ICTP-SAIFR/FAIR Workshop on mass Generation in QCD

Recent Developments on the X, Y and Z States

Marina Nielsen

arXiv:1812.08207

Albuquerque, Dias, Khemchandani, Martínez Torres, Navarra, MN, Zanetti

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	experiment	Year
$X(3872)$	3871.69±0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [22–24], BaBar [25]	2003
				$p\bar{p} \to (\pi^+\pi^- J/\psi)$ (...)	CDF [26–28], DØ [29]	
				$B \to K(\omega J/\psi)$	Belle [30], BaBar [31]	
				$B \to K(D^{*0}\bar{D}^0)$	Belle [32, 33], BaBar [34]	
				$B \to K(\gamma J/\psi)$	Belle [30], BaBar [35, 36]	
				$B \to K(\gamma\psi(2S)$	BaBar [36], LHCb [37]	
				$e^+e^- \to \pi^+\pi^- J/\psi$	BESIII [38]	
				$pp \to (\pi^+\pi^- J/\psi)$ (...)	LHCb [39, 40], CMS [41]	
$Z_c^+(3900)$	3886.6 ± 2.4	28.2±2.6	1^{+-}	$Y(4260) \to (J/\psi\,\pi^+)\pi^-$	BESIII [42], Belle [43], CLEO-c [44]]	2013
				$Y(4260) \to (D\bar{D}^*)^+\pi^-$	BESIII [45]	
$Y(3940)$	3918.4 ± 1.9	20±5	$0/2^{++}$	$B \to K\,(J/\psi\omega)$	Belle [46], BaBar [31, 47]	2004
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [48], BaBar [49]	
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi$ (...)	Belle [50]	2005
				$e^+e^- \to J/\psi\,(DD^*)$	Belle [51]	
$Y(4008)$	3891 ± 42	255±42	1^{--}	$e^+e^- \to \pi^+\pi^- J/\psi$	Belle [43, 52], BESIII [53]	2007
$Z_c^+(4020)$	4024.1 ± 1.9	13 ± 5	$?^{?-}$	$e^+e^- \to \pi^-(\pi^+h_c)$	BESIII [54]	2013
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BESIII [55]	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?-}$	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [56], BaBar [57]	2008
$Z_c^+(4055)$	4054 ± 3	45	$(?^{?-})$	$e^+e^- \to \pi^-(\pi^+\psi(2S))$	Belle [58]	2014
$Z_c^-(4100)$	$(4096\pm^{+28}_{-32})$	$152^{+70}_{-45})$	$0^{++}/1^{-+}$	$B^0 \to K^+(\pi^-\eta_c(1S))$	LHCb [59]	2018
$Y(4140)$	4146.8 ± 2.4	22^{+8}_{-7}	1^{++}	$B \to K(\phi J/\psi)$	CDF [60, 61], D0 [62], LHCb [63], BESIII [64, 65]	2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$	Belle [51]	2007
$Z_c^+(4200)$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$B \to K(\pi^+J/\psi)$	Belle [66]	2014
$Y(4220)$	4218^{+5}_{-4}	59^{+12}_{-10}	1^{--}	$e^+e^- \to \chi_{c0}\,\omega$	BESIII [67]	2014
				$e^+e^- \to h_c\,\pi^+\pi^-$	BESIII [68]	
				$e^+e^- \to \psi(2S)\,\pi^+\pi^-$	BESIII [69]	
				$e^+e^- \to D^0D^{*-}\,\pi^+$	BESIII [70]	

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first one

last one

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	experiment	Year
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [56], BaBar [57]	2008
$Y(4260)$	4230 ± 8	55 ± 19	1^{--}	$e^+e^- \to \pi^+\pi^- J/\psi$	BaBar [71, 72], CLEO-c [73], Belle [43, 52], BESIII [53]	2005
				$e^+e^- \to K^+K^- J/\psi$	CLEO-c [74], BESIII [45]	
				$e^+e^- \to \pi^0\pi^0 J/\psi$	CLEO-c [74]	
				$e^+e^- \to Z_c(3900)^\pm \pi^\mp$	Belle [43], BESIII [42]	
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$?^{?+}$	$e^+e^- \to \phi J/\psi$	Belle [75]	2009
$Y(4360)$	4368 ± 13	96 ± 7	1^{--}	$e^+e^- \to \pi^+\pi^- \psi(2S)$	BaBar [76, 77], Belle [58, 78], BESIII [69]	2007
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$Y(4390)$	$4391.5^{+7.3}_{-7.8}$	$139.5^{+16.3}_{-20.7}$	1^{--}	$e^+e^- \to h_c \pi^+\pi^-$	BESIII [68]	2016
$Z^+(4430)$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$B \to K^-(\pi^+\psi(2S))$	Belle [79–81], BaBar [82], LHCb [83]	2007
				$B \to K^-(\pi^+ J/\psi)$	Belle [66], BaBar [82]	
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \Lambda_c^+\Lambda_c^-$	Belle [84]	2008
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \pi^+\pi^- \psi(2S)$	Belle [58, 78], BaBar [77]	2007
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first charged one ➜ not a $c\bar{c}$ state

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first charged one ➜ not a $c\bar{c}$ state

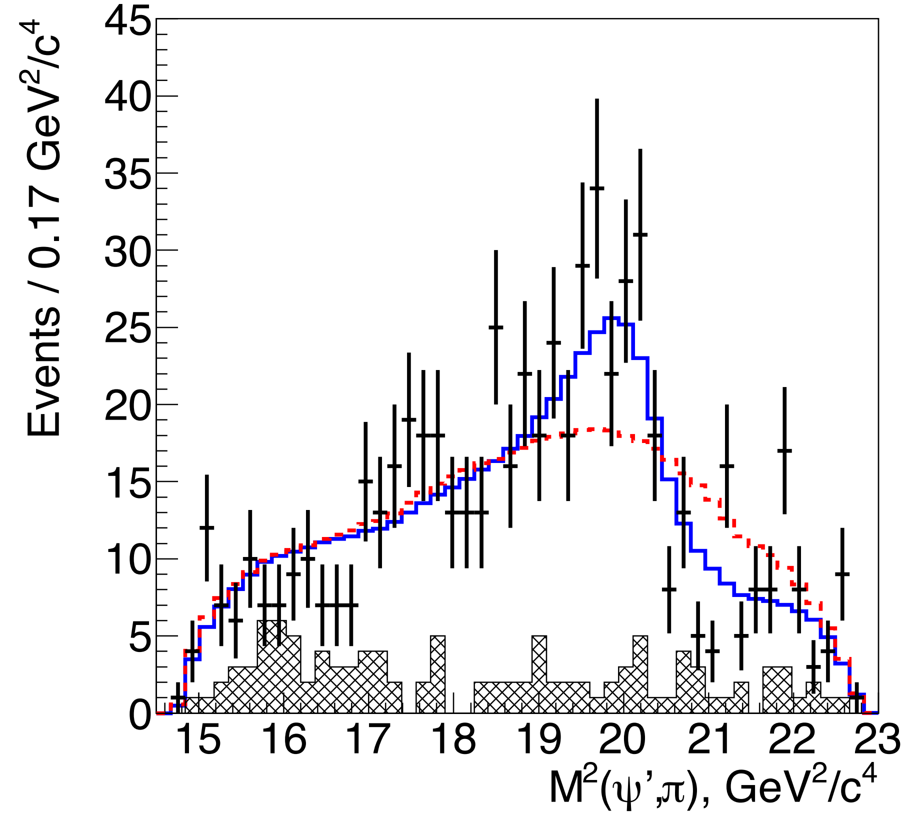
arXiv:0905.2869

searched $Z^-(4430)$ in 4 decay modes:

no conclusive
evidence for the existence of $Z^+(4430)$ seen by
Belle

arXiv:1306.4894

confirm the observation of $Z^+(4430)$ with 6.1σ and $J^P=1^+$



arXiv:1306.4894

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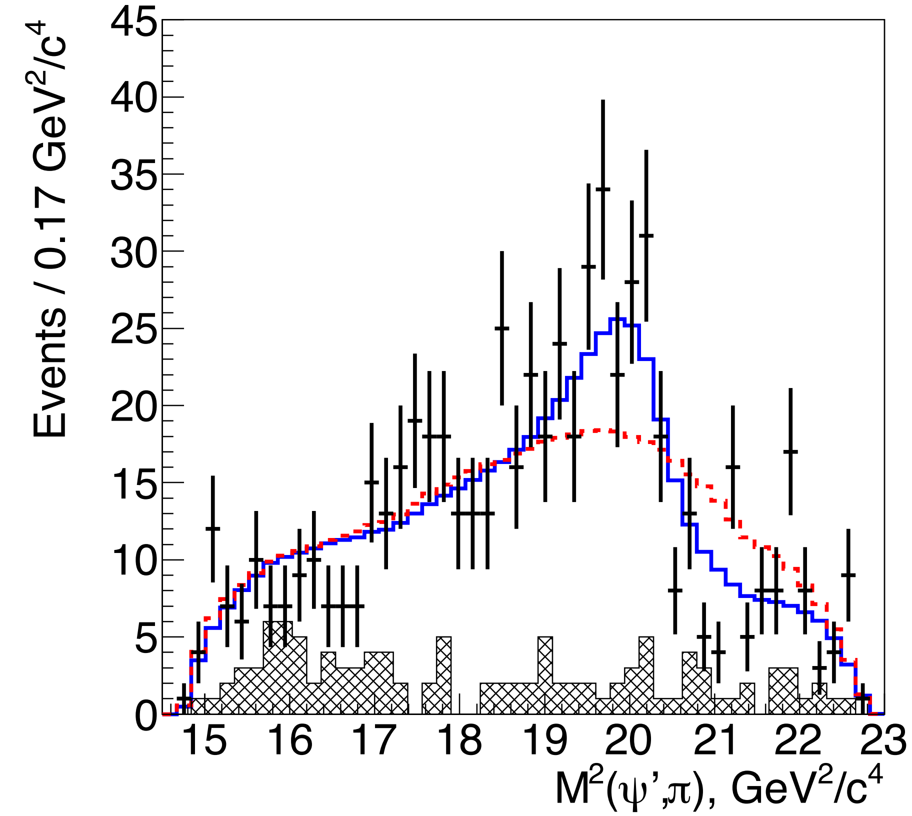
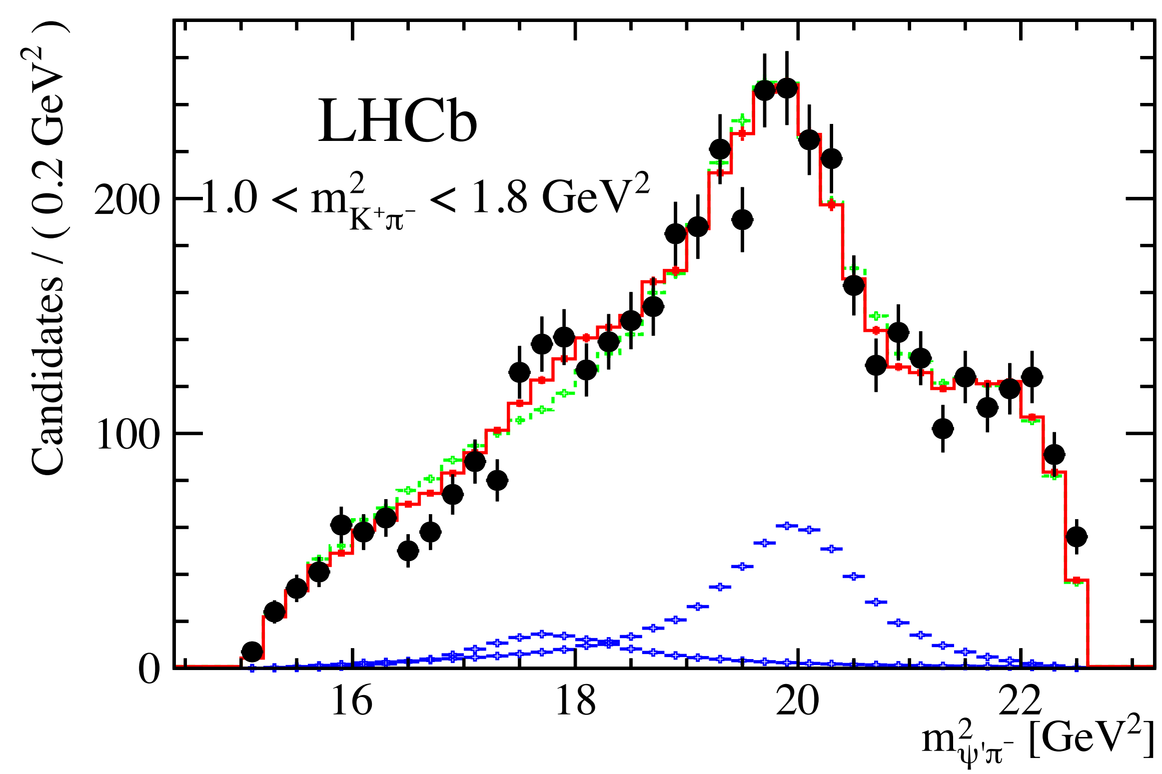


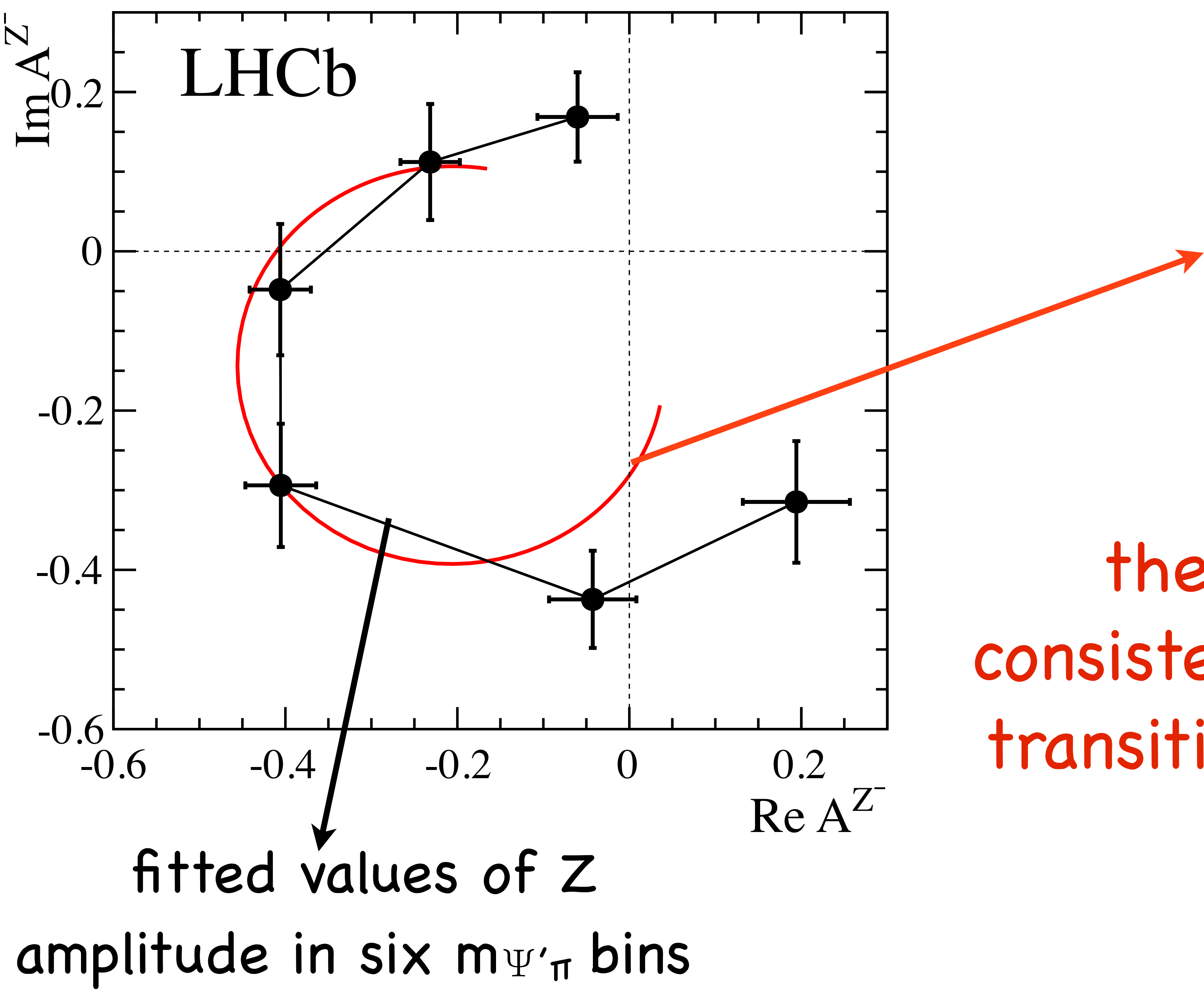
arXiv:1404.1903

has confirmed the observation of $Z^+(4430)$ with 13.9σ and $J^+ = 1^+$

M = (4475±7±20) MeV
Γ = (172±13±35) MeV



(arXiv:1404.1903) also did the first attempt to demonstrate the resonant behavior of $Z^+(4430)$: the Breit-Wigner amplitude was replaced by a combination of independent complex amplitudes at six equally spaced points in $m_{\Psi'\pi}$ range covering the $Z^+(4430)$ peak region



the Argand diagram is consistent with a rapid phase transition, as expected for a resonance

$Z^+(4430)$

threshold effect in the $D_1 D^*$ channel
Rosner, arXiv:0708.3496

four-quark radial excitation with $J^{PC} = 1^{+-}$
Maiani, Polosa & Riquer, arXiv:0708.3997

radial excitation of $\Lambda_c - \Sigma_c^0$ bound state
Qiao, arXiv:0709.4066

$D_1 D^*$ molecular state with $J^P = 0^-, 1^-, 2^-$
Meng & Cheng, arXiv:0708.4222

cusp in the $D_1 D^*$ channel
Bugg, arXiv:0709.1254

$D_1 D^*$ molecular state with $J^P = 1^+$
He, arXiv:1410.8645

$D_1 D^*$ or $D_2 D^*$ molecular state with $J^P = 1^+$
Ma, Liu, Liu, Zhu, arXiv:1404.3450; Barnes, Close, Swanson, arXiv:1409.6651

not a real state

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before LHCb

after LHCb

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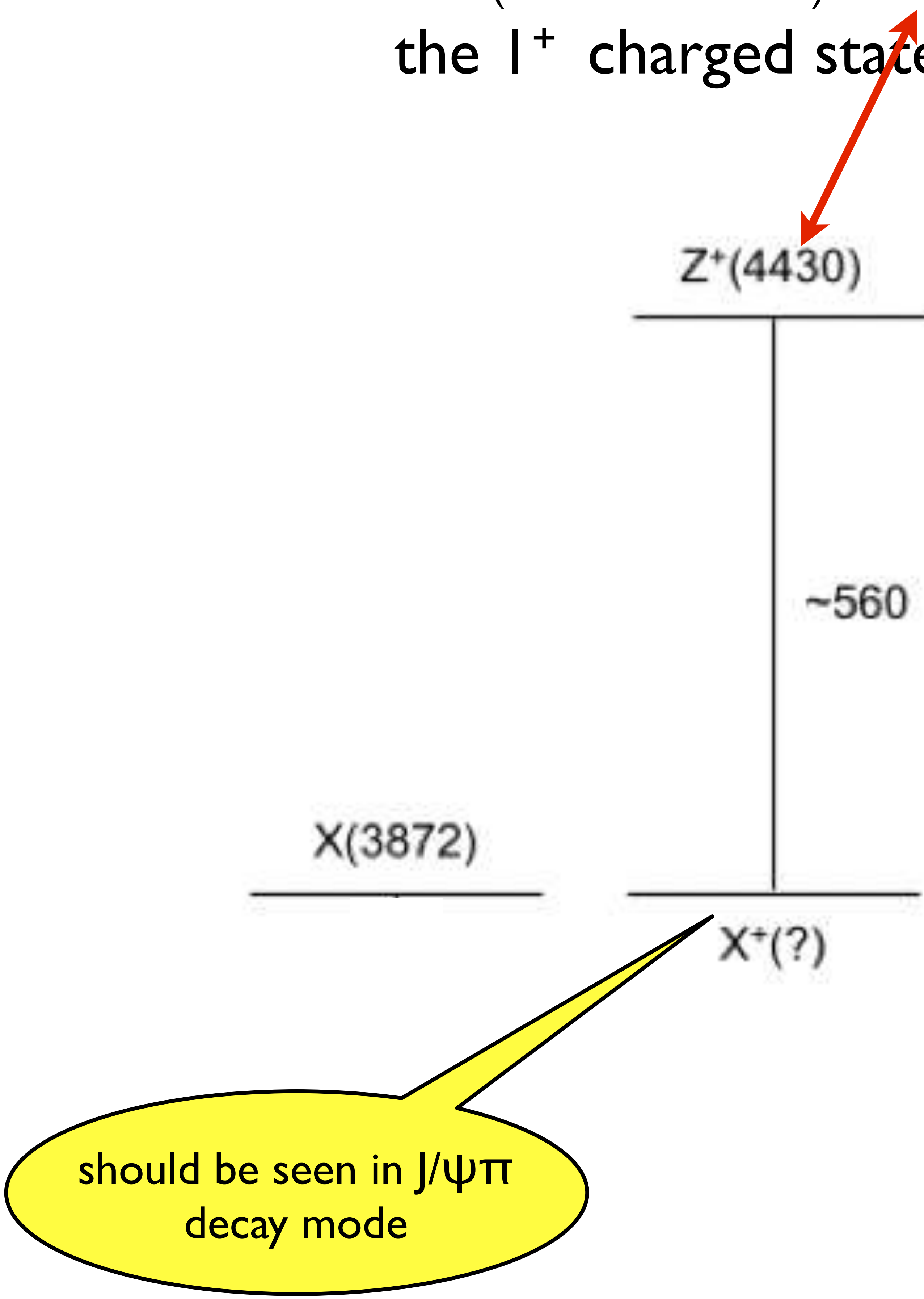
Maiani et al. (arXiv:0708.3997) : four-quark radial excitation of the 1^+ charged state (X(3872) partner)



