Hadron Spectroscopy

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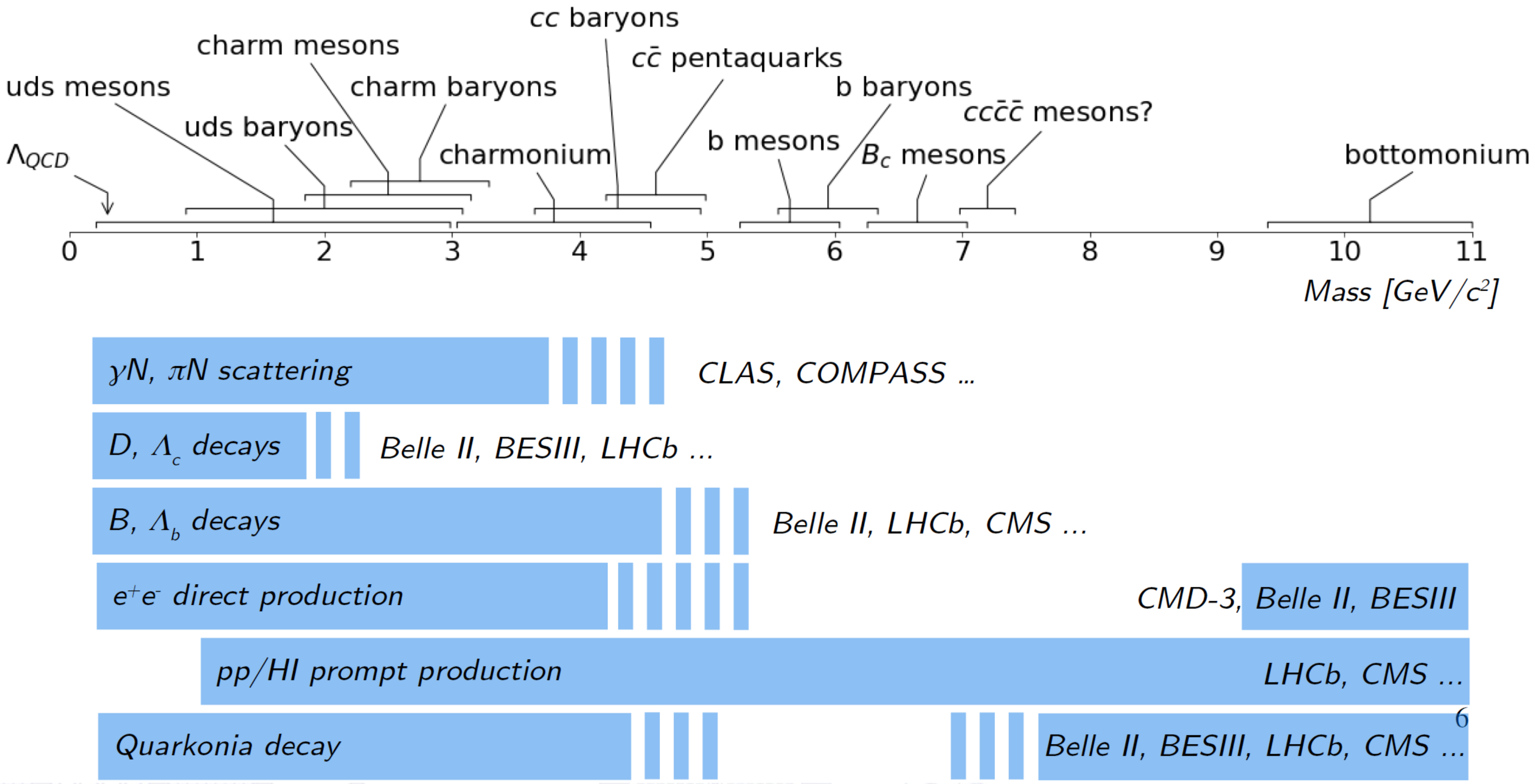
There are four interactions !

- It all started with the big bang! ➔ Gravity governed by General Relativity (it was good!)
- Let there be light: and there was light! ➔ Electromagnetic and weak interactions governed by Electroweak theory (it was good!)
- Let there be quarks and gluons! ➔ strong interaction governed by QCD (it was good at short distance only!)

- Yes, let's study the strong interaction at long distance — non-perturbative part of QCD!

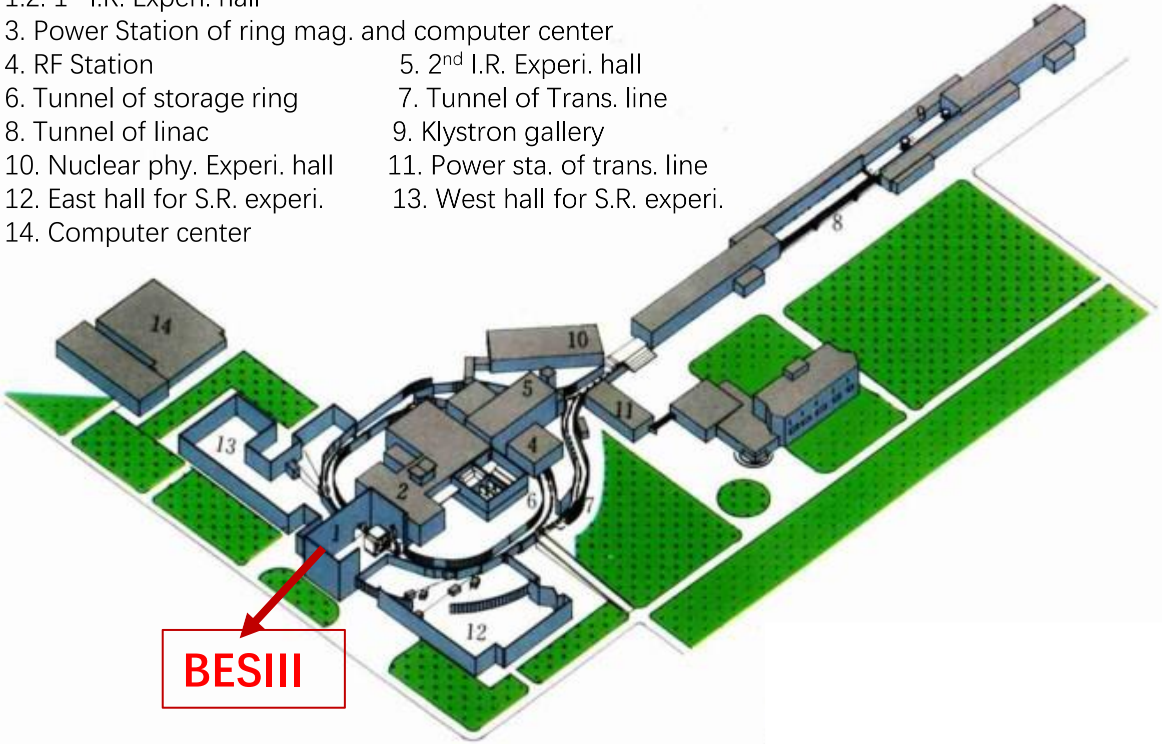
The study of hadron spectrum



Due to the limited time, in these two days I just focus on the charmonium, bottomonium and XYZ states.

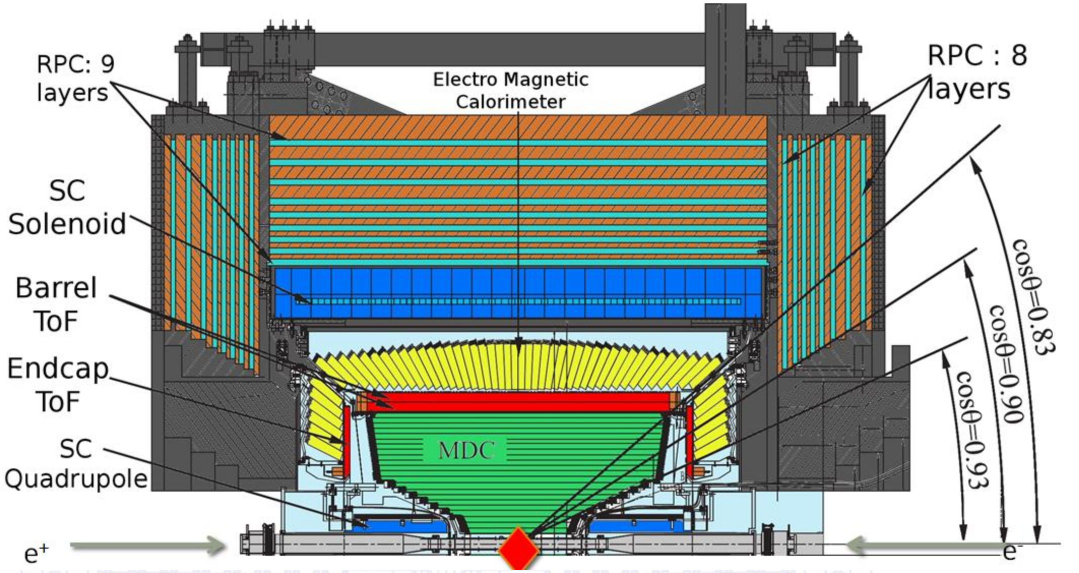
BEPCII and BESIII

1.2. 1st I.R. Experi. hall
3. Power Station of ring mag. and computer center
4. RF Station
5. 2nd I.R. Experi. hall
6. Tunnel of storage ring
7. Tunnel of Trans. line
8. Tunnel of linac
9. Klystron gallery
10. Nuclear phy. Experi. hall
11. Power sta. of trans. line
12. East hall for S.R. experi.
13. West hall for S.R. experi.
14. Computer center

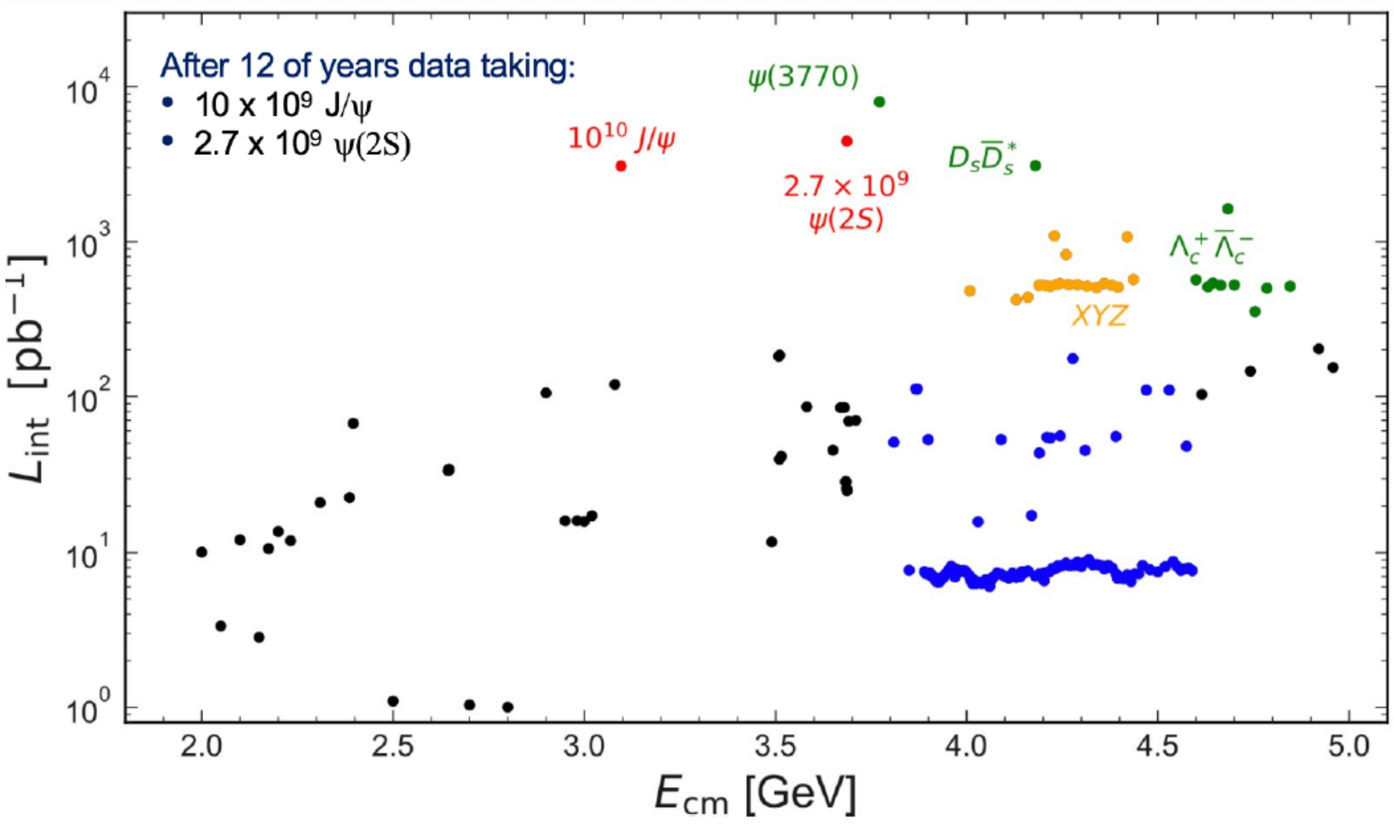


10×10^9 J/ψ events
2.7×10^9 $\psi(3686)$ events
$16\ \mathrm{fb}^{-1}$ $\psi(3770)$ events
World largest J/ψ, $\psi(3686)$, and $\psi(3770)$ data samples on resonance

$\sqrt{s} = 2\sim 4.95\ \mathrm{GeV}$
Peak luminosity: $1.02 \times 10^{33} \mathrm{cm}^{-1}\mathrm{s}^{-1}$



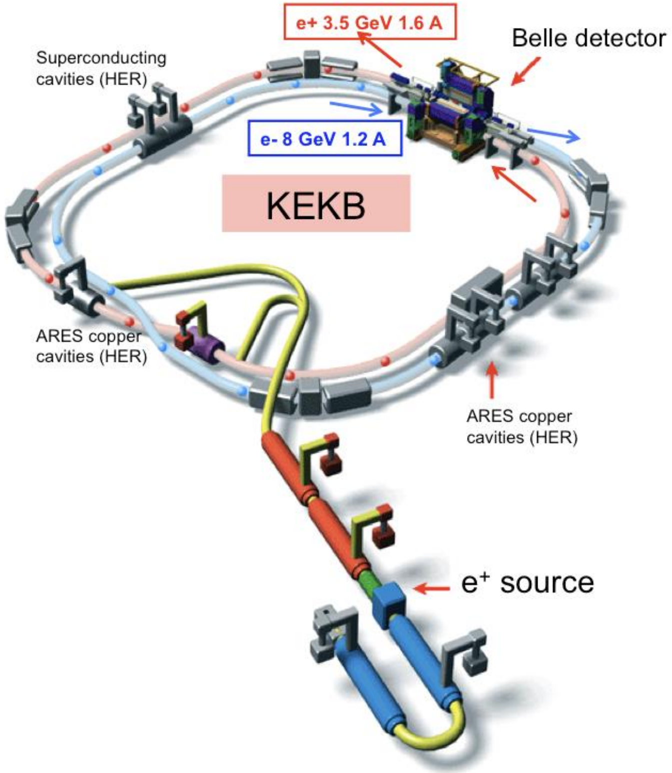
BESIII data samples

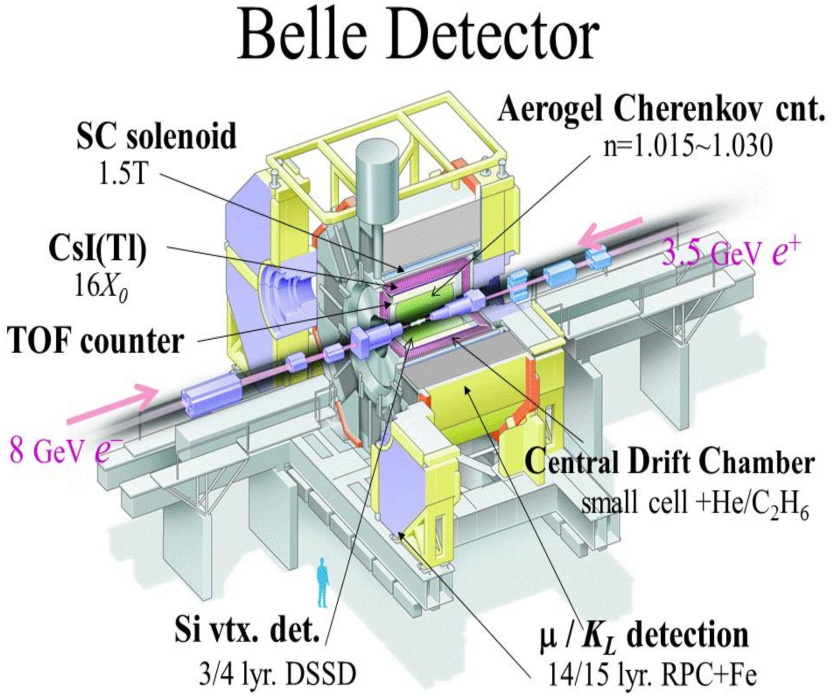


- BESIII has collected rich datasets in the XYZ region $\sqrt{s} > 3.8$ GeV with integrated luminosity of around 22 fb^{-1}.

KEKB and Belle

Peak luminosity: $2.11 \times 10^{34} \mathrm{cm}^{-1}\mathrm{s}^{-1}$
Integrated luminosity (~980 fb^{-1} in total):
$\Upsilon(5S)$: 121 fb^{-1}, $\Upsilon(4S)$: 711 fb^{-1}, $\Upsilon(3S)$: 3 fb^{-1},
$\Upsilon(2S)$: 25 fb^{-1}, $\Upsilon(1S)$: 6 fb^{-1}, continuum: 90 fb^{-1}

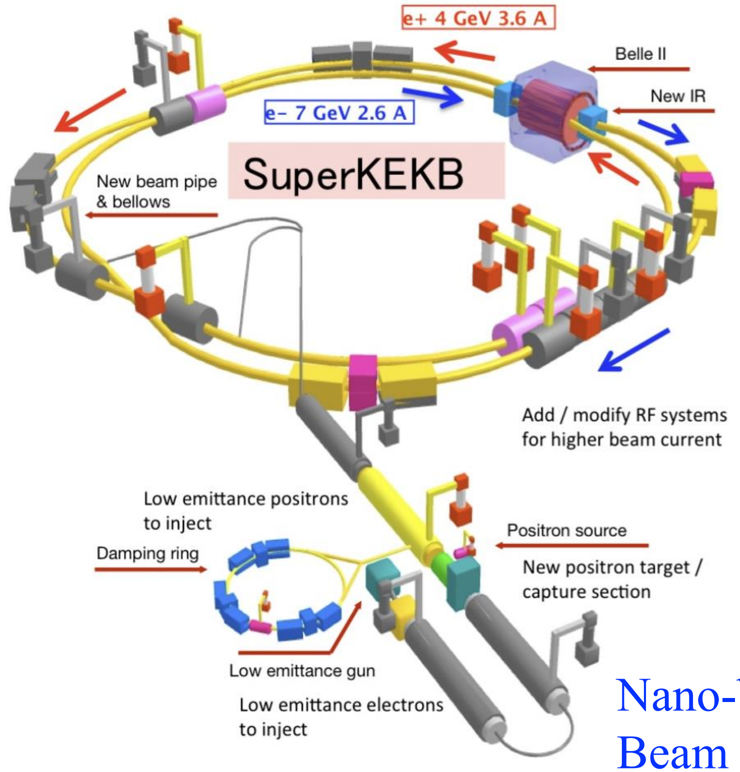




$\sqrt{s} \sim 10.6$ GeV

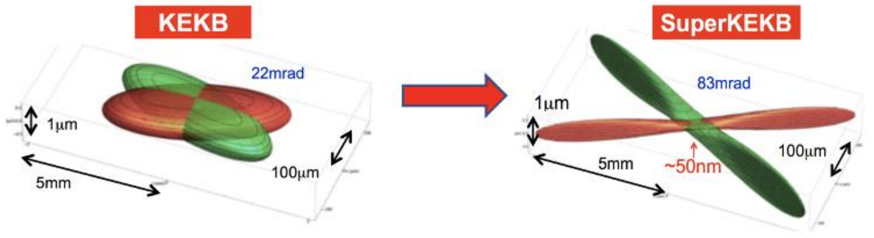
SuperKEKB and Belle II

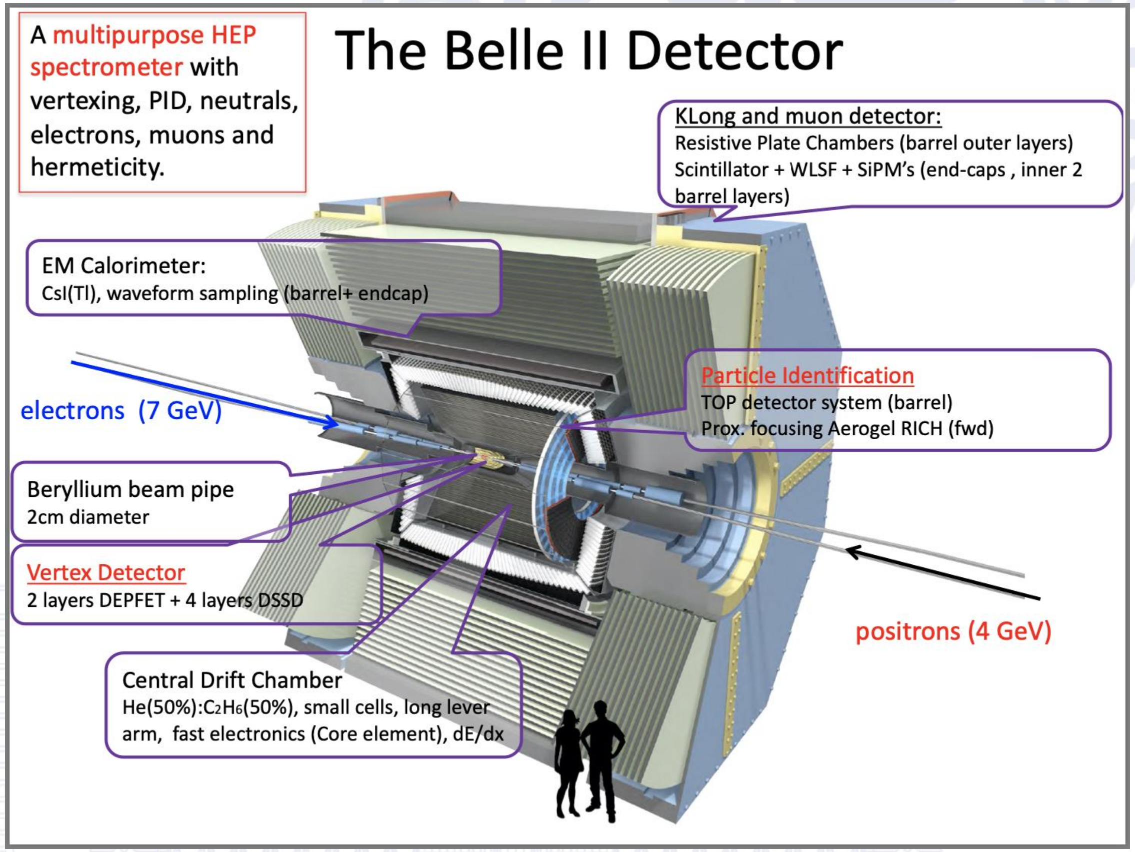
- Achieved peak luminosity: 4.7×10^{34} cm^{-2}s^{-1}
- Integrated luminosity: 435/fb



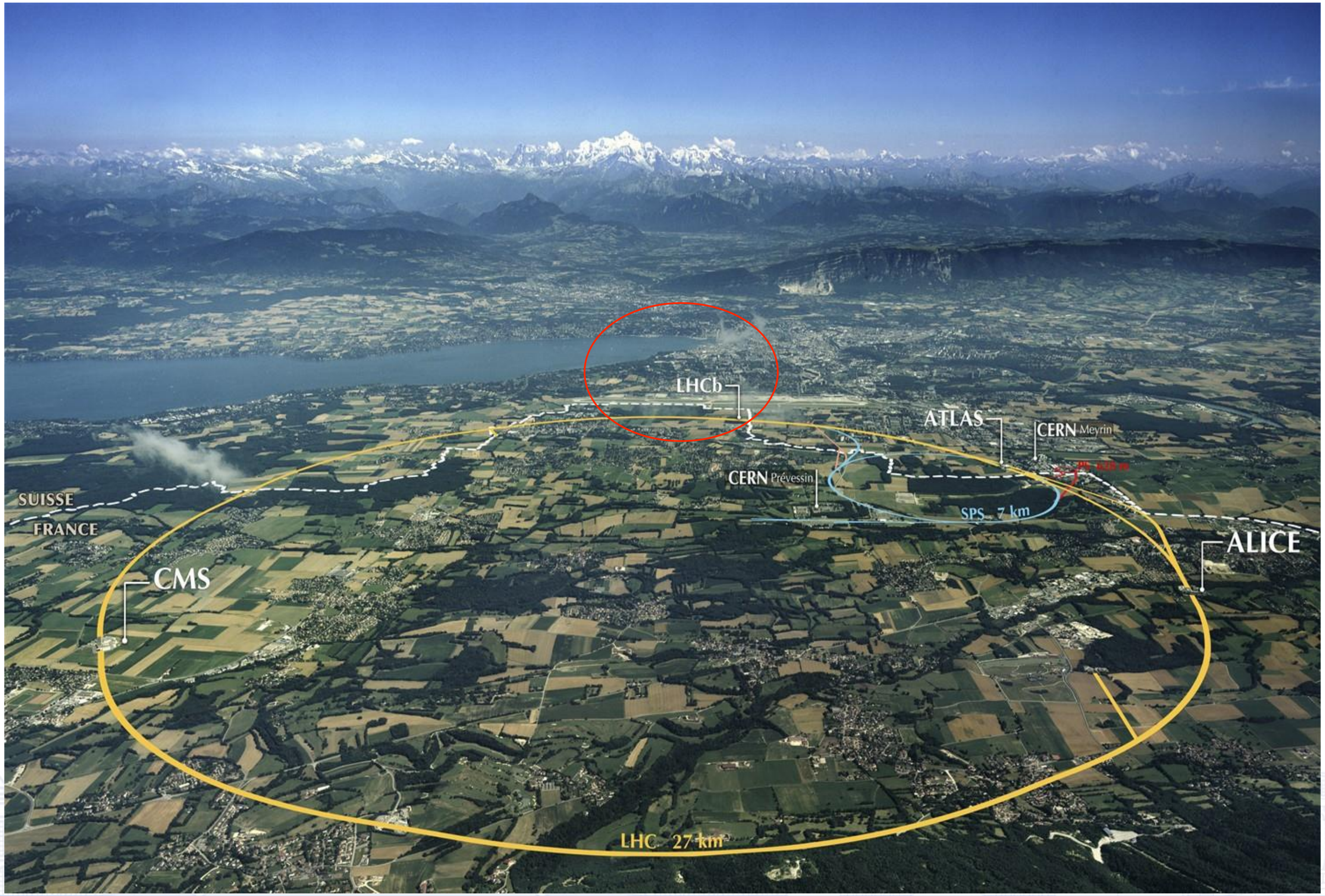
$\sqrt{s} \sim 10.58$ GeV

Nano-beam design:
Beam squeezing: ×20 smaller
Target luminosity: KEKB×40





The LHC as a Beauty and Charm factory



Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs

High B-baryon production fraction

$$B^+ : B^0 : B_s^0 : \Lambda_b^0$$

$$(u\bar{b})\ (d\bar{b})\ (s\bar{b})\ (udb)$$

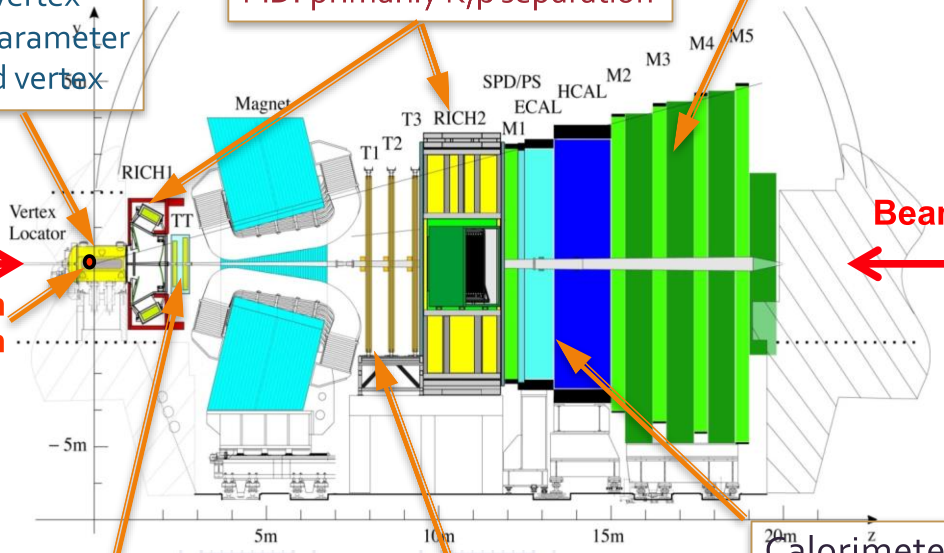
$$4 : 4 : 1 : 2$$

LHCb detector and performance

VELO:
primary vertex
impact parameter
displaced vertex

RICH:
PID: primarily K,p separation

Muon System



Tracking Station: p for lower energy tracks and long lived V° reconstruction

Tracking Stations:
p of charged particles that traverse the magnet

Calorimeters:
PID: h,e,g, p°

[Int. J. Mod. Phys. A 30 (2015) 1530022]

Impact parameter:	$\sigma_{IP} = 20\ \mu\mathrm{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \mathrm{GeV}/c)$
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)
RICH $K-\pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1-3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

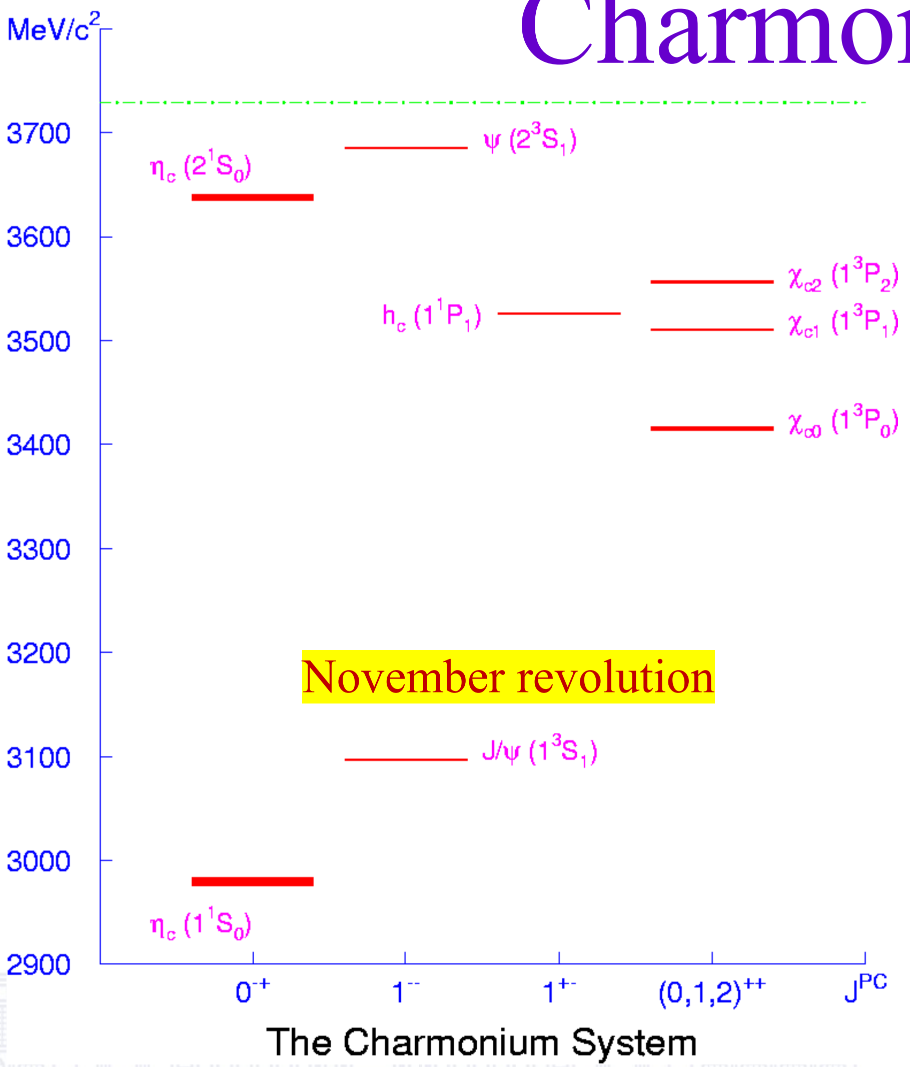
Data process workflow at HEP experiment

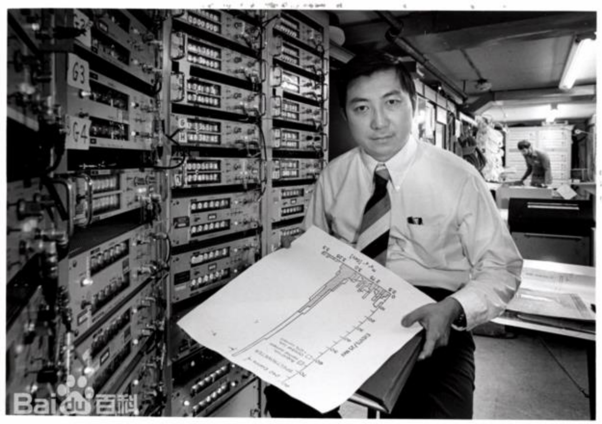
Colllision, MC generator → **Trigger, Simulation** → **Reconstruction** → **Statistical analysis** → **Extract physics variables**

- **Colllision, MC generator**: Accelerator control, initial-state-radiation, parton showering, hadronization, NP-correction, pileup , et. al.
- **Trigger, Simulation**: Data acquisition, fast reconstruction, data input/output, online monitoring, detector geometry, detector noise, calibration, multi-scattering , et. al.
- **Reconstruction**: Track and vertex finding and fitting, clusterization and reconstruction of jet, jet tagging, kinematic fit, detector calibration, et. al.
- **Statistical analysis**: Event selection, optimizations, background analysis, injection test, reweighting, correlation corrections, et. al.
- **Extract physics variables**: systematic uncertainty, fitting, uncertainty propagation, radiation and VP corrections, et. al.

Charmonium States

Charmonium Spectrum

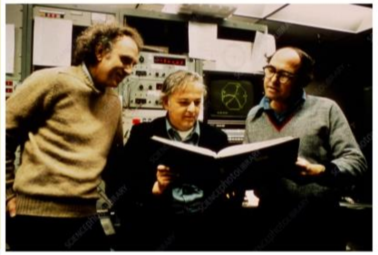


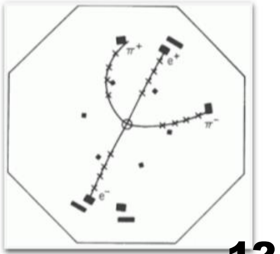


Burton Richter

Samuel C.C.Ting

- All charmonia below charm threshold
- All n=1 charmonia well known and measured
- Mass difference not large (<710 MeV), so not many channels
- Big transition rates
- Study since 1974 !





Charmonium Spectrum

PHYSICAL REVIEW D VOLUME 17, NUMBER 11 1 JUNE 1978

Charmonium: The model

E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 9 February 1978)

A comprehensive treatment of the charmonium model of the ψ family is presented. The model's basic assumption is a flavor-symmetric instantaneous effective interaction between quark color densities. This interaction describes both quark-antiquark binding and pair creation, and thereby provides a unified approach for energies below and above the threshold for charmed-meson production. If coupling to decay channels is ignored, one obtains the "naive" model wherein the dynamics is completely described by a single charmed-quark pair. A detailed description of this "naive" model is presented for the case where the instantaneous potential is a superposition of a linear and Coulombic term. A far more realistic picture is attained by incorporating those terms in the interaction that couple charmed quarks to light quarks. The coupled-channel formalism needed for this purpose is fully described. Formulas are given for the inclusive e^+e^- cross section and for e^+e^- annihilation into specific charmed-meson pairs. The influence of closed decay channels on ψ states below charm threshold is investigated, with particular attention to leptonic and radiative widths.

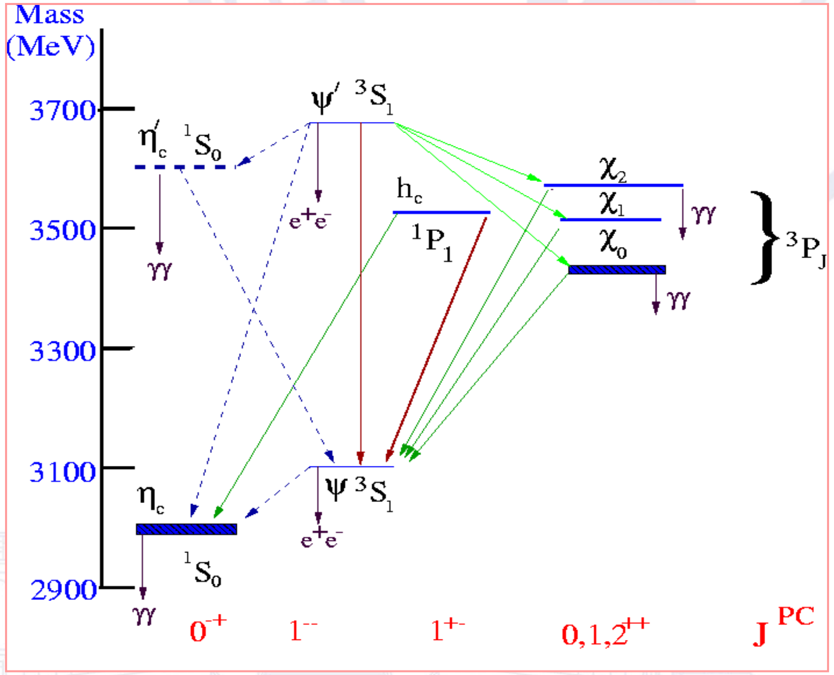
color gauge interaction leads to forces that are so strong at large distances that quarks are permanently confined in color-neutral bound states—the mesons and baryons. We also adopt this assumption.

Secondly, the large masses of the ψ resonances and charmed mesons lead to the assumption that the charmed quarks are so heavy that they may be treated nonrelativistically.[4] No one has yet succeeded in calculating the effective form of the interquark forces from quantum chromodynamics,[16] even in the nonrelativistic limit. To fill this gap we postulate that in this limit many of the gross features of the potential between the charmed quarks can be simulated by the potential

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}\,. \qquad (1.1)$$

Cornell potential

- At short distance
  Cornell model works pretty well
  $V(r) = -4\alpha_s/3r+kr$



Since quark is a spin=1/2 fermion, then for a system of quark and anti-quark the total spin should be 0 or 1. P=$(-1)^{L+1}$、C=$(-1)^{L+S}$。

The possible spin-parity quantum numbers J^{PC} for conventional mesons ($L \leqslant 3$).

L \ S	0	1
0	0^{-+}	1^{--}
1	1^{+-}	$0^{++}, 1^{++}, 2^{++}$
2	2^{-+}	$1^{--}, 2^{--}, 3^{--}$
3	3^{+-}	$2^{++}, 3^{++}, 4^{++}$

$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

L = 0, 1, 2 ... correspond to S, P, D, …

J = S + L

P = $(-1)^{L+1}$ parity

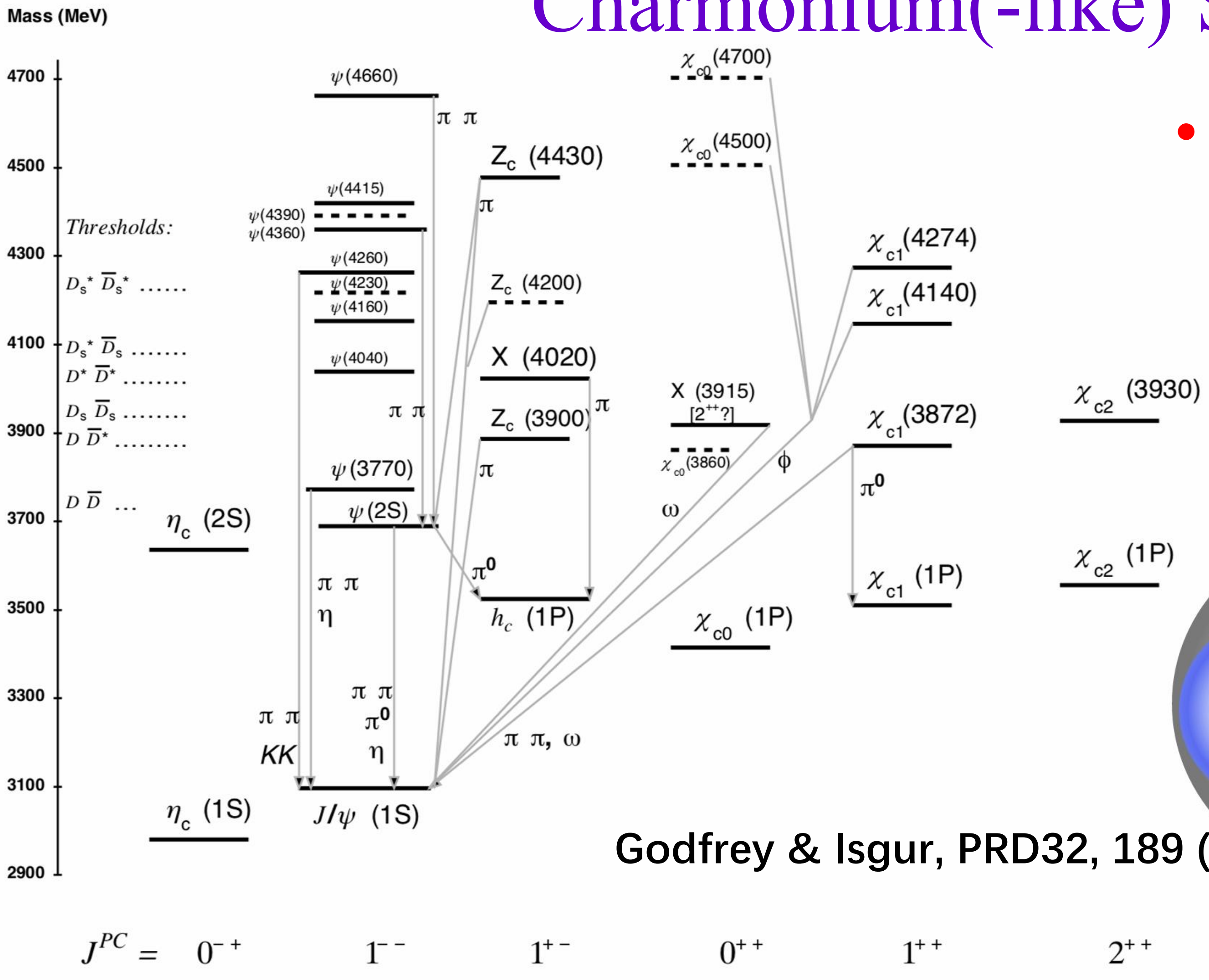
C = $(-1)^{L+S}$ charge conj.

If a state consists of a quark and an anti-quark, its quantum numbers could NOT be 0^{--}、0^{+-}、1^{-+} or 2^{+-} etc., and these quantum numbers are called "exotic".

The quarkonium system

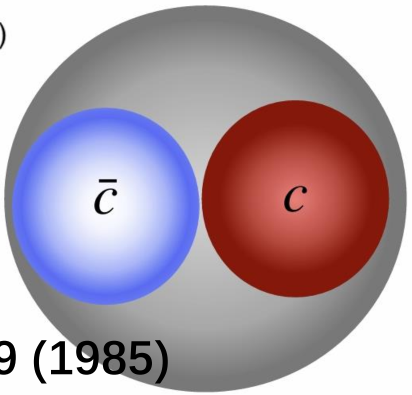
- When distance becomes larger
  - Theory 1: let there be screened potential
  - Theory 2: let there be hybrids with excited gluons
  - Theory 3: let there be tetraquark states
  - Theory 4: let there be meson molecules
  - Theory 5: let there be cusps
  - Theory 6: let there be final state interaction
  - Theory 7: let there be coupled-channel effect
  - Theory 8: let there be mixing
  - Theory 9: let there be mixture of all these effects
  - Theories …
- The world is not that good!

Charmonium(-like) Spectrum



Godfrey & Isgur, PRD32, 189 (1985)

- At short distance
  Cornell model works pretty well
  $V(r) = -4\alpha_s/3r + kr$



$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

L = 0, 1, 2 ... correspond to S, P, D, …

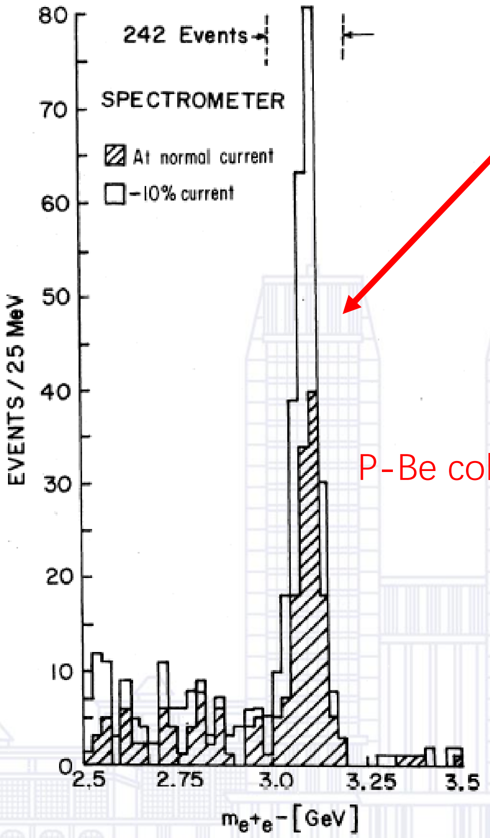
$J = S + L$

$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conj.

Discovery of the J/ψ

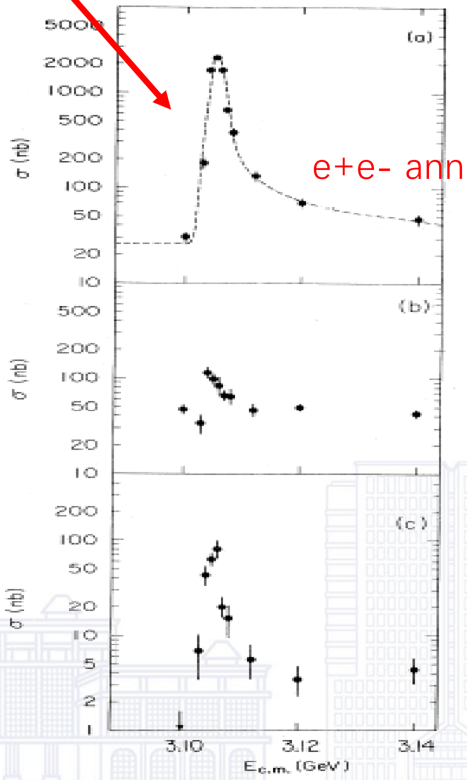
PRL33, 1404 (1974)



P-Be collision

So called "November Revolution of Particle Physics!"

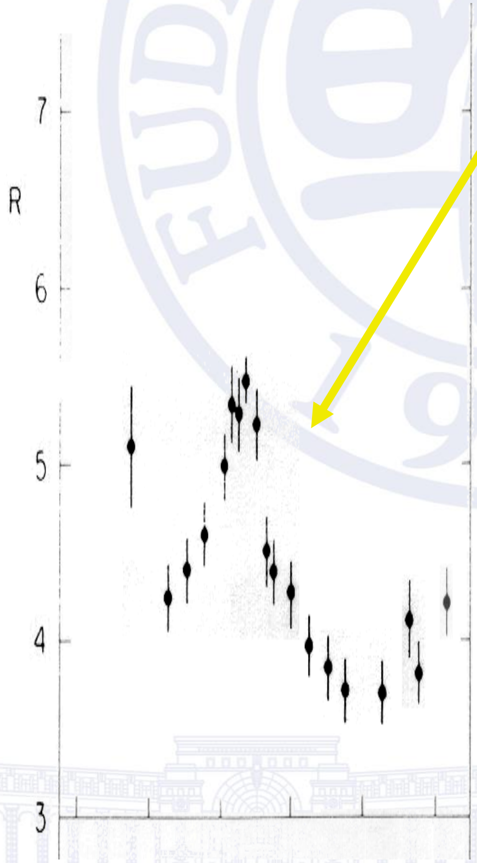
PRL33, 1406 (1974)



e+e- annihilation

Discovery of the ψ(3770)

PRL39, 526 (1977)



What to measure ?

- Masses and widths of the charmonia
- Transition rates
- Multipole amplitudes (helicity amplitudes)
- Mass distributions, intermediate states
- Relations between similar/different modes
- Search for undetected modes
- C-violation, P-violation, CP-violation transitions as a probe of physics beyond SM and/or new physics

$J/\psi(1S)$ $I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS	3096.900 ± 0.006 MeV	
$J/\psi(1S)$ WIDTH	92.6 ± 1.7 keV (S = 1.1)	

$\psi(2S)$ $I^G(J^{PC}) = 0^-(1^{--})$

See the Review on ``$\psi(2S)$ and χ_c branching ratios'' before the $\chi_{c0}(1P)$ Listings.

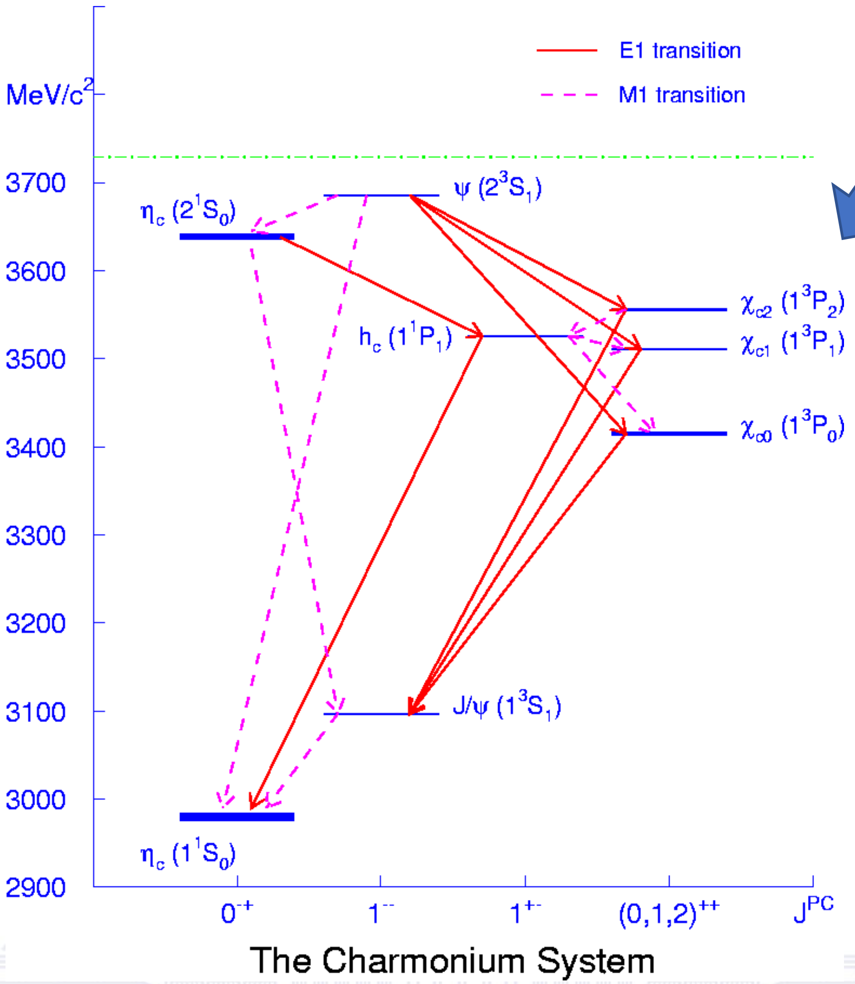
▸ Expand all sections

$\psi(2S)$ MASS	3686.10 ± 0.06 MeV (S = 5.9)	
$m_{\psi(2S)} - m_{J/\psi(1S)}$	589.188 ± 0.028 MeV	
$\psi(2S)$ WIDTH	294 ± 8 keV	

$\psi(3770)$ $I^G(J^{PC}) = 0^-(1^{--})$

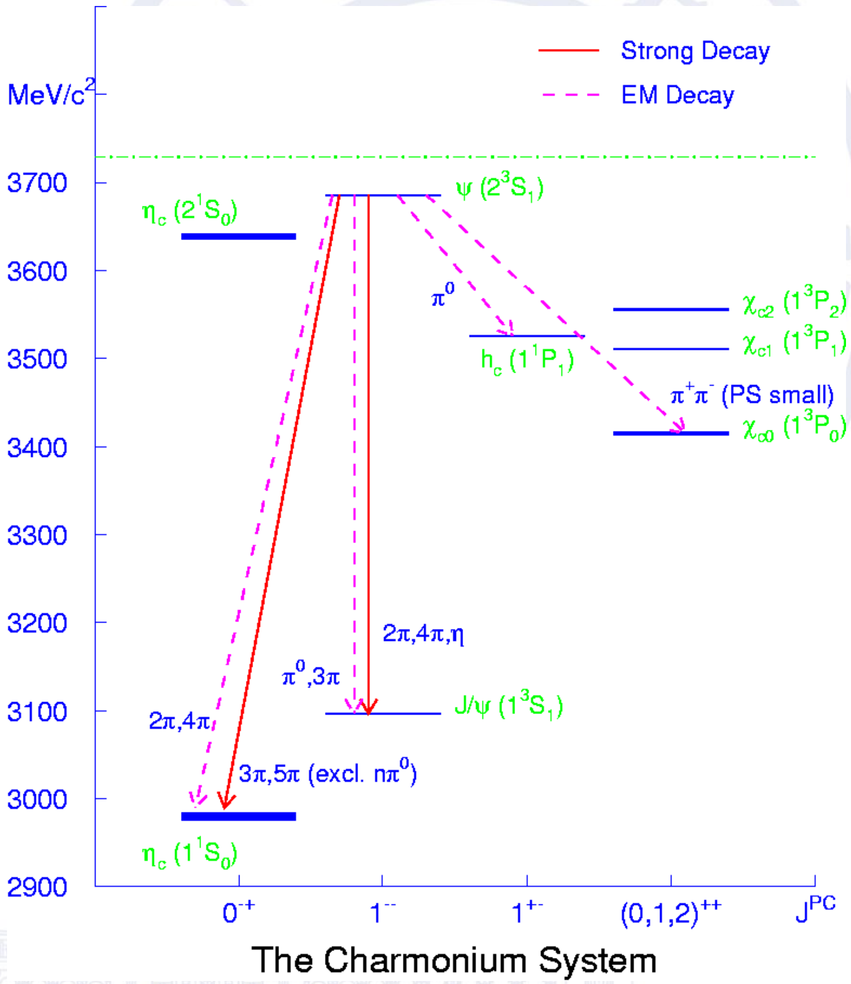
$\psi(3770)$ MASS (MeV)	3773.7 ± 0.4 MeV (S = 1.4)	
$m_{\psi(3770)} - m_{\psi(2S)}$	87.6 ± 0.4 MeV (S = 1.4)	
$\psi(3770)$ WIDTH	27.2 ± 1.0 MeV	

- They can be produced by e^+e^- annihilation directly
- Other lower charmonium states can be produced by their transitions



- E1 dominant transitions rates between ψ' and χ, χ and J/ψ were well measured.
- M1 transition between ψ' and η_c, J/ψ and η_c were measured with big uncertainties.

- Strong and EM transitions between ψ' and J/ψ:
  - $\pi^+\pi^-$, $\pi^0\pi^0$: rates, mass distribution, isospin test, multipoles, σ pole, CPV
  - π^0,η: Isospin violation strength, quark mass
  - EM: $\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$?
  - Strong: $2(\pi^+\pi^-)$, $\pi^+\pi^-\pi^0\pi^0$, $4\pi^0$? PS small, how much?

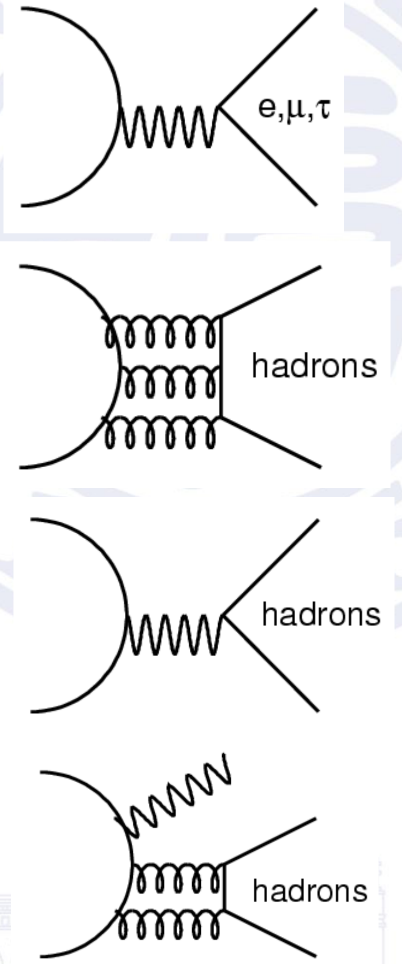


Why study transition ?

- Largest ψ decay modes (experimentally interesting)
- Understand how charm and anti-charm quarks interact (detailed information on the potential between cc-bar)
- Multipole amplitudes --- S-D mixing in ψ’ and ψ’’ (ψ’’ charmless decays)
- Channels with low momentum pions --- does chiral theory work?
- Shed light on ψ hadronic decays and radiative decays (eg. “12% rule”)
- Chance to study η_{c}, h_c and η_c’ more
- Search for rare and forbidden transitions

ψ(2S) decays

- Transitions (~82%)
    - Hadronic transitions (~54%)
    - Radiative transitions (~28%)
- Leptonic decays (~ 2%)
- Hadronic decays (~15%)
    - Strong decays (~13%)
    - EM decays (~ 2%)
- Radiative decays (~ 1%)
- Rare decays and beyond SM (<<1%)



Hadronic decays: The "12% rule"

$$\Gamma_h = |M_h|^2 |\Psi(0)|^2$$

$$= (2/9\pi)(\pi^2 - 9)\tfrac{5}{18}\alpha_s^{\,3}(\tfrac{4}{3}\alpha_s)^3 m_{\psi'}. \quad (3)$$

The leptonic width via one photon into $\bar{l}l$ is

$$\Gamma_l = |M_l|^2 |\Psi(0)|^2 = \tfrac{1}{2}(\tfrac{2}{3}\alpha)^2(\tfrac{4}{3}\alpha_s)^3 m_{\psi'}, \quad (4)$$

where $\alpha \approx \frac{1}{137}$. Although separately these calculations are not trustworthy, the ratio

$$\frac{\Gamma_l}{\Gamma_h} = \frac{\frac{2}{9}\alpha^2}{(2/9\pi)(\pi^2 - 9)5/\alpha_s^{\,3}} \quad (5)$$

is independent of wave-function effects.

