XYZ states at BESIII

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Charm, Charmonium, and Charmoniumlike states

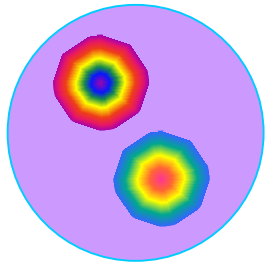
- Charm quark: one of the building blocks of the SM
- Charmonium: bound state of a pair of c and $\bar{c}$ quarks
- charmoniumlike states = XYZ particles : with c $\bar{c}$ in decay product

  & have exotic properties

(could be multiquark states, hybrids, molecules, hadronquarkonia, …)

Charm quark & 1st charmonium: discovered in 1974

1st XYZ particle = X(3872): discovered in 2003



Hadrons are described in quark models

- Gell-Mann & Zweig（1964）
  - Meson：$q\bar{q}$, $q\bar{q}q\bar{q}$, …
  - Baryon：qqq, $qqqq\bar{q}$, …
- Gell-Mann（1972）
  - Exotic states: $q\bar{q}q\bar{q}$, $qqqq\bar{q}$, …

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.

5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

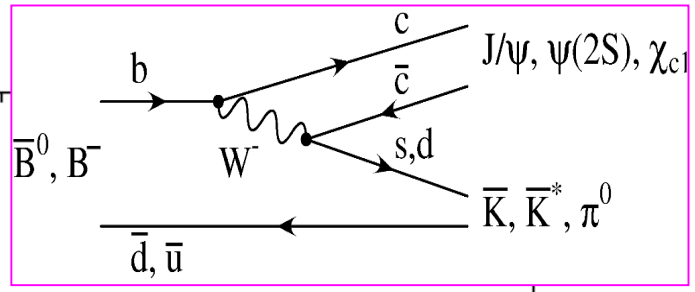
The low-lying bound and resonant states of baryons act like qqq and those of the mesons like $q\bar{q}$. Other configurations, e.g., $q\bar{q}q\bar{q}$, $qqqq\bar{q}$, etc., are called exotic, but they certainly exist in the continuum and may have resonances corresponding to them.

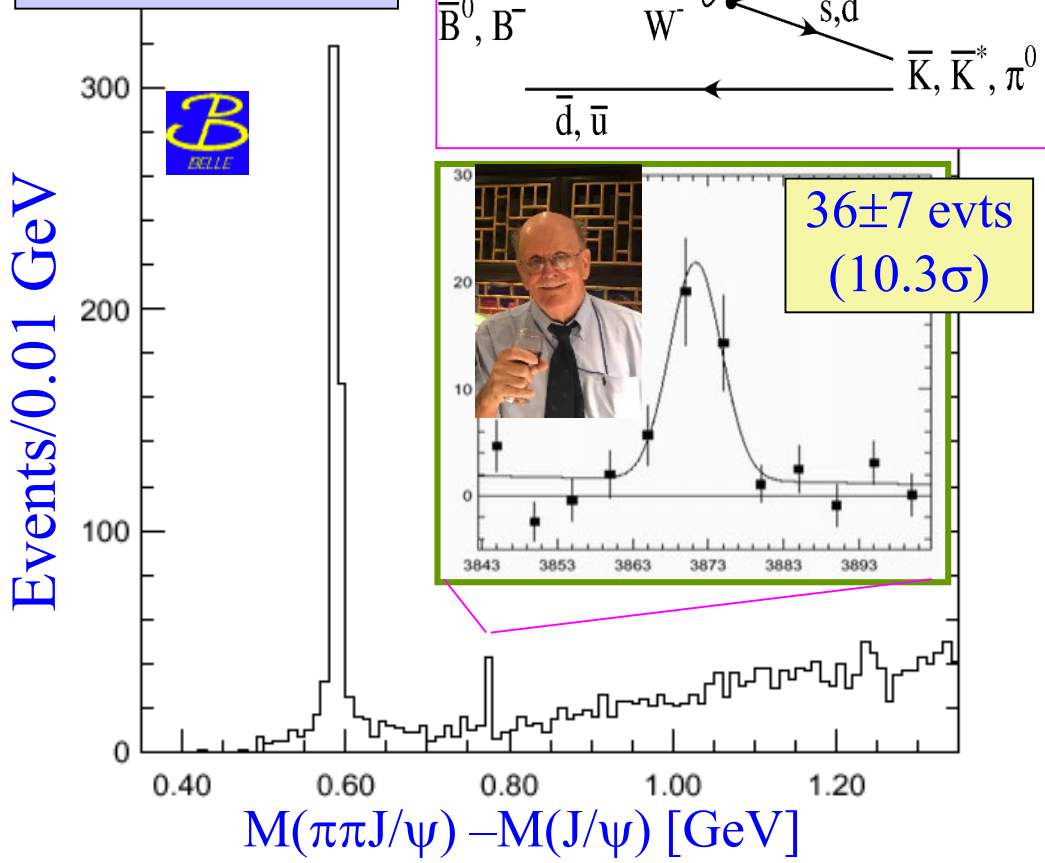
A brief history on exotics hunting

- Lots of experimental searches & theoretical investigations ……
- No hint of the H state (ΛΛ bound state), $\Omega^-\Omega^-$ bound state, …
- No solid signature of glueballs …
- Θ(1540) pentaquark state appeared and disappeared …
- "The story of pentaquark shows how poorly we understand QCD"
  – F. Wilczek, 2005
- "The absence of exotics is one of the most obvious features of QCD"
  – R. L. Jaffe, 2005
- Evidence for "exotic" XYZ particles since 2003!

Discovery of the X(3872) [$\chi_{c1}(3872)$ in PDG2024]

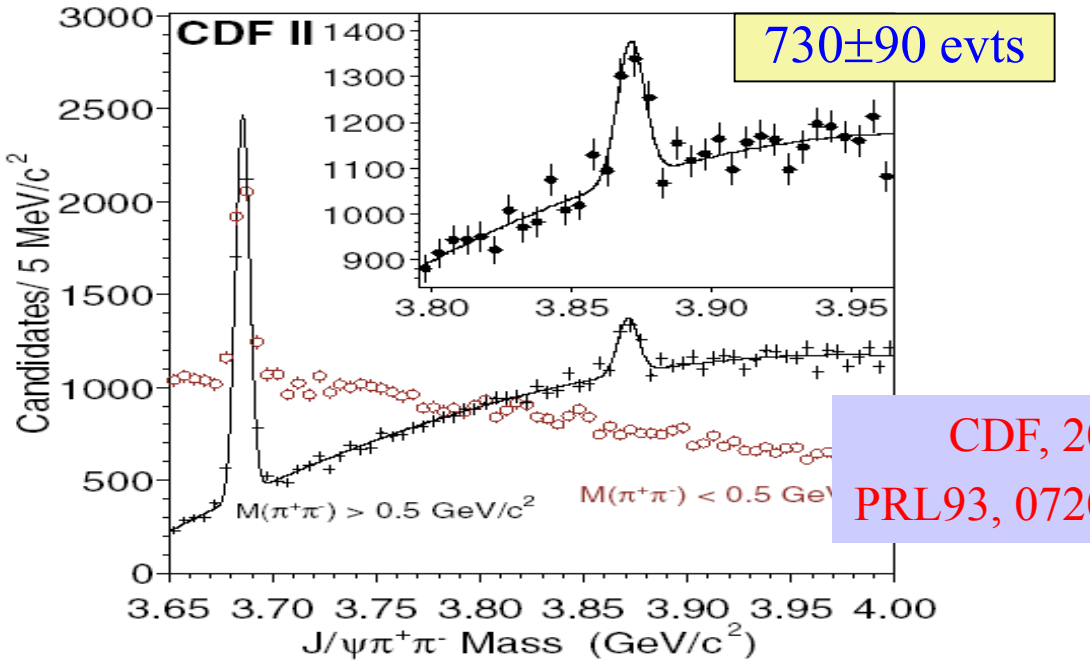
Belle, 20030908,
PRL91, 262001



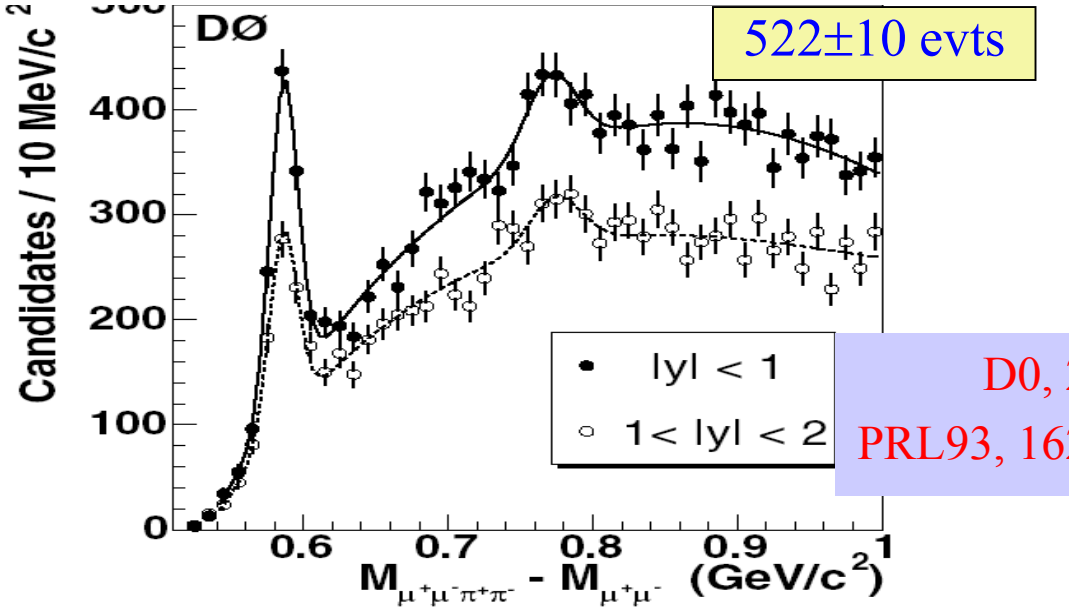


$M = 3872.0 \pm 0.6 \pm 0.5$ MeV, $\Gamma < 2.7$ MeV

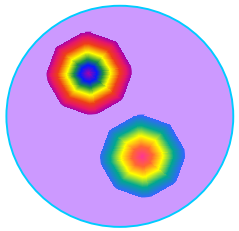
$$\frac{B(B^{\pm} \to XK^{\pm} \to \pi^+\pi^- J/\psi K^{\pm})}{B(B^{\pm} \to \psi' K^{\pm} \to \pi^+\pi^- J/\psi K^{\pm})} = (6.3 \pm 1.2 \pm 0.7)\%$$



CDF, 2004
PRL93, 072001



D0, 2004
PRL93, 162002



Charmonium & beyond

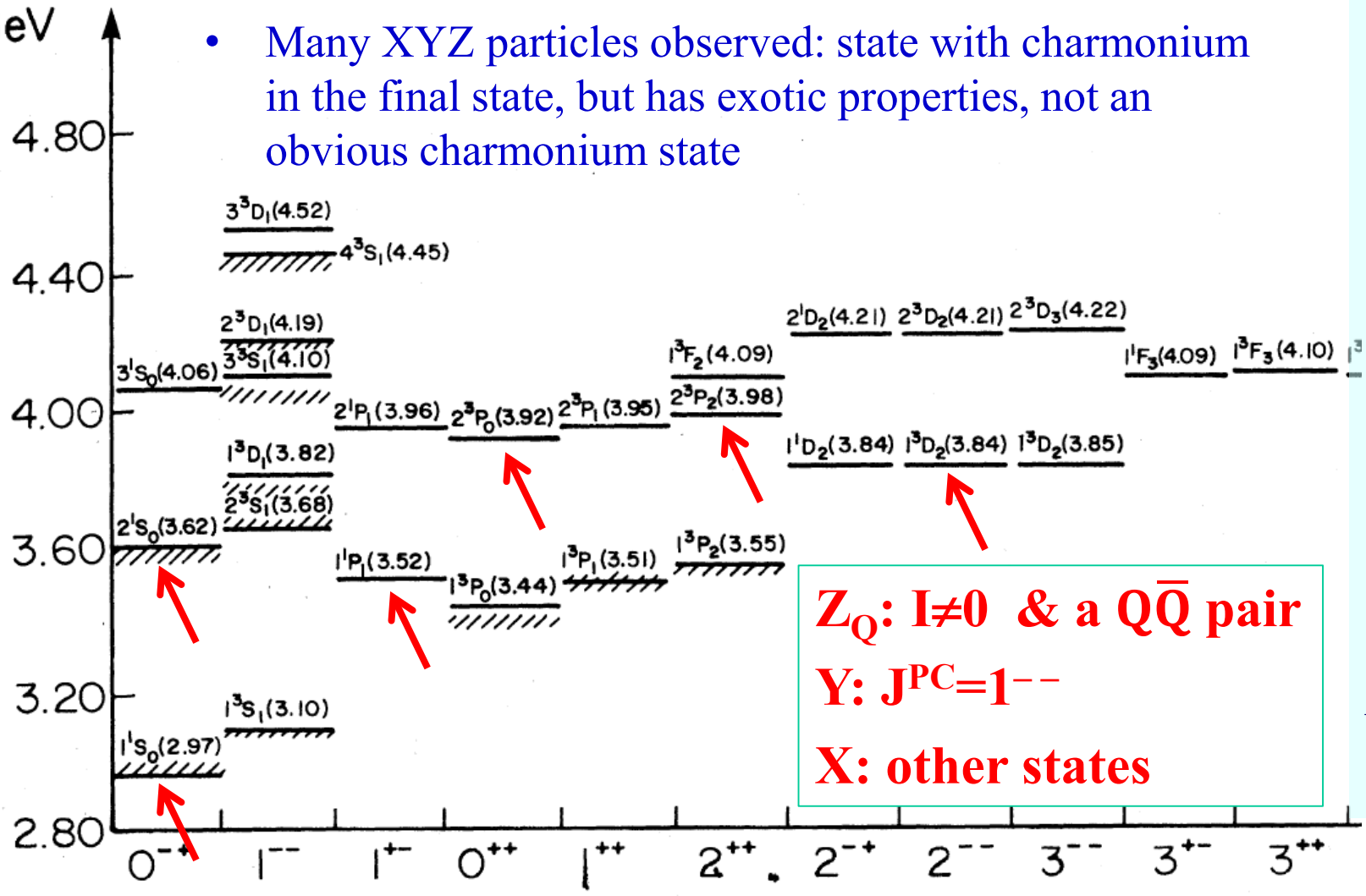
- Charmonia below open charm threshold are identified.
- Many XYZ particles observed: state with charmonium in the final state, but has exotic properties, not an obvious charmonium state

Z(4430)
Z(4250)
Z(4050)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)

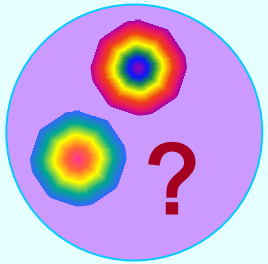


Z_Q: I≠0 & a $Q\bar{Q}$ pair

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

X: other states

What are they ?



Charmonium?
Hybrid?
Tetraquark?
Molecule?
…

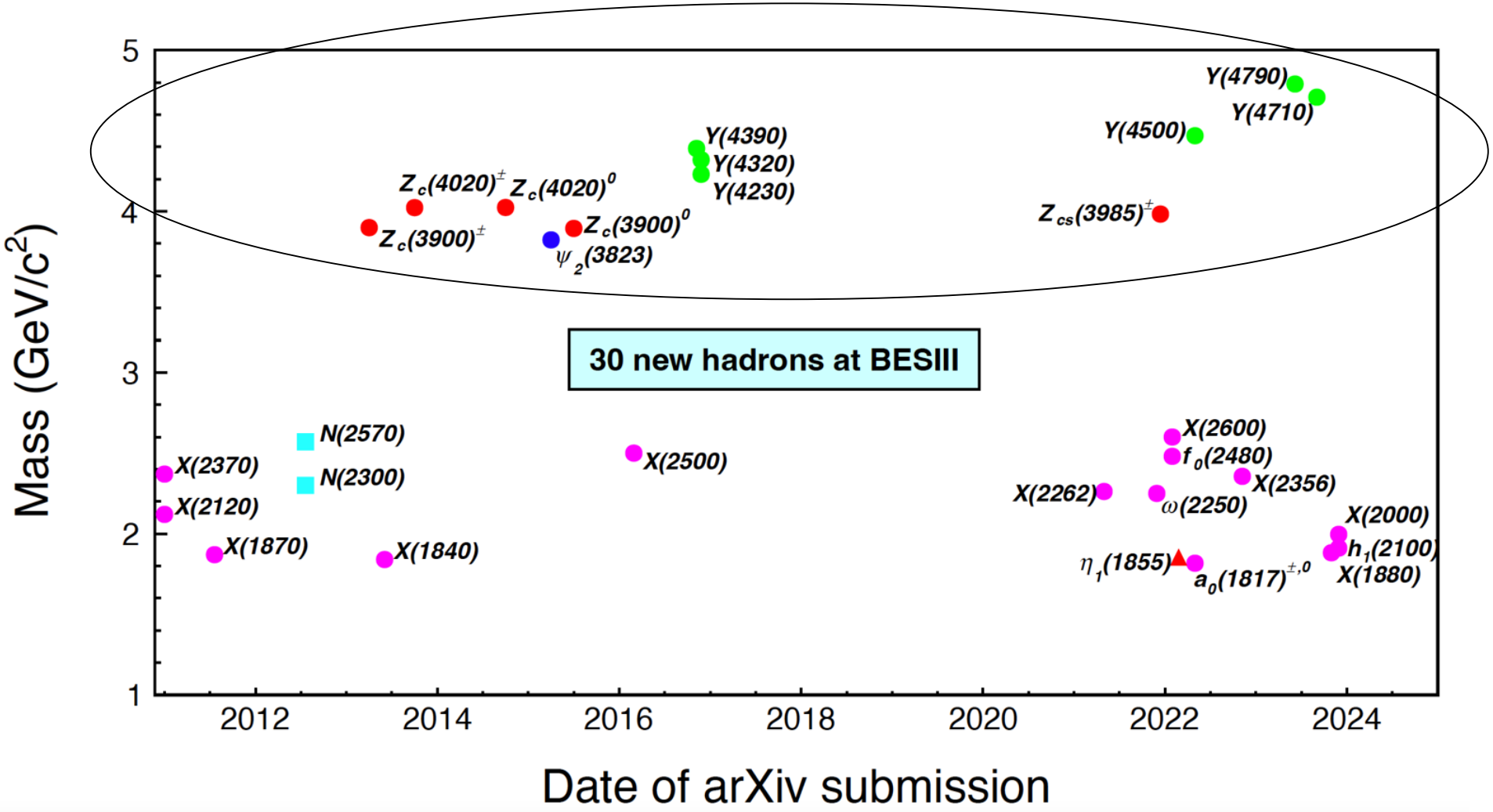
No definite answer!