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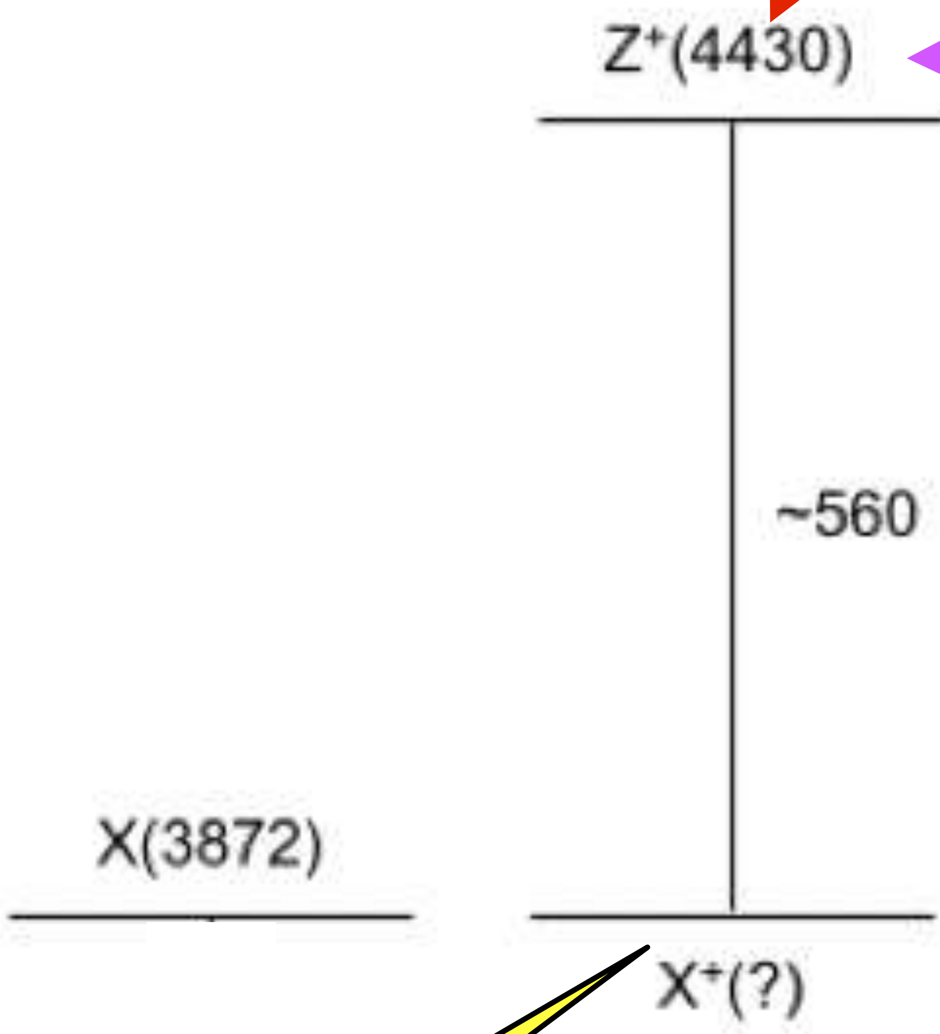

$Z^+(4430) \to \psi(2S)\pi^+$

should be seen in J/ψπ decay mode

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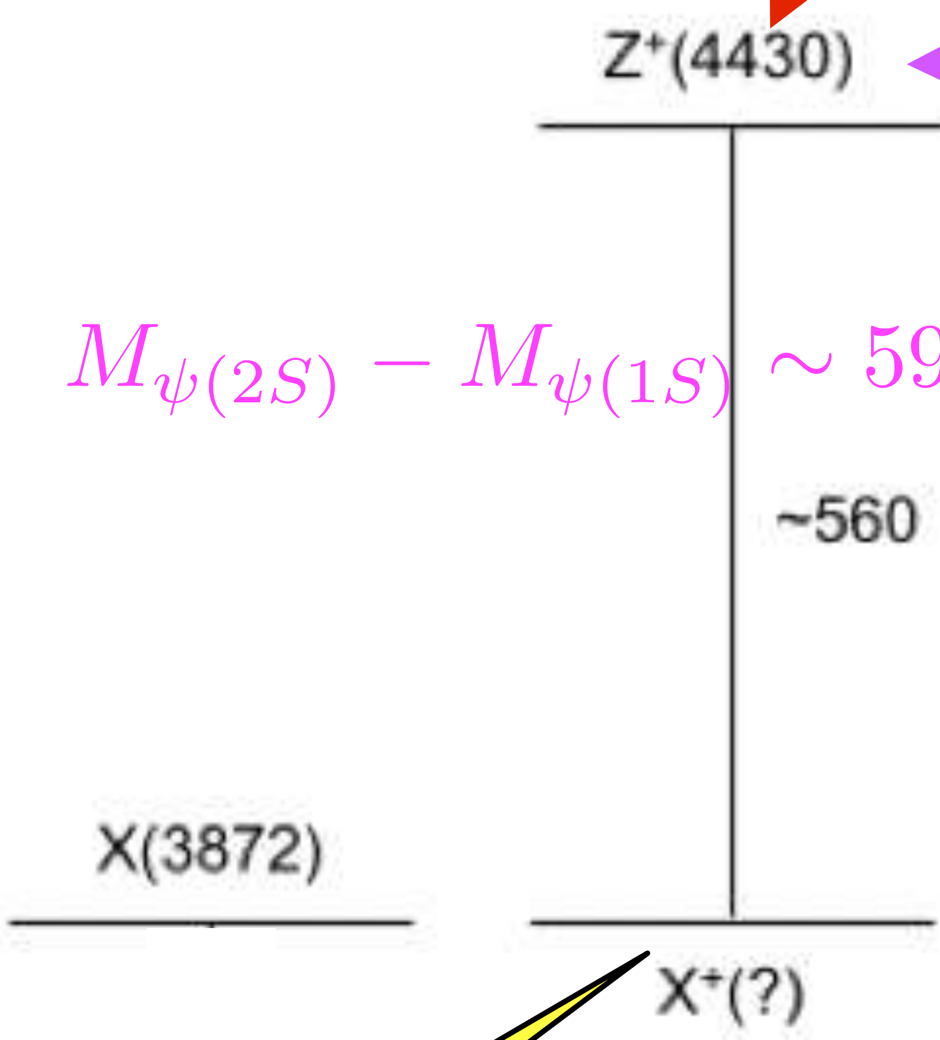

$Z^+(4430) \to \psi(2S)\pi^+$

$$M_{\psi(2S)} - M_{\psi(1S)} \sim 590 \text{ MeV} \sim M_{Z^+} - M_X$$

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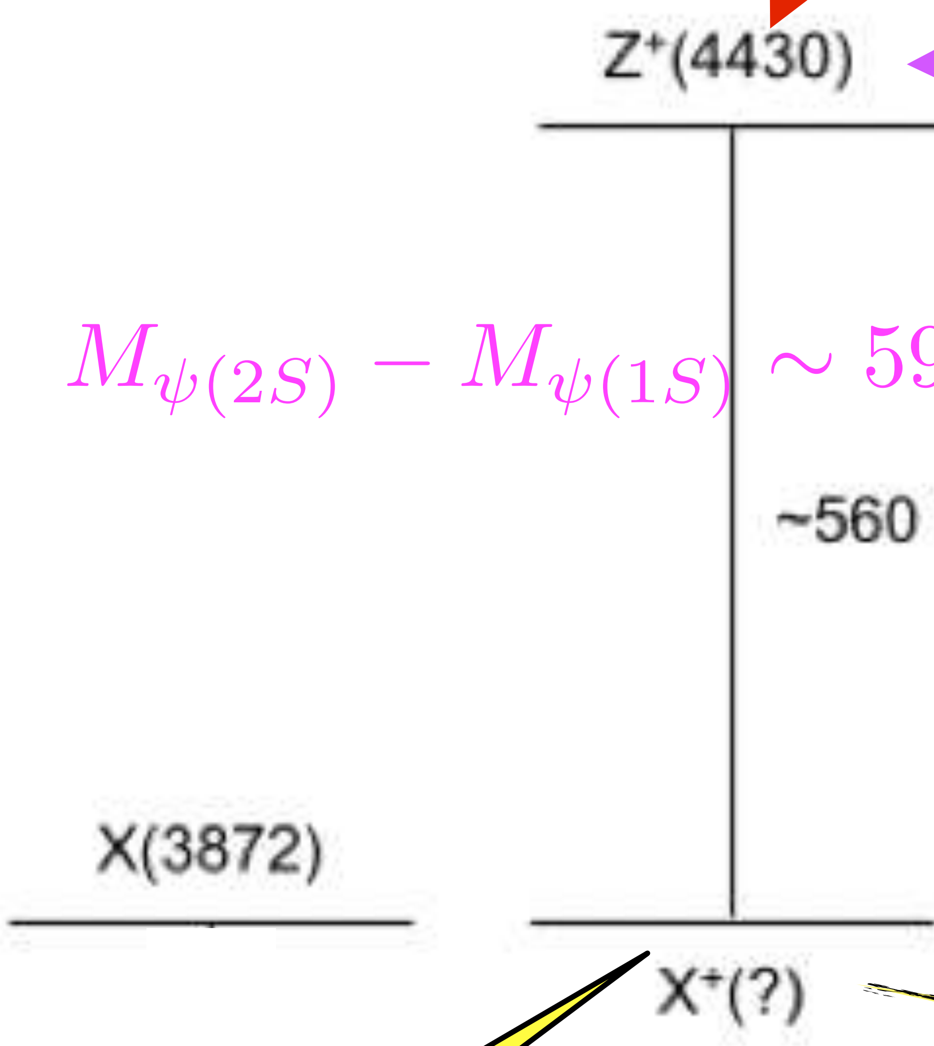

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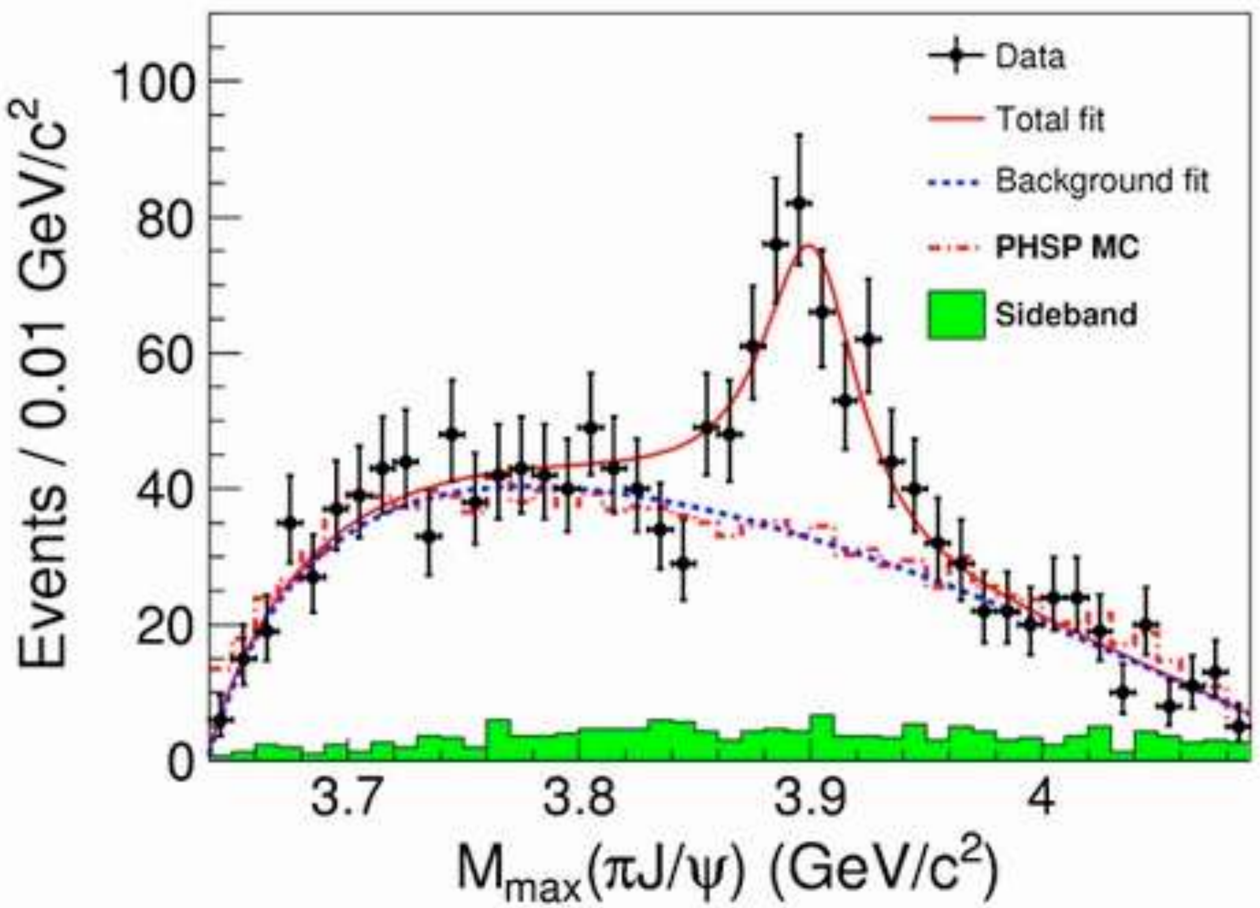
$Z_c^+(3900)$