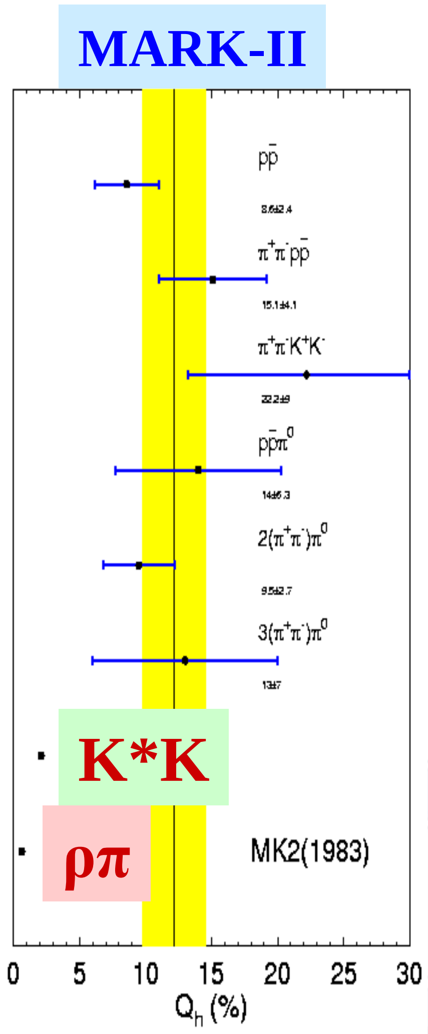
$$Q_h = \frac{B_{\psi'\to X}}{B_{J/\psi\to X}} = \frac{B_{\psi'\to e^+e^-}}{B_{J/\psi\to e^+e^-}} = 12\%$$

This is the famous (or notorious):

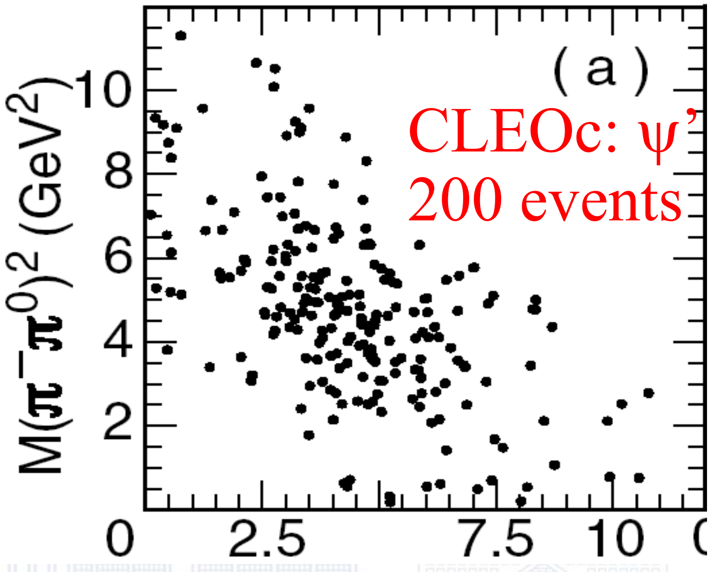
"12% rule".

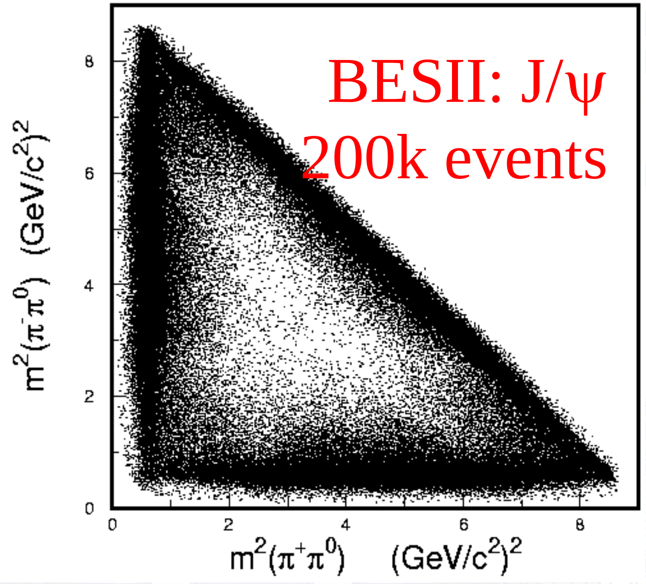
M. Appelquist and H. D. Politzer, PRL34, 43 (1975)

"12% rule" and "ρπ puzzle"

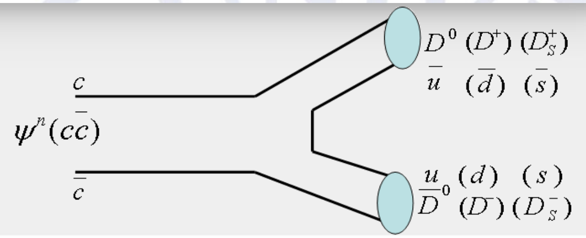


- Violation found by Mark-II , confirmed by BESI at higher sensitivity.
- Extensively studied by BESII, BESIII/CLEOc
- More channels, higher precision





$\psi(3770)$ $I^G(J^{PC}) = 0^-(1^{--})$



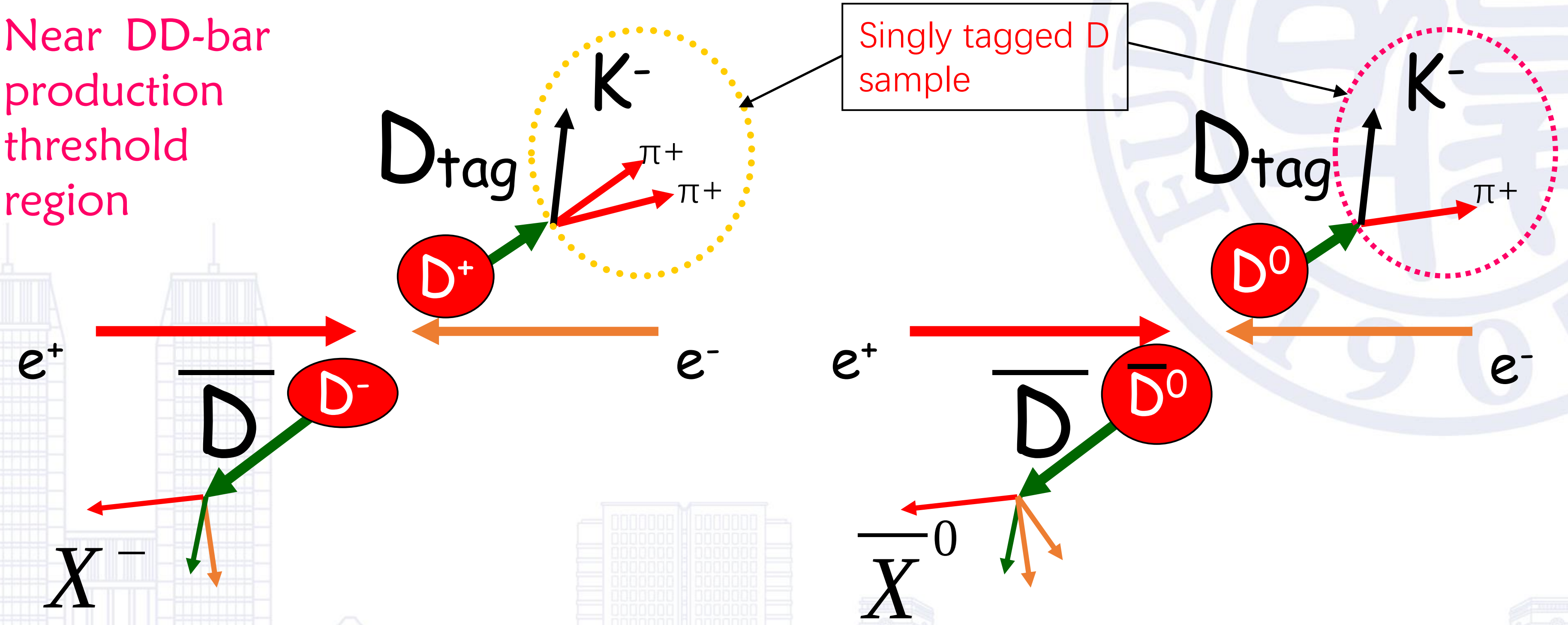
$\psi(3770)$ MASS (MeV)	3773.7 ± 0.4 MeV (S = 1.4)
$m_{\psi(3770)} - m_{\psi(2S)}$	87.6 ± 0.4 MeV (S = 1.4)
$\psi(3770)$ WIDTH	27.2 ± 1.0 MeV

$\psi(3770)$ DECAY MODES

Expand all decays

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D\bar{D}$	$(93^{+8}_{-9})\%$	S=2.0	287
Γ_2	$D^0\bar{D}^0$	$(52^{+4}_{-5})\%$	S=2.0	287
Γ_3	D^+D^-	$(41 \pm 4)\%$	S=2.0	254

With the singly tagged D sample, we can do some absolute measurements and search for some new decay modes of D mesons



Charmed Mesons: The existence of charmed mesons was predicted by Bjorken and Glashow [Phys. Lett. 11, 255(1964)]. A charmed meson is a bound state of c quark and one of the light antiquarks.

$\eta_c(1S)$

$I^G(J^{PC}) = 0^+(0^{-+})$

$\eta_c(1S)$ MASS	2983.9 ± 0.4 MeV (S = 1.2)
$\eta_c(1S)$ WIDTH	32.0 ± 0.7 MeV

$\eta_c(2S)$

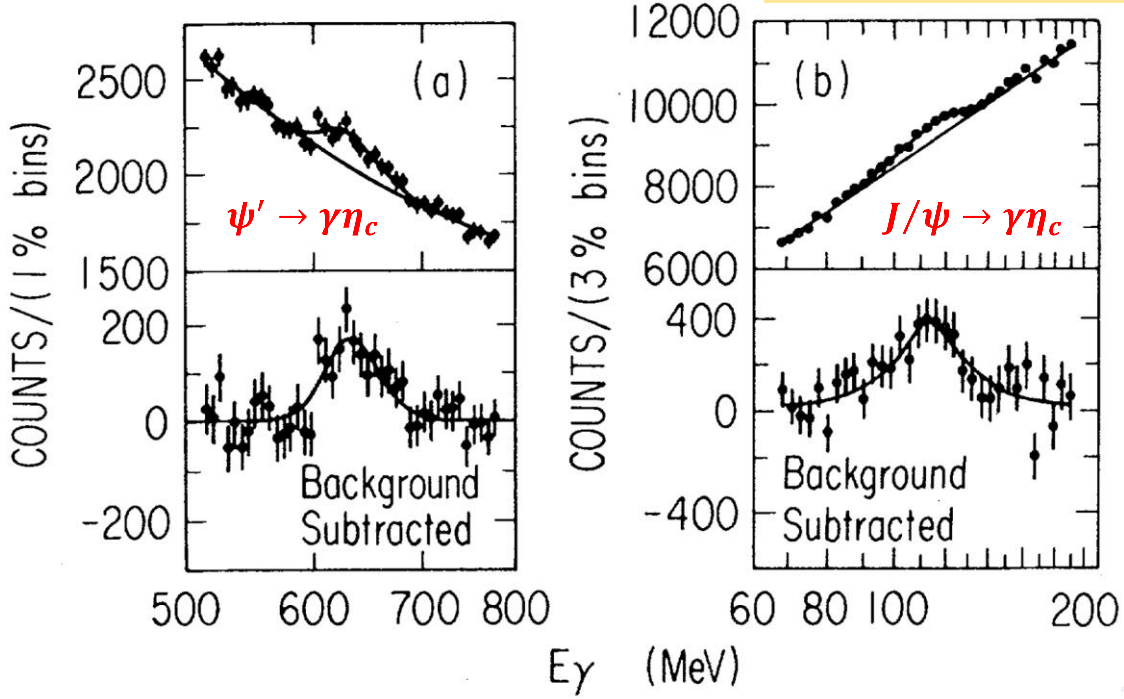
$I^G(J^{PC}) = 0^+(0^{-+})$

Quantum numbers are quark model predictions.

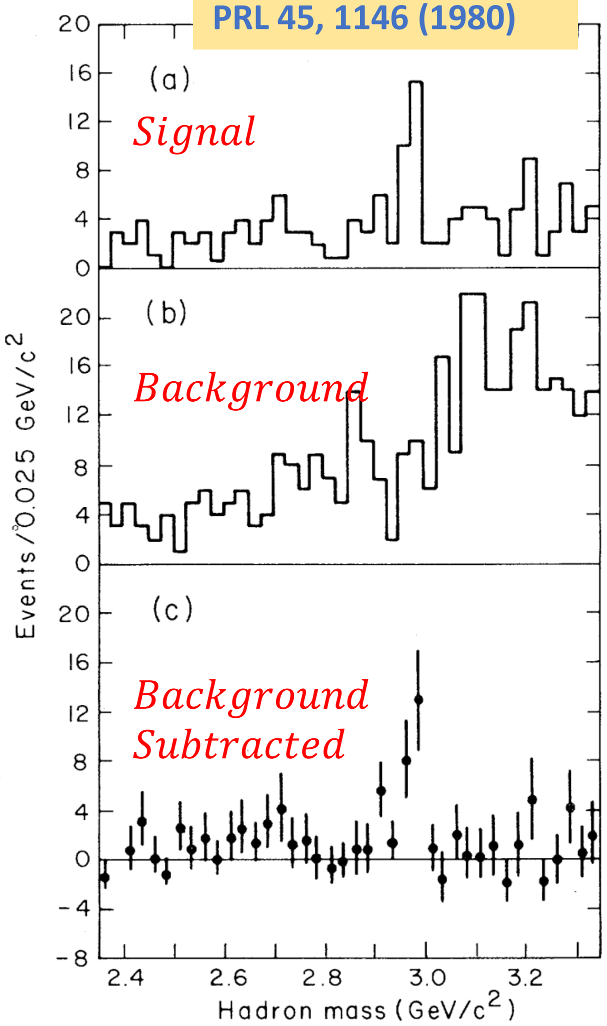
$\eta_c(2S)$ MASS	3637.7 ± 1.1 MeV (S = 1.2)
$\eta_c(2S)$ WIDTH	13.9 ± 2.6 MeV

First Observation of η_c

PRL 45, 1150 (1980)



PRL 45, 1146 (1980)



$\psi' \to \gamma p\bar{p}$,

$\psi' \to \gamma\pi^+\pi^-\pi^+\pi^-$,

$\psi' \to \gamma\pi^+\pi^- K^+K^-$,

$\psi' \to \gamma\pi^+\pi^- p\bar{p}$,

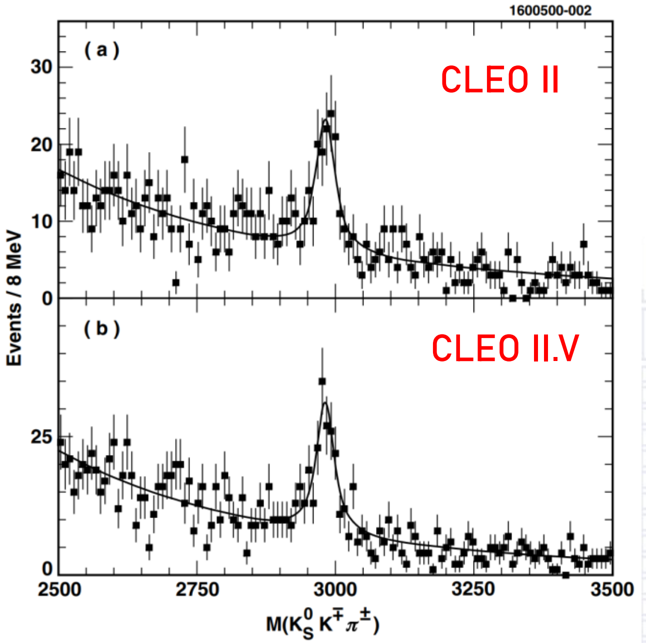
$\psi' \to \gamma K^\pm\pi^\mp K_s$, $K_s \to \pi^+\pi^-$.

- Observed in Radiative transitions from ψ′ by Mark II
- $\mathrm{M} = 2980 \pm 8$ MeV
- $\Gamma < 40$ MeV

- Observed in Radiative transitions from ψ' and J/ψ by Crystal Ball
- Fit inclusive photon mass spectrum
- $M = 2978 \pm 9$ MeV $\quad\Gamma < 20$ MeV

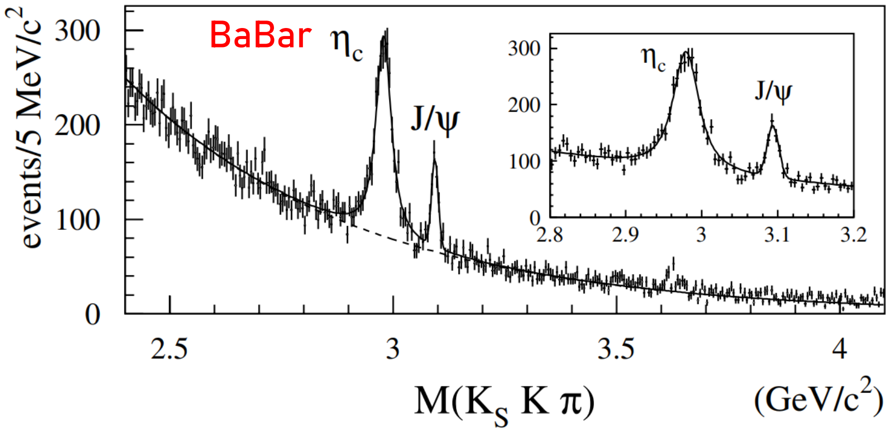
Radiative transitions from ψ' and J/ψ is dominated!

η_c Produced from $\gamma\gamma$-fusion



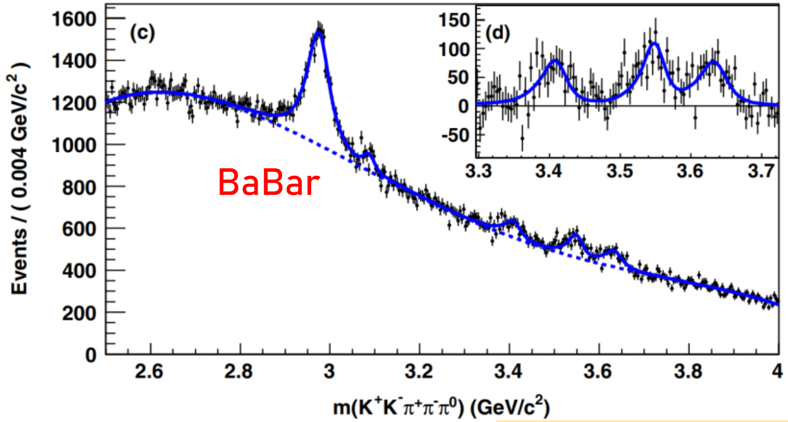
$\gamma\gamma \to K_s^0 K\pi$

PRL 85, 3095 (2000)



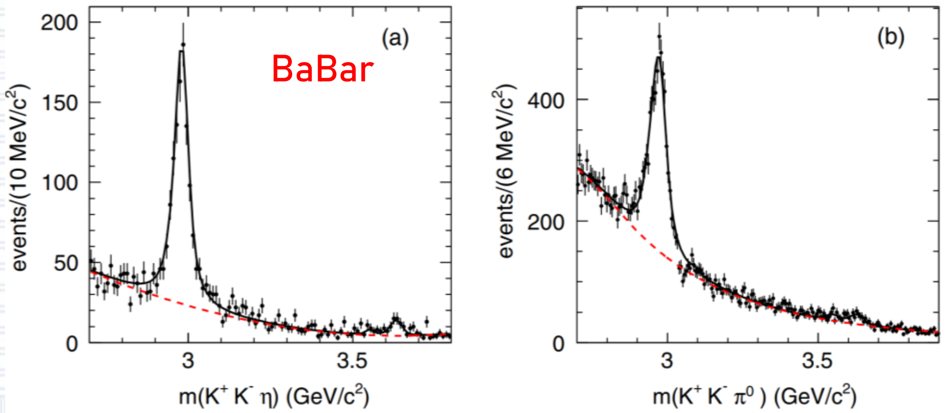
$\gamma\gamma \to K_s^0 K\pi$

PRL 92, 142002 (2004)



$\gamma\gamma \to K^+K^-\pi^+\pi^-\pi^0$

PRD 84, 012004 (2011)



$\gamma\gamma \to K^+K^-\eta/\pi^0$

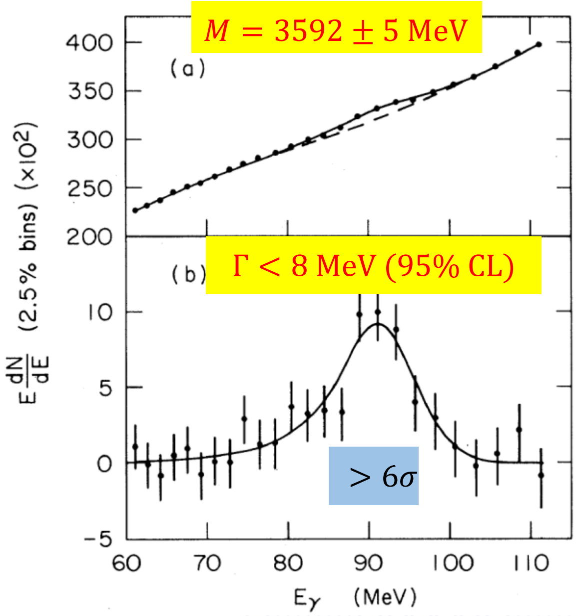
PRD 89, 112004 (2014)

Process	Mass [MeV]	Width [MeV]
$\gamma\gamma \to K_s^0 K\pi$ (CLEO)	2980.4 ± 2.4	27.0 ± 6.0
$\gamma\gamma \to K_s^0 K\pi$ (BaBar)	2982.5 ± 1.4	34.3 ± 2.5
$\gamma\gamma \to KK\pi\pi\pi^0$	2984.5 ± 3.2	36.2 ± 4.1
$\gamma\gamma \to K^+K^-\eta$	2984.1 ± 2.4	34.8 ± 5.1
$\gamma\gamma \to K^+K^-\pi^0$	2979.8 ± 3.6	25.2 ± 3.5

First Observation of η_c'

The search for η_c' has a long and checkered history:

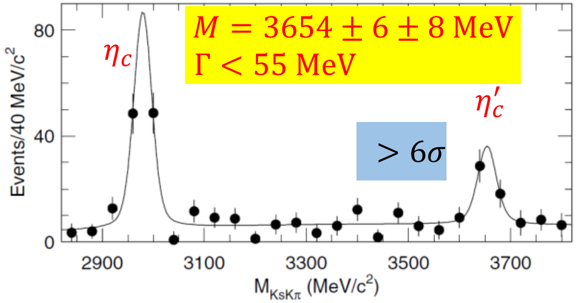
In 1982, an enhancement found at $E_\gamma \approx$ 91 MeV from $e^+e^- \to \psi' \to \gamma X$. It was interpreted as due to $\boldsymbol{\eta_c'}$. [PRL 48,70]



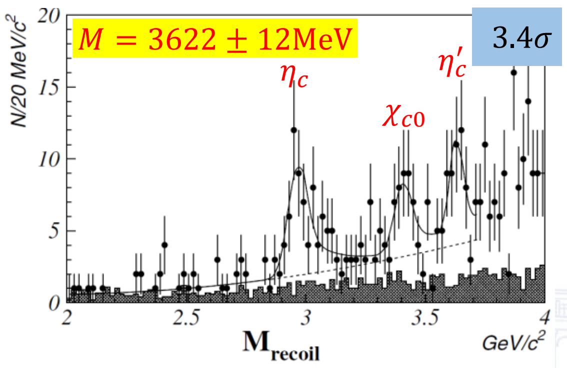
Stanford Linear Accelerator Center

Since then, many experiments tried to search for $\boldsymbol{\eta_c'}$, but they all failed.

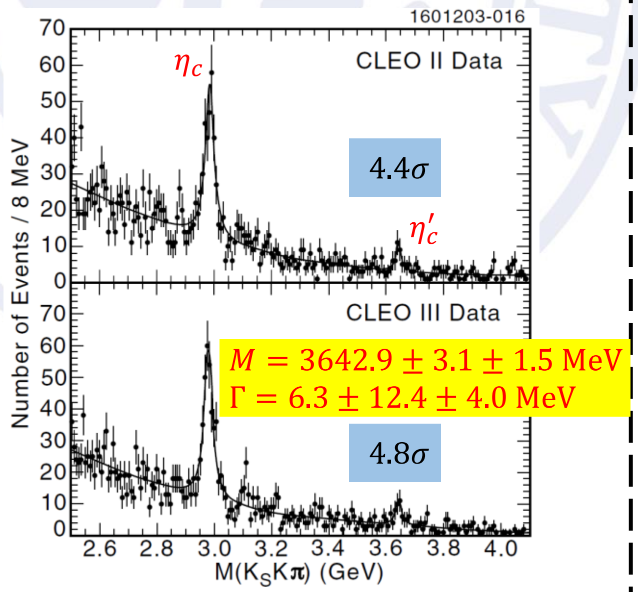
Until in 2002, Belle reported the first successful identification of $\boldsymbol{\eta_c'}$ from $B \to K\eta_c' \to KK_S^0K^-\pi^+$. [PRL 89, 102001]



Belle also observed the $\boldsymbol{\eta_c'}$ in double charmonium production $e^+e^- \to J/\psi + \eta_c'$ in 2002. [PRL 89,142001]

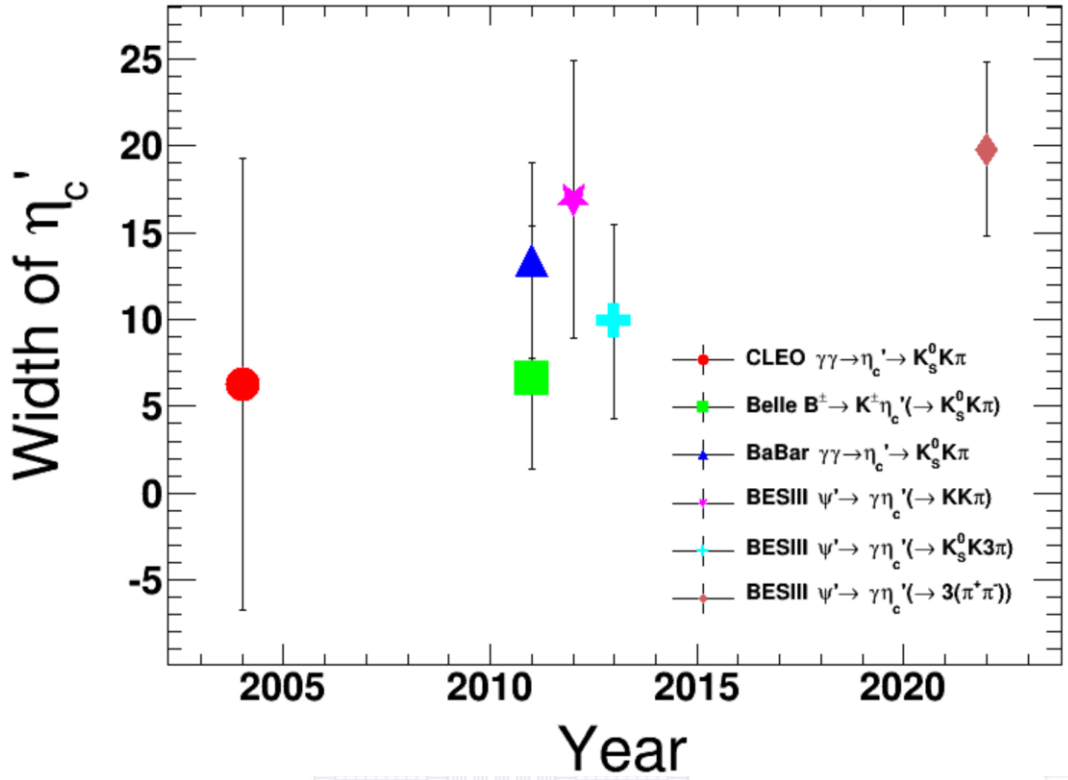


In 2004, CLEO reported the first observation of $\boldsymbol{\eta_c'}$ in the two-photon fusion $\gamma\gamma \to \eta_c' \to K_S^0K^\pm\pi^\mp$.
[PRL 92, 142001]

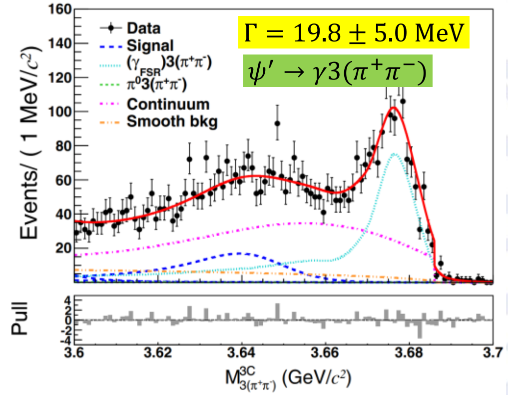


The discovery of η_c' is completely determined by now!

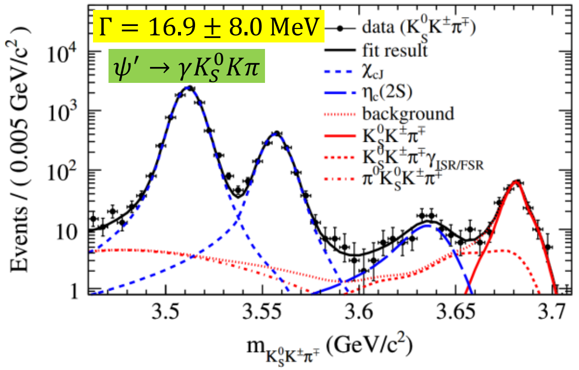
To be clear about η_c' width is important!

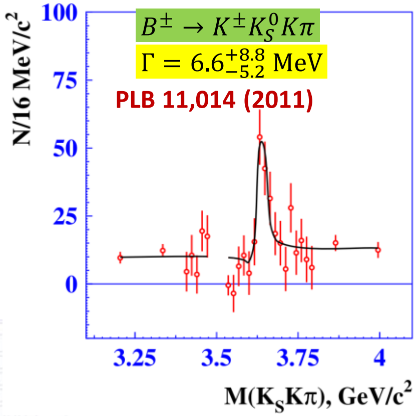


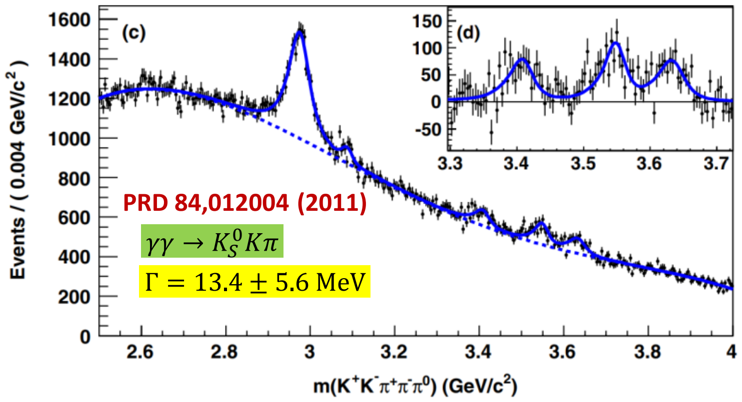
PRD 106,032014(2022)



PRL 109,042003 (2012)





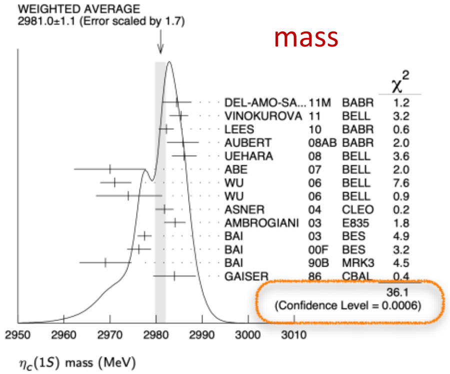


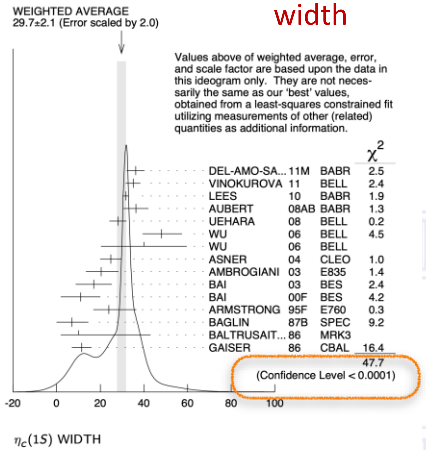
- The measured η_c' widths from ψ' decay and $\gamma\gamma$-fusion vary widely.
- **Interference in both decays may need to be considered in the future!**

Parameters of η_c

Puzzle: the mass and width of η_c determined from different production mechanisms are very different

PDG2012

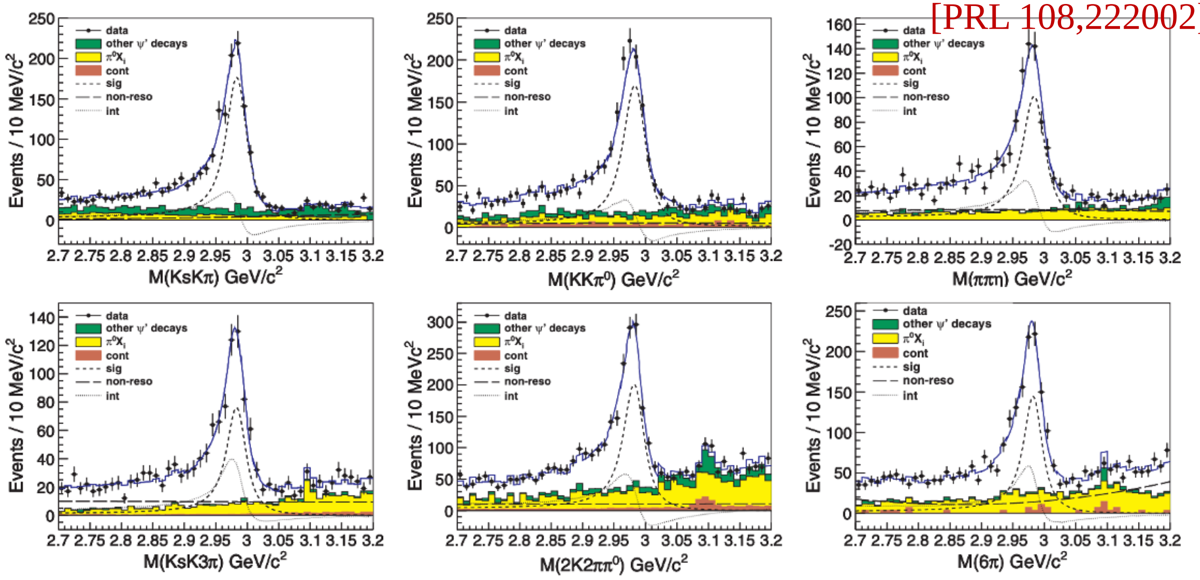




The inference between resonance decay and non-resonant contribution is considered for the first time.
The interference affects the η_c mass and width significantly, implies the parameters determined from previous measurement using the same mechanisms need to be reconsidered.

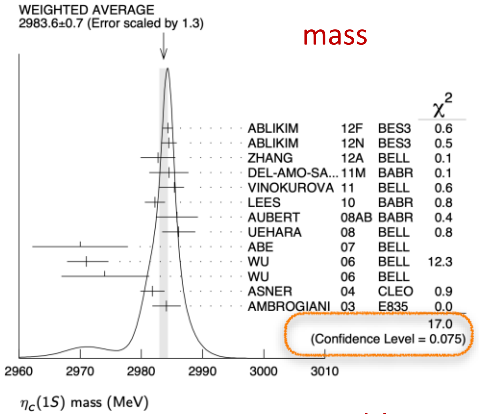
$M = 2984.3 \pm 0.6 \pm 0.6\ \mathrm{MeV}/c^2$, $\Gamma = 32.0 \pm 1.2 \pm 1.0$ MeV(most precise single measurement)

[PRL 108,222002]



significance of the interference:15σ

PDG2014



width

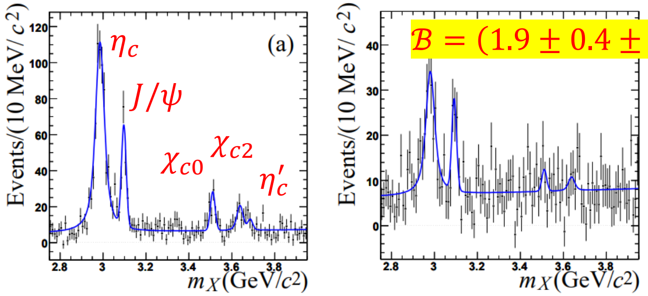
$\eta_c(1S)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
32.0± 0.9 OUR FIT					
32.2± 1.0 OUR AVERAGE		Error includes scale factor of 1.2.			
$32.0\pm1.2\pm1.0$		[1,2] ABLIKIM	12F	BES3	$\psi(2S)\to\gamma\eta_c$
$36.4\pm3.2\pm1.7$	832	[3] ABLIKIM	12N	BES3	$\psi(2S)\to\pi^0\gamma$ hadrons
$36.2\pm2.8\pm3.0$	11k	DEL-AMO-SA...	11M	BABR	$\gamma\gamma\to K^+K^-\pi^+\pi^-\pi^0$
$35.1\pm3.1^{+1.0}_{-1.6}$	920	[2] VINOKUROVA	11	BELL	$B^\pm\to K^\pm(K^0_S K^\pm\pi^\mp)$
$31.7\pm1.2\pm0.8$	14k	[4] LEES	10	BABR	$10.6\ e^+e^-\to e^+e^-K^0_S K^\pm\pi^\mp$
$36.3^{+3.7}_{-3.6}\pm4.4$	0.9k	AUBERT	08AB	BABR	$B\to\eta_c(1S)K^{(*)}\to K\overline{K}\pi K^{(*)}$
$28.1\pm3.2\pm2.2$	7.5k	UEHARA	08	BELL	$\gamma\gamma\to\eta_c\to$ hadrons
$48\ ^{+8}_{-7}\pm5$	195	WU	06	BELL	$B^+\to p\overline{p}K^+$
$40\pm19\pm5$	20	WU	06	BELL	$B^+\to\Lambda\overline{\Lambda}K^+$
$24.8\pm3.4\pm3.5$	592	ASNER	04	CLEO	$\gamma\gamma\to\eta_c\to K^0_S K^\pm\pi^\mp$
$20.4^{+7.7}_{-6.7}\pm2.0$	190	AMBROGIANI	03	E835	$\overline{p}p\to\eta_c\to\gamma\gamma$
$23.9^{+12.6}_{-7.1}$		ARMSTRONG	95F	E760	$\overline{p}p\to\gamma\gamma$

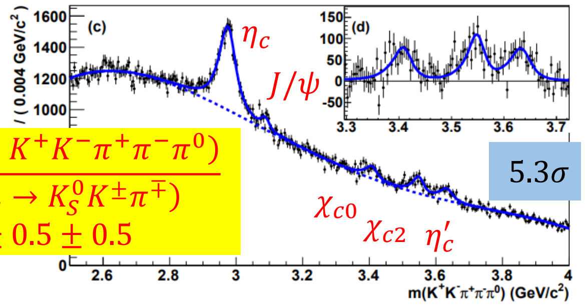
The decays of η_c'

Not much η_c' decays are observed:

In 2008, BABAR studied $\eta_c' \to K_S^0 K^\pm \pi^\mp / K^+ K^- \pi^0$ in B^+ (left) and B^0 (right) decays. [PRD 78, 012006]

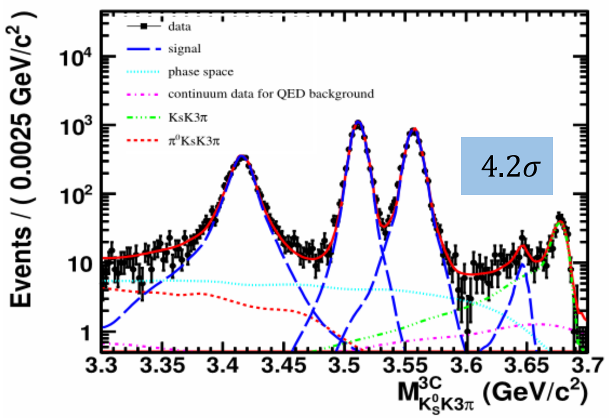


In 2011, BABAR firstly found $\eta_c' \to K^+ K^- \pi^+ \pi^- \pi^0$ in the two-photon fusion process. This is the first found decay other than $K\bar{K}\pi$. [PRD 84, 012004]



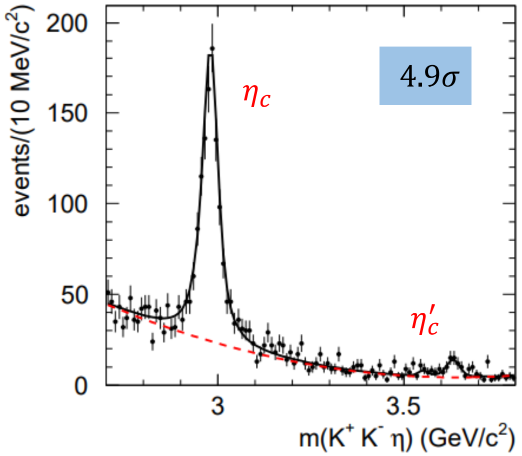
$$\frac{\mathcal{B}(\eta_c' \to K^+ K^- \pi^+ \pi^- \pi^0)}{\mathcal{B}(\eta_c' \to K_S^0 K^\pm \pi^\mp)} = 2.2 \pm 0.5 \pm 0.5$$

In 2013, BESIII firstly observed an evidence of $\eta_c' \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$ in $\psi' \to \gamma \eta_c'$. [PRD 87, 052005]



$$\mathcal{B}(\psi' \to \gamma \eta_c')\mathcal{B}(\eta_c' \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$$

In 2014, BABAR firstly found $\eta_c' \to K^+ K^- \eta$ in two-photon process. [PRD 89, 112004]



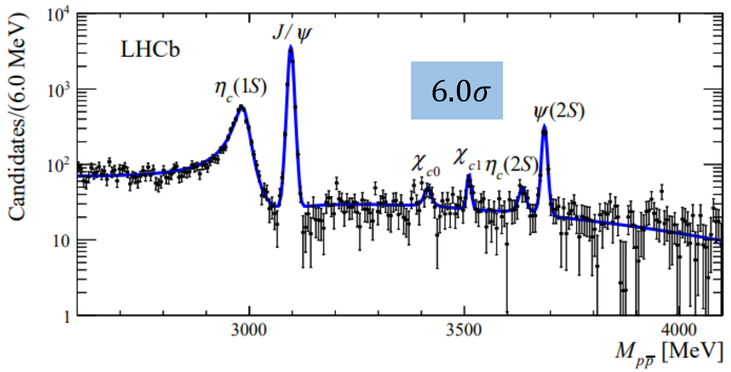
$$\frac{\mathcal{B}(\eta_c' \to K^+ K^- \eta)}{\mathcal{B}(\eta_c' \to K^+ K^- \pi^0)} = 0.82 \pm 0.21 \pm 0.27$$

But the uncertainties of the reference modes are large.

The decays of η_c'

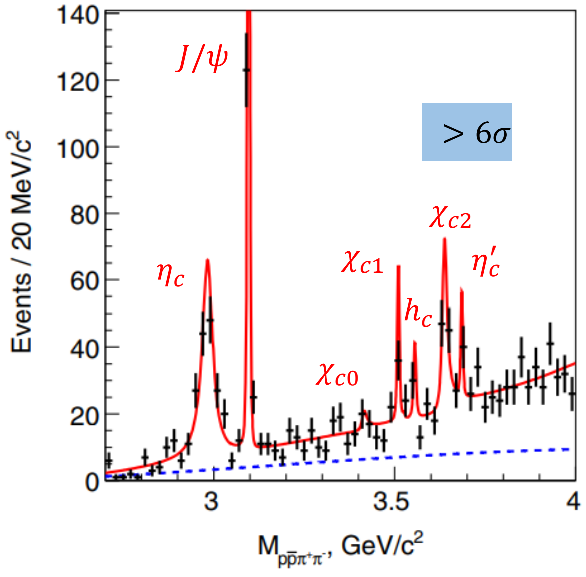
Not much η_c' decays are observed:

In 2016, LHCb firstly found $\eta_c' \to p\bar{p}$. [PLB 769, 305]



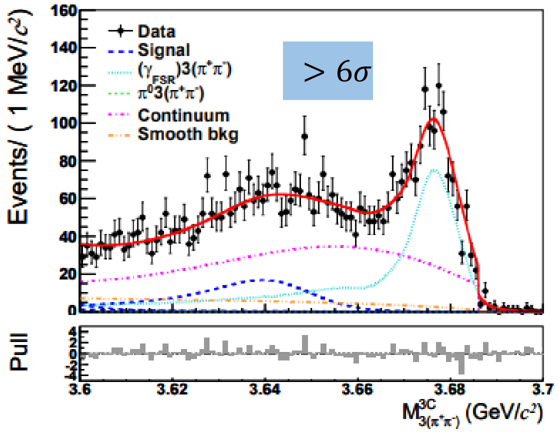
$$\frac{\mathcal{B}(B^+ \to \eta_c' K^+)\mathcal{B}(\eta_c' \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+)\mathcal{B}(J/\psi \to p\bar{p})} = (1.58 \pm 0.33 \pm 0.09) \times 10^{-2}$$

In 2019, Belle firstly observed $\eta_c' \to p\bar{p}\pi^+\pi^-$. [PRD 100, 012001]



$$\mathcal{B}(B^+ \to \eta_c' K^+)\mathcal{B}(\eta_c' \to p\bar{p}\pi^+\pi^-) = \left(11.2^{+1.8}_{-1.6}{}^{+0.5}_{-0.7}\right) \times 10^{-7}$$

In 2022, BESIII firstly found $\eta_c' \to 3(\pi^+\pi^-)$. [PRD 106, 032014]



$$\mathcal{B}(\psi' \to \gamma\eta_c')\mathcal{B}(\eta_c' \to K_S^0 K^{\pm}\pi^{\mp}\pi^+\pi^-) = (9.2 \pm 1.0 \pm 1.2) \times 10^{-6}$$

Currently, the sum of all known decay widths is only ~5% of the total decay width!

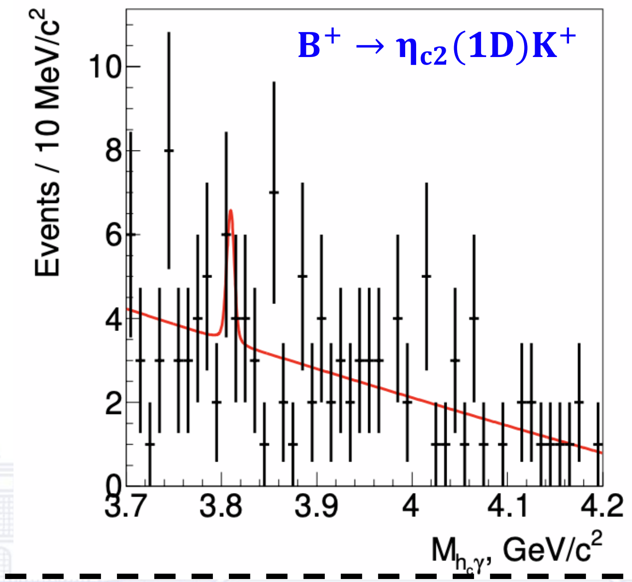
$\eta_{c2}(1D)$: spin-singlet low-lying D-wave charmonium

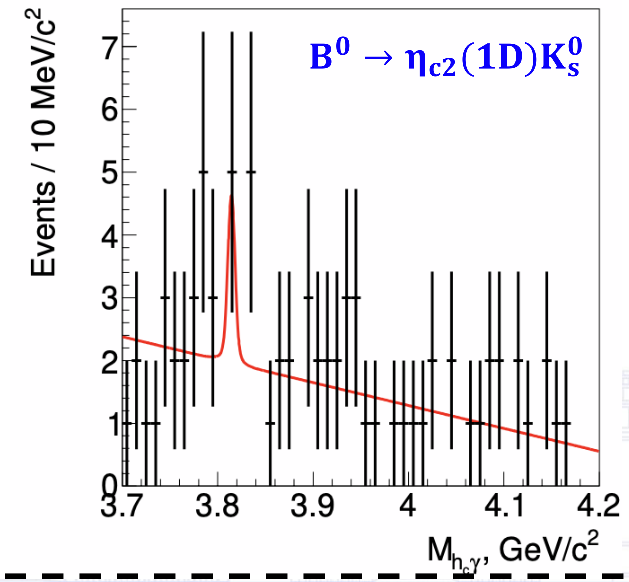
Mass: in the range of 3.80 to 3.88 GeV/c², and lies between $D\bar{D}$ and $D^{*}\bar{D}$ threshold [PRD 72, 054026 (2005), PRD 79, 094004 (2009)].

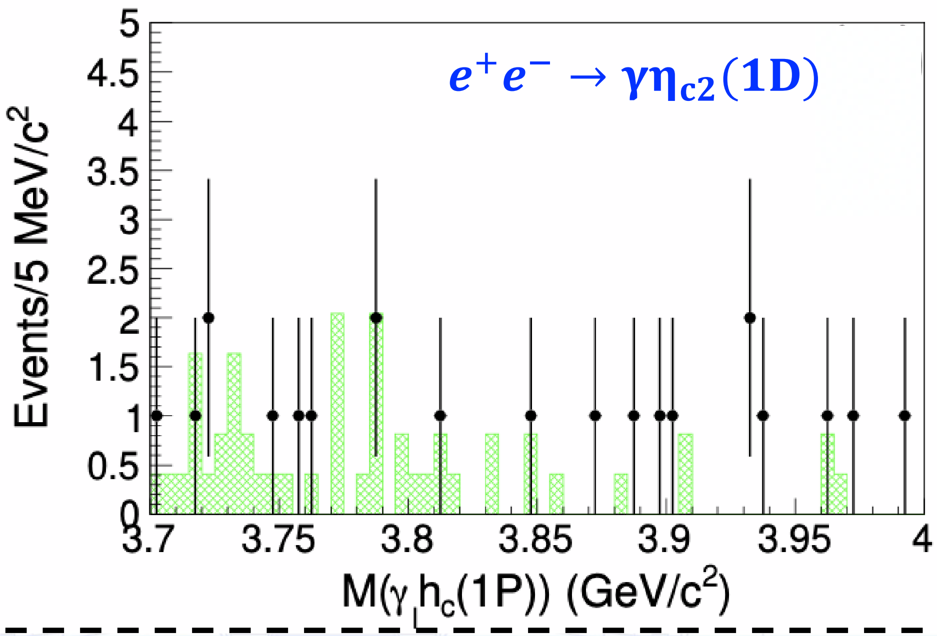
Width: very narrow

Decay mode: branching fraction of $\eta_{c2}(1D) \to \gamma h_c(1P)$ is large (> 50%) [PRD 80, 014001 (2009)].

The $\eta_{c2}(1D)$ was searched in *B* decays and e^+e^- annihilations by Belle, but no signal was found [JHEP 05, 034 (2020), PRD 104, 012012 (2021)].







$h_c(1P)$ $I^G(J^{PC}) = 0^-(1^{+-})$

Quantum numbers are quark model prediction, ^{C} = established by $\eta_c\gamma$ decay.

$h_c(1P)$ MASS	3525.37 ± 0.14 MeV (S = 1.2)
$h_c(1P)$ WIDTH	0.78 ± 0.28 MeV

$h_c(1P)$ **PARTIAL WIDTHS**

$h_c(1P)$ **DECAY MODES**

▸ Expand all decays

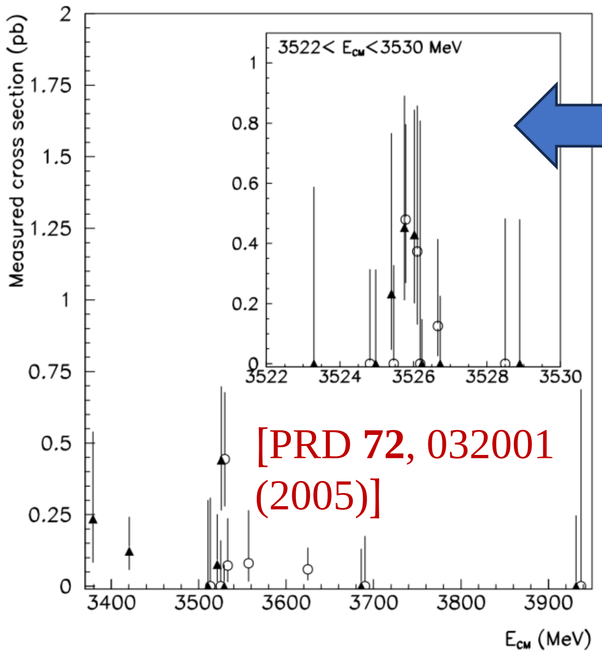
	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi(1S)\pi^0$	$< 5 \times 10^{-4}$	CL=90%	382
Γ_2	$J/\psi(1S)\pi\pi$	not seen		312
Γ_3	$J/\psi(1S)\pi^+\pi^-$	$< 2.7 \times 10^{-3}$	CL=90%	305

▾ Radiative decays

Γ_{23}	$\gamma\eta$	$(4.7 \pm 2.1) \times 10^{-4}$	1720
Γ_{24}	$\gamma\eta'(958)$	$(1.5 \pm 0.4) \times 10^{-3}$	1633
Γ_{25}	$\gamma\eta_c(1S)$	$(57 \pm 5)\%$	500

The importance of h_c in hadron spectroscopy

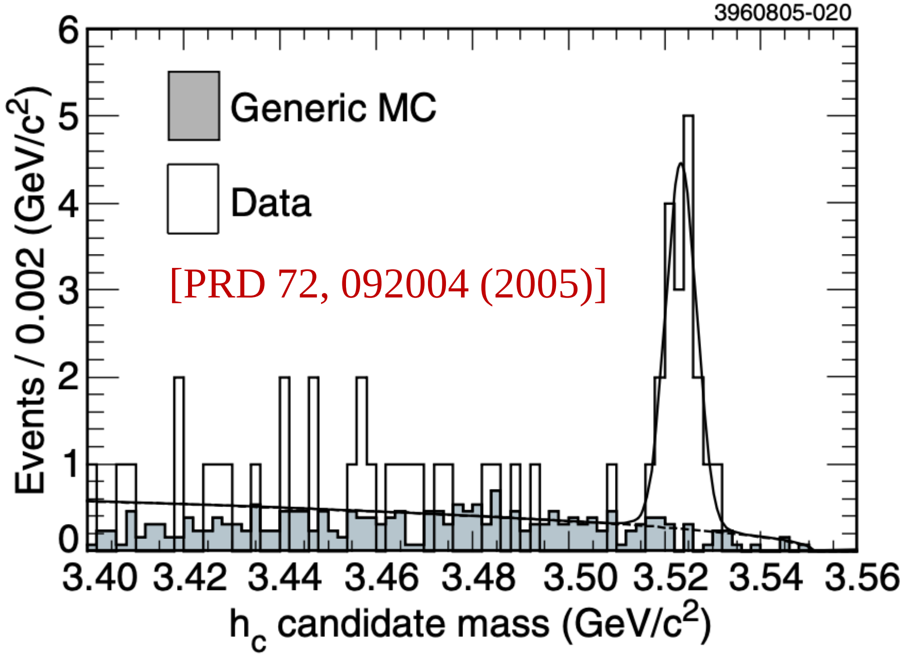
- According to QCD potential model, the hyperfine splitting between spin triplet and spin singlet is determined by the vector component and coupled channel effects.
- The hyperfine splitting between spin triplet and spin singlet of P-wave charmonia is defined as $\Delta M_{HF}(1P) \equiv \langle M(\chi_{cJ})\rangle - M(h_c)$. QCD predicts $\Delta M_{HF}(1P) = 0$.
- Before the discovery of h_c, the spin-weighted average mass of χ_{cJ} $\langle M(\chi_{cJ})\rangle = 3525.4 \pm 0.1\ \mathrm{MeV}/c^2$ [PDG 2004].



[PRD **72**, 032001 (2005)]

In 2005, the evidence of h_c was found by Fermilab E835 Collaboration via $\bar{p}p \to h_c \to \gamma\eta_c \to \gamma\gamma\gamma$ with the p-value $\mathcal{P} < 0.000\,1$ [PRD **72**, 032001 (2005)].

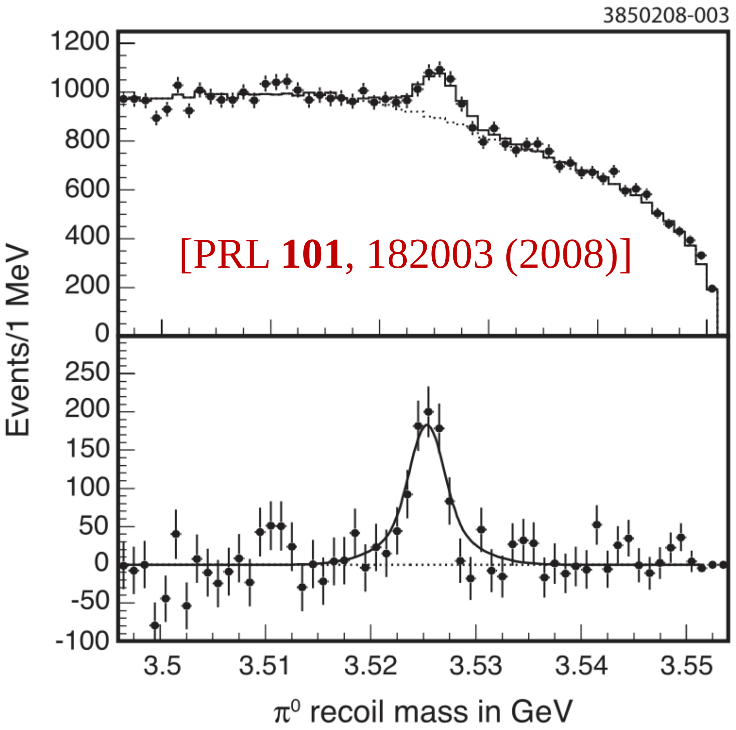
Also in 2005, CLEO Collaboration reported the observation of h_c via $\psi(2S) \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ by the reconstruction of η_c in seven hadronic decay channels [PRL **95**, 102003 (2005) and PRD 72, 092004 (2005)].



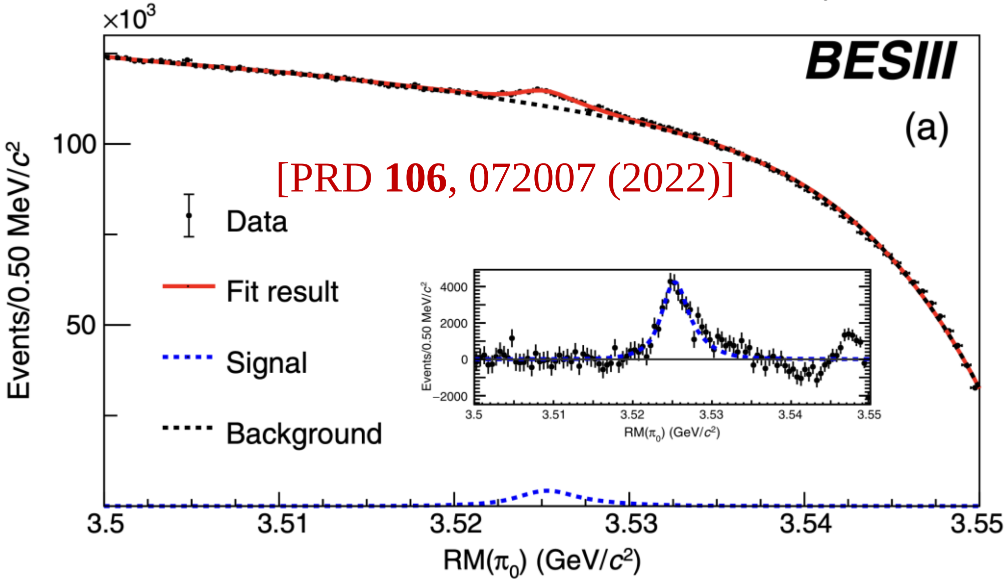
[PRD 72, 092004 (2005)]

Further measurements of h_c

- In 2008, CLEO Collaboration measured the mass of h_c and a product of branching fractions $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c)$ more precisely, with 24.5×10^6 $\psi(2S)$ events (8 times of 2005) [PRL **101**, 182003 (2008)].

