

XYZ States at BESIII

Leonard Koch
on behalf of the BESIII collaboration

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XIIIth Quark Confinement and the Hadron Spectrum / Maynooth, Ireland / August 1st – 6th 2018

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Y States at BESIII

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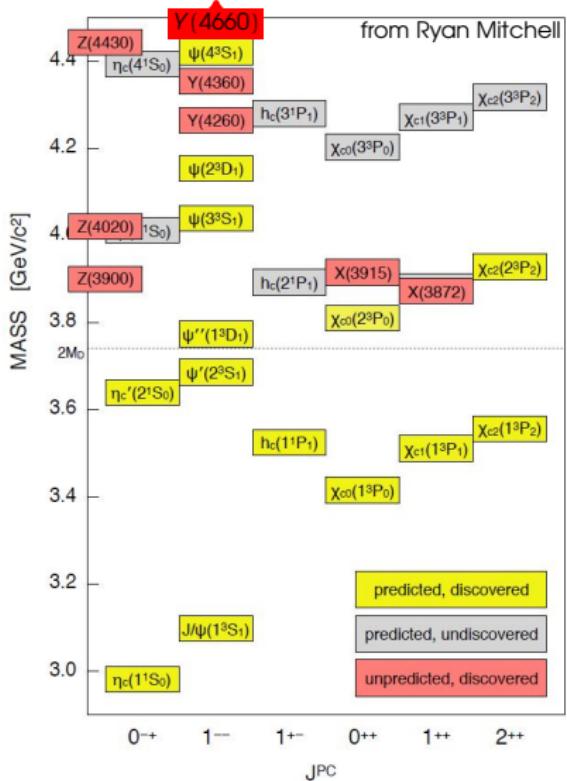
Outline

- 1 Introduction to XYZ States
- 2 The BESIII Experiment at IHEP (Beijing)
- 3 Y States

Section 1

Introduction to XYZ States

What are XYZ States?



Below open charm threshold

- Good agreement between prediction and observation

Above open charm threshold

- Expected states missing
- Unexpected states observed (\rightarrow XYZ States)

X Neutral, other than 1^{--}

Y Neutral, 1^{--}

Z Charged

Possible Explanations

- **Tetraquark:** Compact four quark state made from colored (Qq) and ($\bar{Q}\bar{q}$)
- **Hybrid:** $Q\bar{Q}$ with excited gluon
- **Hadro-Quarkonium:** $Q\bar{Q}$ in cloud of light quarks
- **Glueball:** State only from gluons
- **Meson-Molecule:** Two mesons bound by residual forces (($Q\bar{q}$) and ($\bar{Q}q$))
- **Threshold Effect**
- ... Any new ideas?

Possible Explanations

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

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 $n_L - n_{\bar{L}}$ 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 $u^{\frac{1}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 5) and the members of the anti-triplet as anti-quarks \bar{q} . Baryons can now be constructed from quarks by using the combinations (qqq) , $(qqqq)$, etc., while mesons are made out of $(q\bar{q})$, $(q\bar{q}q)$, etc. It is assuming that the lowest baryon configuration (ttt) 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.

Section 2

The BESIII Experiment at IHEP (Beijing)

The BESIII Experiment

First physics run starts from 2009!

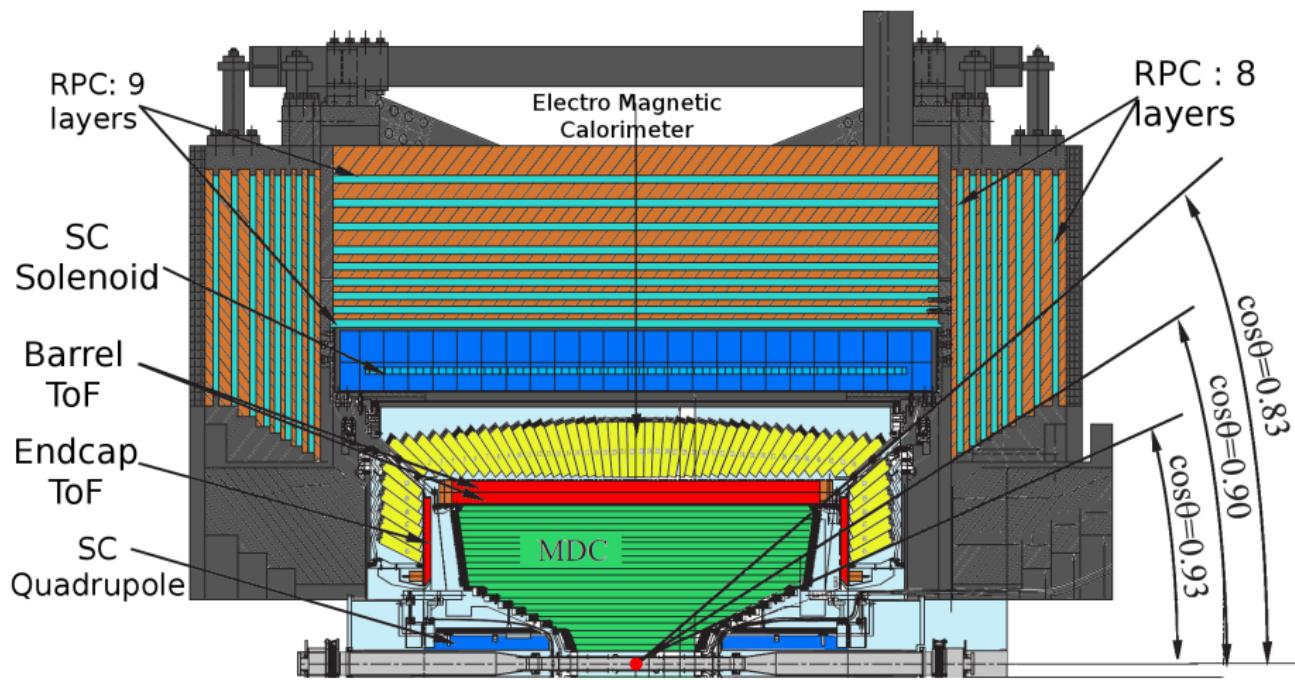
BESIII

Linac

3D Cutaway Diagram of the BESIII Detector

- Founded: 1984, Ecm=2-4.6 GeV
- 1989-2005 (BEPC):
 $L_{peak}=1.0 \times 10^{31} /cm^2s$
- 2008-now (BEPCII):
 $L_{peak}=1.0 \times 10^{33}/cm^2s$
(Apr. 5, 2016)

