Some remarks on Y(4260)

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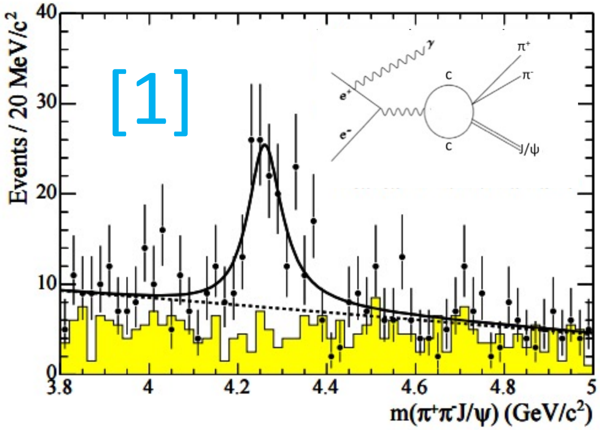
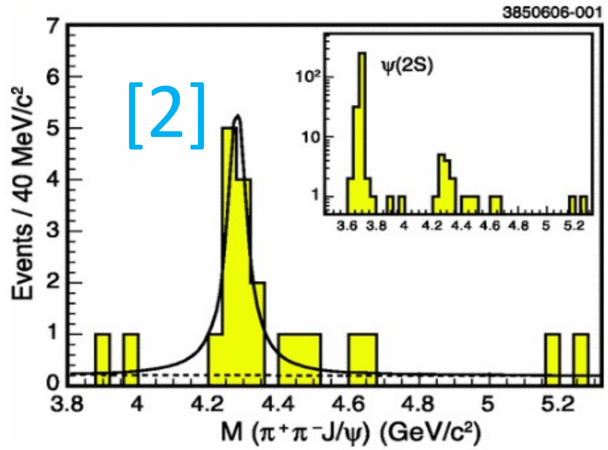
Discovery of $Y(4260)$ in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$

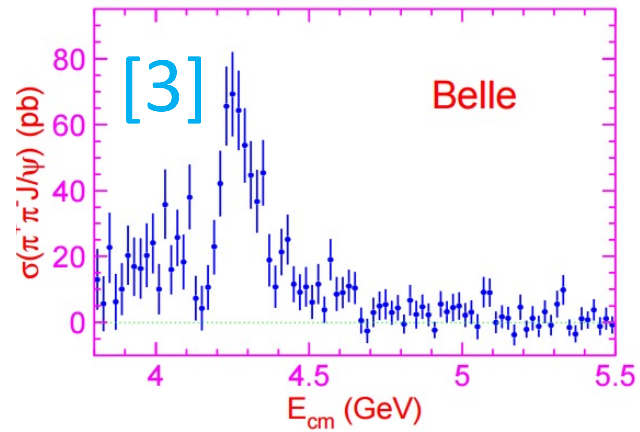
BABAR

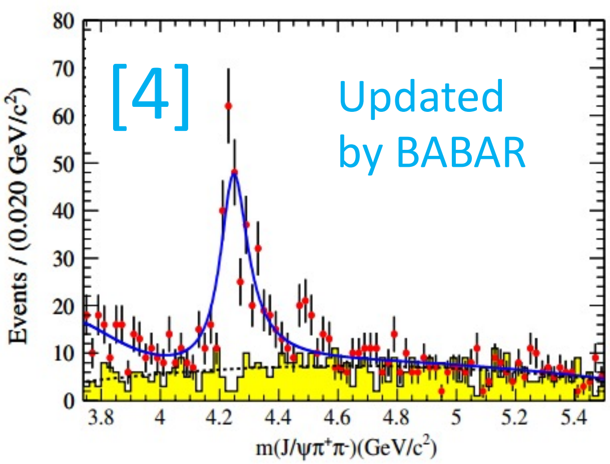


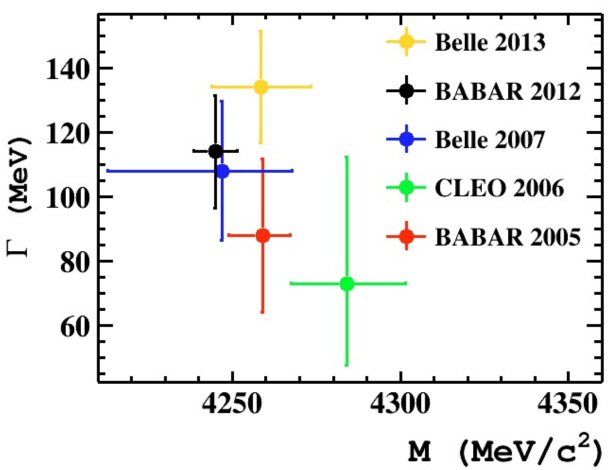
CLEO

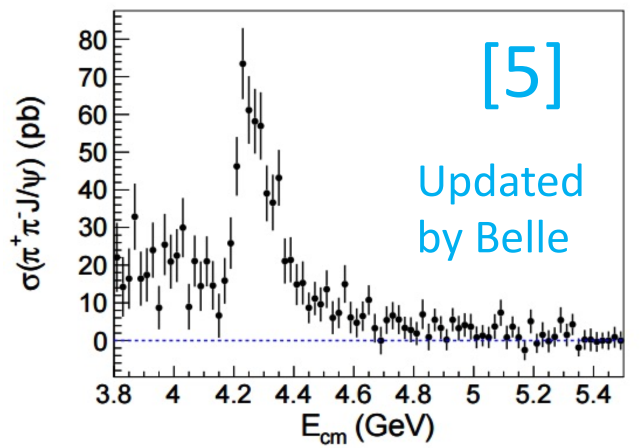


Belle





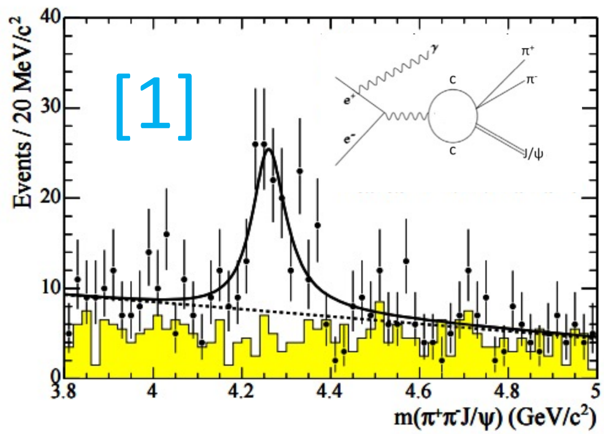




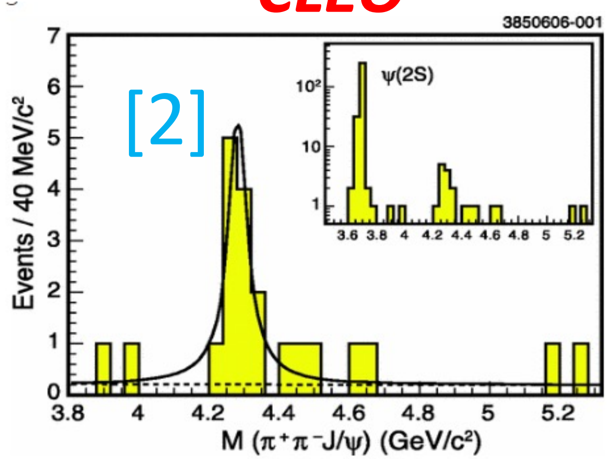
[1] PRL 95, 142001 (2005).
[2] PRD 74, 091104(R) (2006).
[3] PRL 99, 182004 (2007).
[4] PRD 86, 051102(R) (2012).
[5] PRL 110, 252002 (2013).