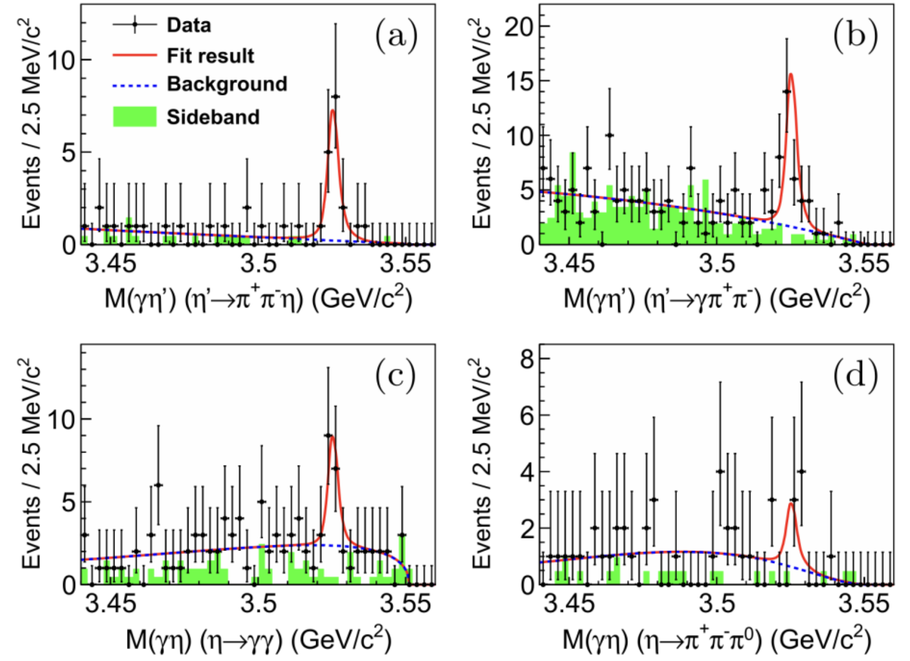


- In 2010, BESIII Collaboration measured the $\mathcal{B}(\psi(2S) \to \pi^0 h_c)$ and $\mathcal{B}(h_c \to \gamma\eta_c)$, and determined the upper limit $\Gamma(h_c) < 1.44$ MeV at the 90% confidence level [PRL **104**, 132002 (2010)].
- In 2022, BESIII Collaboration updated the h_c mass $(3525.32 \pm 0.06 \pm 0.15)$ MeV$/c^2$ and width $(0.78^{+0.27}_{-0.24} \pm 0.12)$ MeV [PRD **106**, 072007 (2022)]. Thus the $\Delta M_{HF}(1P) = 0$ is consistent between experiment and theory.

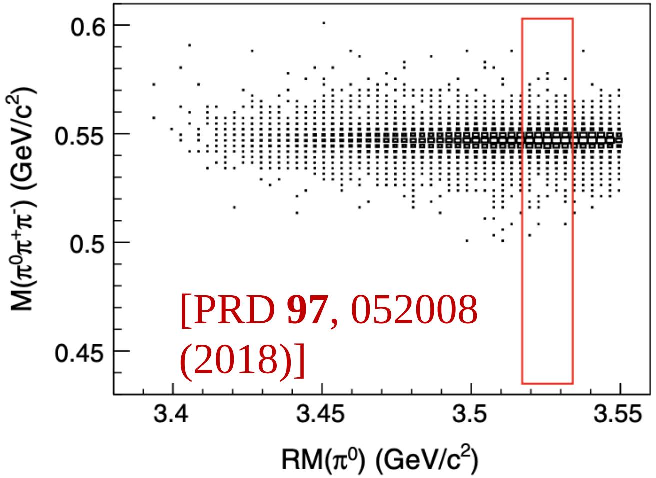


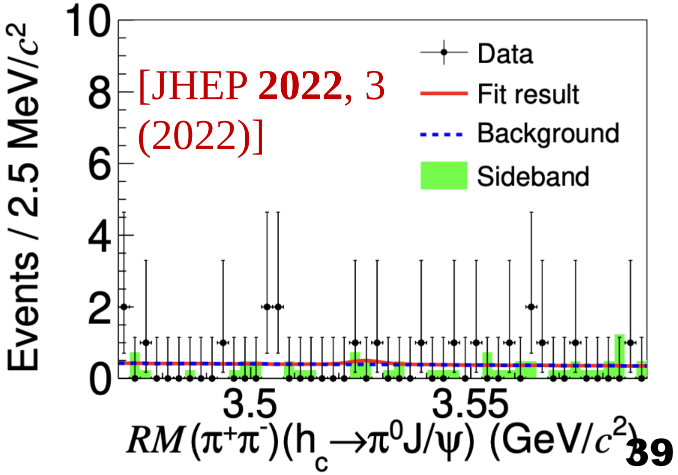
Decay modes of h_c (I) – radiative decay and hadronic transition

- Except $h_c \to \gamma\eta_c$, a dominant decay mode of h_c with the BF of 57%, more decay modes have been investigated.
- In 2016, BESIII Collaboration reported two radiative decay modes of h_c, $h_c \to \gamma\eta'$ (8.4σ) and $h_c \to \gamma\eta$ (4.0σ) [PRL **116**, 251802 (2016)].



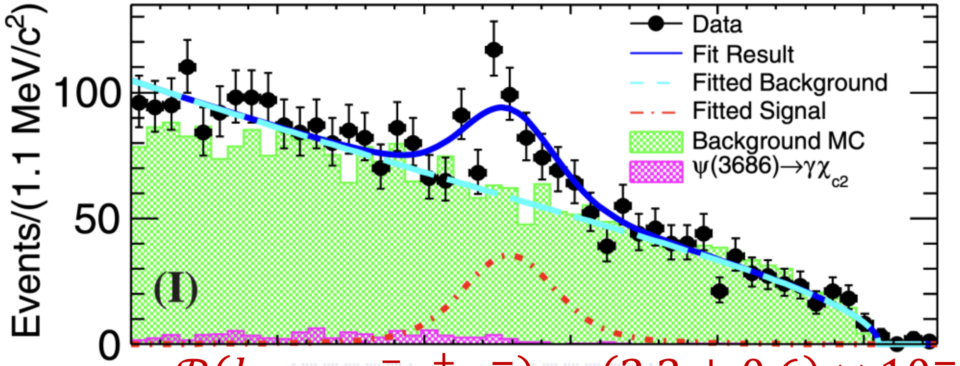
- Hadronic transitions of $h_c \to \pi\pi J/\psi$ and $h_c \to \pi^0 J/\psi$ have been predicted theoretically.
- In 2018, BESIII Collaboration searched for the process $h_c \to \pi^+\pi^- J/\psi$, and the upper limit was determined to be 2.7×10^{-3} (90% confidence) [PRD **97**, 052008 (2018)].
- In 2022, BESIII Collaboration searched for the process $h_c \to \pi^0 J/\psi$ via the reaction $e^+e^- \to \pi^+\pi^- h_c$ with the data samples between 4.189 and 4.437 GeV [JHEP **2022**, 3 (2022)].
- **Q**: Why not use $\psi(2S) \to \pi^0 h_c \to \pi^0(\pi^0 J/\psi)$?



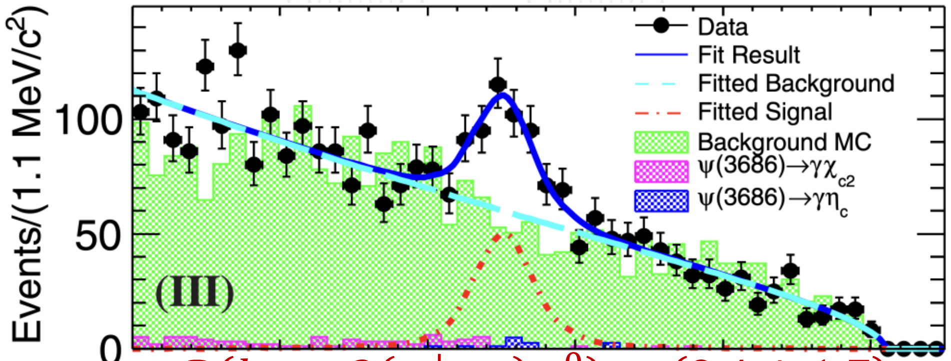


Decay modes of h_c (II) – hadronic decay

- Theoretical predictions of the BFs of $h_c \to$ *light hadrons* vary a lot in different QCD potential models.
- Since 2019, many hadronic decays of h_c have been observed by BESIII Collaboration.

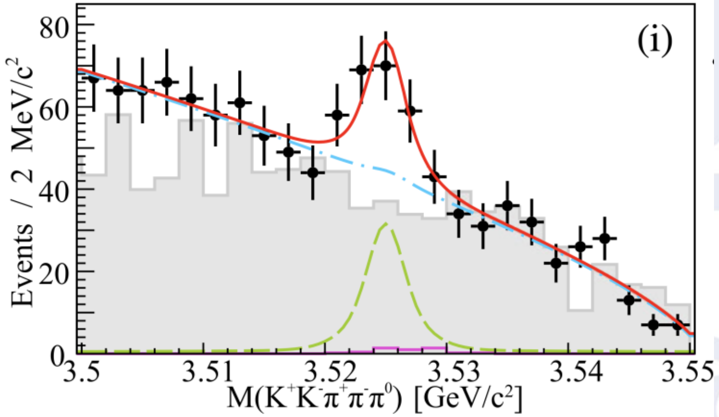


$\mathcal{B}(h_c \to p\bar{p}\pi^+\pi^-) = (3.3 \pm 0.6) \times 10^{-3}$

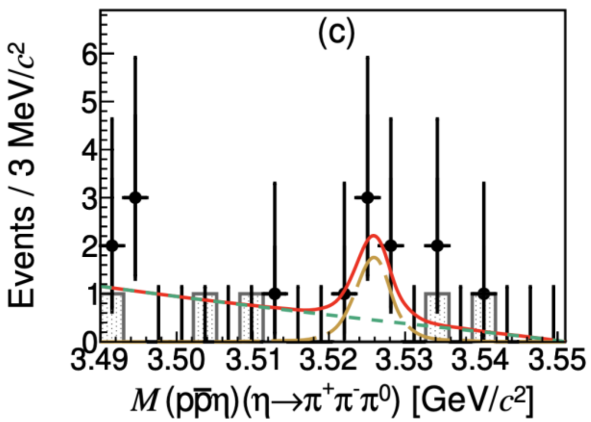


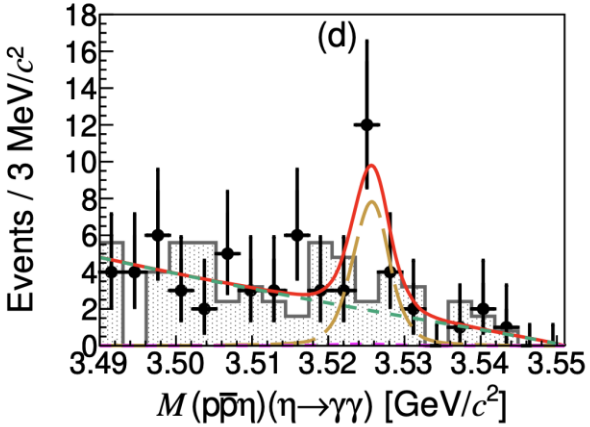
$\mathcal{B}(h_c \to 2(\pi^+\pi^-)\pi^0) = (9.4 \pm 1.7) \times 10^{-3}$

[PRD **99**, 072008 (2019)]



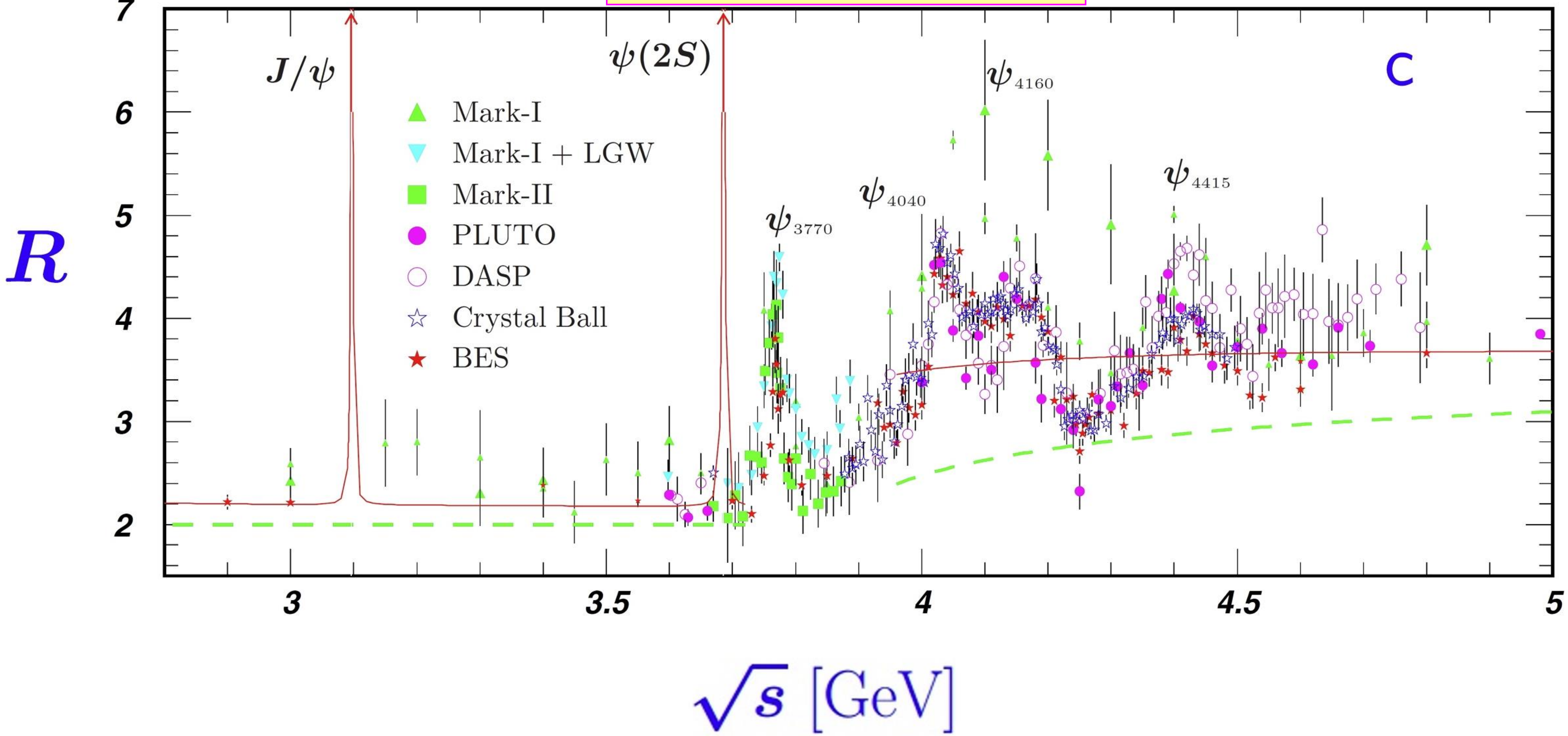
$\mathcal{B}(h_c \to K^+K^-\pi^+\pi^-\pi^0)$
$= (3.8 \pm 0.8) \times 10^{-3}$
[PRD **102**, 112007 (2020)]





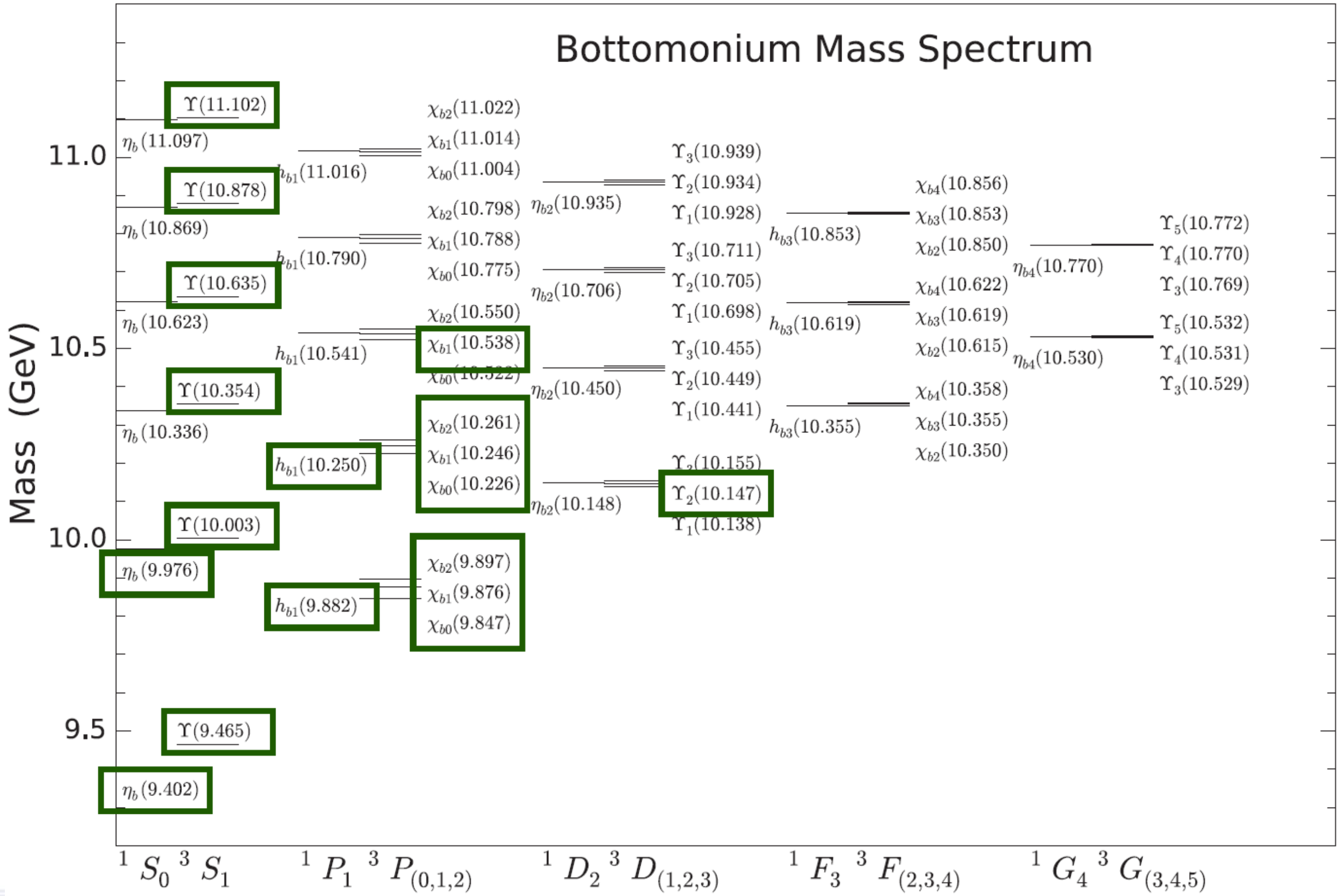
$\mathcal{B}(h_c \to p\bar{p}\eta) = (7.4 \pm 2.2) \times 10^{-4}$, [JHEP 2022, 108 (2022)]

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



Bottomonium States

Bottomonium Spectrum



$$n^{(2S+1)}L_J$$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

L = 0, 1, 2 ... correspond to S, P, D, …

$J = S + L$

$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conj.

S. Godfrey and K. Moats, Bottomonium mesons and strategies for their observation, Phys. Rev. D 92, 054034 (2015)
S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

Bottomonium Spectrum

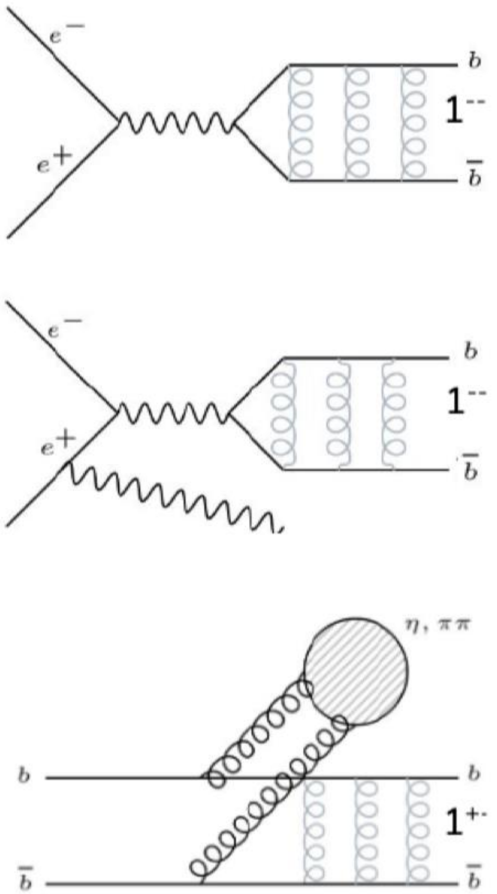
Four main ways to access Bottomonia:

- Direct production from e^+e^-: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- ISR production: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- Hadronic transitions from $\Upsilon(nS)$ through η, $\pi\pi$, etc

$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}$ … : $\Upsilon(nS)$, $\eta_b(nS)$, $h_b(nS)$, …

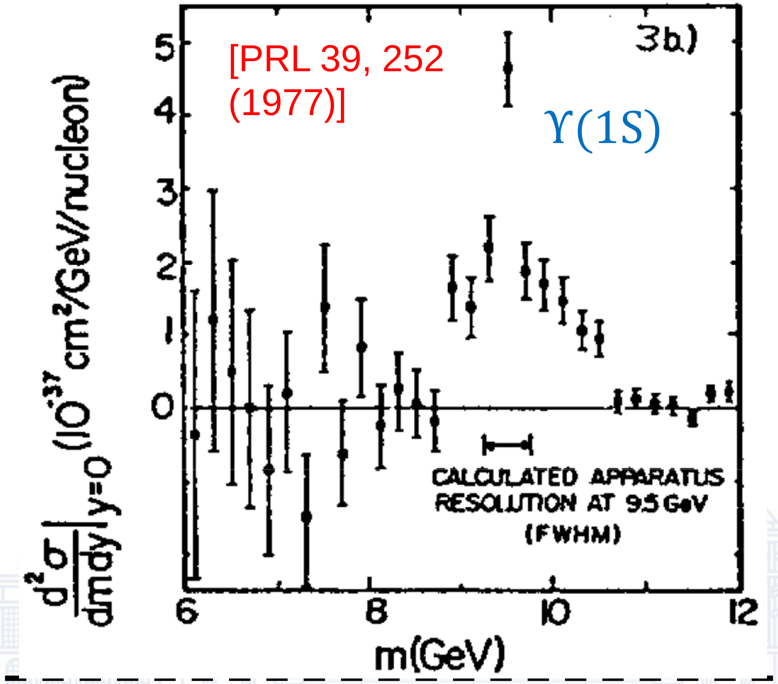
- Radiative transitions from $\Upsilon(nS)$

$J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{++}$: $\eta_b(nS)$, χ_b

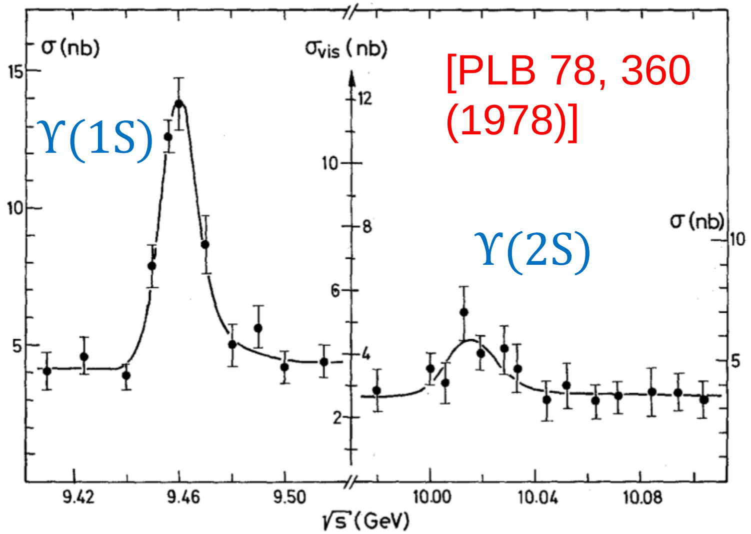


First observation of bottomonium: $\Upsilon(1S)$

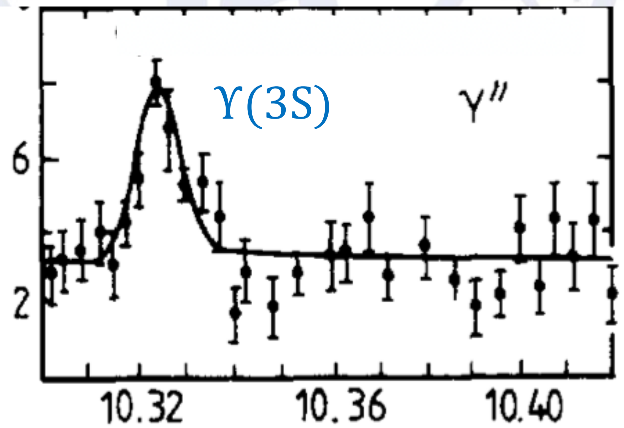
The first bottomonium resonance, i.e. $\Upsilon(1S)$, was discovered in 1977 in the bombardment of a beam of high energy protons to a stationary nuclear target [PRL 39, 252 (1977), PRL 39, 1240 (1977)].



Soon, in the e^+e^- collisions to the $\mu^+\mu^-$ final states, $\Upsilon(1S)$ was confirmed, and $\Upsilon(2S)$ and $\Upsilon(3S)$ were also observed [PLB 76, 243 (1978), PLB 76, 246 (1978), PLB 78, 360 (1978), PRL 44, 1108 (1980)].



[PRL 44, 1108 (1980)]



Masses, widths, and dominant decay modes of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

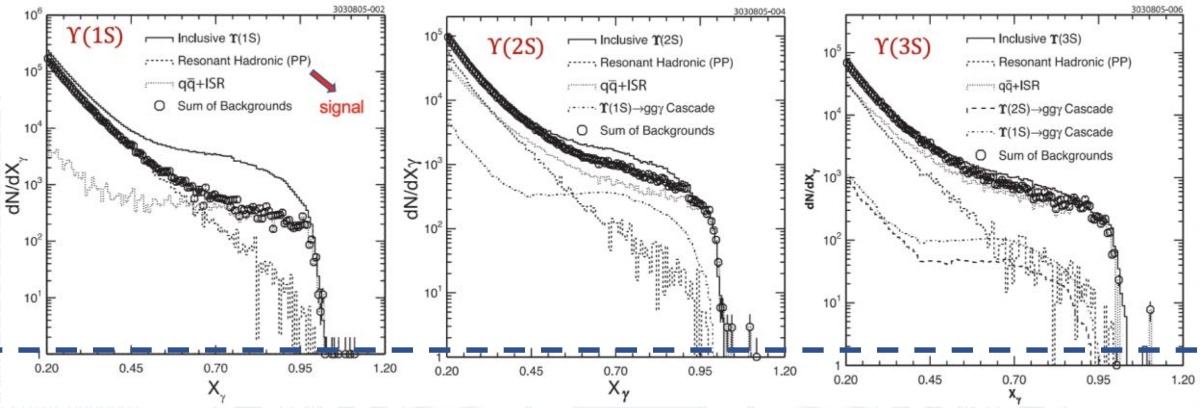
Parameters	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (MeV/c^2)	9460.40±0.10	10023.4±0.5	10355.1±0.5
Width (keV)	54.02±1.25	31.98±2.63	20.32±1.85
$\mathcal{B}(\Upsilon \to ggg)$ (%)	81.7±0.7	58.8±1.2	35.7±2.6
$\mathcal{B}(\Upsilon \to \gamma gg)$ (%)	2.2±0.6	1.87±0.28	1.1±0.2

These numbers are from the latest PDG2023.

- Below the $B\bar{B}$ threshold, $\Upsilon(1S, 2S, 3S)$ decay via this Okubo-Zweig-Iizuka (OZI) suppressed way, thus leading to a narrow natural width.
- They decay into three gluons (ggg) or two gluons plus a photon (γgg) with large branching fractions, providing an entry to many potential final states, including glueballs, light Higgs bosons, and states made of light quarks.

Recent measurement of $\mathcal{B}(\Upsilon \to \gamma gg)$ from CLEO [PRD 74, 012003 (2006)]

Photon energy spectra ($X_\gamma = p_\gamma / E_{beam}$):



"80% rule" for $\Upsilon(1S)$ and $\Upsilon(2S)$ decays?

From the pQCD calculations [PRL 34, 43 (1975)]:

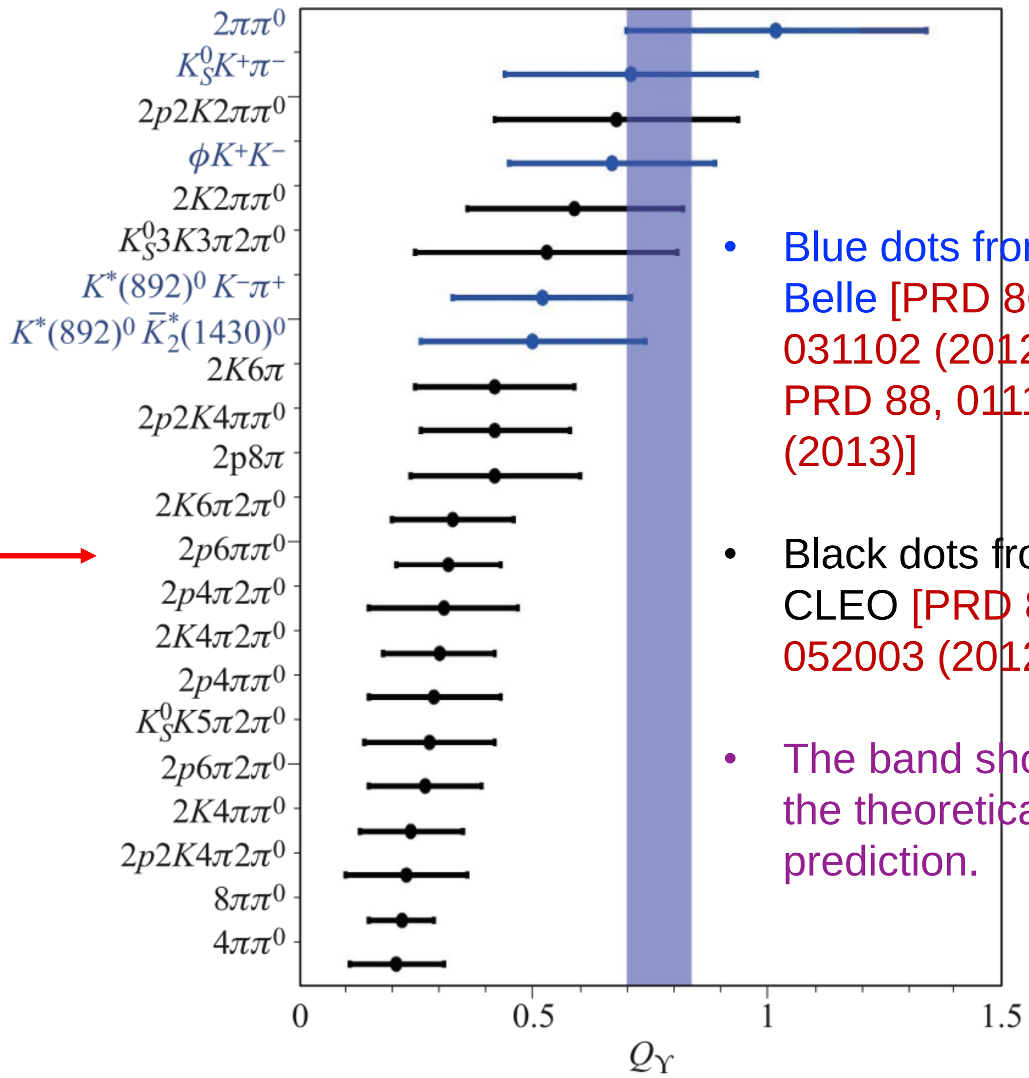
- **The 12% rule for charmonium decay**
- **The 80% rule for bottomonium decay**

$$Q_\psi = \frac{\mathcal{B}_{\psi'\to\text{hadrons}}}{\mathcal{B}_{J/\psi\to\text{hadrons}}} = \frac{\mathcal{B}_{\psi'\to e^+e^-}}{\mathcal{B}_{J/\psi\to e^+e^-}} \approx 12\%$$

$$Q_\Upsilon = \frac{\mathcal{B}_{\Upsilon(2S)\to\text{hadrons}}}{\mathcal{B}_{\Upsilon(1S)\to\text{hadrons}}} = \frac{\mathcal{B}_{\Upsilon(2S)\to e^+e^-}}{\mathcal{B}_{\Upsilon(1S)\to e^+e^-}} = 0.80 \pm 0.08$$

The 12% rule was found to be severely violated for ρπ and other Vector–Pseudoscalar and Vector–Tensor final states [PRL 51, 963 (1983), PRD 69, 072001 (2004)]. This is the so-called **"ρπ puzzle"**.

So, how about bottomonium decays?

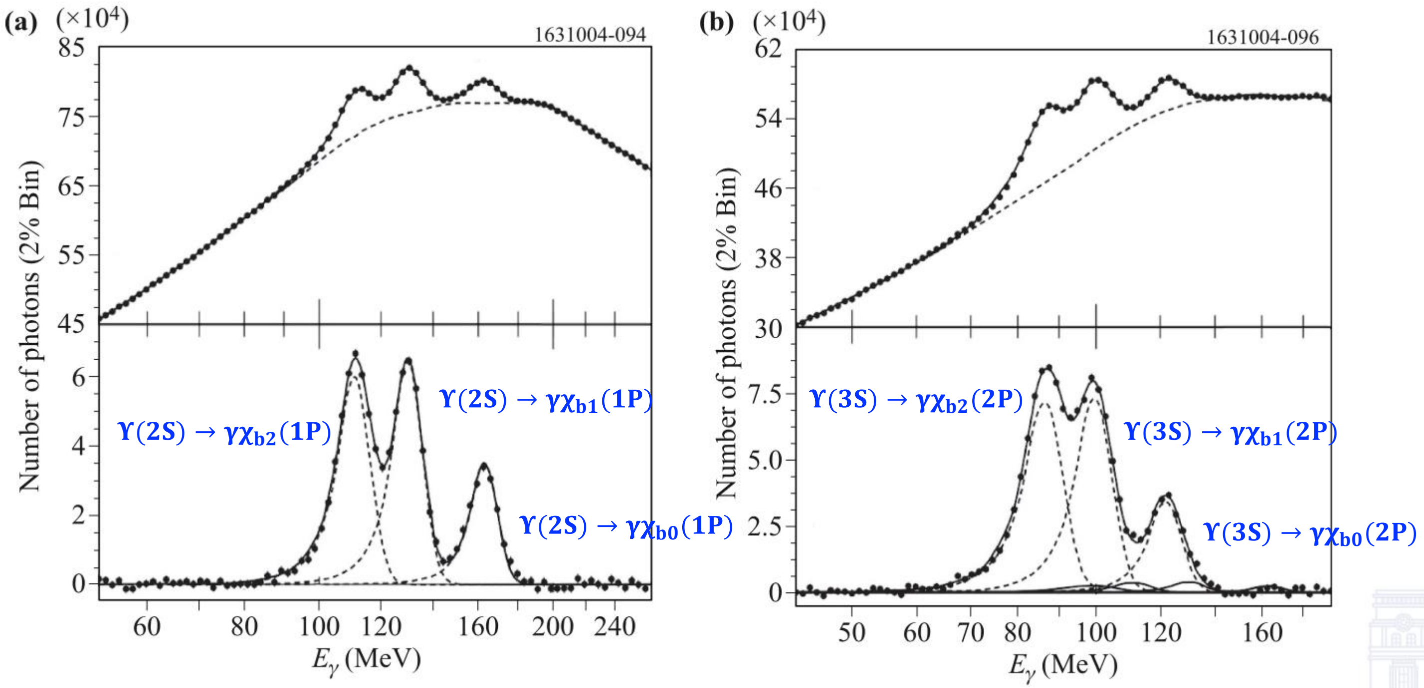


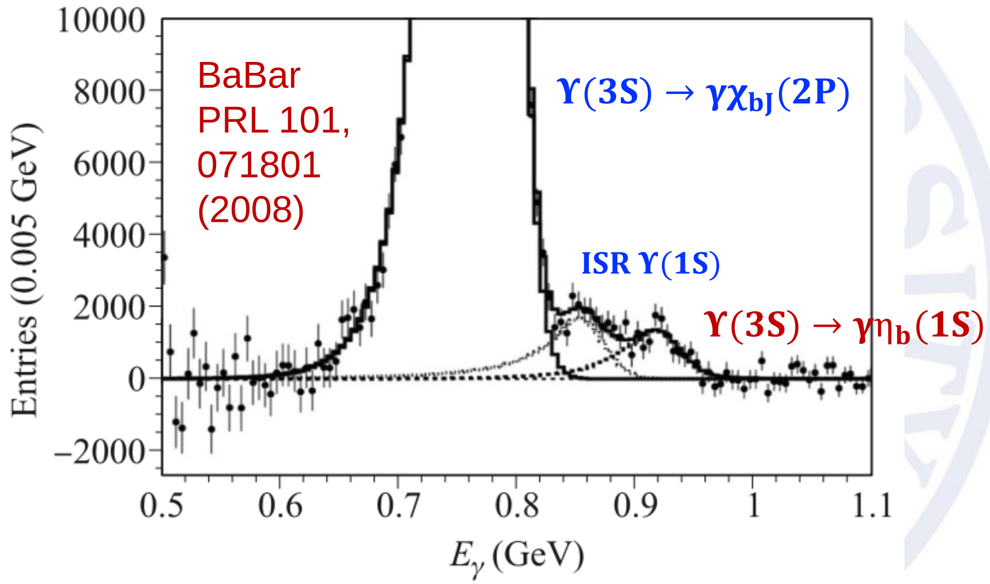
- Blue dots from Belle [PRD 86, 031102 (2012), PRD 88, 011102 (2013)]
- Black dots from CLEO [PRD 86, 052003 (2012)]
- The band shows the theoretical prediction.

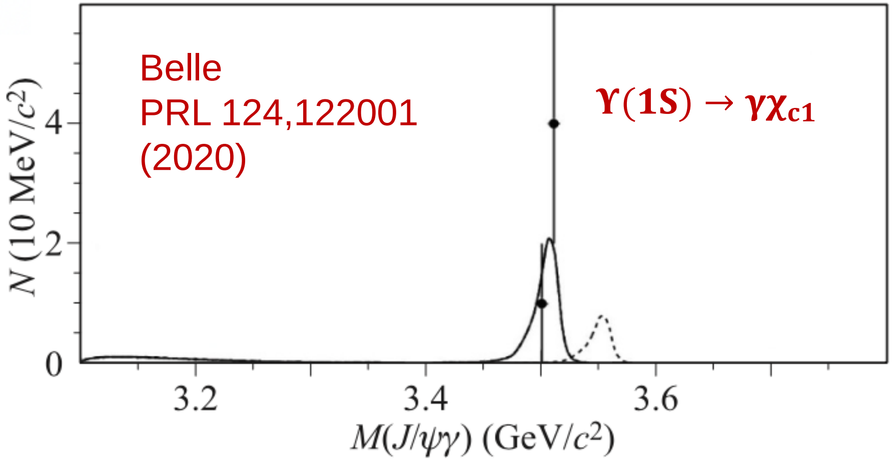
Radiative decays of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

The radiative decays of $\Upsilon(nS)$ can be used to search for η_b and χ_{bJ}.

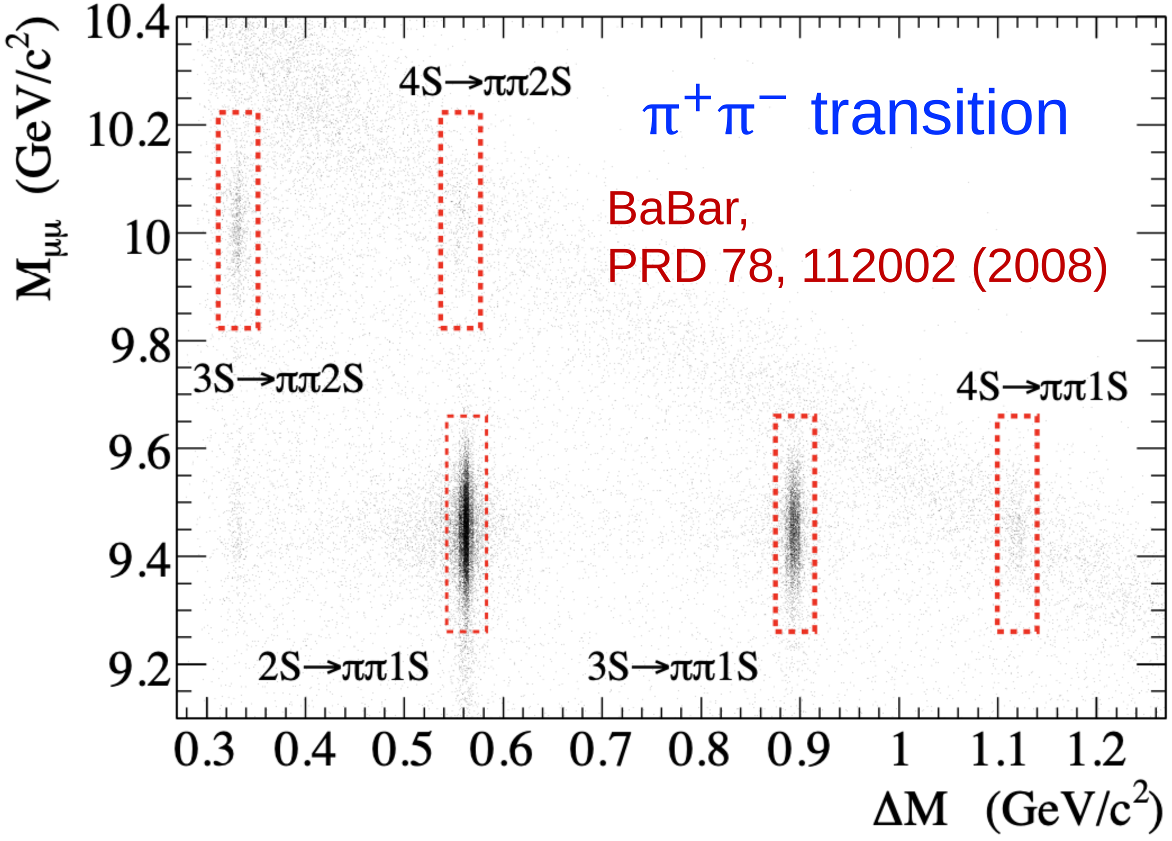
From CLEO, PRL 94, 032001 (2005)



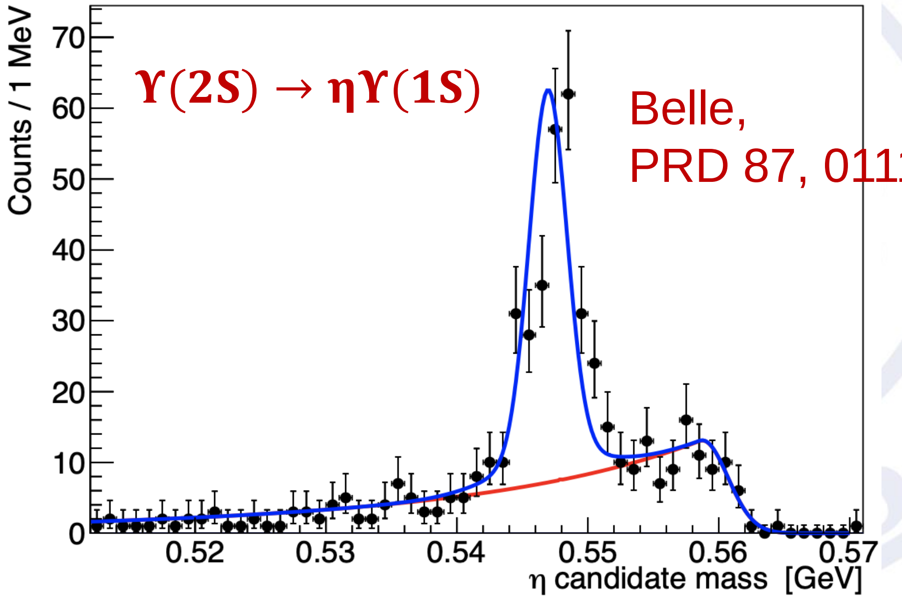




Hadronic transitions among $\Upsilon(nS)$



η transition



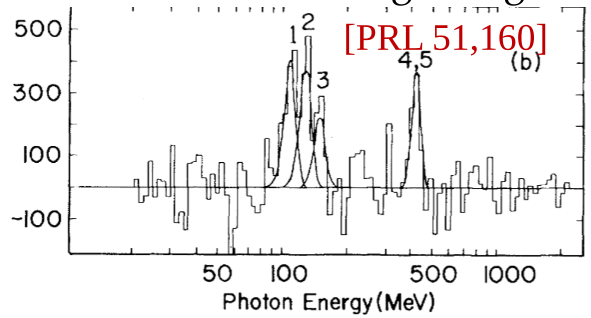
$$\frac{\mathcal{B}(\Upsilon(2S)\to\eta\Upsilon(1S))}{\mathcal{B}(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))} = (1.99\pm0.14\pm0.11)\times10^{-3}$$

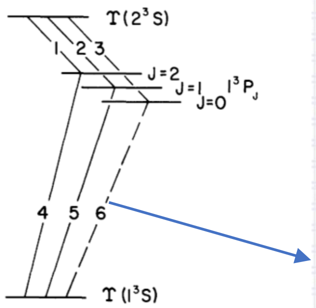
This ratio is slightly lower than the value calculated by the QCD multipole expansion method in Ref. [Front. Phys. 1, 19 (2006)].

First Observation of $\chi_{bJ}(1P)$:

1^3P_J states, observed later than $\chi_b(2P)$.

In 1983, the $\chi_{bJ}(1P)$ are found via the γ energy spectrum of the $\Upsilon(2S) \to \gamma\chi_{bJ}(1P) \to \gamma\gamma\Upsilon(1S)$ by CUSB detector @ Cornell Electron Storage Ring.



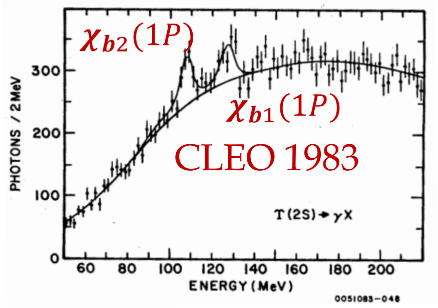


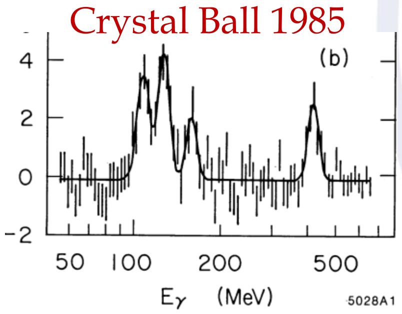
$\chi_{b0}(1P)$:
$M = 9900 \pm 3$ MeV
$\Gamma_{E1} = 4.9 \pm 1.0$ keV

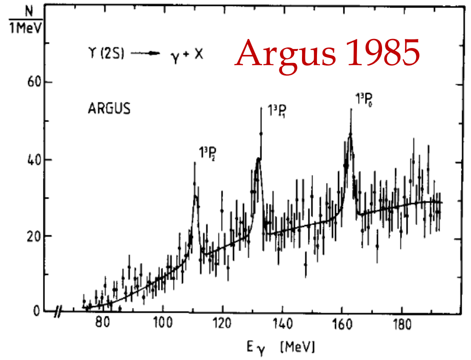
$\chi_{b1}(1P)$:
$M = 10256 \pm 5$MeV
$\Gamma_{E1} = 8.4 \pm 1.4$ keV

$\chi_{b2}(1P)$: not calculated

CLEO[PRL 52, 799], Crystal Ball[PRL 54,2195], Argus[PLB 160, 2195] measured the mass of $\chi_{b2}(1P)$ in 1985, with the same method as CUSB.





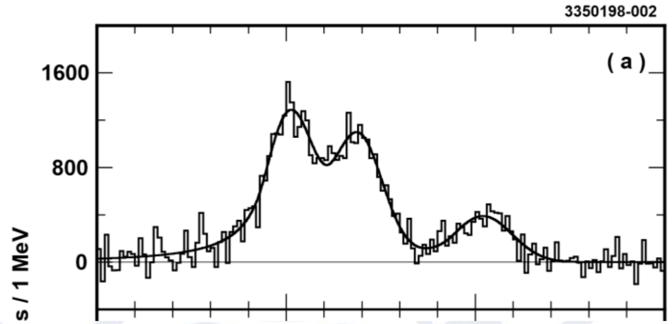


$\chi_{b0}(1P)$:
$M = 9859.6 \pm 2.1$MeV
$\Gamma < 1.0$ MeV@90% CL

$\chi_{b1}(1P)$:
$M = 9890.5 \pm 1.7$MeV
$\Gamma < 2.6$ MeV@90% CL

$\chi_{b2}(1P)$:
$M = 9911.9 \pm 1.5$MeV
$\Gamma < 2.6$ MeV@90% CL

In 1998, CLEO gave very clear results. [PRL 92, 142001]



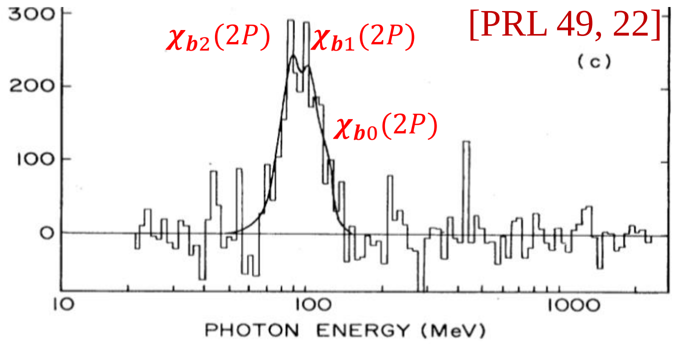
$\chi_{b0}(1P)$:
$M = 9863.0 \pm 1.4$ MeV

$\chi_{b1}(1P)$:
$M = 9894.5 \pm 0.7$ MeV

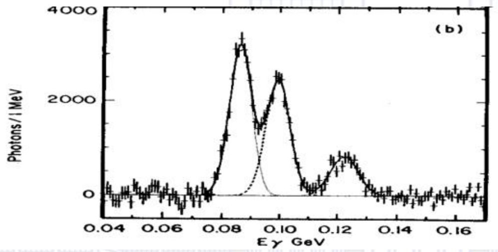
$\chi_{b2}(1P)$:
$M = 9912.5 \pm 0.7$MeV

First Observation of $\chi_{bJ}(2P)$:

In 1982, the $\chi_{bJ}(2P)$ are found via the γ energy spectrum of the $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$ by CUSB detector @ Cornell Electron Storage Ring.



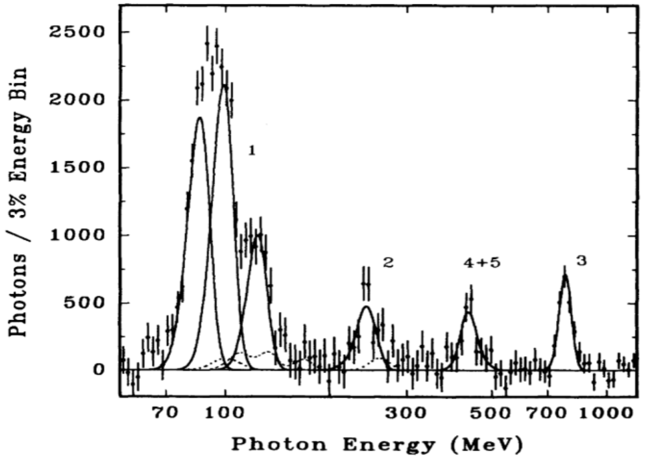
In 1991, CLEO saw very clear $\chi_{bJ}(2P)$ signal with the same method.



But masses are not measured.

CUSB found the decays of $\chi_{bJ}(2P) \to \gamma\Upsilon(1,2S)$ in 1992. [PRD 46, 1928]

1. $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$
2. $\chi_{bJ}(2P) \to \gamma\Upsilon(2S)$
3. $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$
4. $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$
5. $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$



Mass differences between $\chi_{bJ}(2P)$ and $\chi_{bJ}(1P)$ are extracted to be:

$$\mathrm{M}(\chi_{b2}(2P)) - \mathrm{M}(\chi_{b2}(1P)) = 13.10 \pm 0.24\ \mathrm{MeV}$$

$$\mathrm{M}(\chi_{b1}(2P)) - \mathrm{M}(\chi_{b1}(1P)) = 23.5 \pm 1.0\ \mathrm{MeV}$$

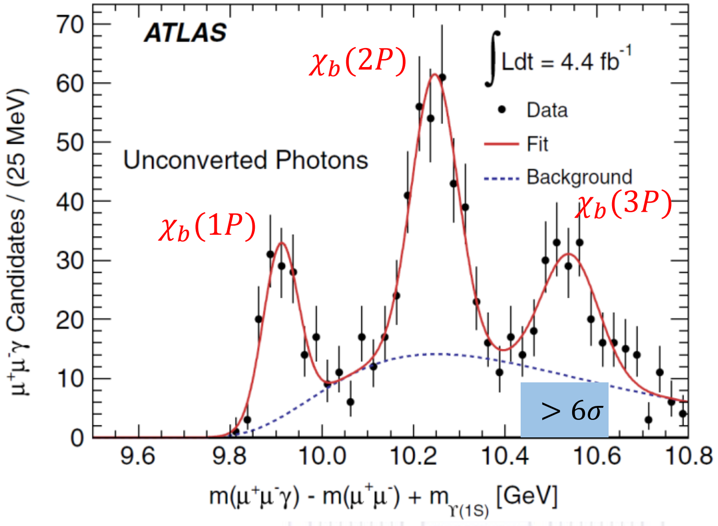
$$\mathrm{M}(\chi_{b0}(2P)) - \mathrm{M}(\chi_{b0}(1P)) = 23.8 \pm 1.7\ \mathrm{MeV}$$

First Observation of $\chi_b(3P)$

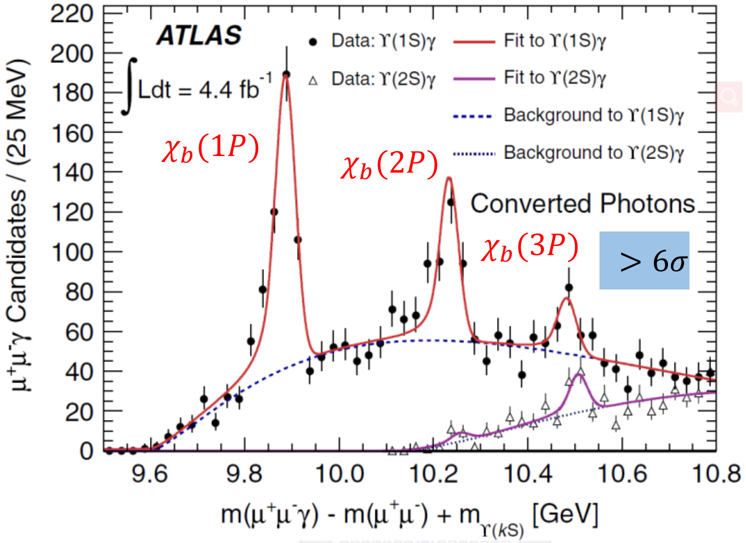
[PRD 36, 3401 (1987); PRD 38, 279 (1988)]

It is predicted that the $\chi_b(3P)$ has an average mass of ~10.52 GeV, with hyperfine mass splitting of 10~20 MeV.

In 2012, ATLAS reported the first observation of $\chi_b(3P) \to \gamma\Upsilon(1S,2S)[\to \mu^+\mu^-]$, in which the photon is reconstructed either through conversion to e^+e^-or by direct calorimetric measurement. [PRL 108, 152001 (2012)]



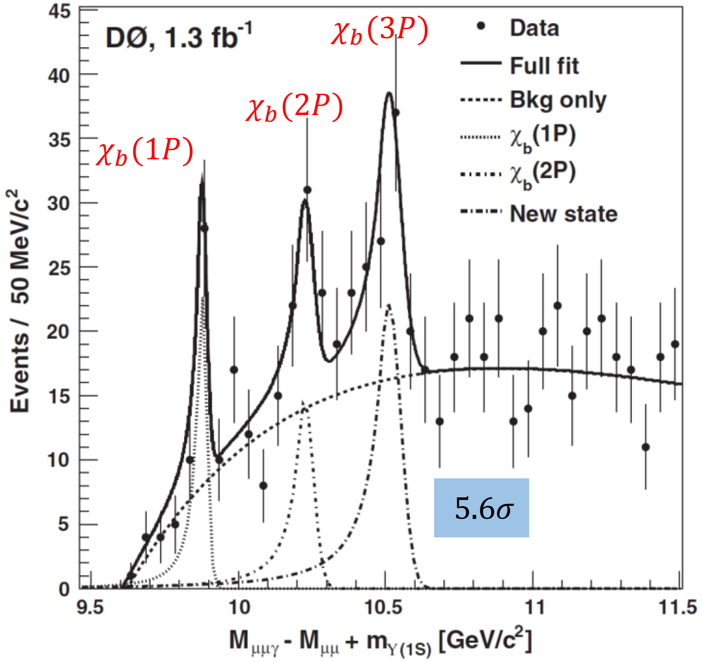
$M[\chi_b(3P)] = 10541 \pm 11 \pm 30$ MeV



$M[\chi_b(3P)] = 10530 \pm 5 \pm 9$ MeV

The mass resolution for the converted photon candidates is found to be 16~20 MeV, of similar magnitude to the hyperfine splittings.

Not long after, D0 also observed $\chi_b(3P) \to \gamma\Upsilon(1S)[\to \mu^+\mu^-]$. [PRD 86, 031103(R) (2012)]



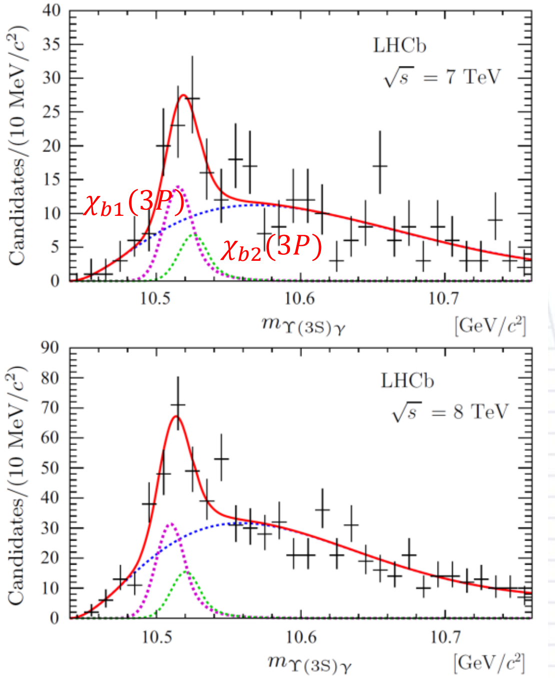
$M[\chi_b(3P)] = 10551 \pm 14 \pm 17$ MeV

Hyperfine Mass Splitting of $\chi_b(3P)$

[PRD 36, 3401 (1987); PRD 38, 279 (1988)]

It is predicted that the $\chi_b(3P)$ has an average mass of ~10.52 GeV, with hyperfine mass splitting of 10~20 MeV.

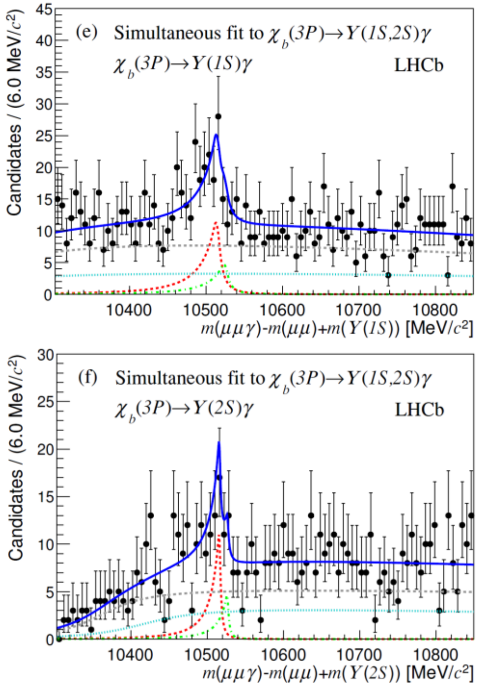
In 2014, LHCb observed $\chi_b(3P) \to \gamma\Upsilon(3S)$ for the first time. [EPJC 74, 3092 (2014)]



Assuming mass splitting $\Delta M = 10.5$ MeV

$M[\chi_{b1}(3P)] = 10511.3 \pm 1.7 \pm 2.5$ MeV

LHCb also measured $\chi_b(3P)$ mass in $\gamma\Upsilon(1S,2S)$ decay modes. [JHEP 10, 088 (2014)]



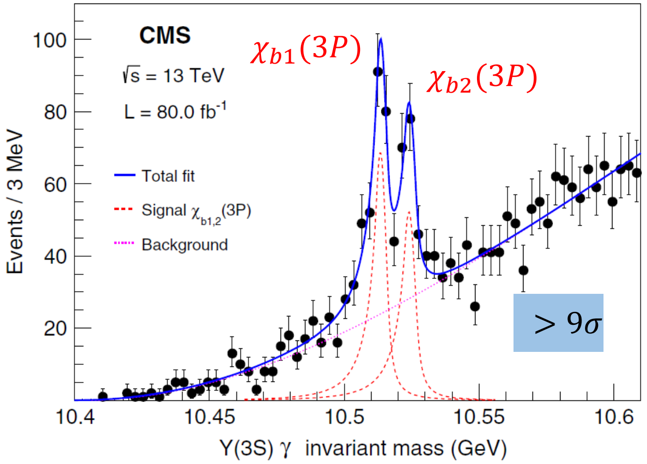
6.9σ

Assuming mass splitting $\Delta M = 10.5$ MeV

$M[\chi_{b1}(3P)] = 10515.7^{+2.2+1.5}_{-3.9-2.1}$ MeV

In 2018, CMS observed $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ through $\gamma\Upsilon(3S)[\to \mu^+\mu^-]$ mode. [PRL 121, 092002 (2018)]

$\chi_{bJ}(3P)$ mass resolution: 2.2 MeV!