BES III

BELLE

2013

Charged Charmonium states discovered in 2013

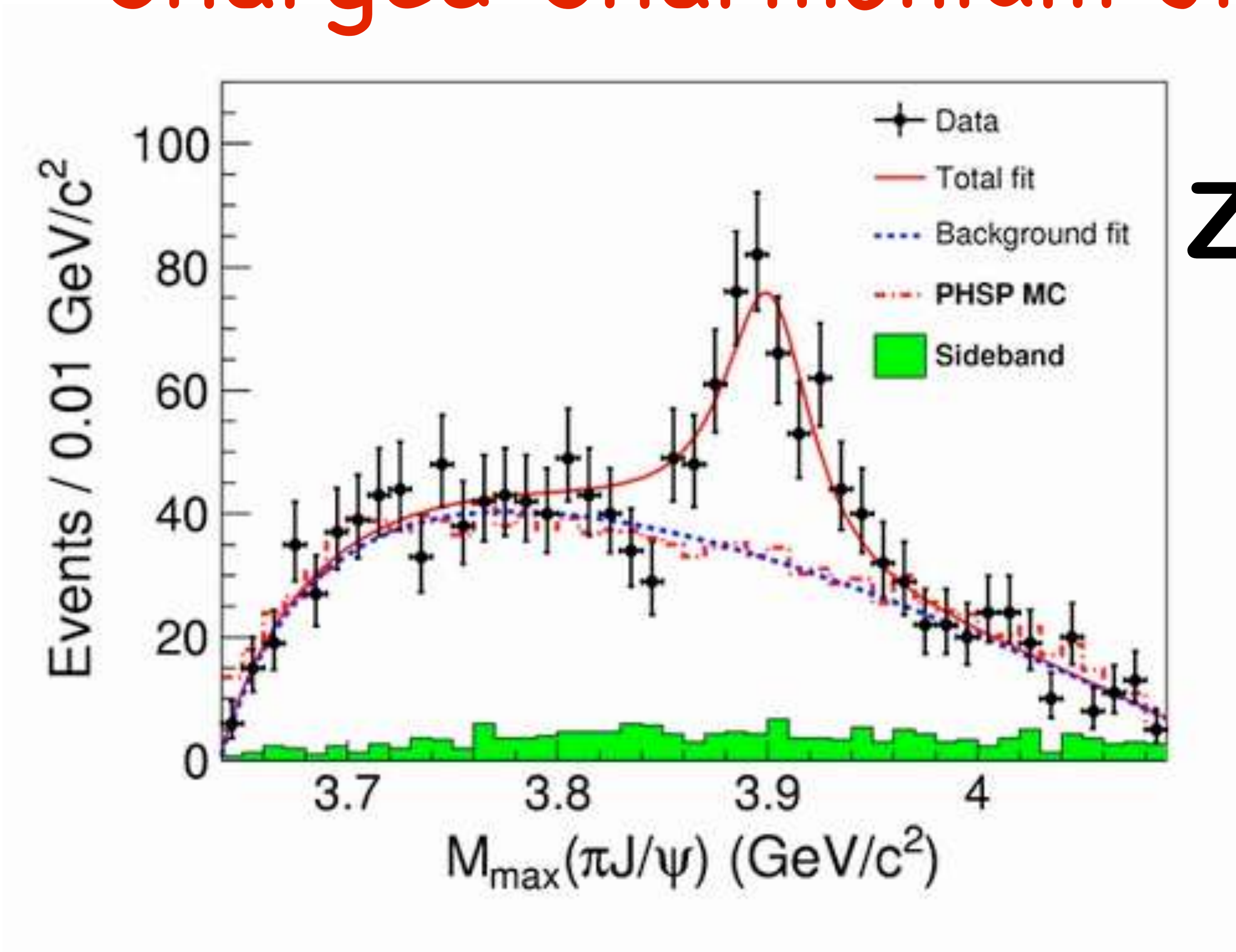


$Z_c^+(3900)$ BES III BELLE

arXiv:1303.5949 arXiv:1304.0121

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

Charged Charmonium states discovered in 2013



$Z_c^+(3900)$ BESIII BELLE

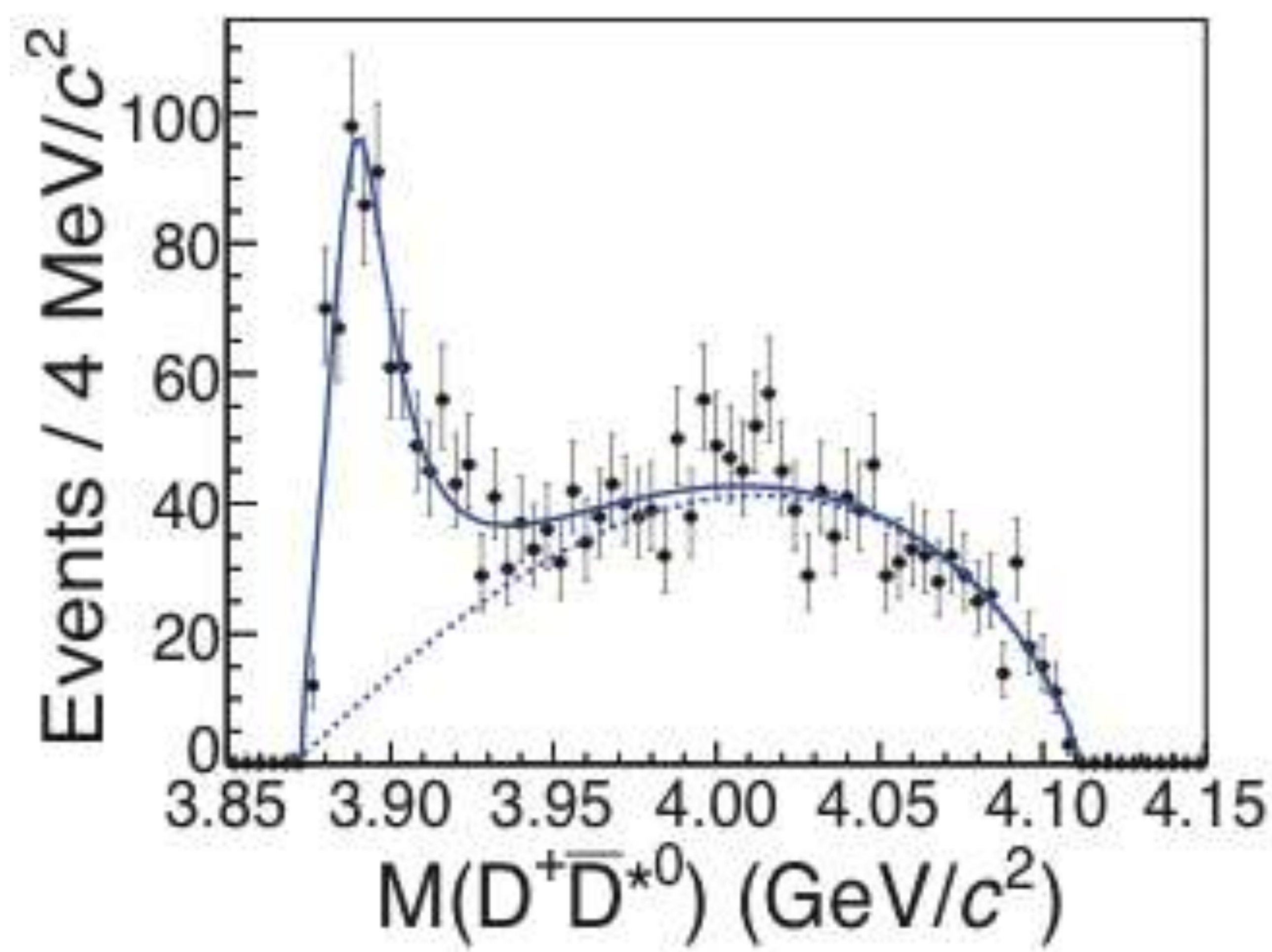
arXiv:1303.5949 arXiv:1304.0121

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

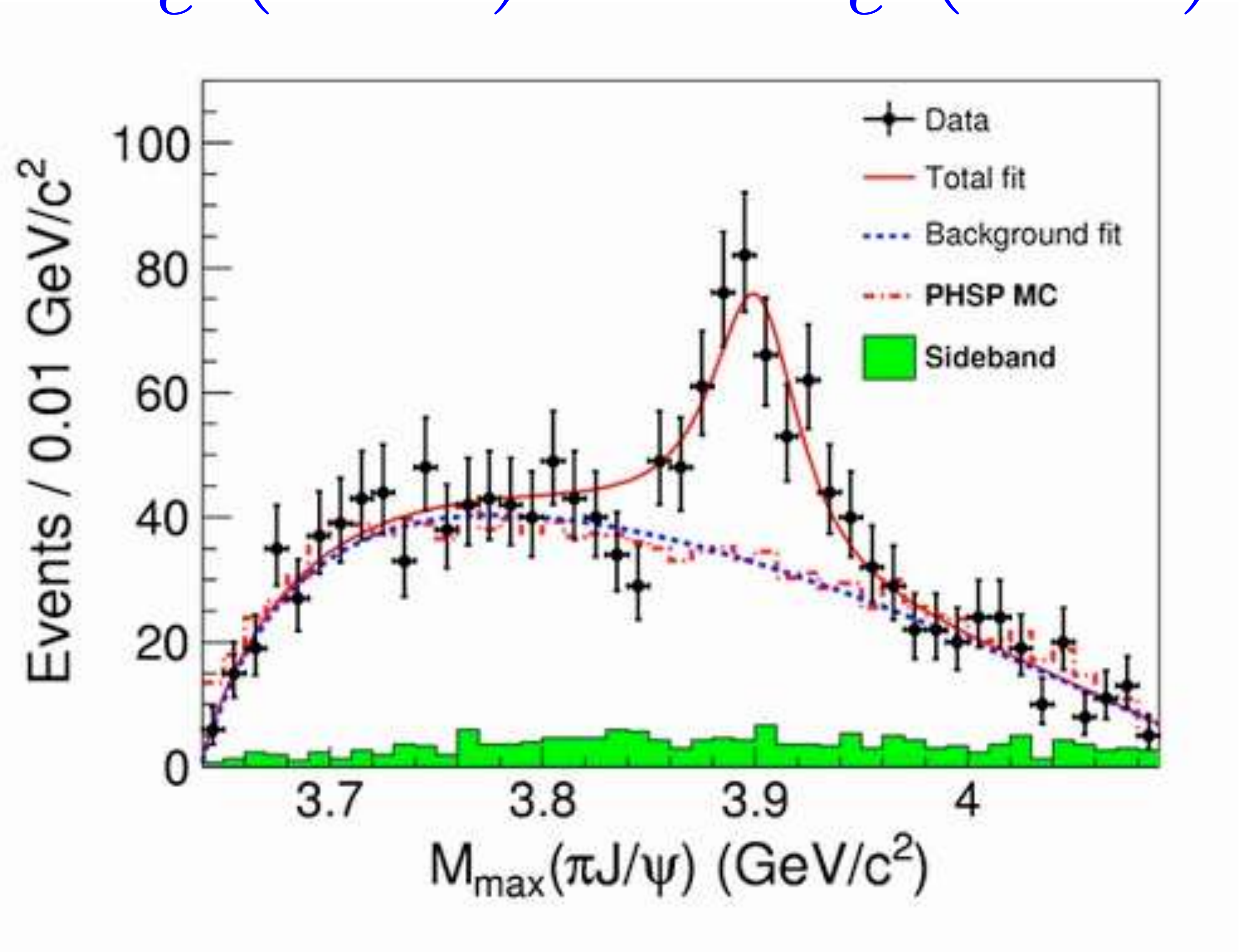
$Z_c^+(3885)$ BESIII

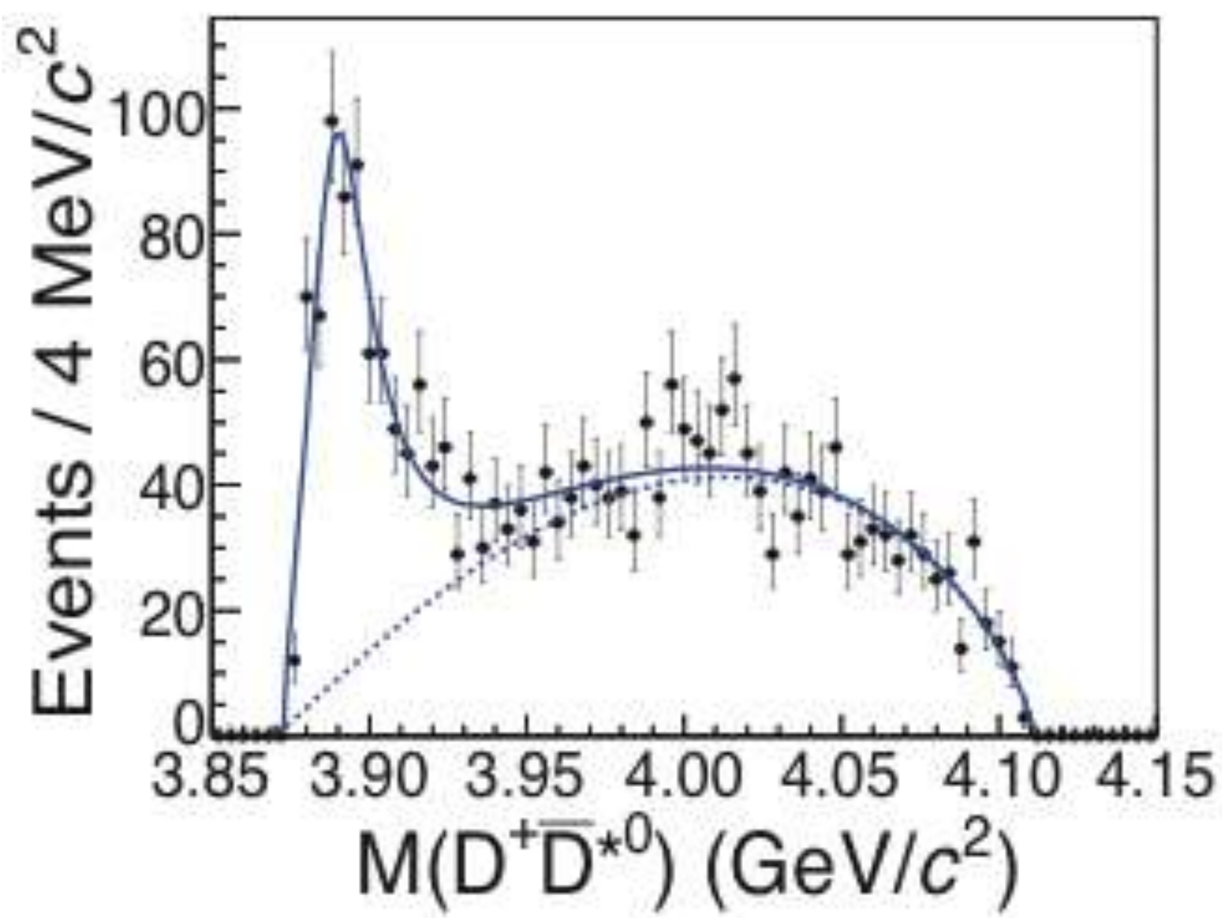
arXiv:1310.1163

$$e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp \text{ @ } \sqrt{s} = 4.26 \text{ GeV}$$



$Z_c^+(3900)$ and $Z_c^+(3885)$ could be the same state?

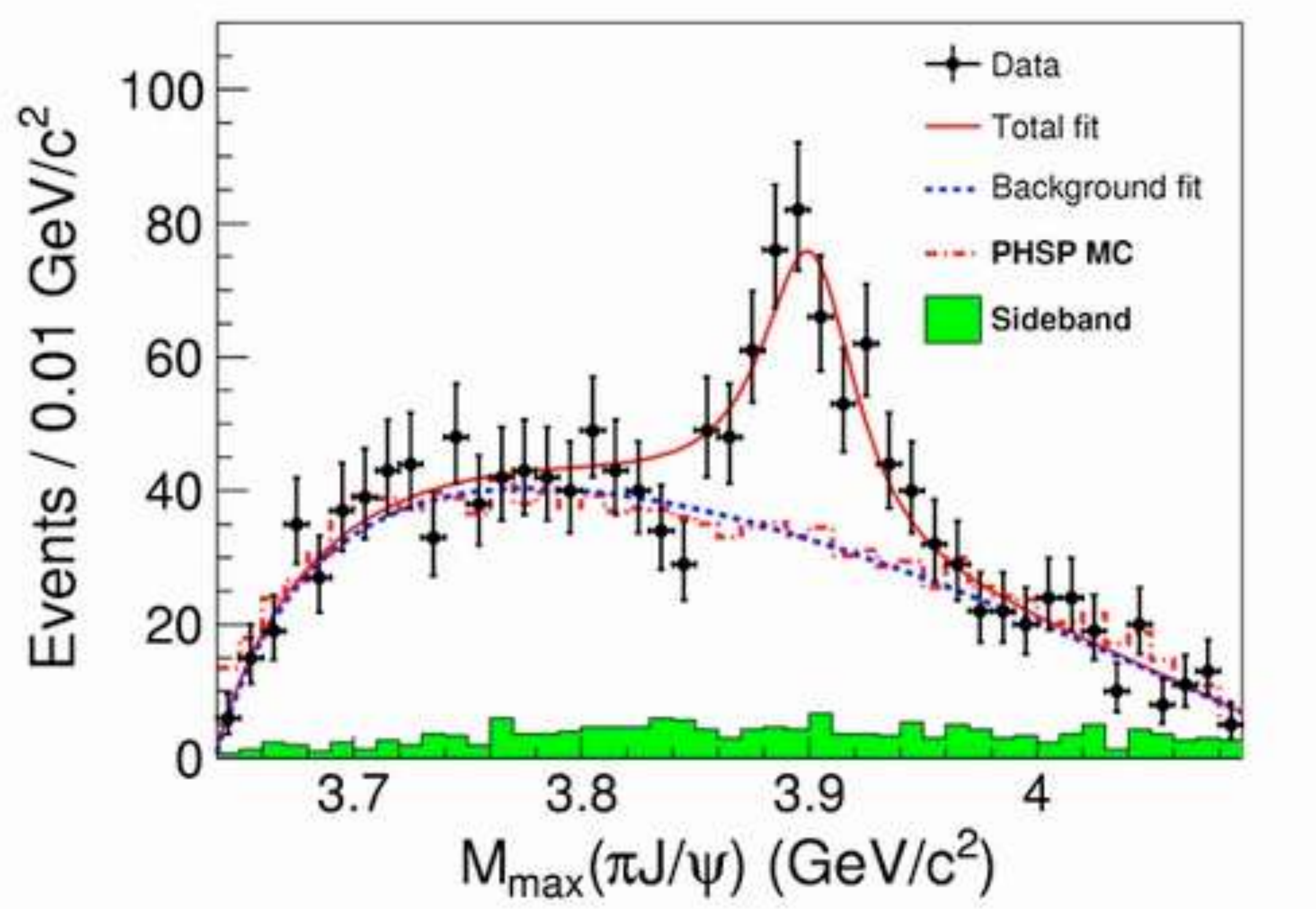


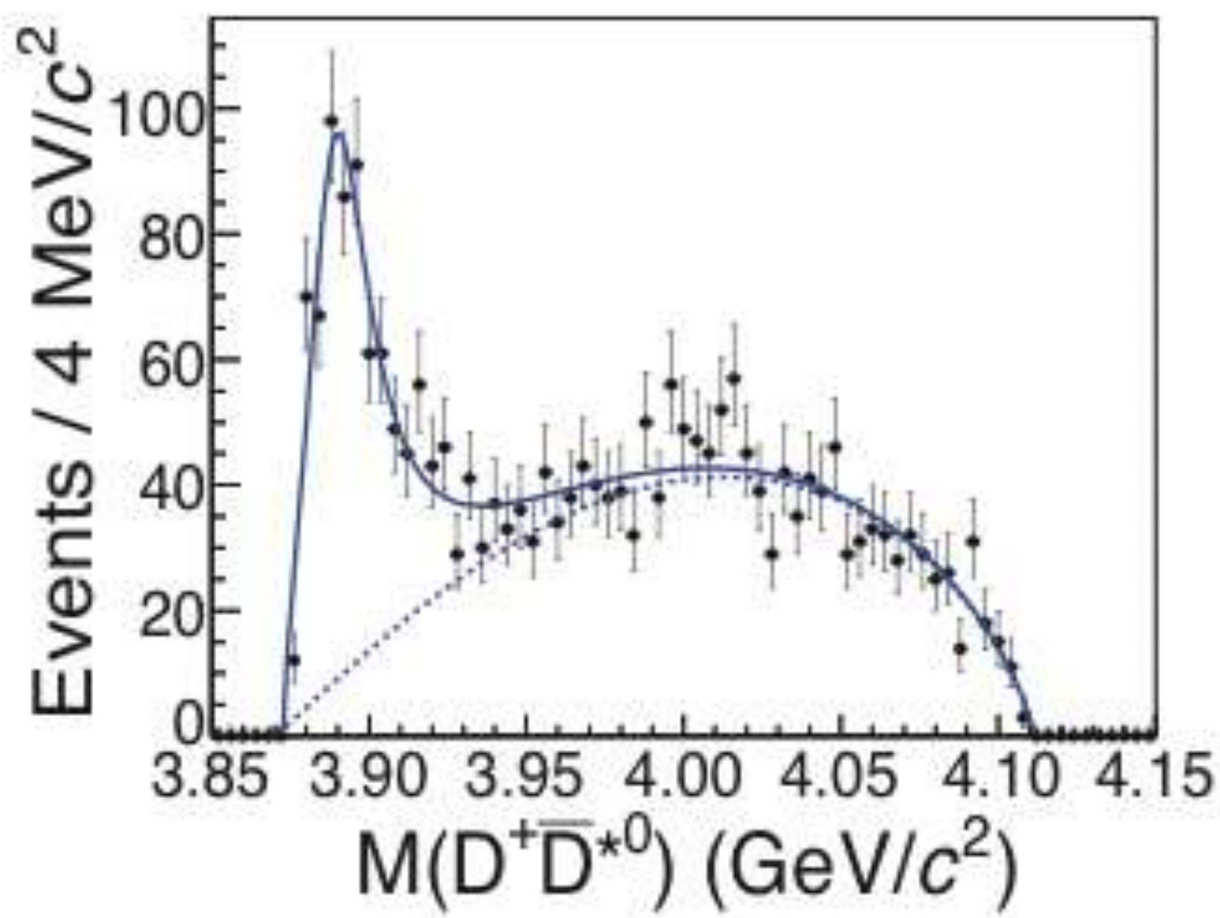


M = (3890±3.6±4.9) MeV
Γ = (46±10±20) MeV

M = (3883.9±1.5±4.2) MeV
Γ = (24.8±3.3±11.0) MeV

$Z_c^+(3900)$ and $Z_c^+(3885)$ could be the same state?





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BESIII

arXiv:1310.1163

Assuming $Z_c(3885)$ and $Z_c(3900)$ to be the same state ⇒

$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

PDG

$Z_c(3900)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$J/\psi\,\pi$	seen
Γ_2	$h_c\,\pi^\pm$	not seen
Γ_3	$\eta_c\,\pi^+\pi^-$	not seen
Γ_4	$(D\,D^*)^\pm$	seen
Γ_5	$D^0\,D^{*-}$ + c.c.	seen
Γ_6	$D^-\,D^{*0}$ + c.c.	seen
Γ_7	$\omega\,\pi^\pm$	not seen
Γ_8	$J/\psi\,\eta$	not seen
Γ_9	$D^+\,D^{*-}$ + c.c	seen
Γ_{10}	$D^0\,\overline{D}^{*0}$ + c.c	seen

PDG

$Z_c(3900)$ DECAY MODES

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Γ_4	$(D D^*)^{\pm}$	seen
Γ_5	$D^0 D^{*-}$ + c.c.	seen
Γ_6	$D^- D^{*0}$ + c.c.	seen
Γ_7	$\omega\pi^{\pm}$	not seen
Γ_8	$J/\psi\eta$	not seen
Γ_9	$D^+ D^{*-}$ + c.c	seen
Γ_{10}	$D^0 \overline{D}^{*0}$ + c.c	seen

$Z_c(3900)$

$Z_c(3885)$

QCDSR Results for decay widths of the $Z_c^+(3900)$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2
$Z_c^+(3900)\eta_c\rho^+$	4.85 ± 0.81	27.5 ± 8.5
$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
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$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 0.22 \pm 0.12$$

same result as in Maiani et al.
using a tetraquark model
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QCDSR Results for decay widths of the $Z_c^+(3900)$

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BES III

$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to\pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

QCDSR and tetraquark model $\Rightarrow$ not the same state!

up to now: 8 charmonium charged states

$Z^+(4430)$ 2007	$Z_1^+(4050)$ 2008	$Z_2^+(4250)$ 2008
$Z_c^+(3900)$ 2013	$Z_c^+(4020)$ 2013	$Z_c^+(4055)$ 2014
$Z_c^+(4200)$ 2014	$Z_c^+(4100)$ 2018 3σ ! needs confirmation	

up to now: 8 charmonium charged states

$Z^+(4430)$ 2007	$Z_1^+(4050)$ 2008 M=(4051±35)MeV Γ=(82±52)MeV $\pi^+\chi_{c1}$	$Z_2^+(4250)$ 2008
$Z_c^+(3900)$ 2013	$Z_c^+(4020)$ 2013	$Z_c^+(4055)$ 2014 M=(4054±3)MeV Γ=(45±15)MeV $\pi^+\Psi(2S)$
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up to now: 8 charmonium charged states

BELLE $Z^+(4430)$ 2007 BELLE LHCb	BELLE $Z_1^+(4050)$ 2008 $M=(4051\pm35)$MeV $\Gamma=(82\pm52)$MeV $\pi^+\chi_{c1}$	BELLE $Z_2^+(4250)$ 2008
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$Z_c^+(4200)$ 2014 BELLE	$Z_c^+(4100)$ 2018 LHCb 3σ ! needs confirmation	

