsilon)$, relative phase ϕ.

Fit results to $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ cross sections

Scan data: 22 points, each point 1fb^{-1}

$\Upsilon(10860)$ on-resonance data: 121 fb^{-1}, between 10.864 and 10.868 GeV

Continuum data at 10.52 GeV, 60 fb^{-1}



	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

$\Gamma_{ee} \times \mathcal{B}$ (in eV)

	$\Upsilon(10860)$	$\Upsilon(11020)$	new
$\Upsilon(1S)\pi^+\pi^-$	$0.75 - 1.43$	$0.38 - 0.54$	$0.12 - 0.47$
$\Upsilon(2S)\pi^+\pi^-$	$1.35 - 3.80$	$0.13 - 1.16$	$0.53 - 1.22$
$\Upsilon(3S)\pi^+\pi^-$	$0.43 - 1.03$	$0.17 - 0.49$	$0.21 - 0.26$

a range due to multi-solutions

global significance: 6.7σ

Interpretation of the Y(10750)

- D-wave bottomonium
  - B. Chen, A.L. Zhang, J. He, arXiv:1910.06065, Bottomonium spectrum in the relativistic flux tube model (3D)
  - Q. Li, M.S. Liu, Q.F. Lü, L.C. Gui, X.H. Zhong, arXiv:1905.10344, Canonical interpretation of Y(10750) and Y(10860) in the Y family (4D)
- $\bar{B}^{(*)}B^{(*)}$ dynamically generated pole
  - P. Bicudo, M. Cardoso, N. Cardoso, M. Wagner, arXiv:1910.04827, Bottomonium resonances with I=0 from lattice QCD correlation functions with static and light quarks
- Hybrid
  - J. T. Castellà, arXiv:1908.05179, Spin Structure of heavy-quark hybrids
- Tetraquark state
  - A. Ali, L. Maiani, A. Y. Parkhomenko, W. Wang, arXiv:1910.07671, Interpretation of Yb (10753) as a tetraquark and its production mechanism
  - Z.G. Wang, arXiv:1905.06610, Vector hidden-bottom tetraquark candidate: Y(10750)

Summary

- Lots of progress in the study of exotic states at B-factories
- More experimental and theoretical efforts are needed to understand heavy flavor spectroscopy
- BESIII, Belle II, LHCb, … will take more data and continue the study

Thanks a lot!

復旦大學
FUDAN UNIVERSITY

Thanks for your attention

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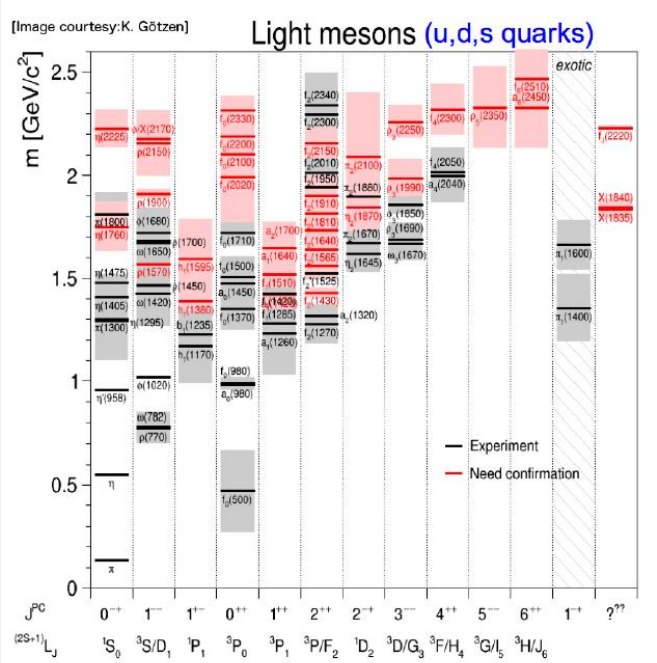
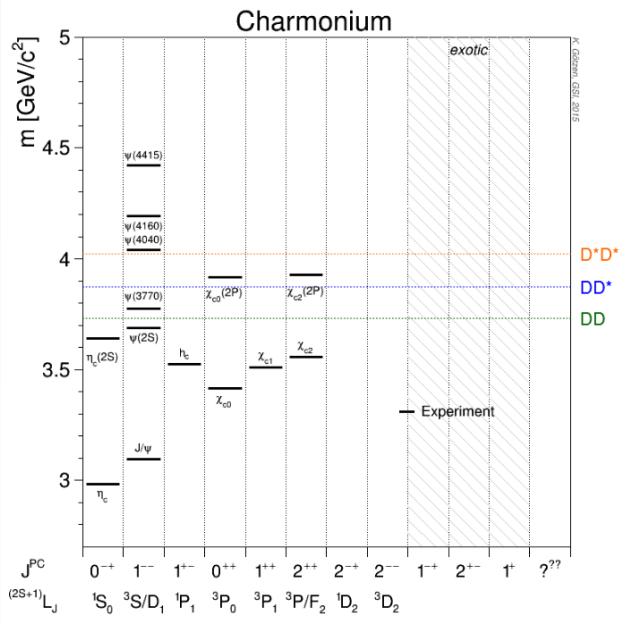
Hadron spectra: normal