$> 9\sigma$

$M[\chi_{b1}(3P)] = 10513.42 \pm 0.41 \pm 0.18$ MeV

$M[\chi_{b2}(3P)] = 10524.02 \pm 0.57 \pm 0.18$ MeV

$\Delta M = 10.60 \pm 0.64 \pm 0.17$ MeV

Decays of χ_b:

The branching fractions of the known decay modes are far below 100%, in which $\chi_b \to \gamma\Upsilon(1S)$ are dominant.

states	Known channels	$\chi_b \to \gamma\Upsilon(nS)$
$\chi_{b0}(1P)$	1.94%	1.94%
$\chi_{b1}(1P)$	52.7%	35.2%
$\chi_{b2}(1P)$	<26.0%	18.0%
$\chi_{b0}(2P)$	1.38%	1.38%
$\chi_{b1}(2P)$	38.4%	29.6%
$\chi_{b2}(2P)$	<27.9%	25.5%
$\chi_{b1}(3P)$	-	Only observed mode
$\chi_{b2}(3P)$	-	Only observed mode

Open question:

- The more hadronic decay modes of χ_b are needed to be found.
  - Prob the physics of soft gluon emission and hadronization.
  - Study the non-perturbative QCD
- Can exotic states be found?
  - Glueball?
  - XYZ via $h\chi_{b0}$ final states or in χ_{b0} decays daughters?
- Fragmentation function: part of the great blueprint for QCD
- Where is $\chi_{b0}(3P)$?
- Detect new physics?
  - Invisible decay?
  - Supersymmetric quarkonia transition?

$\Upsilon(4S)$ $I^G(J^{PC}) = 0^-(1^{--})$

also known as $\Upsilon(10580)$

B factories

$\Upsilon(4S)$ MASS	10579.4 ± 1.2 MeV	
$\Upsilon(4S)$ WIDTH	20.5 ± 2.5 MeV	

$\Upsilon(4S)$ DECAY MODES

Expand all decays

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$B\bar{B}$	$> 96\%$	CL=95%	326
Γ_2	B^+B^-	$(51.4 \pm 0.6)\%$		331
Γ_3	D_s^+ anything + c.c.	$(17.8 \pm 2.6)\%$		
Γ_4	$B^0\bar{B}^0$	$(48.6 \pm 0.6)\%$		326
Γ_5	$J/\psi K_S^0 + (J/\psi, \eta_c) K_S^0$	$< 4 \times 10^{-7}$	CL=90%	
Γ_6	non-$B\bar{B}$	$< 4\%$	CL=95%	

$\Upsilon(10860)$ $I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(10860)$ MASS	$10885.2^{+2.6}_{-1.6}$ MeV
$\Upsilon(10860)$ WIDTH	37 ± 4 MeV

$\Upsilon(10860)$ DECAY MODES

Expand all decays

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$B\bar{B}X$	$(76.2^{+2.7}_{-4.0})\%$		
Γ_2	$B\bar{B}$	$(5.5 \pm 1.0)\%$		1322
Γ_3	$B\bar{B}^* +$ c.c.	$(13.7 \pm 1.6)\%$		
Γ_4	$B^*\bar{B}^*$	$(38.1 \pm 3.4)\%$		1127
Γ_5	$B\bar{B}^{(*)}\pi$	$< 19.7\%$	CL=90%	1015
Γ_6	$B\bar{B}\pi$	$(0.0 \pm 1.2)\%$		1015
Γ_7	$B^*\bar{B}\pi + B\bar{B}^*\pi$	$(7.3 \pm 2.3)\%$		
Γ_8	$B^*\bar{B}^*\pi$	$(1.0 \pm 1.4)\%$		739
Γ_9	$B\bar{B}\pi\pi$	$< 8.9\%$	CL=90%	550
Γ_{10}	$B_s^{(*)}\bar{B}_s^{(*)}$	$(20.1 \pm 3.1)\%$		904
Γ_{11}	$B_s\bar{B}_s$	$(5 \pm 5) \times 10^{-3}$		904
Γ_{12}	$B_s\bar{B}_s^* +$ c.c.	$(1.35 \pm 0.32)\%$		
Γ_{13}	$B_s^*\bar{B}_s^*$	$(17.6 \pm 2.7)\%$		543

Bs factory

$\Upsilon(11020)$ $I^G(J^{PC}) = 0^-(1^{--})$

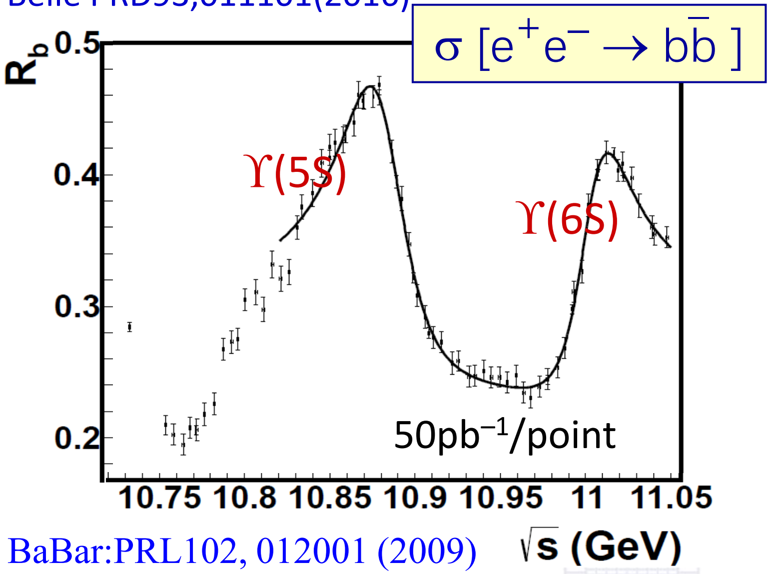
$\Upsilon(11020)$ MASS	11000 ± 4 MeV
$\Upsilon(11020)$ WIDTH	24^{+8}_{-6} MeV

$\Upsilon(11020)$ DECAY MODES

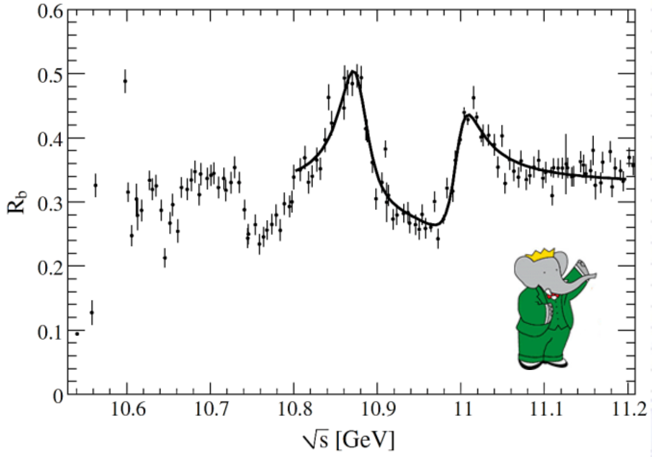
	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	e^+e^-	$(5.4^{+1.9}_{-2.1}) \times 10^{-6}$		5500
Γ_2	$\Upsilon(1S)\pi^+\pi^-$			1408
Γ_3	$\Upsilon(2S)\pi^+\pi^-$			894
Γ_4	$\Upsilon(3S)\pi^+\pi^-$			564
Γ_5	$\chi_{bJ}(1P)\pi^+\pi^-\pi^0$	$(9^{+9}_{-8}) \times 10^{-3}$		1007
Γ_6	$\chi_{b1}(1P)\pi^+\pi^-\pi^0$	seen		975
Γ_7	$\chi_{b2}(1P)\pi^+\pi^-\pi^0$	seen		956

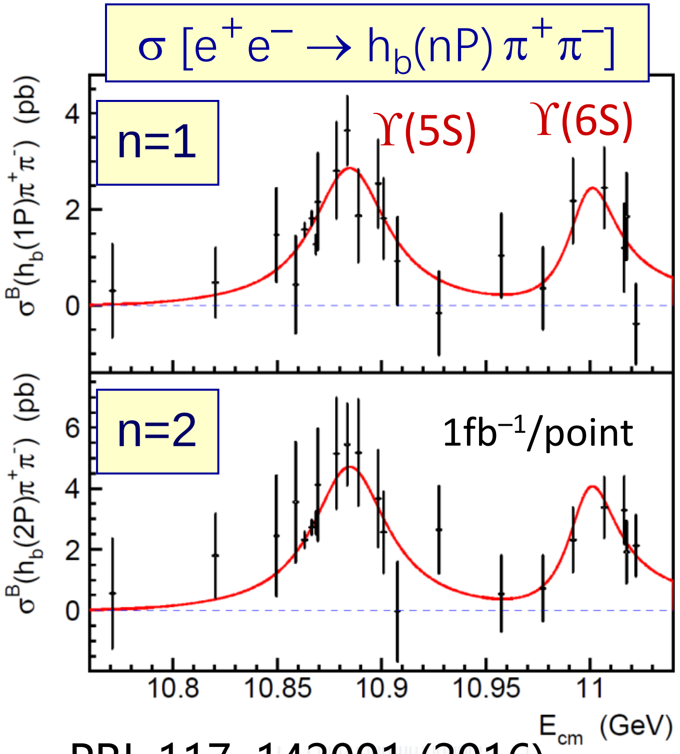
Υ(5S) and Υ(6S)

Belle PRD93,011101(2016)

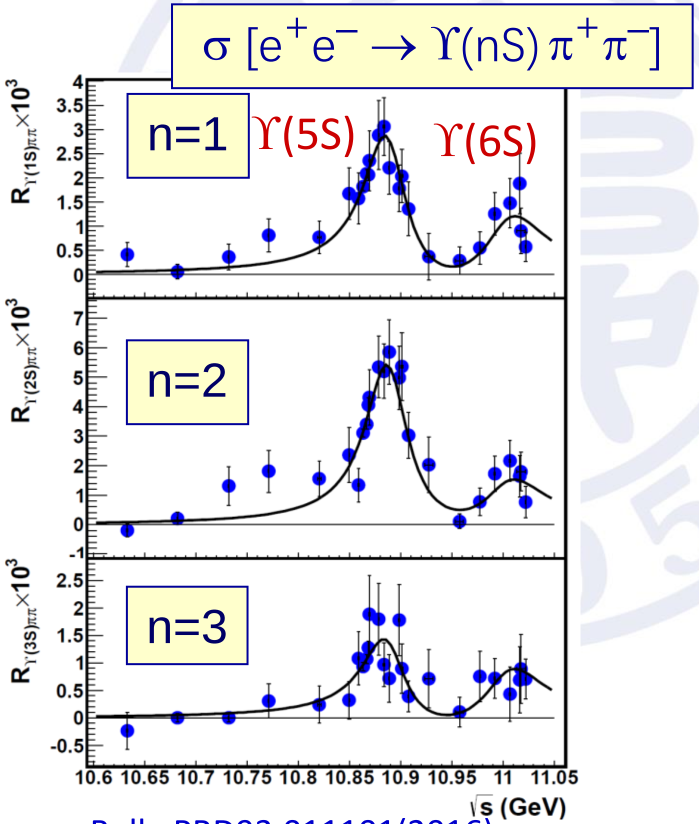


BaBar:PRL102, 012001 (2009)





PRL 117, 142001 (2016)



Belle PRD93,011101(2016)

Only Υ(5S) and Υ(6S) peaks in all cross sections.

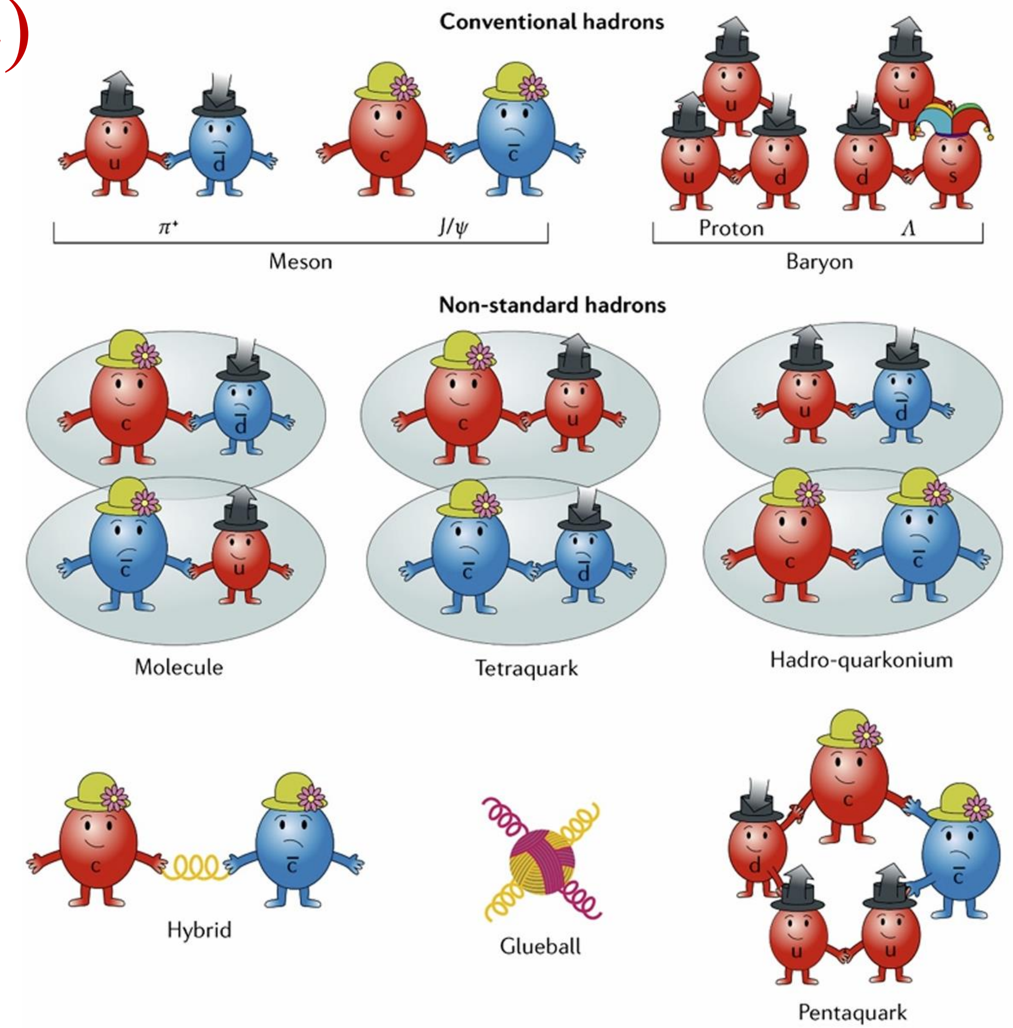
Exotic States

Note: In the light meson energy range exotic states overlap with conventional states; in the charmonium/bottomonium states the density is lower and also the overlap, but it is easier.

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
  - …



Nature Reviews Physics 1, 480 (2019)

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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

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**.

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

Gell-Mann in his quark model paper has mentioned "exotic states" since 1964. After that, many experiments focused on finding exotic hadrons.

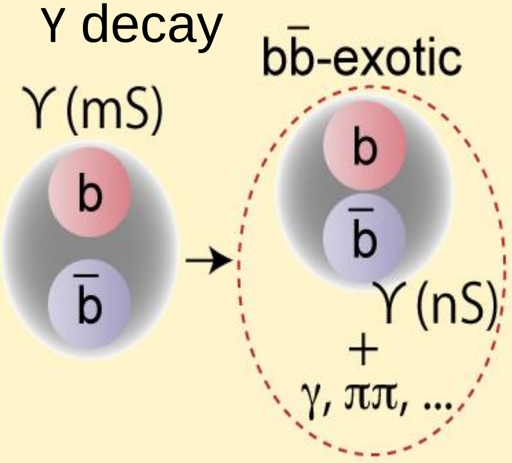
A bit history on exotics hunting

- "The absence of exotics is one of the most obvious features of QCD" – R. L. Jaffe, 2005
- Deuteron ➔ H state, $\Omega^-\Omega^-$ bound state, …
- No solid signature of glueballs
- Pentaquark state appeared and disappeared

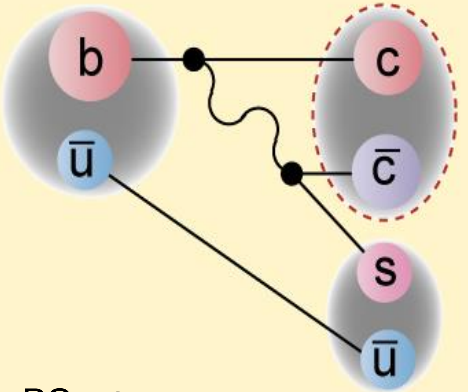
  ("The story of pentaquark shows how poorly we understand QCD" – F. Wilczek, 2005)
- There are lots of new states from low to high mass in various experiments! Are they normal or exotic?

Variety of recorded reactions

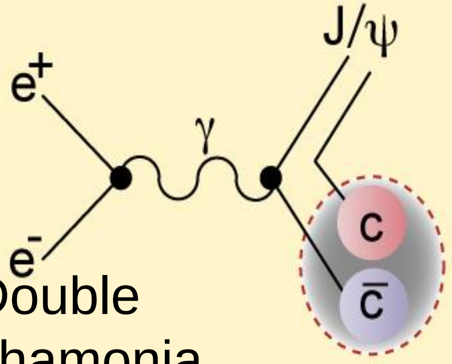
Υ decay



B decay



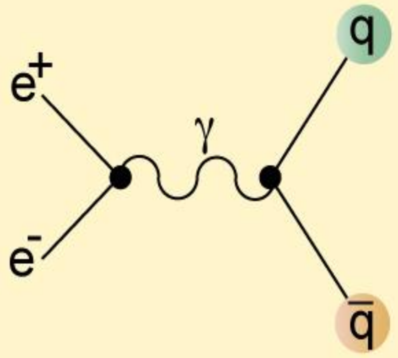
$J^{PC}=0^{-+}, 1^{--}, 1^{++}$ in factorization limit.



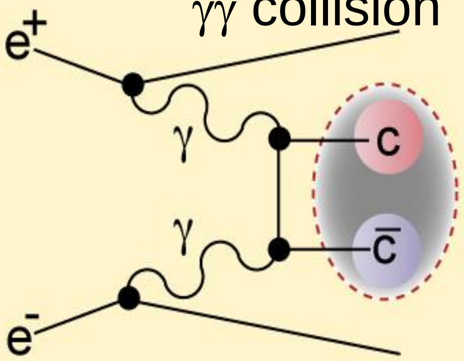
Double chamonia production

C=+1.

Continuum

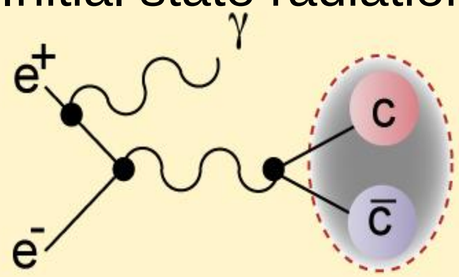


γγ collision



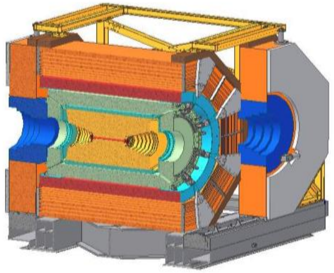
$J^{PC}=0^{-+}, 2^{++}$.

Initial state radiation

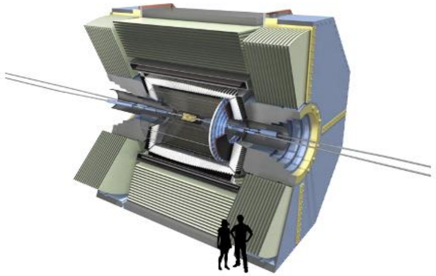


$J^{PC}=1^{--}$.

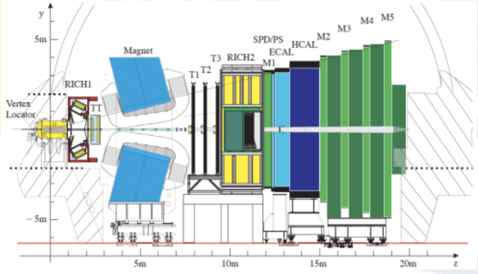
Main suppliers



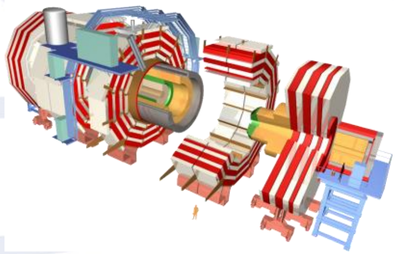
BESIII



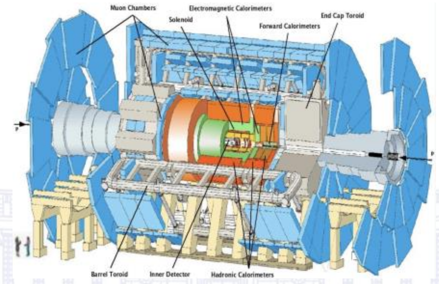
Belle (II)



LHCb



CMS



ATLAS

BaBar

XYZ states

Success=X+Y+Z

Classification:

- $Q\bar{Q}q\bar{q}$

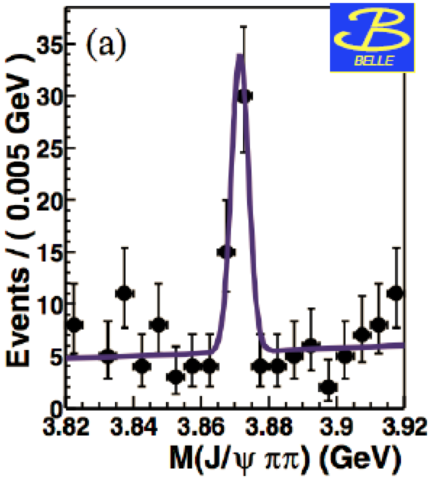
X: Neutral, $J^{PC} \neq 1^{--}$; Y: Neutral, $J^{PC} = 1^{--}$; Z: Charged

- $Q\bar{Q}qqq$: P_c^+

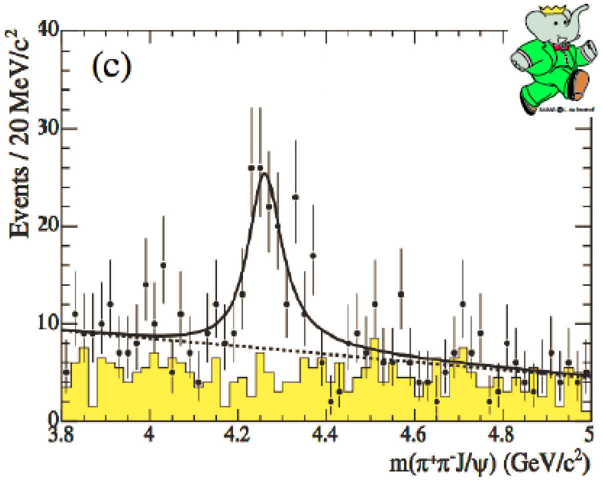
- Study of exotic hadrons can
  - provide new insights into internal structure and dynamics of hadrons
  - act as a unique probe to non-perturbative behavior of QCD

- Quarkonium: $q\bar{q}$, the simplest system of a hadron.
- Below $D\bar{D}/B\bar{B}$ thresholds – both charmonium and bottomonium are successful stories of QCD.
- But there are many exotic states observed in the past decade, and they are hard to fit in the two families.

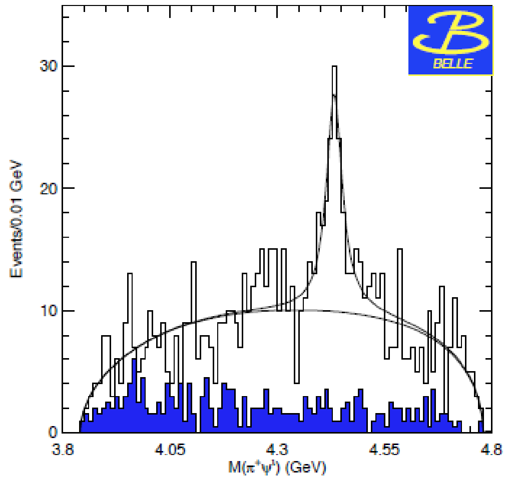
"X Y Z" – *the beginning*



$X(3872)$
PRL 91, 262001 (2003)
$B^{\pm} \to K^{\pm}[\pi^+\pi^- J/\psi]$



$Y(4260)$
PRL 95, 142001 (2005)
$e^+e^- \to \gamma[\pi^+\pi^- J/\psi]$



$Z_c(4430)^{\pm}$
PRL 100, 142001 (2008)
$B \to K[\pi^{\pm}\psi']$

X States

Due to the time limitation, it is impossible to cover all of the XYZ states in this lecture. I select some typical results.

$\chi_{c1}(3872)$

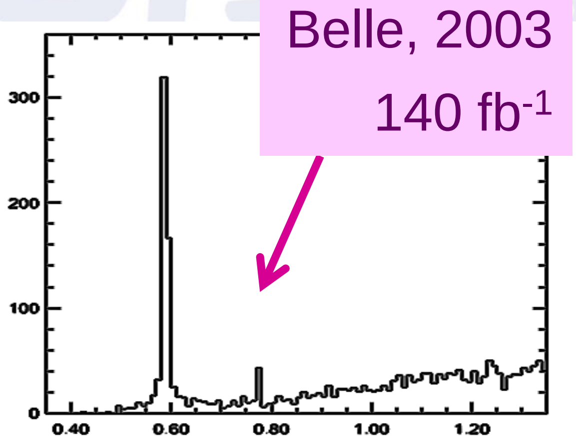
$I^G(J^{PC}) = 0^+(1^{++})$

also known as $X(3872)$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non- $q\bar{q}$ states. First observed by CHOI 2003 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state. Isovector hypothesis excluded by AUBERT 2005B and CHOI 2011 . AAIJ 2013Q perform a full five-dimensional amplitude analysis of the angular correlations between the decay products in $B^+ \to \chi_{c1}(3872)K^+$ decays, where $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$, which unambiguously gives the $J^{PC} = 1^{++}$ assignment under the assumption that the $\pi^+\pi^-$ and J/ψ are in an $S\!-\!wave$. AAIJ 2015AO extend this analysis with more data to limit $D\!-\!wave$ contributions to $< 4\%$ at 95% CL. See the review on ``Spectroscopy of Mesons Containing Two Heavy Quarks."

What is the X(3872)?

- Mass: Very close to D^0D^{*0} threshold
- Width: Very narrow, 1.19 ± 0.21 MeV [LHCb, PRD102, 092005; JHEP (2008) 123]
- $J^{PC}=1^{++}$
- 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)→γ+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?



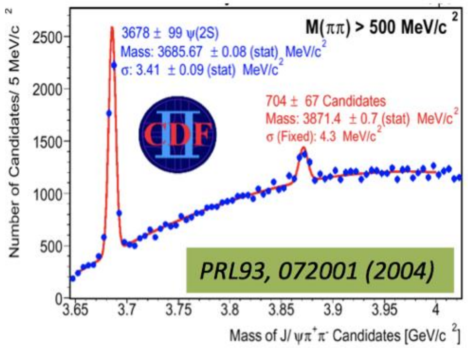
M(ππJ/ψ) –M(J/ψ) [GeV]

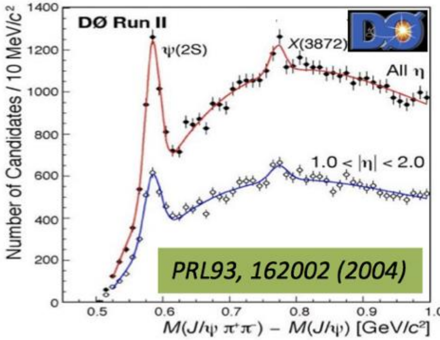
X(3872)→J/ψπ⁺π⁻

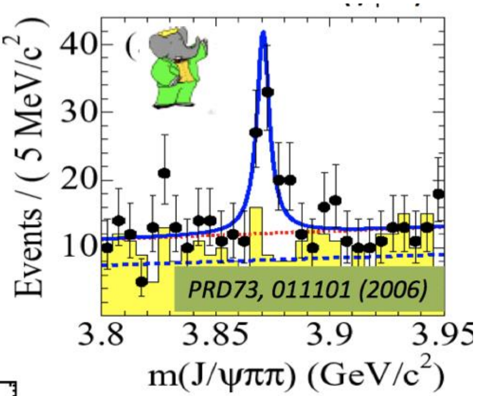
The most-cited article at Belle: >2000

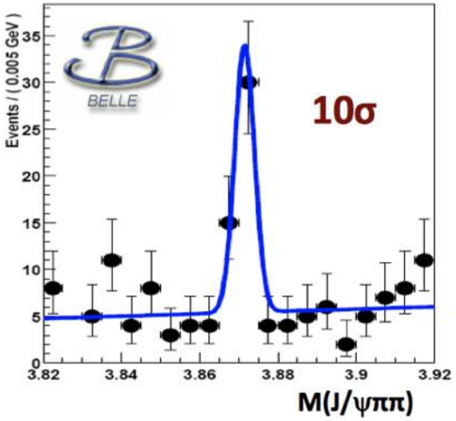
First observed by Belle in $B \rightarrow K\, J/\psi\pi^+\pi^-$ ***PRL91, 262001 (2003)***

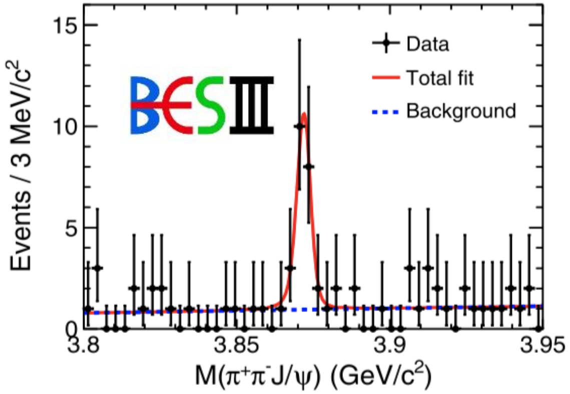
- **M_X close to $D^0\bar{D}^{*0}$ threshold M = (3871.68±0.17) MeV**
- **Surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% C.L.**



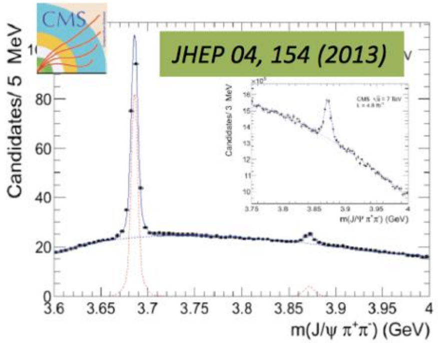


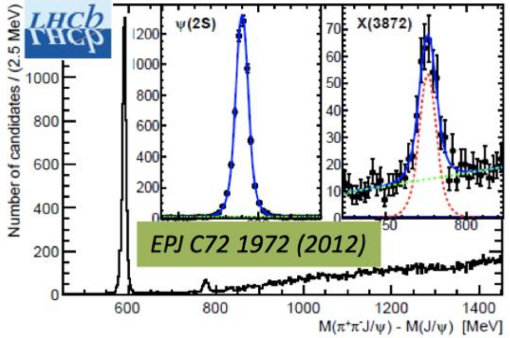






PRL112, 092001 (2014)





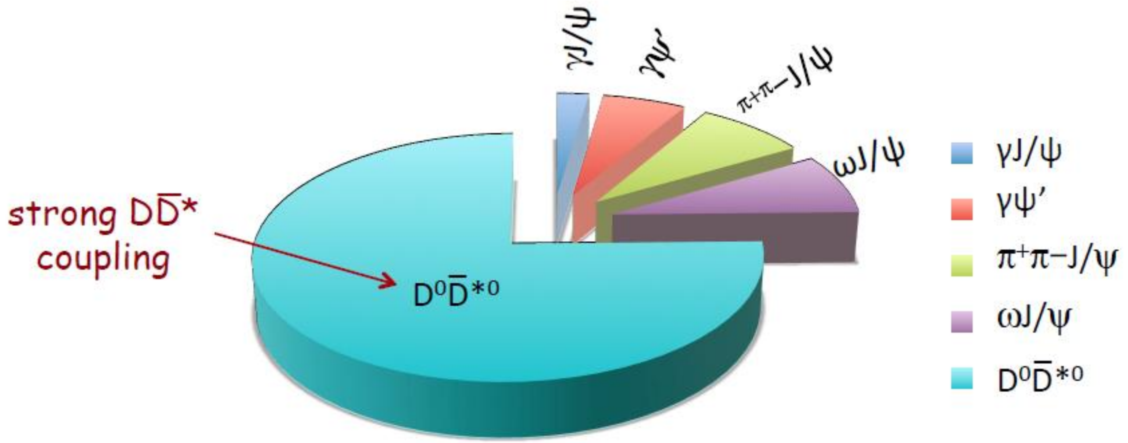
X(3872)→J/ψγ: C-even

Angular analysis:

Belle 2006: $J^{PC} = 1^{++}$ or ≥2
CDF 2008: $J^{PC} = 1^{++}$ or 2^{-+}
Belle 2011: $J^{PC} = 1^{++}$ or 2^{-+}

LHCb 2013: $J^{PC} = 1^{++}$

How to understand X(3872)?



$\Gamma_{\text{"tot"}} \approx 15\ \Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)$

$\Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi) < 80$ keV

D^0-$\bar{D}^{*0}$ molecule?

Lots of literature about this

Impossible to produce such an fragile extended object in prompt high energy hadron colliders at the rates reported by CDF & CMS

QCD diquark-diantiquark?

Maiani et al. PRD 71, 014028 (2005)

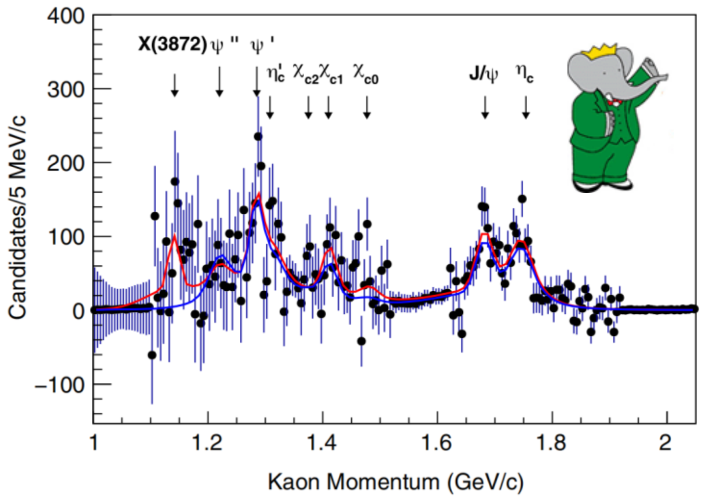
Predicts partner states (e.g., a nearby state with u→d) that have yet be seen.

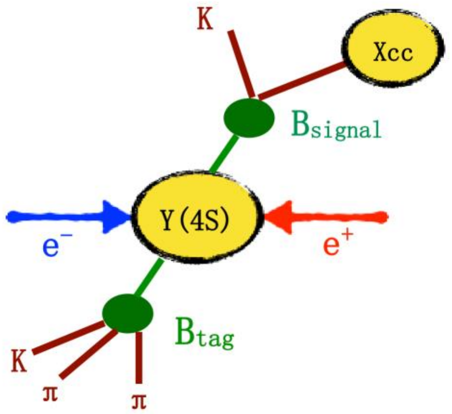
no charged partners of the X(3872)

no nearby neutral X(3872) partners

First determination of B(B$^{\pm}$→X(3872)K$^{\pm}$)

- The determination of the B(B$^{\pm}$→X(3872)K$^{\pm}$) leads to B(X(3872)→J/ψπ^{+}π^{-}), 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 ≲10%.





Branching fraction	Structure
$\mathcal{B}(X(3872) \to J/\psi\pi^{+}\pi^{-})$ $\sim 50\%$	Tetraquark State [PRD 71, 014028 (2005)]
$\mathcal{B}(X(3872) \to J/\psi\pi^{+}\pi^{-})$ $< 10\%$	Molecular state [PRD 72, 054022 (2005), PRD 69, 054008 (2004)]

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

- Increase signal efficiency by a factor of 3 by retaining all B tag candidates instead of the best one.
- There is 3σ evidence of the decay B$^{\pm}$→X(3872)K$^{\pm}$, detected for the first time using this recoil technique.
- B(B$^{\pm}$→X(3872)K$^{\pm}$) =(2.1±0.6±0.3) ×10^{-4}

Absolute branching fractions of X(3872) decays

- Globally analyzing the measurements by BESIII, Belle, Babar, LHCb
- The absolute branching fractions of X(3872) are 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

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	$(31.9^{+18.1}_{-31.5})\%$

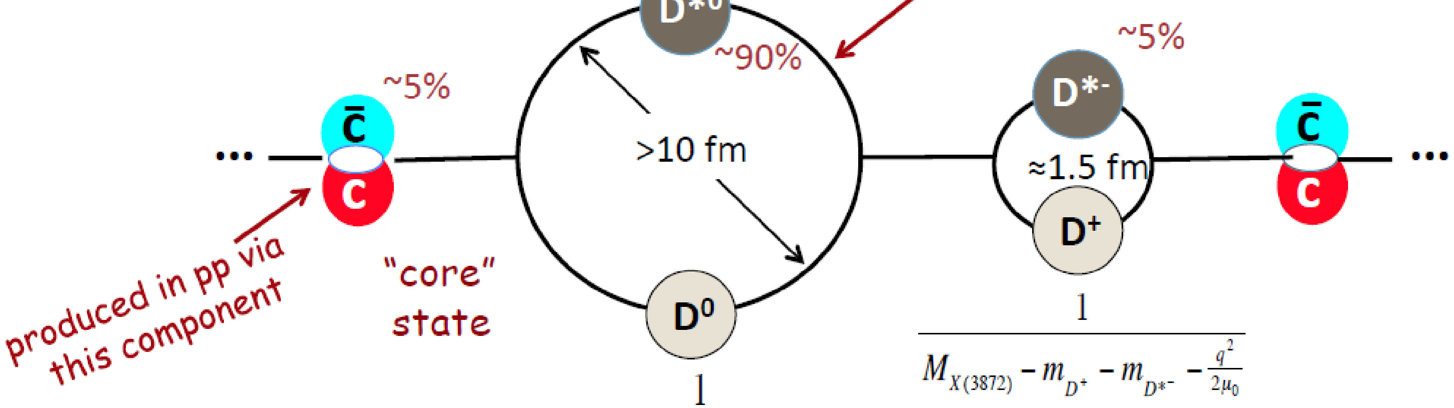
- $X(3872) \to \pi^+\pi^- J/\psi \sim (4.1^{+1.9}_{-1.1})\%$
- $X(3872) \to D^0 D^{*0} \sim (52.4^{+25.3}_{-14.3})\%$
- Unknown decay $\sim (31.9^{+18.1}_{-31.5})\%$

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

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

Probably a mixture of $D\bar{D}^*$ & a $c\bar{c}$ “core”

Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



$$\frac{1}{M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0}}$$

$|BE| < 0.2$ MeV

$d_{\rm rms}^{D^0\bar{D}^{*0}} > 10$ fm

$$\frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}}$$

$|BE| \simeq 8$ MeV

$d_{\rm rms}^{D^+D^{*-}} \simeq 1.5$ fm

$$d_{\rm rms} \approx \frac{1}{\sqrt{2\mu_D |BE|}}:$$

reduced mass → μ_D

$|m_D + m_{D^*} - m_{X3872}|$ → $|BE|$

Hints before the discovery of X(3872)→J/ψπ⁺π⁻

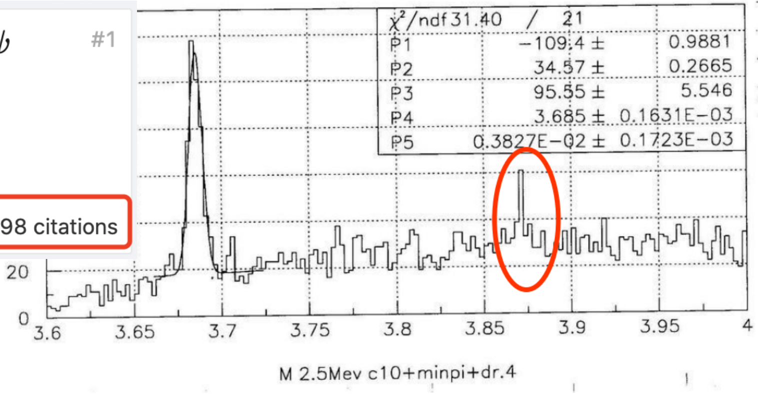
CDF internal, 1994

Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays #1

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

pdf links DOI cite claim reference search 2,498 citations



2016 W.K.H. Panofsky Prize in Experimental Particle Physics Recipient

Stephen L Olsen
Institute for Basic Science

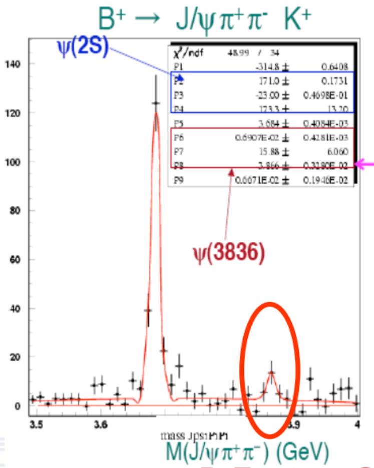
Citation:

"*For leadership in the BaBar and Belle Experiments, which established the violation of CP symmetry in B-meson decay, and furthered our understanding of quark mixing and quantum chromodynamics.*"

Background:

Stephen Lars Olsen received a B.S. from the City College of New York in 1963 and a Ph.D. in physics from the University of Wisconsin in 1970. He is currently an Emeritus Research Fellow at the Center for Underground Physics of the Institute for Basic Science in Korea. His research has concentrated mostly on studies of heavy quarks and their associated hadrons using CLEO at Cornell, AMY and Belle experiments at KEK in Japan, and the BES experiments at IHEP in Beijing. He currently participates in the KIMS dark matter and AMoRE neutrinoless double beta decay searches at the Yangyang Underground Laboratory in Korea. Olsen was an Alfred P. Sloan Fellow (1972-1977), a John Simon Guggenheim Fellow (1986-1987), a Japan Society for the Promotion of Science Fellow (1987-1988). He was awarded the University of Hawaii Regents Medal for Excellence inResearch in 2002 and was designated as a University of Wisconsin Distinguished Alumni in 2007. He was elected Fellow of the APS in 1984.

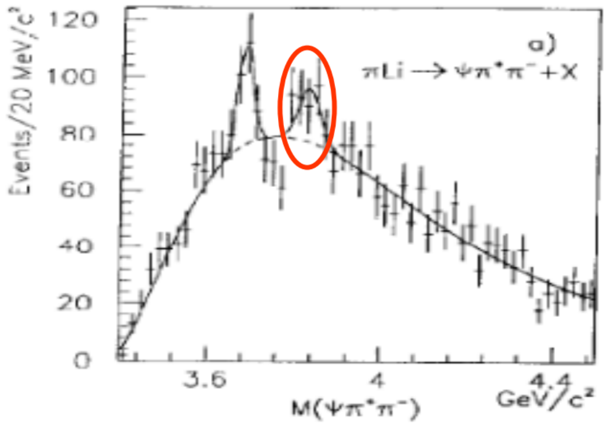
BaBar internal, 2003



AWG meeting June 2003
motivation: background to $J/\psi\ K_L$; test factorization…

From BaBar B-Factory Symposium (C. Hearty)
http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

E705, PRD 50, 4258 (1994)
E705 saw ψ(3836) (2⁻⁻)in 1994, 3.836±0.013 GeV
PRL 115 011803, PRL 111 032001



CDF saw a hint in 1994, unpublished
BaBar saw a hint in 2003, unpublished

Both CDF and Babar spotted hints of X(3872) before its discovery!

What can we learn from this story ?

$\chi_{c1}(4274)$ $I^G(J^{PC}) = 0^+(1^{++})$

was $X(4274)$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non-$q\bar{q}$ states. Seen by AAIJ 2017C in $B^+ \to \chi_{c1} K^+$, $\chi_{c1} \to J/\psi\phi$ using an amplitude analysis of $B^+ \to J/\psi\phi K^+$ with a significance (accounting for systematic uncertainties) of 6.0 σ.

$\chi_{c1}(4274)$ MASS	4286^{+8}_{-9} MeV (S = 1.7)
$\chi_{c1}(4274)$ WIDTH	51 ± 7 MeV

$\chi_{c1}(4274)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi\phi$			

$X(4630)$ $I^G(J^{PC}) = 0^+(?^{?+})$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on "Heavy Non-$q\bar{q}$ Mesons." Seen by AAIJ 2021E in $B^+ \to X(4630)K^+$ with $X(4630) \to J/\psi\phi$ using an amplitude analysis of $B^+ \to J/\psi\phi K^+$ with a significance (accounting for systematic uncertainties) of 5.5 σ. The $J^P = 1^-$ assignment is favored over 2^- with a significance of 3 σ and other assignments are disfavored by more than 5 σ.

$X(4630)$ MASS	4626^{+24}_{-110} MeV
$X(4630)$ WIDTH	174^{+140}_{-80} MeV

$X(4630)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi\phi$	seen		943

All are from an amplitude analysis of $B^+ \to K^+\phi J/\psi$

$\chi_{c1}(4685)$ $I^G(J^{PC}) = 0^+(1^{++})$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on "Heavy Non-$q\bar{q}$ Mesons." Seen by AAIJ 2021E in $B^+ \to \chi_{c1}(4685)K^+$ with $\chi_{c1}(4685) \to J/\psi\phi$ using an amplitude analysis of $B^+ \to J/\psi\phi K^+$ with a significance (accounting for systematic uncertainties) of 15 σ. The $J^P = 1^+$ assignment is favored with high significance.

$\chi_{c1}(4685)$ MASS	4684^{+15}_{-17} MeV
$\chi_{c1}(4685)$ WIDTH	126 ± 40 MeV

$\chi_{c1}(4685)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi\phi$	seen		1002

$\chi_{c0}(4700)$ $I^G(J^{PC}) = 0^+(0^{++})$

was $X(4700)$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non-$q\bar{q}$ states. Seen by AAIJ 2017C in $B^+ \to \chi_{c0} K^+$, $\chi_{c0} \to J/\psi\phi$ using an amplitude analysis of $B^+ \to J/\psi\phi K^+$ with a significance (accounting for systematic uncertainties) of 5.6 σ.

$\chi_{c0}(4700)$ MASS	4694^{+16}_{-5} MeV
$\chi_{c0}(4700)$ WIDTH	87^{+18}_{-10} MeV

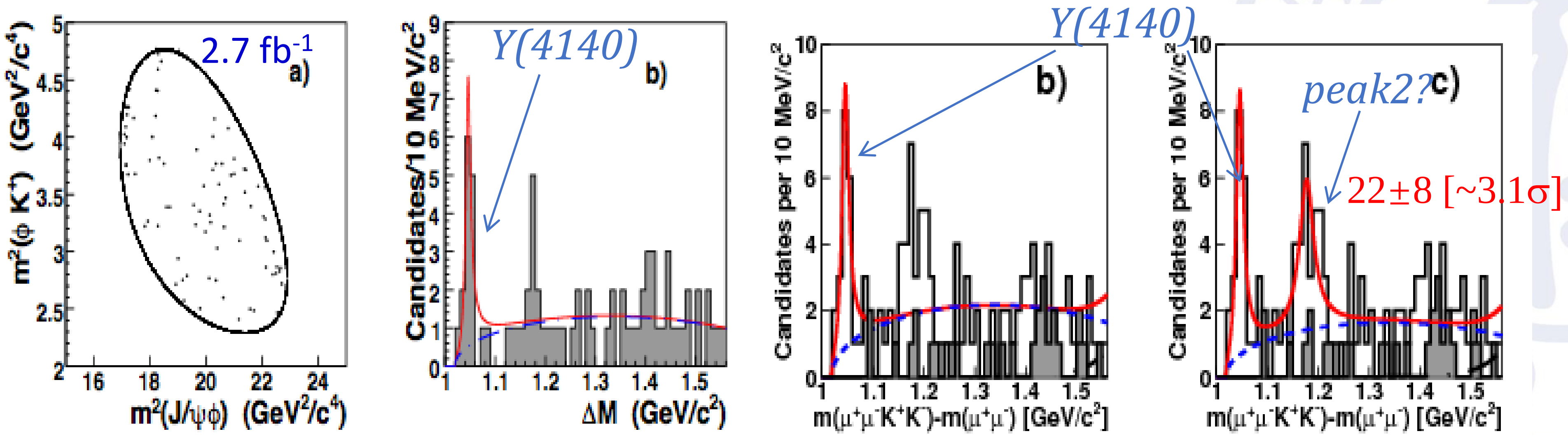
$\chi_{c0}(4700)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi\phi$	seen		1011

The history/story of X(4140)/Y(4140)

CDF—PRL102:242002 (2009)

Mod.Phys.Lett. A32 (2017), 1750139



X(4140) (renamed), mass-4.14 GeV, width—15 MeV

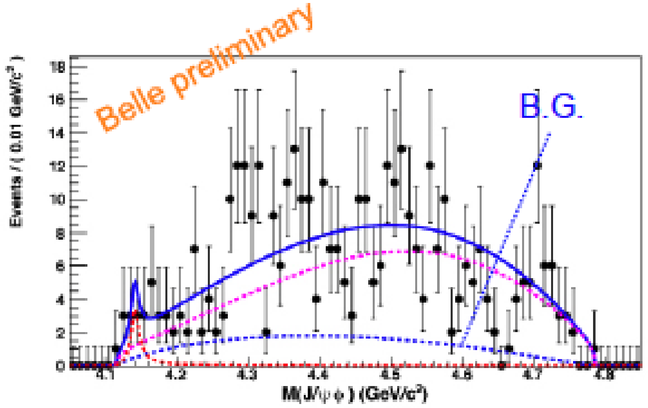
This is the first unexpected particle discovered by Tevatron!

Possible second state: mass—4.27 GeV, width—30 MeV

Experienced a long road for confirmation!

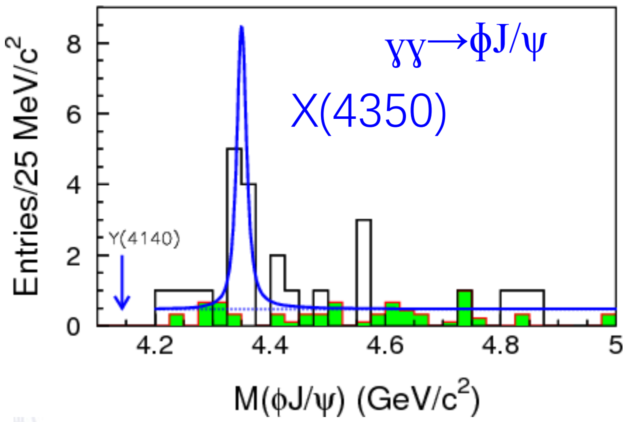
- Necessarily exotic since it is narrow and above the DsDs threshold
- $[cs\bar{c}\bar{s}]$ tetraquark ?
- Hint of a second structure: $X(4274)$

Belle: Confirm or refute? (2009, 2010)



Y(4140): 7.5 +4.9/-4.4 events
Statistical significance: 1.9σ
Signal could not be identified.

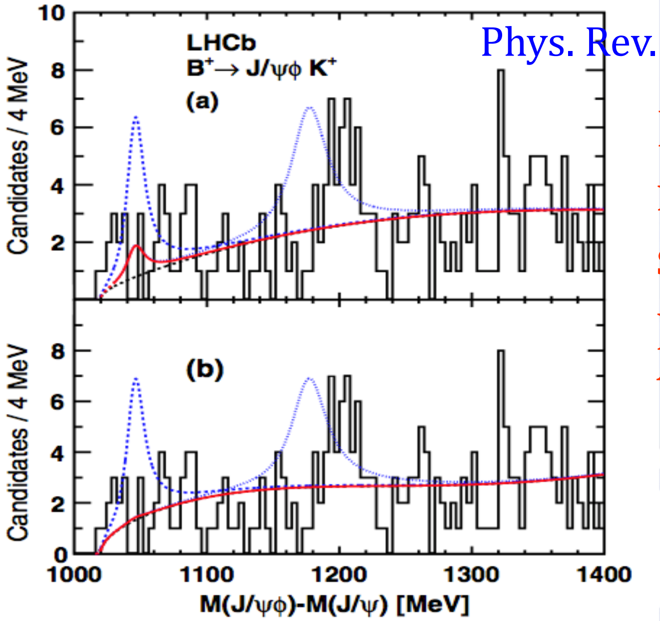
Belle, PRL 104 (2010) 112004



−B factories suffer from low p_t track inefficiency
−Belle cannot confirm or deny the existence of Y(4140)

Belle spotted another possible new state in the same final state but from a different production: X(4350) needs to be confirmed at Belle II with larger data samples.

LHCb: contests CDF report (2011)



Phys. Rev. D85 (2012) 091103

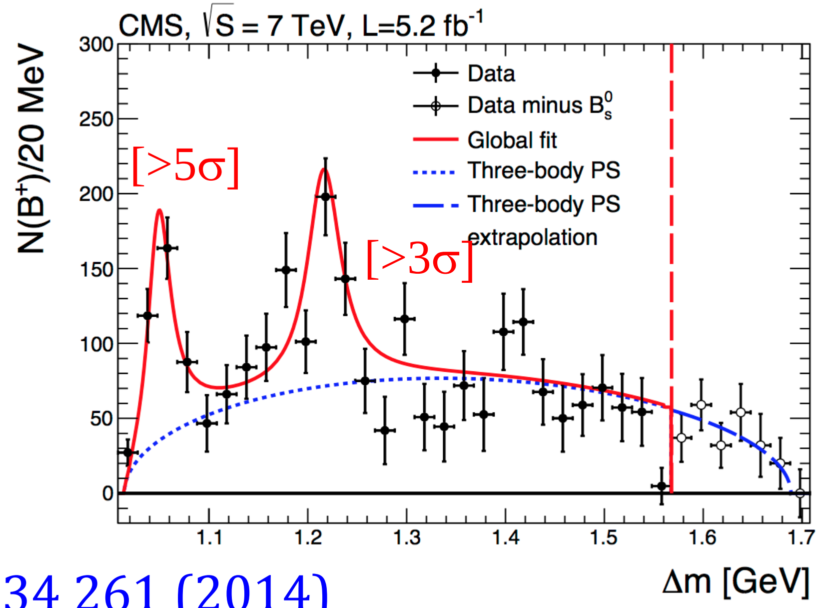
LHCb confirms neither structure(s) with part of their data taken in 2011

LHCb Versus CDF: Two Punches In The Face!

By Tommaso Dorigo | July 27th 2011 05:48 AM | 10 comments | Print | E-mail | Track

result. Note that, as reported in the figure, if the CDF signal were as estimated by CDF, LHCb would have been able to fit 39+-9+-6 events. The Y(4140) is on very shaky ground at the moment, and the new PDG will likely change its status in the particle zoo... This is punch number 1.