Godfrey & Isgur,
PRD32, 189 (1985)

BESIII started XYZ particle study from 2011!

In my talk:

- Discovery of “four-quark matter” Zc(3900) and its cousins (Z)
- Supernumerary vector charmoniumlike states (Y)



Why hard to identify exotic state?

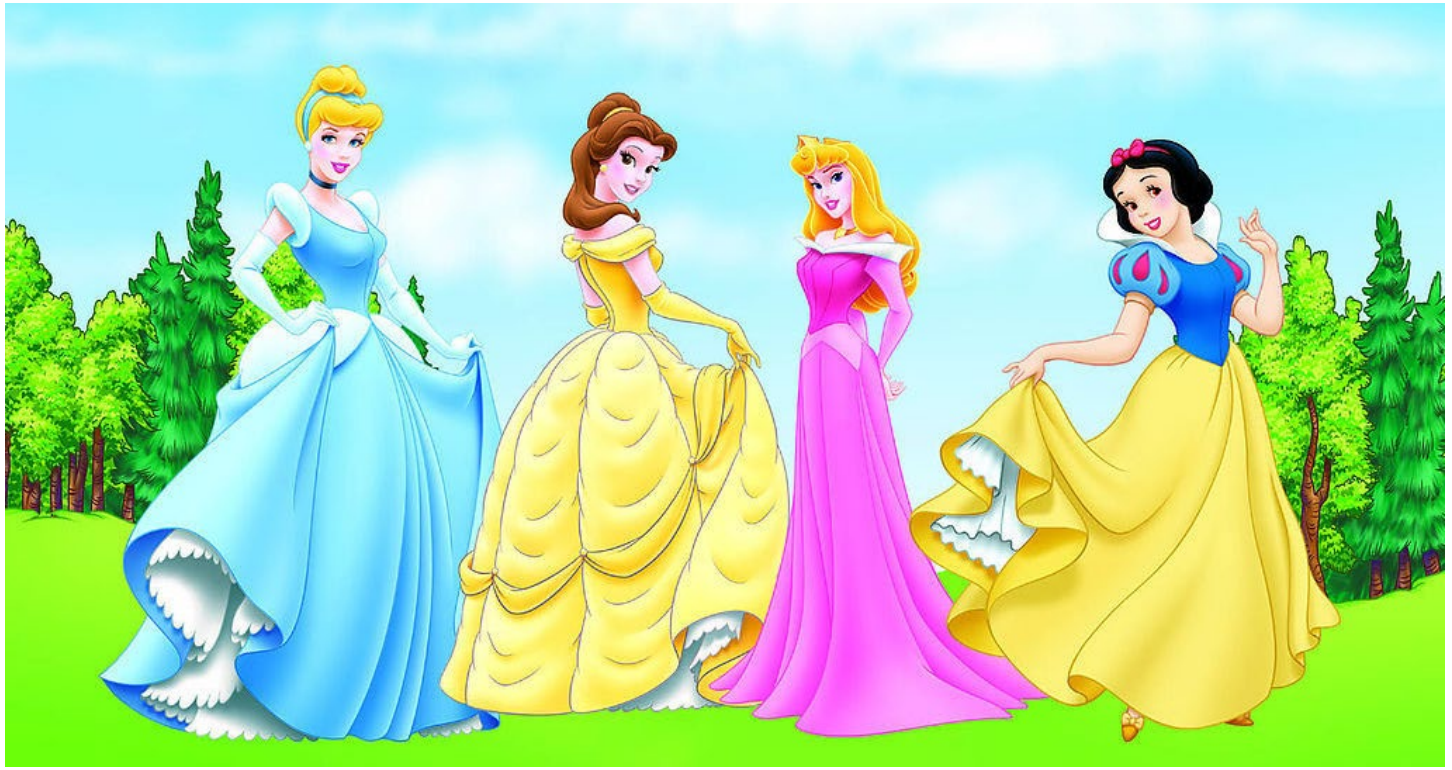
- Which dwarf was named “Happy”?

- I donot know …

No solid signature!

Why hard to identify exotic state?

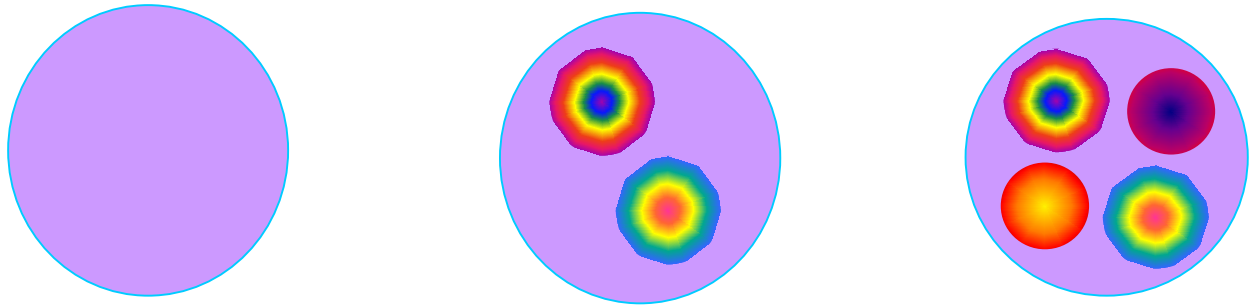
- Which beauty is “Snow White”?



- Yes, I know! “Hair black as ebony [乌木，黑檀]”.
- Very clear signature!

How to identify an exotic meson?

- Find a clear signature for exotic state!



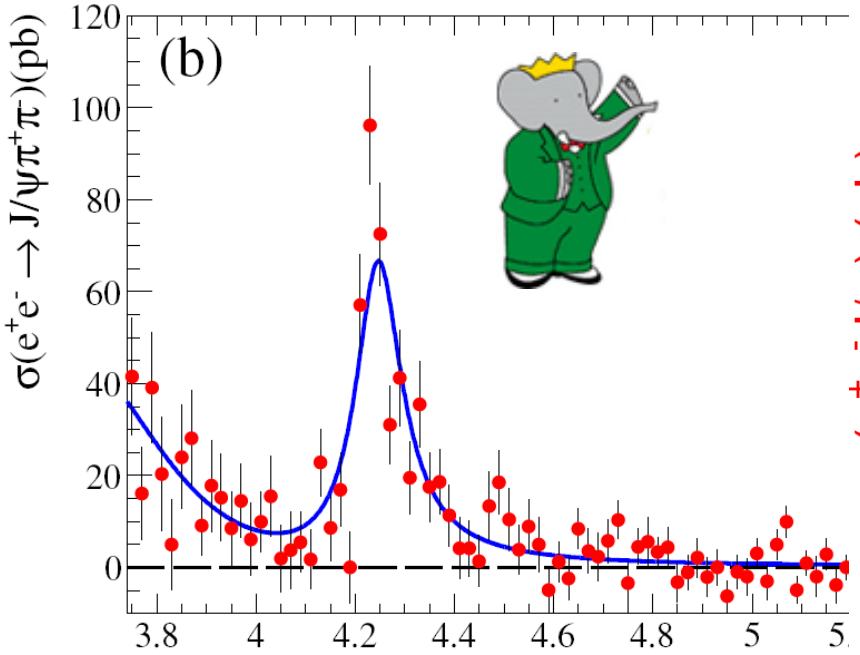
- Decays to charmonium thus has a $\bar{c}c$ pair!
- With electric charge thus has two more light quarks!

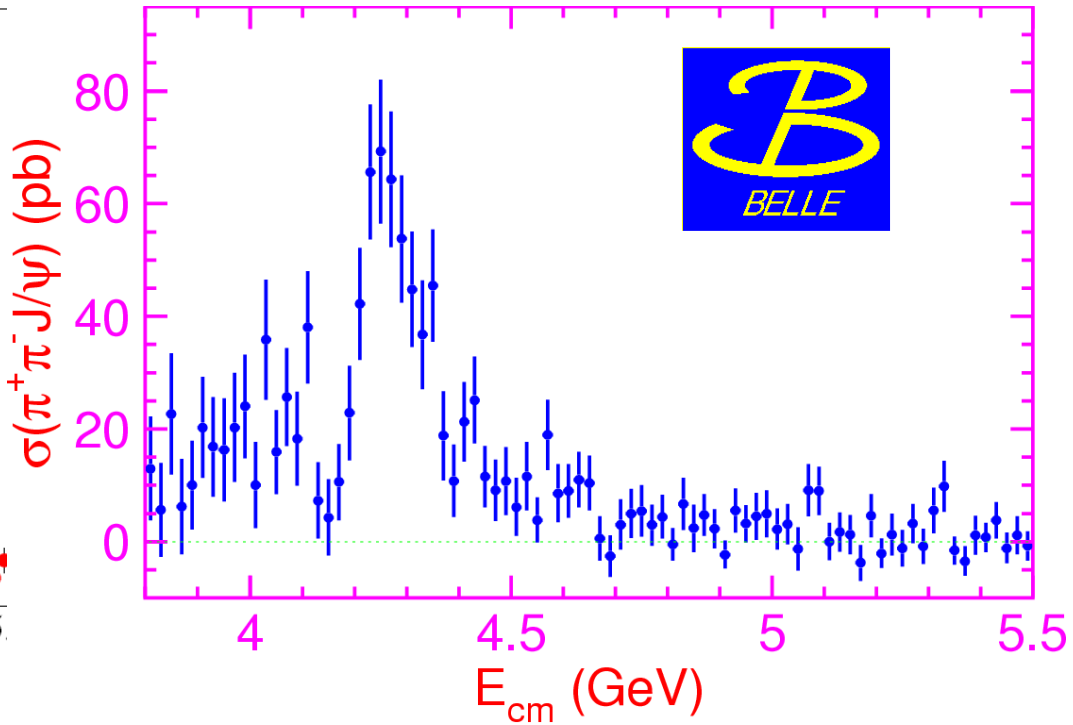
$$\rightarrow N_{quark} \geq 4 \text{ !}$$

- Do searches in $\pi^{\pm}J/\psi$, $\pi^{\pm}h_c$, $\pi^{\pm}\psi(2S)$, …

What do we do at BESIII

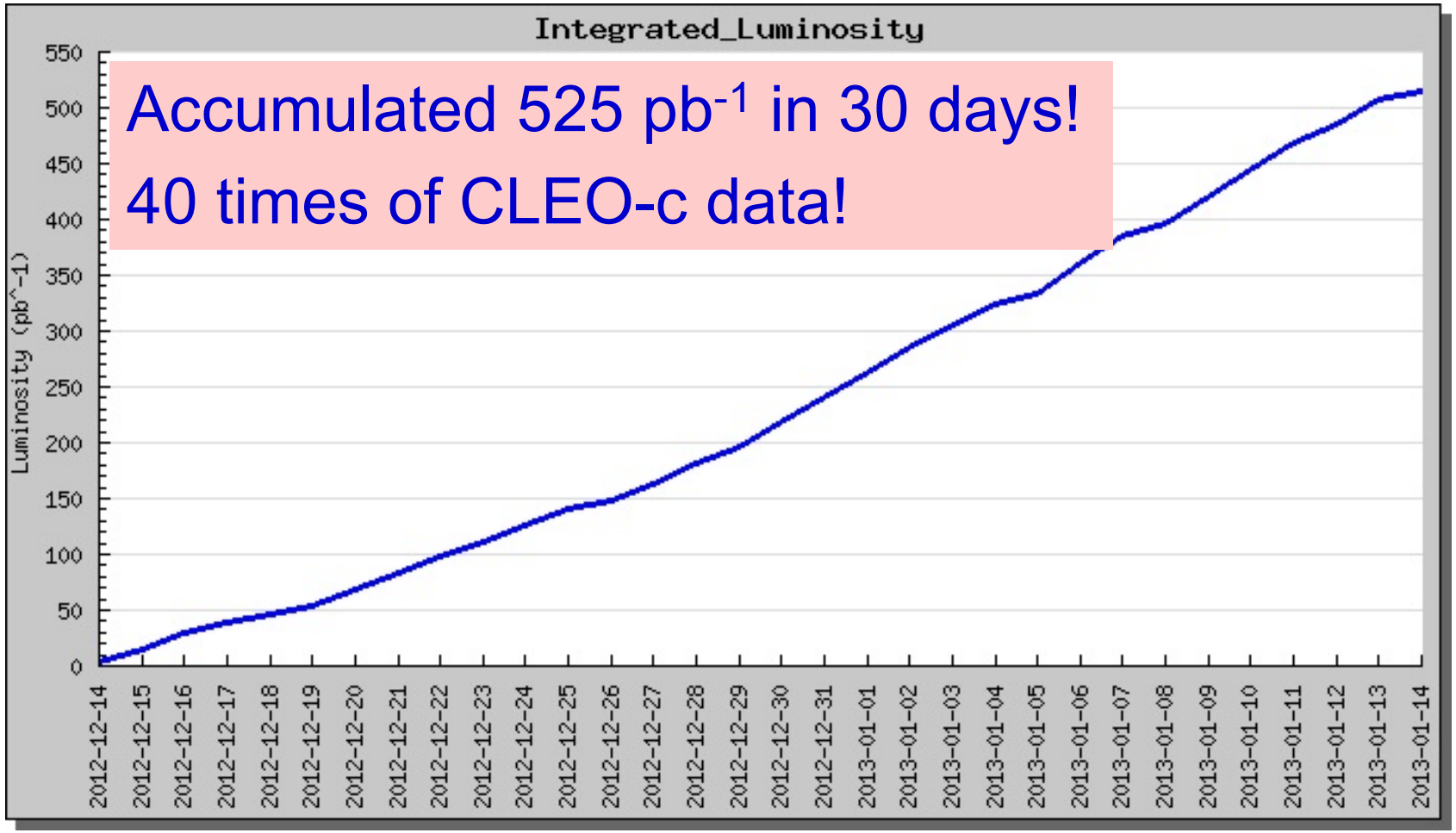
We may search for such state if it decays into $\pi^{\pm}J/\psi$!





- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ reaches maximum at ~4.26 GeV
- We proposed a 45 days' data taking for 500 pb^{-1} data at peak
- ~1500 reconstructed events are expected [3xB-factories]

Data taking at BESIII

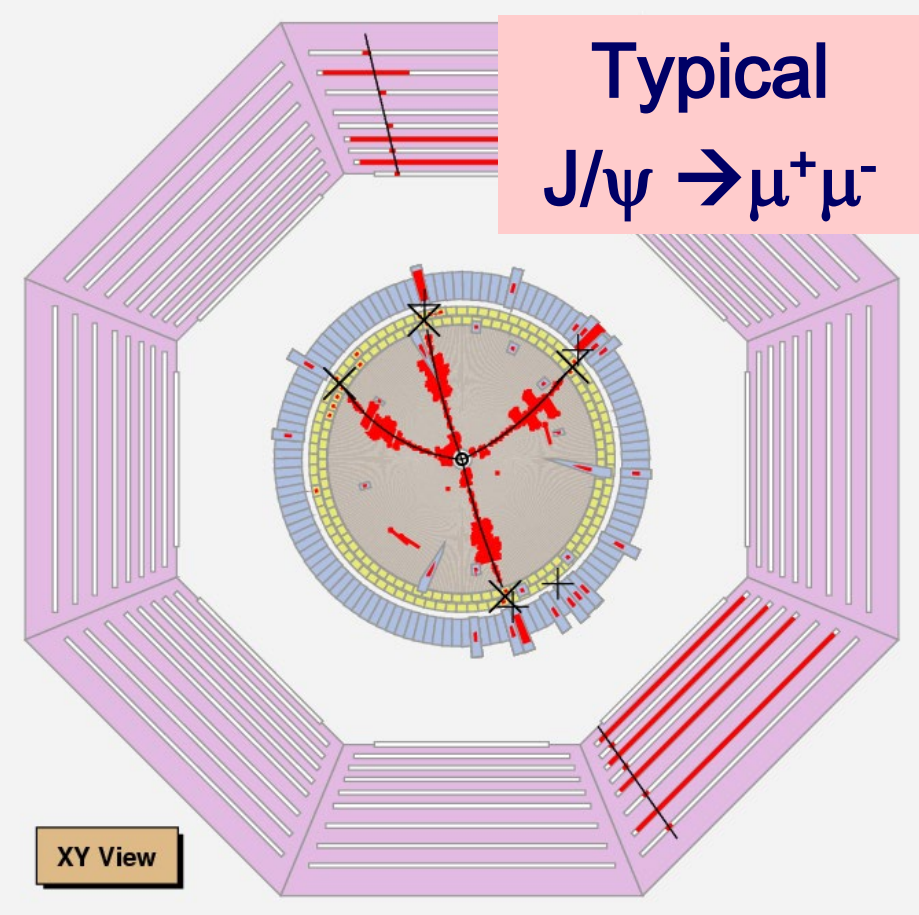


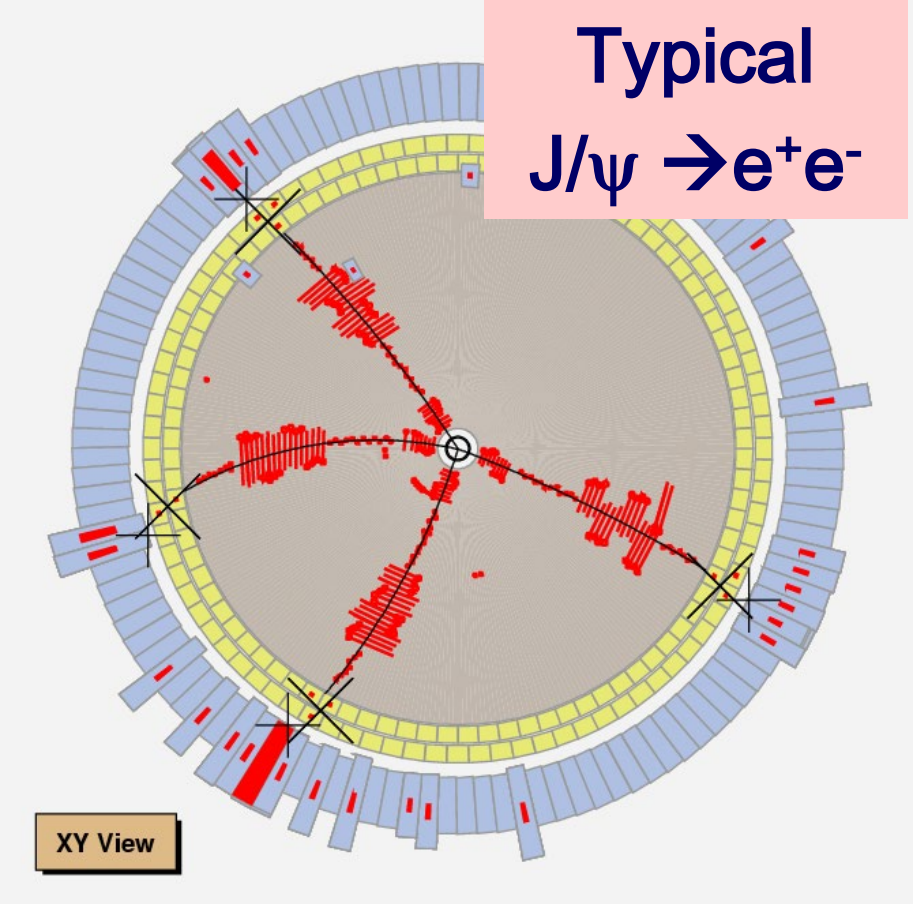
Accumulated 525 pb^{-1} in 30 days!