The BESIII Detector

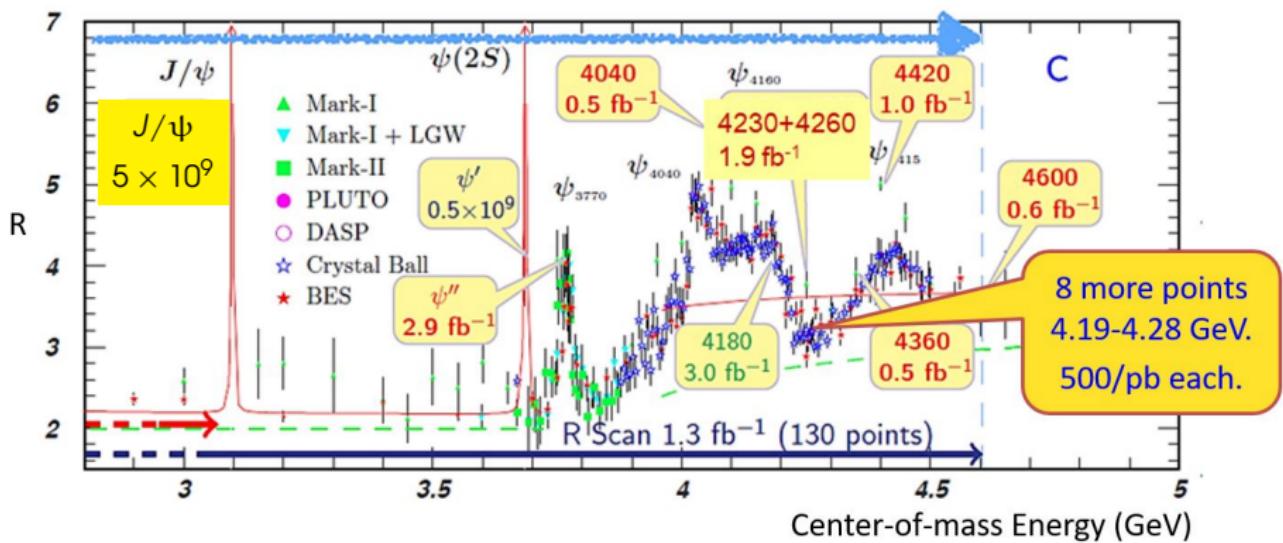


The BESIII Collaboration

Political Map of the World, June 1999



Data Sets at BESIII



$\approx 8 \text{ fb}^{-1}$ above 4 GeV

XYZ States
○○○

BESIII
○○○○○

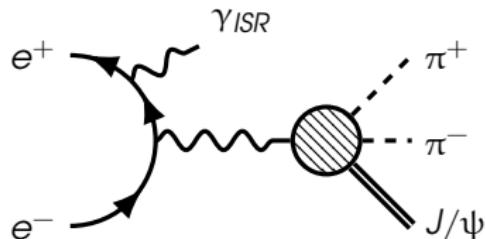
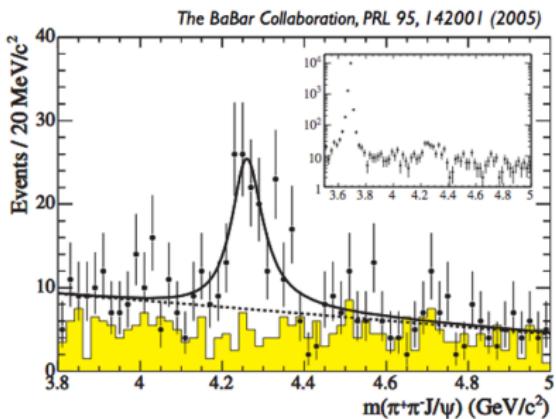
Y States
●○○○○○○○○○

Section 3

Y States

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ Cross Section (1)

$Y(4260)$ discovered by BaBar (PRL 95, 142001 (2005))

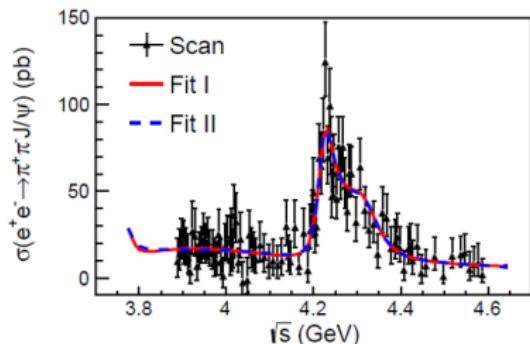
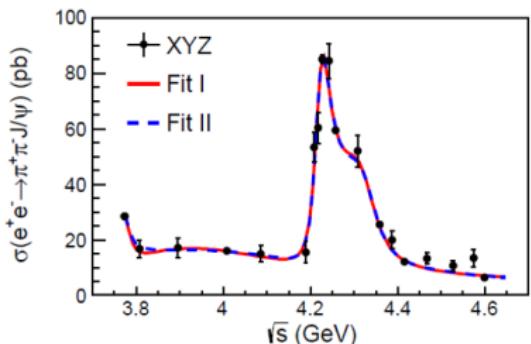


$$e^+e^- \rightarrow \gamma_{ISR} \underbrace{\pi^+\pi^- J/\psi}_{Y(4260)}$$

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

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ Cross Section (2)

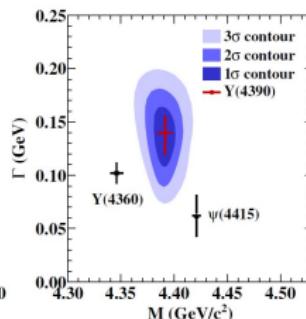
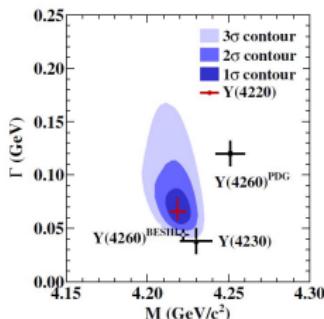
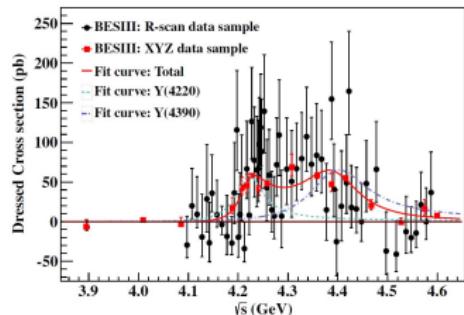
BESIII: Two resonances! (PRL 118, 092001 (2017))