Y ($J^{PC}=1^{--}$) Family

State	Name in PDG	Decay channel	Experiment	Year
$Y(4220)$	$\psi(4230)$	$Y(4220) \to \chi_{c0}\,\omega$	BESIII [67]	2015
		$Y(4220) \to h_c\,\pi^+\pi^-$	BESIII [68]	2017
		$Y(4220) \to \psi(2S)\,\pi^+\pi^-$	BESIII [69]	2017
		$Y(4220) \to D^0 D^{*-}\,\pi^+$	BESIII [70]	2018
$Y(4260)$	$\psi(4260)$	$Y(4260) \to J/\psi\,\pi^+\pi^-$	BaBar [71, 72]; CLEO-c [73]; Belle [43, 52]	2005
		$Y(4260) \to J/\psi\,\pi^0\pi^0$	CLEO-c [74]	2006
		$Y(4260) \to J/\psi\,K^+K^-$	CLEO-c [74]; Belle [201, 202]	2006
		$Y(4260) \to J/\psi\,f_0(980)$	BaBar [72]	2012
		$Y(4260) \to Z_c(3900)^{\pm}\,\pi^{\mp}$	Belle [43]; BESIII [42]	2013
		$Y(4260) \to J/\psi\,\pi^+\pi^-$	BESIII [53]	2017
$Y(4360)$	$\psi(4360)$	$Y(4360) \to \psi(2S)\,\pi^+\pi^-$	Belle [58, 78]; BaBar [76, 77]; BESIII [69]	2007
		$Y(4360) \to J/\psi\,\pi^+\pi^-$	BESIII [53]	2017
$Y(4390)$	$\psi(4390)$	$Y(4390) \to h_c\,\pi^+\pi^-$	BESIII [68]	2017
		$Y(4390) \to \psi(2S)\,\pi^+\pi^-$	BESIII [69]	2017
$Y(4660)$	$\psi(4660)$	$Y(4660) \to \psi(2S)\,\pi^+\pi^-$	Belle [58, 78]; BaBar [77]	2007
		$Y(4660) \to \Lambda_c^+\Lambda_c^-$	BESIII [84]	2008

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first one

last one

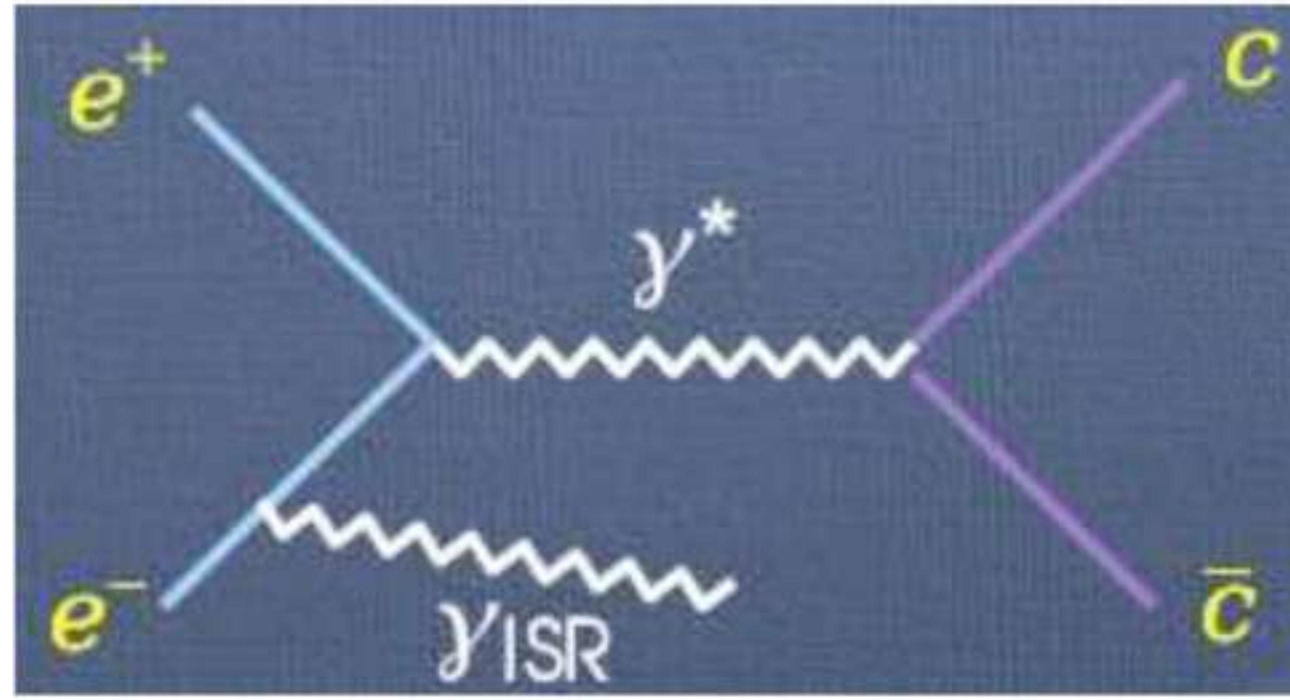
First three states

$e^+e^- \rightarrow 1^{--}$ **Final States**

via Initial State Radiation (ISR)

$e^+e^- \rightarrow \gamma_{IRS}(c\bar{c})$

data collected at 10.6 GeV



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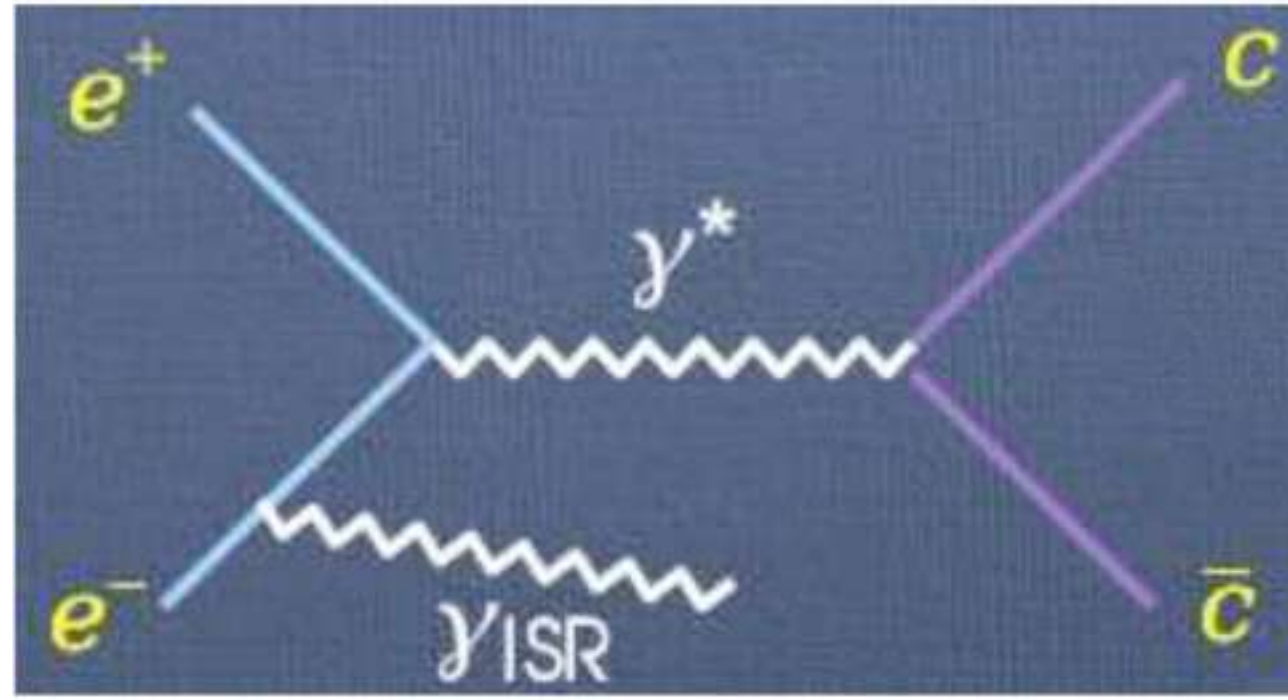

		2008 → 2018
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(07)	$Y(4360) \rightarrow \psi(2S)\pi^+\pi^-$	M =(4361±15) → (4368±13) MeV Γ = (74±23) → (96±7) MeV
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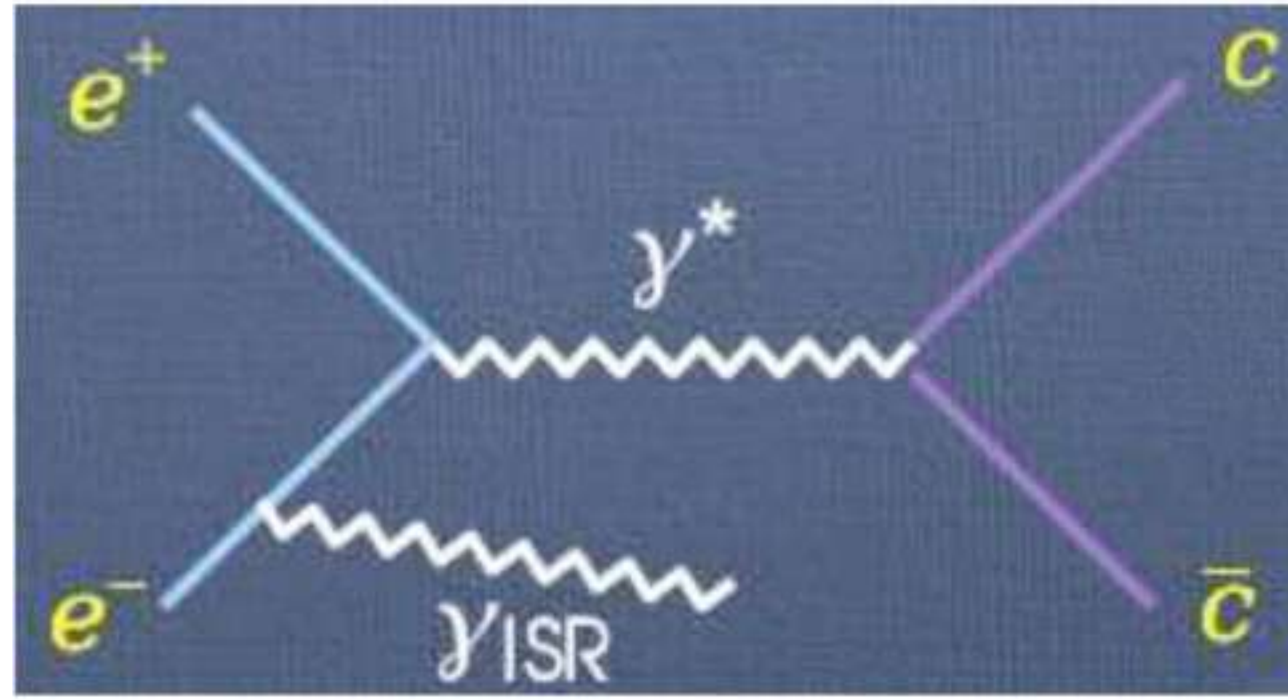

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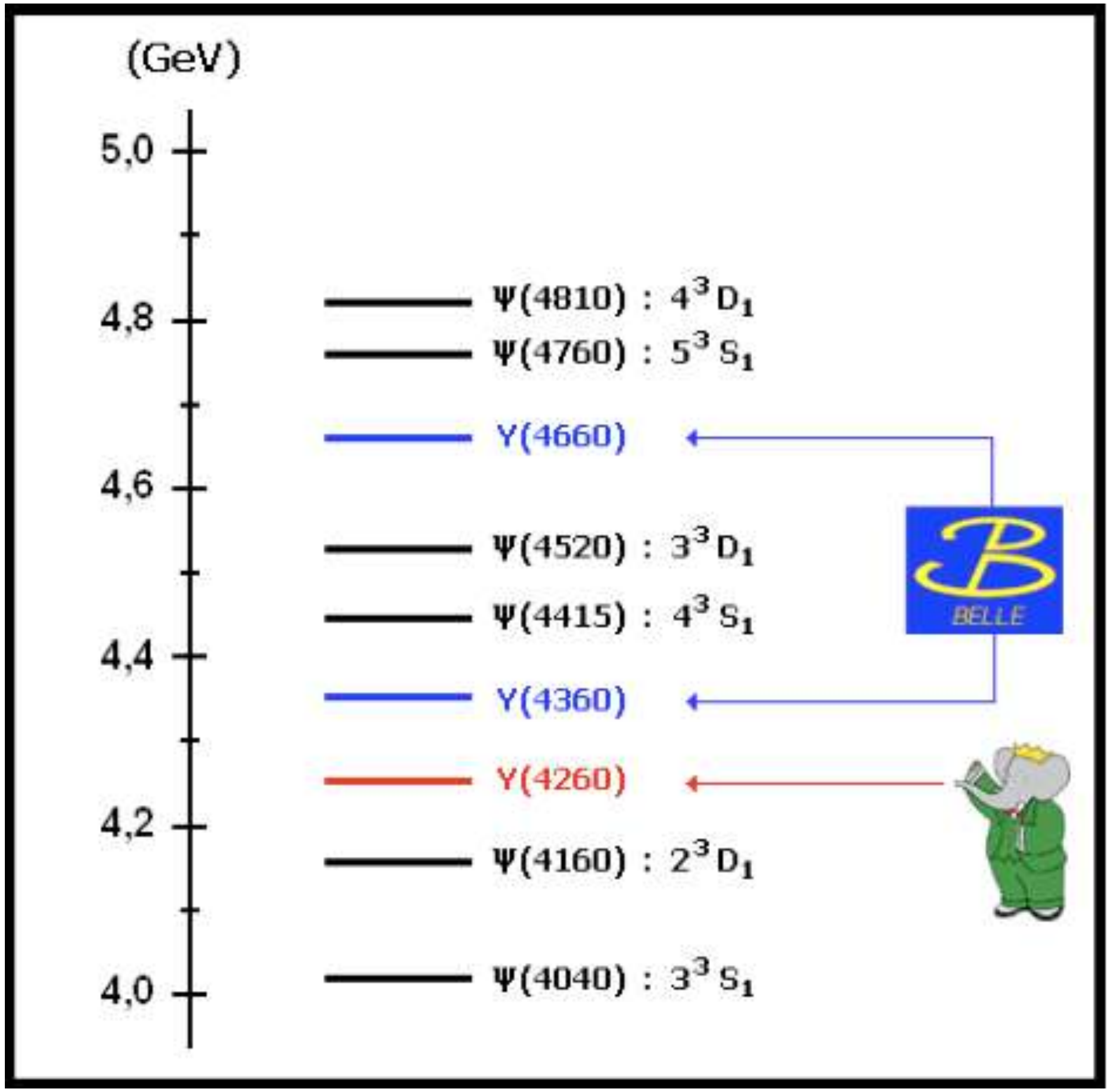
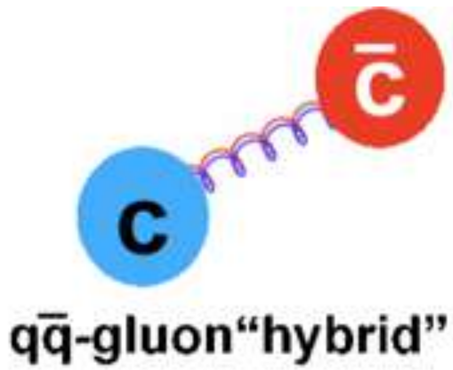
BELLE

Why exotics?

masses and widths of these states are not consistent with any of the 1^{--} charmonium states



Y(4260): charmonium hybrid



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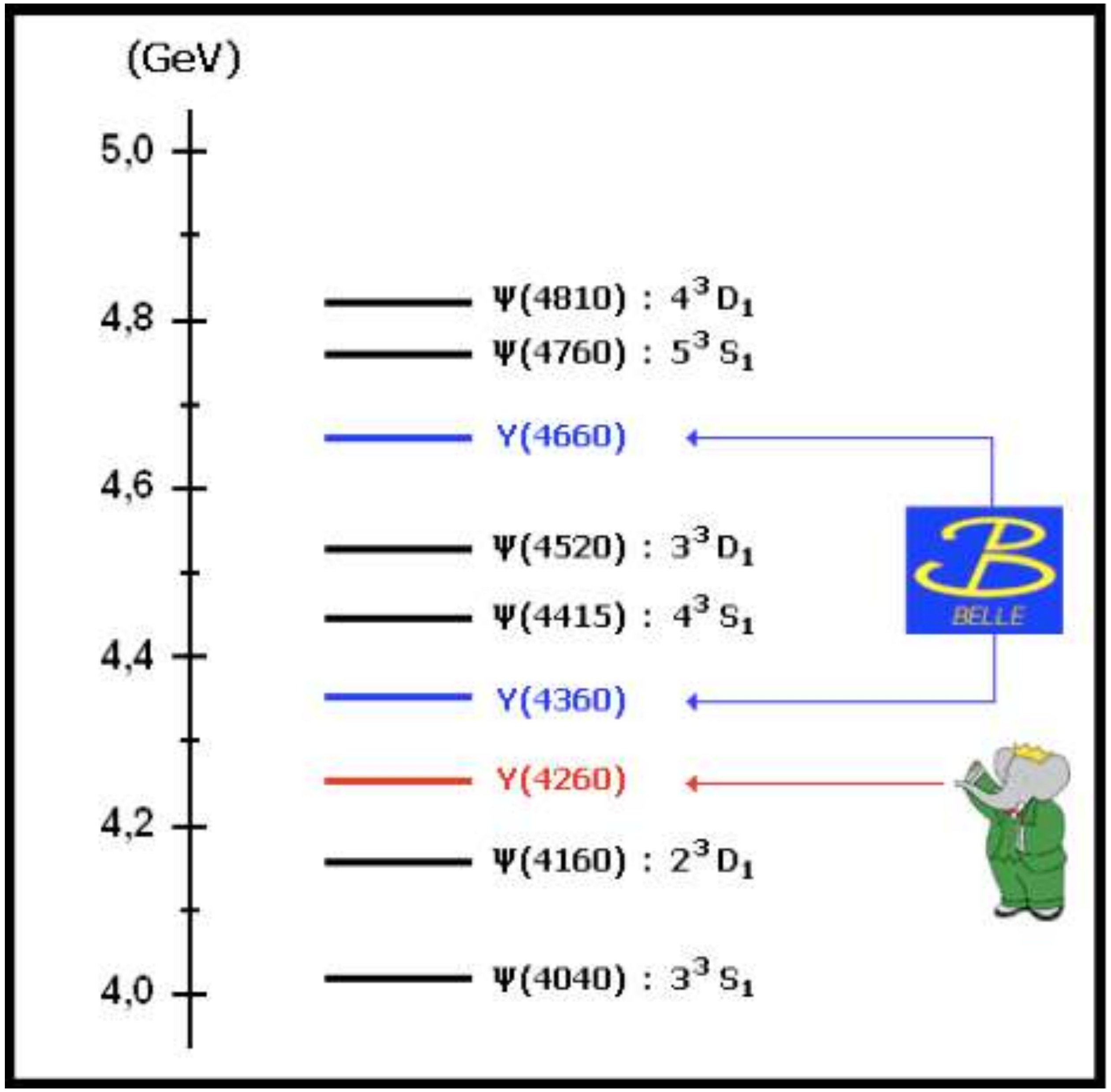

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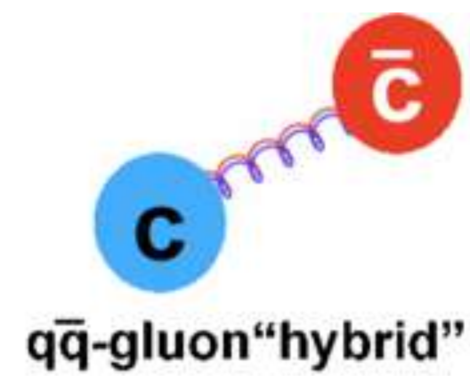

Charmonium hybrids:

- Lattice (EJPA18(04) and string model calc. (PRD77(08): M~4400 MeV
- flux tube (PRD52(95): M~4200 MeV

charmonium hybrid ➡ dominant decay mode $D\bar{D}_1$

(Close & Page, PRLB628(05)215)

Maiani et al. (PRD72 (05)) tetraquark $J^{PC} = 1^{--}$ states:

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{\text{P-wave}}$$

Ebert et al. (EPJC58(08)) ➡ such state would have M ~ 4450 MeV

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Y(4260)

- baryonium $\Lambda_c - \bar{\Lambda}_c$ state (Qiao, PLB639(06))
- *S*-wave threshold effect (Rosner, PRD74(06))
- molecular state (Ding, Liu et al.,Yuan et al., MN et al.,...)
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Observed at B factories with limited statistics