Discovery of $Y(4260) \to \pi^+\pi^- J/\psi$

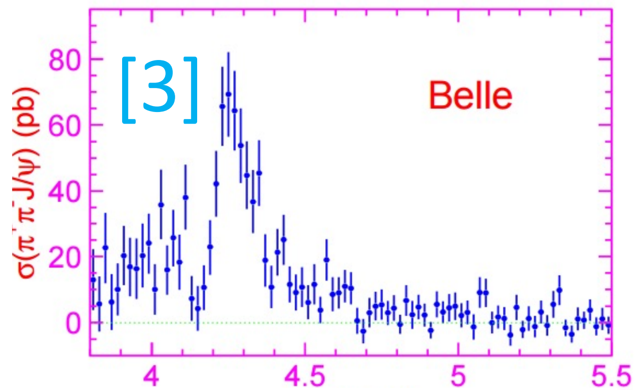
BABAR



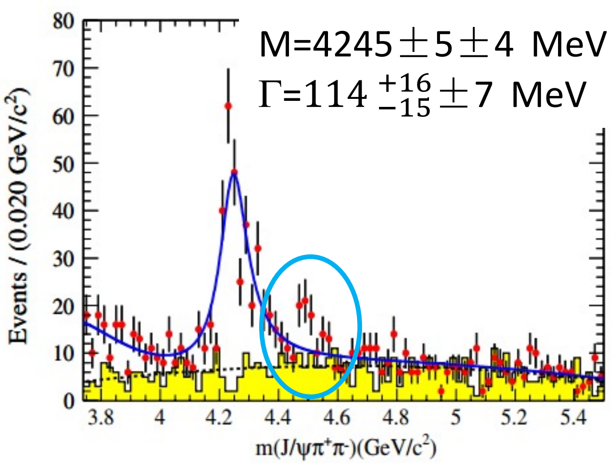
CLEO

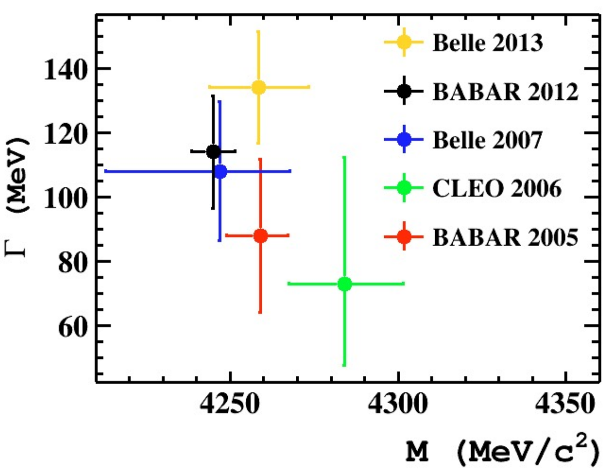


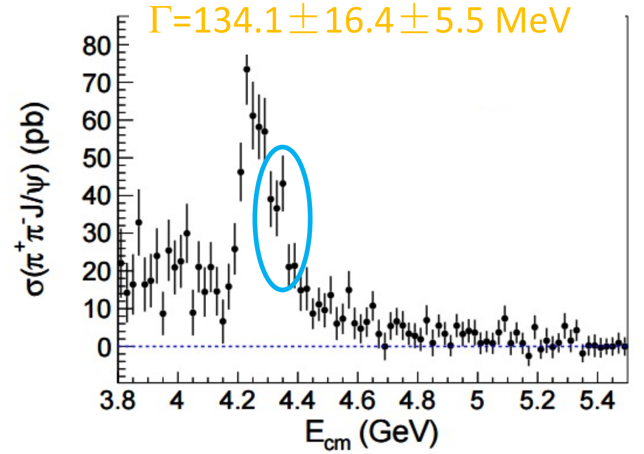
Belle



$M=4258.6 \pm 8.3 \pm 12.1$ MeV
$\Gamma=134.1 \pm 16.4 \pm 5.5$ MeV







- Average [PDG 2014] : M = 4251±9 MeV, $\Gamma = 120 \pm 12$ MeV
- There seem a few bumps in the updated BABAR and Belle data ! Improved measurements are needed.

Intriguing Y(4260)

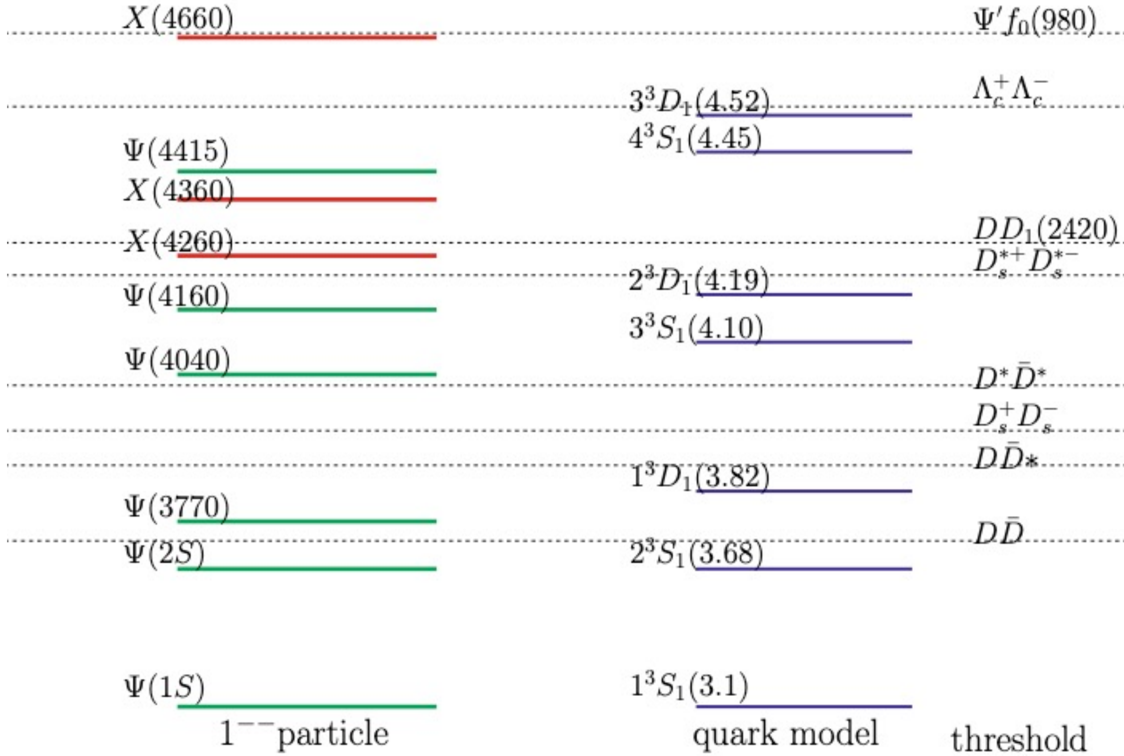
Have attracted considerable attention!

~~Mass~~

- Such 1^{--} states expected up to 4.4 GeV are generally well-established $1S$, $2S$, $1D$, $3S$, $2D$ and $4S$.

- No enough unassigned vector states for Y(4260) in charmonium spectrum

Godfrey & Isgur, PRD32,189(1985)



Green: predicted and discovered
Red: unpredicted but discovered

Intriguing Y(4260)

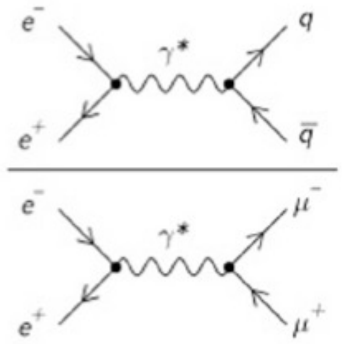
- Mass
- OZI rule

- No open charm process is significantly observed (before 2017).
- If taking Y(4260) as a charmonium state, it violates OZI rule.

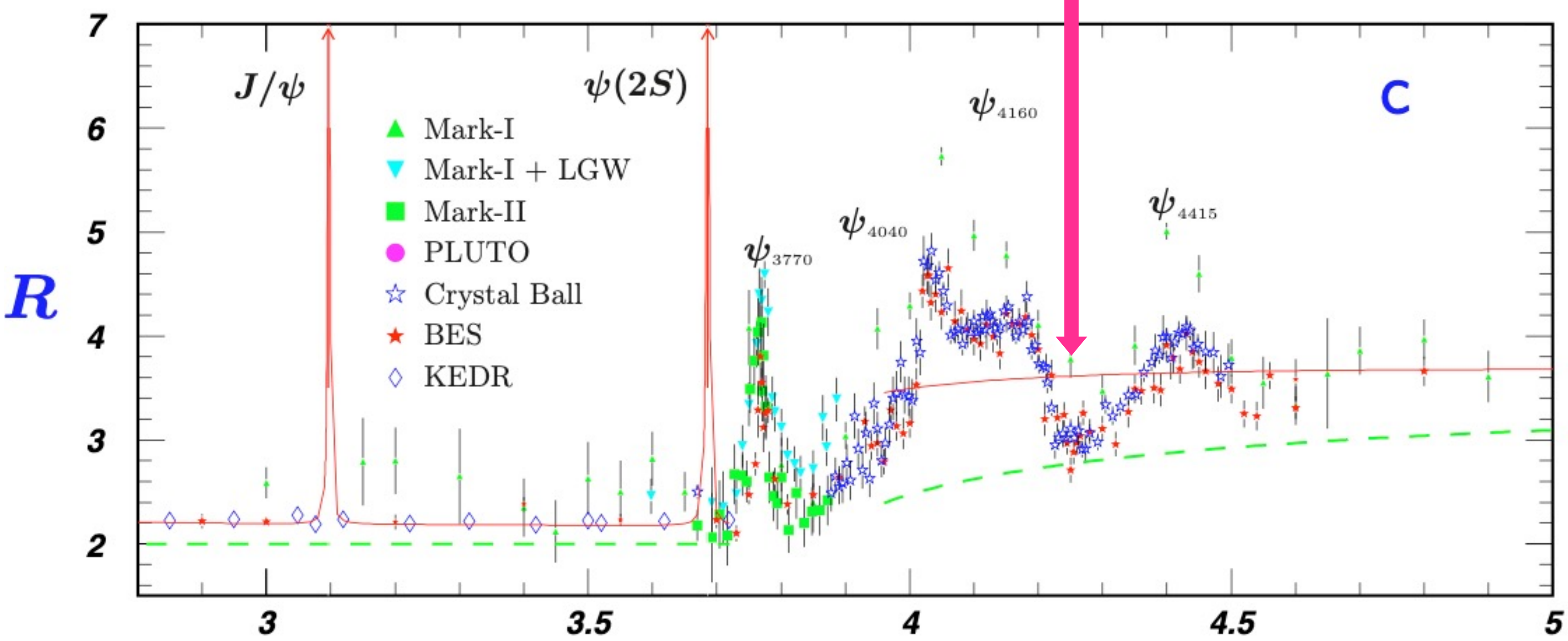
Intriguing Y(4260)

- ~~Mass~~
- ~~OZI rule~~
- ~~Non in R scan~~

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



- No obvious peak around 4.26 GeV in the R distribution is discovered.