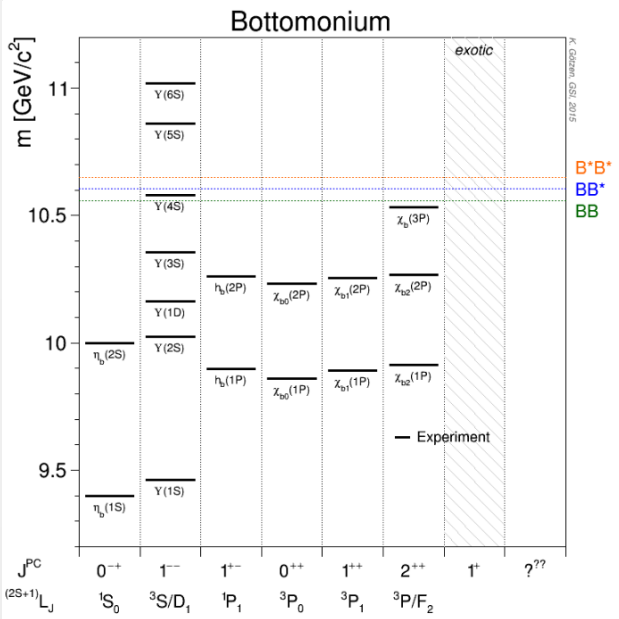
J^{PC} Quantum Numbers

- Parity = $(-1)^{L+1}$
- Charge Conjugation = $(-1)^{L+S}$
- Spin = $J = |L-S|, L, L+S$
- Vacuum = ${}^3P_0 \hat{=} 0^{++}$

Quark Degrees of Freedom **ONLY**

	0^{++}	0^{-+}	
1^{--}	1^{++}		1^{+-}
2^{--}	2^{++}	2^{-+}	
3^{--}	3^{++}		3^{+-}
4^{--}	4^{++}	4^{-+}	
5^{--}	5^{++}		5^{+-}

Experimental observation!!

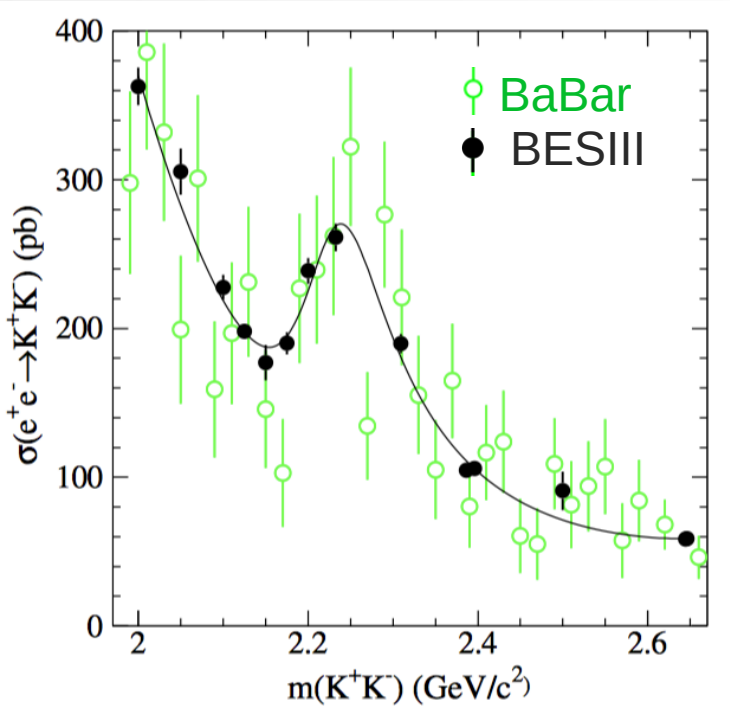


- Light hadron spectroscopy is complicated
- Many broad and overlapping states discovered, some not yet – need complicated PWA technology
- Below open-charm/bottom threshold: good agreement between experiments and theoretical predictions
- Above open-charm/open-bottom threshold: some expected states not discovered yet

Resonances in e^+e^- annihilation near 2.2 GeV

- Recently, BESIII reported the existence of a resonance near 2.2 GeV in $e^+e^- \to K^+K^-$ with a large width of (140±12±21) MeV **[PRD 99, 032001 (2019)]**.
- The $e^+e^- \to K_sK_L$ cross section from 1.98 to 2.54 GeV is measured via ISR by BABAR with a data sample of 469 fb^{-1}.
- The $e^+e^- \to K_sK_L$ results are used together with previous BABAR results for the $e^+e^- \to K^+K^-$ [PRD 88, 032013 (2020)], $e^+e^- \to \pi^+\pi^-$, $e^+e^- \to \pi^+\pi^-\eta$, and $e^+e^- \to \pi^+\pi^-\omega$ cross sections to investigate the nature of the above resonance structure reported by BESIII.