40 times of CLEO-c data!

- Highest energy BEPCII ever reach, L_{peak} ~ $5.3 \times 10^{32}/cm^2/s$!
- BEMS measures CM energy at 1 MeV level !
- Low background, low noise, all sub-detectors excellent !

Select $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ events

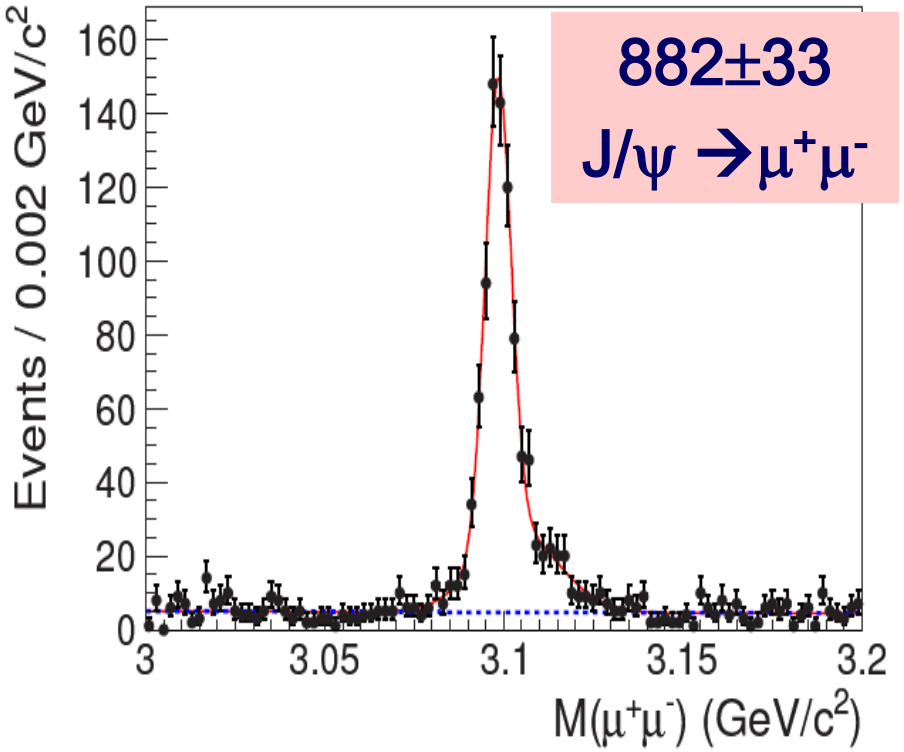


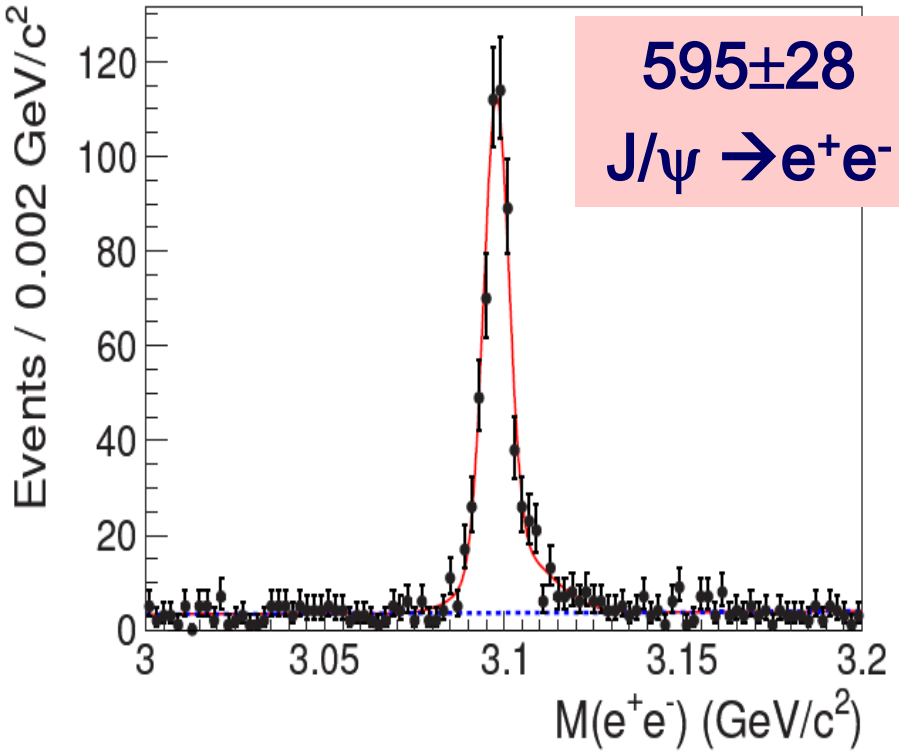


- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency. Use kinematic fit.
- Only use MDC & EMC information, MC simulation reliable.

The J/ψ signals

BESIII: PRL110, 252001

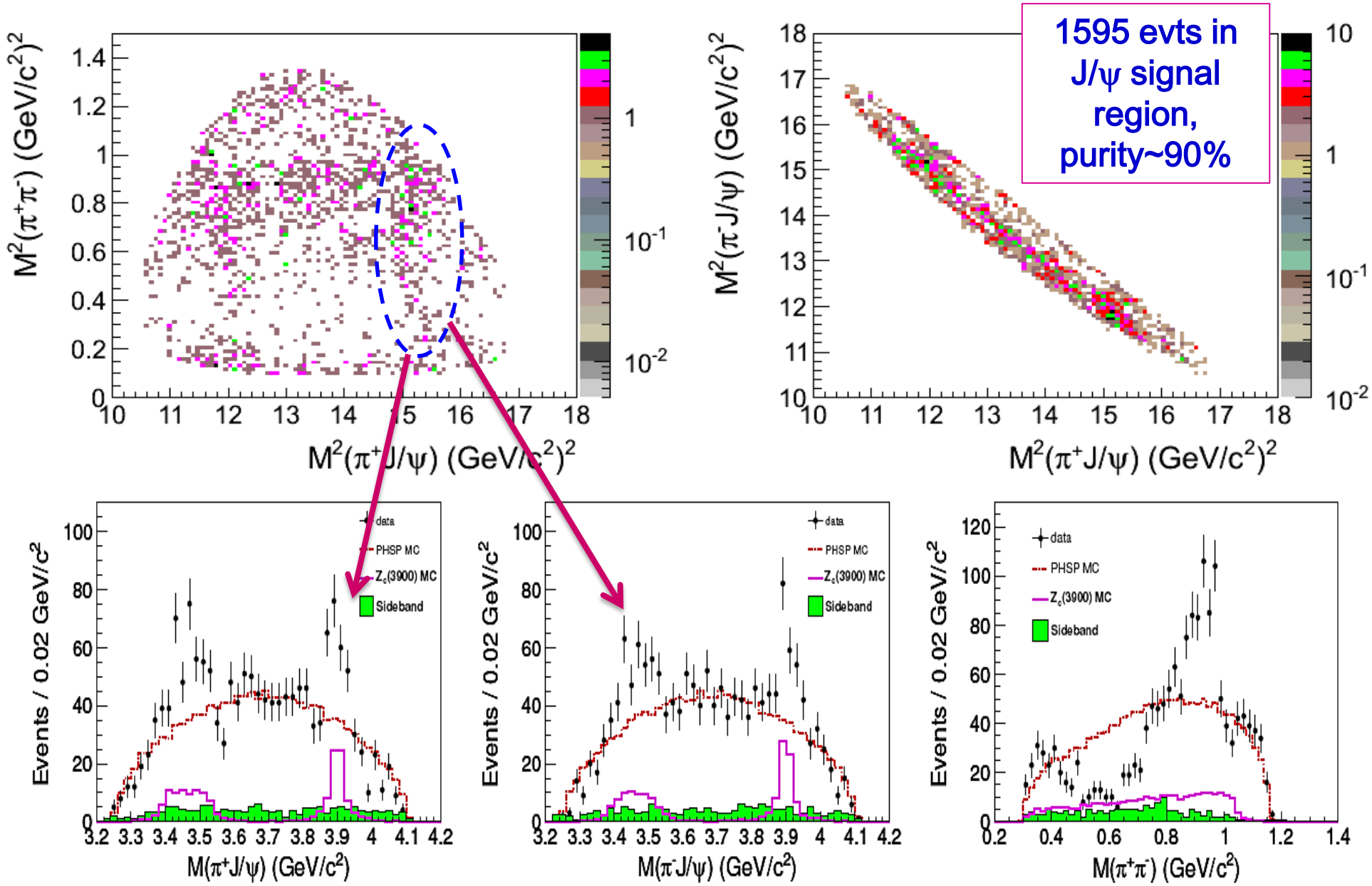




- Dominant background $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$
- J/ψ signal: [3.08,3.12] GeV
- J/ψ sideband: [3.0,3.06] GeV or [3.14,3.20] GeV, 3xsignal
- At least 4 independent analyses, all get similar results !

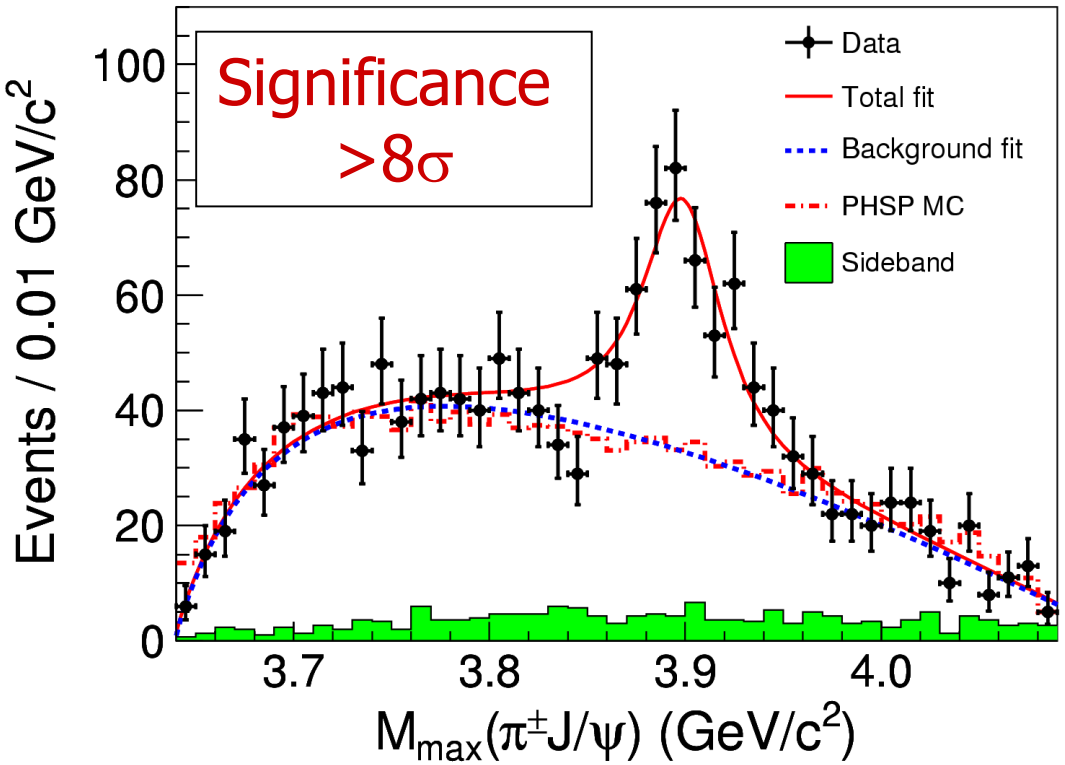
$e^+e^- \to \pi^+\pi^- J/\psi$ at Ecm=4.26 GeV

PRL110, 252001

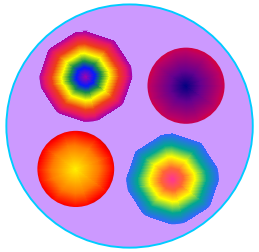


The $Z_c(3900)$ signal

BESIII: PRL110, 252001



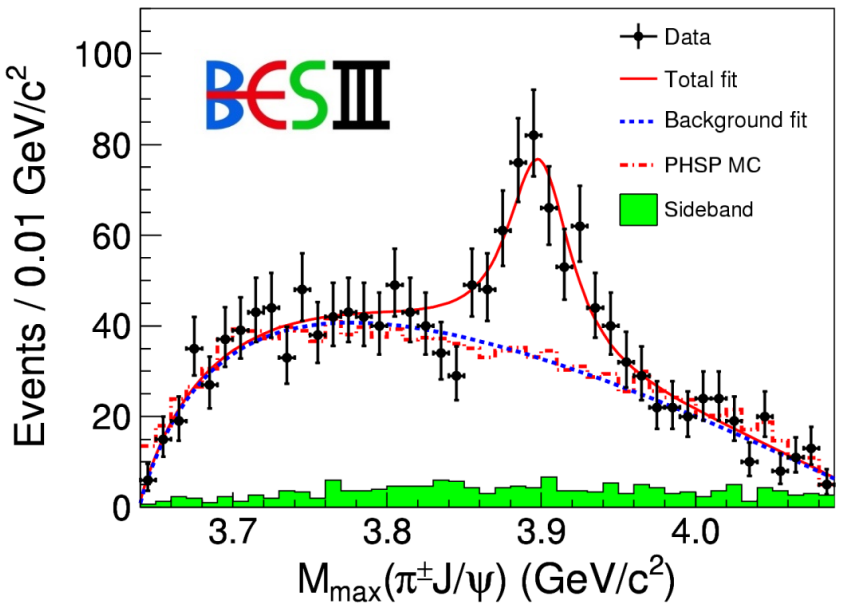
- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks



- S-wave Breit-Wigner with efficiency correction
- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

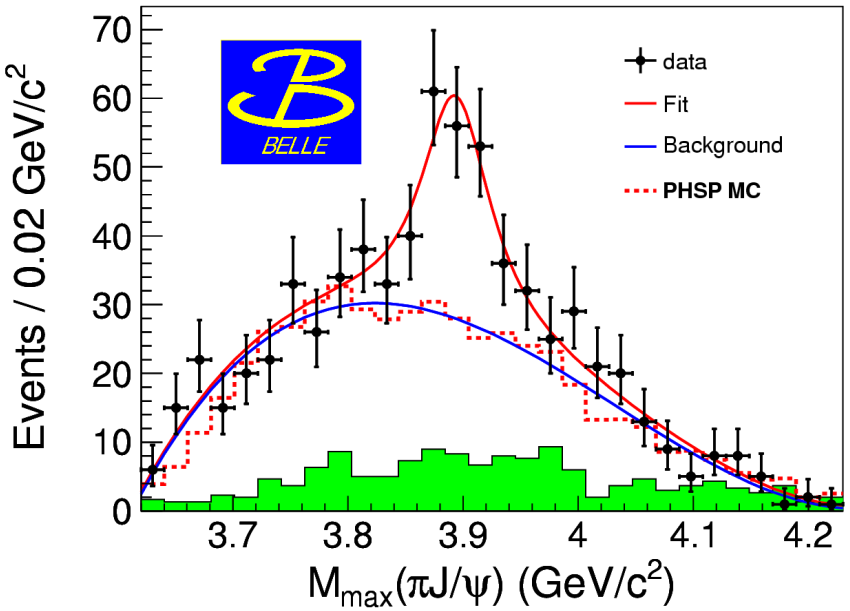
$Z_c(3900)$ observed in **3** experiments!

BESIII at 4.26 GeV: PRL110, 252001



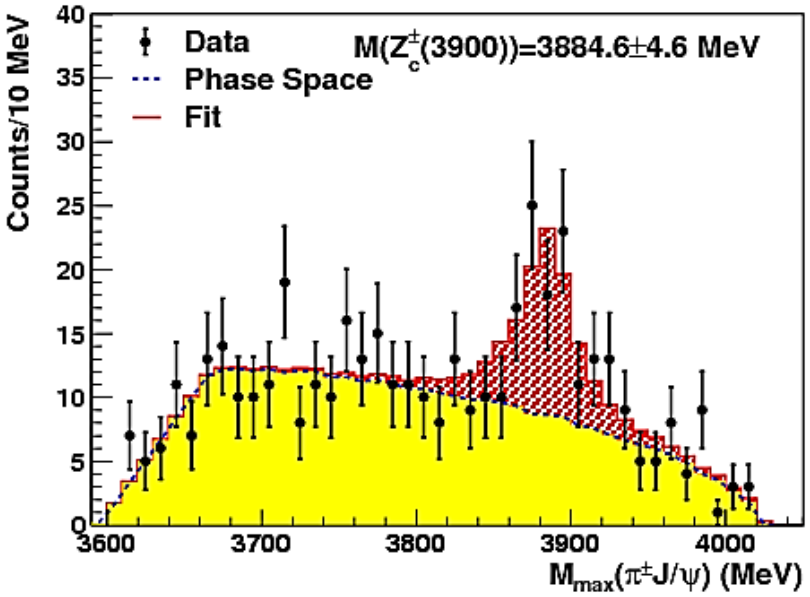
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

Belle with ISR: PRL110, 252002



- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

CLEOc data at 4.17 GeV: 1304.3036



- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ

Zc(3900) is the first confirmed tetraquark state!