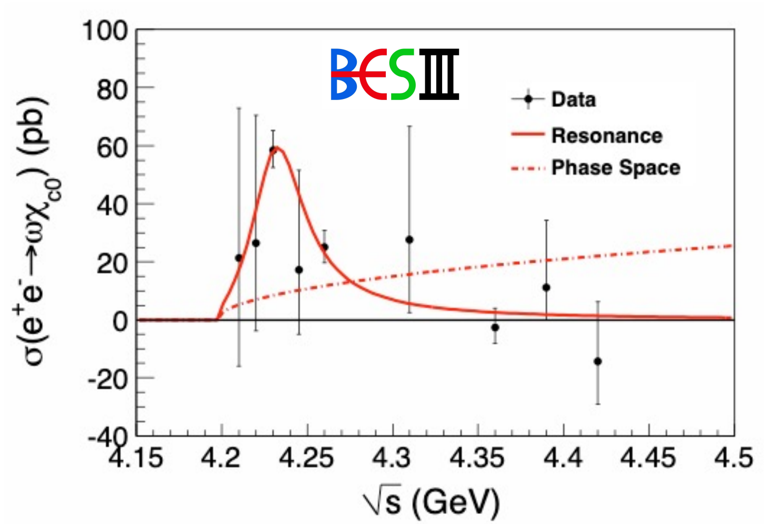


Intriguing Y(4260)

- Mass
- OZI rule
- Non in R scan

- In 2012, Ref[1] predicted that Y(4260) has a sizable coupling to $\omega\chi_{c0}$, and is taken as a $c\bar{c}$ state. Meanwhile, they gave out $\Gamma_{e^+e^-} = 23.30 \pm 3.55$ eV.

- It is as expected that BESIII observed a resonant structure (>9σ) in M($\omega\chi_{c0}$), with mass of $4230 \pm 8 \pm 6$ MeV and width of $38 \pm 12 \pm 2$ MeV [2].



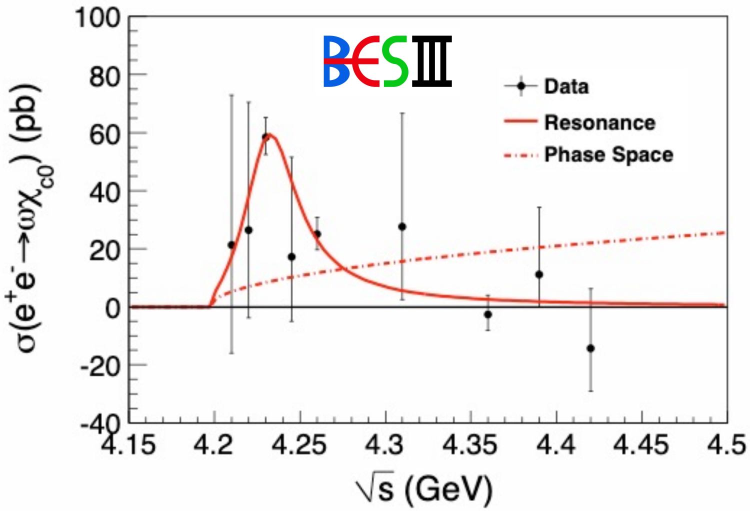
Incompatible!

Average [PDG 2014] : M = 4251 $\pm$ 9 MeV, $\Gamma = 120 \pm 12$ MeV

[1] arXiv:1206.6911, PRD 92, 014020 (2015)
[2] PRL114, 092003 (2015)

Intriguing Y(4260)

- Mass (and width)
- OZI rule
- Non in R scan



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Intriguing Y(4260)

- Mass (and width)
- OZI rule
- Non in R scan

$\psi(4^3S_1)$

More refined potential models has been growing !

- The screened potential model [1] recalculated the charmonium spectra. The $\psi(4^3S_1)$' s mass is reduced from ~4415 to 4273 MeV, which reconciles to some extent the contradiction in "mass" but doesn't explain why Y(4260) in $M(\omega\chi_{c0})$ is so narrow.

In units of MeV

State	NR[2]	GI[2]	SC[1]	Exp [PDG 2014]
$\psi(3^3S_1)$	4072	4100	4022	4039 ± 1
$\psi(2^3D_1)$	4142	4194	4089	4191 ± 5
$\psi(4^3S_1)$	4406	4450	4273	4251 ± 9
$\psi(3^3D_1)$			4317	

[1] PRD 79, 094004 (2009)
[2] PRD 72, 054026 (2005)

NR: nonrelativistic potential model, GI: Godfrey-Isgur model, SC: screened potential model.

Intriguing Y(4260)

- ? Mass (and width)
- ✗ OZI rule
- ✗ Non in R scan
- ✗ Leptonic width

- The screened potential model [1] also calculated the leptonic widths of charmonia included $\psi(4^3S_1)$ state.
- However, Ref[2] gave out $\boxed{\Gamma_{e^+e^-}[Y(4260)] = 23.30 \pm 3.55\ \text{eV},}$ in which the coupling Y(4260) → $\omega\chi_{c0}$ has been successfully predicted, and they also take Y(4260) as a $c\bar{c}$ state.

state	Γ^0_{ee}	Γ_{ee}	$\Gamma^{\text{expt}}_{ee}$
$1^3S_1(3097)$	11.8	6.60	$5.55 \pm 0.14 \pm 0.02$
$2^3S_1(3686)$	4.29	2.40	2.33 ± 0.07
$3^3S_1(4039)$	2.53	1.42	0.86 ± 0.07
$4^3S_1(4263)$	1.73	0.97	
$5^3S_1(4421)$	1.25	0.70	0.58 ± 0.07
$6^3S_1(4664)$	0.88	0.49	
$1^3D_1(3775)$	0.055	0.031	0.259 ± 0.016
$2^3D_1(4153)$	0.066	0.037	0.83 ± 0.07
$3^3D_1(4361)$	0.079	0.044	

[1] PRD 79, 094004 (2009)
[2]PRD 92, 014020 (2015), arXiv:1206.6911

Γ^0_{ee} and Γ_{ee} are without and with QCD corrections, respectively (in unit of keV).

Intriguing Y(4260)

- ? Mass (and width)
- ✗ OZI rule
- ✗ Non in R scan
- ✗ Leptonic width

- The more refined relativistic potential model [1] also calculated the leptonic widths of charmonia included $\psi(4^3S_1)$ state.
- However, Ref[2] gave out $\boxed{\Gamma_{e^+e^-}[Y(4260)] = 23.30 \pm 3.55 \text{ eV},}$ in which the coupling Y(4260) $\rightarrow \omega\chi_{c0}$ has been successfully predicted, and they also take Y(4260) as a $c\bar{c}$ state.

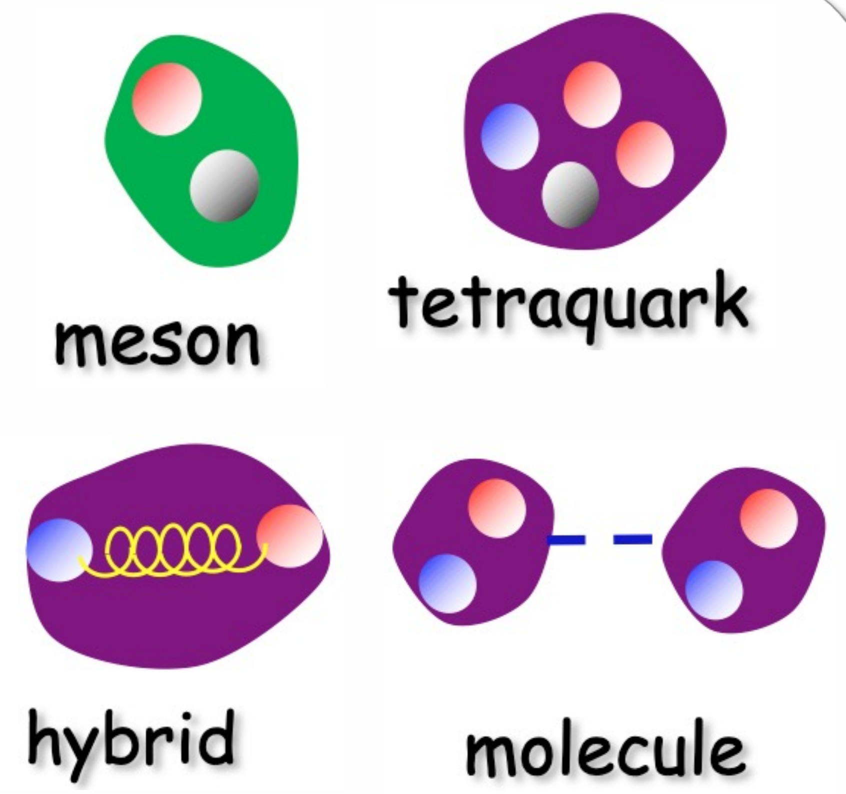
$\Gamma_{e\bar{e}}$ (keV)	Pert	Nonpert
$\psi(1S)$	4.28	1.89
$\psi(2S)$	2.25	1.04
$\psi(3S)$	1.66	0.77
$\psi(4S)$	1.33	0.65
$\psi(1D)$	0.09	0.23
$\psi(2D)$	0.16	0.45

[1] PRD 75, 074031 (2007)
[2] PRD 92, 014020 (2015), arXiv:1206.6911

Pert and NonPert are short for perturbative and Non-perturbative, respectively.