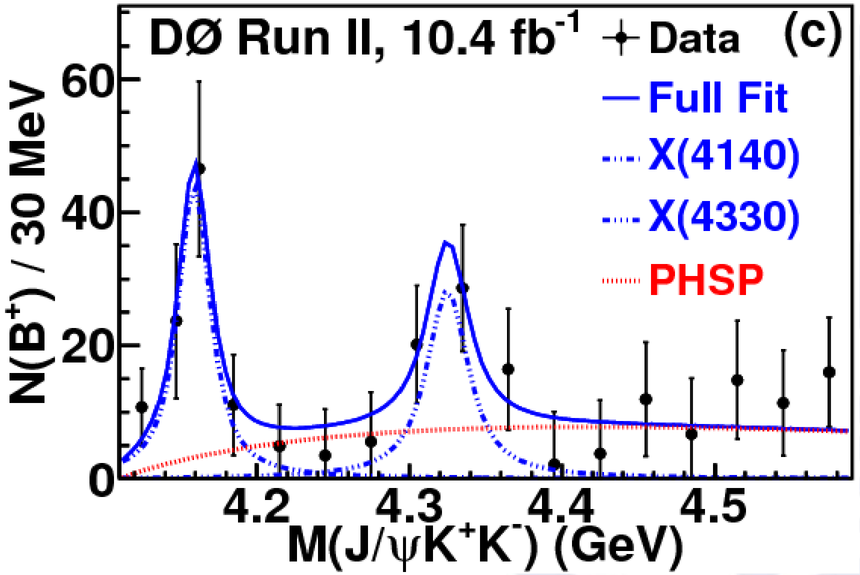
Result from CMS (2012)



PLB 734 261 (2014)

- significance greater than 5σ, confirms the existence of Y(4140) for the first time from another experiment
- evidence for a second structure in the same mass spectrum

Y(4140) @ D0 (2013)

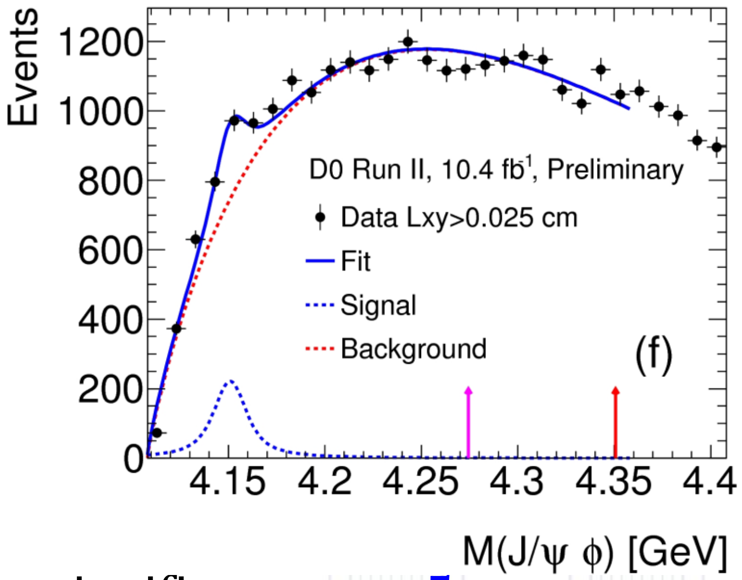


PRD 89, 012004 (2014)

D0 provides the second independent confirmation of Y(4140) with 3.1σ significance

Y(4140) @ D0 (2015)

PRL 115(2015), 232001



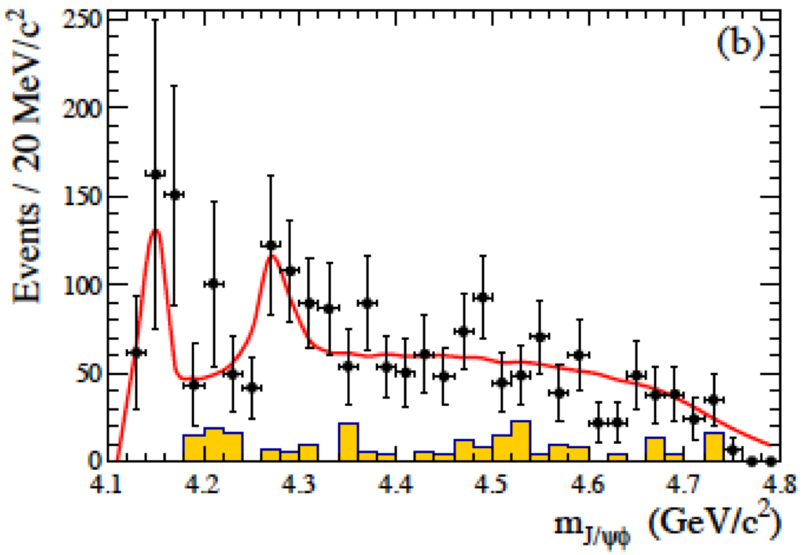
significance: >> 5σ

Mass and width are consistent with their previous measurements and CDF/CMS

D0 provides additional confirmation from a different production

Y(4140) @ BaBar (2015)

PRD91 (2015), 012003



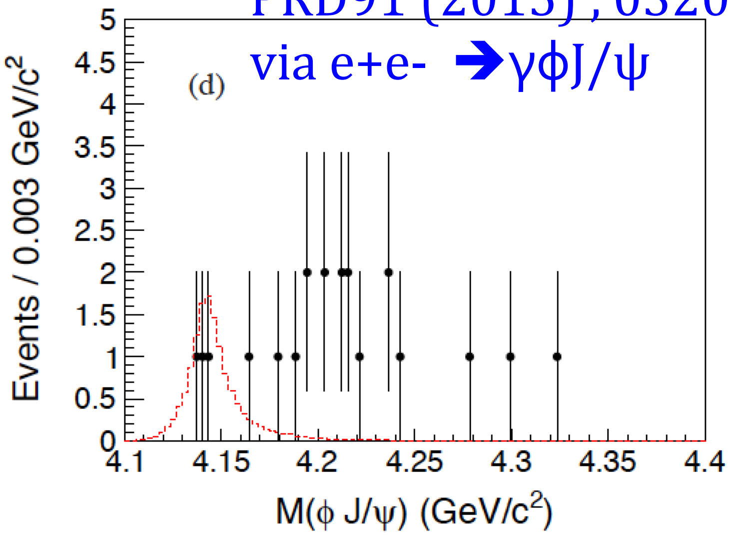
No significance for both structures though there are hints

BaBar provides useful information even though there is no significant signals

Y(4140) @ BES (2015)

PRD91 (2015) , 032002

via e+e- ➔γϕJ/ψ



Three events @4.15 GeV

BES sets limits, cannot compare because it is from a different process

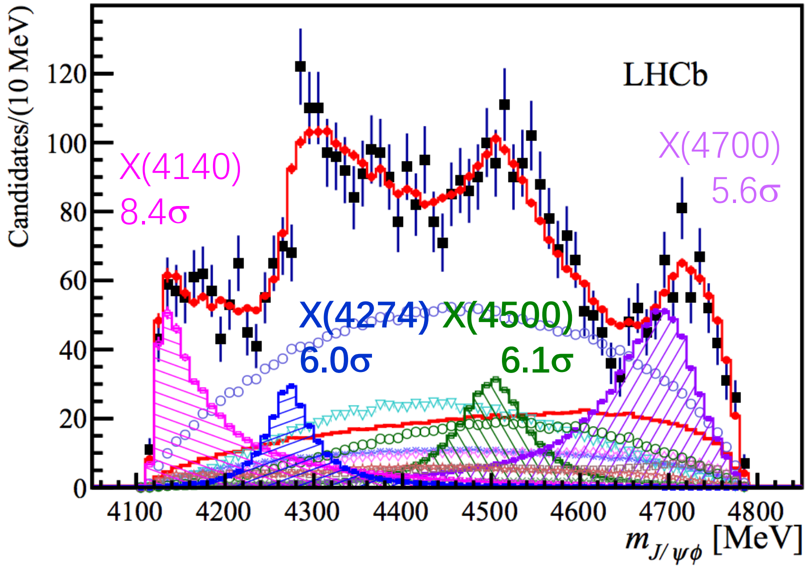
A short summary before LHCb enters

[PRD 95 (2017) 012002]

Year	Experiment luminosity	$B \to J/\psi\,\phi K$ yield	$X(4140)$ peak Mass [MeV]	Width [MeV]	Sign.	Fraction %
2008	CDF 2.7 fb^{-1} [1]	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	
2009	*Belle* [22]	*325 ± 21*	*4143.0 fixed*	*11.7 fixed*	*1.9σ*	
2011	*CDF 6.0 fb^{-1}* [29]	*115 ± 12*	*$4143.4^{+2.9}_{-3.0} \pm 0.6$*	*$15.3^{+10.4}_{-6.1} \pm 2.5$*	*5.0σ*	*$14.9 \pm 3.9 \pm 2.4$*
2011	LHCb 0.37 fb^{-1} [21]	346 ± 20	4143.4 fixed	15.3 fixed	1.4σ	< 7 @ 90%CL
2013	CMS 5.2 fb^{-1} [25]	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0σ	10 ± 3 (stat.)
2013	D0 10.4 fb^{-1} [26]	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.0σ	$21 \pm 8 \pm 4$
2014	BaBar [24]	189 ± 14	4143.4 fixed	15.3 fixed	1.6σ	< 13.3 @ 90%CL
2015	D0 10.4 fb^{-1} [27]	$p\bar{p} \to J/\psi\,\phi \ldots$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ (5.7σ)	
Average			4147.1 ± 2.4	15.7 ± 6.3		

Results from LHCb (2016)

LHCb, PRL 118 (2017), 022003; PRD 95 (2017), 012002

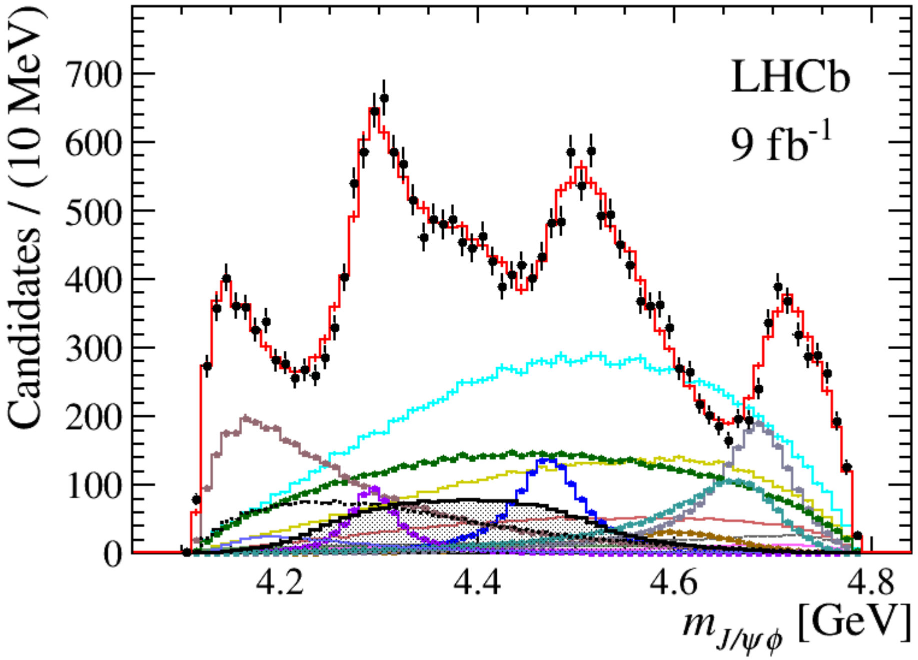


- No light quark (u,d) components
- Cannot exchange pion—J/**φ** or **ϕ** has no isospin
- Cannot exchange photon--pion—J/**φ** or **ϕ** has no charge
- A case of more general tetra-quark dynamics
- New important piece to the exotic meson family

- LHCb re-confirmed both X(4140) and X(4274), Observed $X(4500)$ and $X(4700)$
- LHCb found two additional resonances in the same mass spectrum
- This is 7 years after the first report from CDF
- Waing for Belle II larger data samples: signals should be more cleaner

Updated Results from LHCb (2021)

Phys.Rev.Lett. 127 (2021) 082001



6D amplitude fit: Measured mass of $X(4140)$ is $4118 \pm 11^{+19}_{-36}$ MeV, width $162 \pm 21^{+24}_{-49}$ MeV, not very narrow; the mass is around the threshold of $J/\psi\phi$.

- New states: $Z_{cs}(4000)$, $X(4685)$ > 15σ; $Z_{cs}(4220)$, $X(4630)$ > 5σ
  $X(4150)$ < 5σ

Contribution	Significance [×σ]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$	Stat.(Syst. included)			$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

Updated Results from LHCb (2021)

- For $X(4140)$, no evidence of a narrow threshold resonance at $J/\psi\phi$ in our data

- 4 new $J/\psi K^+$ and $J/\psi\phi$ structures observed in $B^+ \to J/\psi\phi K^+$ decays with 6 times data and much clean environment
  - **A 1^+ $Z_{cs}(4000)^+ \to J/\psi K^+$ observed for 1st time, significance$> 15\sigma$**
  - **A broad $Z_{cs}(4220)^+ > 5\sigma$**
  - **A new 1^+ $X(4685)$ is $> 15\sigma$, and new $X(4630) > 5\sigma$**
  - **4 X states previously observed are confirmed, and J^P determined with higher significances**

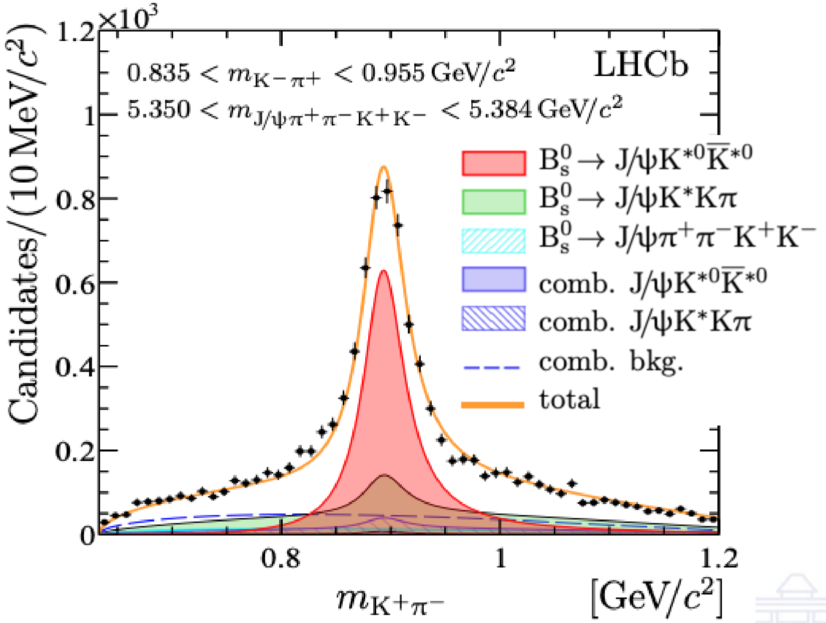
CMS should update their results on this channel with a (much) larger data sample, and more sophisticated analysis technique, than previously.

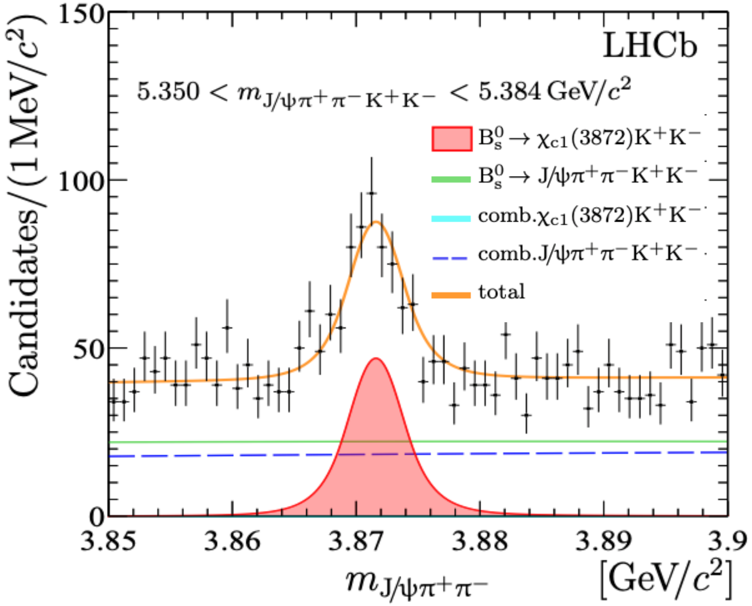
The story of J/ψϕ system is not finished yet !

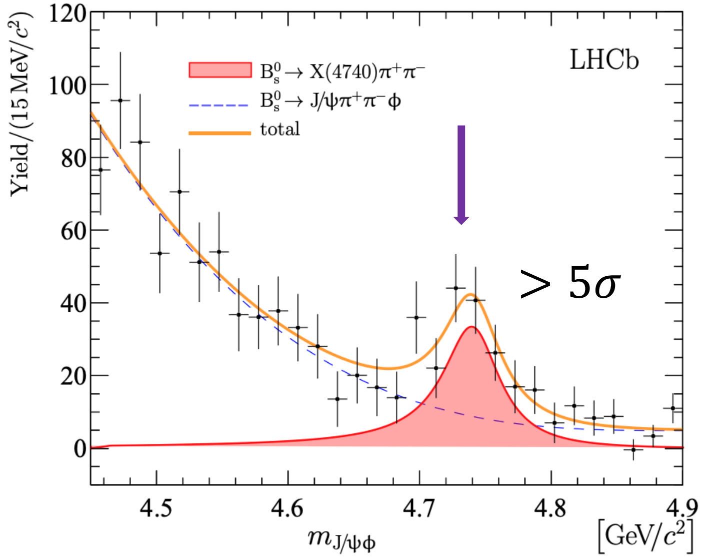
Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays [JHEP 02 (2021) 024]

- $\chi_{c1}(3872)$ and $J/\psi\phi$ structures can be studied in this decay
- Production rate measurements can shed light on the nature of exotic states

Are $X(4700)$ and $X(4740)$ the same state? Further amplitude studies are required.



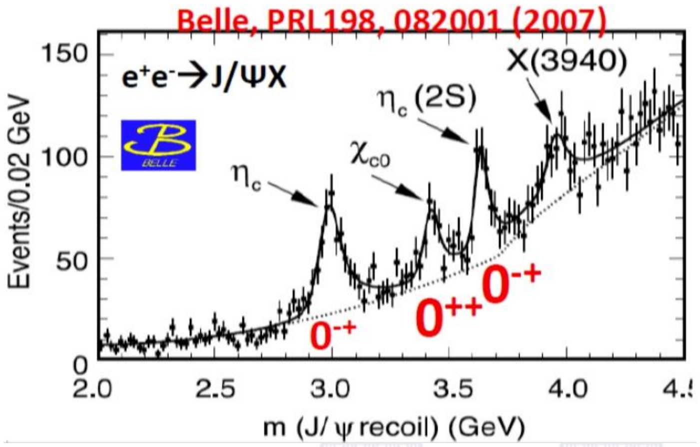




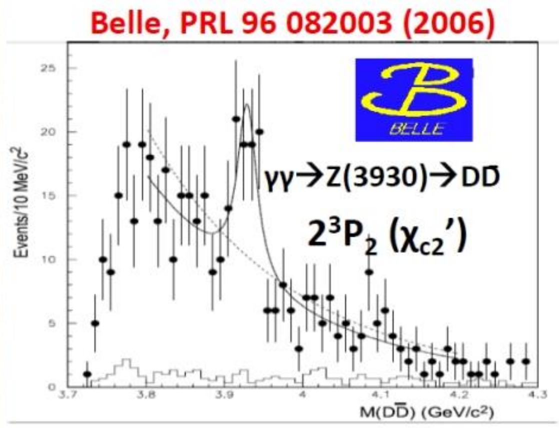
$$m_{X(4740)} = 4741 \pm 6 \pm 6 \ \text{MeV}/c^2,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \ \text{MeV},$$

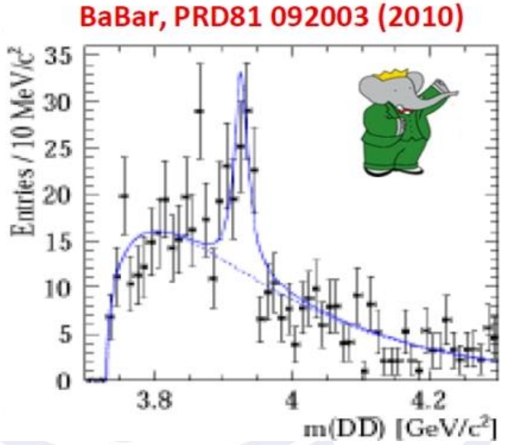
- Decay $B_s^0 \to \chi_{c1}(3872)K^+K^-$ observed for the first time.

Other productions for charmonium-like states



Double charmonium production, another interesting process through which Belle II can access C=+ even states.

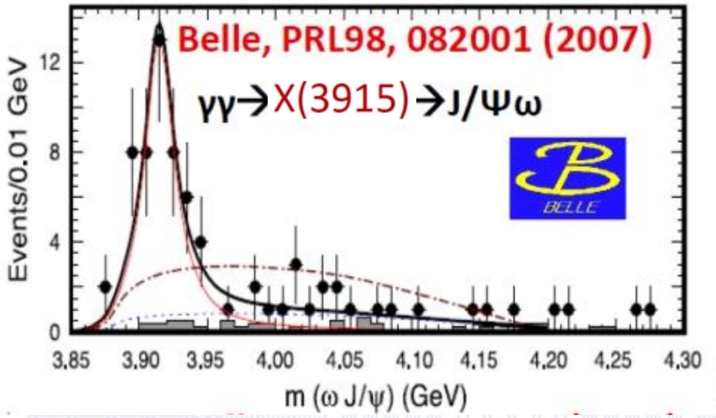


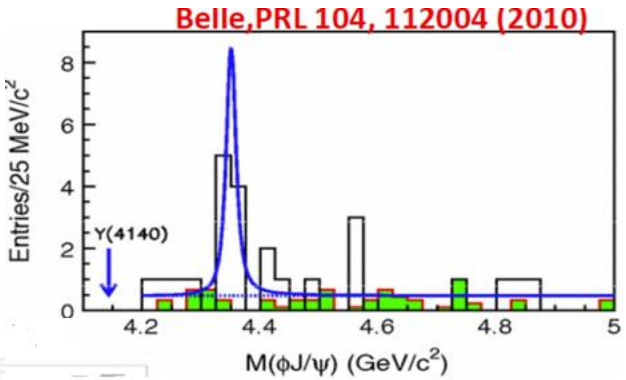


Two photon processes

Study of χ_{c2}(3930) using $\gamma\gamma$→$Z(3930)$→$D\bar{D}$

Mass and width precision study.



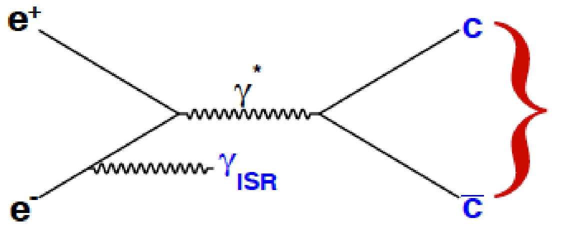


X(3915) (thought to be χ_{c0}(2P))was discovered in two photon process. Currently, χ_{c0}(2P) has been suggested to be recently found X(3860) in $J/\psi D\bar{D}$.

Υ States

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section : Y(4260)

BABAR PRL95,142001(2005)

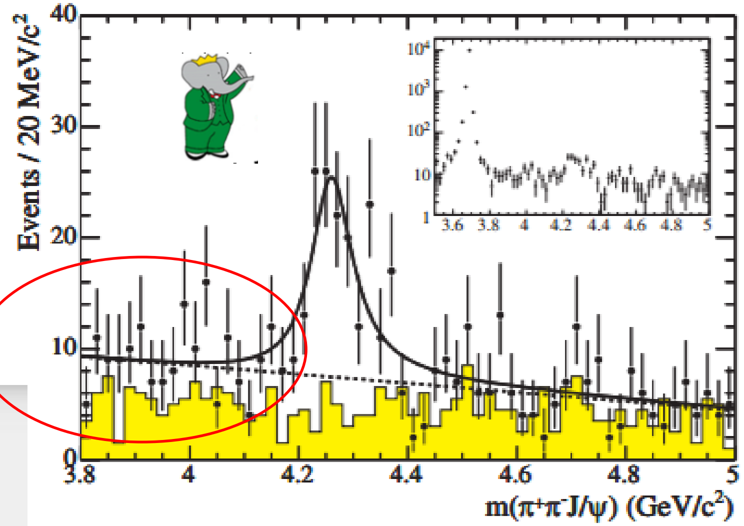


$J^{PC} = 1^{--}$

ψ', ψ'', Y…

X(4260) $I^G(J^{PC}) = ?^?(1^{--})$

X(4260) MASS	4251 ± 9	AVERAGE
X(4260) WIDTH	120 ±12	AVERAGE



$\psi(4230)$ $I^G(J^{PC}) = 0^-(1^{--})$

also known as $Y(4230)$; was $\psi(4260)$

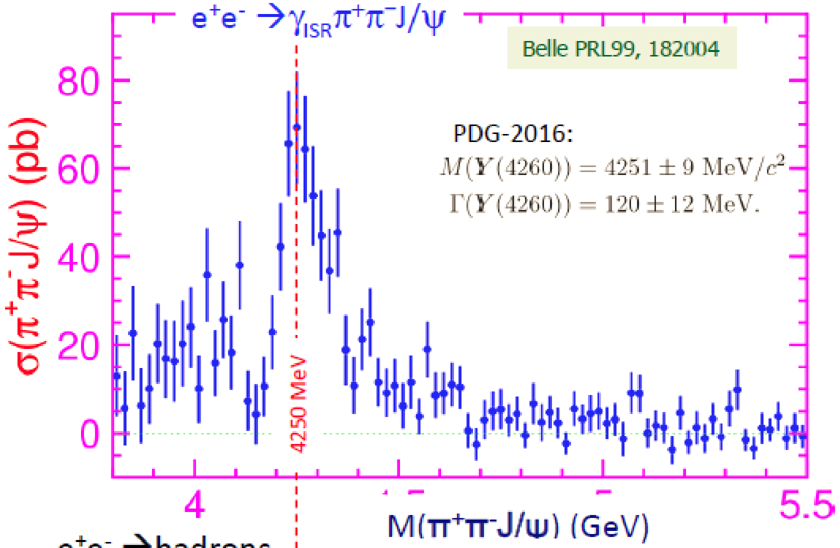
The original $\psi(4260)$ (also known as $Y(4260)$) was observed by AUBERT,B 2005I as a peak in the energy dependence of the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section and was confirmed by HE 2006B, YUAN 2007 , LEES 2012AC, and LIU 2013B in the same process. A higher-statistics analysis by ABLIKIM 2017B revealed an asymmetry in the cross section and resulted in a shift of the peak position to a lower mass. The $\psi(4260)$ was therefore renamed $\psi(4230)$. The energy-dependent cross sections for e^+e^- to other channels also exhibit peaks in the same mass region. The parameters corresponding to those peaks are also listed here, but the number of states in this region remains to be determined. For details see the review on "Spectroscopy of mesons containing two heavy quarks."

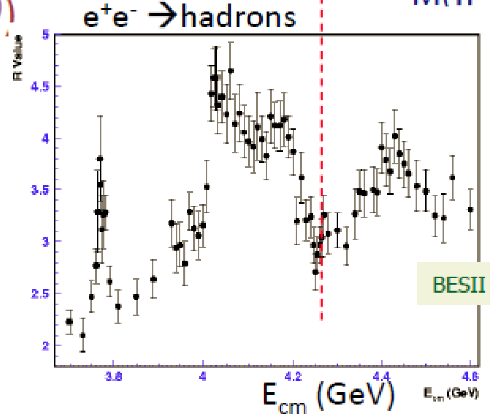
Y(4260) → $\pi^+\pi^- J/\psi$ confirmed by Belle

no sign of Y(4260) → $D^{(*)}\bar{D}^{(*)}$

Y(4260) peak in $\sigma(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}\bar{D}^{(*)})$

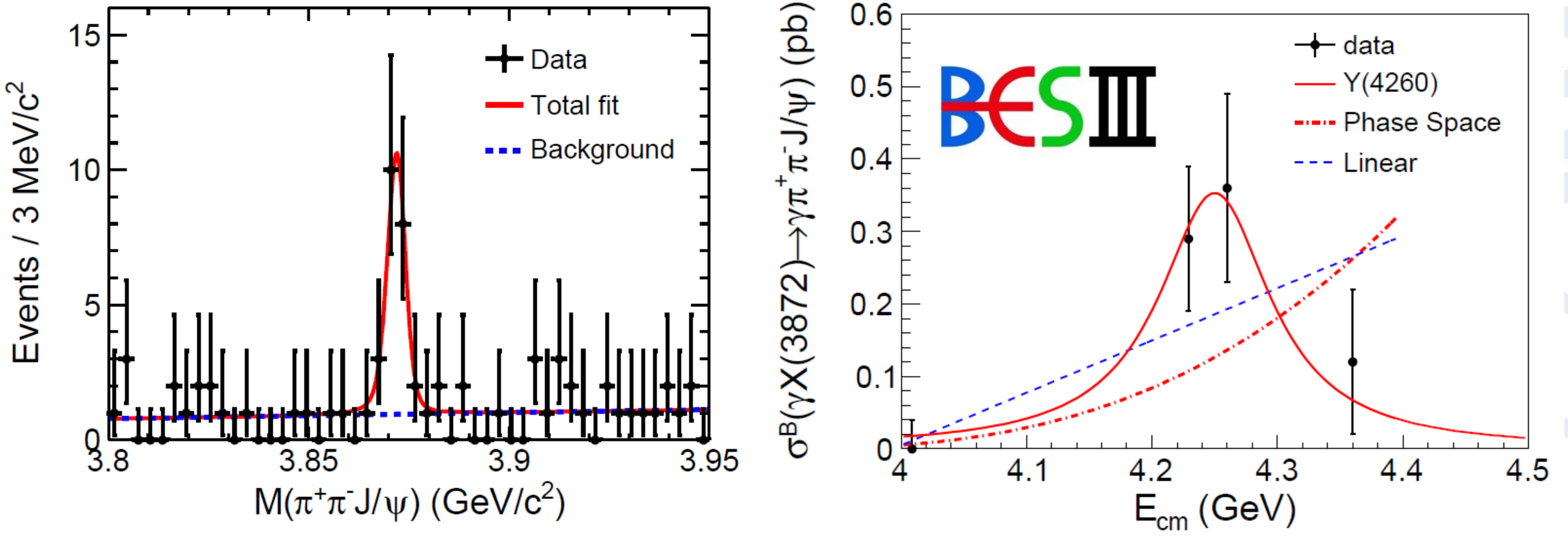
$\Gamma(\pi^+\pi^- J/\psi)$ is large, but should be OZI suppressed if $c\bar{c}$





Observation of Y(4260)→γX(3872)

PRL 112, 092001 (2014)



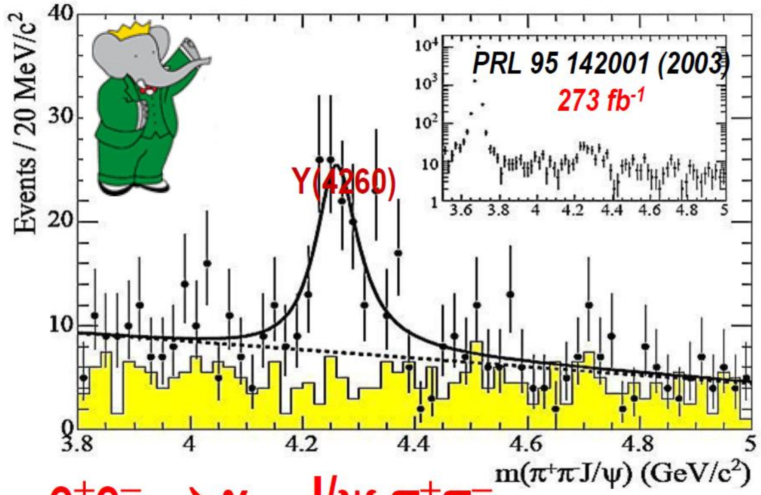
A new Y(4260) decay mode
A new X(3872) production mode

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)

$$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 10\%$$

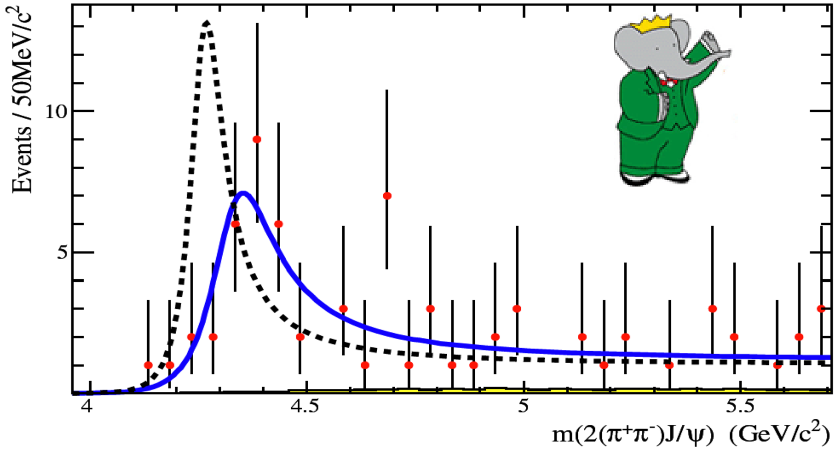
Large transition ratio !

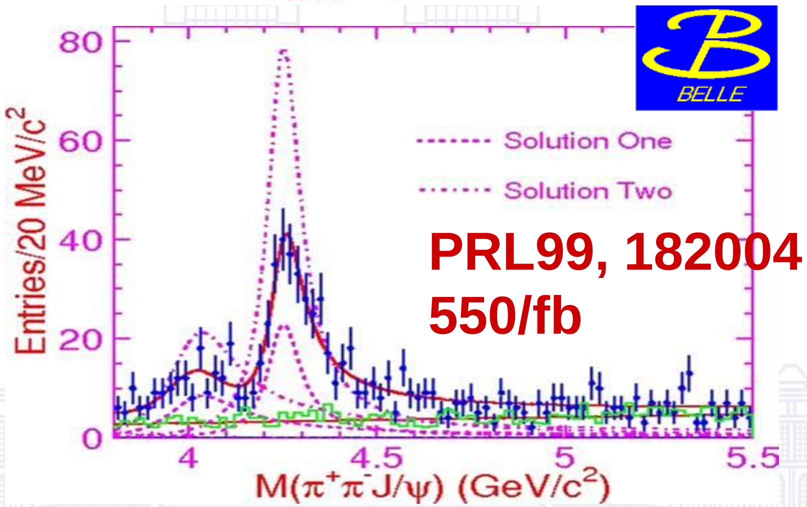
The Y states



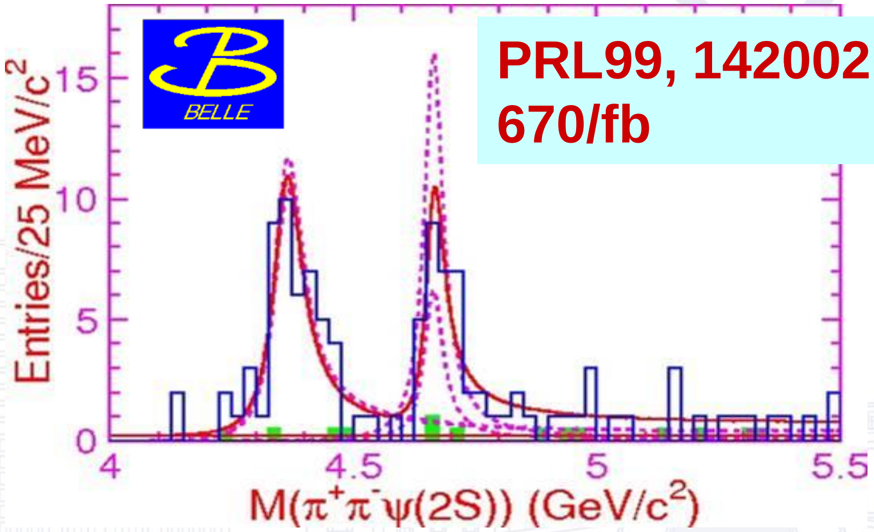
$e^+e^- \to \gamma_{ISR} J/\psi\ \pi^+\pi^-$

PRL98, 212001. 298/fb





PRL99, 182004
550/fb

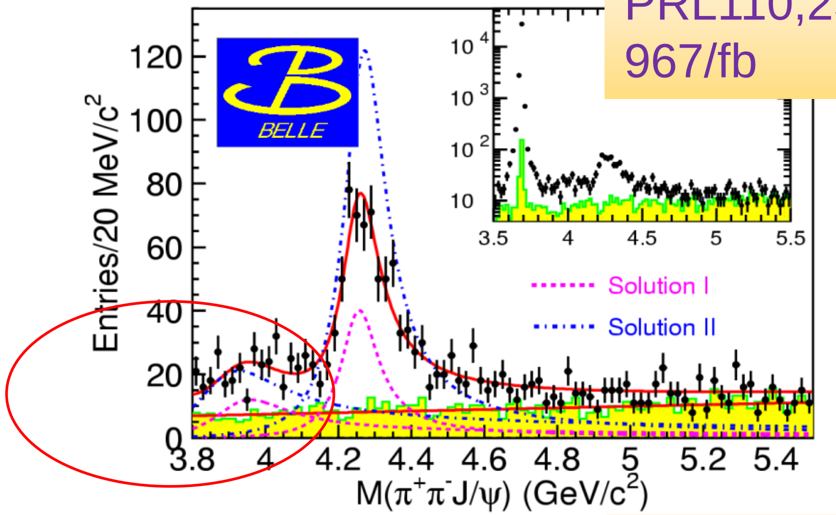


PRL99, 142002
670/fb

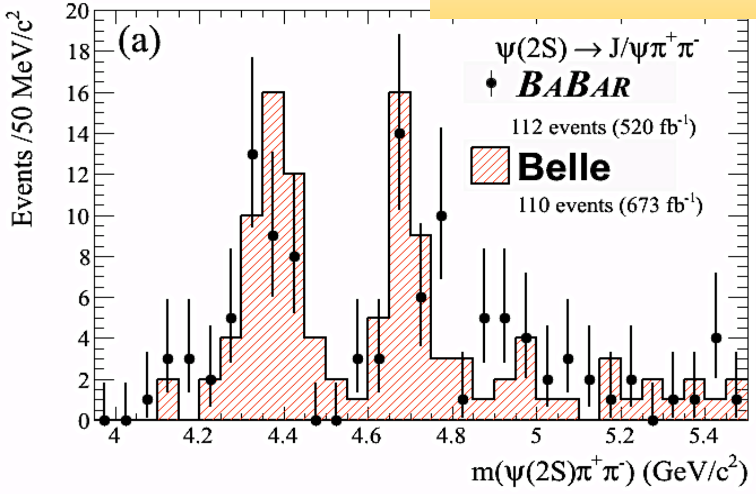
Y(4008) Y(4260)
Y(4360) Y(4660)

The Y states

PRL110,252002
967/fb

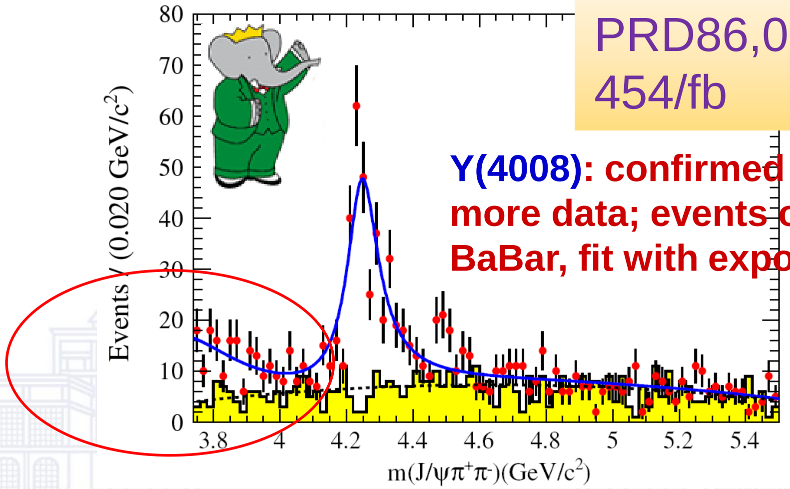


Belle: PRL99,142002, 670/fb
BaBar: PRD89, 111103, 520/fb



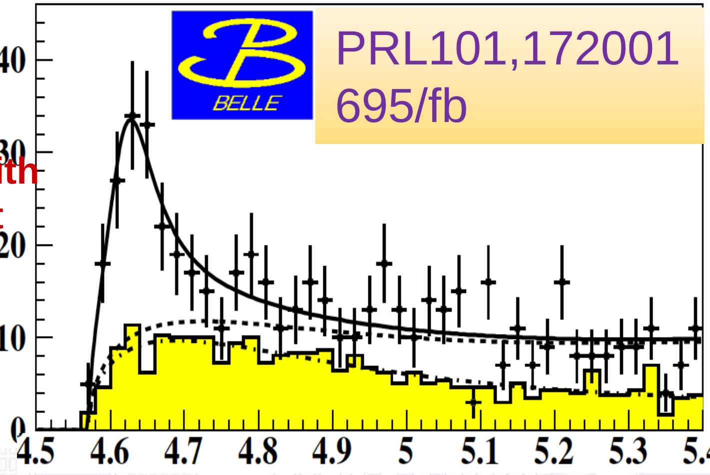
Y(4660): confirmed by BaBar

PRD86,051102
454/fb

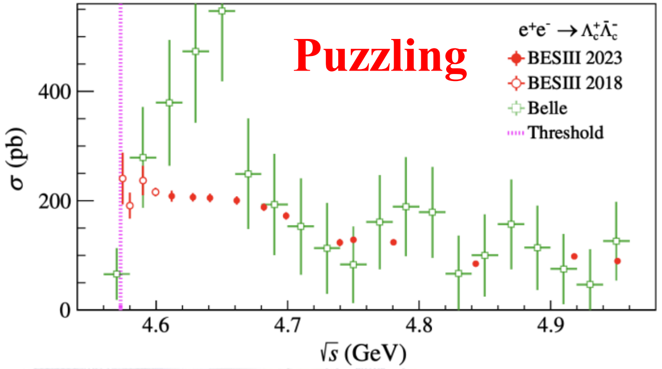


Y(4008): confirmed by Belle with more data; events observed at BaBar, fit with exponential

PRL101,172001
695/fb

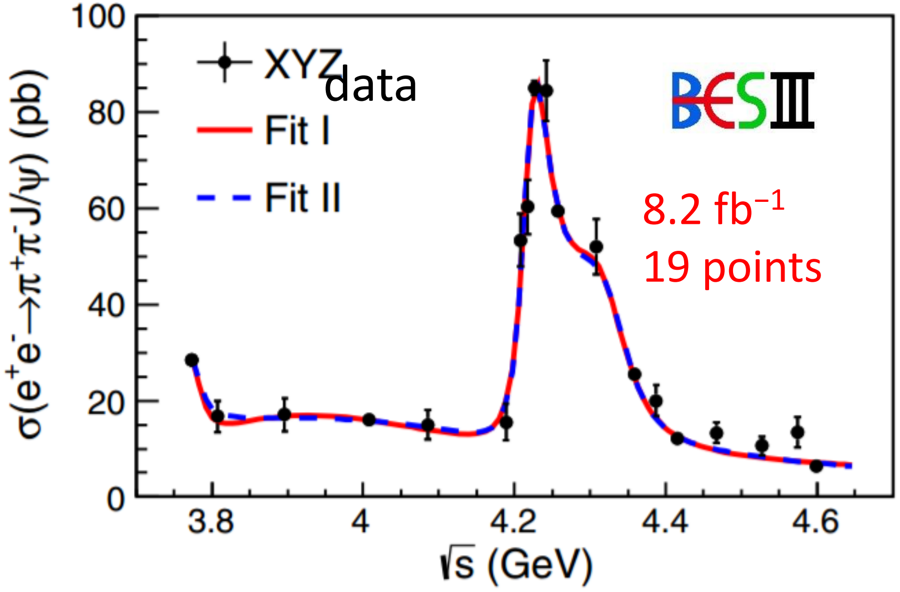


PRL 131, 191901 (2023)

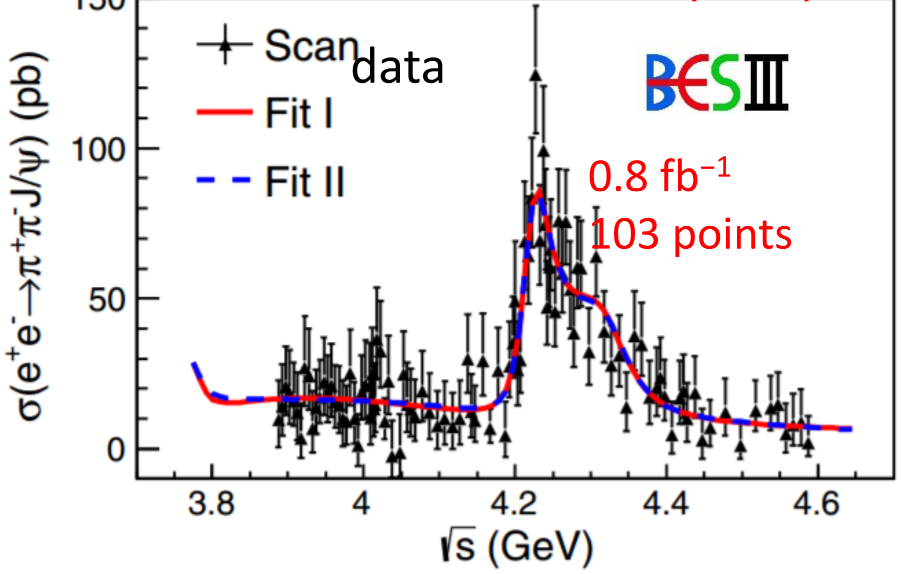


M($\Lambda_c^+\Lambda_c^-$)

Y(4260)→Y(4230)+Y(4320)



PRL118, 092001 (2017)

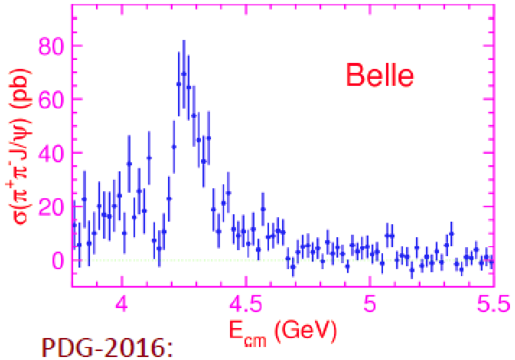


- Fit I =$|BW_1+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ or Fit II =$|exp+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ (other fits ruled out)
- M = 4222.0±3.1±1.4 MeV (lower)
- Γ = 44.1±4.3±2.0 MeV (narrower)

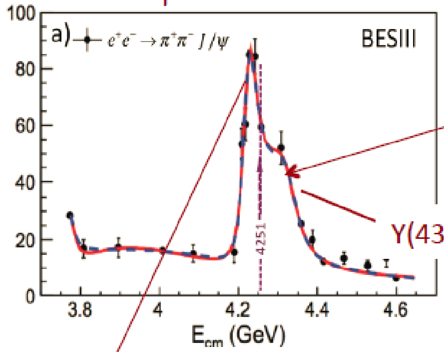
- A 2nd resonance Y_2 with M=4320.0±10.4±7.0 MeV/c^2
  $\Gamma=101.4^{+25.3}_{-19.7}\pm 10.2$ MeV
- Observed for the first time, significance > 7.6σ

Y(4260): mass → lower & width → narrower

pre-2017

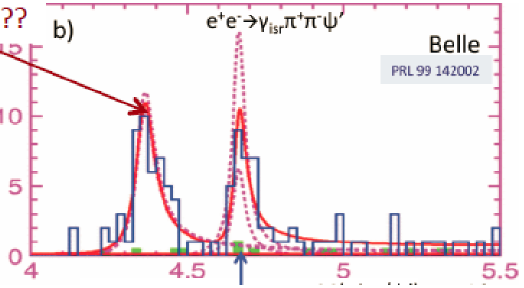


post-2017



what is the 2nd peak?

Y(4360)??



PDG-2016:

$M(Y(4260)) = 4251 \pm 9\ \mathrm{MeV}/c^2$ —(-31 MeV)→ $M_1 = 4220 \pm 4\ \mathrm{MeV}/c^2$

$\Gamma(Y(4260)) = 120 \pm 12\ \mathrm{MeV}.$ —(×1/3)→ $\Gamma_1 = 44 \pm 5\ \mathrm{MeV}$

$M_2 = 4320 \pm 13\ \mathrm{MeV}/c^2$ —(δM≈-1.8σ)→ $M(Y(4360)) = 4346 \pm 6\ \mathrm{MeV}/c^2$

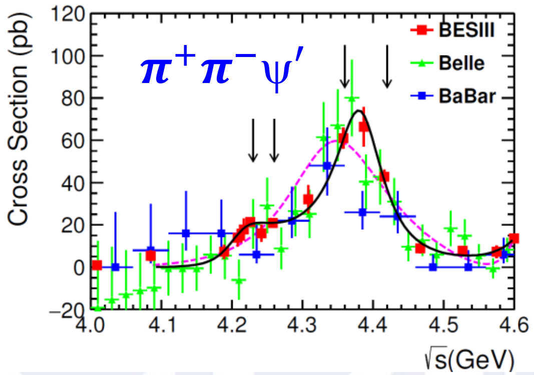
$\Gamma_2 = 101^{+27}_{-22}\ \mathrm{MeV}$ —(spot on)→ $\Gamma(Y(4360)) = 102 \pm 12\ \mathrm{MeV}.$

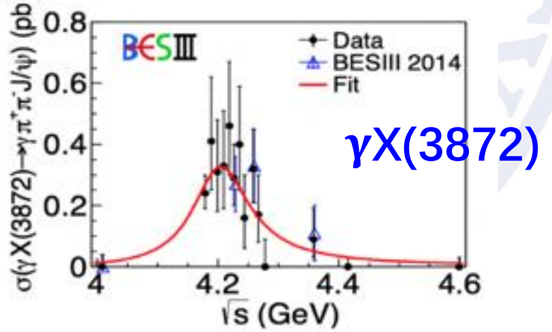
Y(4220) decay modes:

- $\pi^+\pi^- J/\psi$
  - $\pi Z_c(3900)$
  - $f_0(980)\ J/\psi$
- $\pi^+\pi^- h_c$
- $\omega\chi_{c0}$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

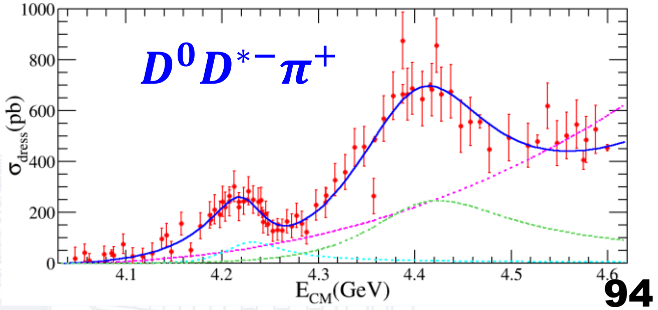
Y(4320) decay modes:

- $\pi^+\pi^- J/\psi$
- $\pi^+\pi^- \psi'$

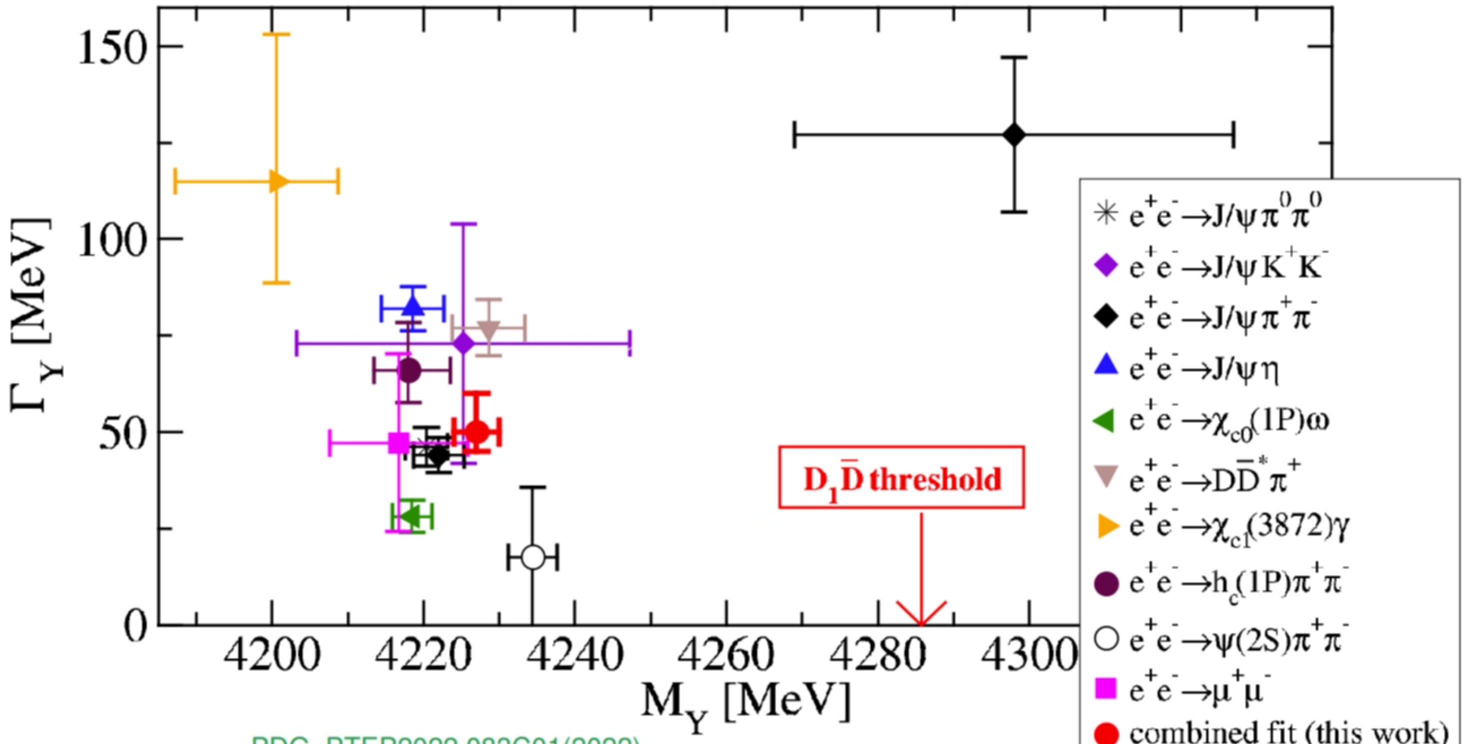




PRL 122, 232002 (2019)



Y(4230) parameters



PDG, PTEP2022,083C01(2022)

- Why do mass and decay width scatter so much for different reactions?
- How big is the influence of the $D_1\bar{D}$ threshold?
- Why $Y(4320)$ only seen in $e^+e^-\to J/\psi\pi\pi$?

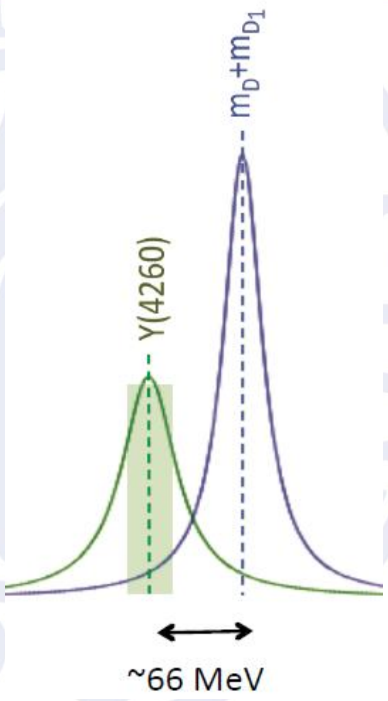
What is the Y(4260)?

The Y(4260) mass is lower and width narrower than previously thought

"Y(4260)" → Y(4220)?

If it is a $D\bar{D}_1$(2420) molecule:
B.E. ≈ 66 MeV ← too large??
"affinity" to $D\bar{D}_1$(2420) should be high

2012 LQCD calc. (m_π≈400 MeV):
"Lowest 1^{--} $c\bar{c}$-gluon hybrid: M=4285 ± 14 MeV"
pre-2017: too high by ~35 MeV
post-2017: too high by ~65 MeV
Had. Spectr. Collab. JHEP07, 126



If it is a $c\bar{c}$-gluon hybrid:
its mass is ~65 MeV below current (m_π≈400 MeV) LQCD predictions ← not so bad?
"affinity" to $D\bar{D}_0$(2400) should be high

If it is a QCD diquark–diantiquark tetraquark: Maiani et al. PRD89,114010
it should have Isospin- & SU_F(3)-multiplet partner states ← not seen

Dubynskiy & Voloshin, PLB 666, 344
Li & Voloshin, Mod. Phys. Lett. A29, 1450060

If it is hadrocharmonium:
decays to non-J/ψ(h_c) charmonium states should be suppressed ← they aren't

BESIII is well suited to further investigate this intriguing puzzle ← a "Y(4260)" factory

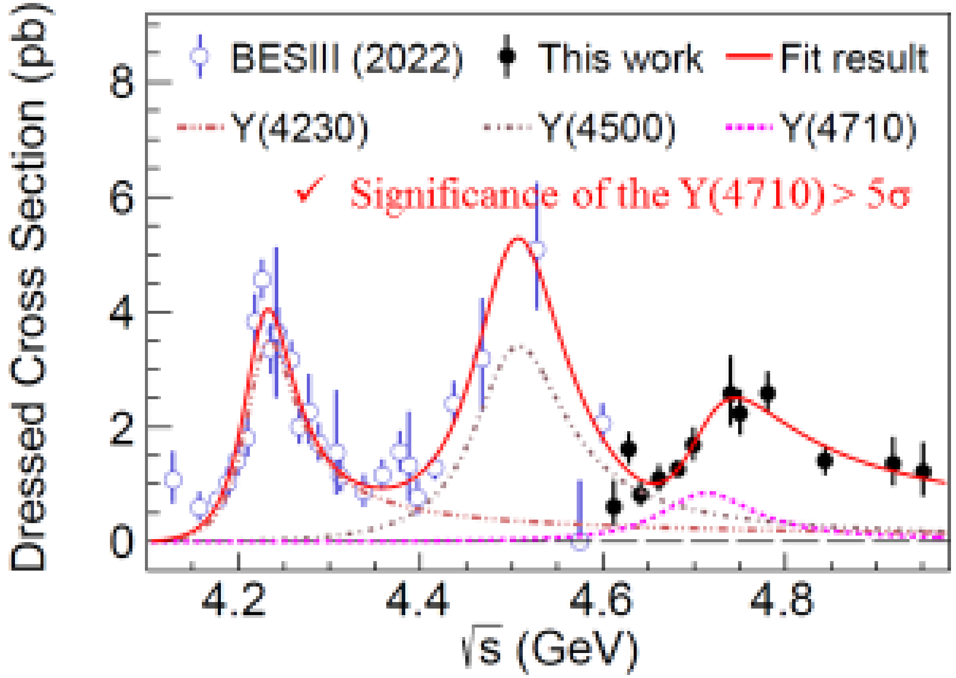
An even higher mass vector state Y(4710) in KKJ/ψ

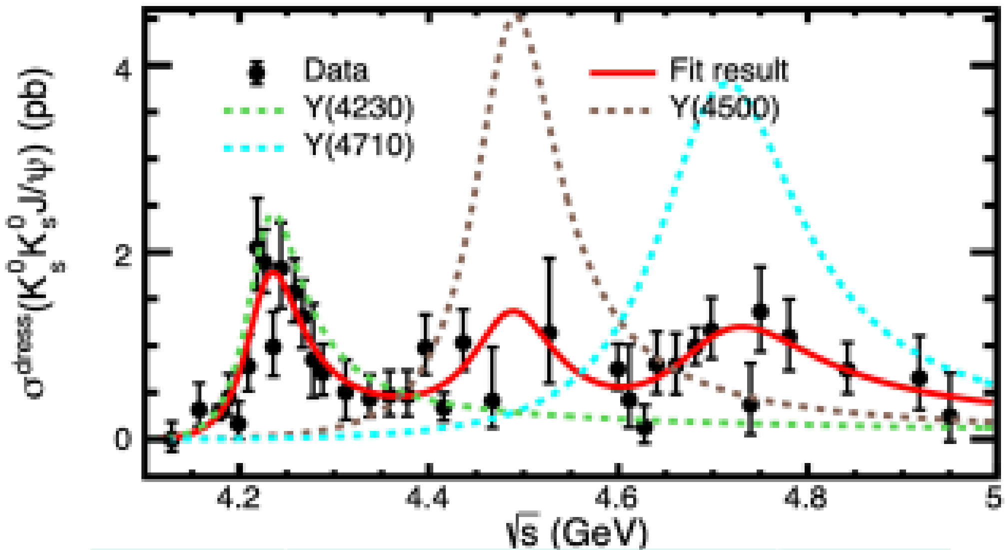
BESIII

PRL131, 211902 (2023) $e^+e^- \to K^+K^-J/\psi$

5.85 fb^{-1}, Ecm=4.61-4.95 GeV

PRD107, 092005 (2023) $e^+e^- \to K_SK_SJ/\psi$



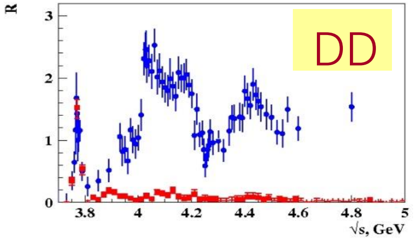


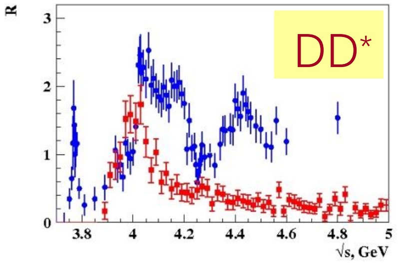
resonance	mass (MeV)	width (MeV)	note
Y(4230)	4226±2	70±4	Stat. only
Y(4500)	4499±8	124±20	Stat. only
Y(4710)	4708^{+17}_{-15}±21	126^{+27}_{-23}±30	>5σ

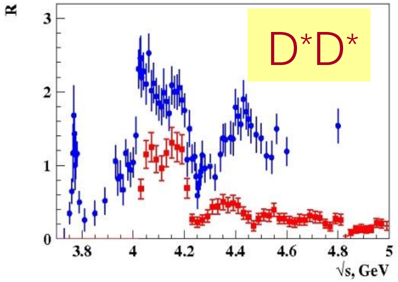
resonance	mass (MeV)	width (MeV)	note
Y(4230)	4227±7±22	72±16±33	
Y(4500)	Fixed	Fixed	1.4σ
Y(4710)	4704±52±70	183±114±96	4.0σ

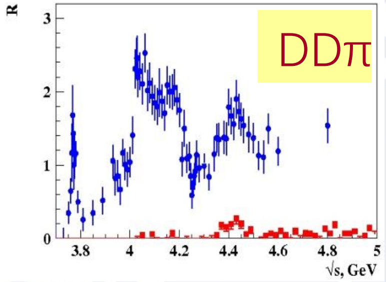
5S vector charmonium states?