- Coherent sum of two BWs + incoherent $\psi(3770)$
 - Fit I: + coherent 3rd BW, Fit II: + exponential
- $M_1 = (4222.0 \pm 3.1 \pm 1.4)$ MeV, $\Gamma_1 = (44.1 \pm 4.3 \pm 2.0)$ MeV
 - lower and narrower than previous $Y(4260)$ PDG value
- $M_2 = (4320.0 \pm 10.4 \pm 7.0)$ MeV, $\Gamma_2 = (101.4^{+25.3}_{-19.7} \pm 10.2)$ MeV
 - a little bit lower than $Y(4360)$ PDG value
- Significance of double BW vs. single BW $> 7.6\sigma$

$e^+e^- \rightarrow \pi^+\pi^- h_c$ Cross Section

PRL 118, 092002 (2017)

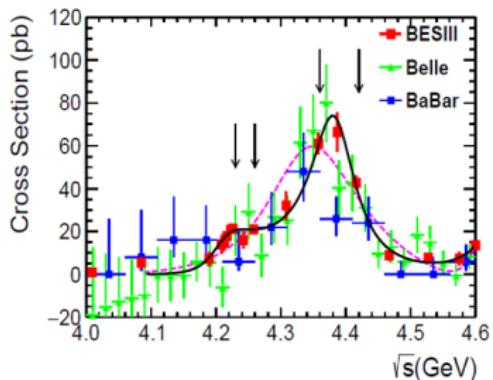


- h_c reconstructed in $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow 16$ exclusive hadronic final states
- Coherent sum of two BWs
 - $M_1 = (4218.4^{+5.5}_{-4.5} \pm 0.9) \text{ MeV}$, $\Gamma_1 = (66.0^{+12.3}_{-8.3} \pm 0.4) \text{ MeV}$
 - $M_2 = (4391.5^{+6.3}_{-6.8} \pm 1.0) \text{ MeV}$, $\Gamma_2 = (139.5^{+16.2}_{-20.6} \pm 0.6) \text{ MeV}$
- First one has consistent mass with $\pi^+\pi^- J/\psi$ state at 4222 MeV
- Significance of double BW vs. single BW is 10σ

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

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

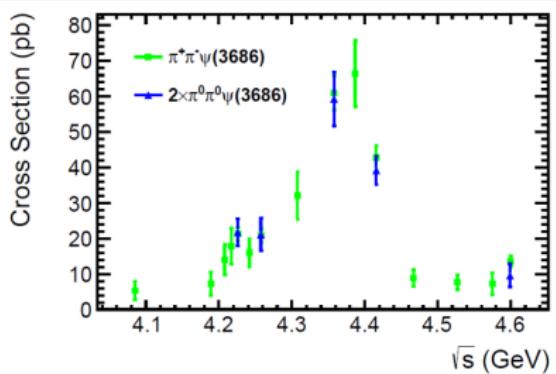
PRD 96, 032004 (2017)



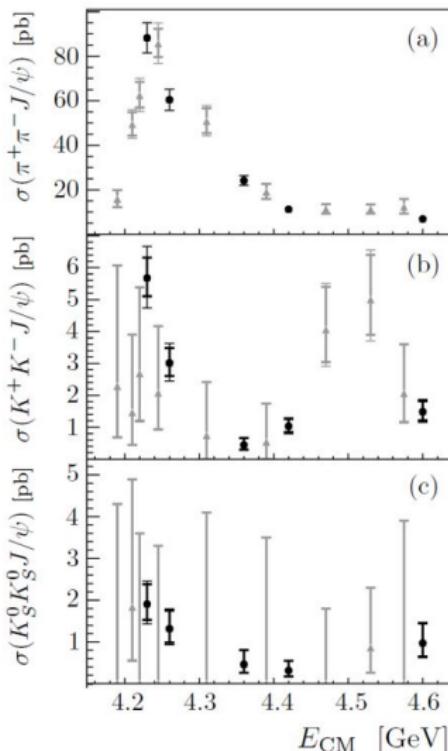
- Clear peak around $Y(4360)$, consistent with results from Belle and BaBar
 - Fit with three resonances: $Y(4220)$, $Y(4390)$, $Y(4660)$
 - $Y(4220)$ significance is 5.8σ

$$e^+ e^- \rightarrow \pi^0 \pi^0 \psi'$$

PRD 97, 052001 (2018)



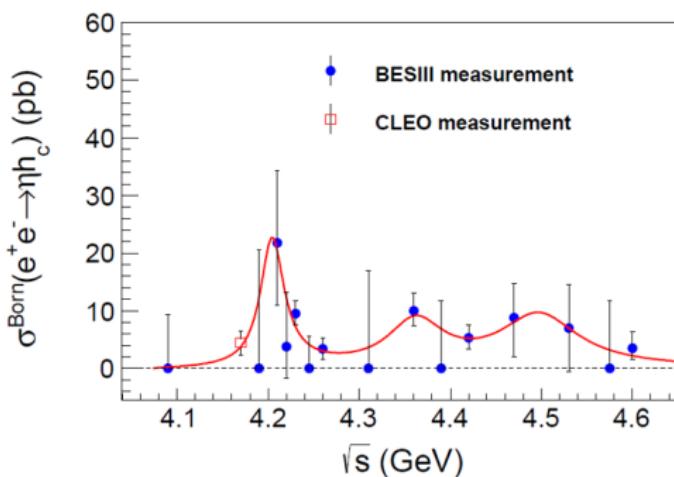
- Cross section consistent with isospin expectations from $\pi^+\pi^-\psi'$

$e^+e^- \rightarrow KKJ/\psi$ Cross Section

black: high statistics data
gray: low statistics data

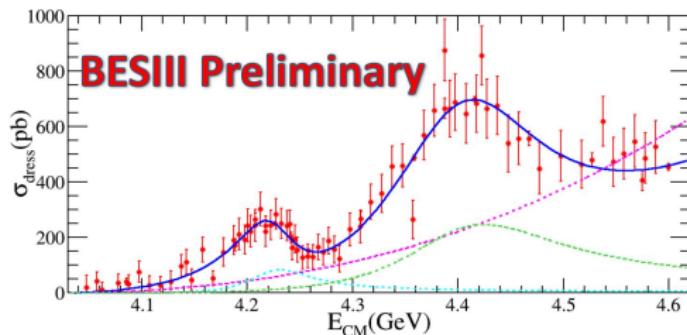
PRD **97**, 071101(R) (2018)