Theoretical interpretations for $Y(4260) \to \pi\pi J/\psi$

- Excited charmonium
- Compact tetraquark
- $c\bar{c}$-gluon hybrid
- Meson-meson molecule
- Threshold effect
- et al.



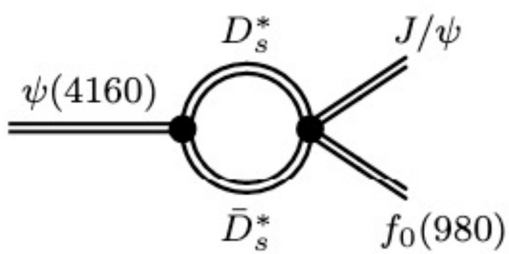
* Main references are moved into backup.
* These pictures come from Shuangshi Fang's talk.

Theoretical interpretations for $Y(4260) \to \pi\pi J/\psi$

Exited $c\bar{c}$ state	? Mass	✗ OZI rule	✗ Non R scan	✗ $\Gamma_{e^+e^-}$
Tetraquark	? Mass	✓ OZI rule	? ✗ Non R scan	? $\Gamma_{e^+e^-}$
$c\bar{c}$-gluon hybrid	? Mass	✓ OZI rule	? ✗ Non R scan	? $\Gamma_{e^+e^-}$
$D_1\bar{D}$ molecule	✓ Mass	✓ OZI rule	? ✗ Non R scan	? $\Gamma_{e^+e^-}$

- **Kinematic effect** Loop-driven decay [1]

It can well explain why Y(4260) is not seen in OZI-allowed decays experimentally.

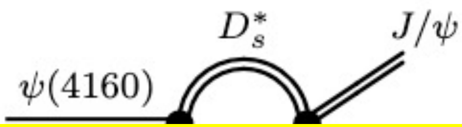


[1] Acta Phys. Pol. B. 51(8),1713 (2020)
* Other references are moved into backup.

Theoretical interpretations for $Y(4260) \to \pi\pi J/\psi$

• Exited $c\bar{c}$ state	? Mass	✗ OZI rule	✗ Non R scan	✗ $\Gamma_{e^+e^-}$
• Tetraquark	? Mass	✓ OZI rule	✗ Non R scan	? $\Gamma_{e^+e^-}$
• $c\bar{c}$-gluon hybrid	? Mass	✓ OZI rule	✗ Non R scan	? $\Gamma_{e^+e^-}$
• $D_1\bar{D}$ molecule	✓ Mass	✓ OZI rule	✗ Non R scan	? $\Gamma_{e^+e^-}$
• Kinematic effect	✓ Mass	✓ OZI rule	✓ Non R scan	

- et al.



- All of resonant interpretations for Y(4260) is failed in R-scan distribution, instead, the interpretation of non-resonance enhancement can match the experiments (before 2017). Is that the truth ?

* Main references are moved into backup.

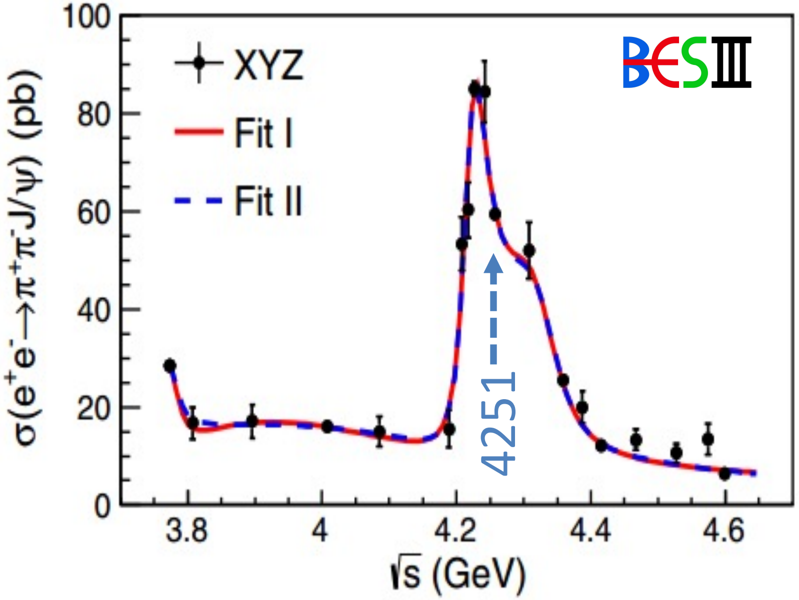
November revolution for Y(4260) ?

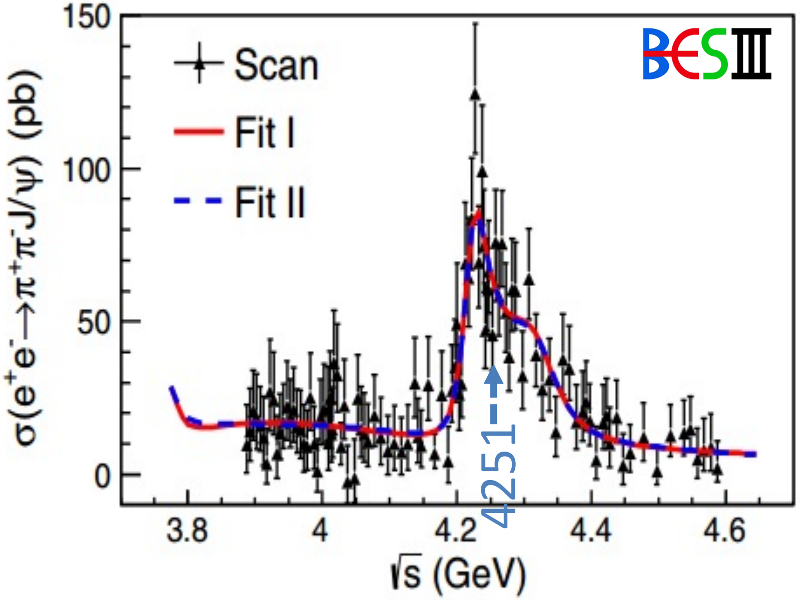
2017

- In spring of 2017, BESIII published a precise measurement of $e^+e^- \to \pi^+\pi^- J/\psi$ cross sections at c.m. energies from 3.77 to 4.60 GeV using data samples with an integrated luminosity of 9 fb^{-1}.
- The mass and width of lower state, called Y(4220), are well consistent with those observed in M($\omega\chi_{c0}$).

PRL 118, 092001 (2017)

Y(4260) = Y(4220) + Y(4320)



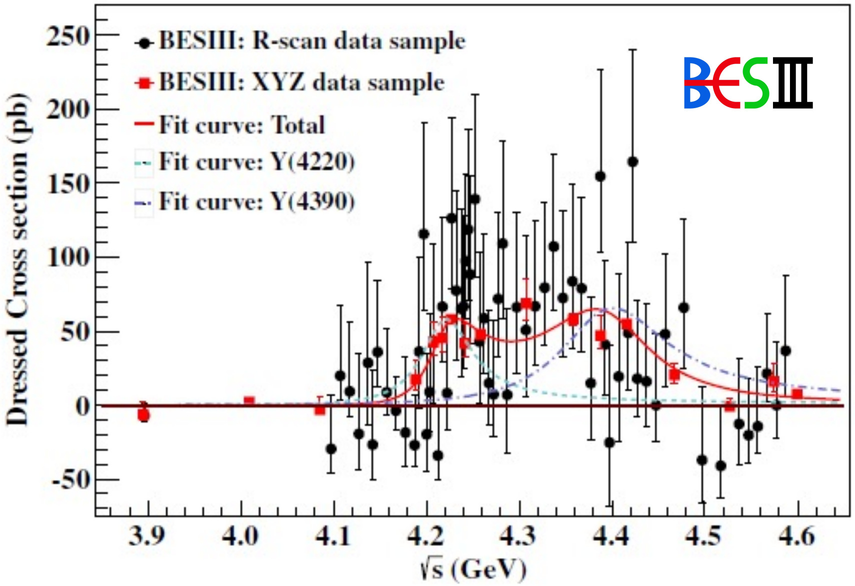


$M = (4222.0 \pm 3.1 \pm 1.4)\ \text{MeV}, \Gamma = (44.1 \pm 4.3 \pm 2.0)\text{MeV}$

November revolution for Y(4260) ?