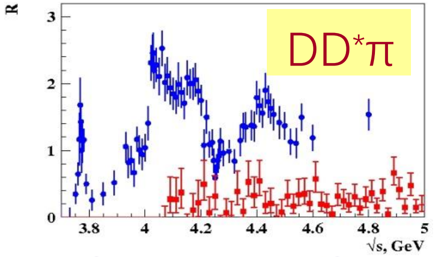
20

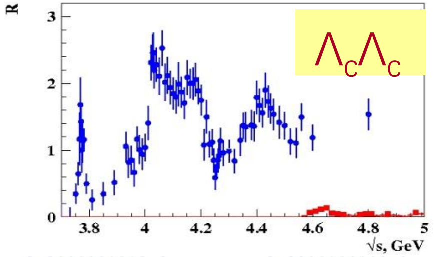


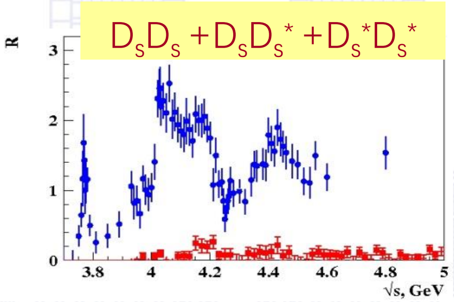








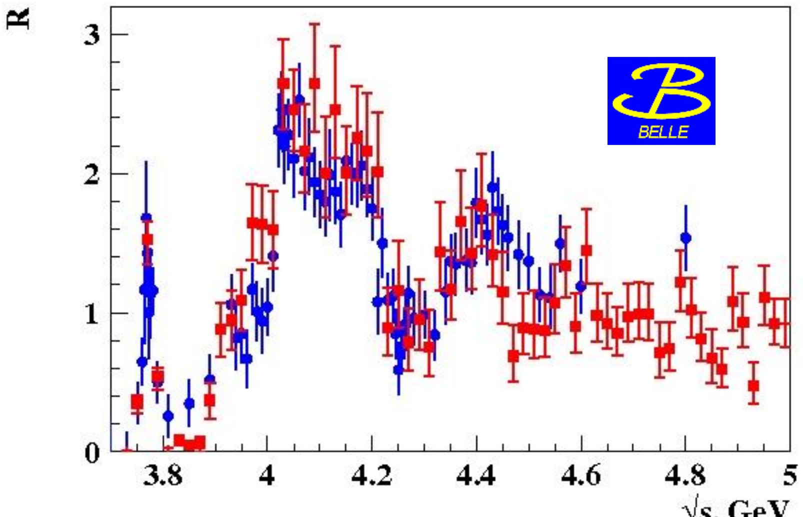




Exclusive cross sections contribution to the total cross section

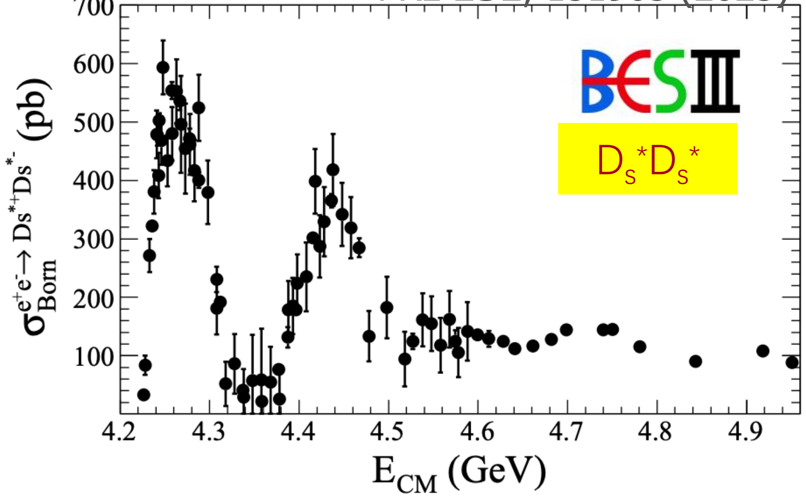
Blue: R-measurement

Red: Cross section measurements



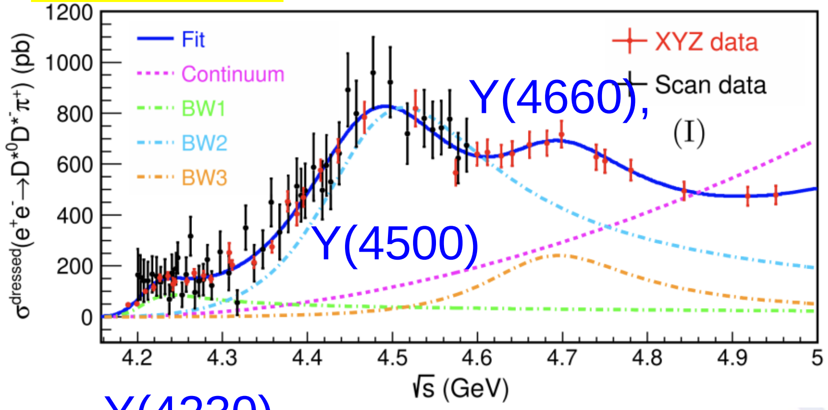
Contributions of D^+D^{*-}, $D^{*+}D^{*-}$, $D^0D^-\pi^+$ and $D^0D^{*-}\pi^+$ are scaled following isospin symmetry

PRL **131**, 151903 (2023)

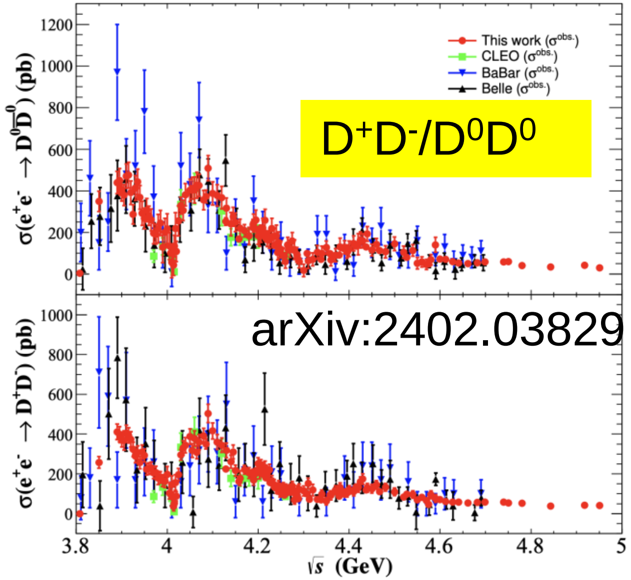


$D^{*0}D^{*+}\pi^-$

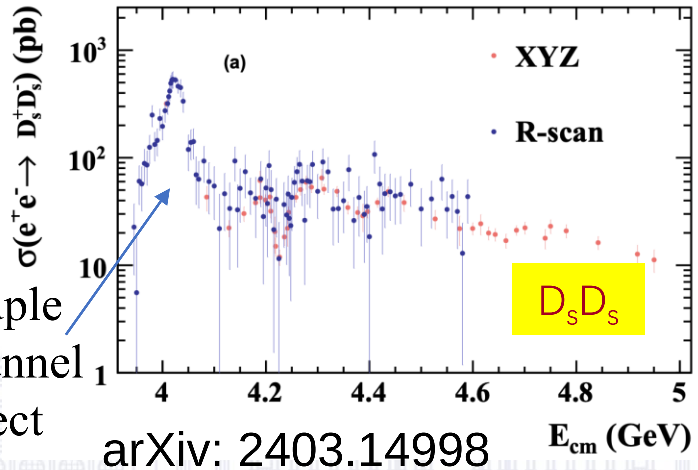
PRL 130, 121901 (2023)



Y(4230)

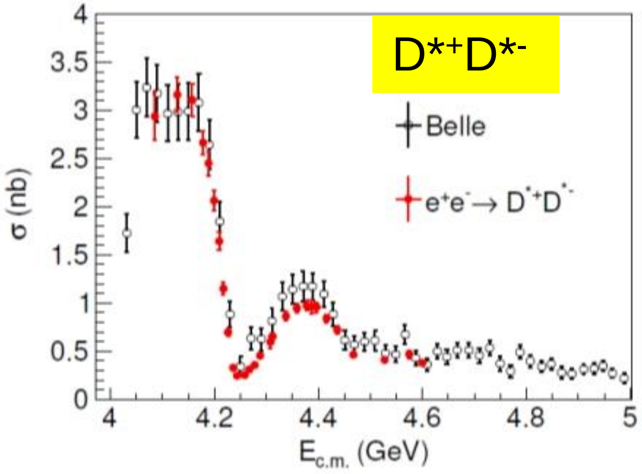


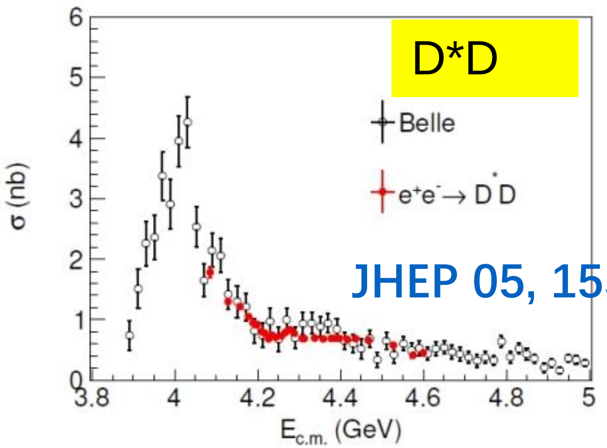
arXiv:2402.03829



couple channel effect

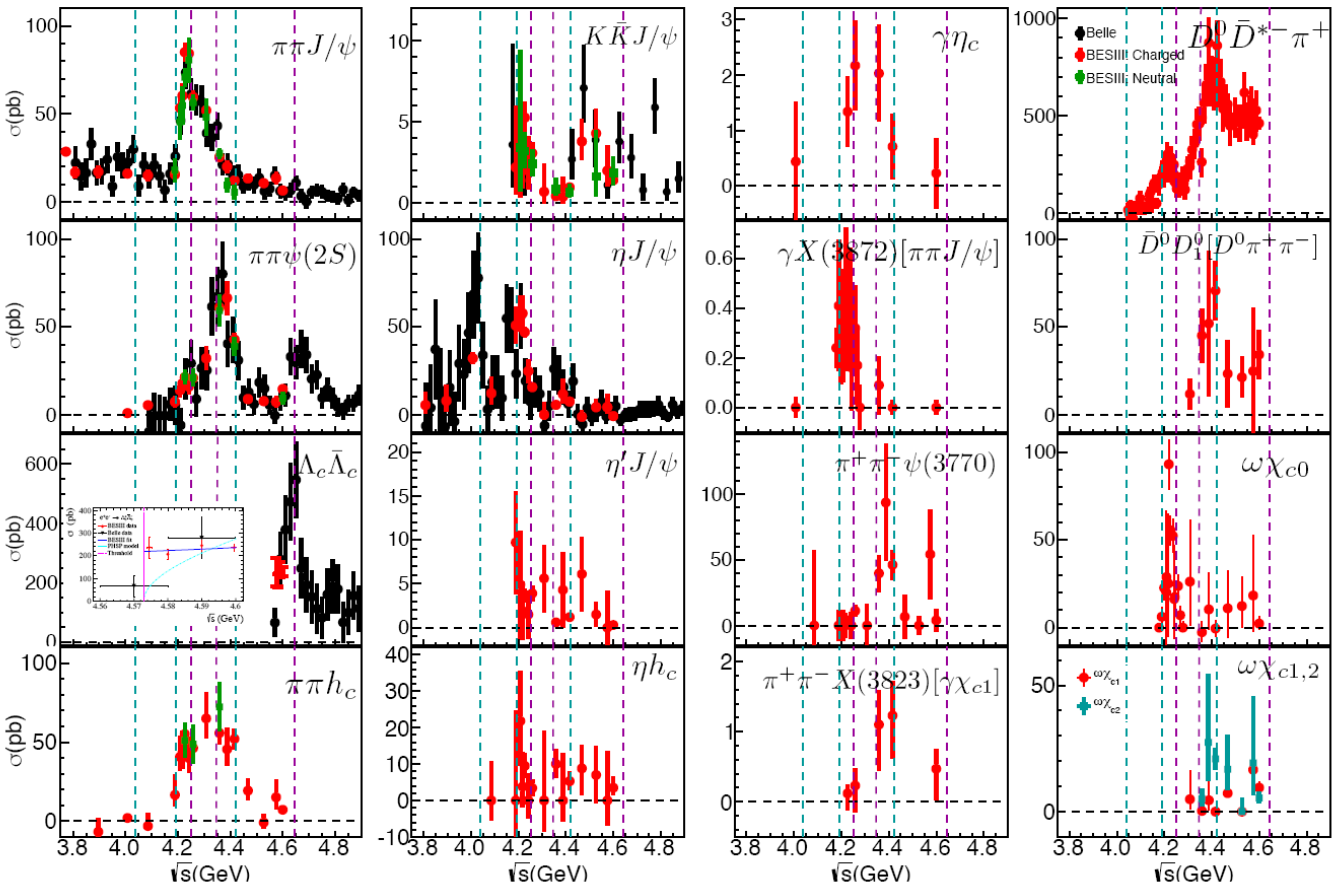
arXiv: 2403.14998

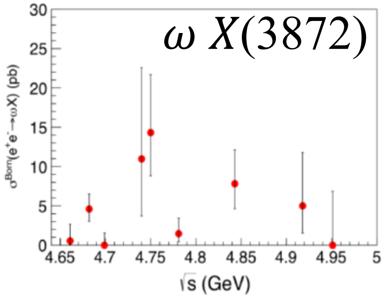




JHEP 05, 155, (2022)

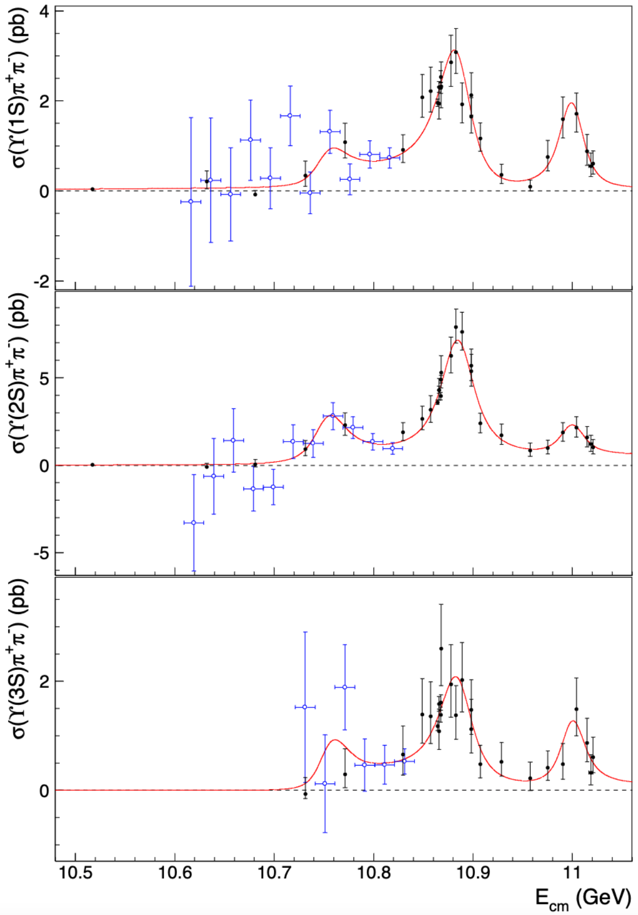
After we have measured all the e^+e^- annihilation cross sections, what do we do to get the resonant parameters of the vector charmonium(-like) states?



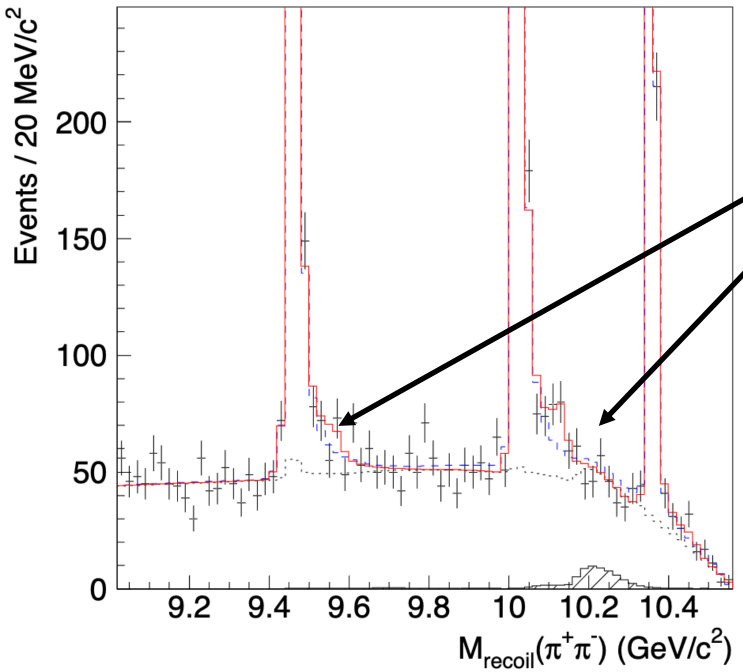


Υ(10753) --- discovery and studies

JHEP 10, 220(2019)



- The Υ(10753) was firstly observed in the process of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-(n=1,2,3)$ by Belle.
- Simultaneous fit to cross sections and $M_{\mathrm{recoil}}(\pi\pi)$



Existence of Υ(10753)

Computed as blue dots in left plot

$M = (10752.7 \pm 5.9^{+0.7}_{-1.1})\mathrm{MeV}/c^2$

$\Gamma = (35.5^{+17.6+3.9}_{-11.3-3.3})\mathrm{MeV}$

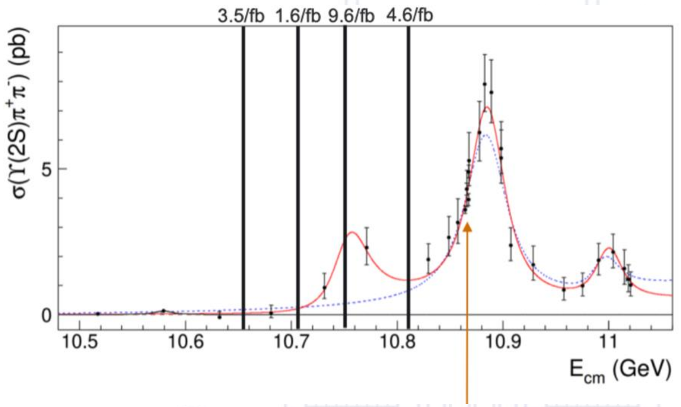
Interpretation of the Y(10753)

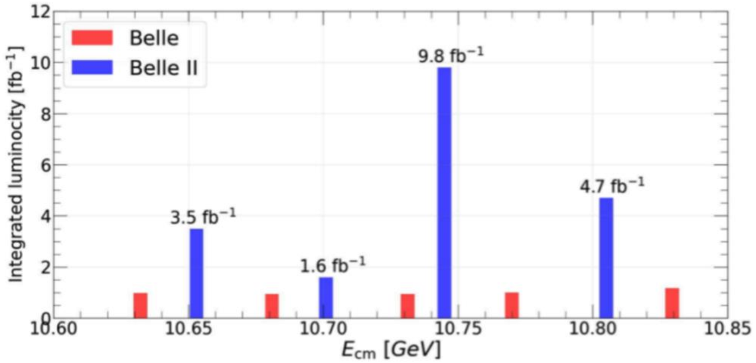
- D-wave bottomonium
  - B. Chen, A.L. Zhang, J. He, arXiv:1910.06065, Bottomonium spectrum in the relativistic flux tube model (3D)
  - Q. Li, M.S. Liu, Q.F. Lü, L.C. Gui, X.H. Zhong, arXiv:1905.10344, Canonical interpretation of Y(10750) and Y(10860) in the Y family (4D)
- $\bar{B}^{(*)}B^{(*)}$ dynamically 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)

Study of properties of $\Upsilon(10753)$

- Largest bottomonium data sample at Belle and Belle II
- In Nov. 2021, Belle II collected ~20/fb of unique scan data at energies near 10.75 GeV
  - Fill the gaps in Belle Scan data
  - Physics goal is to understand the nature of $\Upsilon(10753)$

Unique data

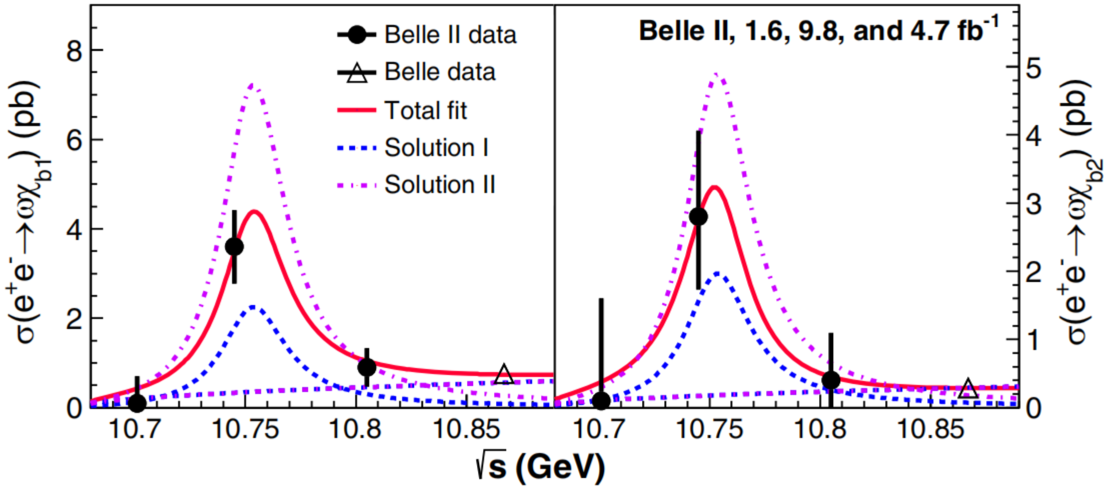




- **More analyses are ongoing**
  - $\Upsilon(10753) \to K^+K^-\Upsilon(nS)$
  - $\Upsilon(10753) \to \eta(\eta')\Upsilon(nS)$
  - $\Upsilon(10753) \to \gamma X_b, X_b \to \pi\pi\chi_{bJ}, \pi\pi\Upsilon(nS)$
  - etc…

Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$

PRL 130, 091902 (2023)



The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$.

Fit cross section with function:

$$\sigma_{e^+e^-\to\omega\chi_{b1}}(\sqrt{s}) = |\sqrt{PS_2(\sqrt{s})} + \mathrm{BW}(\sqrt{s})e^{i\phi}|^2, \mathrm{BW}(\sqrt{s}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 + iM\Gamma}\sqrt{\frac{PS_2(\sqrt{s})}{PS_2(M)}}$$

M and Γ of $\Upsilon(10753)$ are fixed according to Ref. [JHEP 10, 220(2019)].

$\Gamma_{ee}\mathcal{B}_f$	**Solution I** (constructive interference)	**Solution II** (destructive interference)
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$	(0.63±0.39±0.20) eV	(2.01±0.38±0.76) eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$	(0.53±0.46±0.15) eV	(1.32±0.44±0.55) eV

1. $\sigma(e^+e^- \to \omega\chi_{b1})/\sigma(e^+e^- \to \omega\chi_{b2})$=1.3±0.6 at 10.745 GeV, contradicts the expectation for a pure D-wave bottomonium state of 15 [PLB 738, 172 (2014)]
2. There is also a 1.8σ difference with the prediction for a S-D-mixed state of 0.2 [PRD 104, 034036 (2021)]

Updated measurement of the energy dependence of the $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ cross sections

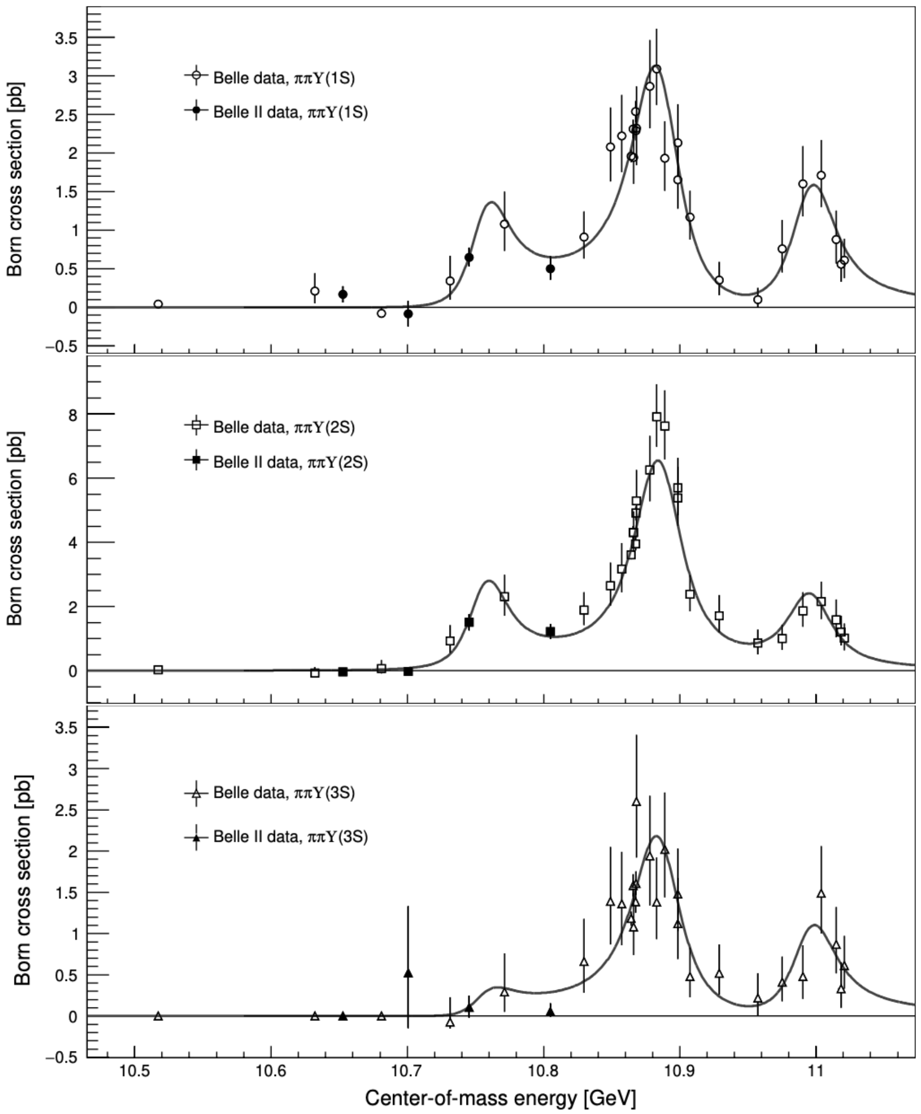
arXiv:2401.12021

$$\sigma \propto \left|\sum_i^3 \frac{\sqrt{12\pi\Gamma_i\mathcal{B}_i}}{s - M_i + iM_i\Gamma_i} \cdot \sqrt{\frac{f(\sqrt{s})}{f(M_i)}} e^{i\phi_i}\right|^2 \otimes G(0, \delta E)$$

Parameters of $\Upsilon(10753)$:
$M = 10756.3 \pm 2.7_{(stat.)} \pm 0.6_{(syst.)} \mathrm{MeV}/c^2$
$\Gamma = 29.7 \pm 8.5_{(stat.)} \pm 1.1_{(syst.)} \mathrm{MeV}$

Agree with previous Belle measurement.
Improve uncertainties ~2 times smaller

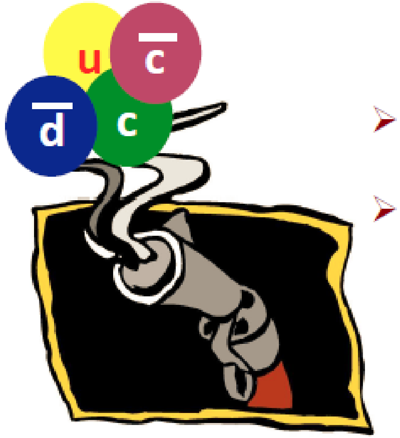
resonance	mass (MeV/c^2)	width (MeV)
$\Upsilon(5S)$	10884.7 ± 1.2	38.7 ± 3.7
$\Upsilon(6S)$	10995.5 ± 4.2	34.6 ± 8.6



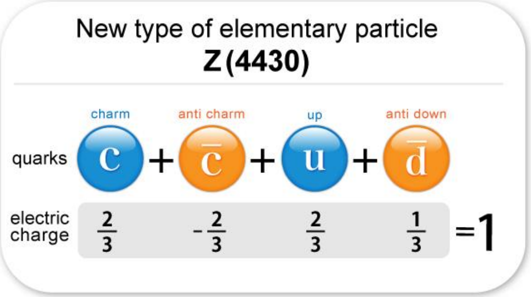
Z States

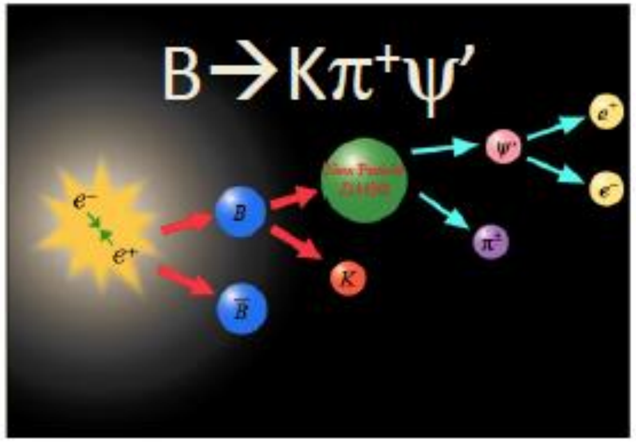
The Z(4430)$^+ \rightarrow \pi^+ \psi'$

"smoking gun" evidence for a 4-quark meson



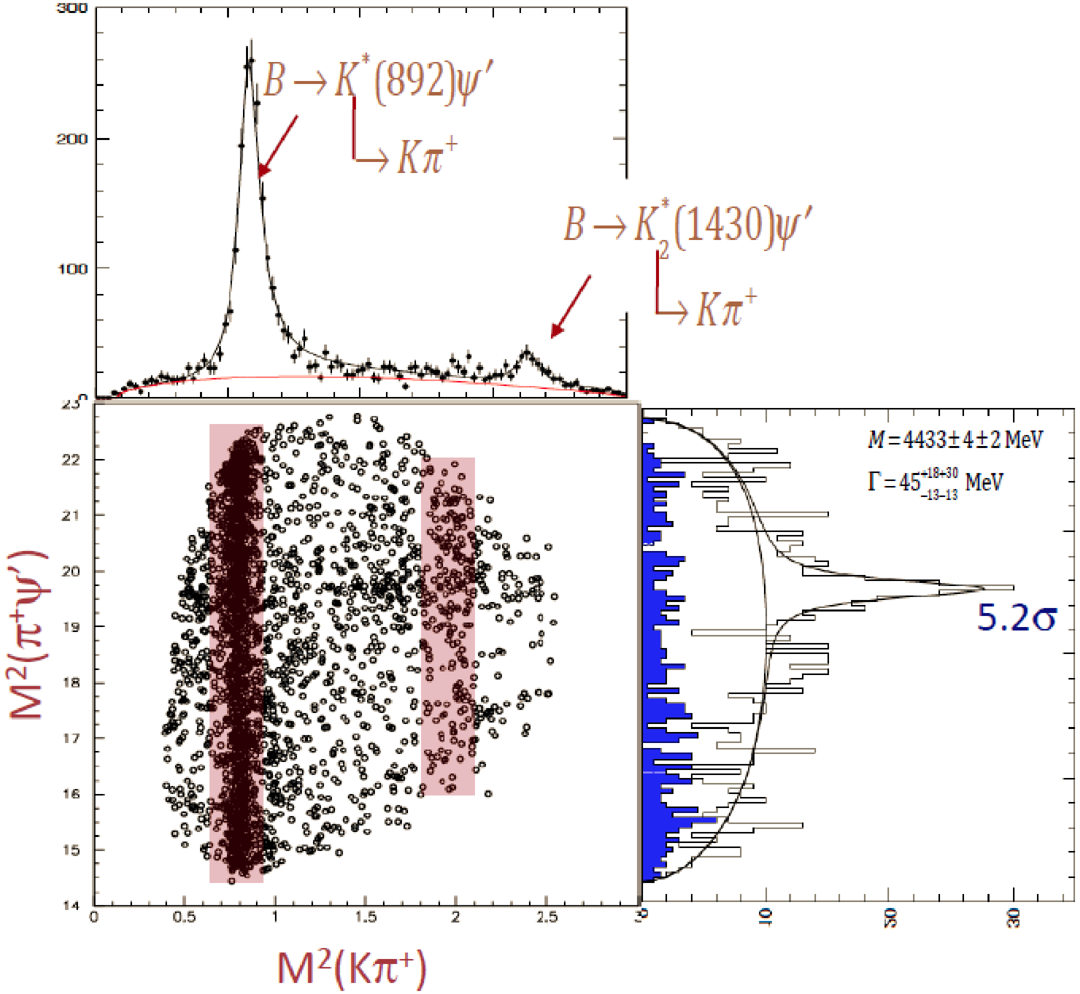
- decays to ψ' ➔ must contain cc̄ pair
- electrically charged ➔ must contain ud̄ pair



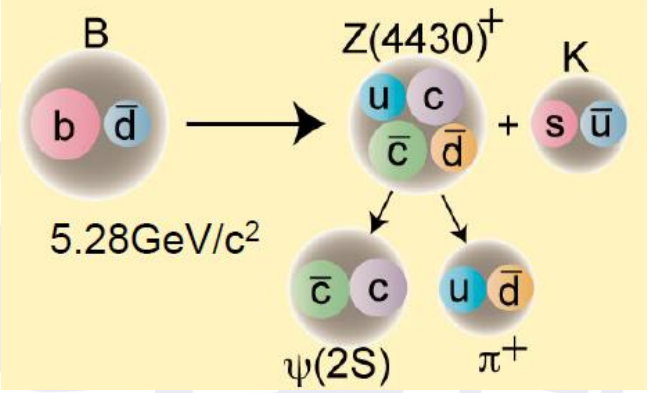


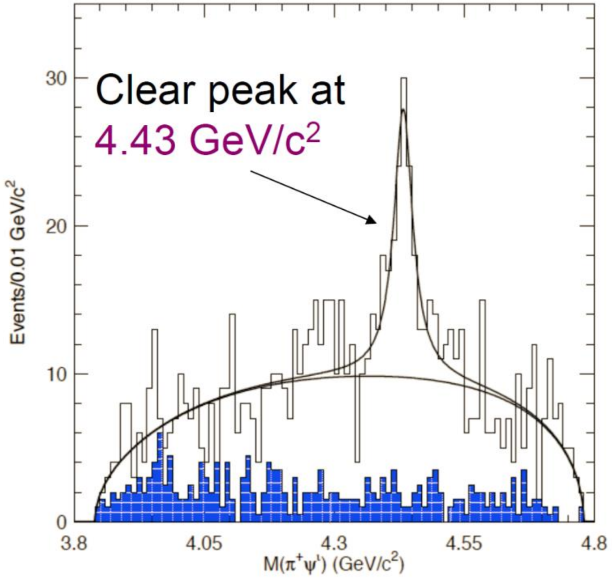
PRL 100, 142001 (2008)

S-K Choi et al Belle: PRL 100 142001

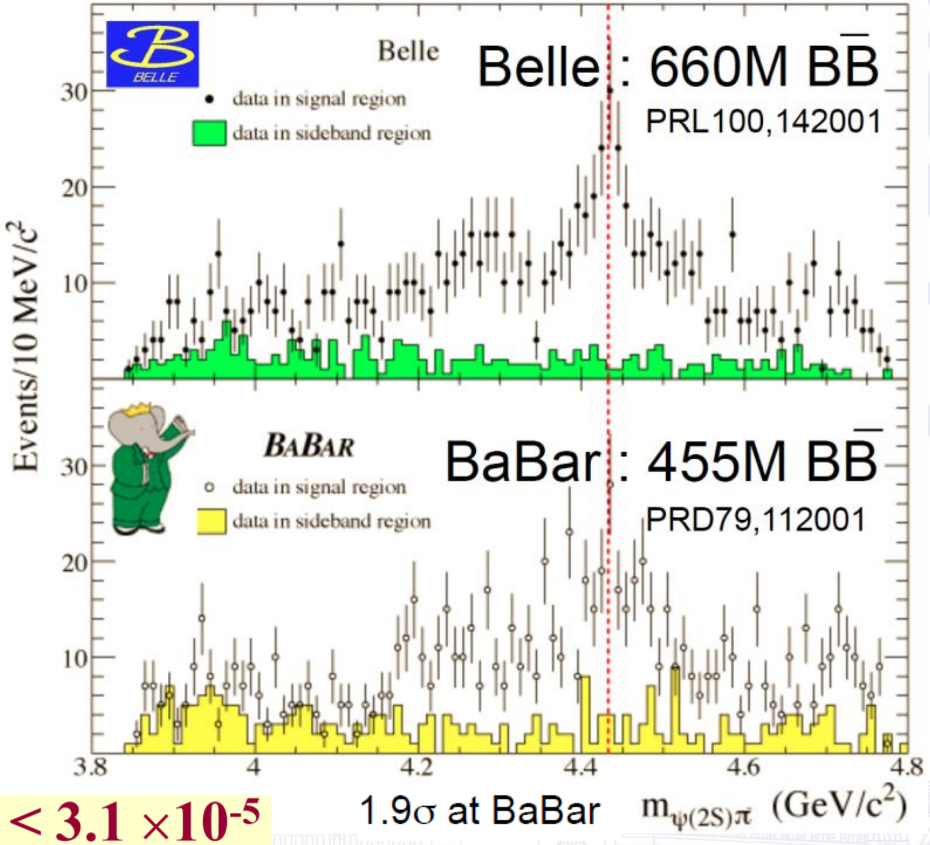


$Z_c(4430)^{\pm}$ exist or not ?





PRL 100, 142001 (2008)



"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9s from zero; fixing mass and width increases this to only ~3.1s."

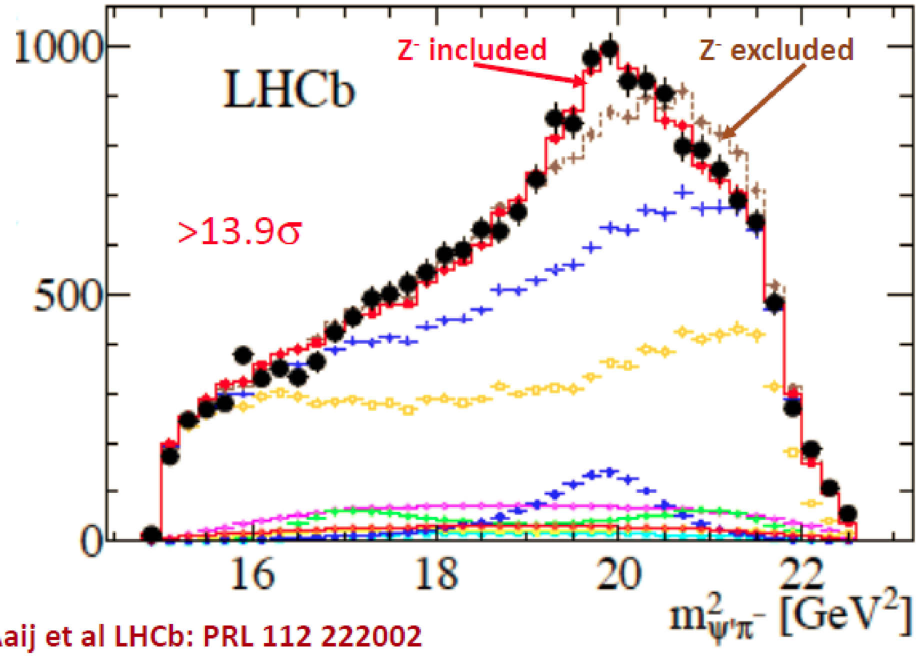
$BF(B^0 \to Z^+K) \times BF(Z^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

Phys.Rev.D 79 (2009) 112001

LHCb 4-dim analysis of B→K⁺π⁻ψ′

B→K⁺π⁻ ψ′ 4-dim amplitude analysis



R. Aaij et al LHCb: PRL 112 222002

$J^P = 1^+$

$M = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Good agreement with Belle,
(with smaller errors)

$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$

- *PRL* 112 (2014), 222002

Belle observed Two $Z^{\pm}\to\chi_{c1}\pi^{\pm}$

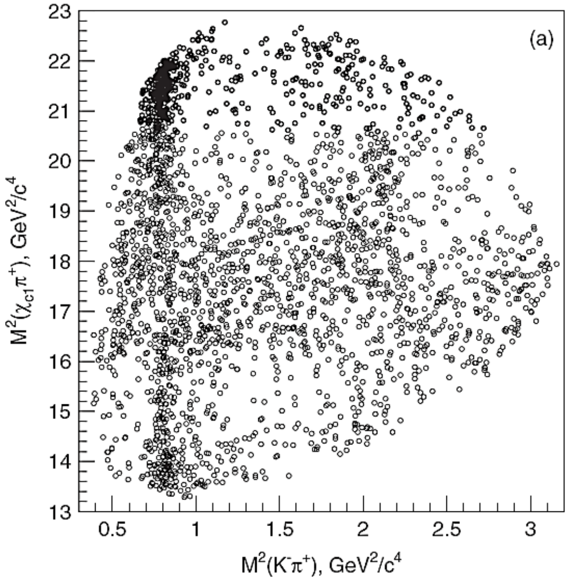
- Dalitz-plot analysis of $\underline{B}^0\to\chi_{c1}\pi^+K^-$ $\chi_{c1}\to J/\psi\gamma$ with 657M $B\underline{B}$
- Dalitz plot models: known $K^*\to K\pi$ only

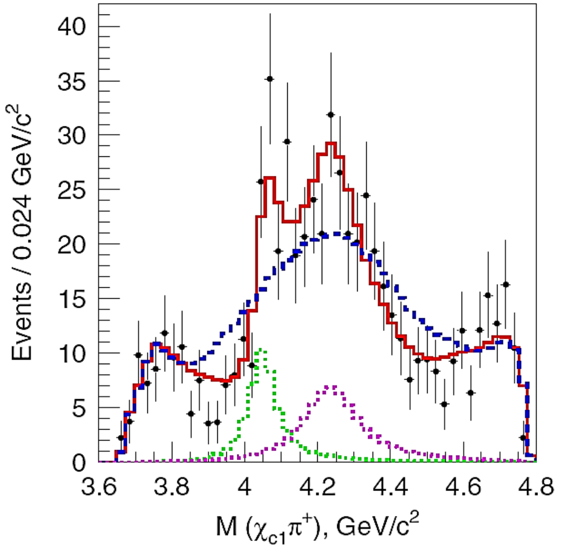
  K^*'s + one Z $\to\chi_{c1}\pi^{\pm}$

  K^*'s + two $Z^{\pm}$ states ⇨ favored by data

PRD 78, 072004 (2008)

Significance: 5.7σ





fit for model with K*'s

fit for double Z model

Z_1 contribution

Z_2 contribution

$M(\chi_{c1}\pi^+)$

for $1<M^2(K^-\pi^+)<1.75\text{GeV}^2$

$$M_{Z_1} = 4051\pm14{}^{+20}_{-41}\ \text{MeV}$$

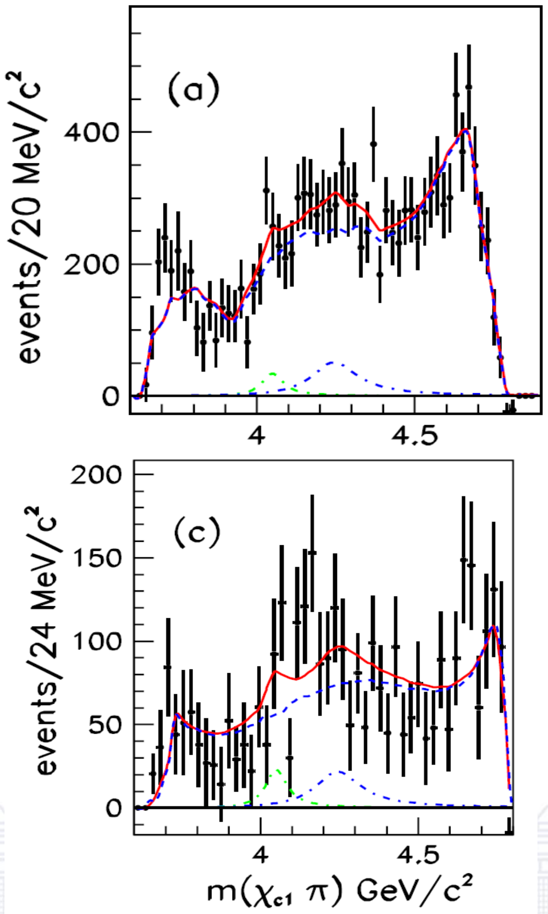
$$\Gamma_{Z_1} = 82{}^{+21}_{-17}{}^{+47}_{-22}\ \text{MeV}$$

$$M_{Z_2} = 4248{}^{+44}_{-29}{}^{+180}_{-35}\ \text{MeV}$$

$$\Gamma_{Z_2} = 177{}^{+54}_{-39}{}^{+316}_{-61}\ \text{MeV}$$

BaBar doesn't see significant $Z^{\pm} \to \chi_{c1}\pi^{\pm}$

PRD85, 052003 (2012)



for $1<M^2(K^-\pi^+)<1.75 GeV^2$

$$\mathcal{B}(\bar{B}^0 \to Z_1(4050)^+ K^-) \times \mathcal{B}(Z_1(4050)^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5},$$

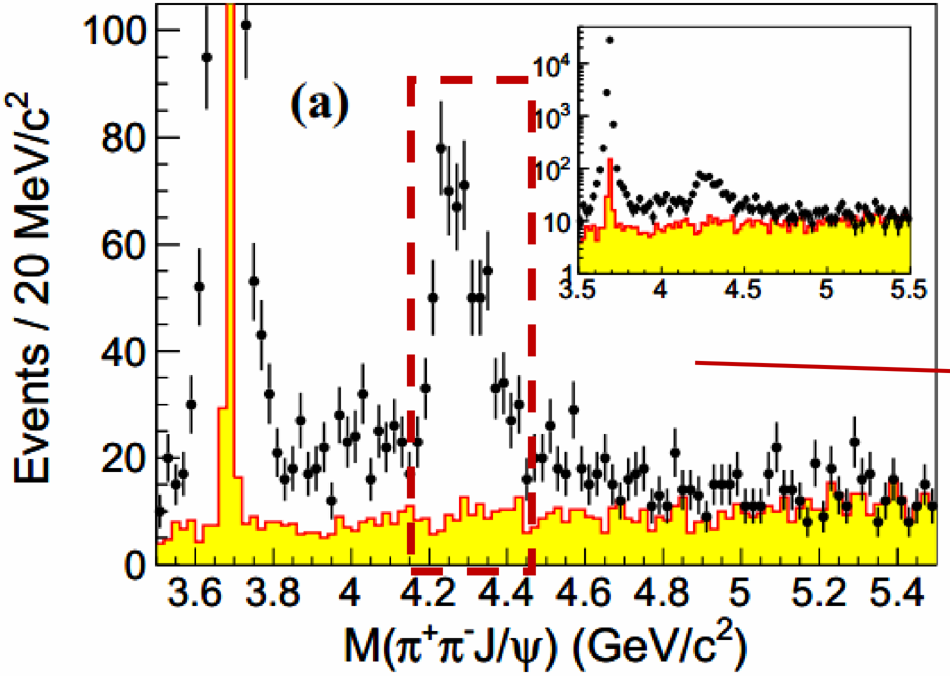
Belle: $(3.0^{+1.5}_{-0.8}{}^{+3.7}_{-1.6})\mathrm{x}10^{-5}$

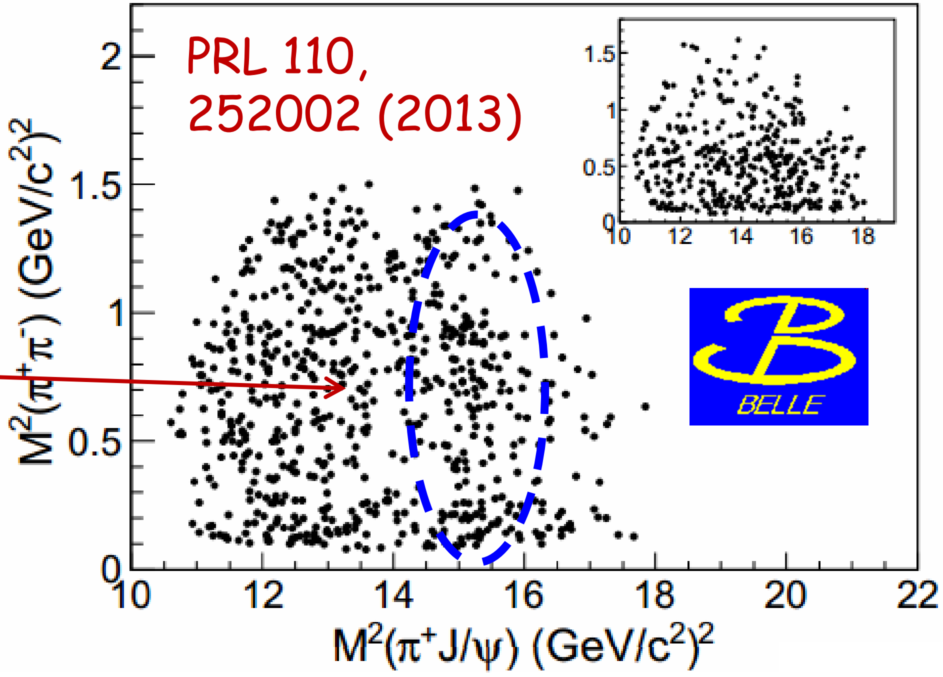
$$\mathcal{B}(\bar{B}^0 \to Z_2(4250)^+ K^-) \times \mathcal{B}(Z_2(4250)^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5},$$

Belle: $(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5})\mathrm{x}10^{-5}$

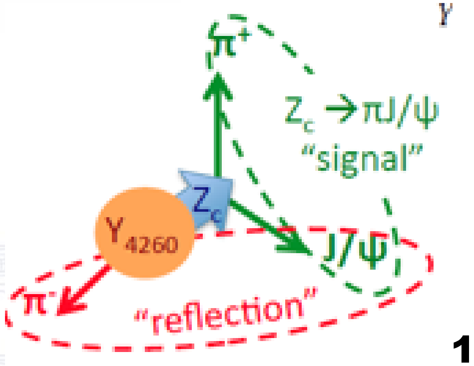
"We find that it is possible to obtain a good description of our data without the need for additional resonances in the $\chi_{c1}\pi$ system."

Zc(3900)$^{\pm}$ from Belle

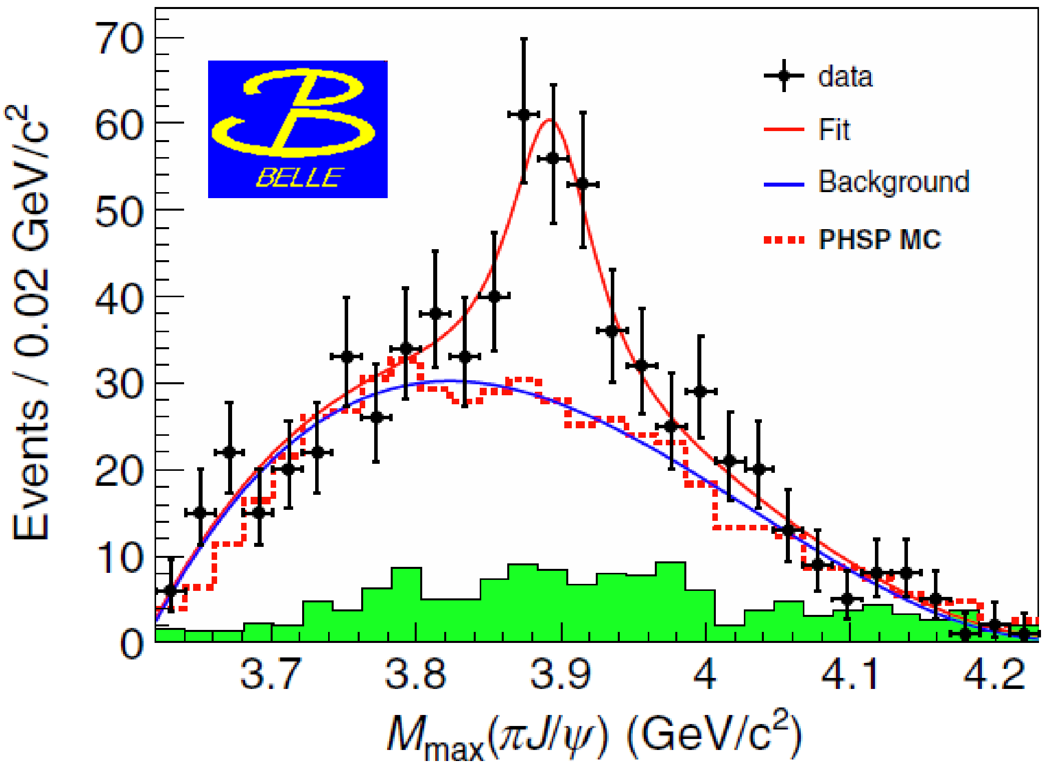




1. Almost full Belle data sample used: Lum=967 fb^{-1} data.
2. Using ISR photon non-tagged method, Y(4260) was observed significantly.
3. $4.15<M(p^+p^-J/y)<4.45$ GeV to select Y(4260) resonance.
4. Dalitz plot also shows structures.



Zc(3900)$^{\pm}$ from Belle

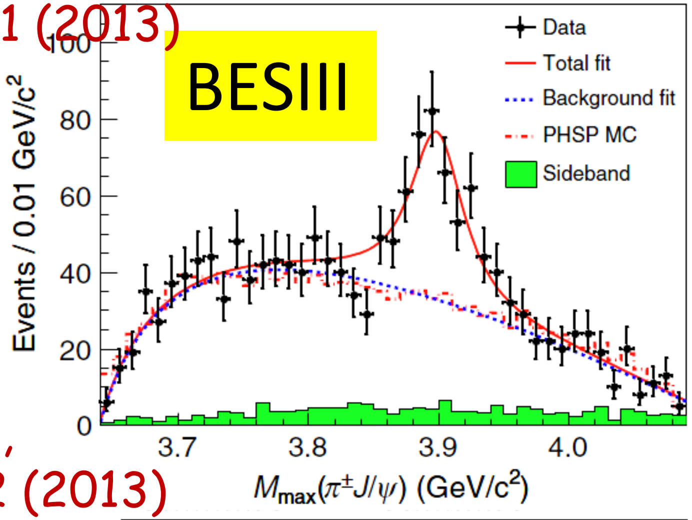


1. S-Wave BW, p*q phase space factor, efficiency applied, to fit $M_{max}(\pi^{\pm}J/\psi)$ distribution
2. Belle observed 689 events, with 139 background.
3. M=(3894.5±6.6±4.5) MeV; Γ=(63±24±26) MeV.
4. Significance:5.2σ.

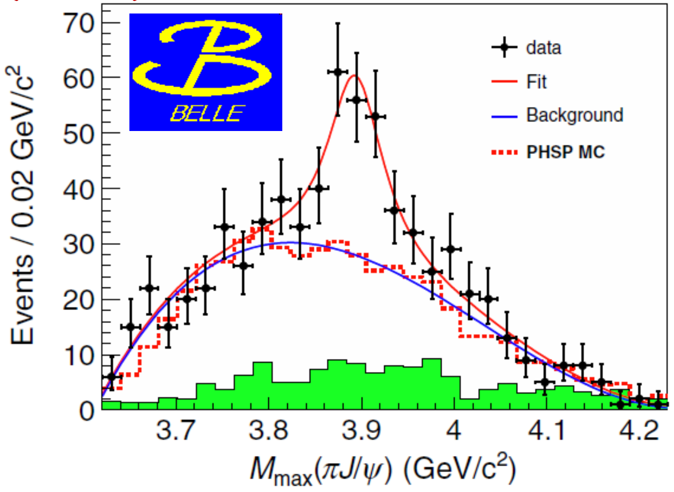
Comment: Since Zc(3900) is charged and can decay into πJ/ψ, it must have at least four quarks.

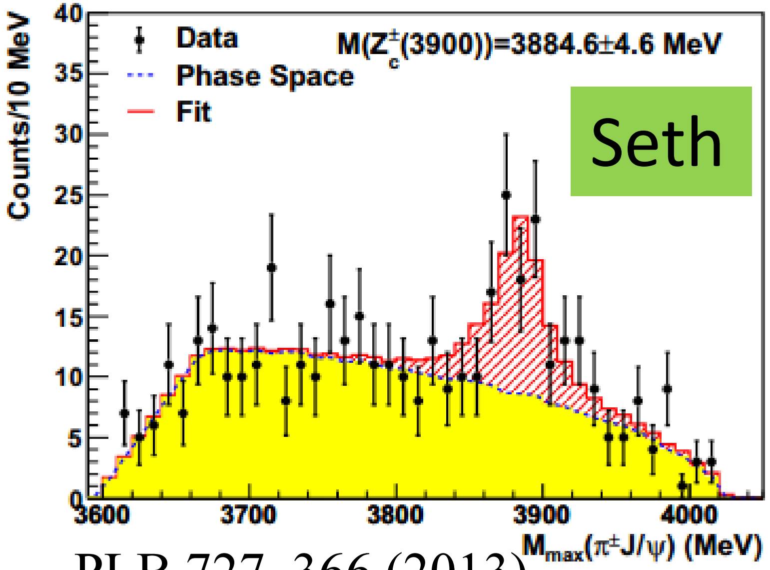
BESIII + Belle + CLEO's data

PRL 110, 252001 (2013)



PRL 110, 252002 (2013)





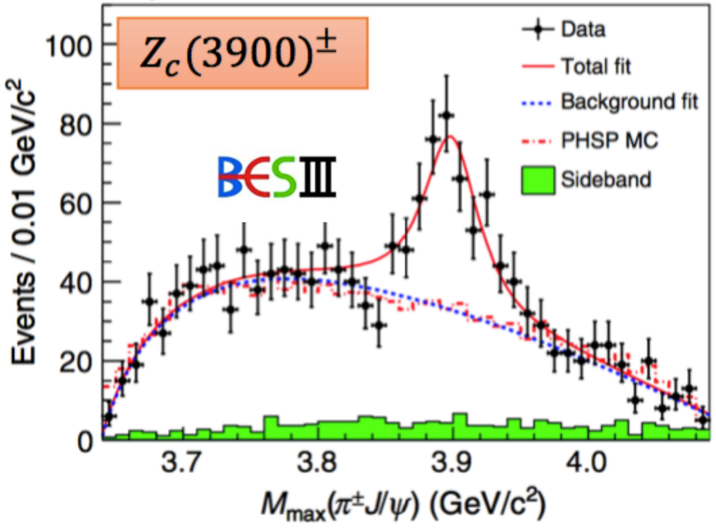
PLB 727, 366 (2013)

1. CLEO's data at 4.17 GeV by K. Seth.
2. M=3885±5 MeV, Γ=34±13 MeV.
3. Significance: 6σ

$$M(Z_c(4430)) - M(Z_c(3900)) = 589 \pm 30\ \text{MeV}$$
$$M(\psi') - M(J/\psi) = 589\ \text{MeV}$$

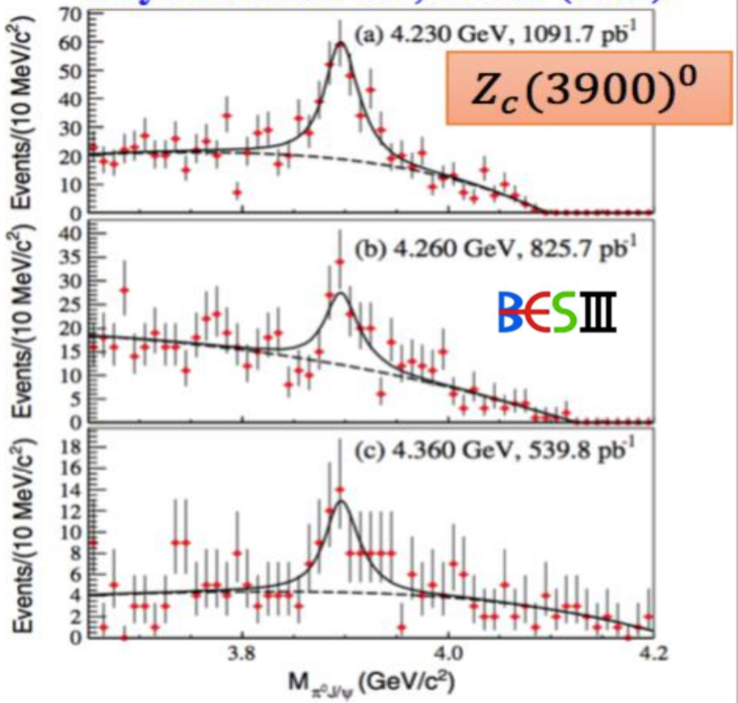
Z_c(3900) State (I=1)

Phys. Rev. Lett 110, 252001 (2013)



- Charged charmonium-like structure (>10 σ)
- Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- $\frac{\sigma(e^+e^- \to \pi^{\mp} Z_c(3900)^{\pm} \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5$ %
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

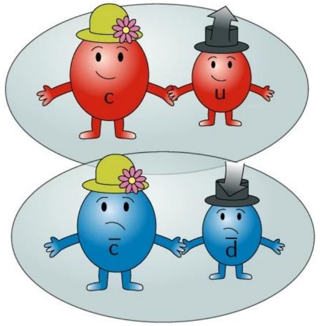
Phys. Rev. Lett 115, 112003 (2015)

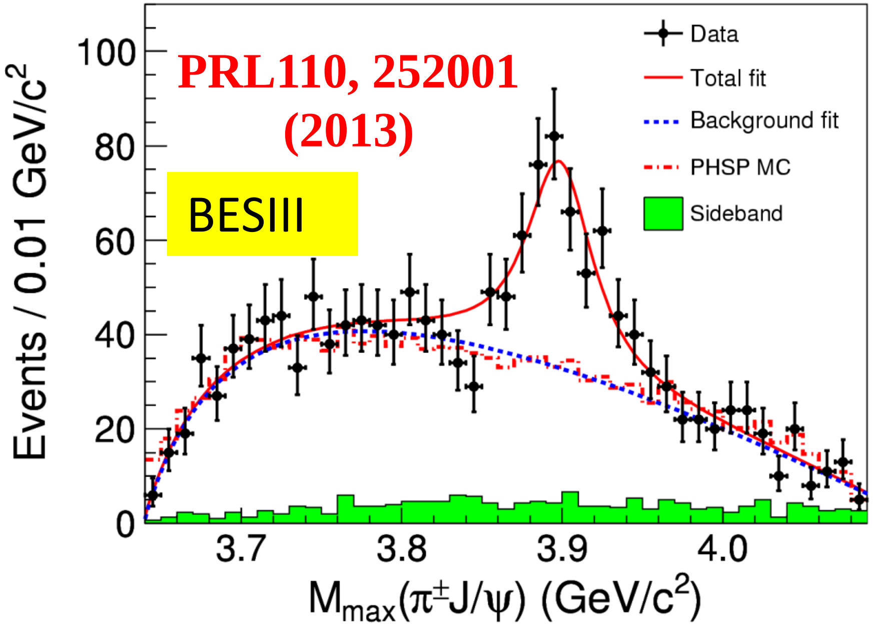


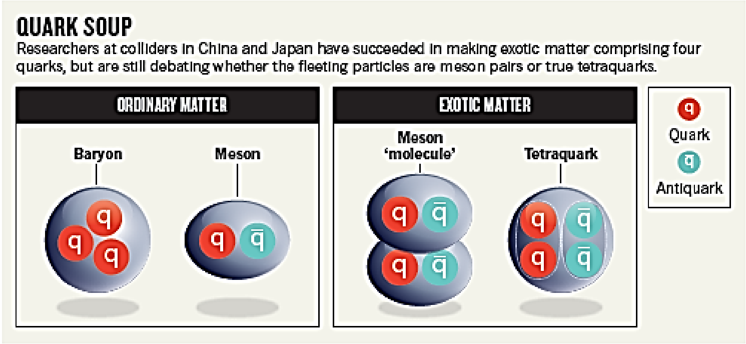
- Neutral charmonium-like structure (10.4 σ)
- Using 3 data samples (~2.5 fb⁻¹)
- Evidence with 3.7σ by using CLEO-c data
- $M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c², $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- An iso-spin triplet is established!