High precision measurements at BESIII supply new insights

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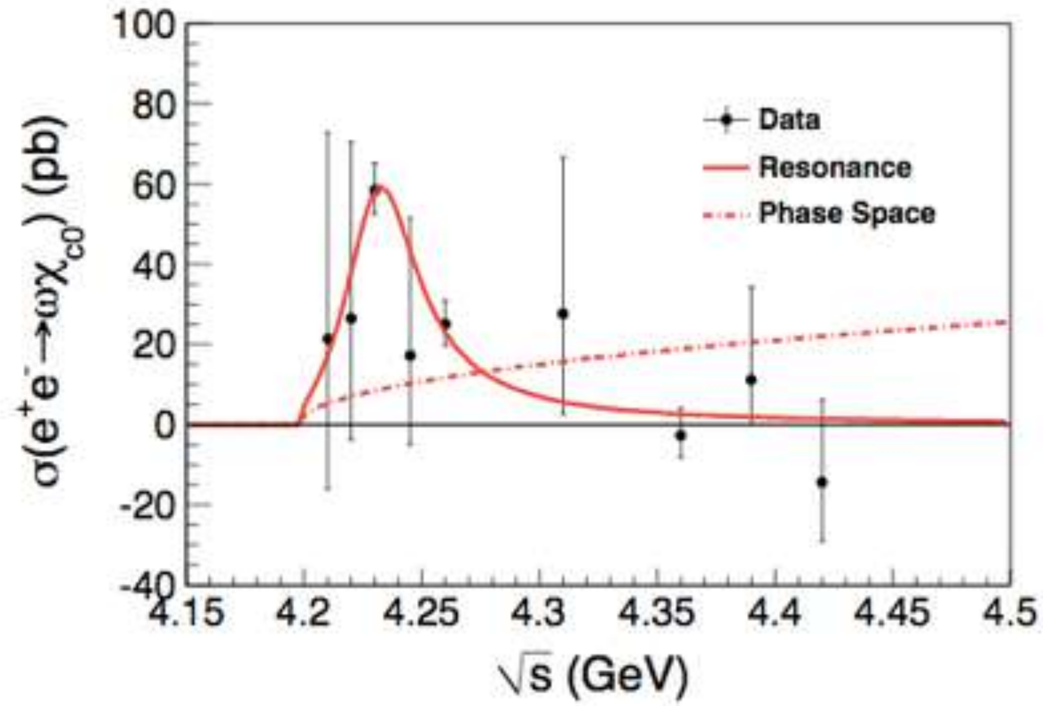
M =(4263±9) → (4230±8) MeV
Γ = (95±14) → (55±19) MeV

BESIII

arXiv:1410.6538 ⟹ $e^+e^- \to \omega\chi_{c0}$

M = (4230±8±6) MeV
Γ = (38±12±6) MeV, 9σ

Inconsistent with the Y(4260) line shape. It was called Y(4220)



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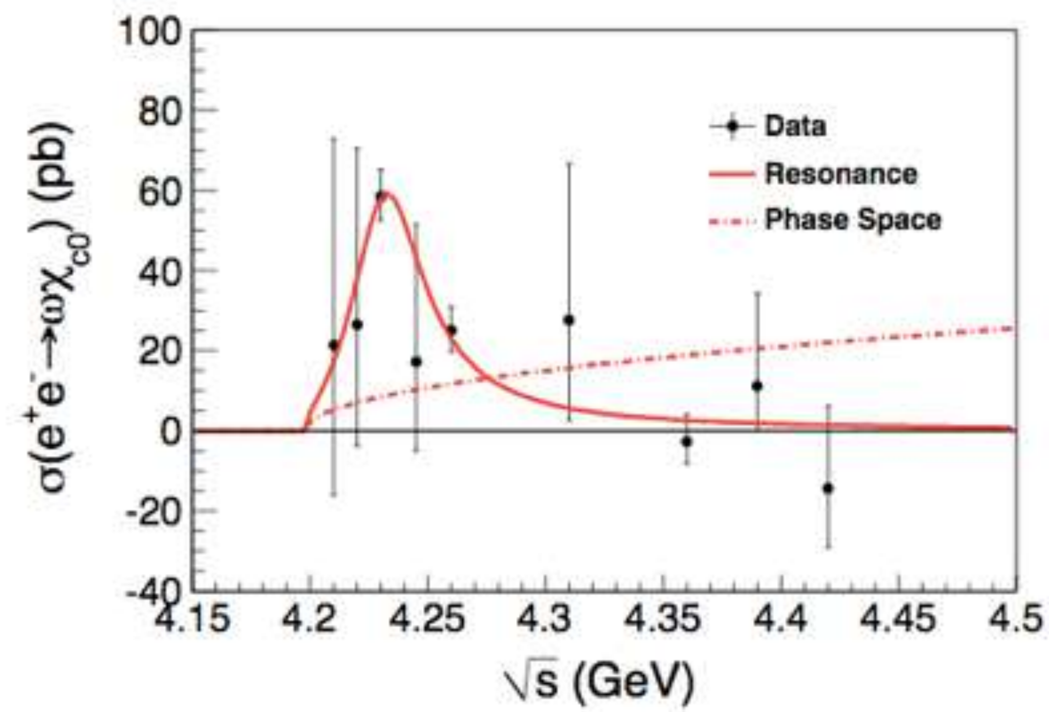

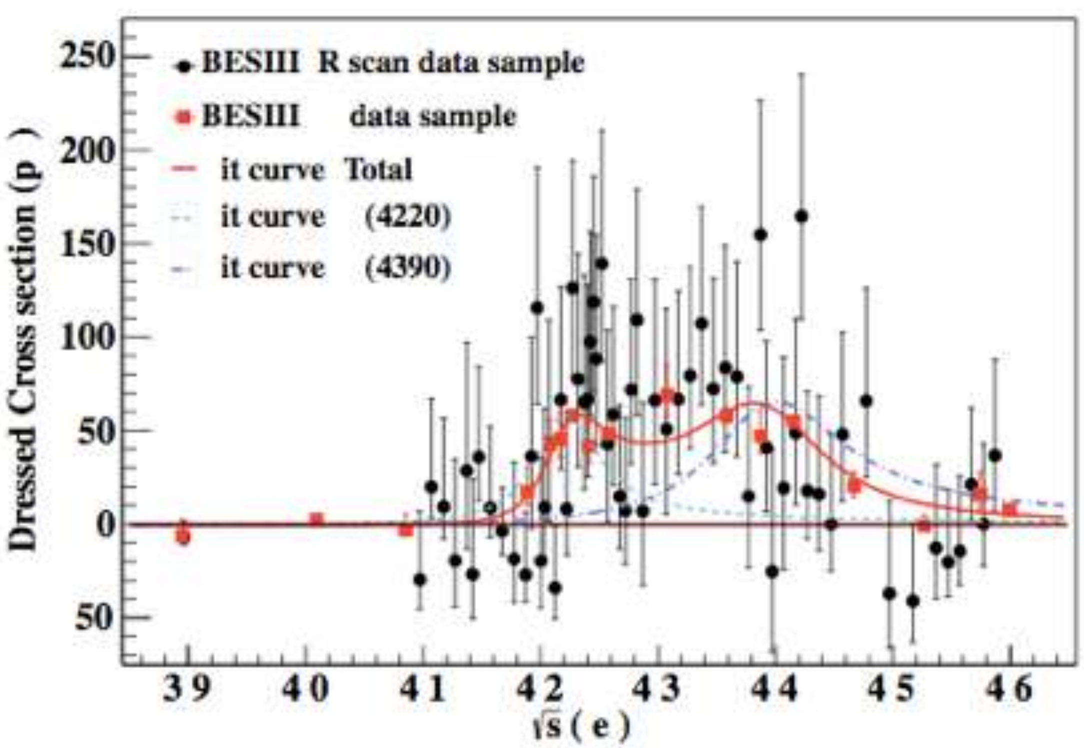

arXiv:1610.07044 $\Longrightarrow \quad e^+e^- \to \pi^+\pi^-h_c$

M = (4218.4±5.1±0.9) MeV
Γ = (66.0±10.3±0.4) MeV, 10σ

M = (4391.5±6.5±1.0) MeV
Γ = (139.5±18.4±1.0) MeV, 10σ

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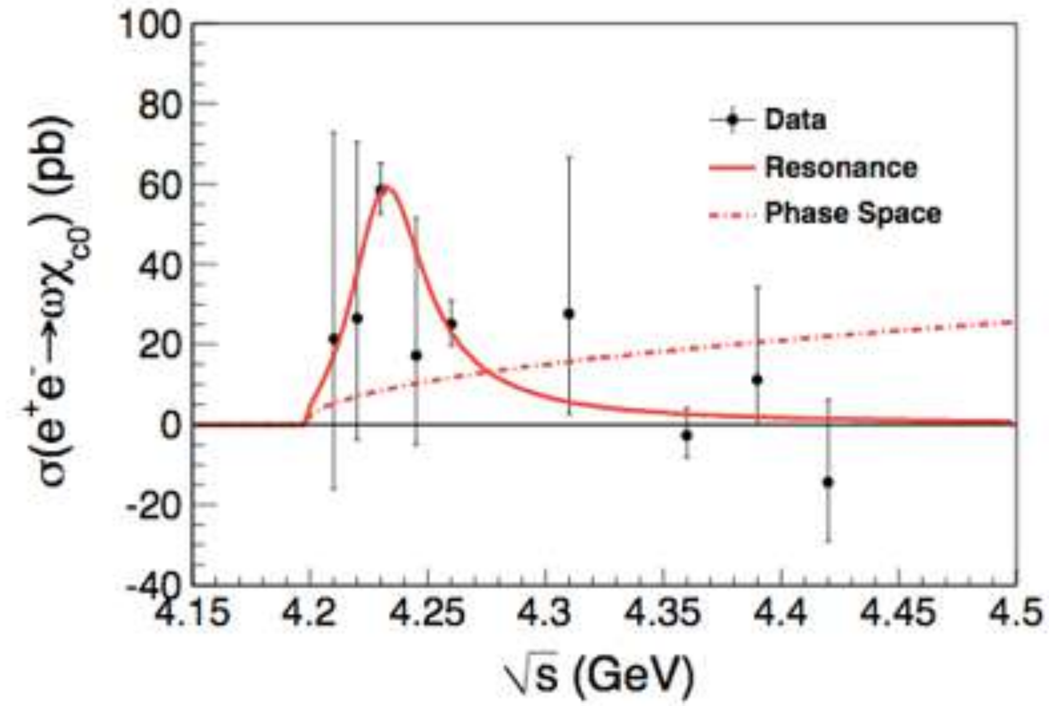

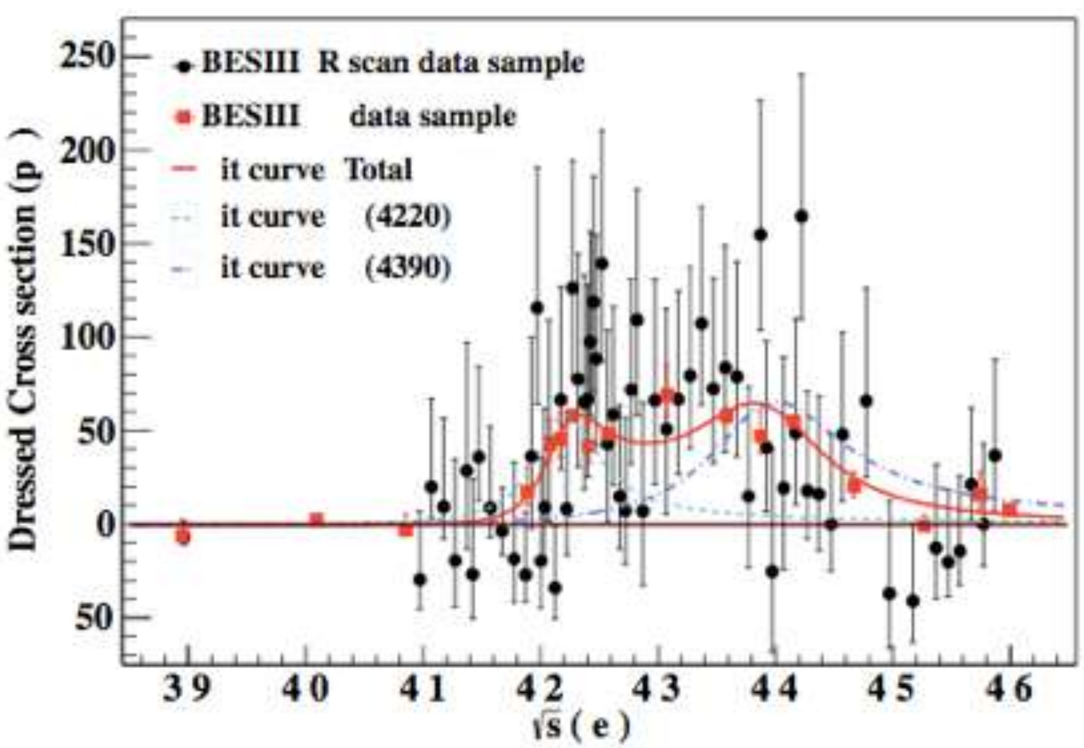

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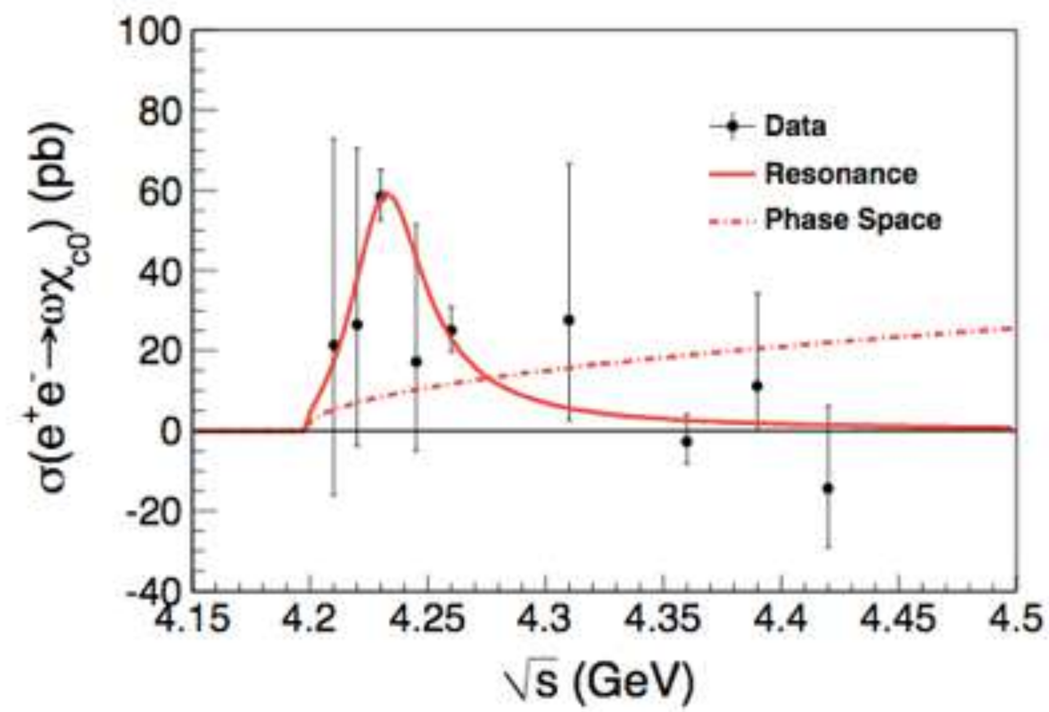

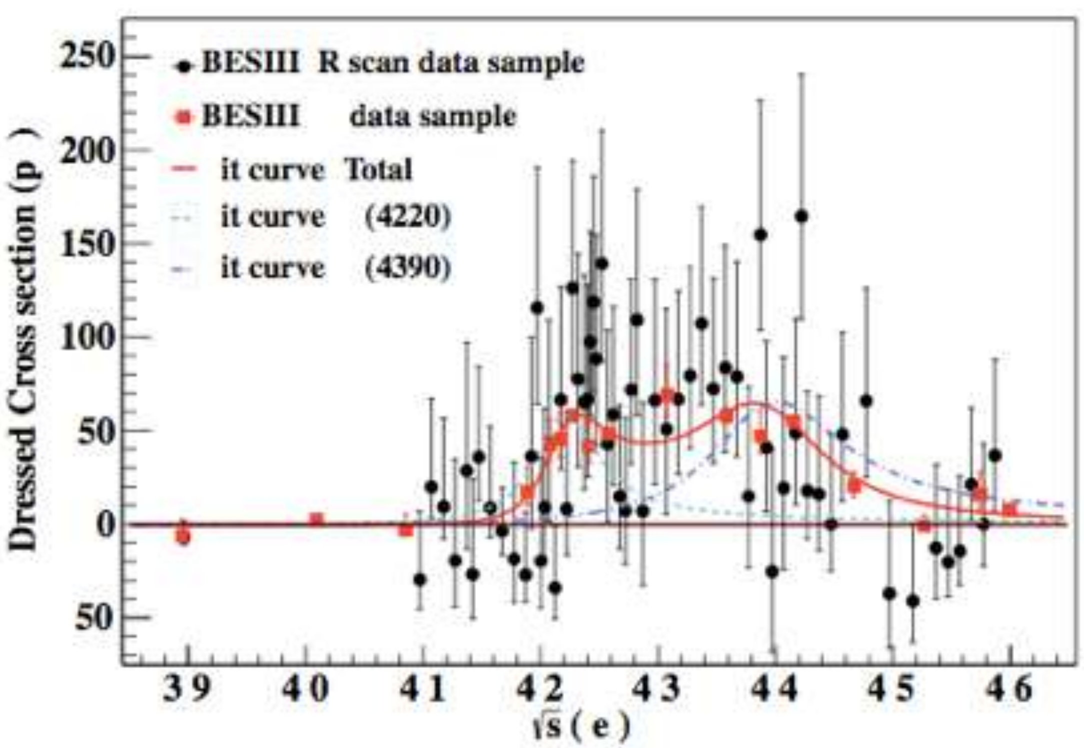

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Inconsistent with the Y(4260) and Y(4360), but consistent with Y(4220)

The higher mass state was called Y(4390)

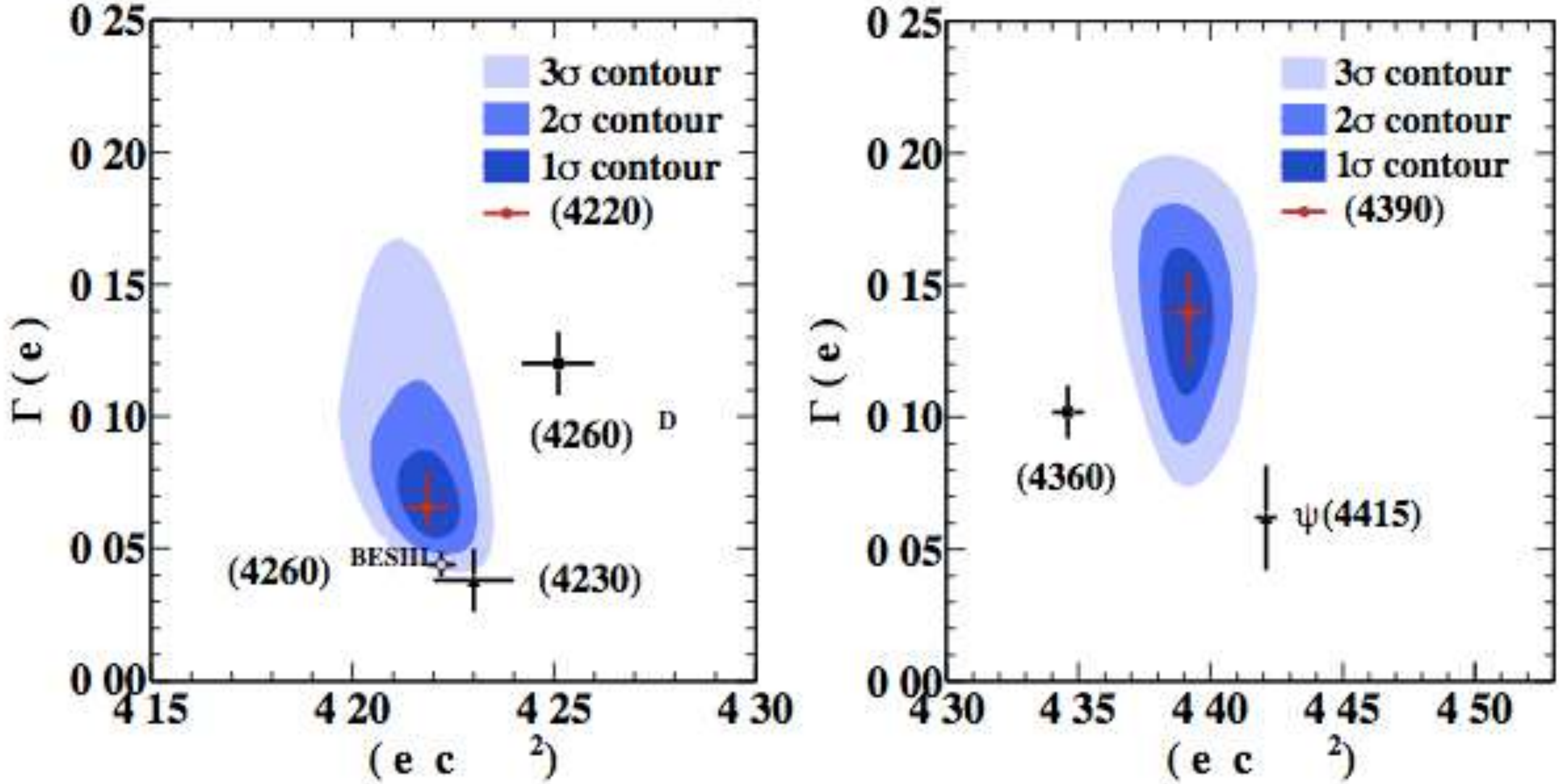
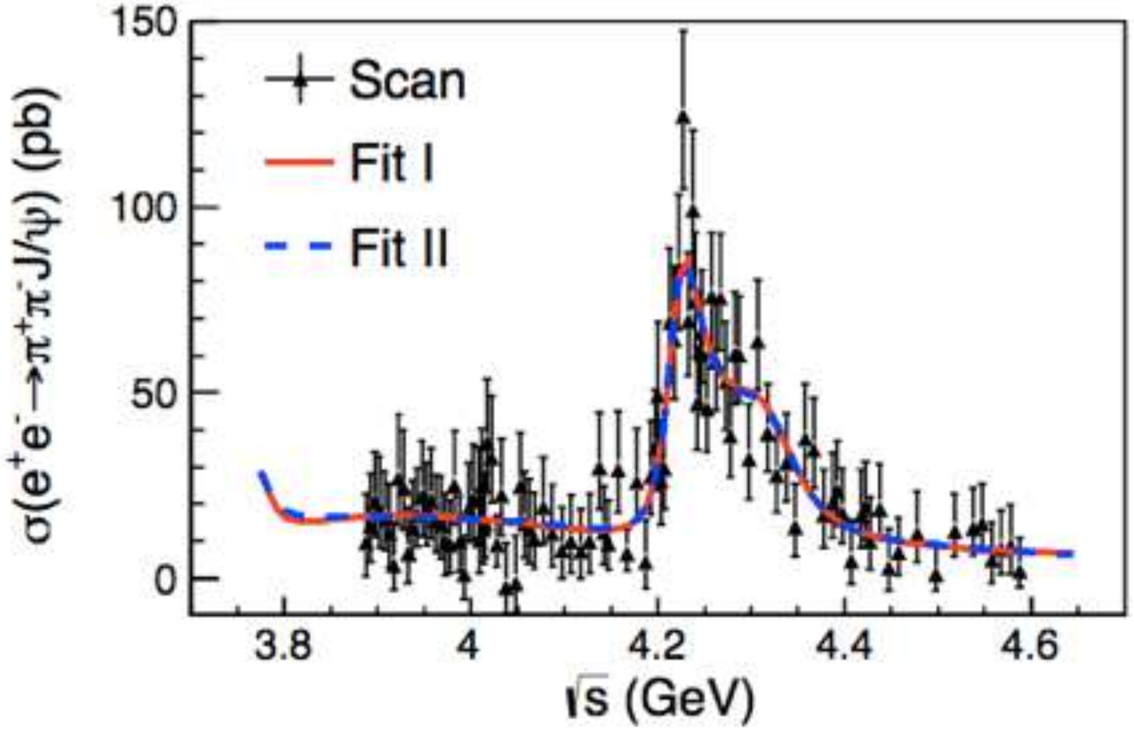