Observation of the $Z_c(3900)$

— a charged charmoniumlike structure —

This happened in 17 days

BESIII：Mar. 24

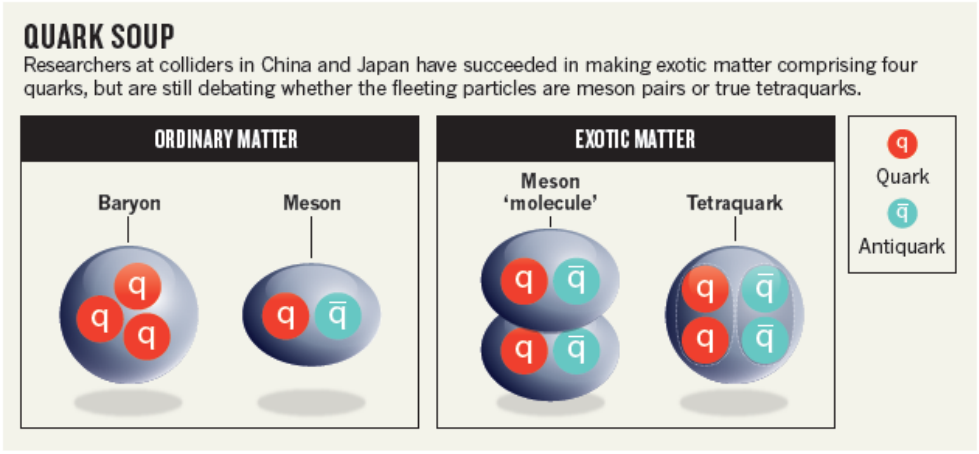
Belle： Mar. 30

CLEOc：Apr. 10

Z_c established !

Highlighted by *PRL* & *Nature* & *physics* !

J/ψ is a tool for further physics discoveries!



PARTICLE PHYSICS

D. Powell, *Nature* 498, 280 (2013)

Quark quartet opens fresh vista on matter

First particle containing four quarks is confirmed.

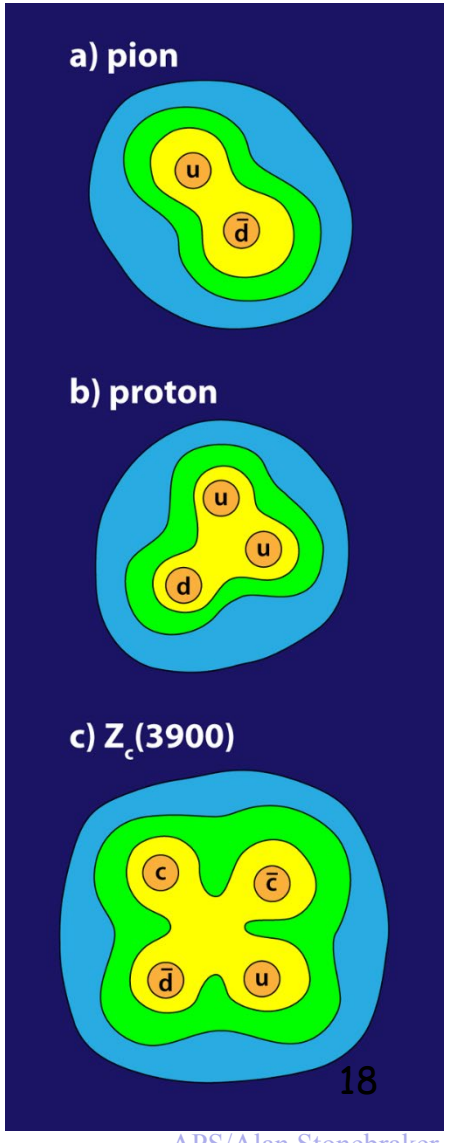
BY DEVIN POWELL

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

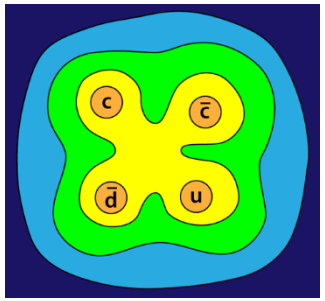
antimatter counterparts, positrons. These crashes have one-thousandth the energy of those at the world's most powerful accelerator, the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland, but they are still energetic enough to mimic conditions in the early Universe. Collision rates at KEK are more than twice those at the LHC, and they occasion-

"They have clear evidence of a

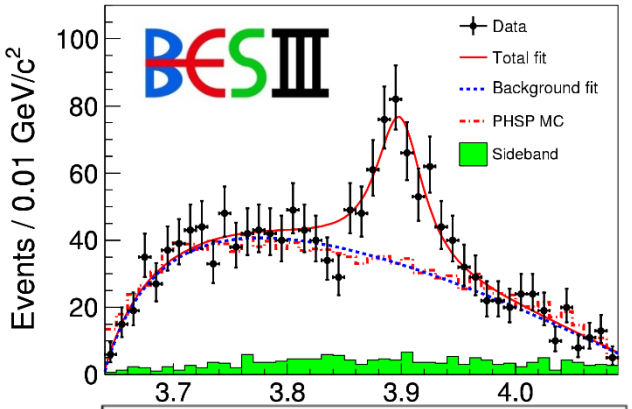


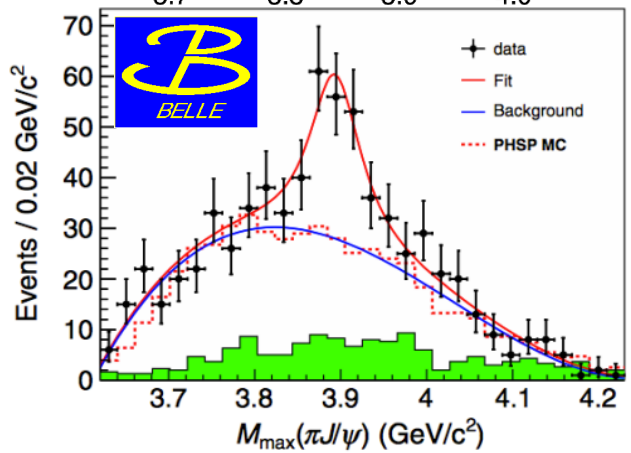
APS/Alan Stonebraker

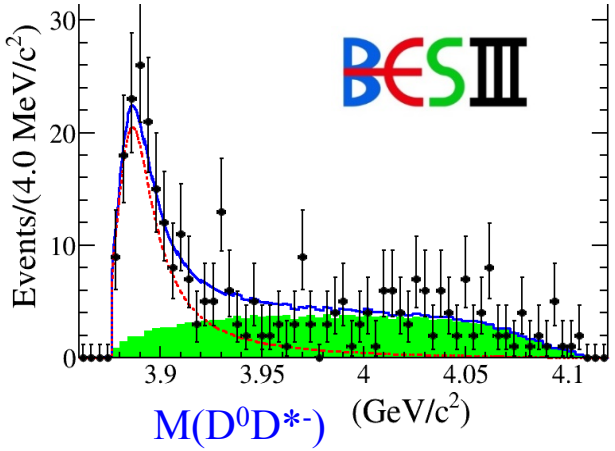
The Z_c states with u,d-quark



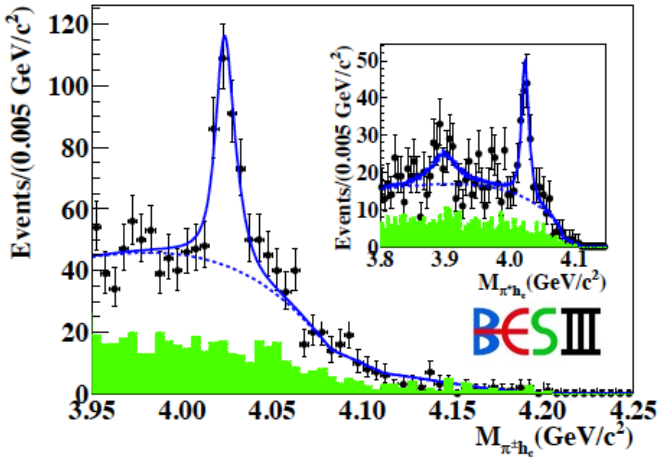
$Z_c(3900)$, 2013

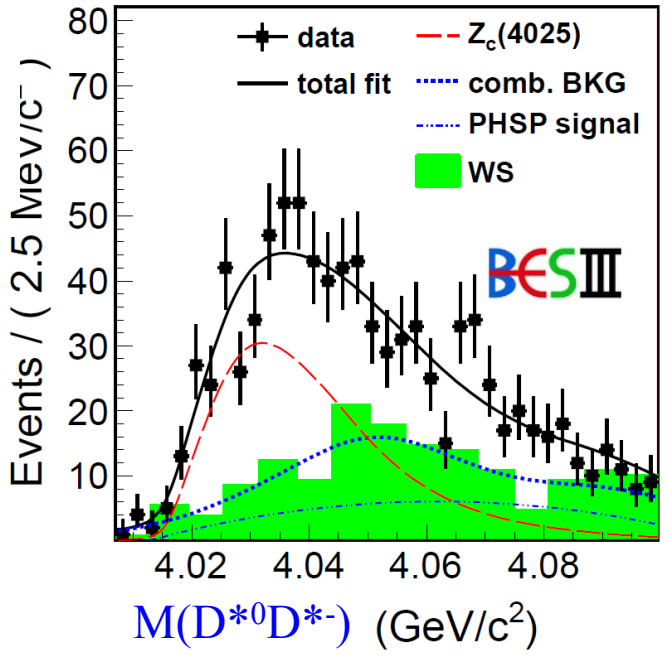




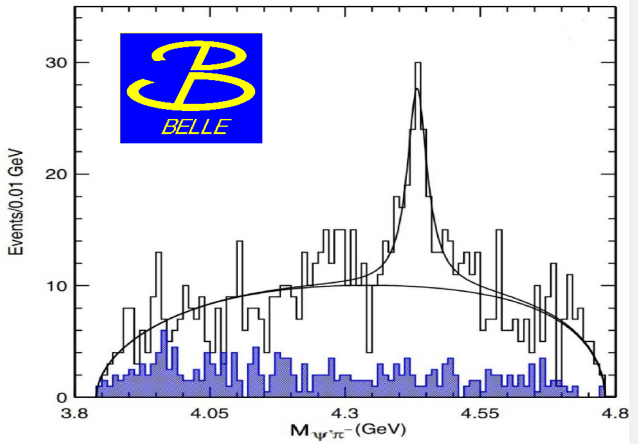


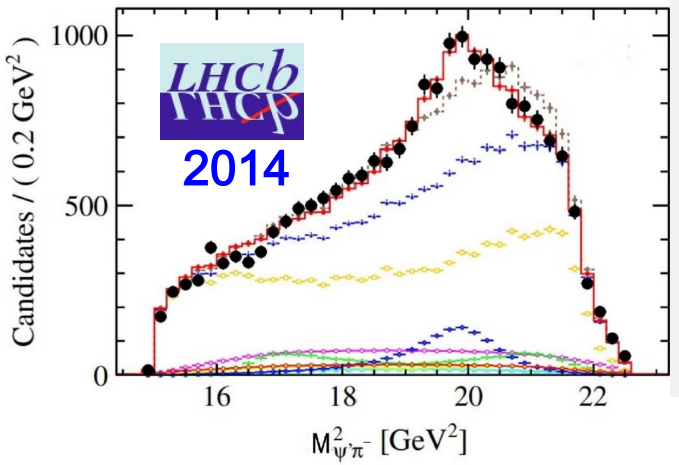
$Z_c(4020)$, 2013





$Z_c(4430)$, 2008



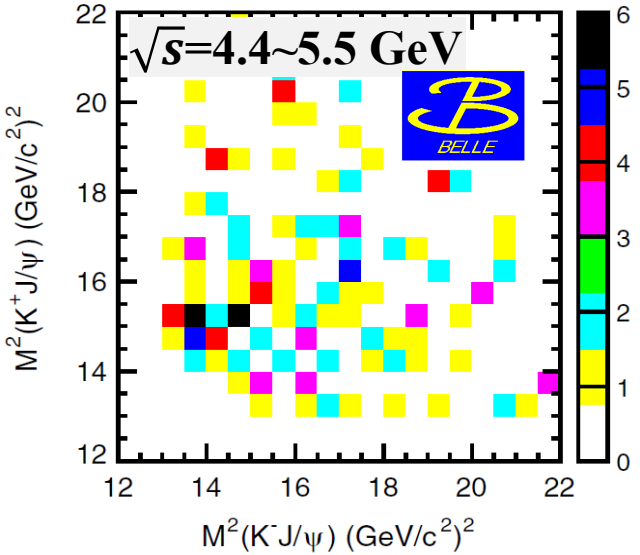


All are observed in π+charmonium (J/ψ, h_c, ψ(2S)) final states, candidate $c\bar{c}u\bar{d}$ tetraquark states

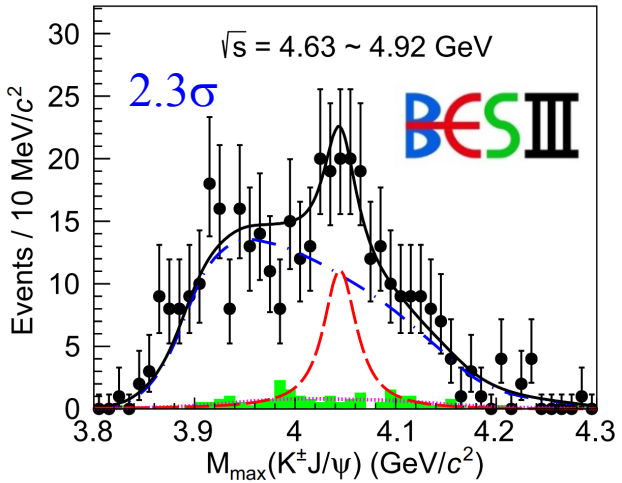
➔ Existence of states with d→s?

➔ Search for states decay into $K^{\pm}J/\psi$, $\bar{D}^*D_s + \bar{D}D^*_s$!

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



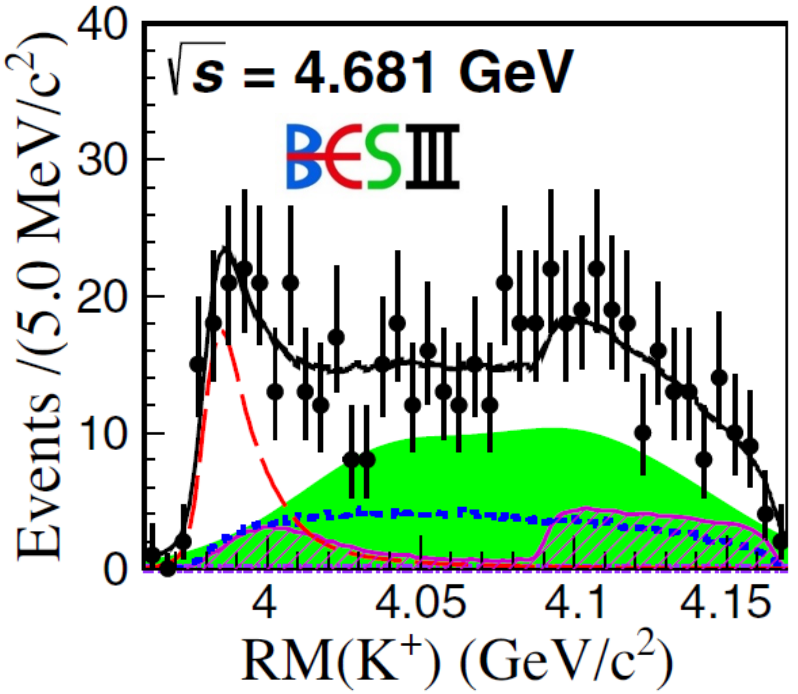
PRD 89, 072015 (2014)



PRL 131, 231902 (2023)

No significant Zcs in Belle/BESIII $e^+e^- \to K^+K^-J/\psi$ data samples.

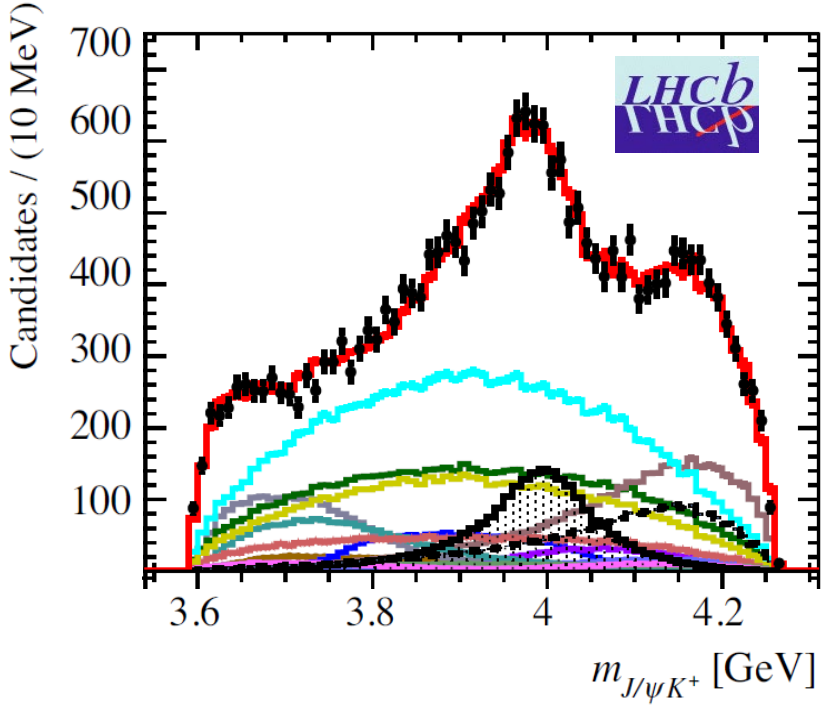
$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$



PRL 126, 102001 (2021)

$Z_{cs}(3985)$ in $\bar{D}^*D_s + \bar{D}D^*_s$ mode!