2017

- In spring of 2017, BESIII also published a updated measurement of $e^+e^- \to \pi^+\pi^- h_c$ cross sections at c.m. energies with improved significance with two resonant structures.
- The mass and width of the lower state are well consistent with those observed in M($\omega\chi_{c0}$).



Y(4220) + Y(4390)

PRL 118, 092002 (2017)

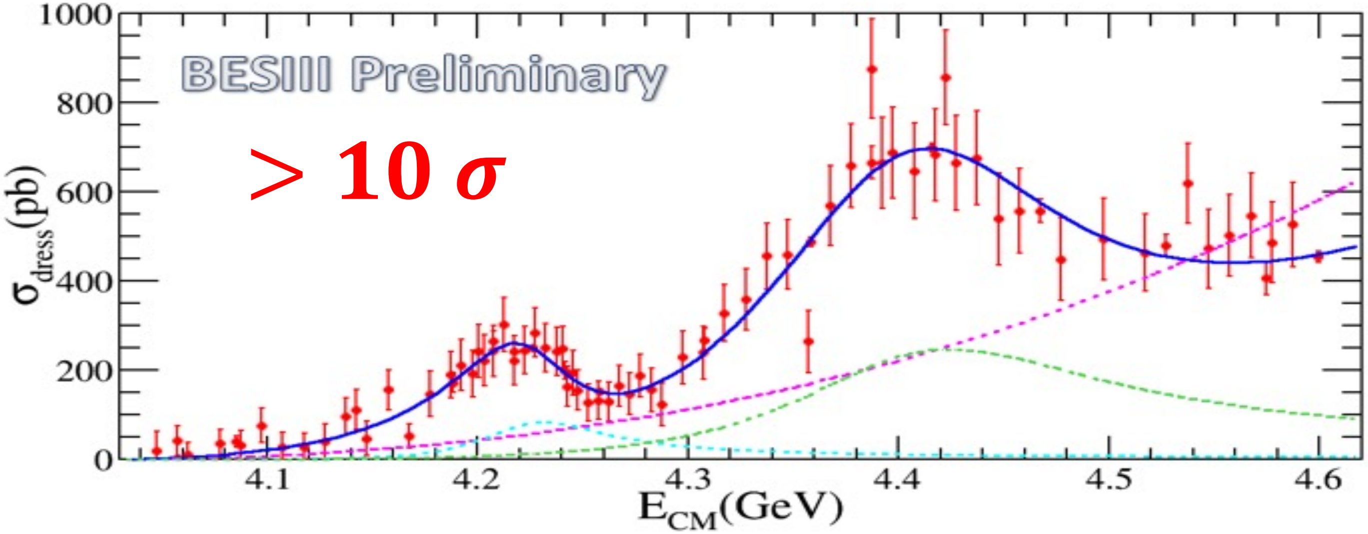
$$M = (4218.4^{+5.5}_{-4.5} \pm 0.9)\ \text{MeV}, \Gamma = (66.0^{+12.3}_{-8.3} \pm 0.4)\ \text{MeV}$$

November revolution for Y(4260) ?

2017

- What's more, the first open charm decays of $Y(4260)$ is found !
- In 10th workshop of the France China Particle Physics Laboratory in spring of 2017, BESIII announced the heavy news. The results published afterwards in PRL 122, 102002 (2019)
- The mass and width of the lower state are well consistent with those observed in M($\omega\chi_{c0}$).

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



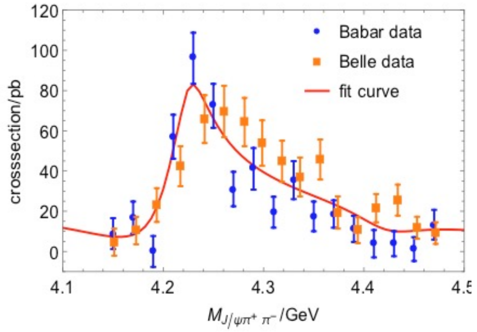
$$M = (4228.6 \pm 4.1 \pm 6.3)\ \text{MeV}, \Gamma = (77.0 \pm 6.8 \pm 6.3)\text{MeV}$$

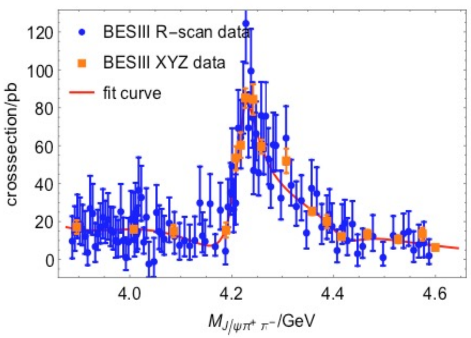
November revolution for Y(4260) ?

2017

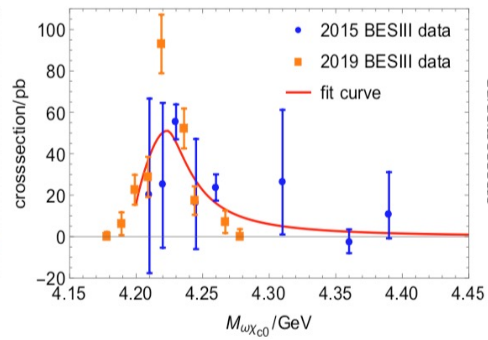
- Since the narrow Y(4220) and the broad Y(4260) observed in the same process, i.e. $e^+e^- \to (\gamma_{ISR})\pi^+\pi^- J/\psi$, all of experiments should see the same scenario. It is reasonable to infer that the broad Y(4260) observed by BABAR, Belle, and CLEO is the combination of Y(4220) and Y(43xx).
- Perhaps for historical reasons, the new Y(4220) with lower mass and narrower width is also called Y(4260). Therefore, the label "Y(4260)" indicated the narrow Y(4220) in the following slides.
- In recent years, BESIII observed and/or searched for a number of Y(4260) decays, which is crucial to probe the nature of Y(4260). Because of this, Stephen & Tomasz & Daria called BESIII as "Y(4260) factory" [Rev.Mod.Phys. 90 (2018)1, 015003].

Observation of main Y(4260) decays

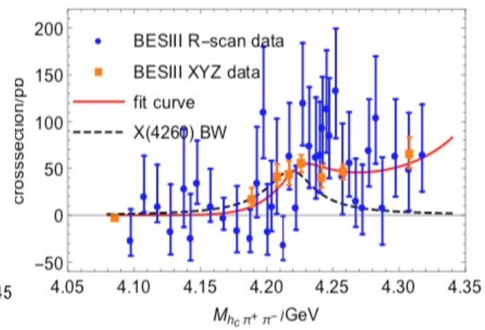




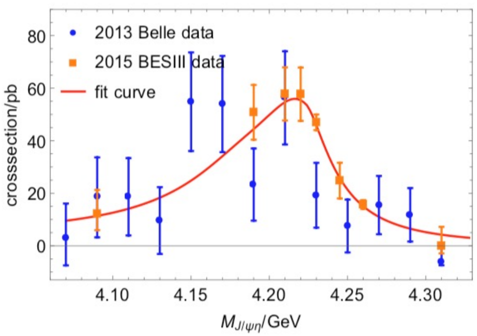
$J/\psi\pi^+\pi^-$



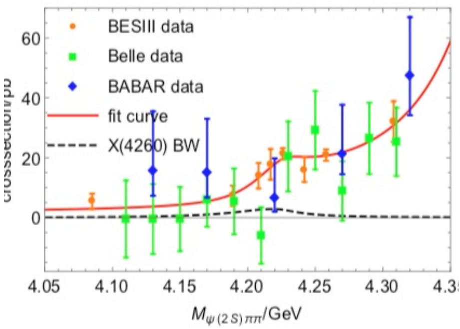
$\omega\chi_{c0}$



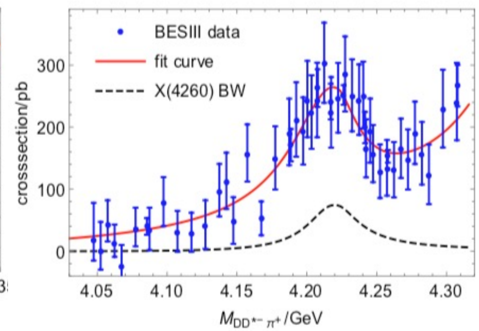
$h_c\pi^+\pi^-$



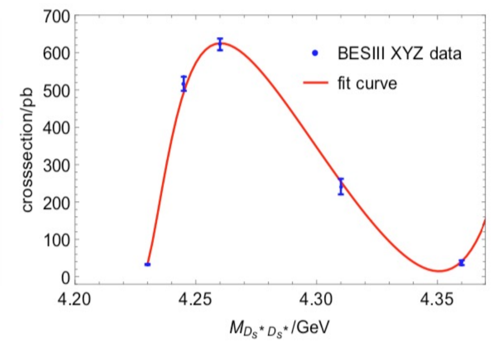
$J/\psi\,\eta$



$\psi(2S)\pi^+\pi^-$



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



$D_s^{*+}D_s^{*-}$

$\sigma(e^+e^- \rightarrow final\ states)$ >10 pb^{-1} (up to 2020)

* Figures are from EPJC81(2021)83, and the reference for each measurement can also seen in EPJC81(2021)83.