FIG. 3. The likelihood contours in the mass and width planes for $Y(4220)$ (*left panel*) and $Y(4390)$ (*right panel*). The filled areas are up to 3σ likelihood contours and the dots with error bars are the locations of Y or ψ states. The parameters of $Y(4260)^{\mathrm{PDG}}$ are taken from the PDG average [3] and $Y(4260)^{\mathrm{BESIII}}$ from the measurement of $e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII [35].

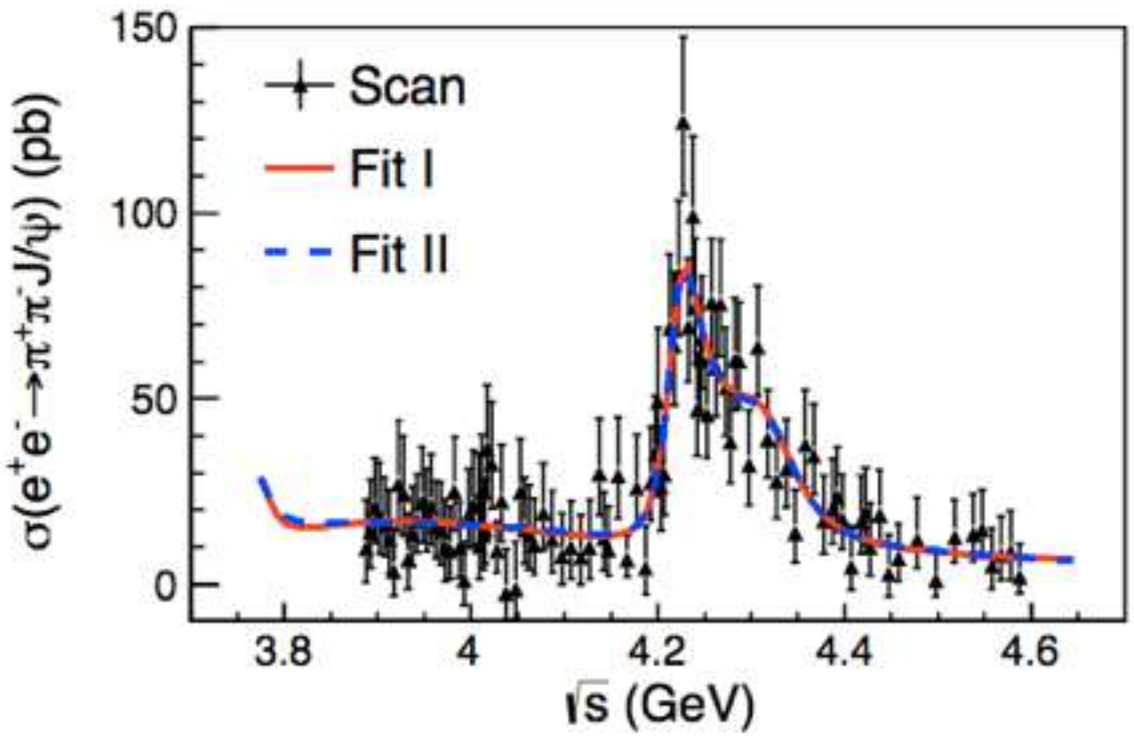


arXiv:1611.01317 $\Longrightarrow$ $e^+e^- \to \pi^+\pi^- J/\psi$

M = (4222.0±3.1±1.4) MeV
Γ = (44.1±4.3±2.0) MeV, 10σ

M = (4320.0±10.4±7) MeV
Γ = (101.4±23.2±10.2) MeV, 7.6σ

Consistent with the Y(4260) and Y(4360) (first time in this channel)



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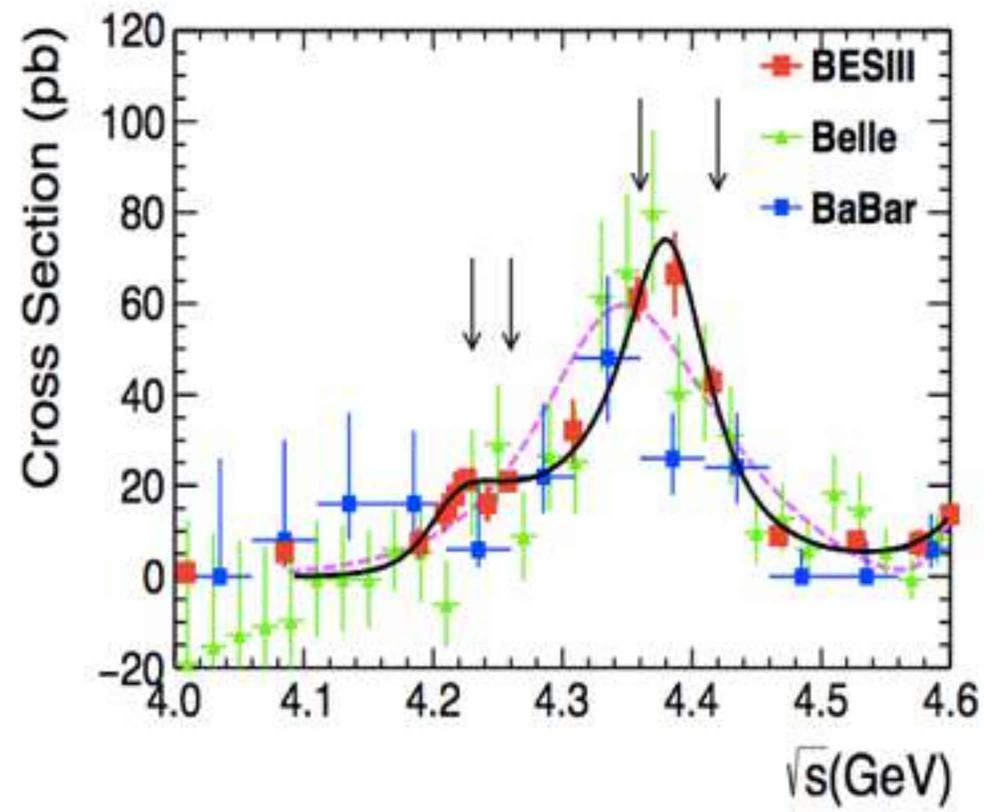
Consistent with the Y(4260) and Y(4360) (first time in this channel)

arXiv:1703.08787 $\Longrightarrow$ $e^+e^- \to \pi^+\pi^- \psi(2S)$

M = (4209.5±7.4±1.4) MeV
Γ = (80.1±24.6±2.9) MeV, 5.8σ

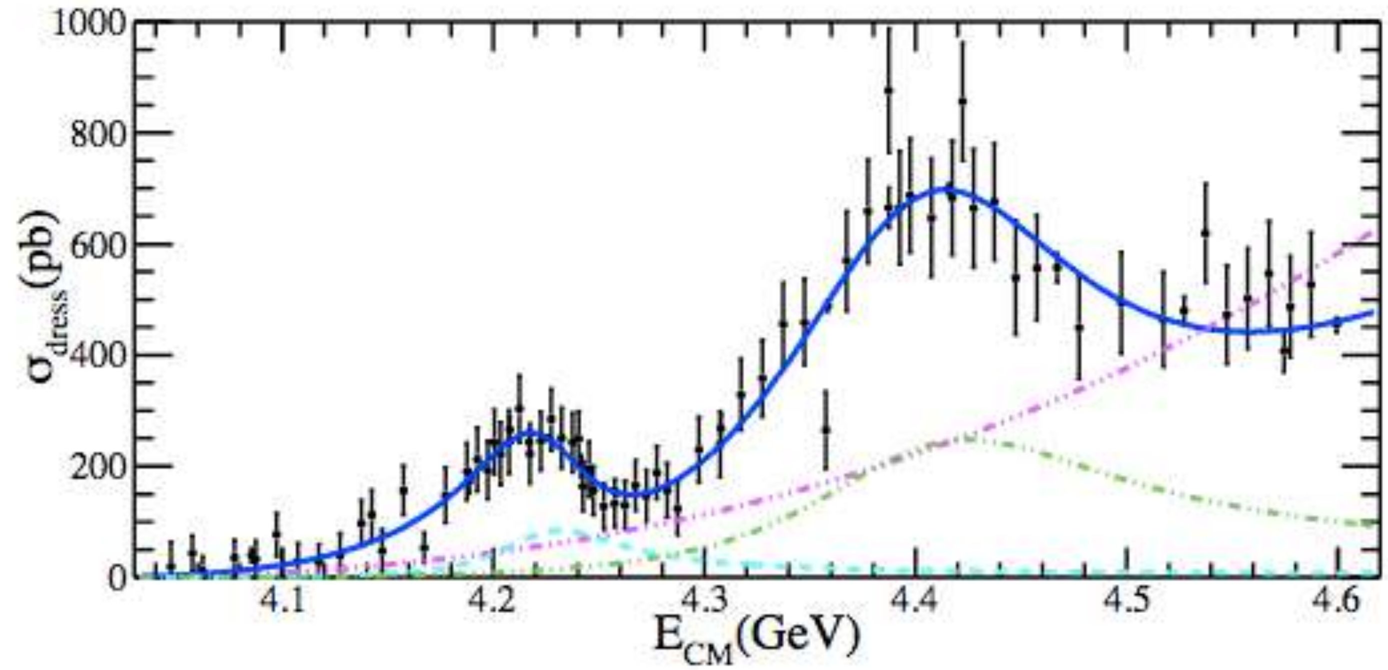
M = (4383.8±4.2±0.8) MeV
Γ = (84.2±12.5±2.1) MeV, 10σ



Consistent with the Y(4220) and Y(4390) observed in $e^+e^- \to \pi^+\pi^- h_c$

arXiv:1808.02847 $\Longrightarrow$ $e^+e^- \rightarrow \pi^+ D^0 D^{*-}$

M = (4224.8±5.6) MeV
Γ = (72.3±9.1) MeV
M = (4400.1±9.3) MeV
Γ = (181.7±16.9) MeV



lower mass resonance in good agreement with the Y(4220) arXiv:1808.02847 $\Longrightarrow$ $e^+e^- \to \pi^+ D^0 D^{*-}$

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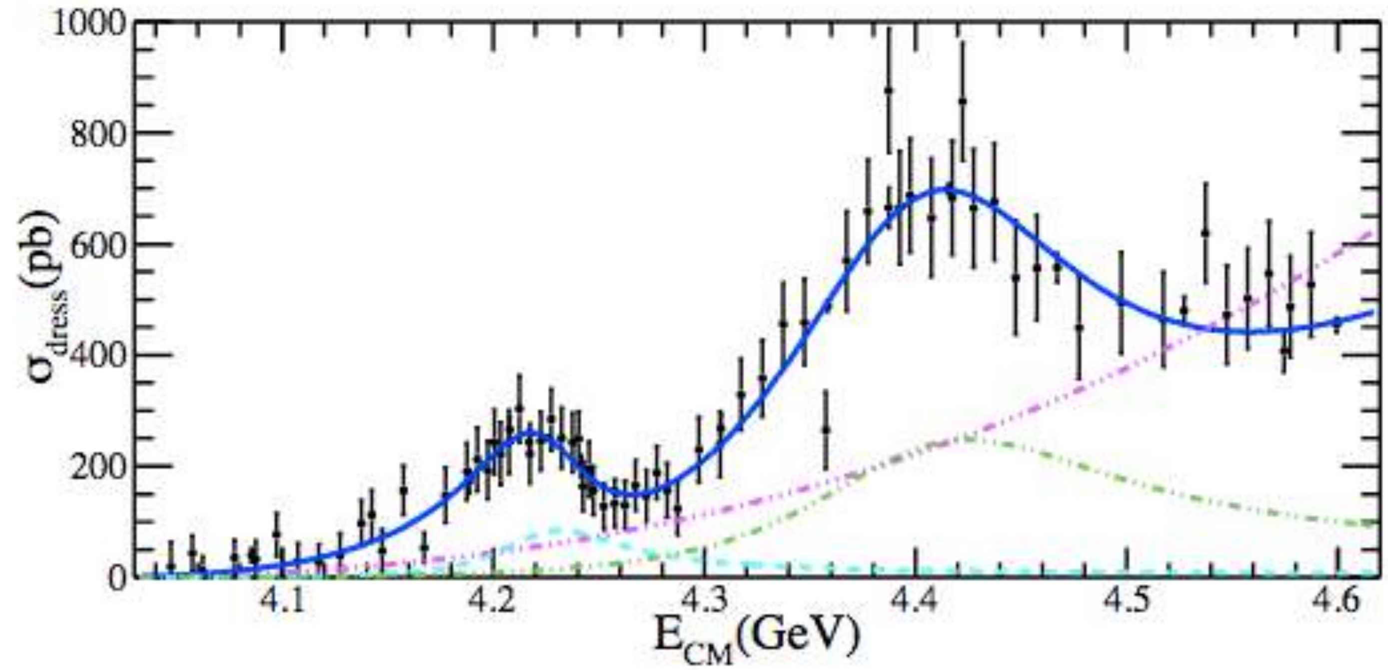

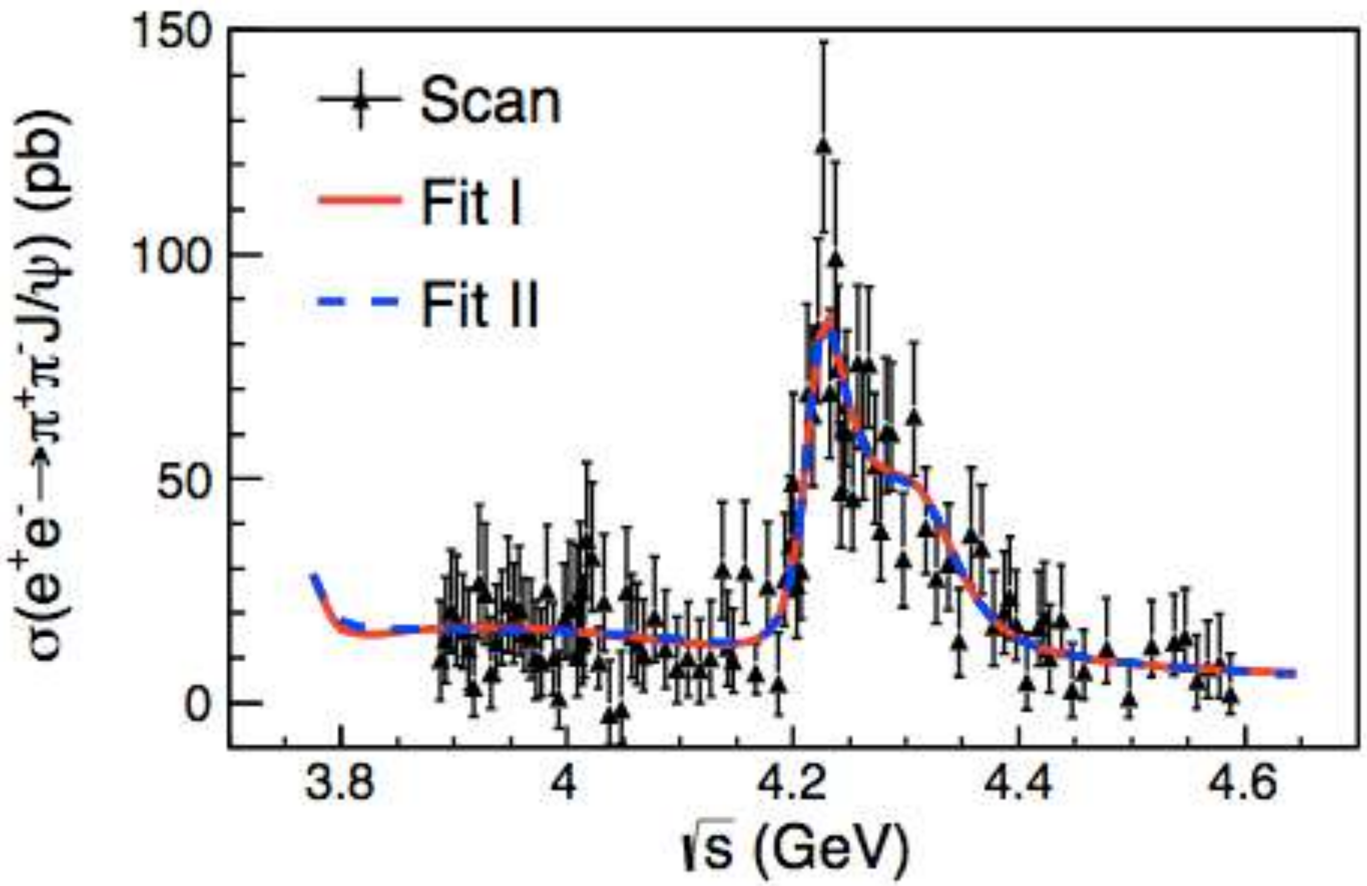

BESIII data indicate that the structure Y(4260) actually consists of two resonances with masses 4220 and 4320 MeV, observed in the $e^+ e^- \to \pi^+ \pi^- J/\Psi$, with the Y(4220) being its main component

QCD sum rules calculation for $Y(J^{PC}=1^{--})$

tetraquark current (Albuquerque, MN, arXiv:0804.4817)

$$j^Y = [cs]_{S=1}[\bar{c}\bar{s}]_{S=0} + [cs]_{S=0}[\bar{c}\bar{s}]_{S=1}$$

$m_Y = (4.65 \pm 0.10)$ GeV in good agreement with $Y(4660)$

molecular current (Albuquerque, MN, Silva, arXiv:1110.2113)

$$j^Y = D_0\bar{D}^* + \bar{D}_0 D^*$$

m_Y = (4.96 ± 0.11) GeV not compatible with Y(4260)

other currents

- $D_s^*\bar{D}_{s0} \Rightarrow m = (5.12 \pm 0.10)$ GeV
- $D\bar{D}_1 \Rightarrow m = (4.12 \pm 0.09)$ GeV
- $[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} \Rightarrow m = (4.49 \pm 0.11)$ GeV

QCD sum rules calculation for $Y(J^{PC}=1^{--})$

tetraquark current (Albuquerque, MN, arXiv:0804.4817)

$$j^Y = [cs]_{S=1}[\bar{c}\bar{s}]_{S=0} + [cs]_{S=0}[\bar{c}\bar{s}]_{S=1}$$

$m_Y = (4.65 \pm 0.10)$ GeV in good agreement with $Y(4660)$

molecular current (Albuquerque, MN, Silva, arXiv:1110.2113)

$$j^Y = D_0\bar{D}^* + \bar{D}_0 D^*$$

m_Y = (4.96 ± 0.11) GeV not compatible with Y(4260)

other currents:

- $D_s^*\bar{D}_{s0} \Rightarrow m = (5.12 \pm 0.10)$ GeV
- $D\bar{D}_1 \Rightarrow m = (4.12 \pm 0.09)$ GeV
- $[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} \Rightarrow m = (4.49 \pm 0.11)$ GeV

none of them compatible with Y(4260)

Y(4260) as a mixed charmonium 4-quark state

Dias, Albuquerque, MN, Zanetti: PRD86 (12)

$$j_\mu^{(2)} = \frac{1}{\sqrt{2}}\langle\bar{q}q\rangle\,\bar{c}_a(x)\gamma_\mu c_a(x)$$

$$j_\mu(x) = \sin(\theta)\, j_\mu^{(4)}(x) + \cos(\theta)\, j_\mu^{(2)}(x)$$

$$j_\mu^{(4)} = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\left[\left(q_a^T(x)C\gamma_5 c_b(x)\right)\left(\bar{q}_d(x)\gamma_\mu\gamma_5 C\bar{c}_e^T(x)\right) + \left(q_a^T(x)C\gamma_5\gamma_\mu c_b(x)\right)\left(\bar{q}_d(x)\gamma_5 C\bar{c}_e^T(x)\right)\right].$$

$$52.5^\circ \leq \theta \leq 53.5^\circ \quad \longleftrightarrow \quad m_Y = (4.26 \pm 0.13)\ \text{GeV}$$

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$$52.5^\circ \le \theta \le 53.5^\circ \longleftrightarrow m_Y = (4.26 \pm 0.13)\ \mathrm{GeV}$$

$$\Gamma(Y \to J/\psi\,\pi\pi) = (4.1 \pm 0.6)\ \mathrm{MeV}$$

much smaller than the total experimental width: $\Gamma^{exp} = (55 \pm 19)$ MeV

⬇

possible indication that the main decay channel is in D mesons ⇒

the Y(4220) is indeed the main component of the Y(4260)!