- Different lineshape than $\pi^+\pi^- J/\psi$
- Evidence for a structure around 4.5 GeV
- Charged and neutral mode consistent with isospin expectations

$e^+e^- \rightarrow \eta h_c$ Cross SectionPRD **96**, 012001 (2017)

- h_c reconstructed in $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow$ 16 exclusive hadronic final states

- Clear signals at 4.226 GeV and evidence at 4.358 GeV
- Fit with three BWs only for calculation of radiative correction factors

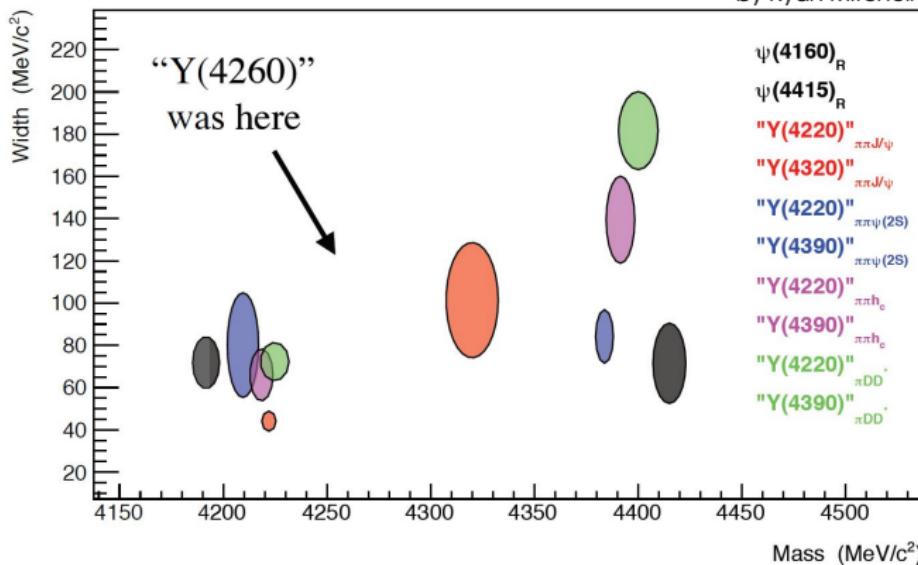
$e^+e^- \rightarrow \pi^+ D^0 D^{*-} + \text{c.c.}$ Cross Section

- Fit with three-body phase space and two BWs hadronic final states

- $M_1 = (4228.6 \pm 4.1 \pm 5.0) \text{ MeV}$,
 $\Gamma_1 = (77.1 \pm 6.8 \pm 2.7) \text{ MeV}$
- $M_1 = (4404.6 \pm 7.4 \pm 4.8) \text{ MeV}$, $\Gamma_1 = (192 \pm 13 \pm 15) \text{ MeV}$
- Both masses consistent with those in $\pi^+\pi^- h_c$ and $\pi^+\pi^- \psi'$

"Y(4260)" in the Light of High Luminosity Measurements

by Ryan Mitchell



Conclusion

Summary

- Lots of progress in exotic charmonium-like studies
- Many cross section lineshapes measured
- $Y(4260) \rightarrow Y(4220)$, seen in many final states

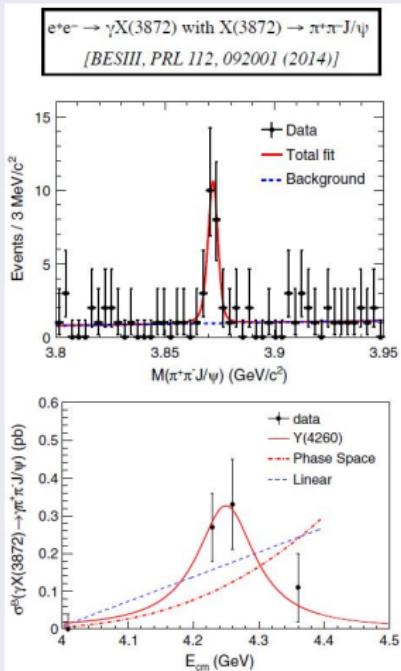
Outlook

- More data expected within next few years (high statistics scan between ≈ 4.2 and ≈ 4.4 GeV)
- Machine upgrade approved (\sqrt{s} up to 4.9 GeV + top up injection)

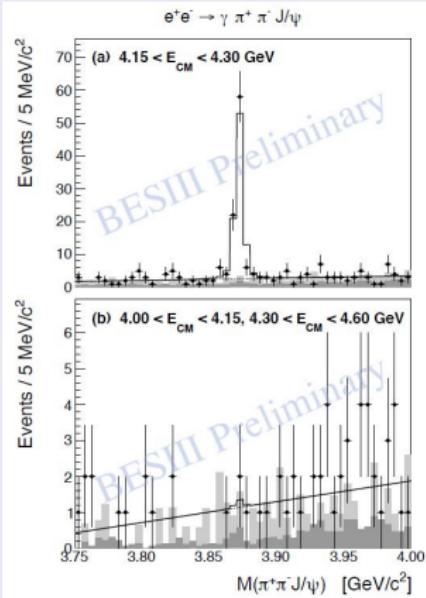
Thank You!