$B^+ \to J/\psi\phi K^+$



PRL 127, 082001 (2021)

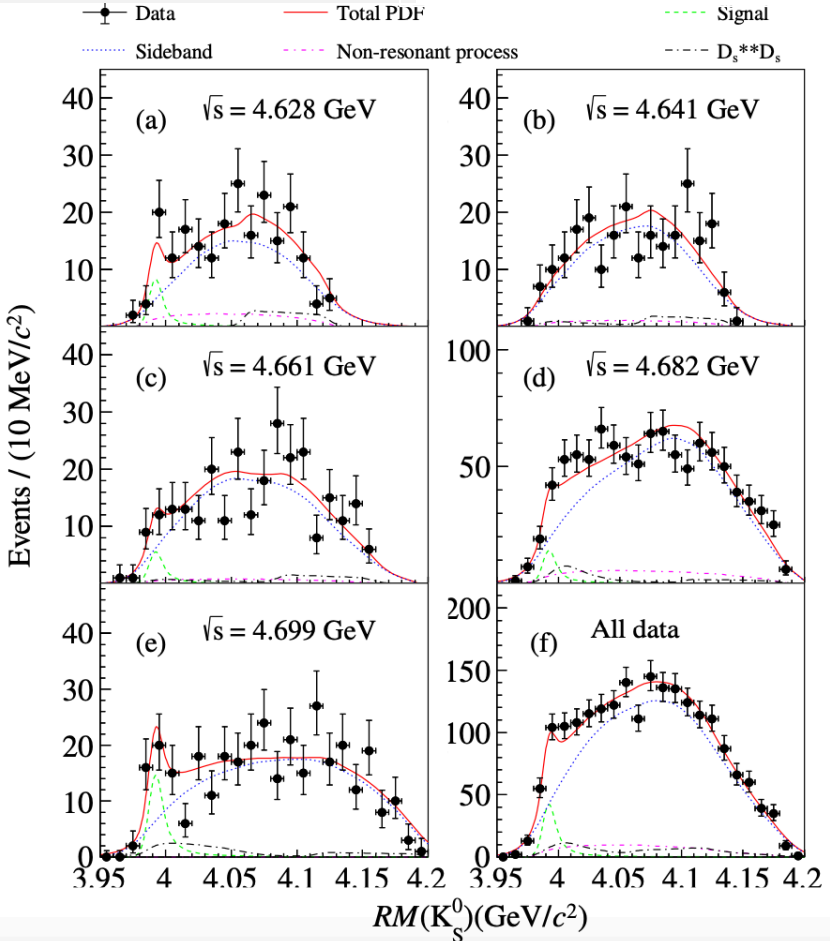
$Z_{cs}(4000)$ and $Z_{cs}(4220)$ in $K^{\pm}J/\psi$ decay mode!

State	Signif.	JP	Mass (MeV)	Width (MeV)
$Z_{cs}(3985)$	5.3σ	??	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$
$Z_{cs}(4003)$	15σ	1+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

Widths different, not the same state?

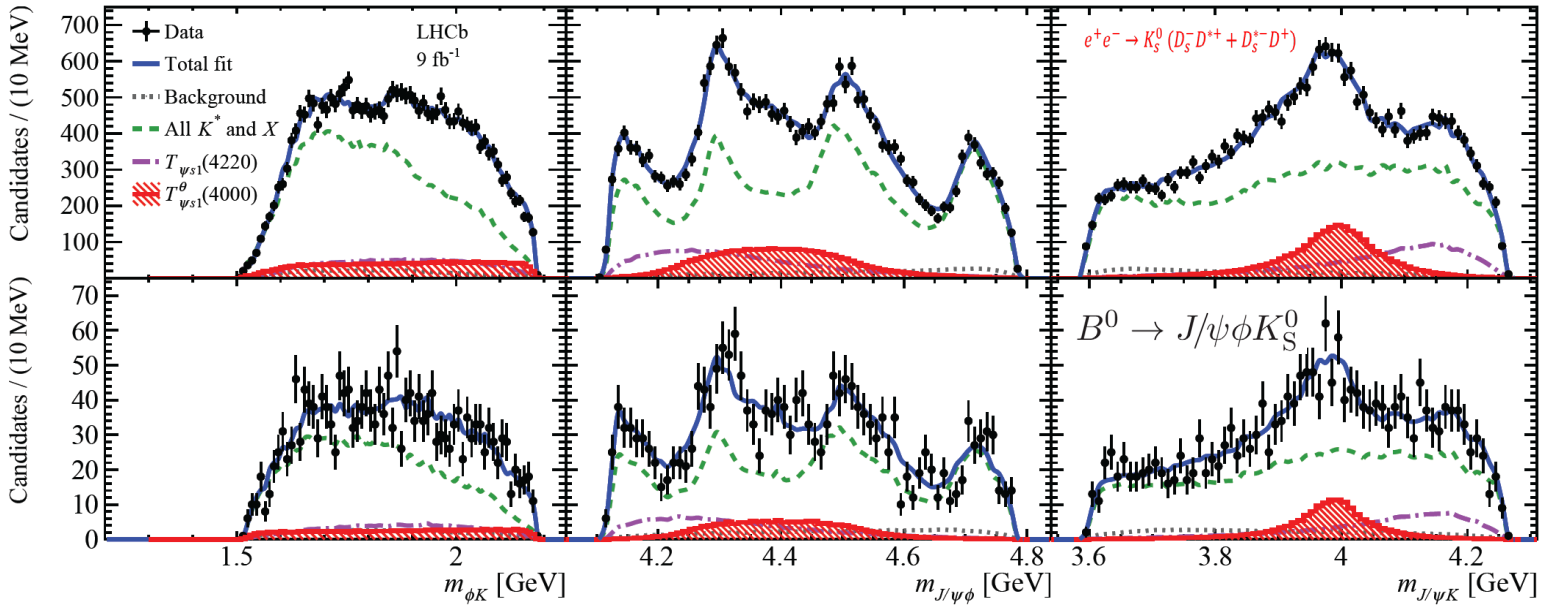
Evidence for the neutral $Z_{cs}(3985)$ & $Z_{cs}(4003)$

PRL129, 112003 (2022) $e^+e^- \to K^0_S\,(D_s^- D^{*+} + D_s^{*-} D^+)$



$B^0 \to J/\psi\phi K^0_S$

PRL131, 131901 (2023)



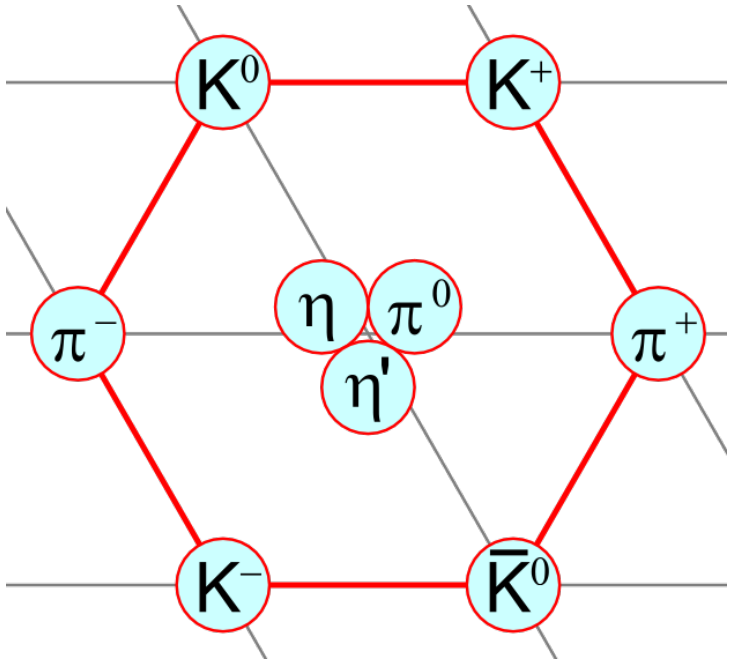
Significance >4.0σ after including systematic uncertainties

Significance 5.4σ with isospin symmetry imposed

State	Mass (MeV/c^2)	Width (MeV)	Significance
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$	5.3σ
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$	4.6σ

Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$3991\,^{+12\ +9}_{-10\ -17}$	$105\,^{+29\ +17}_{-25\ -23}$	$7.9 \pm 2.5\,^{+3.0}_{-2.8}$	$-12\,^{+11\ +6}_{-10\ -4}$

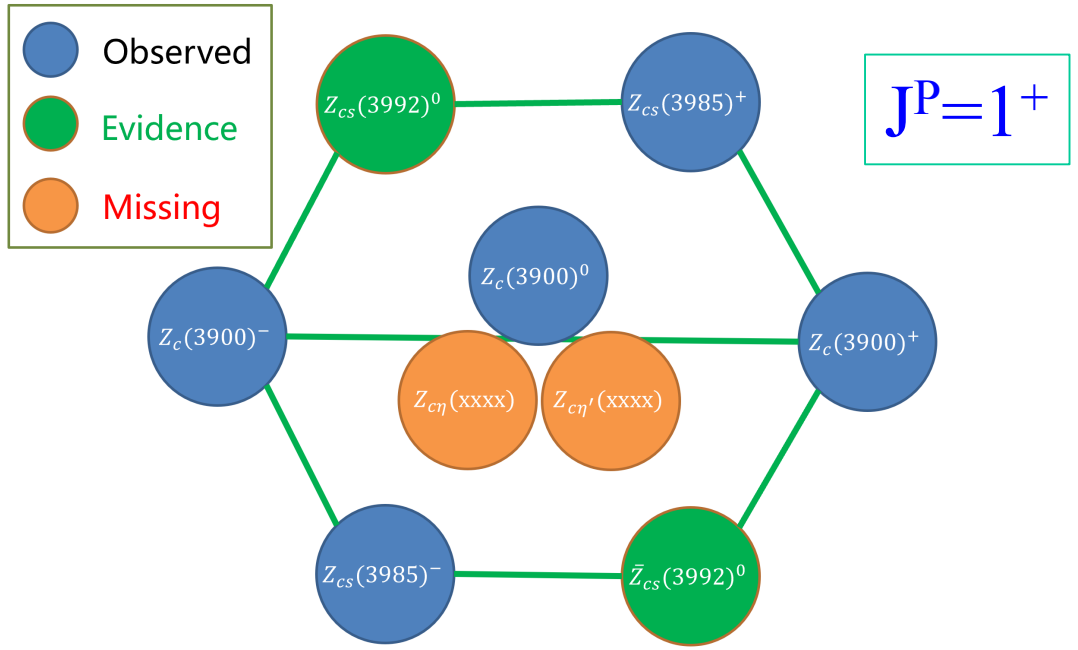
- Minimal quark content $c\bar{c}s\bar{d}$? Mass and width consistent with charged Z_{cs} → isospin partner

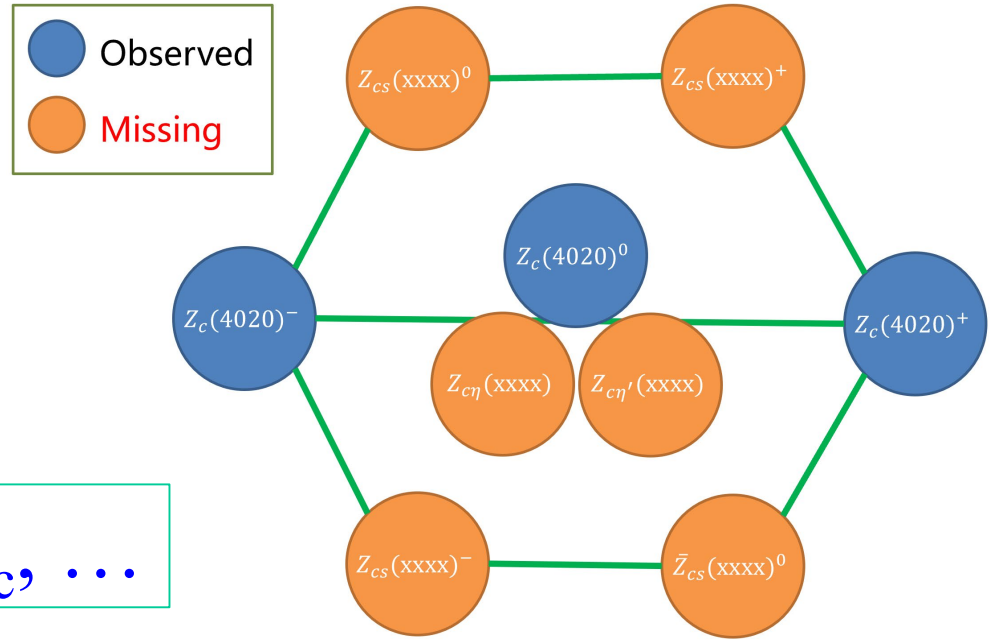


+ J/ψ

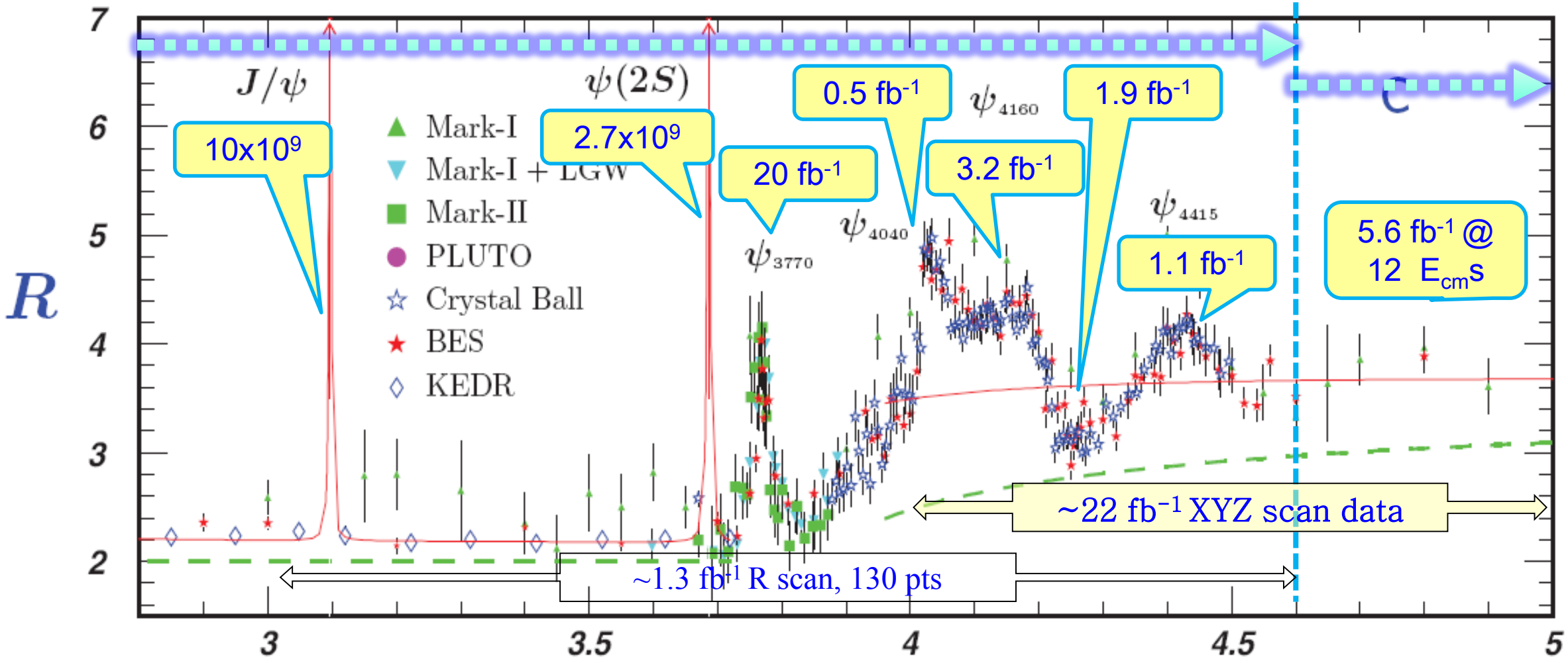
+ h_c

+ ψ(2S), χ_{cJ}, η_c, …





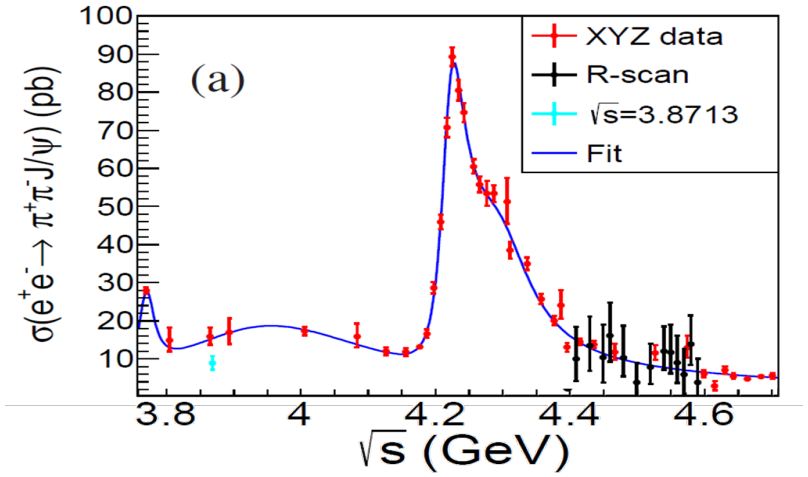
How many vectors in charmonium energy region?



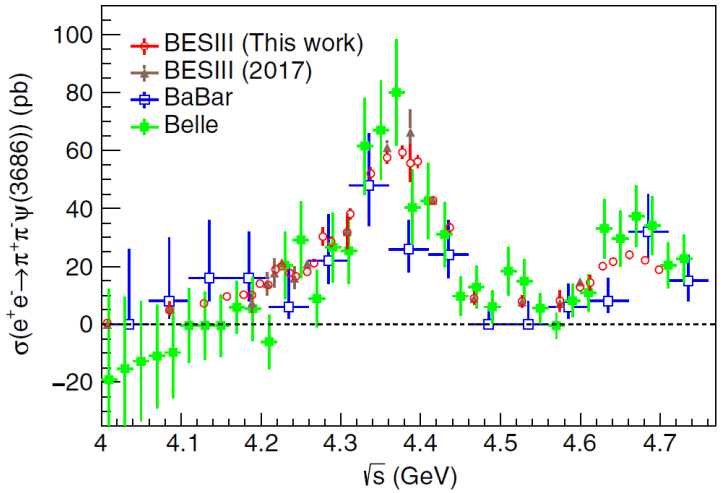
BESIII data samples cover full charmonium energy region make high precision cross section measurements possible, NEW vector states are identified!