Fit to the BESIII and BABAR $e^+e^- \to K^+K^-$ cross sections:

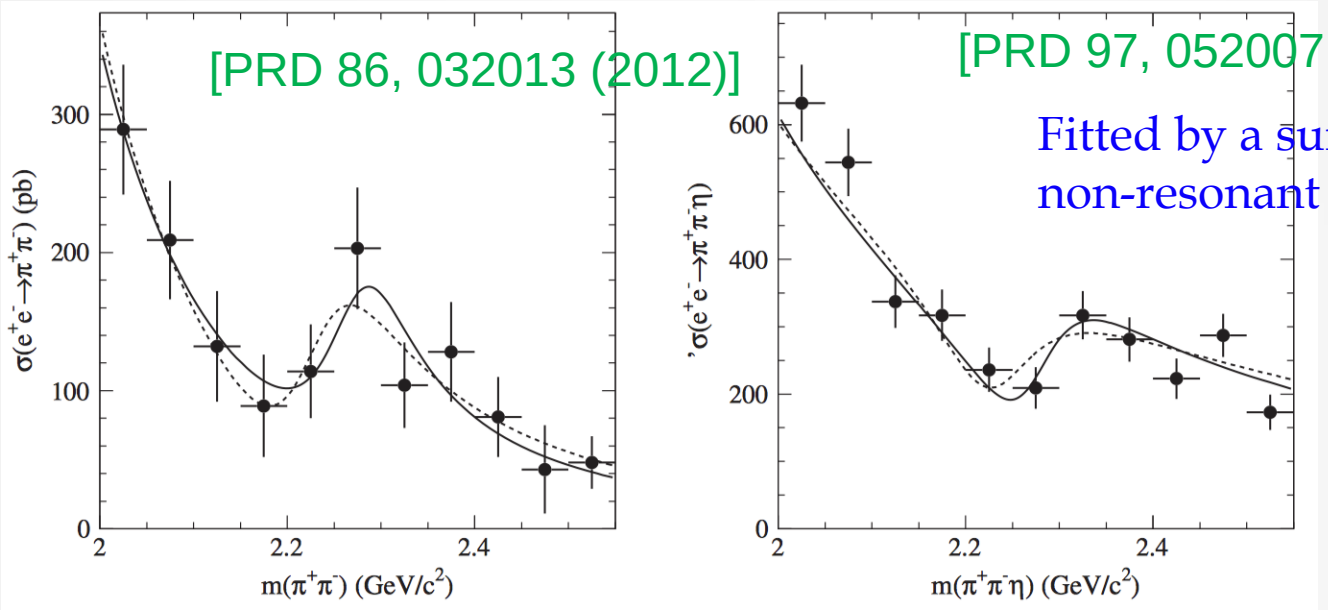


The $e^+e^- \to K^+K^-$ cross section is fitted by a sum of resonant and non-resonant contribution.

M_R	$2227 \pm 9 \pm 9$ MeV/c^2
Γ_R	$127 \pm 14 \pm 4$ MeV
σ_R	$39 \pm 6 \pm 4$ pb
φ	$143 \pm 8 \pm 9$ deg

BaBar, PRD 101, 012011 (2020)

Simultaneous fit to the $e^+e^- \to K^+K^-, e^+e^- \to \pi^+\pi^-, e^+e^- \to \pi^+\pi^-\eta$ cross sections



The solid curves: the simultaneous fit to the $e^+e^- \to \pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\eta$ cross sections
The dashed curves: the simultaneous fit to the $e^+e^- \to K^+K^-, e^+e^- \to \pi^+\pi^-, e^+e^- \to \pi^+\pi^-\eta$ cross sections. **BaBar, PRD 101, 012011 (2020)**

	$\pi^+\pi^-$ and $\pi^+\pi^-\eta$	K^+K^-, $\pi^+\pi^-$, and $\pi^+\pi^-\eta$
M_R (MeV/c^2)	$2270 \pm 20 \pm 9$	$2232 \pm 8 \pm 9$
Γ_R (MeV)	$116^{+90}_{-60} \pm 50$	$133 \pm 14 \pm 4$
$\sigma(e^+e^- \to R \to K^+K^-)$ (pb)	$\cdots$	$41 \pm 6 \pm 4$
$\sigma(e^+e^- \to R \to \pi^+\pi^-)$ (pb)	$34^{+26}_{-19} \pm 4$	$36^{+27}_{-20} \pm 4$
$\sigma(e^+e^- \to R \to \pi^+\pi^-\eta)$ (pb)	$33^{+34}_{-13} \pm 4$	$27^{+14}_{-11} \pm 4$
$\varphi(e^+e^- \to K^+K^-)$ (deg)	$\cdots$	$140 \pm 8 \pm 9$
$\varphi(e^+e^- \to \pi^+\pi^-)$ (deg)	$147 \pm 30 \pm 10$	$188 \pm 19 \pm 9$
$\varphi(e^+e^- \to \pi^+\pi^-\eta)$ (deg)	$217 \pm 24 \pm 9$	$251 \pm 15 \pm 9$
χ^2/ν	13.96/12	17.2/14

The existence of the isovector resonance $\rho(2230)$ with a 4.6σ significnace seen in $e^+e^- \to \pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\eta$ cross sections. All three cross sections are well described by a model with $\rho(2230)$ mass and width.