Observation of the $Z_c(3900)$
— a charged charmoniumlike structure —

BESIII: 2013.3.24
Belle: 3.30
CLEOc: 4.10
Z_c established!







PARTICLE PHYSICS

Quark quartet opens fresh vista on matter

First particle containing four quarks is confirmed.

BY DEVIN POWELL

Physicists have resurrected a particle that may have existed in the first hot moments after the Big Bang. Arcanely called $Z_c(3900)$, it is the first confirmed particle made of four quarks, the building blocks of much of the Universe's matter.

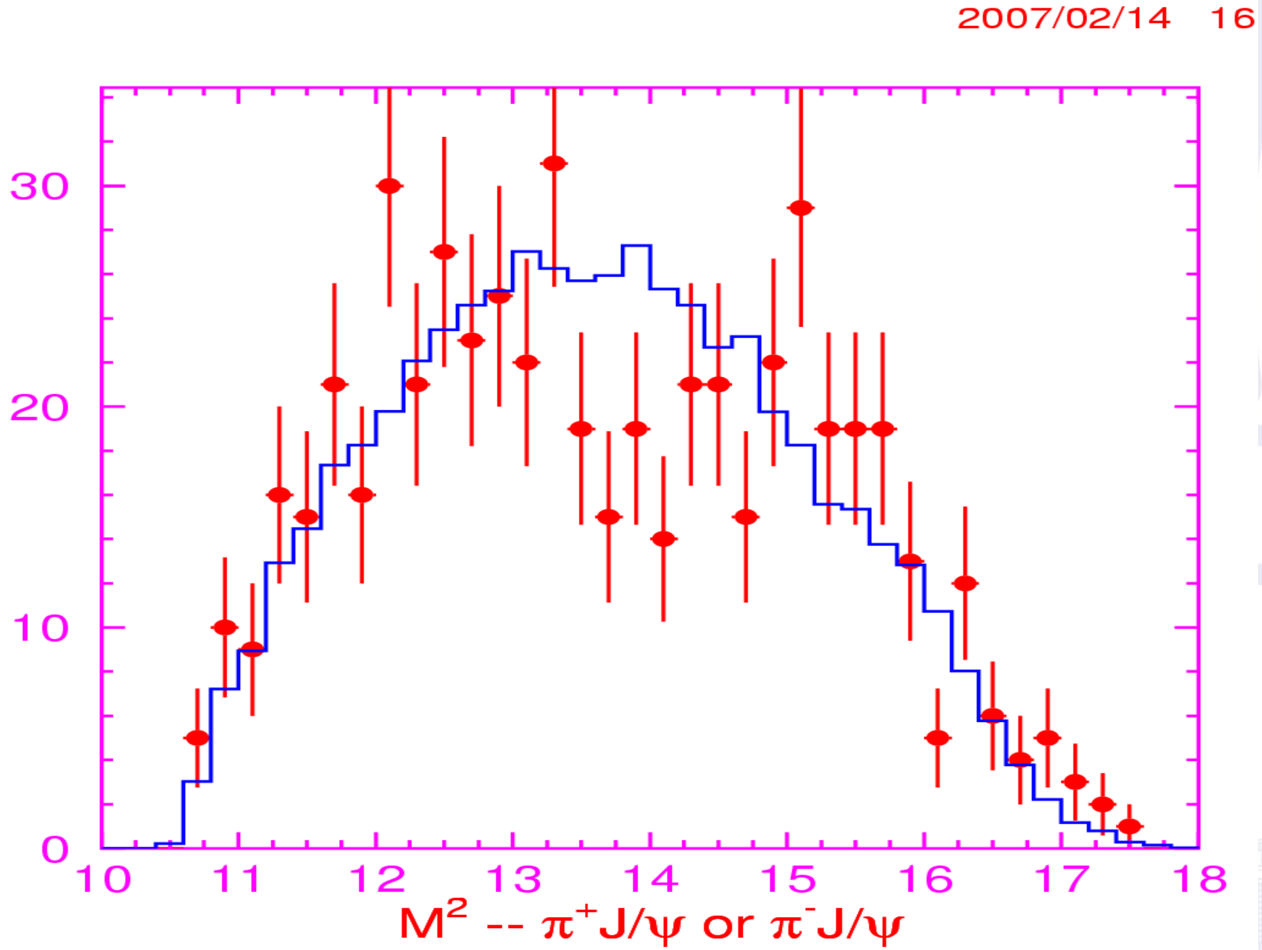
Until now, observed particles made of quarks have contained only three quarks (such as protons and neutrons) or two quarks (such as the pions and kaons found in cosmic rays). Although no law of physics precludes larger antimatter counterparts, positrons. These crashes have one-thousandth the energy of those at the world's most powerful accelerator, the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland, but they are still energetic enough to mimic conditions in the early Universe. Collision rates at KEK are more than twice those at the LHC, and they occasionally give birth to rare particles not found in nature today —

"They have clear evidence of a particle with four quarks."

Question: Zc has been confirmed. How about Zs ? How to search for it ?

M(ππJ/ψ)∈[4.2, 4.4] GeV via ISR

548/fb at 10.58 GeV
Peaks at 12 & 15 GeV^2?
Shown at QWG'2011



Spin-parity hypothesis with likelihood test

- Amplitude model
  helicity amplitude, covariant tensor amplitude
- null and alternative hypothesis
  Null: spin=J, alternative: spin $\neq J$
- test with data events
  Minimize log-likelihood function
- check with angular distributions, moment analysis and invariant mass lineshape
- significance test:
  likelihood ratio or ToyMC ensemble (avoid look elsewhere effect)

$Z_c(3900)$

$I^G(J^{PC}) = 1^+(1^{+-})$

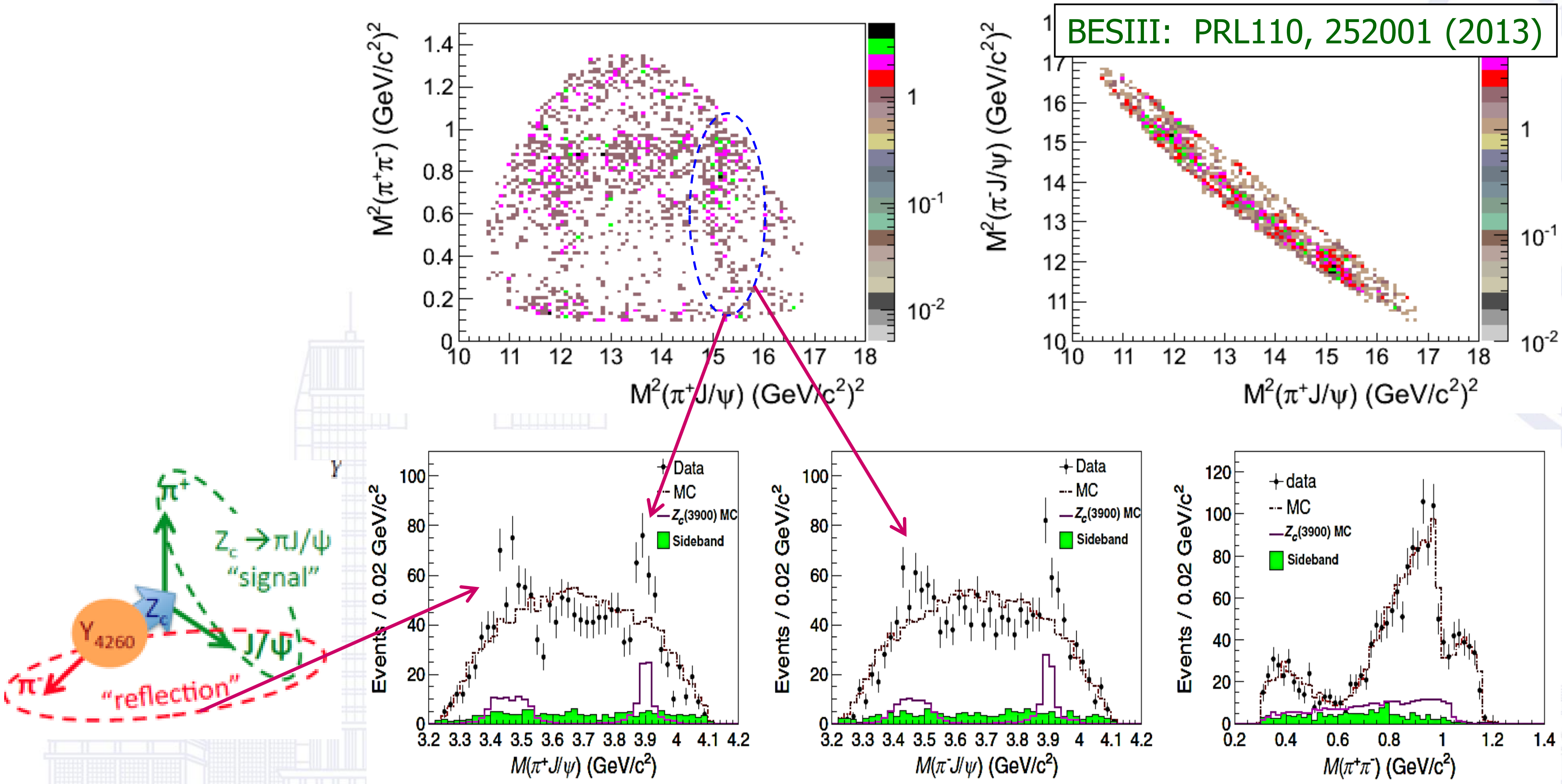
was $X(3900)$

Properties incompatible with a $q\bar{q}$ structure (exotic state). See the review on non- $q\bar{q}$ states. Charged $Z_c(3900)$ seen as a peak in the invariant mass distribution of the $J/\psi\pi^\pm$ system by BES III (ABLIKIM 2013T) in $e^+ e^- \to \pi^+\pi^- J/\psi$ at c.m. energy of 4.26 GeV and by radiative return from $e^+ e^-$ collisions at $\sqrt{s}$ from 9.46 to 10.86 GeV at Belle (LIU 2013B). Partial wave analysis of ABLIKIM 2017J determines $J^P = 1^+$ with more than 7 σ significance. Neutral $Z_c(3900)$ seen in the $J/\psi\pi^0$ invariant mass distribution in $e^+ e^- \to \pi^0\pi^0 J/\psi$ at c.m. energies of 4.23, 4.26, and 4.36 GeV by BES III (ABLIKIM 2015U) and at 4.17 GeV by XIAO 2013A. Peaks in ($D\bar{D}^*$)$^{0,\pm}$ reported by BES III (ABLIKIM 2014A, ABLIKIM 2015AB) are assumed to be related.

$Z_c(3900)$ MASS	3887.1 ± 2.6 MeV (S = 1.7)
$Z_c(3900)$ WIDTH	28.4 ± 2.6 MeV

1. M. Ablikim, et al. (BESIII), Phys.Rev.Lett.,110, 252001 (2013).
2. M. Ablikim, et al. (BESIII), Phys.Rev.Lett.,119, 072001 (2017).

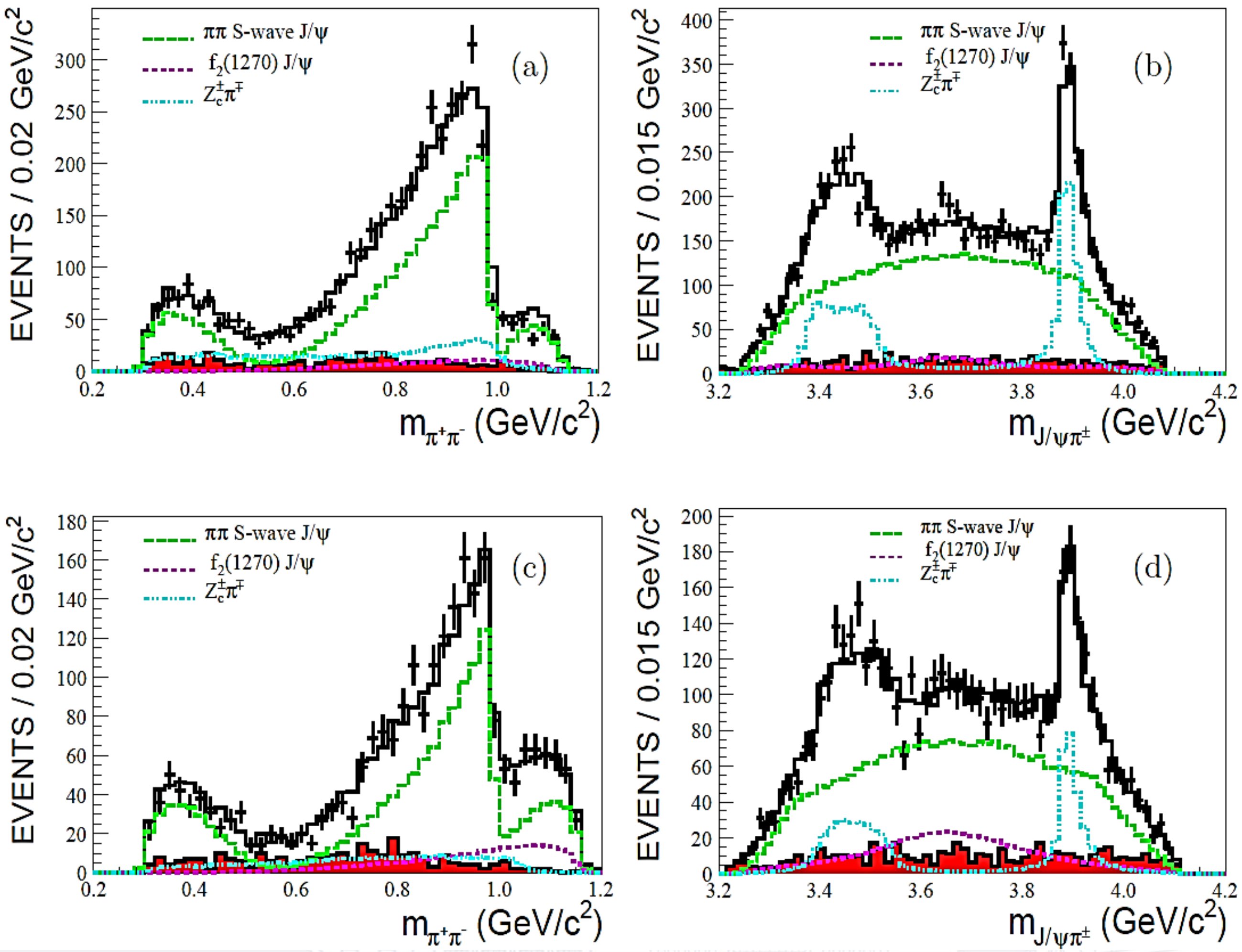
Dalitz plot and mass spectrum



Spin and parity measurement of Zc(3900)

4.23 GeV
1092/pb

4.26 GeV
826/pb



- ✓ simultaneous fit of two data sets
- ✓ helicity amplitude for $e^+e^- \to \gamma^* \to R(\pi\pi)\psi$ & $Z_c\psi, \psi \to l^+l^-$
- ✓ Isobar model: $\sigma, f_0, f_0(1370), f_2(1270), Z_c^\pm$
- ✓ $Z_c^\pm$ as 1^+ state

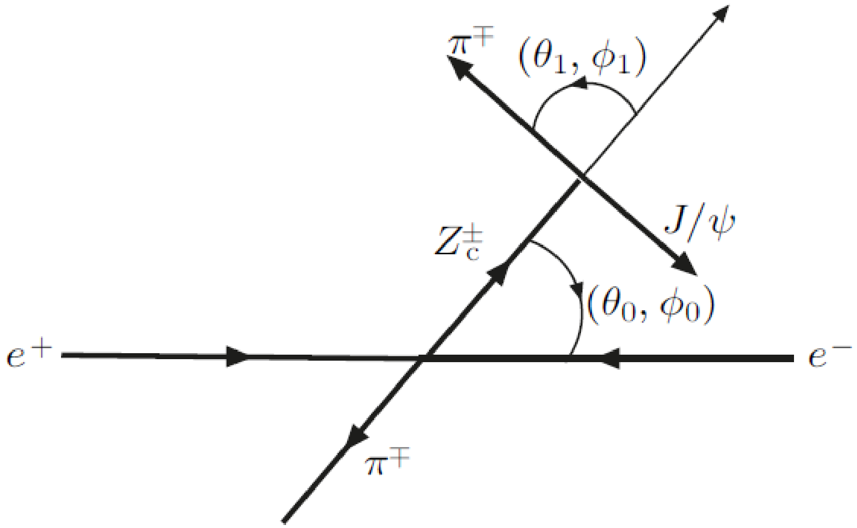
Angular distribution for the Zc(3900) J^P assumption

1. $e^+e^- \to \pi^\pm Z_c^\mp$

$$\frac{dN}{d\cos\theta_0} \propto \begin{cases} \sin\theta_0 & (J^p = 0^-) \\ 1+\alpha_0\cos^2\theta_0 & (J^P = 1^+) \\ 1+\cos^2\theta_0 & (J^P = 1^-) \\ 1+\alpha_0\cos^2\theta_0 & (J^P = 2^-) \\ 1+\cos^2\theta_0 & (J^P = 2^+) \end{cases}$$

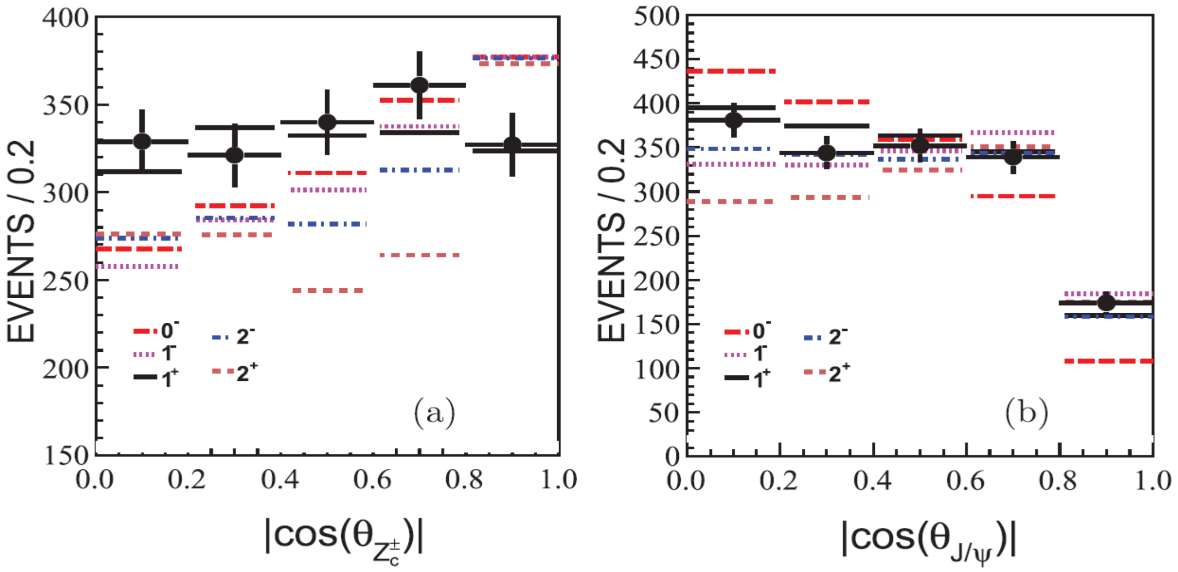
2. $Z_c^\mp \to \pi^\mp J/\psi$

$$\frac{dN}{d\cos\theta_1} \propto \begin{cases} 1 & (J^p = 0^-) \\ 1+\alpha_1\cos^2\theta_1 & (J^P = 1^+) \\ 1+\cos^2\theta_1 & (J^P = 1^-) \\ 1+\alpha_1\cos^2\theta_1+\alpha_2\cos^4\theta_1 & (J^P = 2^-) \\ 1-3\cos^2\theta_1+4\cos^4\theta_1 & (J^P = 2^+) \end{cases}$$



Chin. Phys. Lett. 33, 061401 (2016)

Angular distribution for the Zc(3900) J^P assumption



Hypothesis	$\Delta(-2\ln L)$	$\Delta(\text{ndf})$	Significance
1^+ over 0^-	94.0	13	7.6σ
1^+ over 1^-	158.3	13	10.8σ
1^+ over 2^-	151.9	13	10.5σ
1^+ over 2^+	96.0	13	7.7σ

- H_0 hypothesis: $J^P = 1^+$;
  H_1 hypothesis: $J^P = 0^-$ or $(1^-, 2^\pm)$;
- Statistics:

$$t \equiv -2\ln\lambda = 2[\ln L_{\max}(H_1) - \ln L_{\max}(H_0)],$$

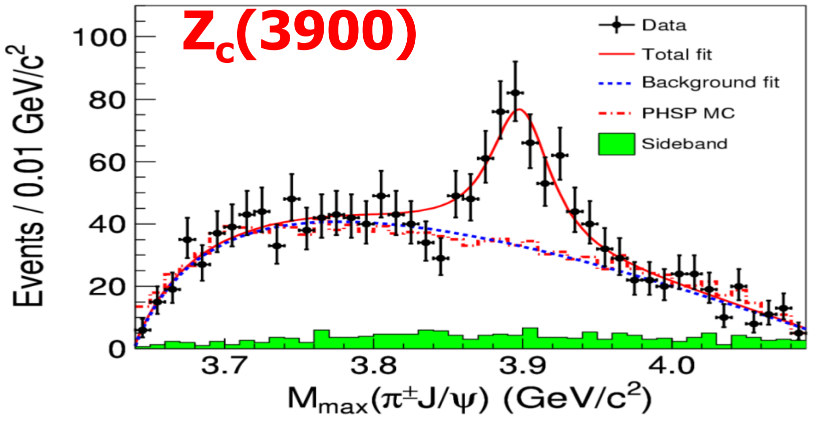
- p-value :

$$p(t_{\text{obs}}) = \int_{t_{\text{obs}}}^{\infty} \chi^2(t;r)dt.$$

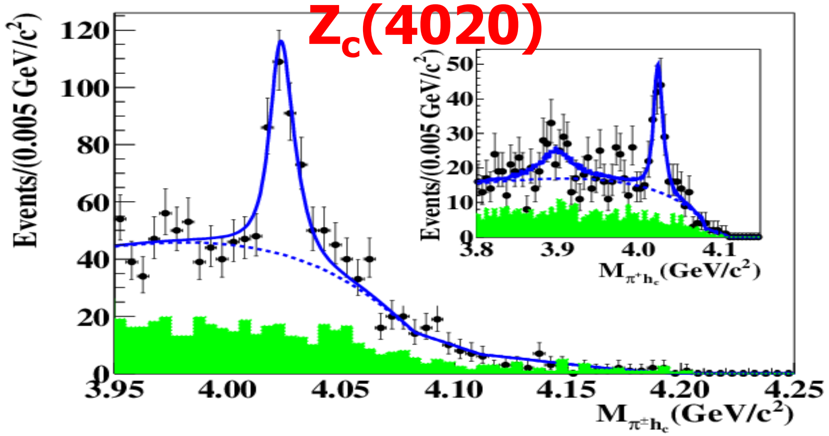
- Significance

$$\int_{-S}^{S} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx = 1 - p(t_{\text{obs}}) = \int_0^{t_{\text{obs}}} \chi^2(t;r)dt.$$

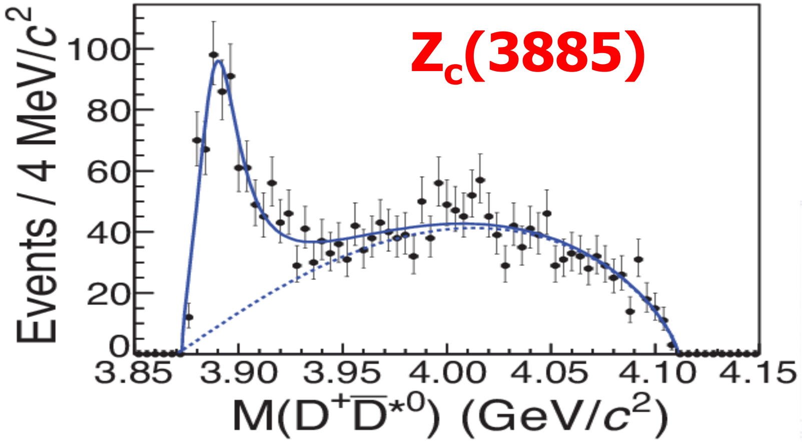
Open the Zc door !



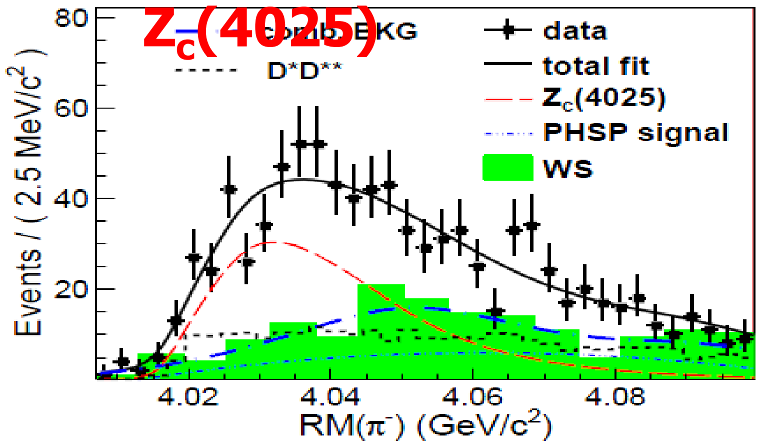
Phys. Rev. Lett. 110, 252001 (2013)



Phys. Rev. Lett. 111, 242001 (2013)



Phys. Rev. Lett. 112, 022001 (2014)

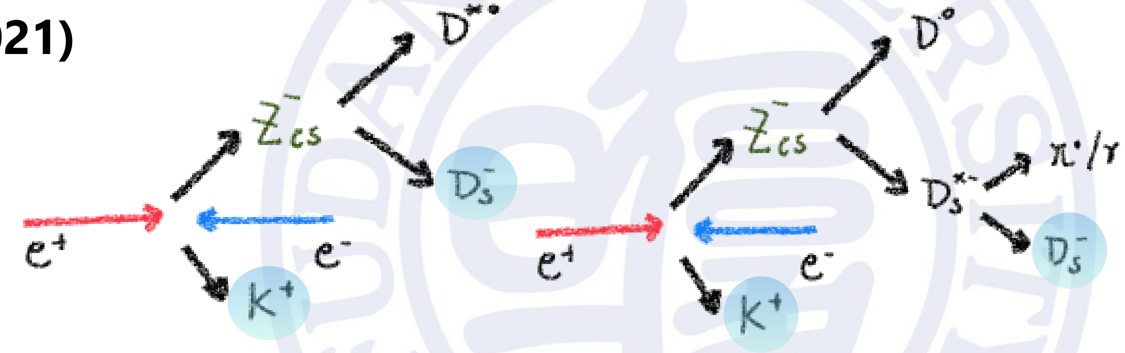


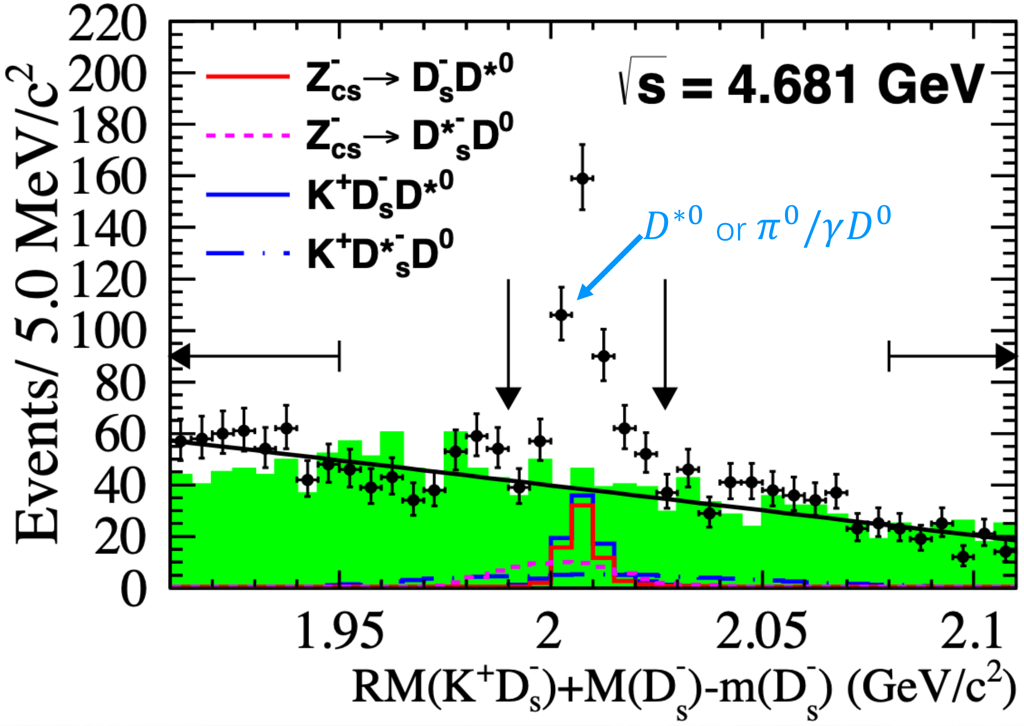
Phys. Rev. Lett. 112, 132001 (2014)

Observation of $Z_{cs}(3985)$—first Z_c with a strange quark

BESIII

- $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ **PRL 126, 102001 (2021)**
  - 3.7fb^{-1} data at 4628, 4640, 4660, 4680, and 4700
  - Partial reconstruction of the process, tag K and D_s^-
  - D_s^- reconstructed with $K^+K^-\pi^-$ [$\phi\pi$ or K^*K]and $K_S^0K^-$

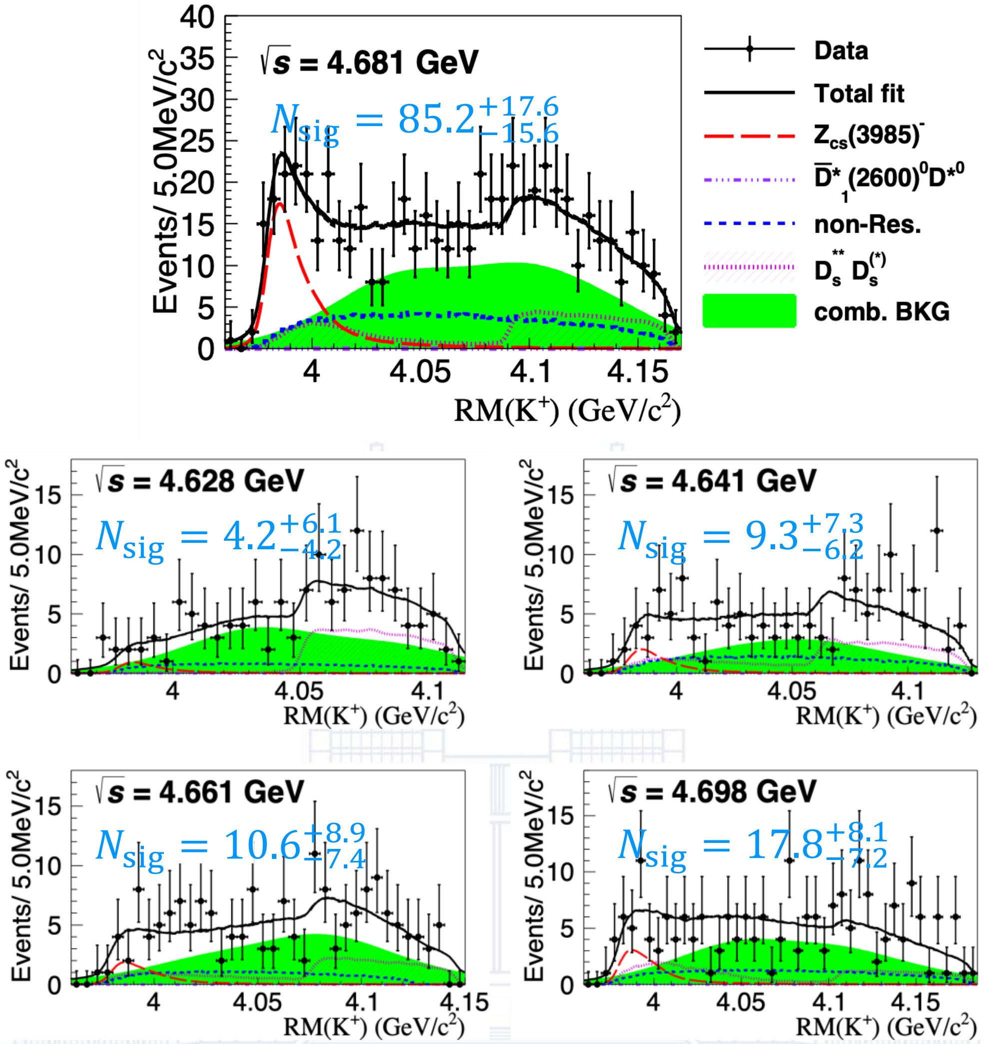




- Both decay modes can survive the selection
- Combinatorial background described by wrong sign (WS) events
- Absolute contribution in signal region determined from a fit to RM$(K^+D_s^-)$

Observation of $Z_{cs}(3985)$—first Z_c with a strange quark

BESIII



PRL 126, 102001 (2021)

- Assume $J^P=1^+$
- Simultaneous fit to five data samples
- Signal component:

$$\left|\frac{\sqrt{q \cdot p_j}}{M^2 - m_0^2 + i m_0 (f \Gamma_1(M) + (1-f)\Gamma_2(M))}\right|^2$$

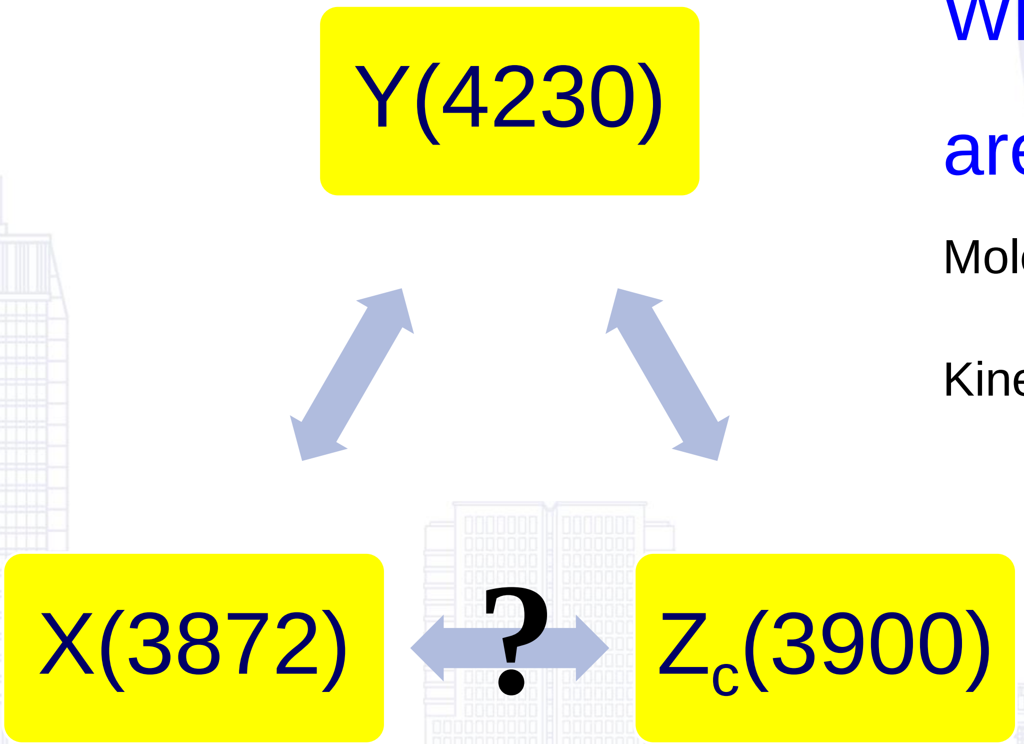
$f = 0.5$ represents the fraction of the two decay modes

- Pole position:

$m = 3982.5^{+1.8}_{-2.6} \pm 2.1 \mathrm{MeV}/c^2$ $\quad \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0 \mathrm{MeV}$

- Significance: 5.3σ
- At least four quarks $c\bar{c}s\bar{u}$

X, Y, Z particles are correlated

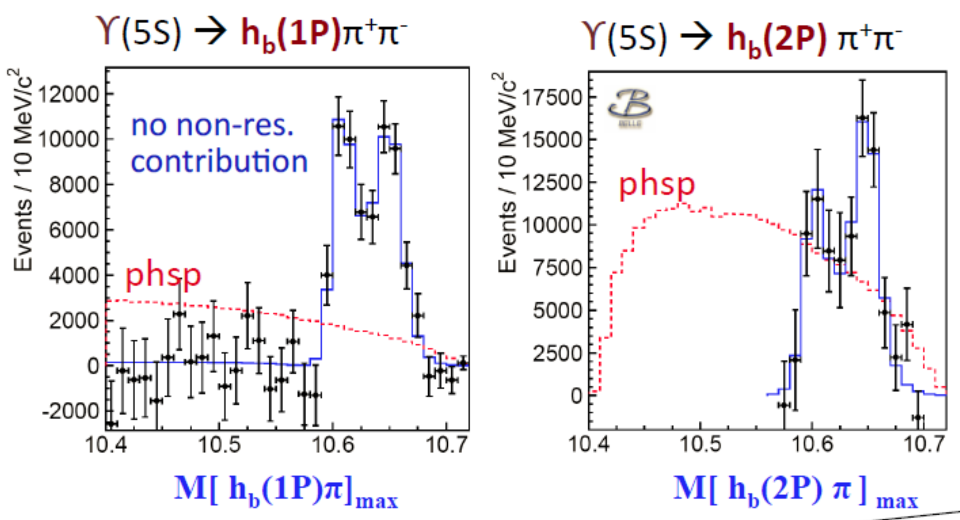


Whatever they are, they are very similar.

Molecule? Compact tetraquark?

Kinematic effect?

Resonant structure of $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$

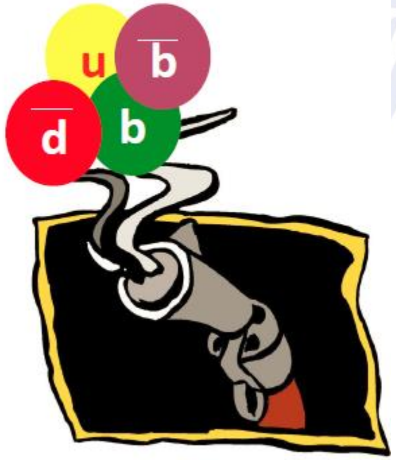


➢decays to $\Upsilon(nS)$ & $h_b(nP)$ ➔ must contain $b\bar{b}$ pair

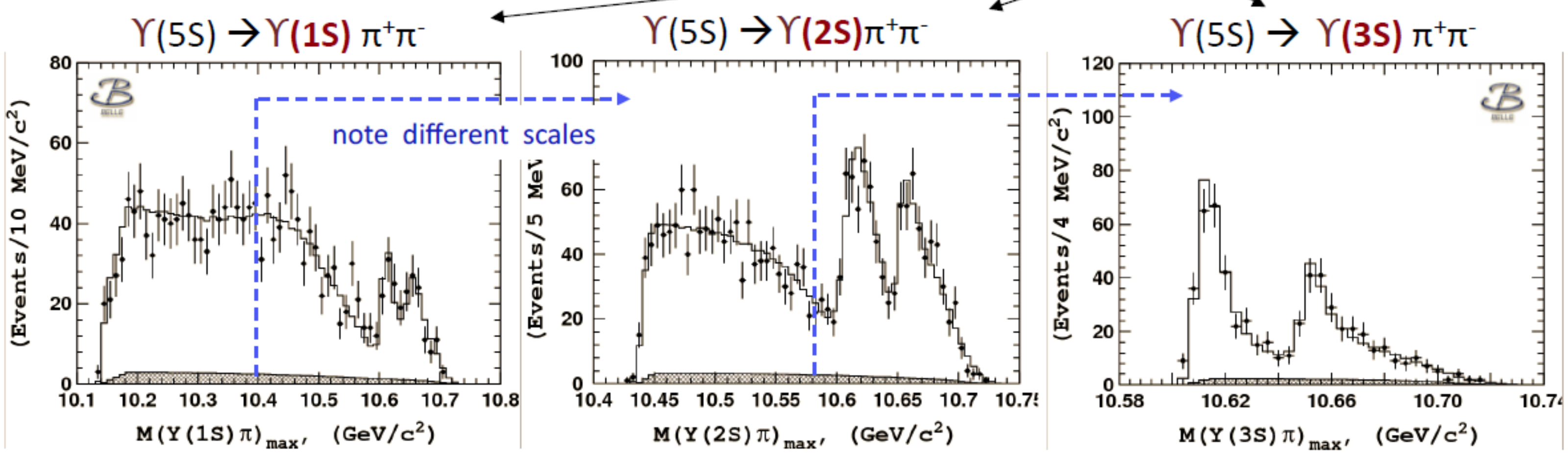
➢electrically charged ➔ must contain $u\bar{d}$ pair

Belle: PRL108, 232001 (2012)

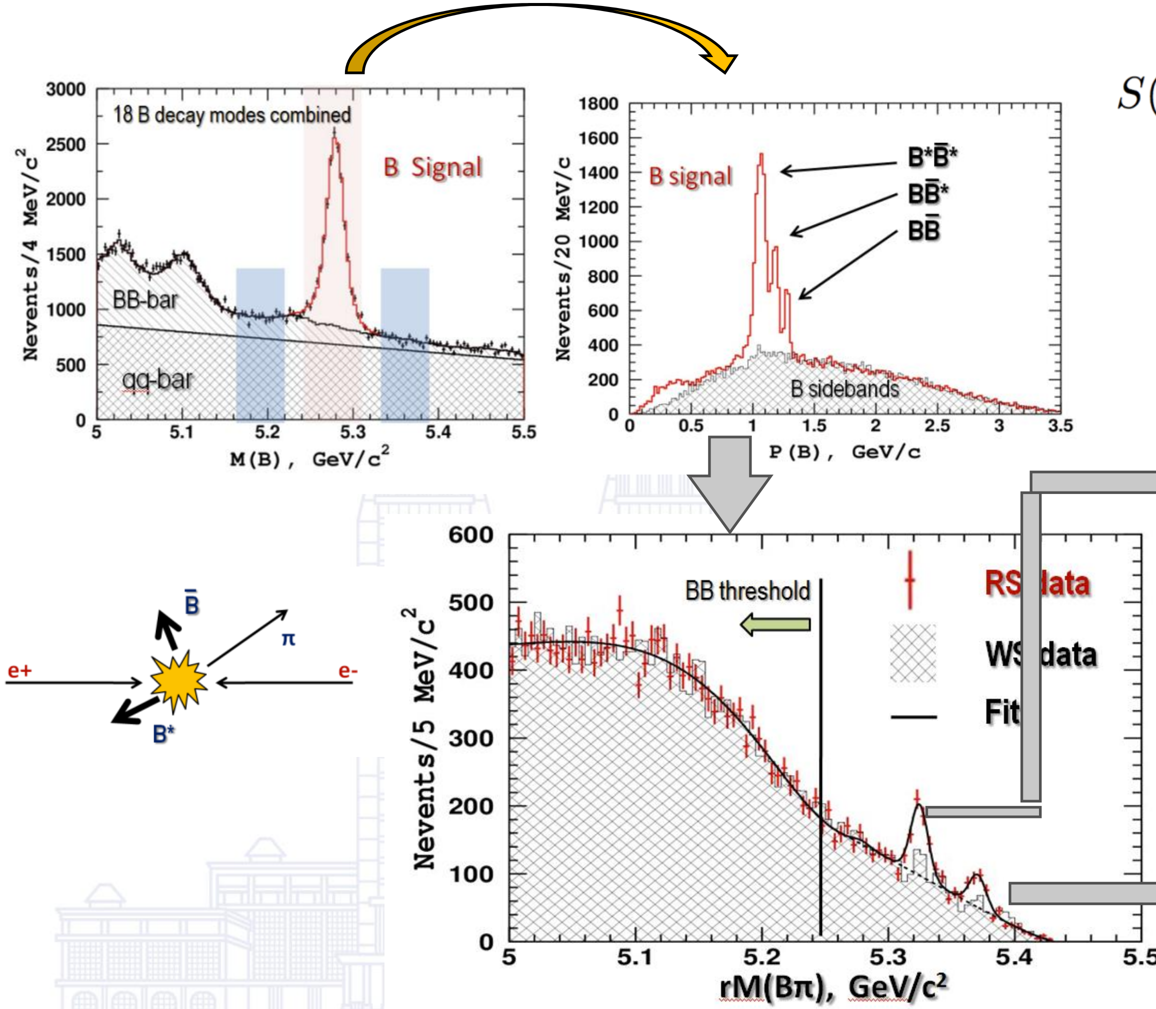
$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states



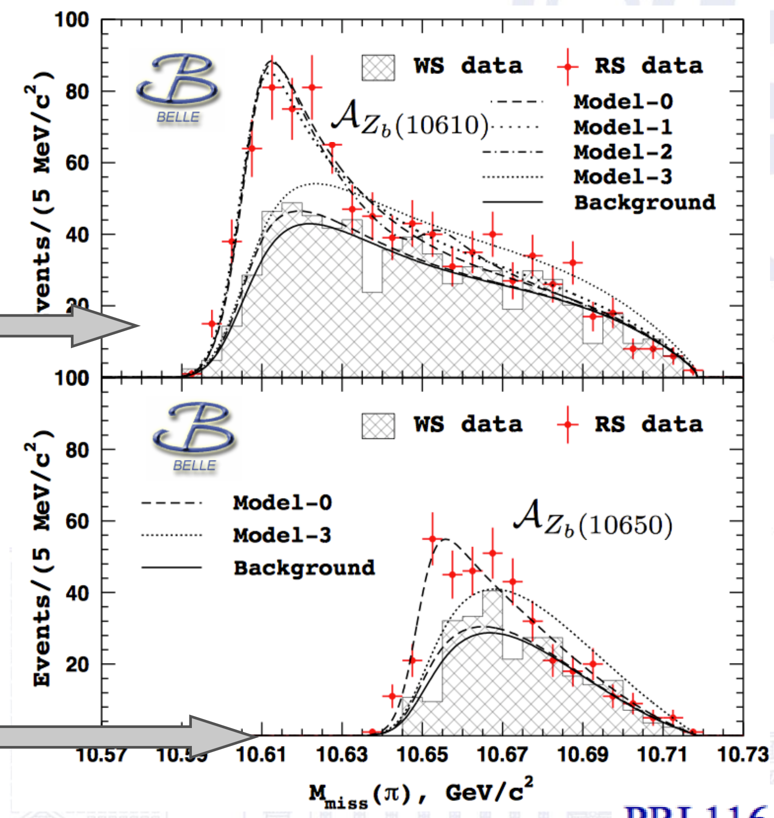
Dalitz plot analysis



$Z_b^{\pm} \rightarrow$ Open Beauty



$$S(m) = |\mathcal{A}_{Z_b(10610)} + \mathcal{A}_{Z_b(10650)} + \mathcal{A}_{\rm nr}|^2$$



Assuming that Z_b decays are saturated by the $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, branching fractions are here:

Channel	Fraction, % $Z_b(10610)$	Fraction, % $Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	–
$B^{*+}\bar{B}^{*0}$	–	$70.6 \pm 4.9 \pm 4.4$

Model-0 : $Z_b(10650)$ only

Model-1: $Z_b(10610)$ + Non-res.

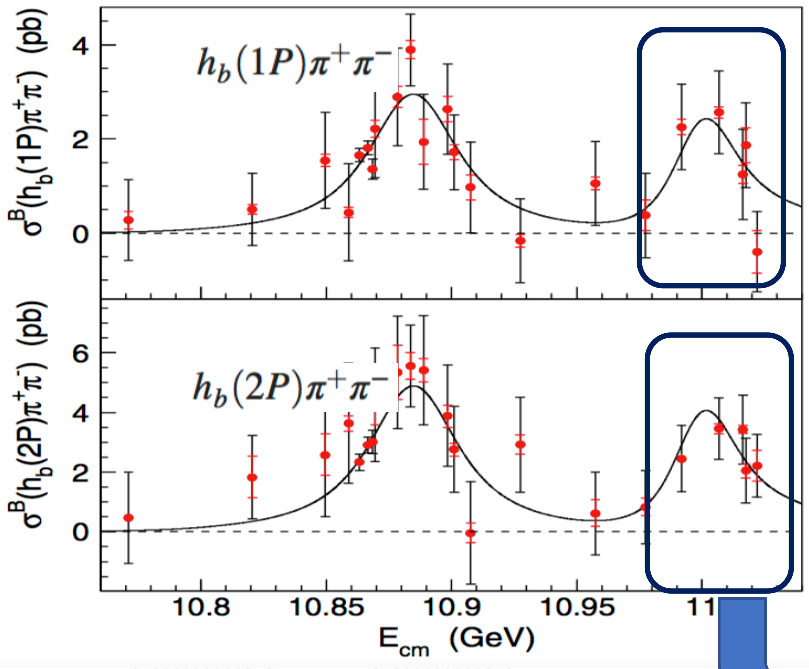
Model-2: $Z_b(10610)$ + $Z_b(10650)$ with interference

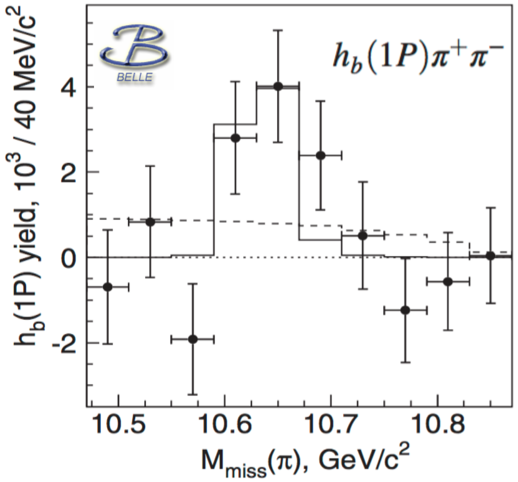
Model-3: Non-resonance

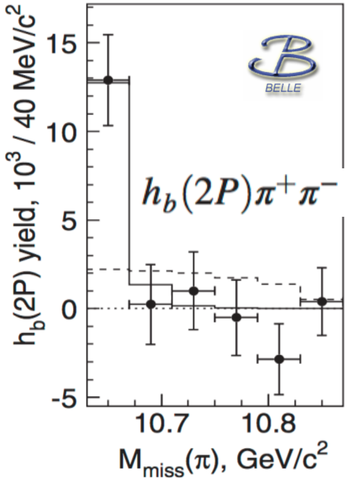
PRL116,212001(2016)

$Z_b^{\pm}$ Production at ϒ(6S)

PRL117,142001(2016)







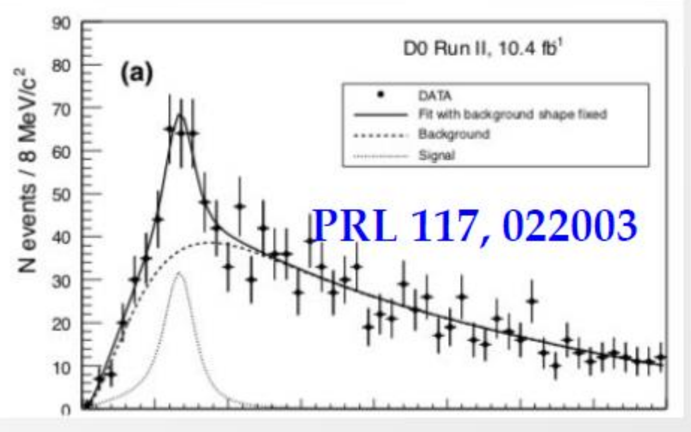
ϒ(6S) Data: 5 fb^{-1}

- 1st obs. of ϒ(6S)→$\pi^+\pi^-h_b(nP)$
  3.5σ for 1P, 5.3σ for 2P.

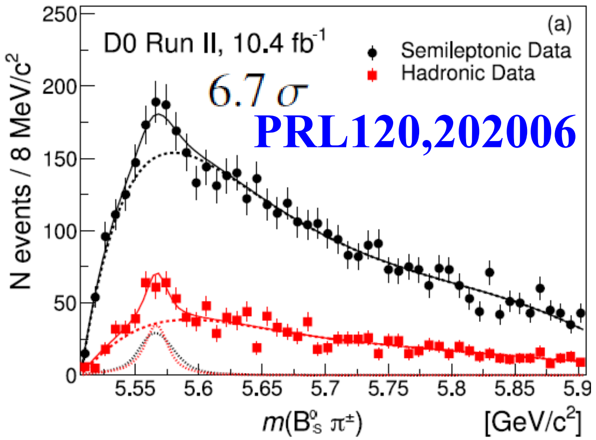
The two Z_b states can not be separated with current statistics

ϒ(6S) → $h_b(mP)\pi^+\pi^-$ transition is dominated (saturated) by the intermediate $Z_b^{\pm}$ production.
Two Z_b can be separated at Belle II !

X(5568) – puzzle ?



PRL 117, 022003



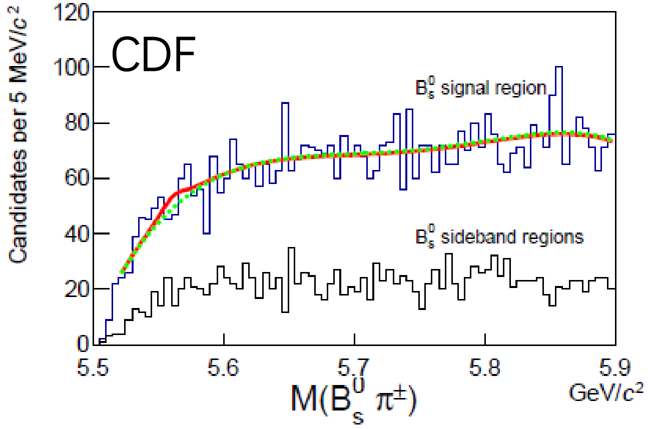
PRL120,202006

- Possible tetraquark candidate of four different quarks
- Seen by D0 with **4.8 σ** significance

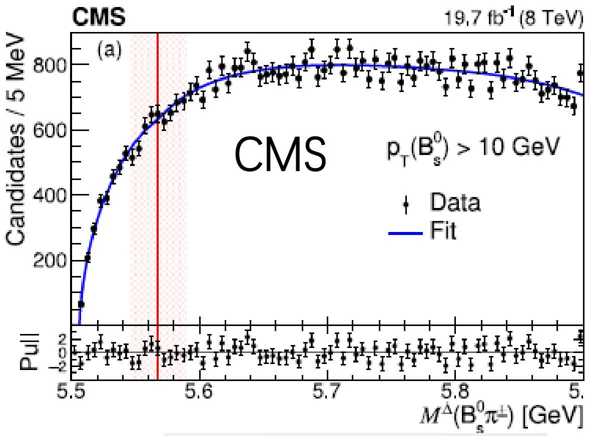
$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

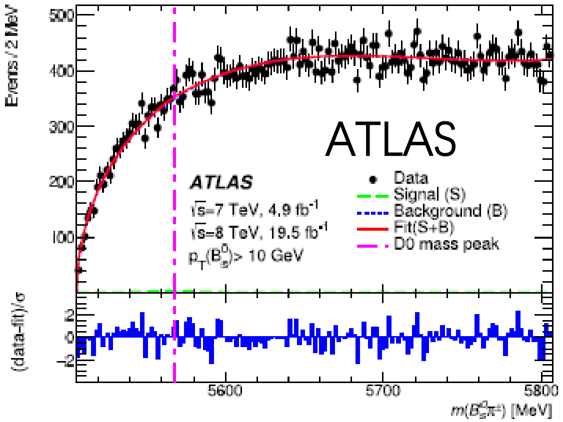
If confirmed, would be unique with 4 different flavors



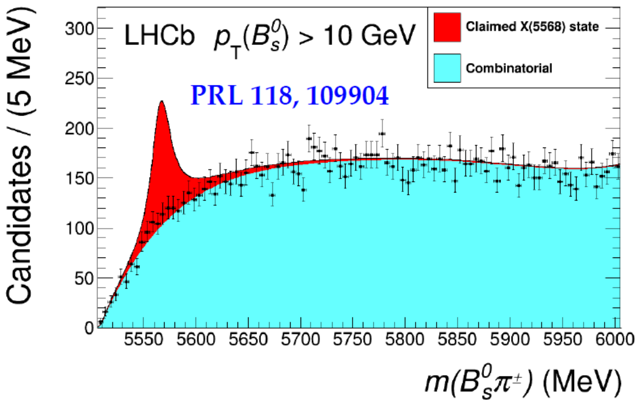
PRL 120, 202006



PRL 120, 202005



PRL 120, 202007

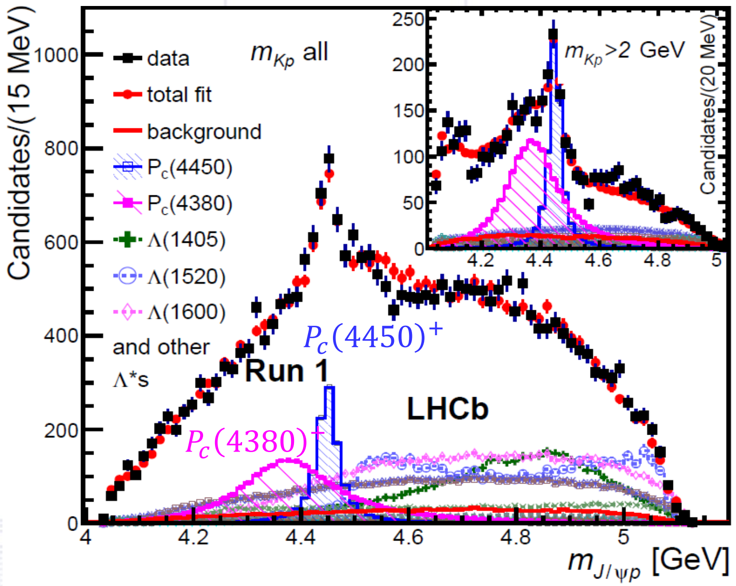


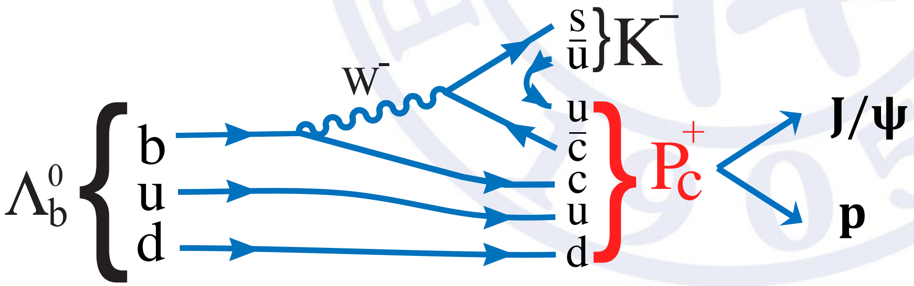
Pc States

Open the pentaquark door: LHCb observation in 2015

- **Two $J/\psi p$ resonant structures** are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ ← the prominent peak
  - $P_c(4380)^+$ ← required to obtain a good fit to the data
  - Consistent with **pentaquarks** with minimal quark content of $uudc\bar{c}$

26k Λ_b signals   **PRL 115 (2015) 072001 (most cited paper at LHCb so far)**





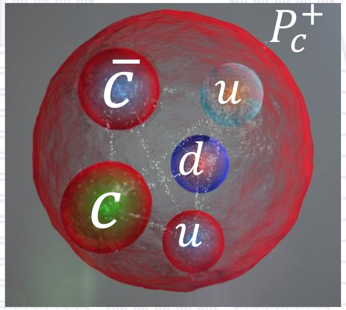
	$P_c(4380)^{\pm}$	$P_c(4450)^{\pm}$
Mass (MeV)	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width (MeV)	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit Fraction (%)	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$

Lots of open questions

- To interpret the nature of P_c, more studies are needed
  - Inner structures?
  - More states, SU(3) partners?
  - J^P, mode decay modes, production mechanism …?