Observation of Y(4230) in many final states

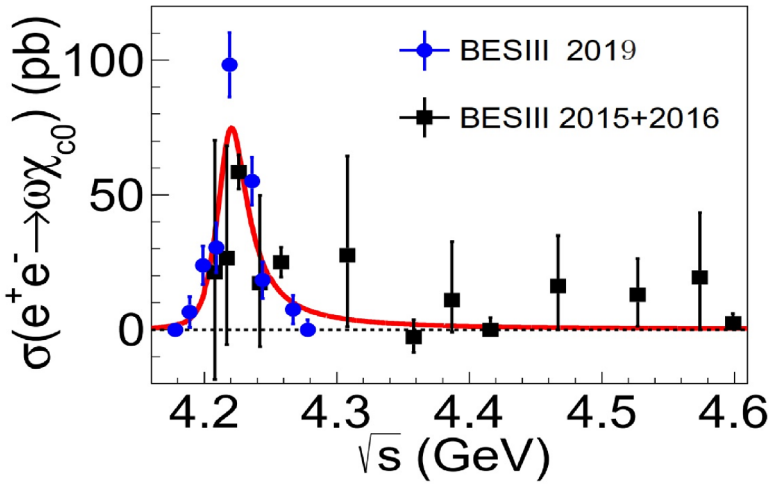
PRD106, 072001 (2022)



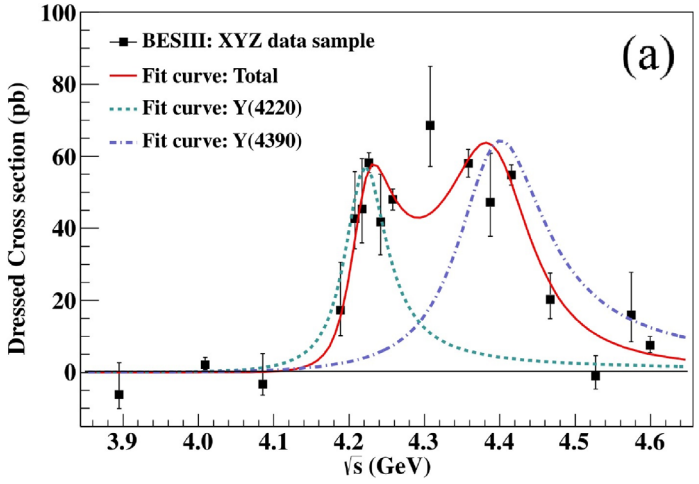
PRD104, 052102 (2021)



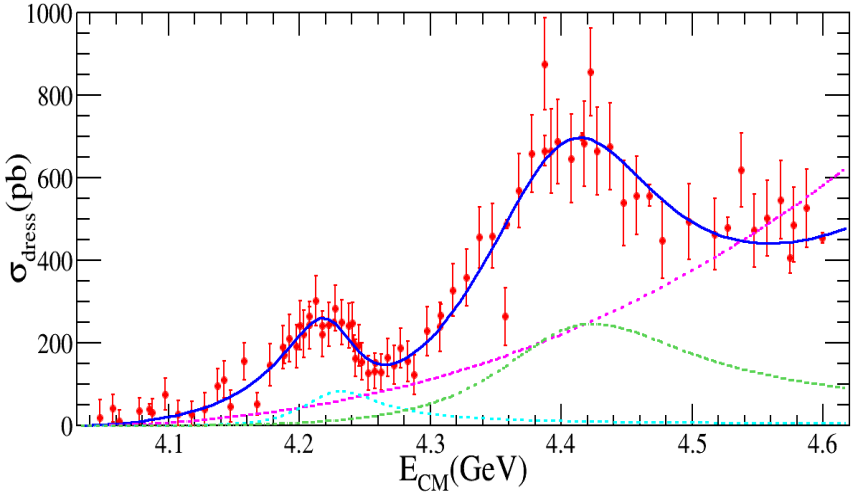
PRD99, 091103 (2019)



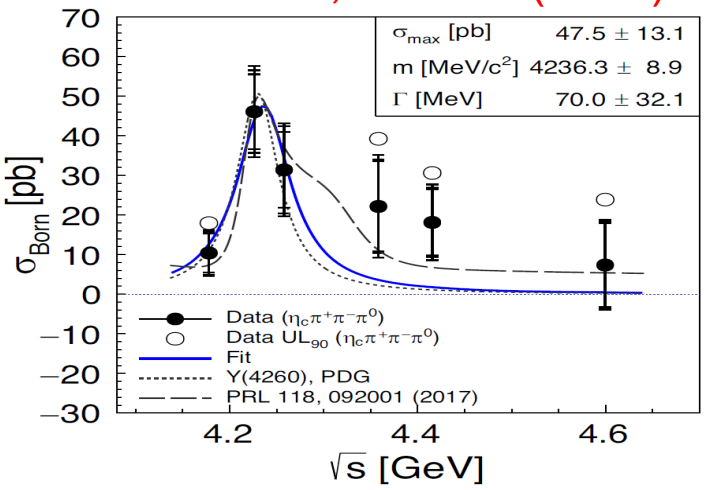
PRL118, 092002 (2017)



PRL122, 102002 (2019)



PRD 103, 032006 (2021)



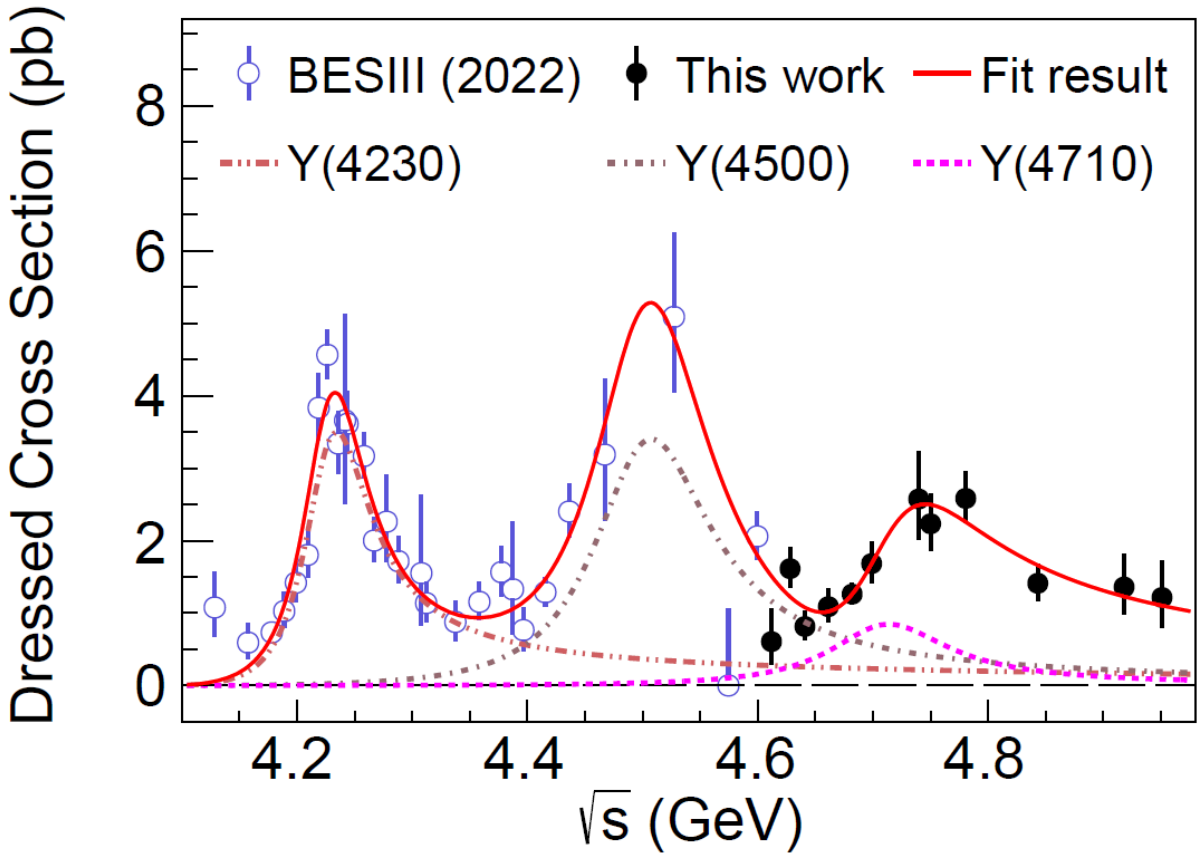
Y(4230) [ψ(4230) in PDG] appears in $\omega\chi_{c0}$, $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^- h_c$, $D^0 D^{*-}\pi^+$, $\eta_c\pi^+\pi\pi^0$, $K^+K^- J/\psi$, ...

Mass~4220 MeV, width~ 50 MeV!

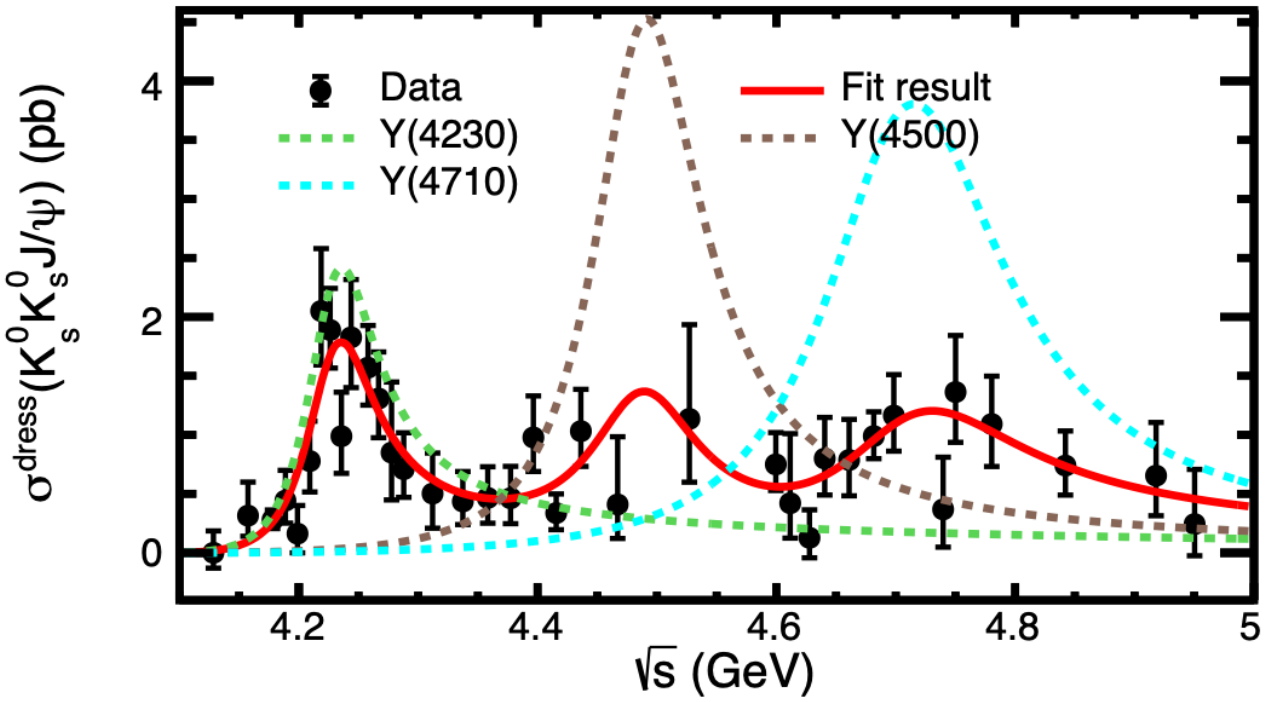
Observation of two new vectors Y(4500) & Y(4710) in KKJ/ψ

CPC46, 111002 (2022) & PRL131, 211902 (2023) & PRD107, 092005 (2023)

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



$e^+e^- \to K_SK_SJ/\psi$

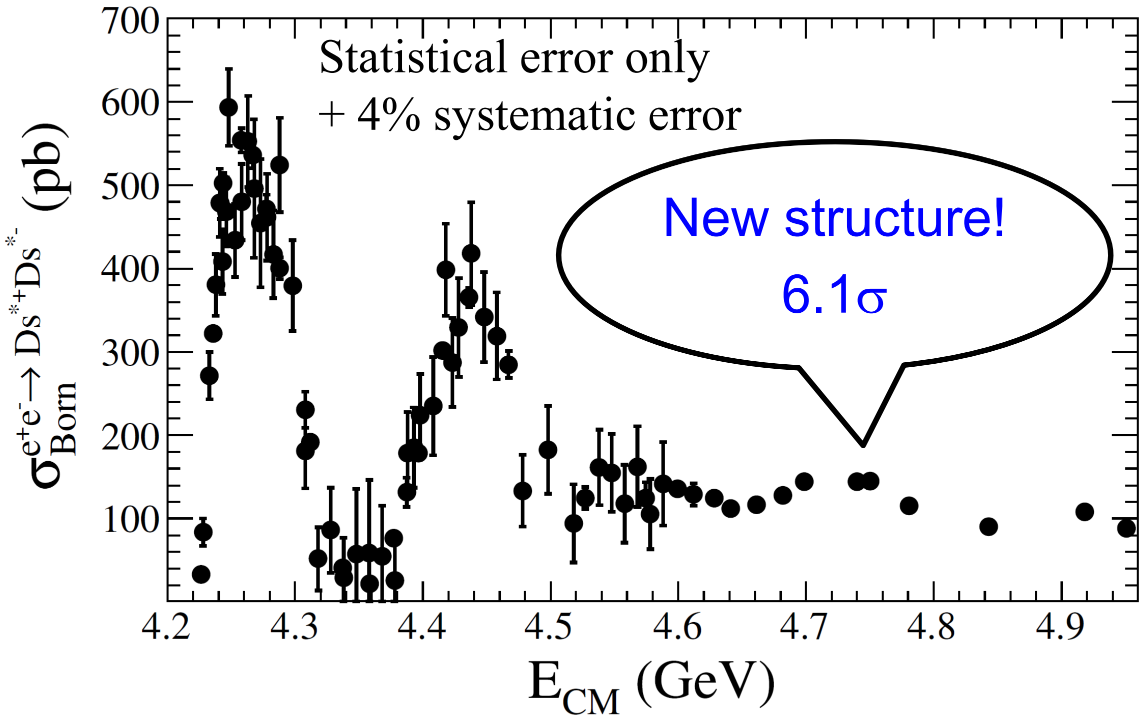


- ✓ Significance of the Y(4500) > 8σ
- ✓ Significance of the Y(4710) > 5σ

resonance	mass (MeV)	width (MeV)
Y(4500)	$4485\pm13\pm24$	$111\pm30\pm15$
Y(4710)	$4708^{+17}_{-15}\pm21$	$126^{+27}_{-23}\pm30$

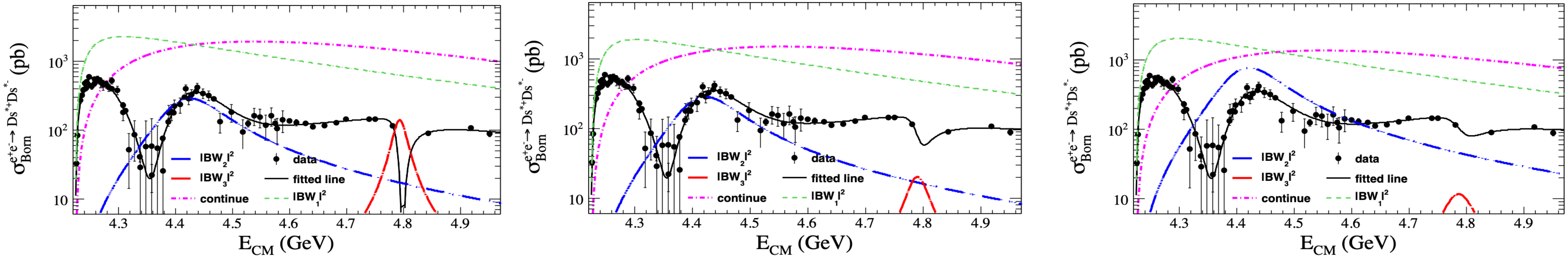
A new vector charmoniumlike state Y(4790) in $e^+e^- \to D_s^{*+} D_s^{*-}$?

arXiv: 2305.10789, PRL 131, 151903 (2023)



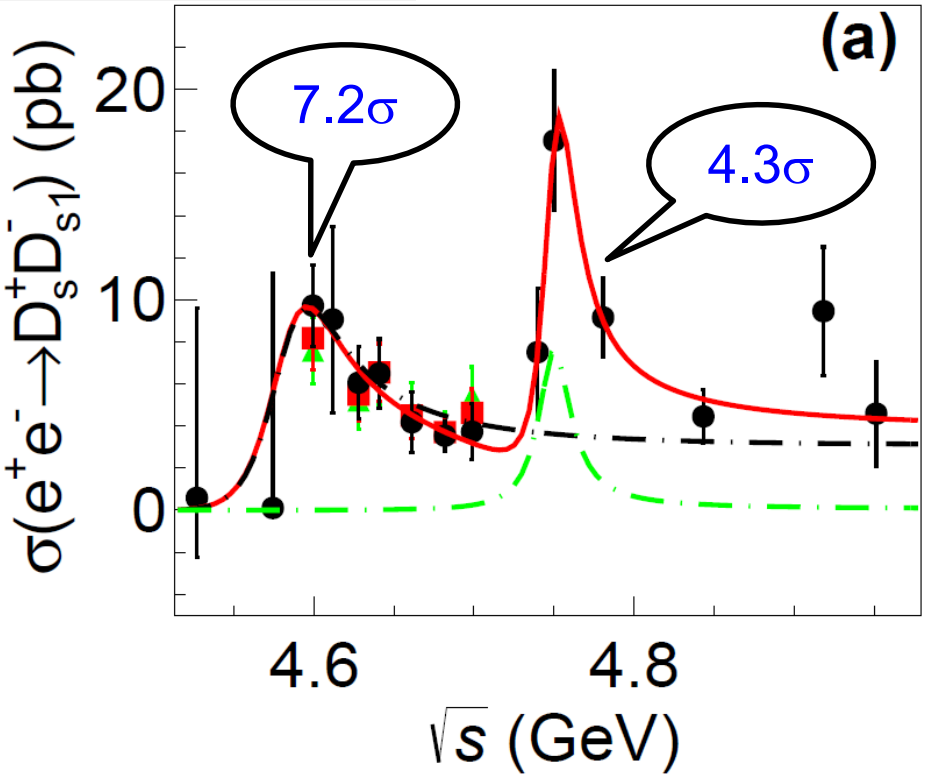
- The peak position depends on the parametrization of the background amplitudes.
- Data at around 4.8 GeV are needed to understand the line shape.
- Could it be the Y(4710) in KKJ/ψ?