$X(3872)$ at BESIII

2014



2018



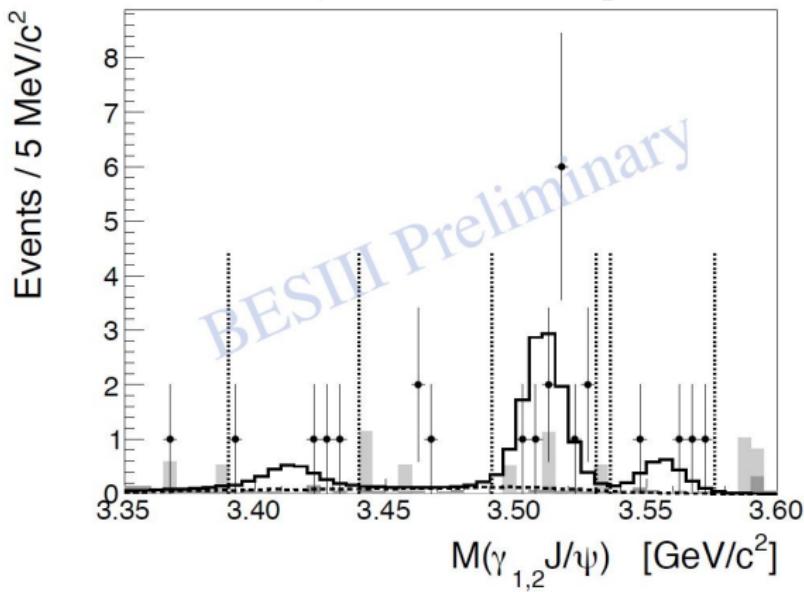
Search for $X(3872) \rightarrow \pi^0 \chi_{cJ} (1)$

$$e^+ e^- \longrightarrow \gamma_1 X(3872)$$

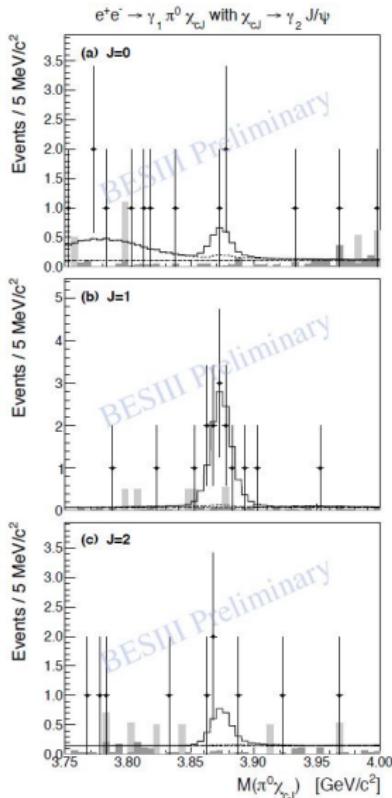
$$e^+ e^- \rightarrow \gamma_1 \pi^0 \chi_{cJ} \text{ with } \chi_{cJ} \rightarrow \gamma_2 J/\psi$$

$$\longrightarrow \pi^0 \chi_{cJ}$$

$$\longrightarrow \gamma_2 J/\psi$$



Search for $X(3872) \rightarrow \pi^0 \chi_{cJ}$ (2)



Fit to $mass(\pi^0 \chi_{cJ})$:

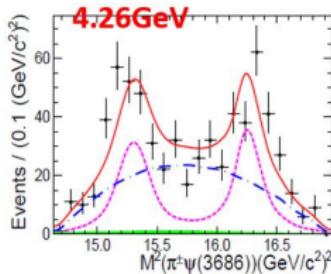
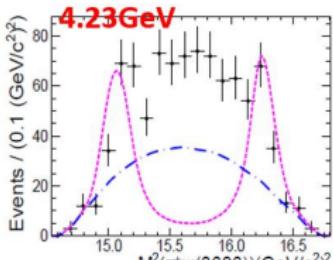
- $J = 0, 2$: no evidence
- $J = 1$: 5.2σ

Define

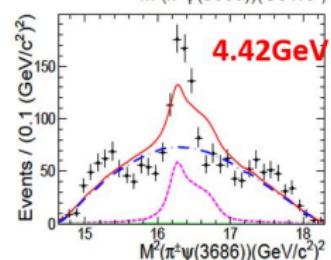
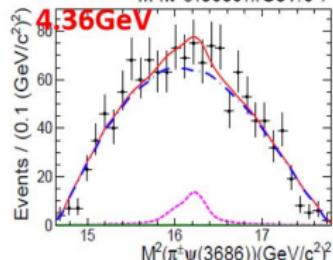
$$R_J = \mathcal{B}(X \rightarrow \pi^0 \chi_{cJ}) / \mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi)$$

- $R_0 < 19$ (90 % C.L.)
- $R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14$
- $R_2 < 1.0$ (90 % C.L.)

Charged Structure in $\pi^+\psi'$



Different structures
at different energy
points.



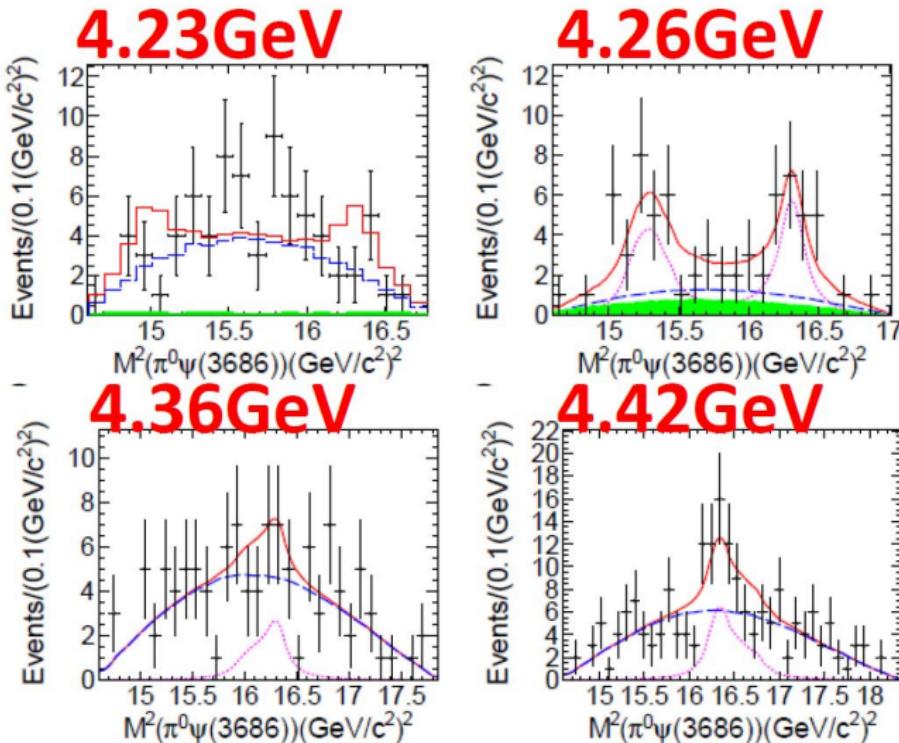
Structure @4.42 GeV
Significance of 9.2σ
 $M=4032.1 \pm 2.4\text{MeV}$
 $\Gamma = 26.1 \pm 5.3\text{MeV}$

New Zc? Need more
Investigation!!!