Y(4260) as a mixed charmonium 4-quark state

Dias, Albuquerque, MN, Zanetti: PRD86 (12)

$$j^{(2)}_\mu = \frac{1}{\sqrt{2}}\langle\bar{q}q\rangle\,\bar{c}_a(x)\gamma_\mu c_a(x)$$

$$j_\mu(x) = \sin(\theta)\, j^{(4)}_\mu(x) + \cos(\theta)\, j^{(2)}_\mu(x)$$

$$j^{(4)}_\mu = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\Big[\big(q_a^T(x)C\gamma_5 c_b(x)\big)\big(\bar{q}_d(x)\gamma_\mu\gamma_5 C\bar{c}_e^T(x)\big) + \big(q_a^T(x)C\gamma_5\gamma_\mu c_b(x)\big)\big(\bar{q}_d(x)\gamma_5 C\bar{c}_e^T(x)\big)\Big].$$

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⬇

possible indication that the main decay channel is in D mesons ⇒

the Y(4220) is indeed the main component of the Y(4260)!

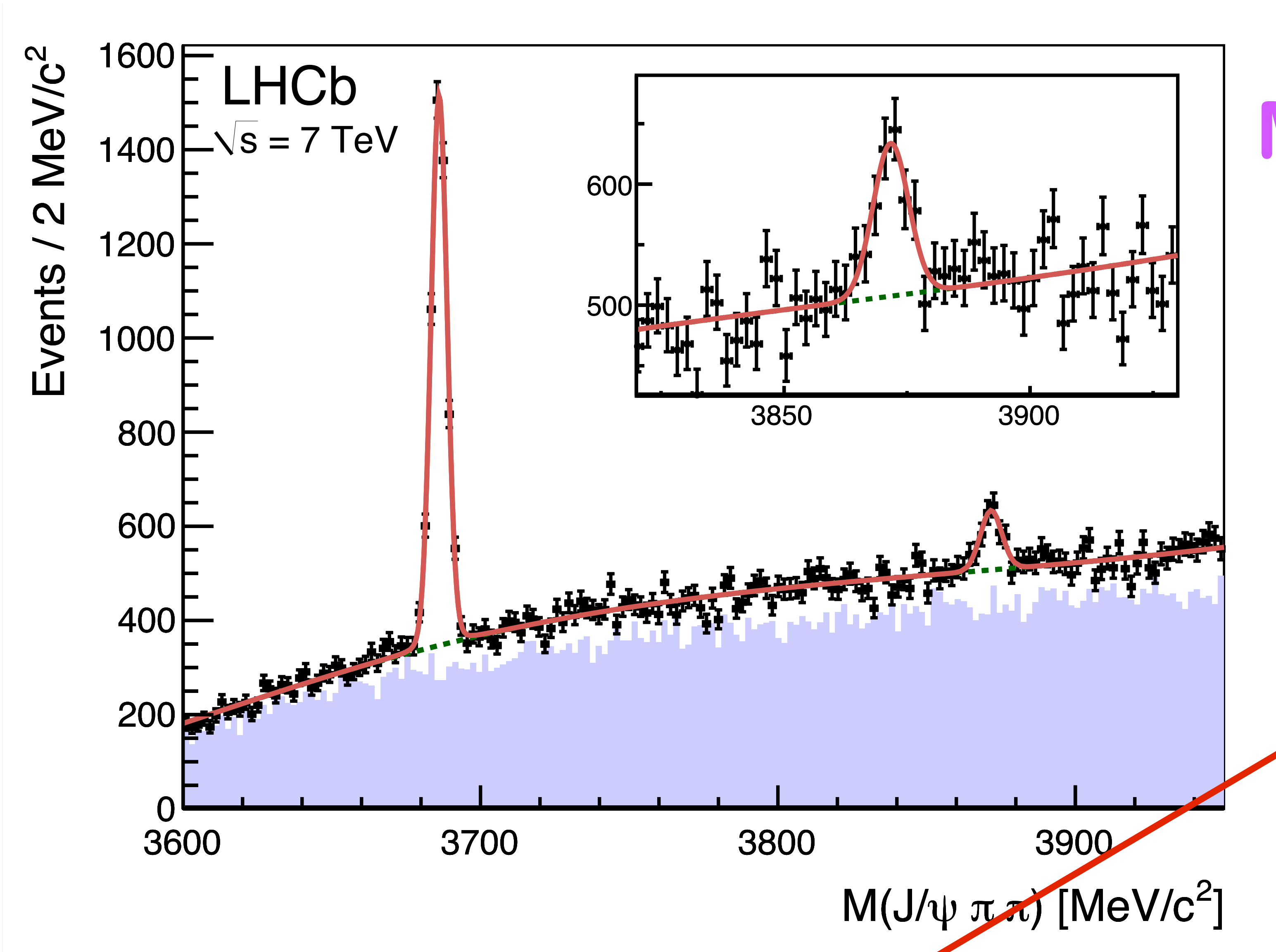
production in B meson decay: $\mathcal{B}(B \to Y(4260)K) = (1.34 \pm 0.47) \times 10^{-6}$

compatible with the experimental limit: $\mathcal{B}^{exp} < 2.9 \times 10^{-5}$

X(3872) Belle II @ KEK (PRL91(2003))

very narrow state observed in the decay: $B^{\pm} \rightarrow K^{\pm}(J/\psi\pi^{+}\pi^{-})$

best studied charmonium exotic candidate



$M_X = (3871.69 \pm 0.17)$ MeV

$\Gamma < 1.2$ MeV

$c\bar{c}$ spec. for $J^{PC} = 1^{++}$ (Barnes & Godfrey, PRD69 (2004))

$\rightarrow 2\ ^3P_1\ (3990)$

$\rightarrow 3\ ^3P_1\ (4290)$

$$\frac{X \to J/\psi\ \pi^+\pi^-\pi^0}{X \to J/\psi\ \pi^+\pi^-} = 0.8 \pm 0.3$$ ➡ strong isospin and G parity violation

$$M(D^{*0}\bar{D}^0) = (3871 \pm 1)$$

X(3872): molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Swanson, Close, Voloshin, Wong ...)

Maiani et al. (PRD71 (05)) tetraquark $J^{PC} = 1^{++}$ state

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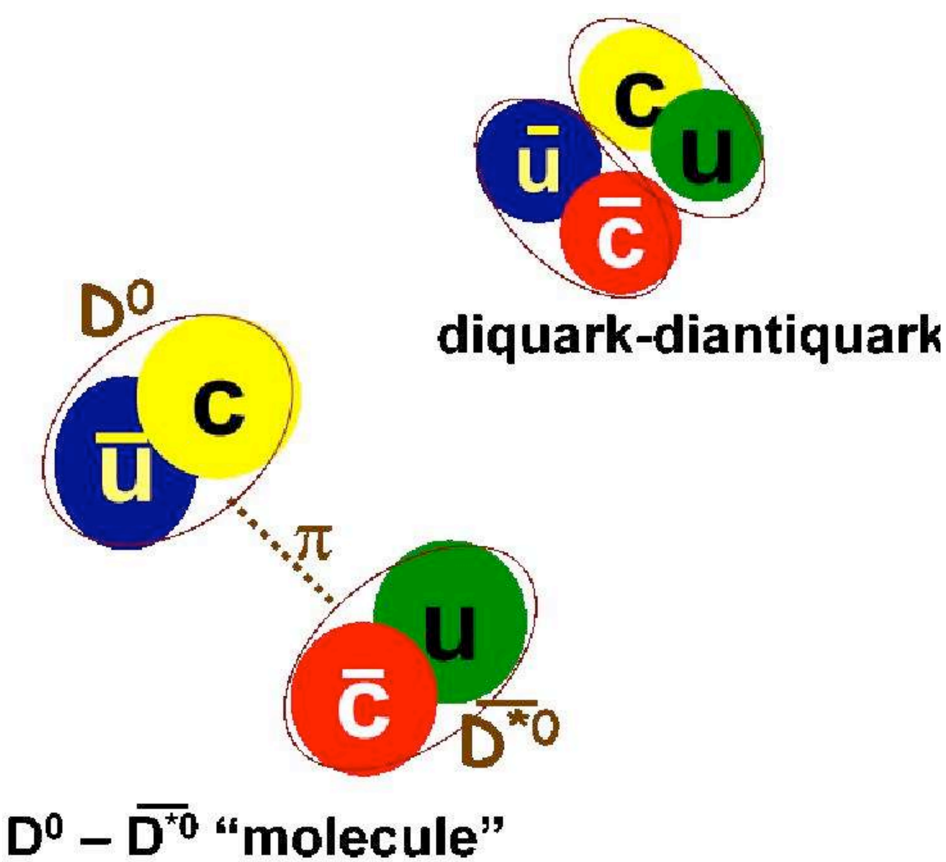


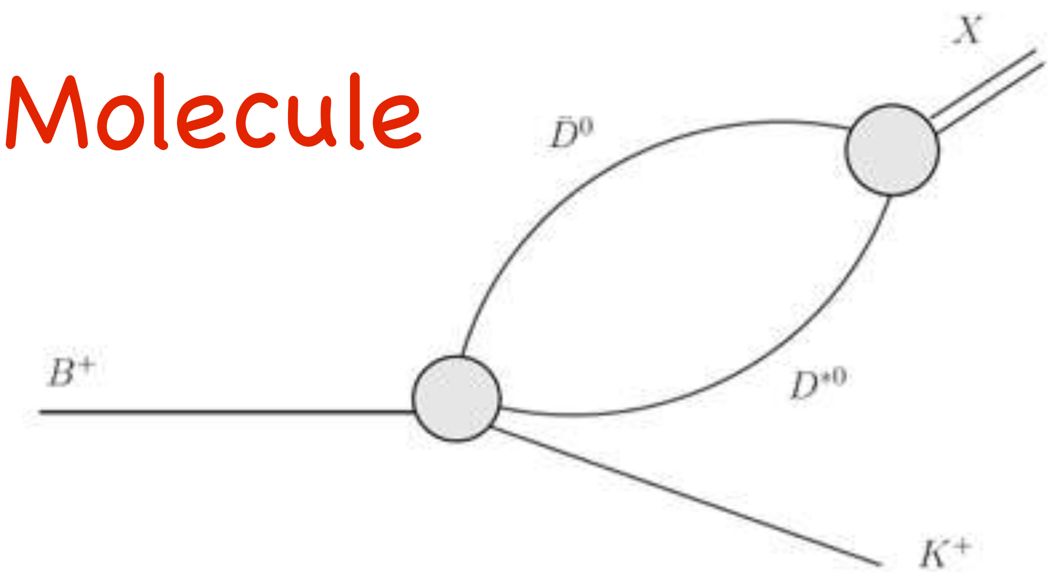
molecular and tetraquark interpretations differ by the way quarks are organized in the state

X(3872) production

B decays at B factories

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

Meson Molecule



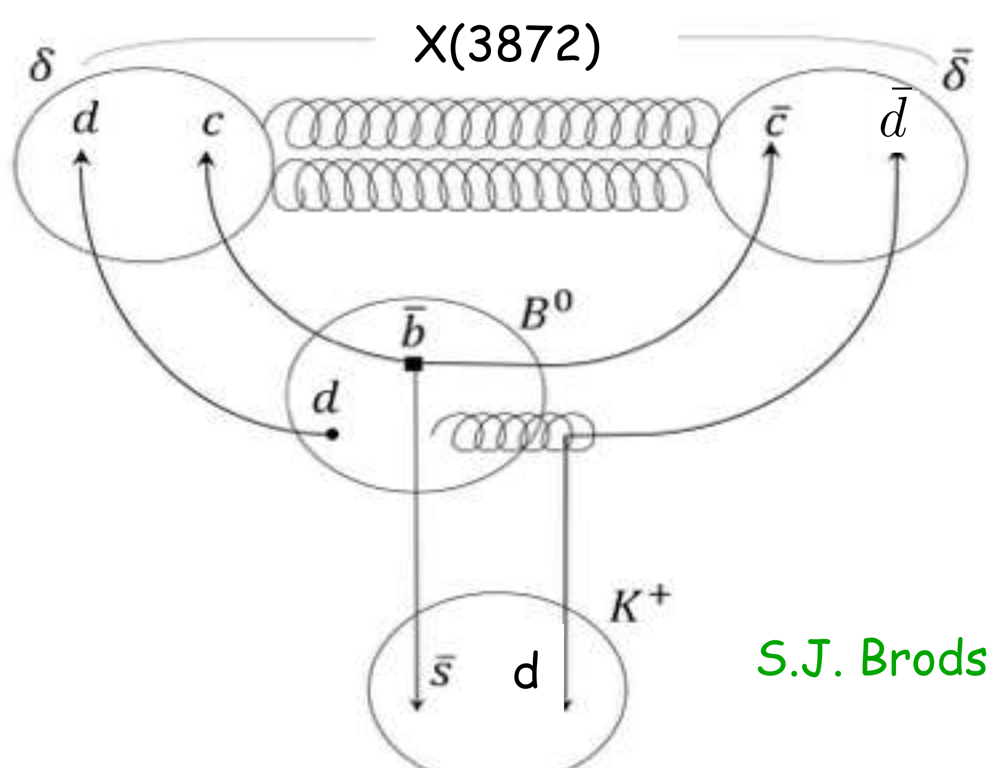
Meson coalescence

Small binding energy

Agreement with data !

E. Braaten, M. Kusunoki, hep-ph/0404161

Tetraquark



Diquark-antidiquark picture

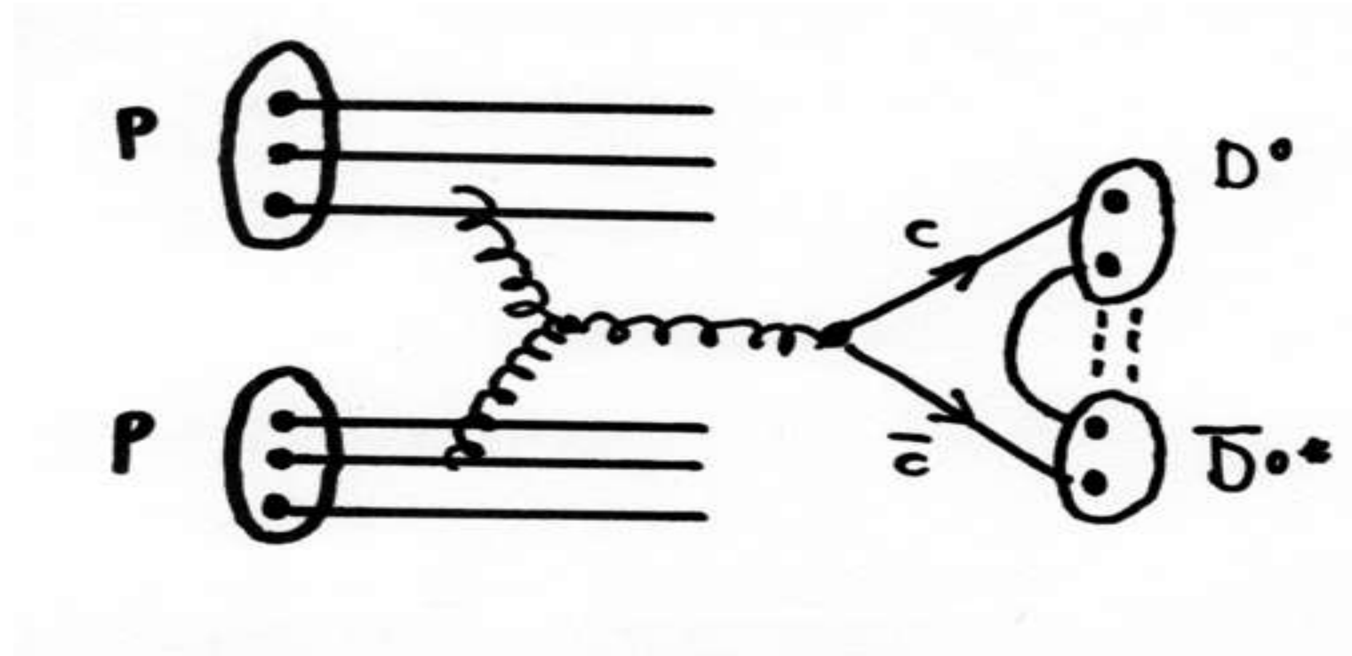
Non-relativistic potential

Agreement with data !

S.J. Brodsky, D.S. Hwang, R.F. Lebed, arXiv:1406.7281

Proton - (anti)Proton $\sigma_{exp} = 30\ nb$ (CMS)

Meson molecule



How can a molecule, with small binding energy, be produced in high energy collision with large cross section?