Tightly-bound pentaquark?

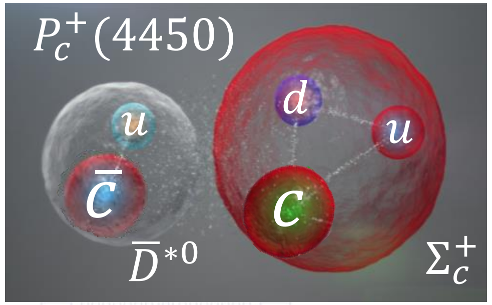
$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$



Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

Loosely-bound pentaquark?

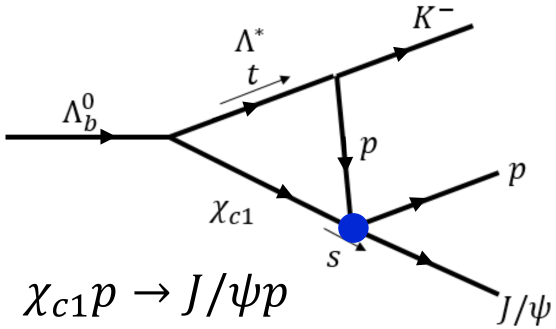
$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$



Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

Kinematical effect: triangle diagram?

$P_c(4450)^+ = \chi_{c1}p$ threshold?

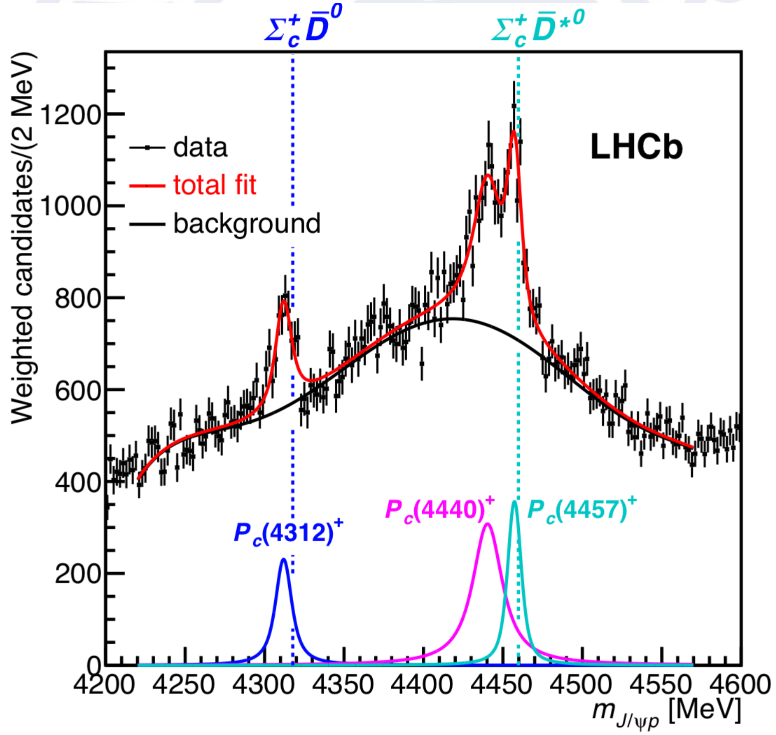


Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

Fine structures from update

246k Λ_b signals
PRL 122 (2019) 222001

- Run1+Run2, x10 $\Lambda_b^0 \to J/\psi p K^-$ yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)
- $P_c(4312)^+$ is observed
- $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$
- Their near-threshold masses **favor** the predicted "molecular" pentaquarks with meson-baryon substructure, but **other hypotheses are not ruled out**



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

1D $m_{J/\psi p}$ is fitted, ongoing amplitude analysis is in advanced stage

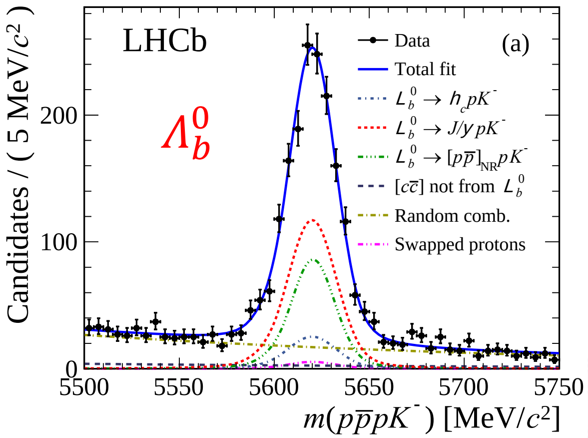
1^{st} observation of $\Lambda_b^0 \to \eta_c p K^-$

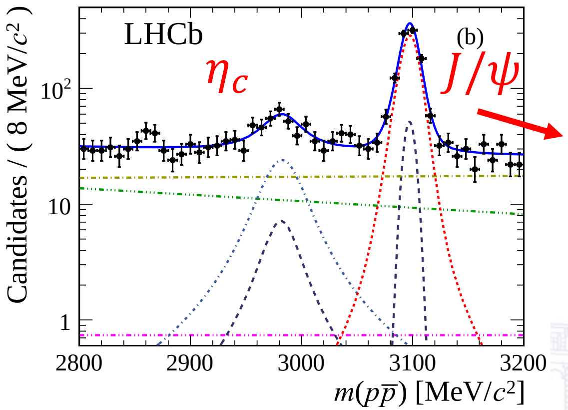
- **$\eta_c p$ final state is very sensitive to $1/2^-$ P_c, where $\eta_c p$ is in S-wave**
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$
  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- LHCb run2 data (5.5 fb^{-1}) using $\eta_c \to p\bar{p}$
- Fit 2D mass spectrum to confirm the existence
- Obtain

$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.333 \pm 0.050\ (\text{stat.}) \pm 0.019\ (\text{syst.}) \pm 0.032\ (\mathcal{B})$$

$P_c(4312)^+$ production fraction in $\Lambda_b^0 \to \eta_c p K^-$ is ~ 3% (predicted)

~170 $\Lambda_b^0 \to \eta_c p K^-$ signals





$\Lambda_b^0 \to J/\psi p K^-$ used as reference mode for branching fraction measurement

Search for P_c^+ in $\eta_c p$ system

[PRD 102 (2020) 112012]

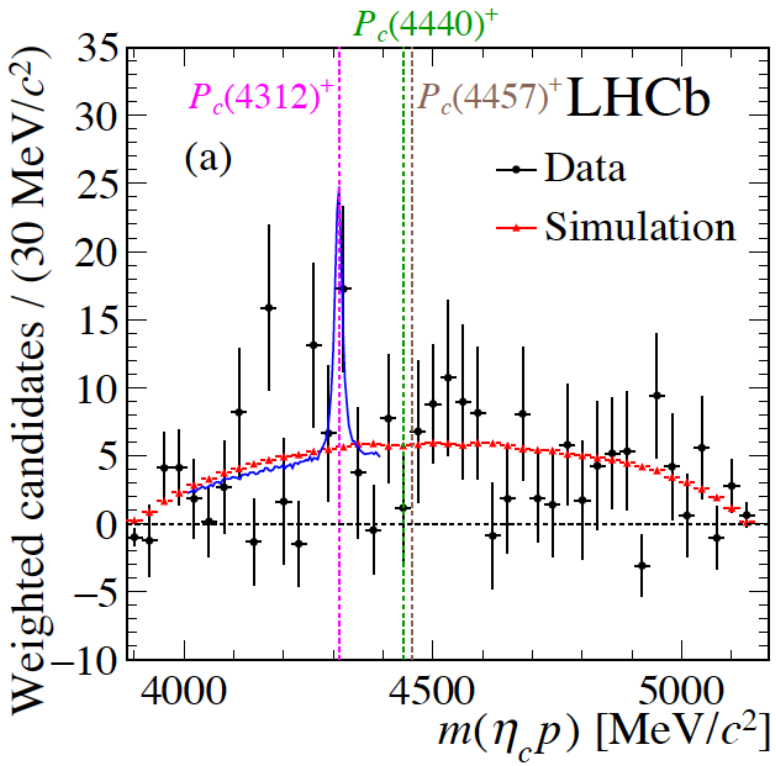
- Check background-subtracted $\eta_c p$ mass spectrum

No significant $P_c(4312)^+$ contribution (~2s)

P_c^+ production fraction obtained

$$R(P_c(4312)^+) < 24\% \ @ \ 95\% \ \mathrm{C.L.}$$

much larger than the predicted value 3%
(no conclusion yet)



- **Need run3+4 data, amplitude fit can be performed**

Search for pentaquarks via open charm

[LHCb-PAPER-2023-018]

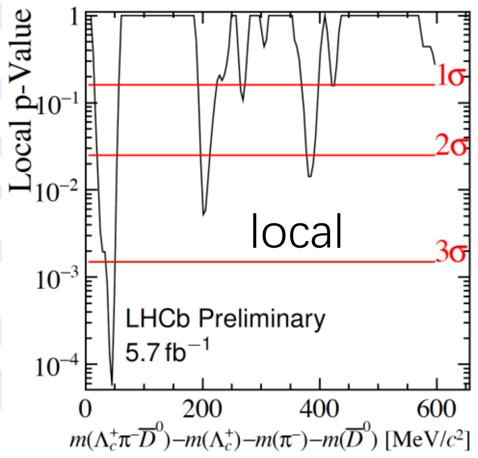
- Prompt production with 32 final states
  - $\Lambda_c^+\overline{D}$, $\Lambda_c^+\overline{D}^*$, $\Lambda_c^+\pi\overline{D}$, $\Sigma_c^{(*)}\overline{D}^{(*)}$ and Λ_c^+D, $\Lambda_c^+D^*$, $\Lambda_c^+\pi D$, $\Sigma_c^{(*)}D^{(*)}$
- Scan to search for pentaquarks with narrow width (0-15 MeV)
- No significant narrow peak is found for all the modes
- Upper limits are set on the production rates related to Λ_c^+

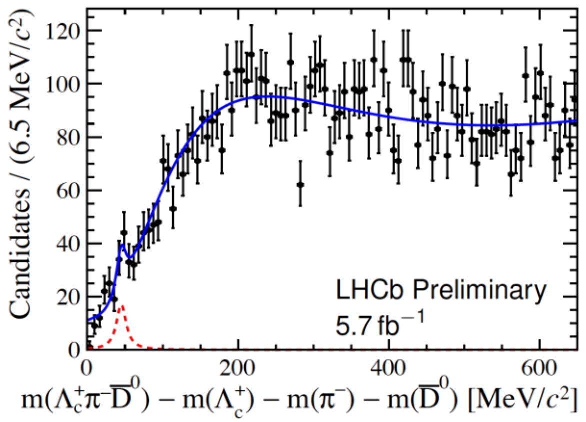
$$R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \rightarrow \frac{\sigma(P_c)\times\mathcal{B}\left(P_c\to\Lambda_c^+D(\pi)\right)\times\mathcal{B}(D)}{\sigma(\Lambda_c^+)}$$

Decay Mode	Significance (σ) Local	Global	Corresponding Mass (MeV/c^2)	Signal Yield	Upper Limit ($\times10^{-3}$) 90% CL	95% CL
$\Lambda_c^+\overline{D}^0$	2.85	1.01	349	46.8 ± 23.4	1.16	1.21
$\Lambda_c^+D^{*-}$	2.32	0.00	365	15.0 ± 10.3	2.16	2.39
$\Lambda_c^+\pi^+D^-$	2.82	0.99	225	68.6 ± 13.3	1.95	2.40
$\Sigma_c^0\overline{D}^0$	1.90	0.00	65	4.7 ± 4.2	1.02	1.15
$\Lambda_c^+\pi^-\overline{D}^0$	3.86	2.56	45	60.1 ± 25.9	1.40	1.70
$\Sigma_c^0D^-$	2.03	0.00	261	7.0 ± 2.6	0.71	0.89
$\Lambda_c^+\pi^-D^-$	3.67	2.35	249	82.8 ± 14.3	2.23	2.67
$\Lambda_c^+\pi^-D^{*-}$	2.31	0.00	409	23.6 ± 23.0	2.79	3.28
$\Sigma_c^{*++}D^{*-}$	1.74	0.00	453	3.3 ± 2.4	1.24	1.43
$\Sigma_c^{*0}D^-$	1.86	0.00	109	10.7 ± 29.1	1.32	1.59
$\Lambda_c^+D^+$	2.52	0.59	169	14.9 ± 9.6	1.34	1.50
$\Lambda_c^+\pi^+D^0$	3.21	1.72	45	24.8 ± 39.3	0.98	1.18
$\Lambda_c^+\pi^+D^{*+}$	3.37	1.99	165	13.8 ± 3.5	0.97	1.22
$\Lambda_c^+\pi^-D^{*+}$	2.70	0.58	73	5.8 ± 71.3	1.70	1.94
$\Sigma_c^{*++}D^0$	2.11	0.00	113	3.9 ± 2.8	0.87	0.99
$\Sigma_c^{*0}D^+$	2.18	0.00	69	4.7 ± 4.6	1.13	1.32

Largest significance

preliminary



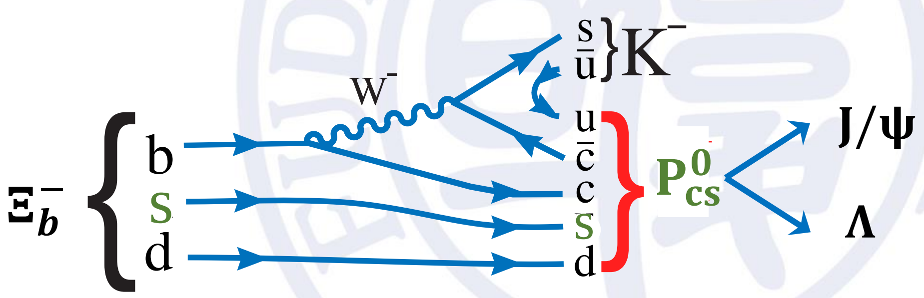


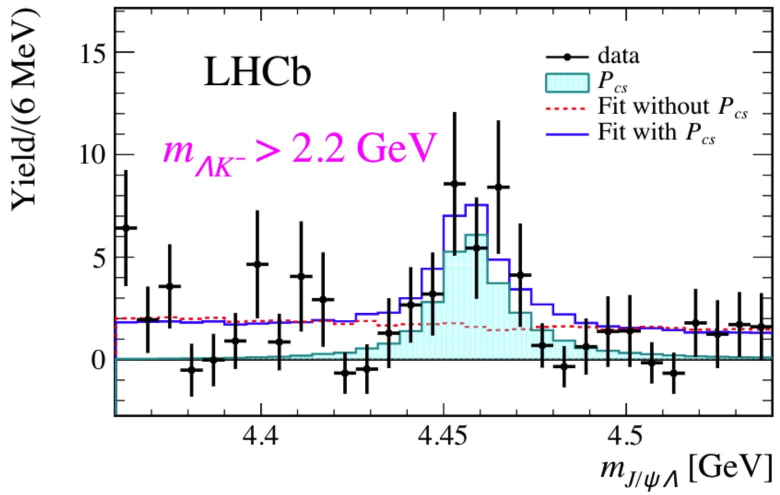
$c\bar{c}udd$: $M\sim4335.87$ MeV

Evidence of P_{cs} in $J/\psi\Lambda$

[Science Bulletin 66 (2021) 1278]

- SU(3) partner P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$ **[JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]**
- Amplitude analysis with improved helicity formalism
  - $P_{cs}(4459)^0$ found, significance >3.1s





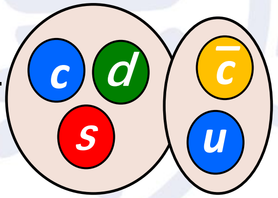
Mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold

State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

P_{cs} in $B^- \to J/\psi\Lambda\bar{p}$

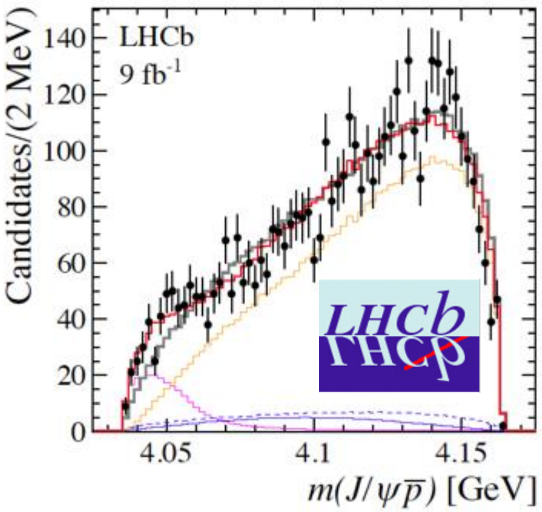
[PRL 131 (2023) 031901]

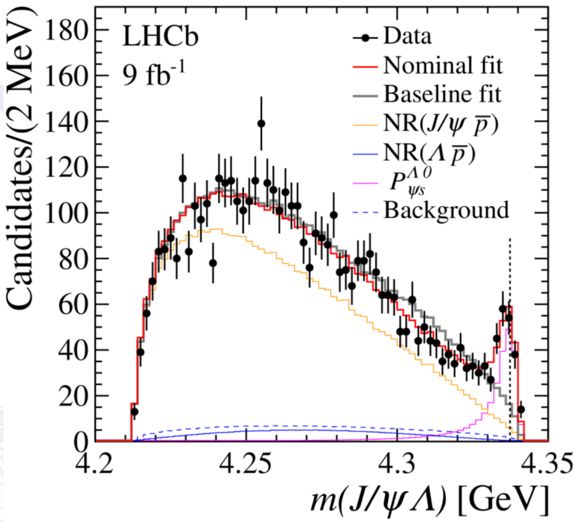
- Can search for pentaquark both in $J/\psi p$ & $J/\psi\Lambda$
  - Limited range: $m(J/\psi p) < 4.16$ GeV, $m(J/\psi\Lambda) < 4.34$ GeV, Cover thresholds of $\Lambda_c^+\bar{D}$ and $\Xi_c\bar{D}$
- A new pentaquark with strangeness $P_{\psi s}^{\Lambda}(4338)^0$ $(c\bar{c}sud)$ observed in the $B^- \to J/\psi\Lambda\bar{p}$ decay



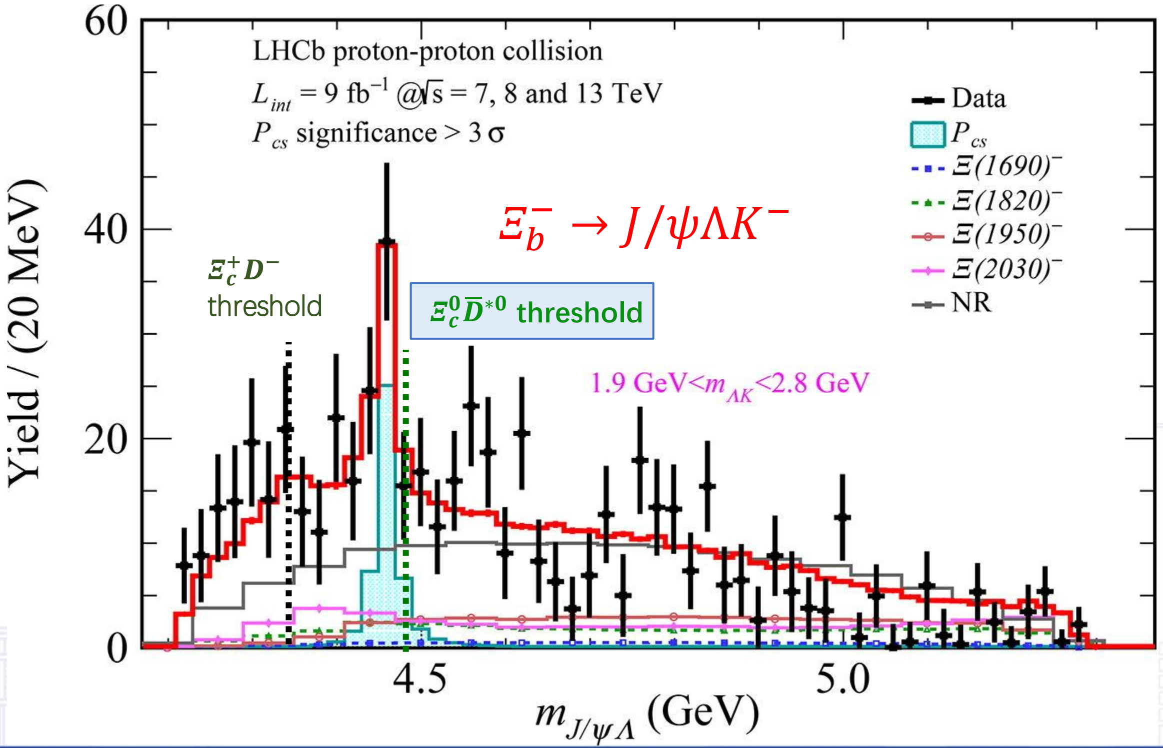
  - **At $\Xi_c^+ D^-$ threshold**
  - $m = 4338.2 \pm 0.7 \pm 0.4$ **MeV**
  - $\Gamma = 7.0 \pm 1.2 \pm 1.3$ **MeV**
  - **Fit fraction** $= (12.5 \pm 0.7 \pm 1.9)\%$
  - $J^P = (1/2)^-$ **preferred,**

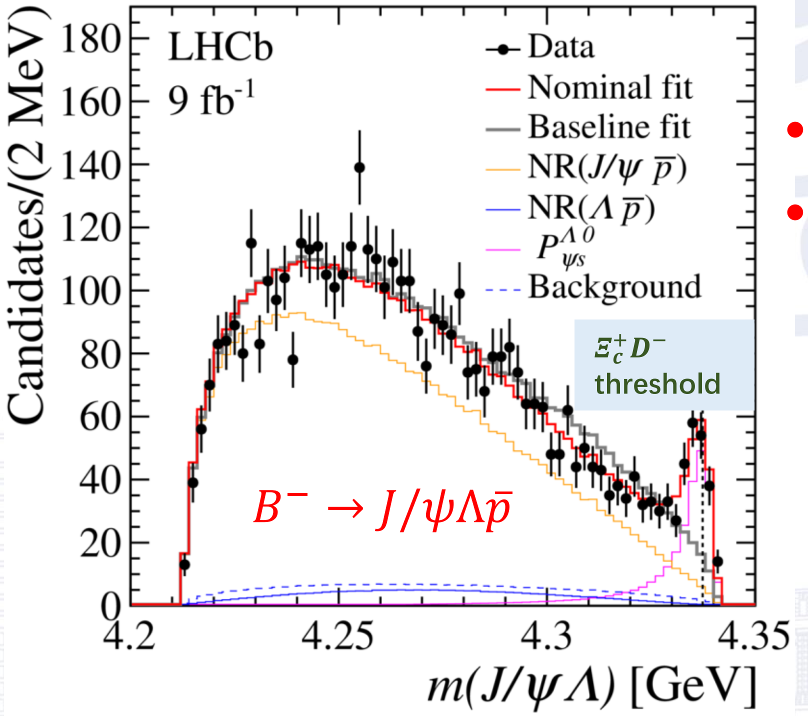
    $J^P = \frac{1}{2}^+$ **rejected under 90%** CL_s





State	M_0 [MeV]	Γ [MeV]	FF (%)	Threshold
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$	$\Xi_c \bar{D}^*$
$P_{cs}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	$12.5 \pm 0.7 \pm 1.9$	$\Xi_c \bar{D}$



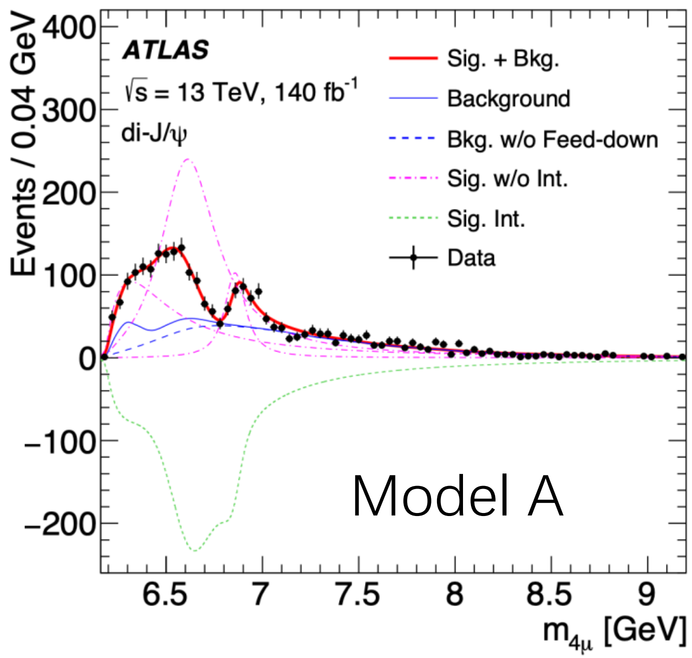


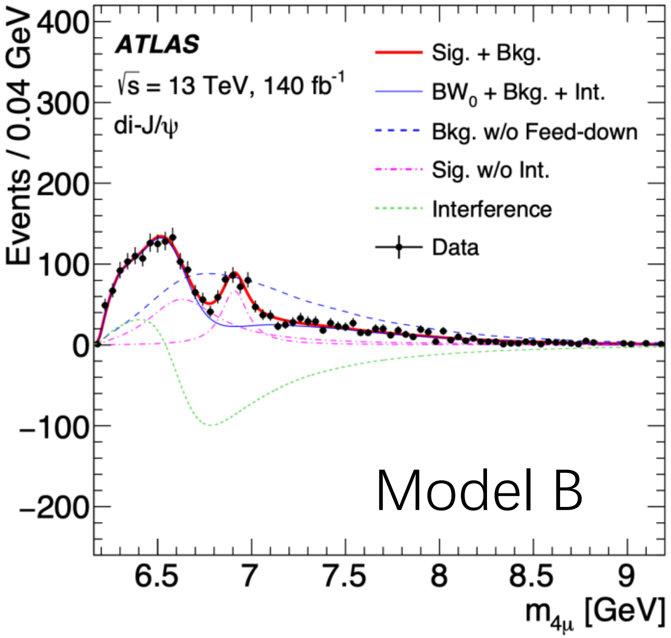
- **more P_{cs}?**
- **Open-charm pentaquarks?**

di-J/ψ States

X(4c) states at ATLAS --All-charm Tetra-quarks

Phys. Rev. Lett. 131 (2023) 151902



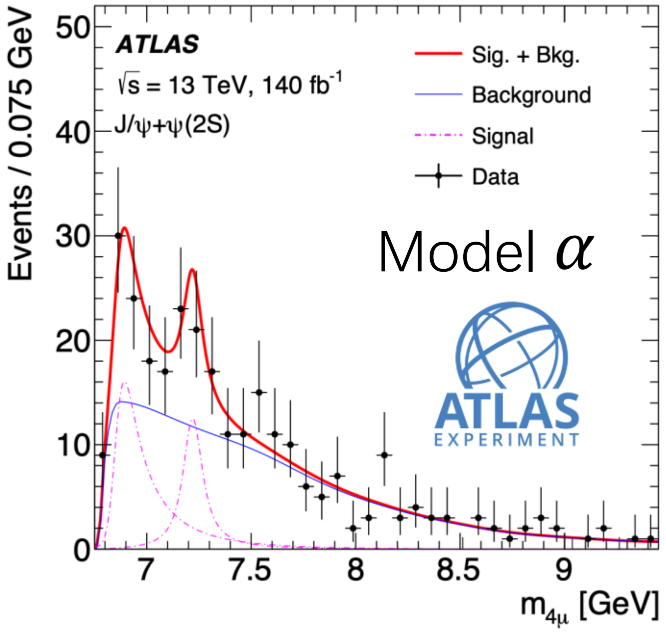


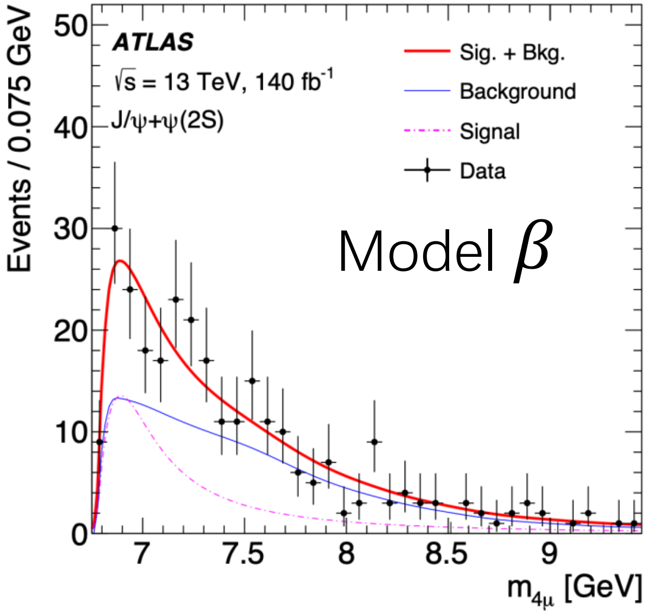
di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

X(6900) > 5σ

- In the di-J/ψ channel, two signal models are tested:
  - **Model A**: three interfering signal peaks; **Model B**: two signal peaks
- The peak around **6.9 GeV** is consistent with the LHCb observed X(6900) (arXiv:2006.16957), with significance far above 5σ

X(4c) states at ATLAS



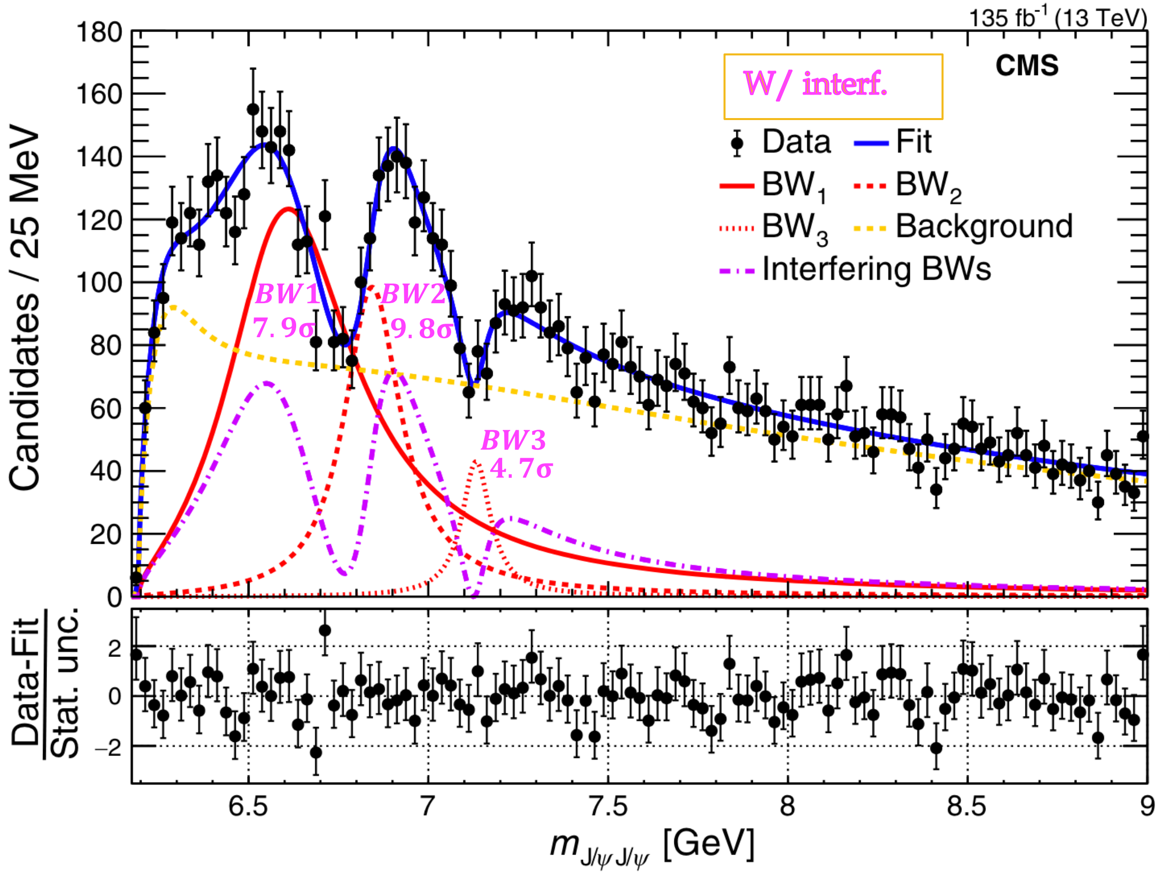


J/ψ+$\psi(2S)$	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

- The signal significance is 4.7σ (4.3σ) for model α (β). The significance of the **2nd peak** (7.2 GeV) reaches **3.0σ**, also hinted by LHCb and CMS (arXiv:2306.07164) in the di-J/ψ spectrum

- In the $J/\psi + \psi(2S)$ channel, also two signal models are tested:
  - **Model α**: the same peaks observed in the di-J/ψ channel also decaying into $J/\psi + \psi(2S)$ plus a standalone peak.
  - **Model β**: only one signal peak

X(4c) structures in di-Jpsi channel at CMS



- **Interference model:** Phys. Rev. Lett. 132 (2024) 111901
  - Signal: interference between BW1, BW2, BW3
  - Background: BW0 + NRSPS + NRDPS

	BW_1	BW_2	BW_3
m (MeV)	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ (MeV)	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

CMS found 3 significant $J/\psi J/\psi$ structures using Run II data

- BW2 consistent with X(6900) reported by LHCb [Sci. Bull. 65, 1983 (2020)]
- Two new structures named as X(6600) [>5σ], X(7300) [4.7σ]

A family of structures which are candidates for all-charm tetra-quarks

Comparison with some theoretical calculations

arXiv:2108.04017 [hep-ph] *P-wave* *Ground state*

$N^{2S+1}L_J$	J^{PC}	$\langle K.E.\rangle$	$E^{(0)}$	$\langle V_C^{(0)}\rangle$	$\langle V_L^{(0)}\rangle$	$\langle V_{SS}^{(1)}\rangle$	$\langle V_{LS}^{(1)}\rangle$	$\langle V_T^{(1)}\rangle$	$V^{(1)}(r)$	M_f
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220

M[BW1] = 6552^{+10+12}_{-10-12} MeV

M[BW2] = 6927^{+9+4}_{-9-4} MeV

M[BW3] = 7287^{+20+5}_{-18-5} MeV

CMS: Interference fit results

Nucl. Phys. B 966 (2021) 115393 *S-wave*

$T_{4Q}(nS)$ states	J^P	Mass(n=1)	Mass(n=2)	Mass(n=3)	Mass(n=4)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}

M[BW1] = 6638^{+43+16}_{-38-31} MeV

M[BW2] = 6847^{+44+48}_{-28-20} MeV

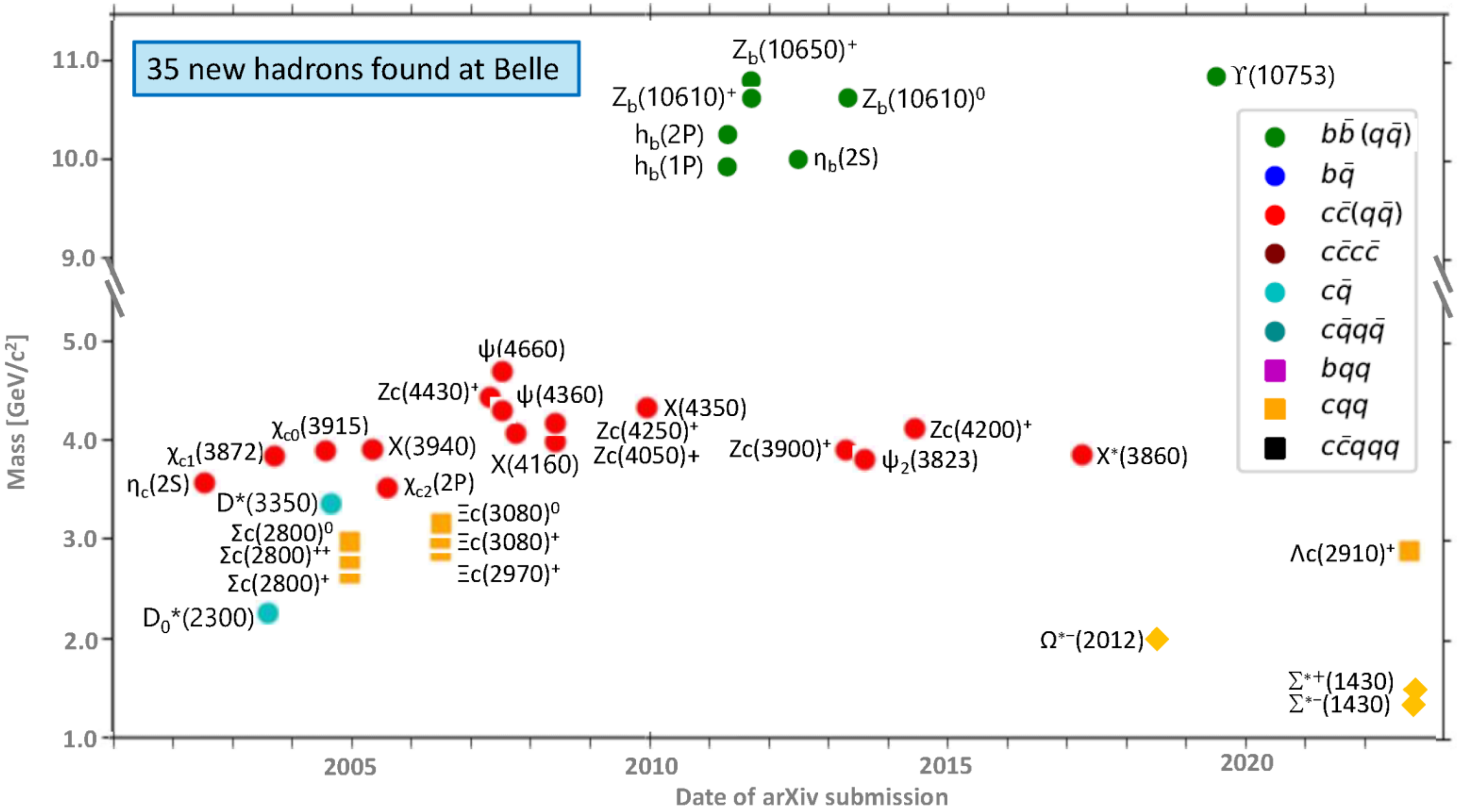
M[BW3] = 7134^{+48+41}_{-25-15} MeV

CMS: Non-interference fit results

Ground states
Missing n=1

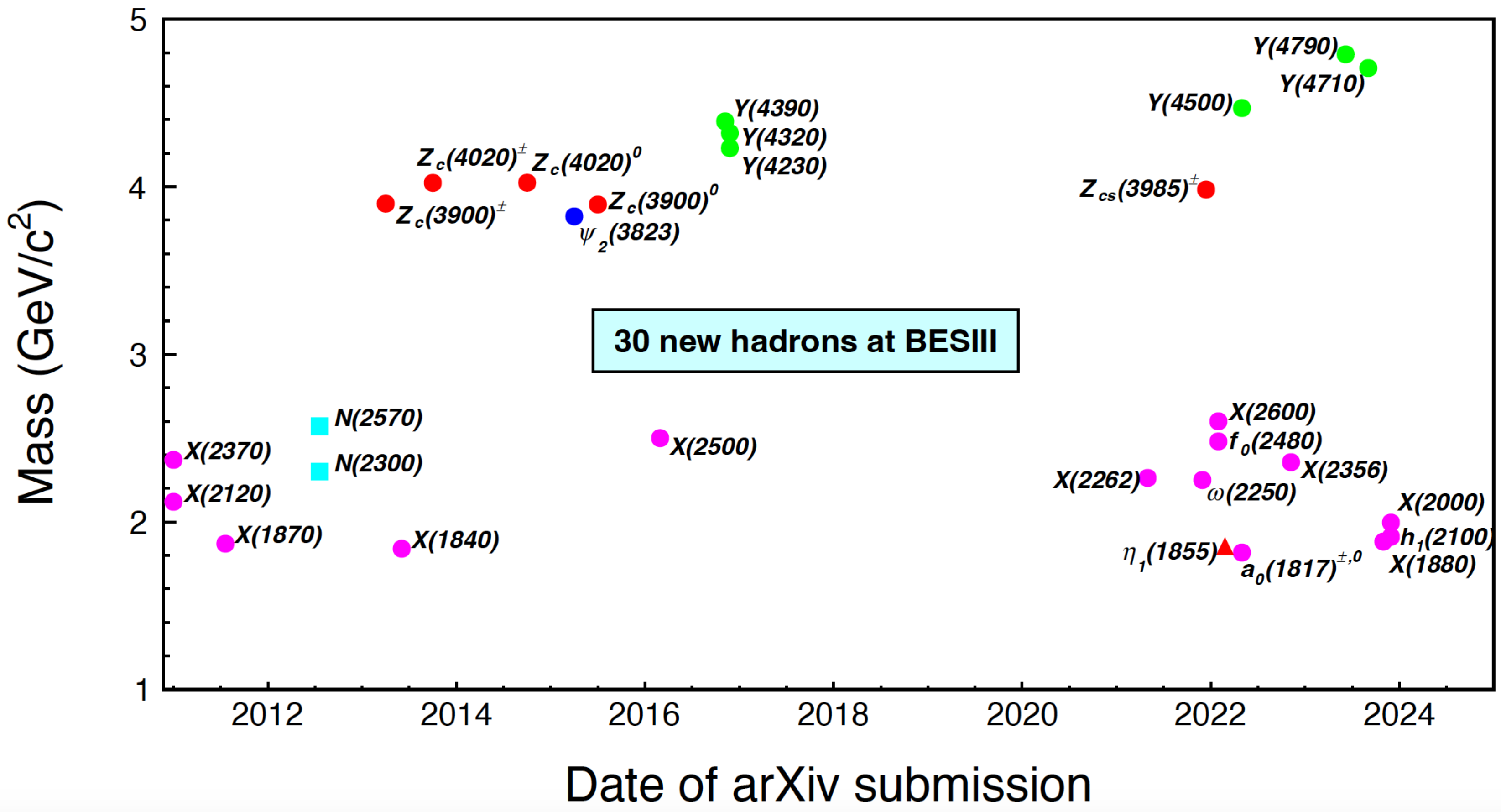
- Radial excited states?
- measure J^{PC} to clarify
- PRD 109, 054034 (2024) new theoretical result

XYZ Summary



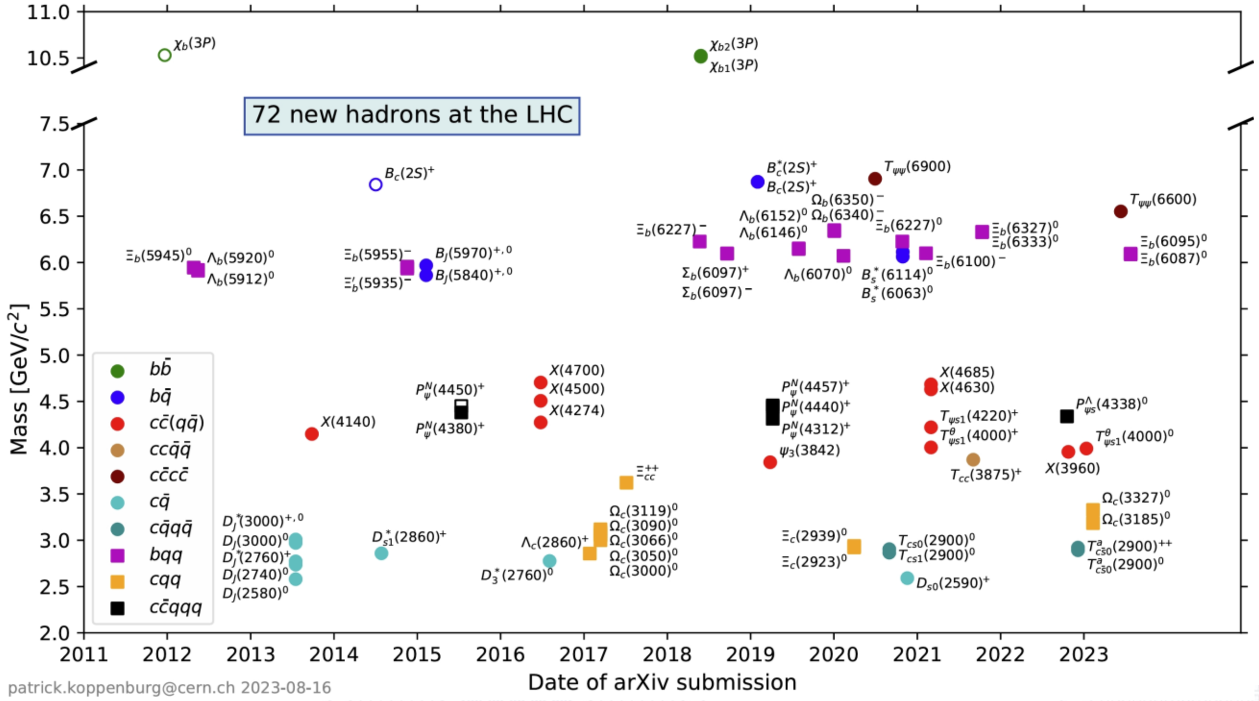
https://qwg.ph.nat.tum.de/exoticshub/

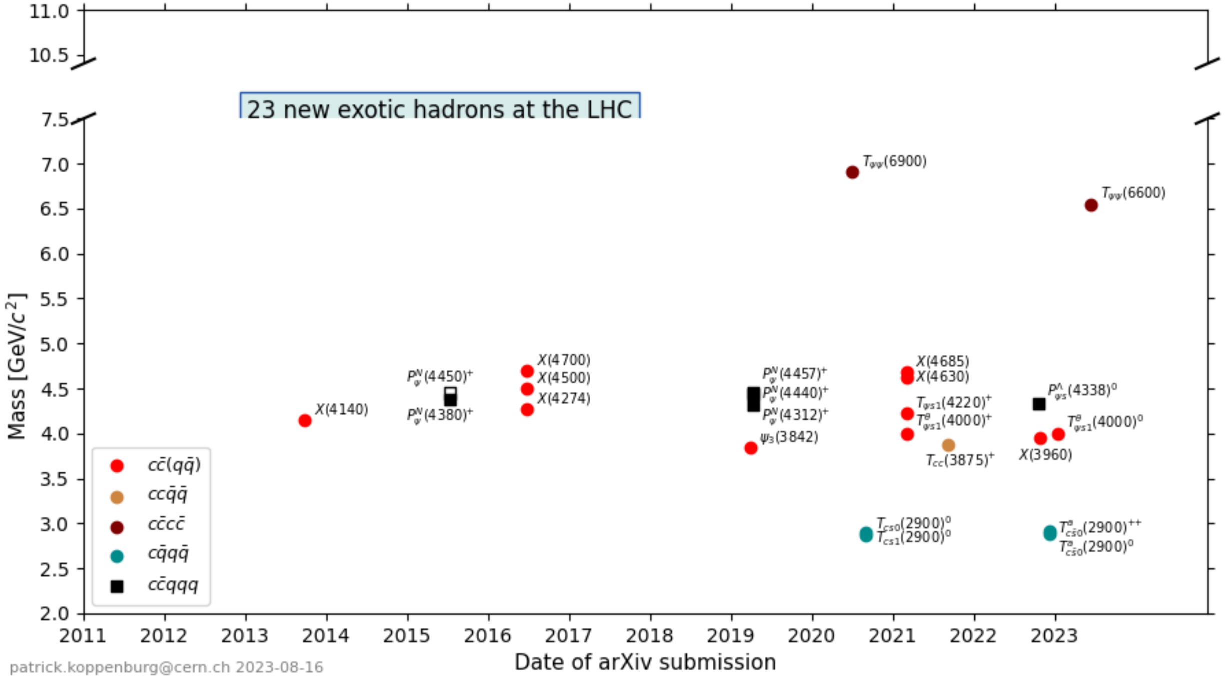
35 new hadrons were found at Belle. **10 of these are "exotic"** and cannot be explained in the conventional quark model while the nature of 8 of them are still under investigation. The remaining 17 states are consistent with the quark model. Measurements of all these states will provide critical insights for QCD.



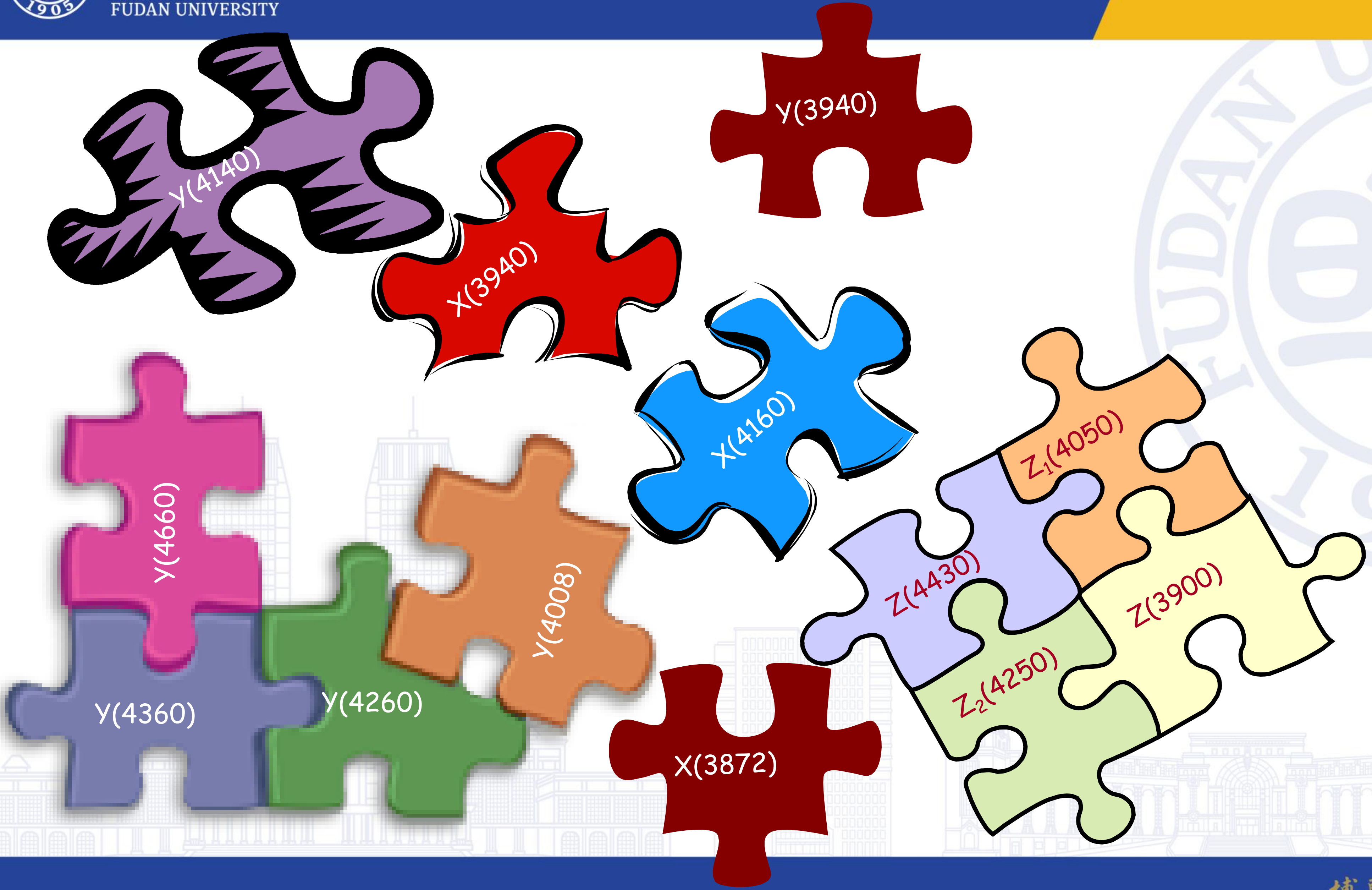
30 new hadrons were found at BESIII. **12 of these are charmonium and charmonium-like states** and 18 are light hadrons.

72 new hadrons were found at LHC. **23 of these are "exotic"**



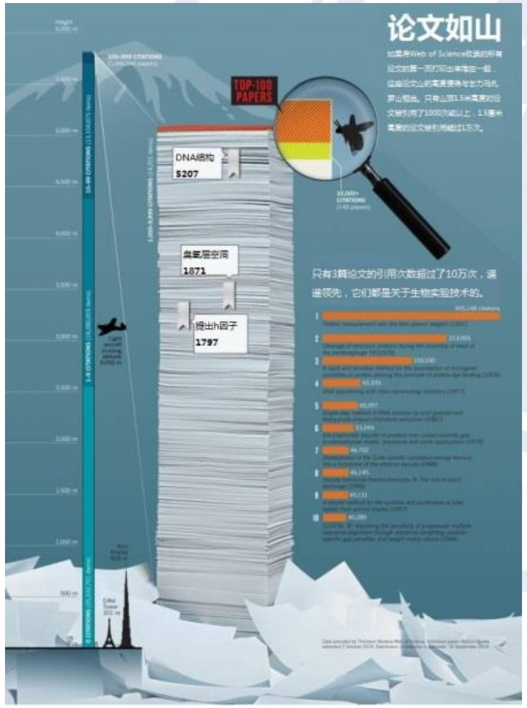


Particle "Zoo" again !


Y(4140)
Y(3940)
X(3940)
X(4160)
Z1(4050)
Y(4660)
Y(4008)
Z(4430)
Z(3900)
Y(4360)
Y(4260)
Z2(4250)
X(3872)

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！

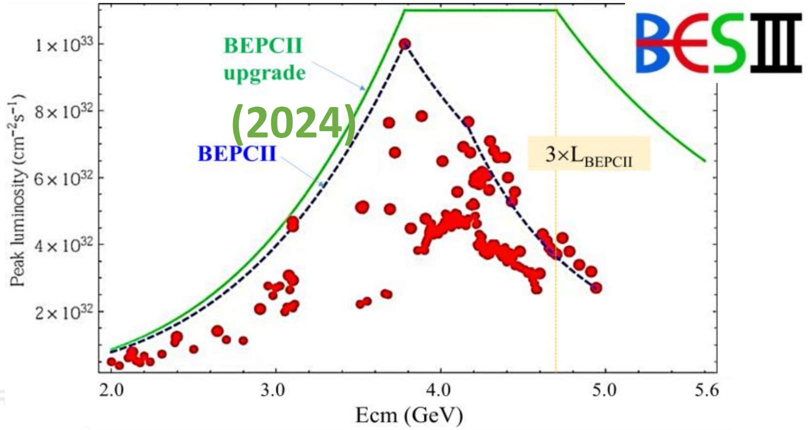
We found more questions to answer, works to do

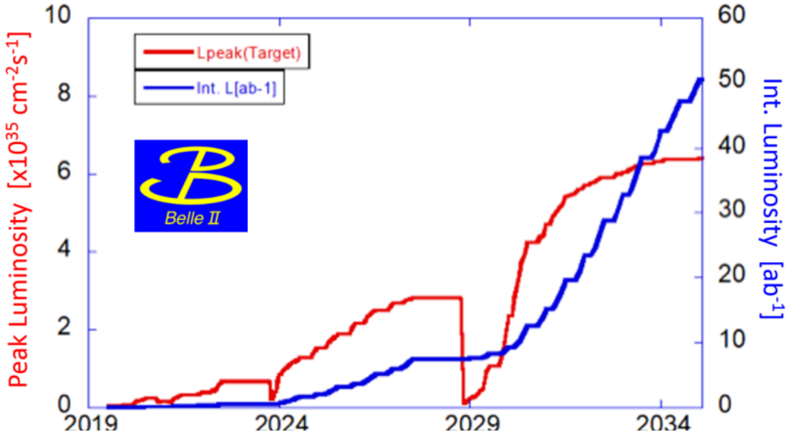
- In the Experiments sector
  - Search for flavor analog exotic states (Z_s, X_b, …)
  - Confirm marginal states (X(3940), Y(4008), Z_1(4050), X(4160), Z_2(4250), X(4350)….)
  - Search for missing charmonium/bottomonium states (η_{c2}, h_c(2P) …)
  - Are there excited Z_c states and Z_{cs} states [D^*D_s or DD_s^*]?
  - Search for flavor analogs of the P_{cs} (P_s, …)
  - Search for quantum number partners of XYZ states
  - Precise measurements of relative strength to different final states
  - Check more di-charmonium systems or di-bottomonium systems
  - Correlation between charm production & charmonium transitions?
  - Make experimental results more accessible for subsequent interpretation (publish Dalitz plot in text format, supply also efficiency curve …)
  - Publish upper limits for negative searches
  - …….

We found more questions to answer, works to do

- In the Theory sector
  - Study exclusive e^+e^- cross sections using better coupled-channel formalism
  - Give differences in key physical quantities to distinguish between different interpretations (molecule, hybrid, tetraquark state, …)
  - Improve parameterizations of the data (when appropriate and beneficial, experimentalists and theorists directly work together)
  - theorists, when possible, to publish complete functional forms
  - ……

More data, more surprises, more opportunities





ATLAS EXPERIMENT

CMS

LHC: L = 2-3x10^{34} cm^{-2}.s^{-1}
~80 interactions per bunch crossing

HL-LHC, Phase II Upgrade : L = 7.5x10^{34} cm^{-2}.s^{-1}
~200 interactions per bunch crossing

2019 **2020** 2021 2022 2023 2024 **2025** 2026 2027 2028 2029 **2030** 2031 2032 2033 2034 2035 2036 2036 2037

LHC: LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5

LHCb

Upgrade I : L = 2x10^{33} cm^{-2}.s^{-1}
~5 interactions per bunch crossing
~50 fb^{-1} (Run 3 and 4)

Upgrade II : L = 1.5x10^{34} cm^{-2}.s^{-1}
~50 interactions per bunch crossing
~300 fb^{-1} (Run 5….)

XYZ particles: review articles, books, & web pages

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- A. Hosaka et al., Exotic hadrons with heavy flavors: X, Y, Z, and related states, PTEP 2016 (2016) 062C01
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- G. Yang, J. Ping, J. Segovia, Tetra- and penta-quark structures in the constituent quark model, Symmetry 12 (2020) 1869
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- A. Ali, L. Maiani, A. D. Polosa, Multiquark Hadrons, Cambridge University Press (2019)
- QWG: https://qwg.ph.nat.tum.de/exoticshub/

✧ Welcome to join the study of hadrons！