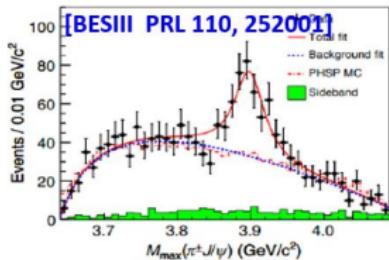
Discrepancies between the fit model and data!

PRD 96, 032004 (2017)

Structure in $\pi^0\psi'$, PRD **97**, 052001 (2018)



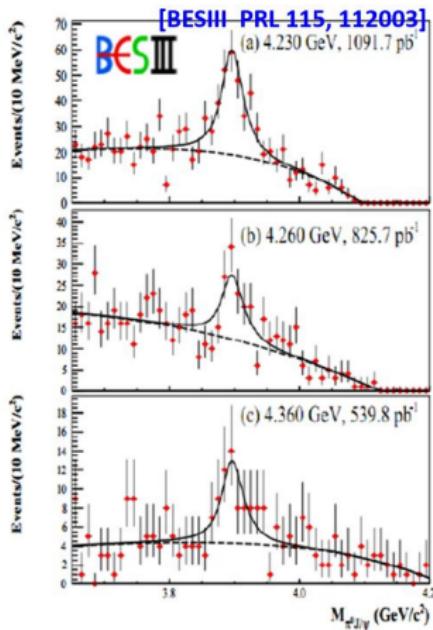
$Z_c(3900)$ in $\pi J/\psi$



- $Z_c(3900)^\pm$, BESIII, Belle, CLEOc data, in 2013
- $Z_c(3900)^0$, evidence with 3.7σ by CLEOc, observed with $>10\sigma$ by BESIII

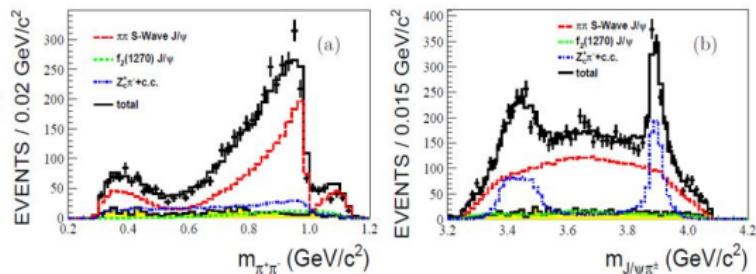
$Z_c(3900)$	Mass(MeV)	Width(MeV)
$Z_c(3900)^\pm$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$

An iso-spin triplet established!

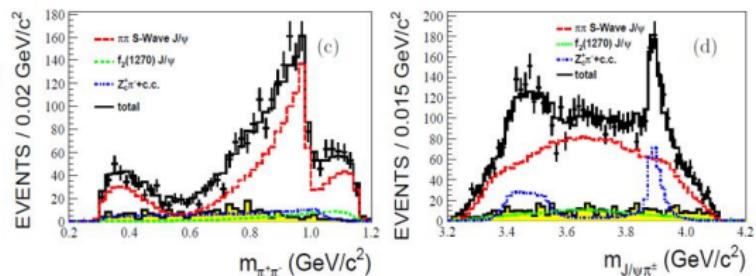


Quantum Numbers of $Z_c^\pm(3900)$

4.23GeV



4.26GeV



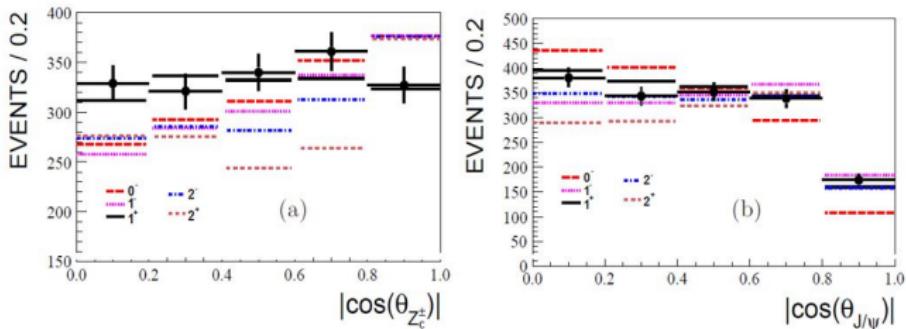
Amplitude analysis with helicity formalism

Simultaneous fit to data samples at 4.23 GeV and 4.26 GeV

$\pi\pi$ spectrum parameterized by σ , $f_0(980)$, $f_2(1270)$, $f_3(1370)$,

PRL 119, 072001 (2017)

Quantum Numbers of $Z_c^\pm(3900)$



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

J^P of Z_c favor 1^+ with statistical significance larger than 7σ over other quantum numbers.

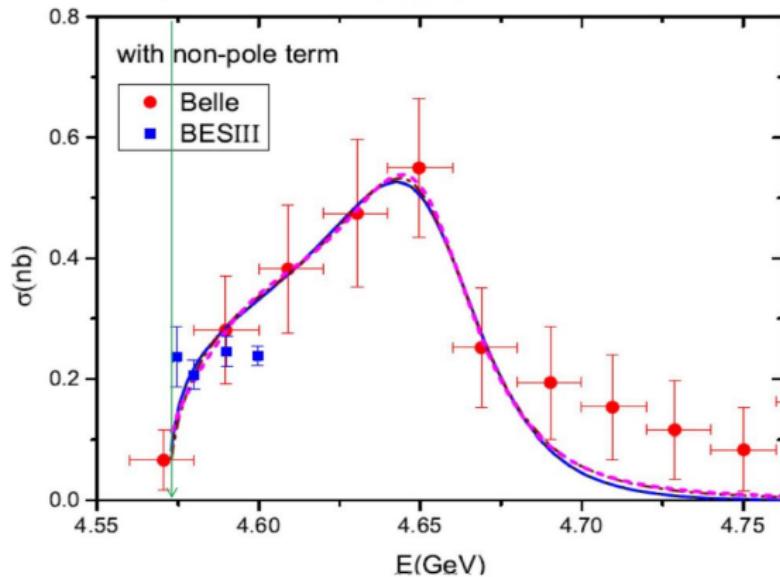
$$M_{\text{pole}} = (3881.2 \pm 4.2_{\text{stat}} \pm 52.7_{\text{syst}}) \text{ MeV}/c^2$$

$$\Gamma_{\text{pole}} = (51.8 \pm 4.6_{\text{stat}} \pm 36.0_{\text{syst}}) \text{ MeV}$$