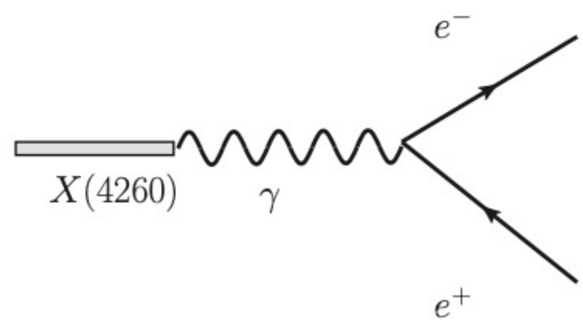
Eur. Phys. J. C (2021) 81:83
https://doi.org/10.1140/epjc/s10052-020-08813-y

THE EUROPEAN PHYSICAL JOURNAL C

On leptonic width of $X(4260)$

- The leptonic decay width

$$\mathcal{L}_{\gamma X} = \frac{g_0}{M_X} X_{\mu\nu} F^{\mu\nu} \Longrightarrow \Gamma_{e^+e^-} = \frac{4\alpha}{3} \frac{g_0^2}{M_X}$$



- The cross section for each decay

$$\sigma_{e^+e^- \to X(4260) \to f} = \frac{3\pi}{k^2} \left| \underbrace{\frac{\sqrt{s\Gamma_{ee}\Gamma_f}}{s - M_X^2 + i\sqrt{s}\Gamma_{tot}(s)}}_{X(4260) \to f} + \underbrace{\sum_i \frac{c_i e^{i\phi_i}}{s - M_i^2 + i\sqrt{s}\Gamma_i}}_{\text{Bkg for } \psi \to f} + \underbrace{\tilde{c}}_{\text{Non-Resonance bkg}} \right|^2$$

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THE EUROPEAN PHYSICAL JOURNAL C

On leptonic width of $X(4260)$

- The propagator of X(4260)→ f

$$\frac{1}{D_X(s)} = \frac{1}{s - M_X^2 + i\sqrt{s}\Gamma_{tot}(s)}$$

$$\Gamma_{tot}(s) = \Gamma_{J/\psi\pi\pi}(s) + \Gamma_{h_c\pi\pi}(s) + \Gamma_{D\bar{D}^*\pi}(s) + \Gamma_{\psi(2S)\pi\pi}(s) + \Gamma_{\omega\chi_{c0}}(s) + \Gamma_{J/\psi\eta}(s) + \Gamma_{D_s^*\bar{D}_s^*}(s) + \Gamma_{D\bar{D}}(s) + \Gamma_{D\bar{D}^*}(s) + \Gamma_{D^*\bar{D}^*}(s) + \boxed{\Gamma_0}$$

unknown decay width

- two body decay width

$$\Gamma_{\omega\chi_{c0}}(s) = g_{\omega\chi_{c0}} k_{\omega\chi_{c0}}, \quad \Gamma_{J/\psi\eta}(s) = g_{J/\psi\eta} k^3_{J/\psi\eta}, \quad \Gamma_{D_s^*\bar{D}_s^*}(s) = g_{D_s^*\bar{D}_s^*} k^3_{D_s^*\bar{D}_s^*},$$
$$\Gamma_{D^+D^-}(s) = g_{D^+D^-} k^3_{D^+D^-}, \quad \Gamma_{D^+D^{*-}}(s) = g_{D^+D^{*-}} k^3_{D^+D^{*-}},$$
$$\Gamma_{D^{*+}D^{*-}}(s) = g_{D^{*+}D^{*-}} k^3_{D^{*+}D^{*-}}.$$

Flatte parameterization

- Three-body decay width [PDG]

$$d\Gamma_f = \frac{1}{(2\pi)^5} \frac{1}{16M_X^2} |\mathcal{M}|^2 |p_1^*||p_3| dm_{12} d\Omega_1^* d\Omega_3.$$

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https://doi.org/10.1140/epjc/s10052-020-08813-y
THE EUROPEAN PHYSICAL JOURNAL C

On leptonic width of $X(4260)$

- Considering the isospin symmetry and heavy quark spin symmetry

$$\Gamma_{J/\psi\pi\pi}(s)=\frac{3}{2}\Gamma_{J/\psi\pi^+\pi^-}(s),\ \Gamma_{h_c\pi\pi}(s)=\frac{3}{2}\Gamma_{h_c\pi^+\pi^-}(s),\ \Gamma_{\psi(2S)\pi\pi}(s)=\frac{3}{2}\Gamma_{\psi(2S)\pi^+\pi^-}(s),\ \Gamma_{D\bar{D}^*\pi}(s)=3\Gamma_{D^0D^{*-}\pi^+}(s),\ \Gamma_{D\bar{D}}(s)=2\Gamma_{D^+D^-}(s),$$
$$\Gamma_{D\bar{D}^*}(s)=2\Gamma_{D^+D^{*-}+c.c.}(s),\ \Gamma_{D^*\bar{D}^*}(s)=2\Gamma_{D^{*+}D^{*-}}(s),$$

$$g_{D^+D^-}:g_{D^+D^{*-}}:g_{D^{*+}D^{*-}}=1:4:7\ [1]$$

- Combined fit

parameters	value
g_0(MeV)	23.865 ± 0.602
M_X(GeV)	4.219 ± 0.001
Γ_0(GeV)	0.005 ± 0.002
$\Gamma_{e^+e^-}$(keV)	0.3~1.3
$\chi^2/d.o.f.$	$292.84/(357-43)=0.93$

Due to interfered multiplicity and different bkg. shapes, we only gave out the leptonic width range, which is consistent with that of $\psi(4^3S_1)$ (or mixed with a small $\psi(2^3D_1/3^3D_1)$) in the refined potential models.

[1] M.B. Voloshin, Phys. Rev. D **85**, 034024 (2012)

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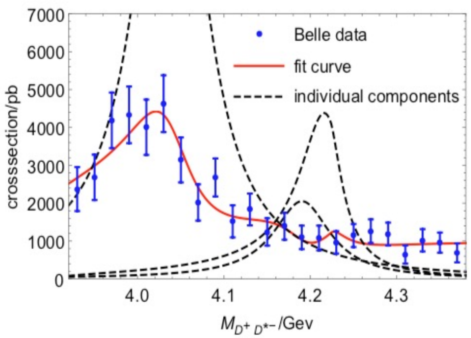
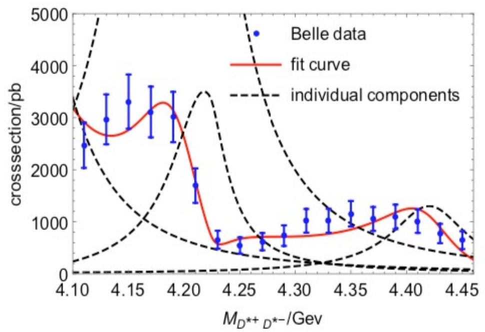
An interpretation of non-peak in M($D^{(*)}\bar{D}^{(*)}$) @4220 MeV

D^+D^{*-}



$D^{*+}D^{*-}$



Other fit projections see Slide 20 for details.