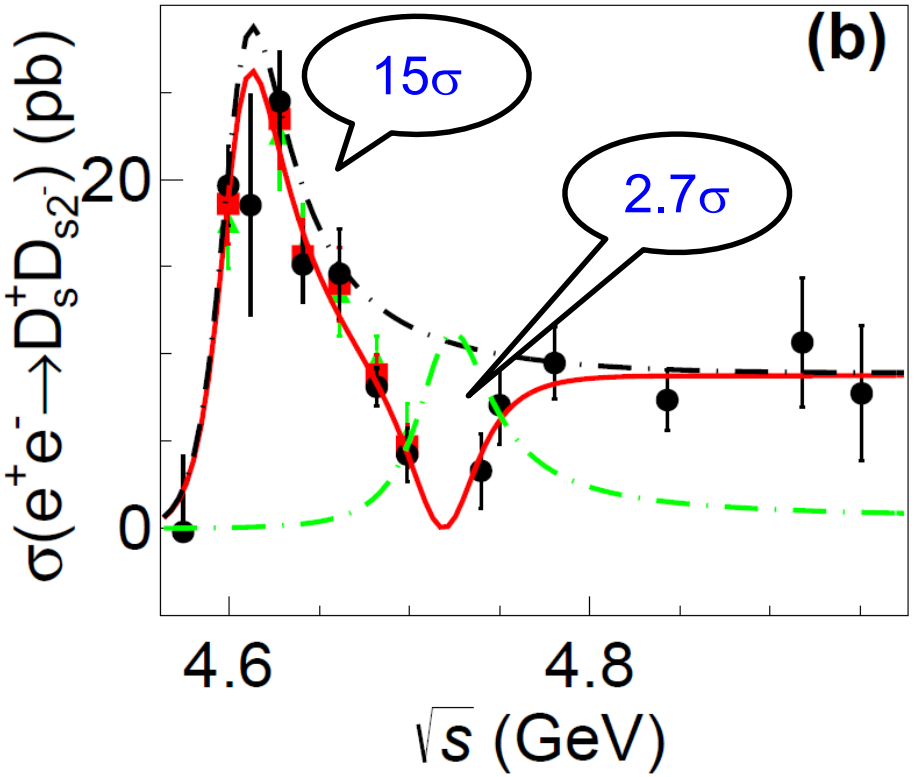
	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.5±9.0	4193.8±7.5	4195.3±7.5
Γ_1 (MeV)	55±17	61.2±9.0	61.8±9.0
M_2 (MeV/c^2)	4414.5±3.2	4412.8±3.2	4411.0±3.2
Γ_2 (MeV)	122.6±7.0	120.3±7.0	120.0±7.0
M_3 (MeV/c^2)	4793.3±7.5	4789.8±9.0	4786±10
Γ_3 (MeV)	27.1±7.0	41±39	60±35



Two new vector structures in $e^+e^- \to D_s^+ D_{s1}^-$ and $D_s^+ D_{s2}^{*-}$?

arXiv: 2407.07651, PRL (in press)



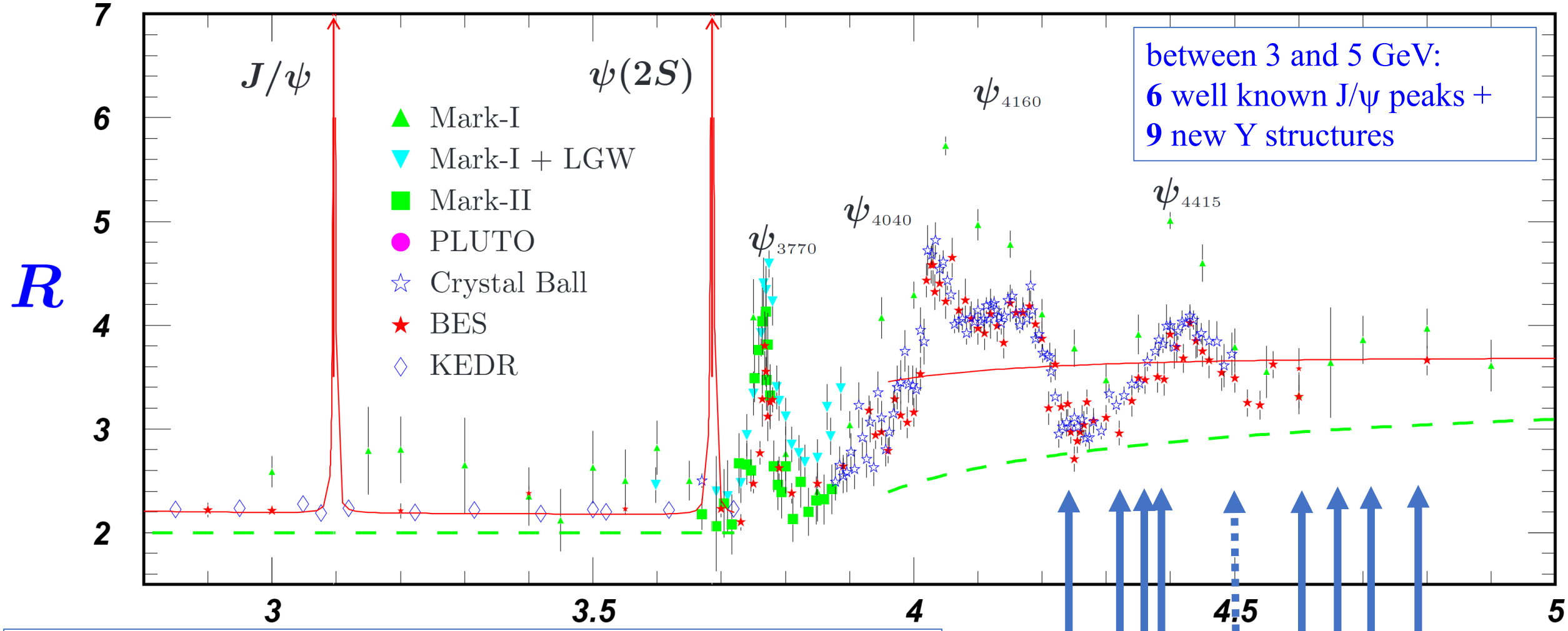


resonance	mass (MeV)	width (MeV)
R1	4584±14±80	57±12±219
R2	4750±8±6	25±8±1

resonance	mass (MeV)	width (MeV)
R1	4603±4±1	45±6±1
R2	4720±13±2	50±12±1

- Could the low mass structure be the Y(4630)?
- Could the high mass structure be the Y(4710) in KKJ/ψ or Y(4790) in $D_s^{*+} D_s^{*-}$?

Supernumerary vectors may suggest exotic states!



between 3 and 5 GeV:
6 well known J/ψ peaks +
9 new Y structures

Y(4230), Y(4320),
Y(4360), Y(4390)

Y(4500)

Y(4630), Y(4660),
Y(4710), Y(4790)

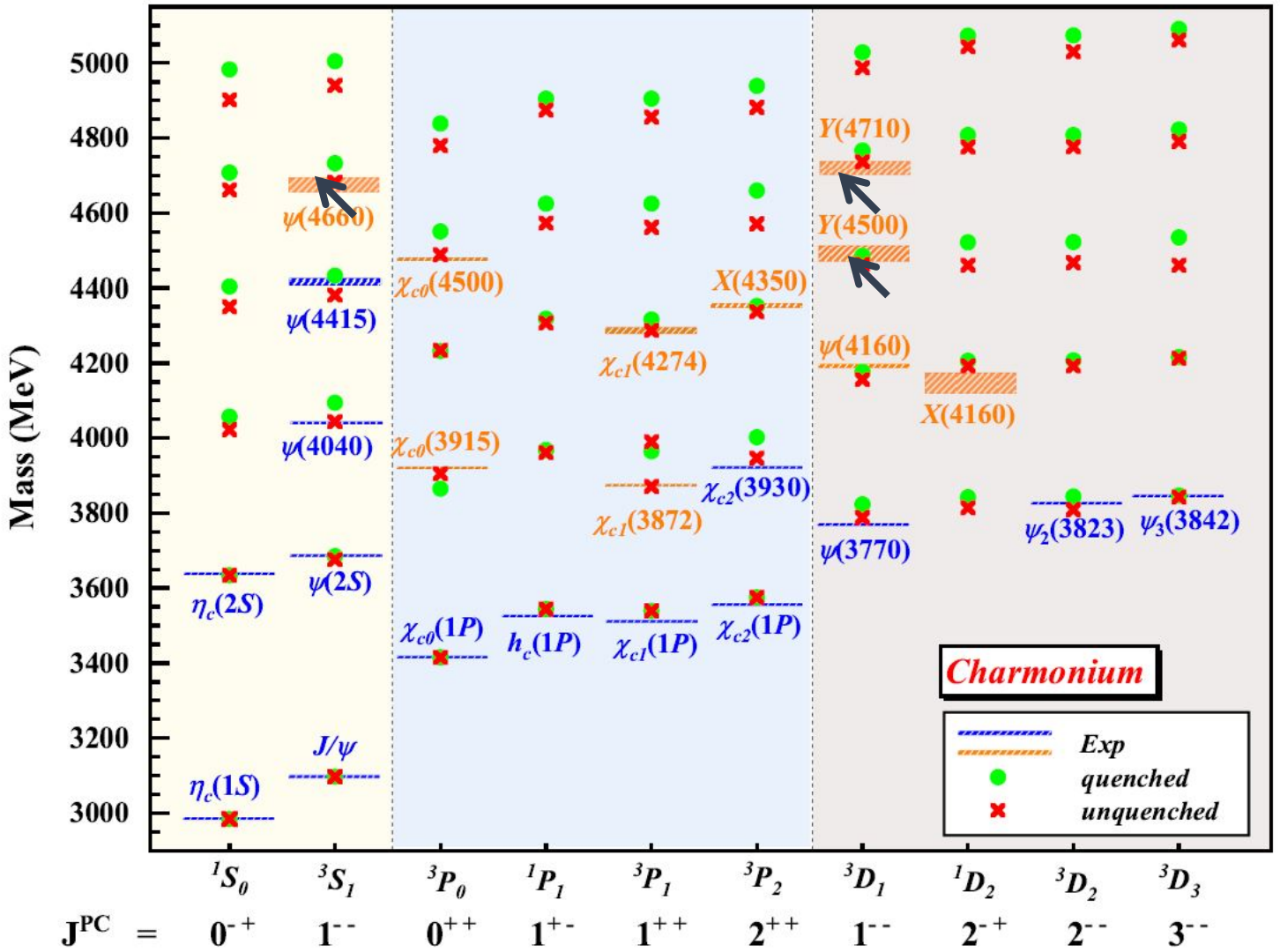
Besides vector charmonium ($c\bar{c}$) states, we also expect $c\bar{c}g$ hybrids, and $c\bar{c}q\bar{q}$ tetraquark states. Have they already been observed?

➔ More theoretical/experimental efforts necessary!

A potential model solution of the charmonium states

Qian Deng, Ru-Hui Ni, Qi Li, Xian-Hui Zhong, arXiv:2312.10296

"Charmonia in an unquenched quark model"



3 states assigned as S- and D-wave charmonium states.

No places for the

Y(4230)

Y(4320)

Y(4360)

Y(4390)

Y(4630)

Y(4790)

Sophisticated theoretical calculations/models are necessary!

N. Husken, et al., PRD109, 114010 (2024)

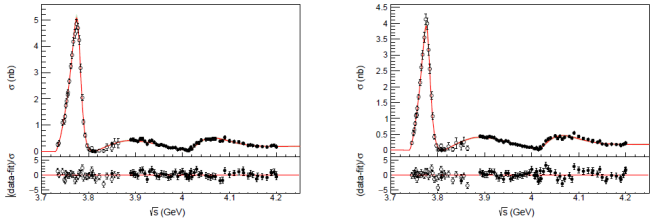


FIG. 2. Fit result for Model 1. Left: $e^+e^- \to D^0\bar{D}^0$. Right: $e^+e^- \to D^+D^-$. Open data points are the Born cross section values based on observed cross sections, as reported in Ref. [18]; closed data points are from Ref. [1].

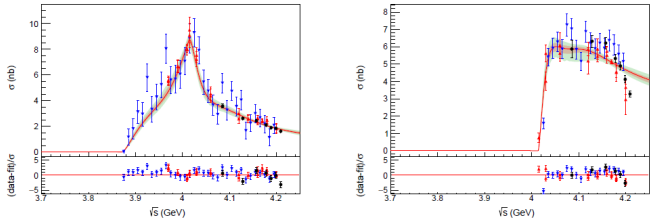


FIG. 3. Fit result for Model 1. Left: $e^+e^- \to D^*\bar{D}$. Right: $e^+e^- \to D^*\bar{D}^*$. The red region indicates the 68% confidence level, while green is the 90% confidence level. Black data points are from BESIII [21], red data is from CLEO-c [23, 24], blue data is from Belle [22].

S. G. Salnikov & A. I. Milstein, PRD109, 114015 (2024)

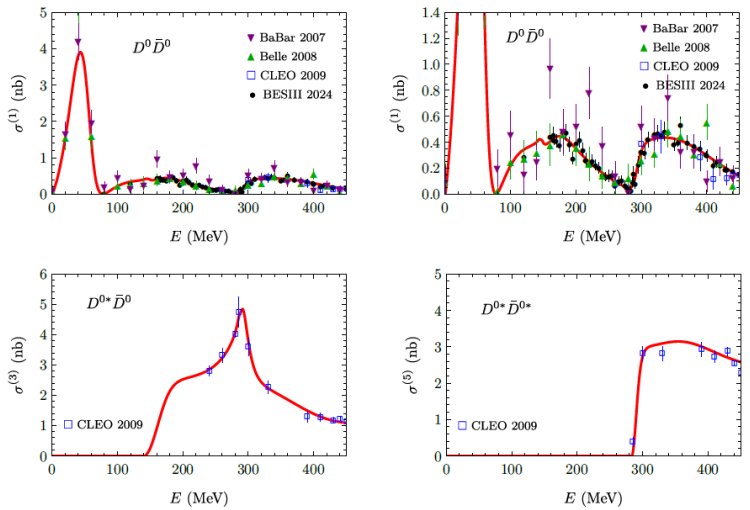


FIG. 1. Energy dependence of the cross sections for the production of neutral particles. Experimental data are taken from Refs. [32, 34–36, 39].

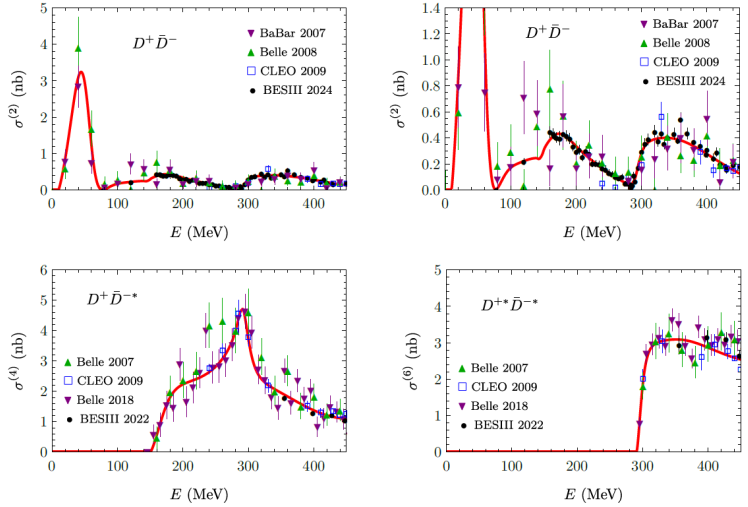
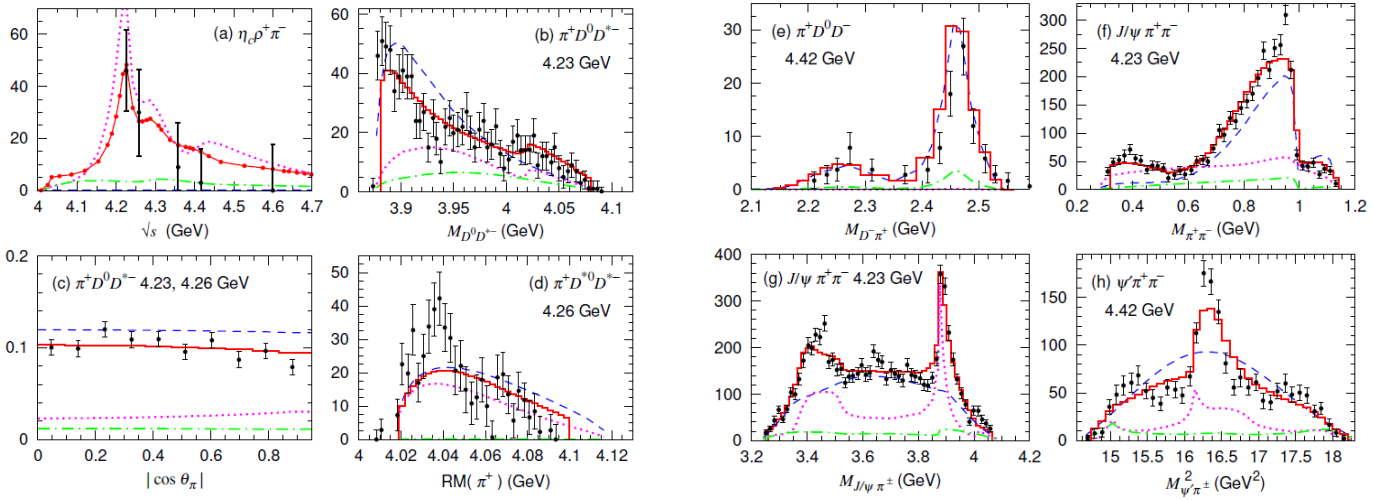
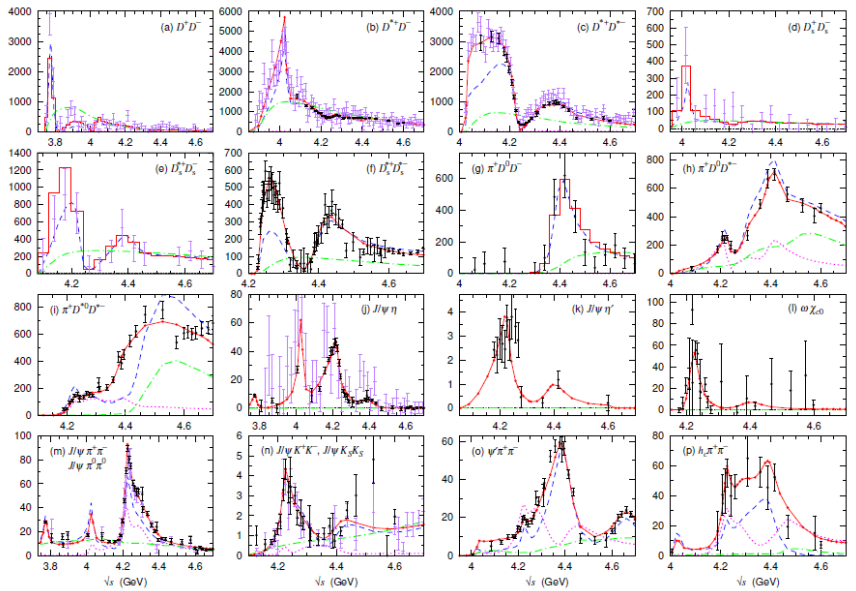


FIG. 2. Energy dependence of the cross sections for production of charged particles. Experimental data are taken from Refs. [32–39].