PRL 119, 072001 (2017)

$e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$

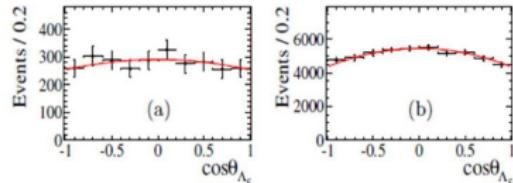
Belle G. Pakhlova *et al.* [Belle Collaboration], Phys. Rev. Lett. 101, 172001 (2008).
BESIII Ablikim *et al.*, arXiv:1710.00150 [hep-ex].



$$e^+ e^- \rightarrow \Lambda_c \bar{\Lambda}_c$$

- The BESIII measurements indicate that:
 - At thr there is indeed a jump in $\sigma(e^+ e^- \rightarrow \Lambda_c \bar{\Lambda}_{c\bar{b}ar})$,
 - Followed by a kind of a plateau
 - At thr $\sigma(e^+ e^- \rightarrow \Lambda_c \bar{\Lambda}_{c\bar{b}ar})$ is close to the pointlike value, once the Coulomb enhancement factor is taken into account:
$$\sigma(e^+ e^- \rightarrow \Lambda_c \bar{\Lambda}_{c\bar{b}ar})_{pointl} \approx \pi^2 \alpha^3 / (2M_B) \approx 145 \text{ pb}$$
 - Qualitatively, If $\sigma(e^+ e^- \rightarrow BB_{bar})$ would be driven by strong interaction, [asymptotically scaling as $(M_p / M_{\Lambda_c})^{10}$] a quite smaller value (< 1 fb) would be expected
[$\sigma(e^+ e^- \rightarrow pp_{bar}) \approx 0.85 \text{ nb}$, at thr].

$$e^+ e^- \rightarrow \Lambda_c \bar{\Lambda}_c$$

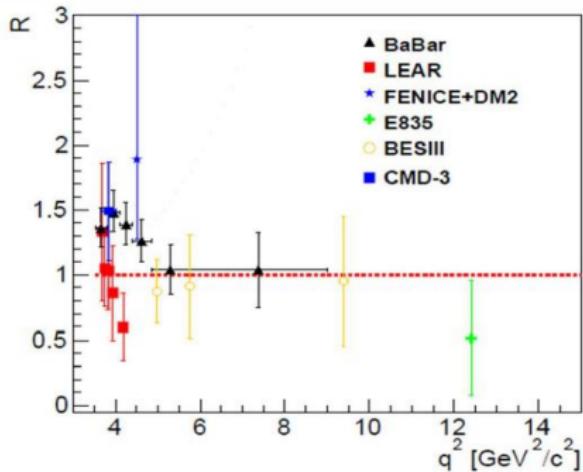


Angular distribution after efficiency correction and results of the fit to data at $\sqrt{s} = 4574.5$ MeV (a) and 4599.5 MeV (b).

- The angular distr. Is almost flat, as expected, at $W= 4.57$ GeV ($\beta_{\Lambda_c}=0.026$) within the errors.
By the way very close to $\pi\alpha=0.023$, where Coulomb should matter
- The collected statistics is quite high at $W=4.60$ GeV ($\beta_{\Lambda_c}=0.11$) and as already seen in $e^+ e^- \rightarrow pp_{\text{bar}}$ at $W=1.91$ GeV ($\beta_p = 0.20$), there is a **very early onset of the D wave**.

$G_E(q^2)/G_M(q^2)$: D wave at thr or early onset ?

- $R(q^2) = G_E(q^2)/G_M(q^2)$



- Present data on $R(q^2)$ (in the case of BaBar unfortunately integrated on a too large Q^2 interval) indicate that

$G_D(q^2)$ seems not vanishing, close to thr :

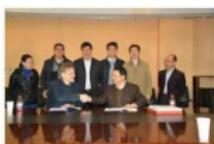
$G_D(q^2) \neq 0 \quad q^2 \approx 4M_B^2$?

BESIII versus Belle in $e^+ e^- \rightarrow \Lambda_c \Lambda_{c\bar{b}ar}$

- Not settled yet, since there is **some tension between BESIII and Belle in $\sigma(e^+ e^- \rightarrow \Lambda_c \Lambda_{c\bar{b}ar})$** , as pointed out by **Ulf Meissner and his collaborators** and shown in the following , in particular:
 - Belle data show a wide resonance, consistent with the $Y(4660)$, seen by BaBar and Belle in $e^+ e^- \rightarrow \psi(3686) \pi^+ \pi^-$, hardly compatible with BESIII flat behaviour up to 4.6 GeV
 - Belle data are fit by means of a resonance on top of $\Lambda_c \Lambda_{c\bar{b}ar}$ FSI, that predicts again a fast rise at thr, but not a jump.
 - **More data at thr and above are needed and BESIII already got funds to increase maximum energy up to $W = 4.9$ GeV**

Fit to Belle Measurements

- Ling-Yun Dai, Johann Haidenbauer, Ulf-G. Meißner
arXiv:1710.03142v1 [hep-ph] 9 Oct 2017
- Resonance Y(4660) [called X(4660) in this paper] + FSI @thr:
 $M = (4652.5 \pm 3.4) \text{ MeV}$
 $\Gamma = (62.6 \pm 5.6) \text{ MeV}$
 $\sigma_{\text{peak}} \sim 0.55 \text{ nb}$ [comparable to $\sigma(e^+ e^- \rightarrow pp_{\text{bar}}) \sim 0.8 \text{ nb}$ @ threshold]
- Concerning BESIII measurements they write:
*"While they agree with the Belle data, as far as cross sections magnitude, they indicate a different trend in energy.
It is impossible to fit both data.
Hopefully BESIII will extend their measurements at higher energies and thereby clarify the situation."*