$$\psi(4040)_{fixed} + \psi(4160)_{fixed} + Y(4260) + \psi(4415)_{fixed}$$

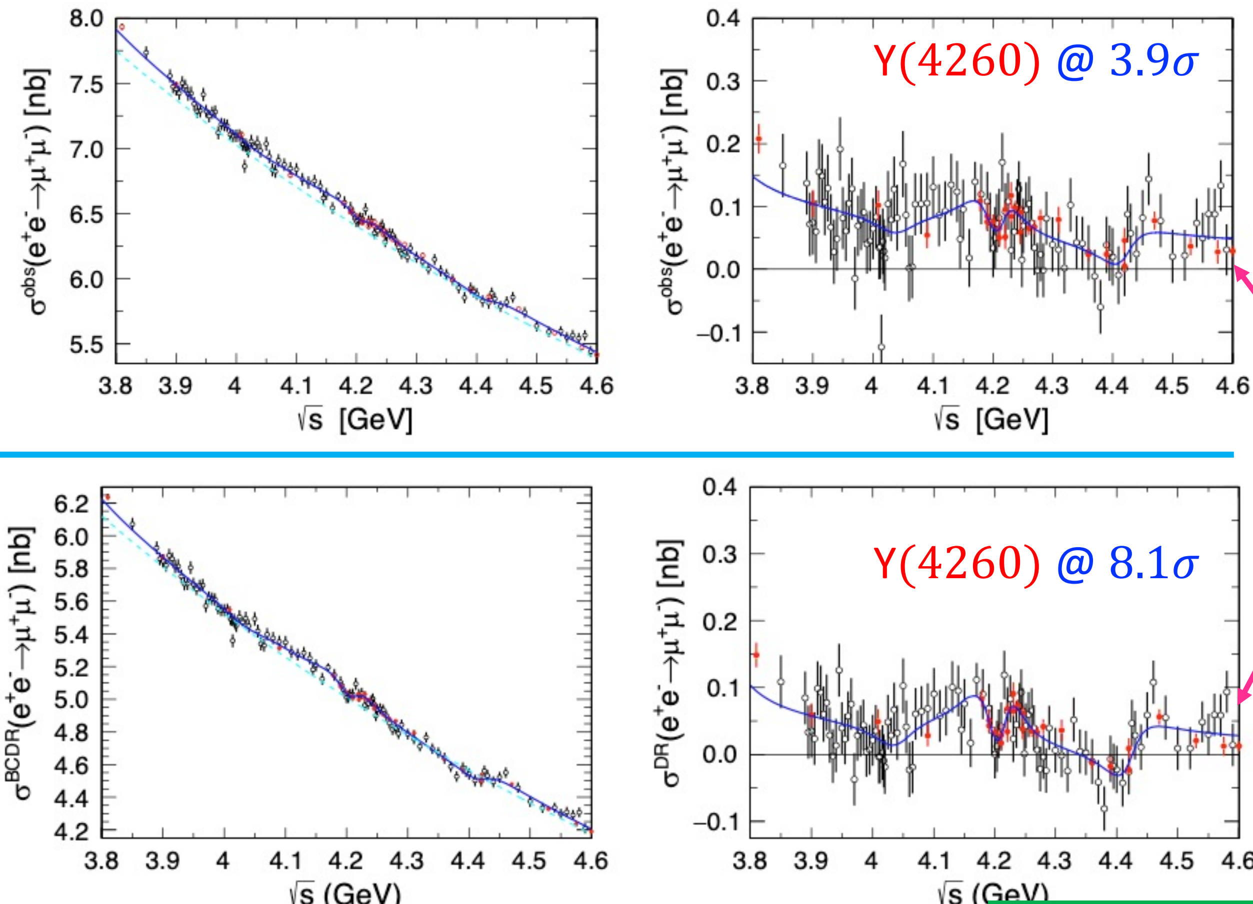
- Interference among multiple ψ states can describe M($D^{(*)}\bar{D}^{(*)}$) very well.

- Certainly, more improved measurements of $e^+e^- \to D^{(*)}\bar{D}^{(*)}$ is necessary to further confirmed if non-peak around 4220 MeV is caused by destructive interference.

Good news from BESIII

Without ISR correction

With ISR correction



Subtracted both the continuum and $\psi(2S) \to \mu^+\mu^-$ contributions

$$M_{S(4220)} = 4216.7 \pm 8.9 \pm 4.1 \text{ MeV}$$

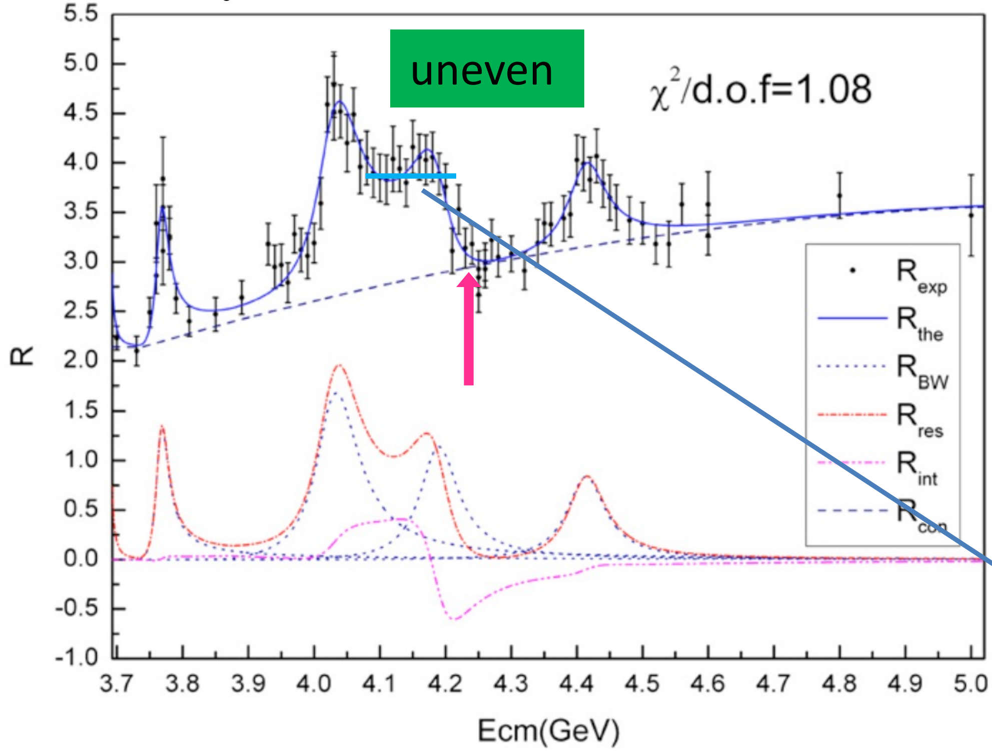
$\Gamma_{\mu^+\mu^-}$: 1.09 ~ 1.53 keV

$$\Gamma^{\text{tot}}_{S(4220)} = 47.2 \pm 22.8 \pm 10.5 \text{ MeV}$$

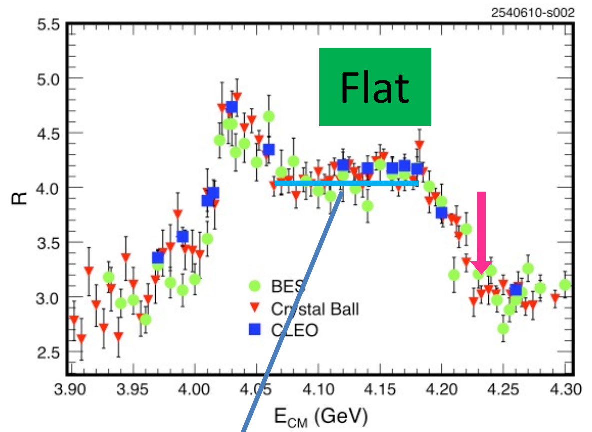
Consistent well with the combined fit to multiple hadron channels as well as refined potential models !

Investigation of non-peak in R scan @4220 MeV

Physics Letters B 660 (2008) 315



Eur. Phys. J. C (2011) 71: 1534



The fit seems not consistent well with all data. Might another charmonium state be required.

- At present, the $\psi(4040)$ and $\psi(4160)'$s parameters in PDG mainly derives from the BESII fit to the R-scan distribution. We believe that it is time to update the experimental data as well as the fit.

Y(4260) is ψ(4S) ?

If this law of mass gap relation still holds for states with n = 3, 4 in J/ψ and ϒ families, the mass of ψ(4S) should be located at 4,264~4290 MeV rather than 4415 MeV, which is compatible with the screened potential model prediction[PRD 79, 094004 (2009)].

Eur. Phys. J. C 74, 3208 (2014)