S. X. Nakamura, et al., arXiv:2312.17658





Summary

- BESIII made significant contribution to the study of exotic states with a pair of charmed quark and antiquark
- BESIII discovered Zc & Zcs tetraquark states
- BESIII observed supernumerary vector states, some of them must be exotic states
- More data will be accumulated for the study of the XYZ particles, more results will come from BESIII

Thank you very much!

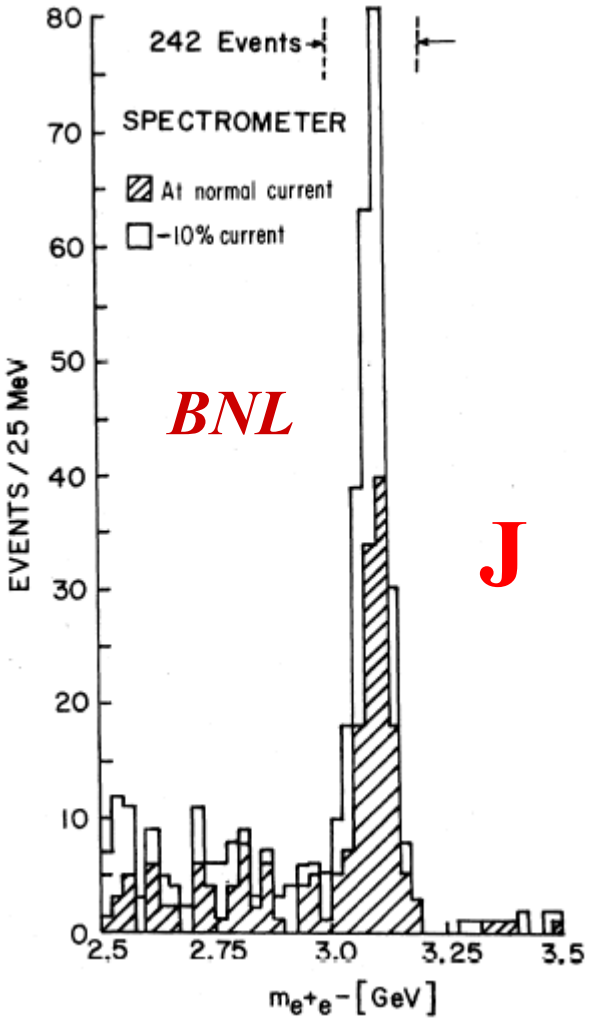
Thank you very much!

谢谢！

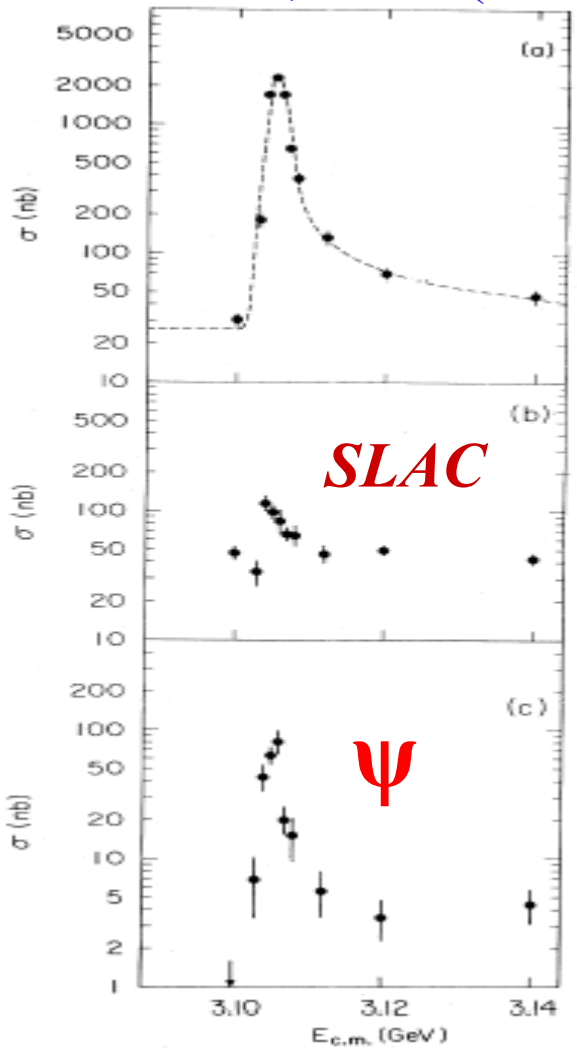
Discovery of charm quark and the 1st charmonium state

"November Revolution of Particle Physics!"

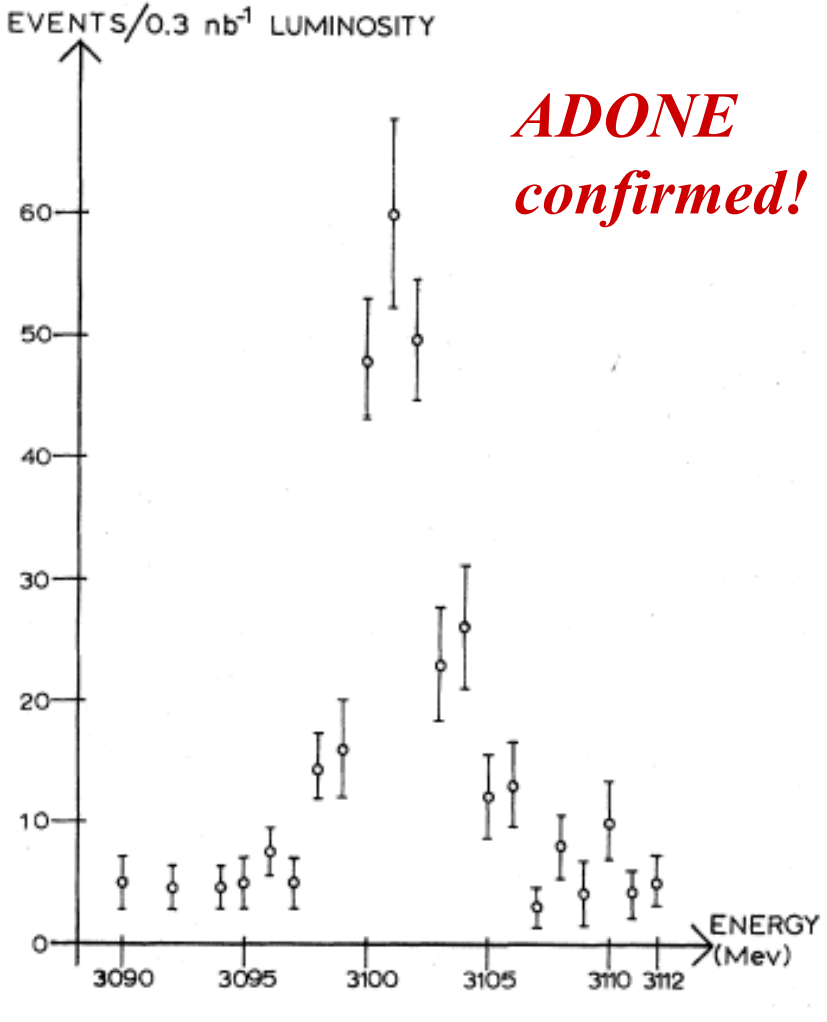
PRL33, 1404 (1974)



PRL33, 1406 (1974)

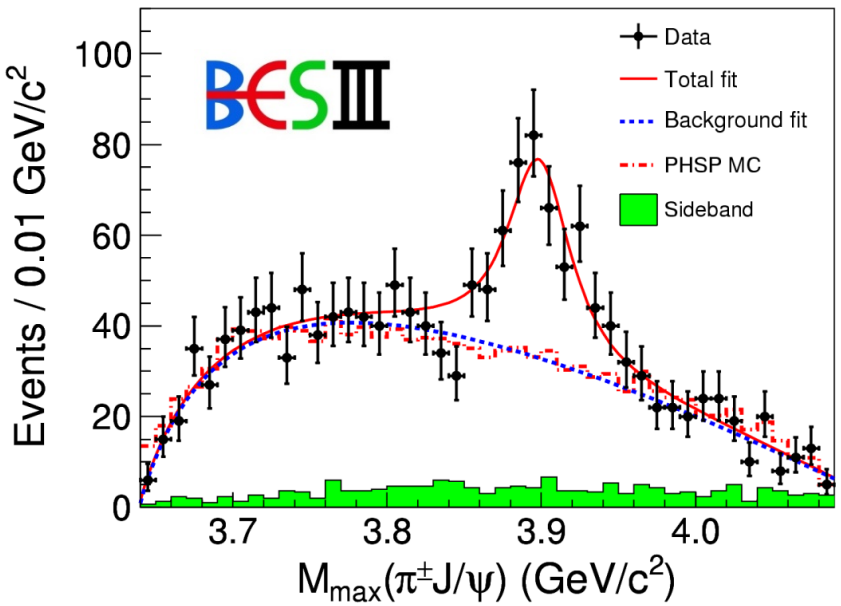


PRL33, 1408 (1974)



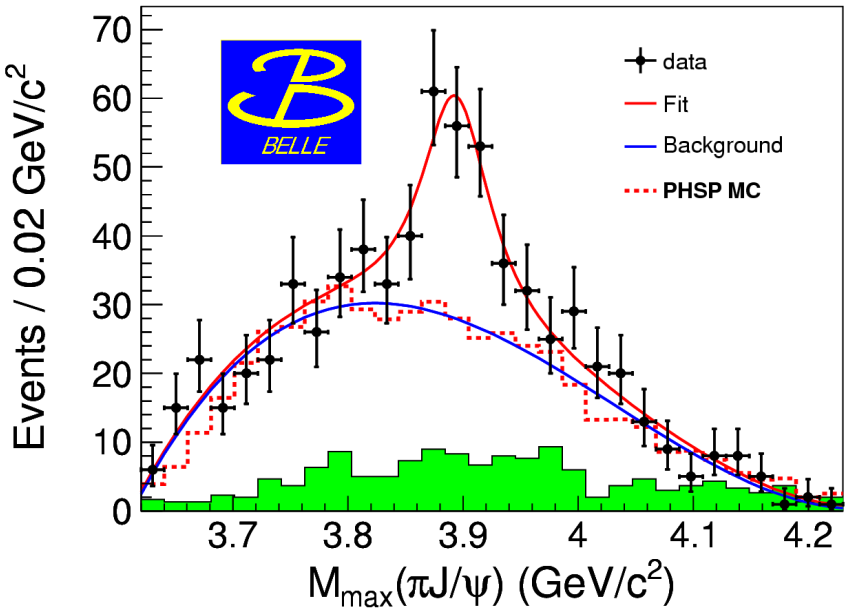
$Z_c(3900)$ observed in **3** experiments!

BESIII at 4.26 GeV: PRL110, 252001



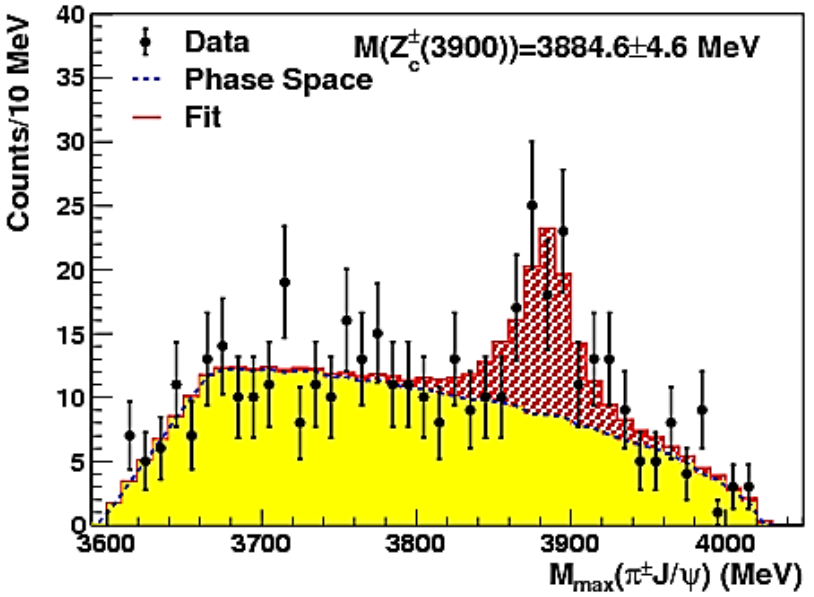
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

Belle with ISR: PRL110, 252002



- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

CLEOc data at 4.17 GeV: 1304.3036

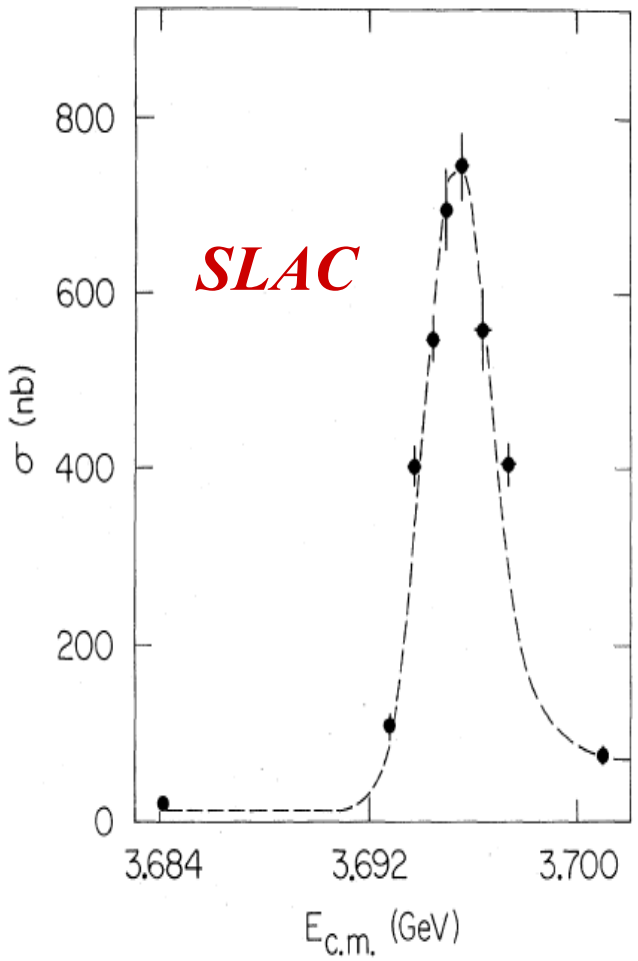


- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ

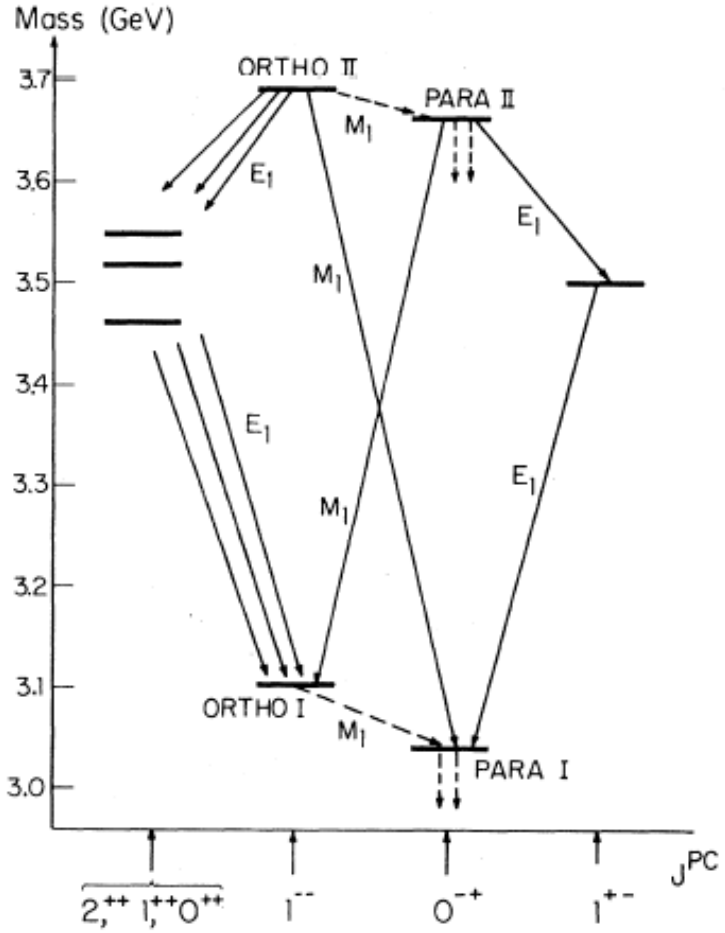
Zc(3900) is the first confirmed tetraquark state!

charmonium spectroscopy & charmonium physics

PRL33, 1453 (1974)



T. Appelquist, A. De Rujula,
H. D. Politzer, S. L. Glashow,
PRL34, 365 (1975)



E. Eichten, K. Gottfried, T. Kinoshita,
J. B. Kogut, K .D. Lane,
PRL 34, 369 (1975)