Our Friend Ulf Meissner
IHEP, 2018 May 31st

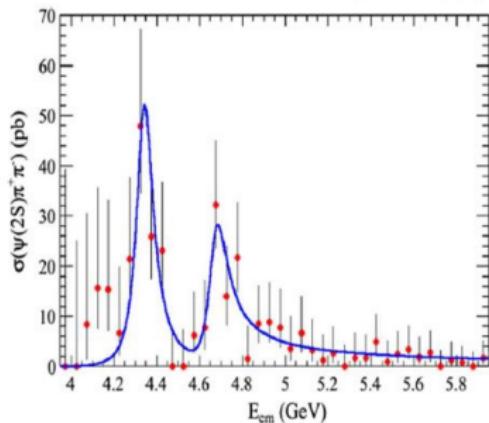
Other evidences of the $\Upsilon(4660)$

$e^+ e^- \rightarrow \psi(3686) \pi^+ \pi^-$ by means of ISR

BaBar

$$M=4669 \pm 22, \Gamma=104 \pm 49$$

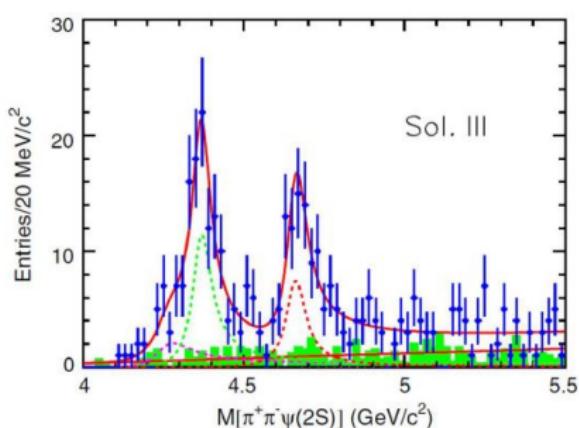
PHYSICAL REVIEW D 89, 111103(R) (2014)



Belle

$$M=4652 \pm 13, \Gamma=68 \pm 11$$

PHYSICAL REVIEW D 91, 112007 (2015)



Y(4660) in $e^+ e^- \rightarrow \psi(3686) \pi \pi$ cross section

- $M = (4667 \pm 7) \text{ MeV}$
- $\Gamma = [36+32 (-14)] \text{ MeV}$ (updated in PDG: $72 \pm 11 \text{ MeV}$)
- $B\Gamma_{ee} = (1.4 \pm 0.5) \text{ eV}$
- $\sigma_{\text{peak}} = 12\pi/M^2 B\Gamma_{ee}/\Gamma \times 1.5(\text{incl } \pi^0 \pi^0) \sim 0.04 \pm 0.025 \text{ nb}$
consistent with BaBar cross section $\sim 30 \times 1.5 \text{ nb}$
- to be compared to $e^+ e^- \rightarrow \Lambda_c \Lambda_{c\bar{b}} \sigma_{\text{peak}} \sim 0.55 \text{ nb}$
- **Y(4660) baryonic coupling ≥ 10 mesonic coupling
Unexpected !**

There is another mesonic decay
with much larger BR than $\psi(3686) \pi \pi$?

or

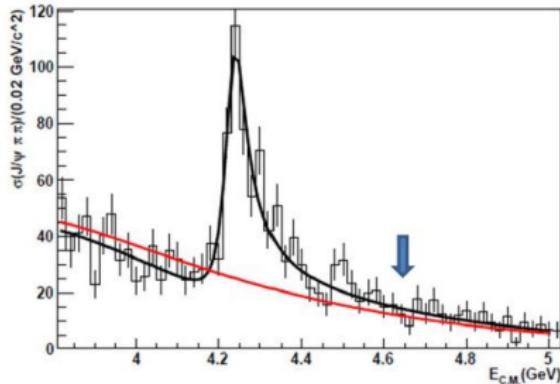
Y(4660) is a Hidden charm baryonium ?

Y(4660) Charmed Baryonium ?

- The decay $\text{Y}(4660) \rightarrow \text{J}/\psi \pi\pi$ would be expected to be large if it is a $cc_{\bar{b}ar}$ state, while at 90 % C.L.

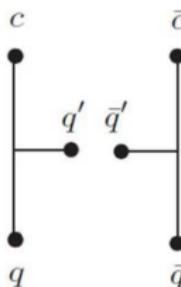
$\text{BR}[\text{Y}(4660) \rightarrow \text{J}/\psi \pi\pi] / \text{BR}[\text{Y}(4660) \rightarrow \psi(3686) \pi\pi] < 0.46$,
 according to BaBar data (arXiv:0808.1543 [hep-ex]) ,
 as elaborated in arXiv:0911.2178v5 [hep-ph] (2017).

$$\text{e}^+ \text{e}^- \rightarrow \text{J}/\psi \pi^+ \pi^-$$



Y(4660) Charmed Baryonium ?

- According to R. Faccini et al. arXiv:0911.2178(2017),
[see also L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 72, 031502]
Y(4660) fulfills the old Rossi Veneziano, G.F. Chew paradigm
[Nucl.Phys. B123,507(1977) , G.F.Chew Nucl.Phys. B79 (1974) 365]
of a charm tetraquark (hidden charm baryonium) decay:
mostly popping up from the vacuum a light quark pair and
falling apart as a charmed baryon pair



Y(4660) Charmed Baryonium ?

- Y(4660) mass, close to the $\Lambda_c \Lambda_{c\bar{b}ar}$ threshold, is in favour of its interpretation as a **charmed baryonium**.
- $\text{Y}(4660) \rightarrow \Lambda_c \Lambda_{c\bar{b}ar}$ shape and width, actually (expected large, according to the Rossi Veneziano model) is constrained by the threshold close by.
- If BESIII would not confirm the $\text{Y}(4660) \rightarrow \Lambda_c \Lambda_{c\bar{b}ar}$ decay a strong support of the interpretation of the **XYZ states as tetraquark states** would be somewhat in trouble.
- **It might be that the Meissner et al conclusions are too drastic.** In the following slide a fit with a Y(4660) on top of a Coulomb amplitude closer to a pointlike $\Lambda_c \Lambda_{c\bar{b}ar}$ at threshold is shown.
More data by BESIII at threshold and above $W=4.6 \text{ GeV}$ will settle all these questions.

Try to fit by means of a simple model Belle + BESIII data

- Belle+ BESIII: $M = 4644 \pm 6 \text{ MeV}$, $\Gamma = 80 \pm 17 \text{ MeV}$ $P = 63 \%$