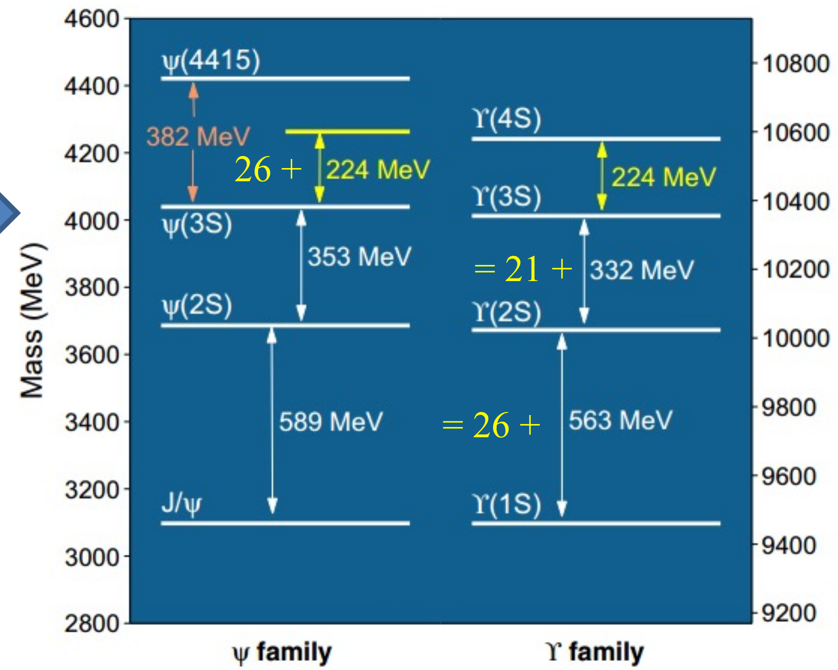
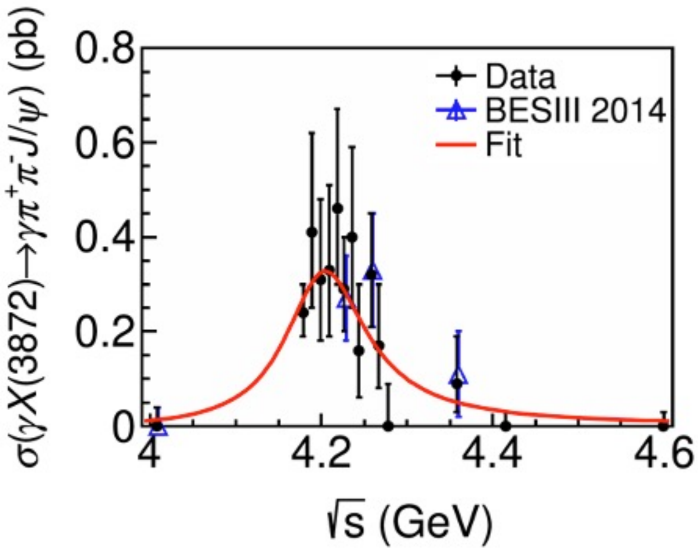


Fig. 1 A comparison between the J/ψ and Υ families

Radiative decay of Y(4260)

PRL 122, 232002 (2019)



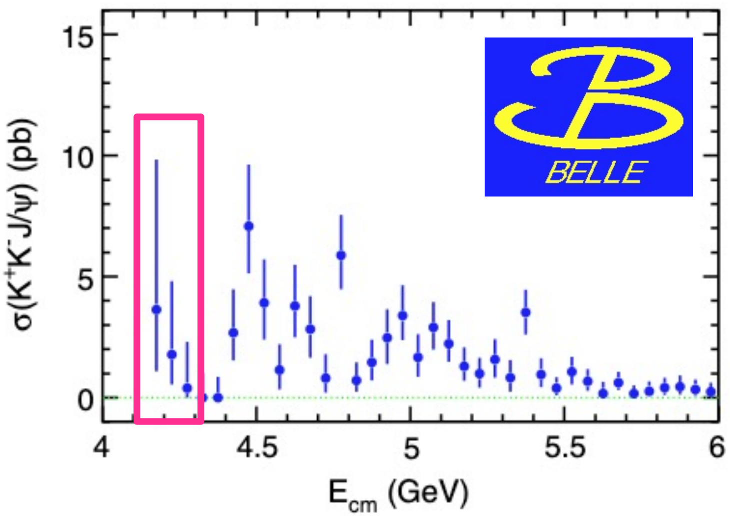
- The product of the cross section and Br. around 4220 MeV is ~0.3 pb. Exploiting Br $(X(3872) \to \pi^+\pi^- J/\psi)$=4.1% measured by BABAR[1], $\sigma_{top}(e^+e^- \to \gamma X(3872)) = 7.3$ pb, which is about one tenth of $\sigma_{top}(e^+e^- \to \pi^+\pi^- J/\psi)$.

- According to Ref [2], Br$(Y(4260) \to \pi^+\pi^- J/\psi)$ is $\mathcal{O}(10^{-4})$ and $\Gamma_{tot}(Y(4260))$~50 MeV, and we can do an analogy to gain $\Gamma(Y(4260) \to X(3872))$ =5×$\mathcal{O}(10^{-1})$ keV. assuming X(3872) as the $\chi_{c1}(2P)$ state, $\Gamma(4^3S_1 \to 2^3P_1)$ =5×$\mathcal{O}(10^{-1})$ keV.

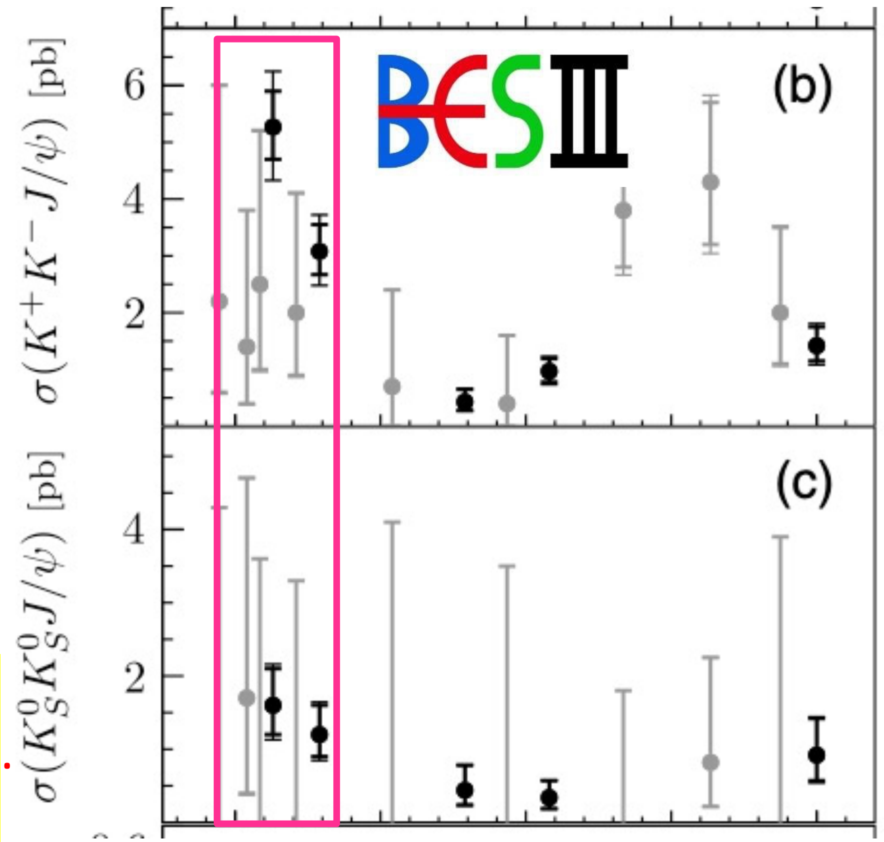
- The radiative widths $\Gamma(4^3S_1 \to 2^3P_1)$ [3] used GI and non-relativistic models are calculated to be 0.49 and 0.92 keV, which is consistent with the above rough estimation and suggests Y(4260) is the $\psi(4^3S_1)$ candidate.

[1] PRL124,152001 (2020) [2]EPJC81,83 (2021) [3]PRD **72,** 054026 (2005)

$Y(4260) \to K\bar{K}J/\psi$?



PRD 89, 072015 (2014)



PRD 97, 071101(R) (2018)

- If Y(4260) is a charmonium state, it should be observed in the $K\bar{K}J/\psi$ system.
- There are some hints for this decay, and it would be confirmed in the near future.

Summary of $\psi(4260)$

● **Excited $c\bar{c}$ state**	✓ Mass	✓ OZI rule	? Non R scan	✓ $\Gamma_{e^+e^-}$	✓ Γ_γ
● **Tetraquark**	? Mass	✓ OZI rule	? Non R scan	? $\Gamma_{e^+e^-}$	? Γ_γ
● **$c\bar{c}$-gluon hybrid**	? Mass	✓ OZI rule	? Non R scan	? $\Gamma_{e^+e^-}$	? Γ_γ
● **$D_1\bar{D}$ molecule**	✓? Mass	✓ OZI rule	? Non R scan	? $\Gamma_{e^+e^-}$	? Γ_γ
● **$D_s^{*+}D_s^{*-}$ effect**	~~✓ Mass~~	~~✓ OZI rule~~	~~✓ Non R scan~~		
● **et al.**					

Open charm channels significantly!

- As mentioned above, Y(4260) might interpreted as a mixture of 4^3S_1 (or mixed with a
- M
na

Thank you!

Backup

Theoretical interpretations

- **Excited charmonium:** PRD 99, 114003 (2019), EPJC 79, 613 (2019), EPJC **78**, 136 (2018), PRD**79**,094004(2009), PRD72,031503(2005)
- **Compact tetraquark:** PRD 89, 114010 (2014), EPJC 71, 1534
- **$c\bar{c}$-gluon hybrid:** Phys. Lett. B 628, 215. Phys. Lett. B 631, 164. Phys. Lett. B 625, 212.
- **Meson-meson molecule:** PRL 111, 132003, PRD 94, 054035 (2016), PRD 79, 014001, PRL**102**, 242003 (2009),
- **Threshold effect:** Acta Phys.Pol.B.**51**(8),1713–1737(2020)
- **et al.**