Proton - (anti)Proton $\sigma_{exp} = 30\ nb$ (CMS)

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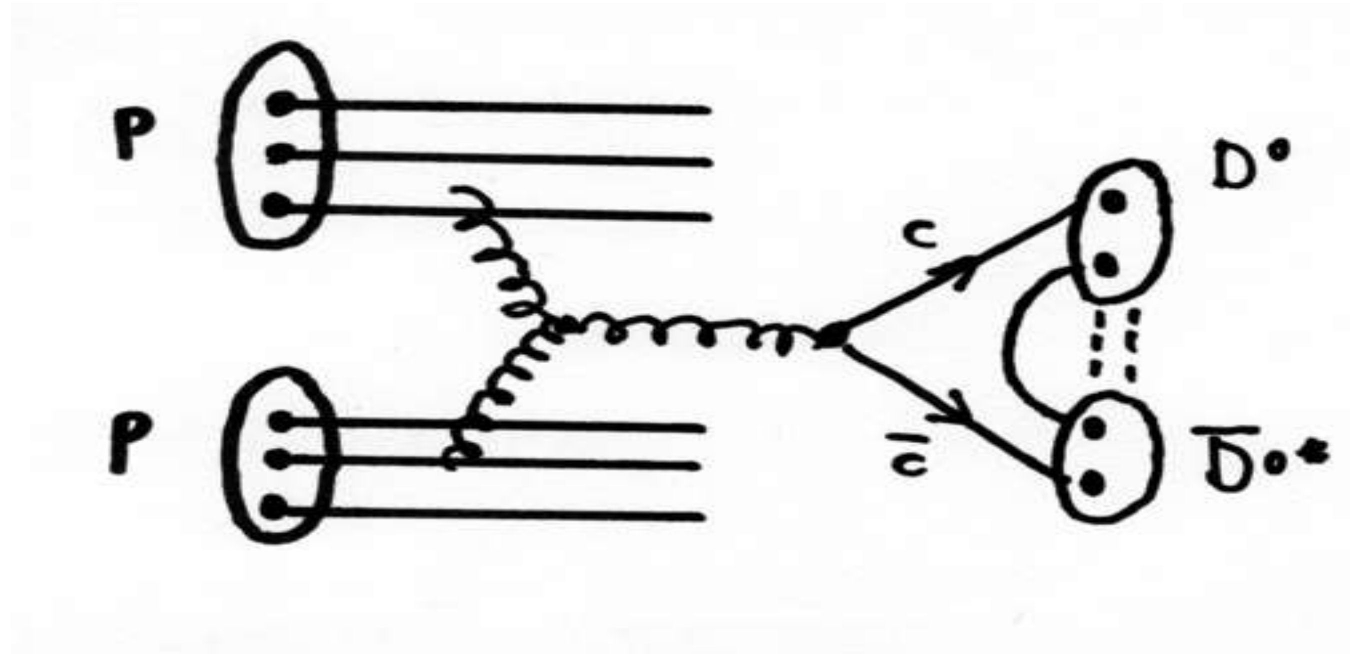
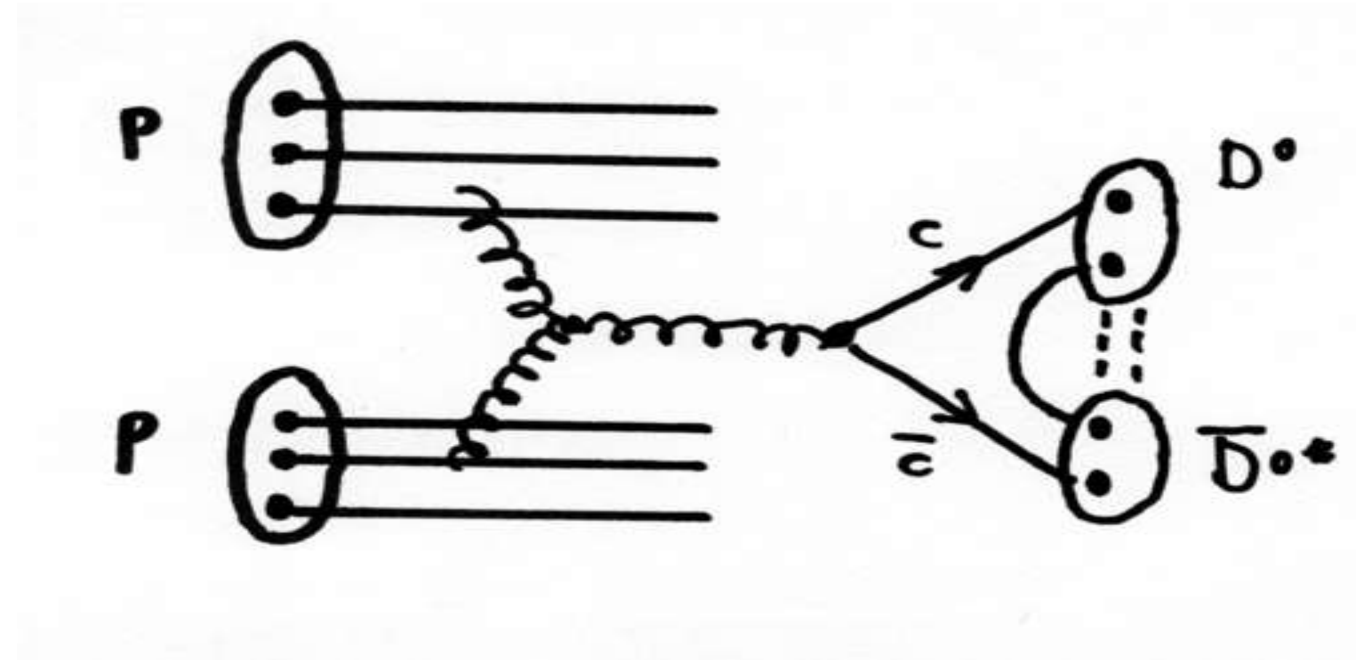


How can a molecule, with small binding energy, be produced in high energy collision with large cross section?

theoretical estimates + MC → production cross section smaller by factor 300! (Bignamini et. al., PRL103(09)162001) Problem for molecular approach

Proton - (anti)Proton $\sigma_{exp} = 30\, nb$ (CMS)

Meson molecule



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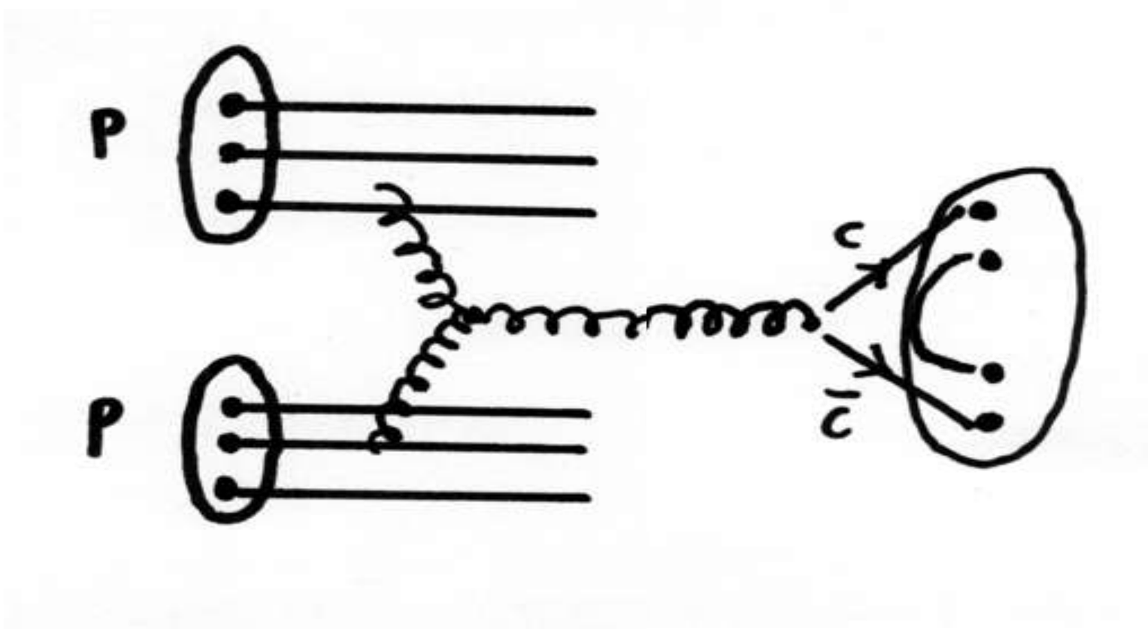
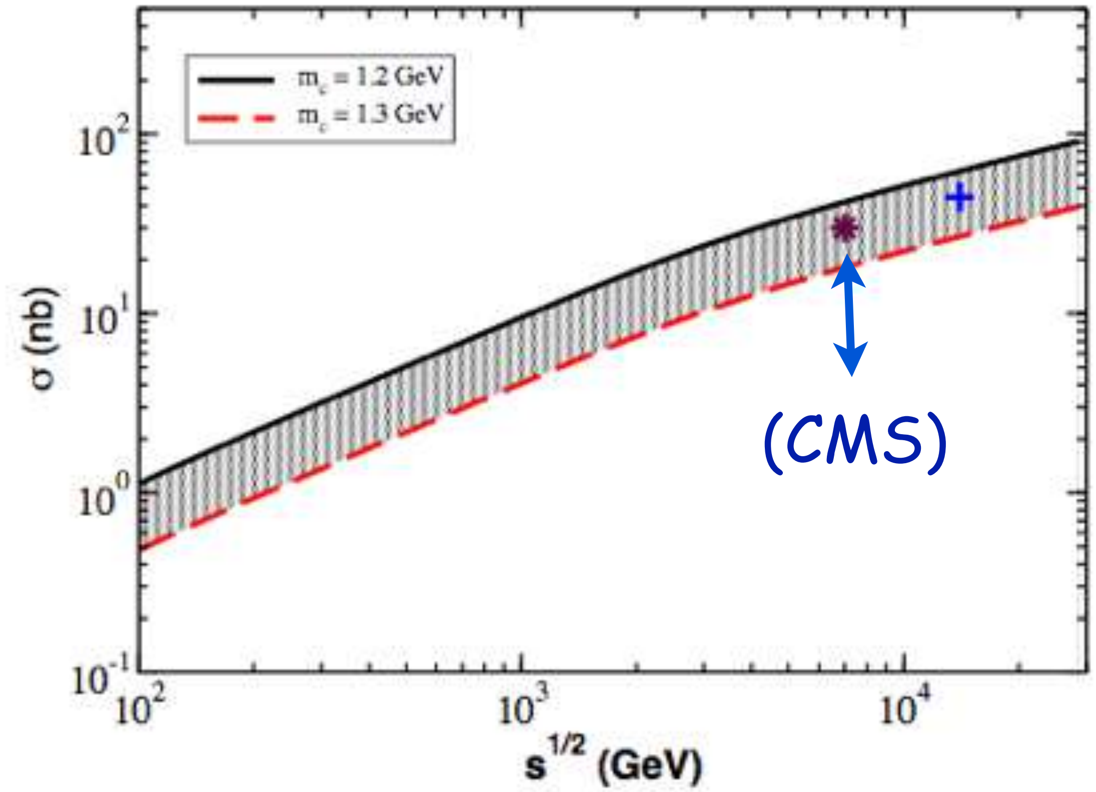
NRQCD plus production from rescattering of $D\bar{D}^*$ created at a point: molecular approach can describe the CDF data !   E Braaten, L-P He, K Ingles, arXiv:1811.08876

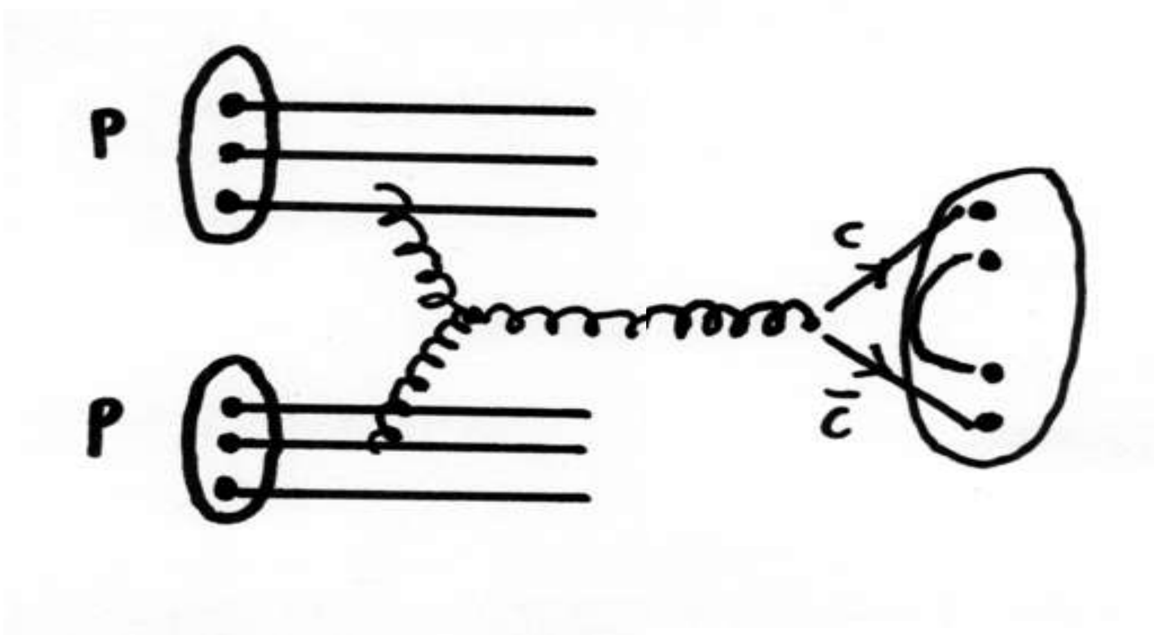
Tetraquark

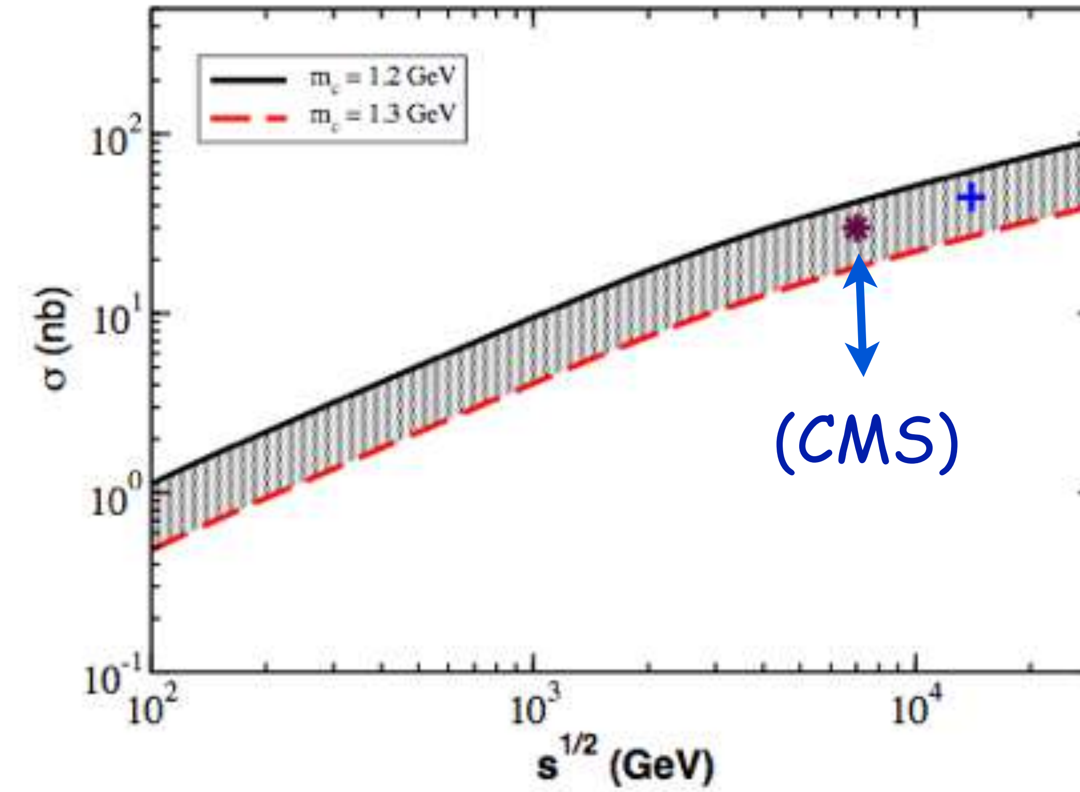




double parton scattering with parameters fixed to reproduce CMS data (Carvalho et al., arXiv:1511.05209)

Tetraquark





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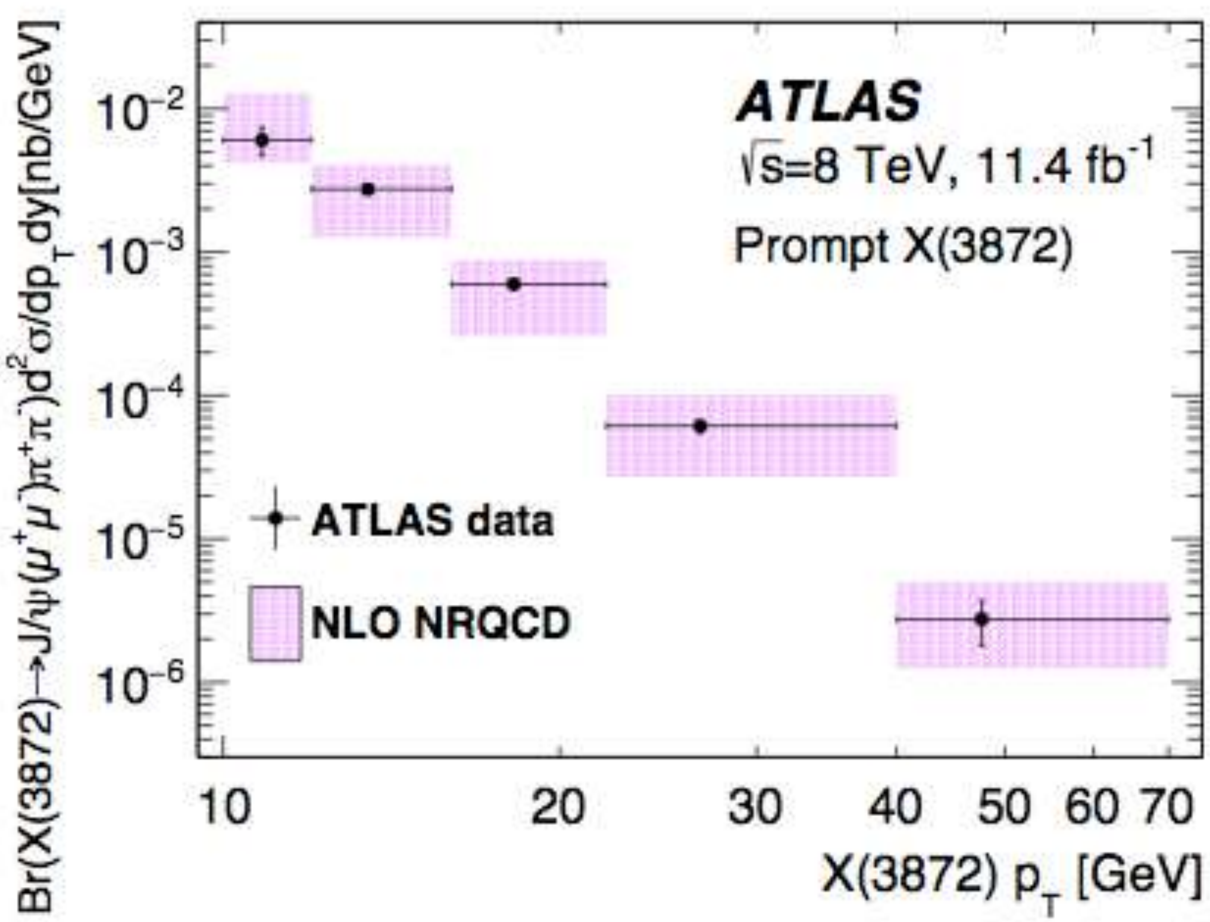

The X(3872) is modeled as a mixture of a $\chi_{c1}(2P)$ and a $\bar{D}^0 D^{*0}$ molecular state.

arXiv:1610.09303

Theoretical calculation from Meng et al., arXiv:1304.6710

QCD sum rules calculation for $\boldsymbol{X(3872)}$

Matheus, Narison, MN, Richard: PRD75 (07)

$$j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T) + (q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)]$$

$$\boldsymbol{m_X = (3.92 \pm 0.13)} \text{ GeV}$$

QCD sum rules calculation for $X(3872)$

Matheus, Narison, MN, Richard: PRD75 (07)

$$j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T) + (q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)]$$

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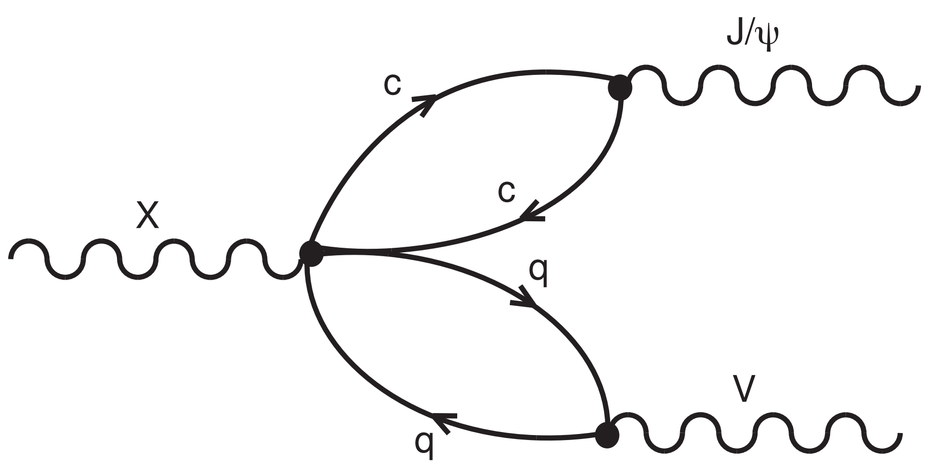

Problem: decay width X → J/ψππ ~ 50 MeV (Navarra, MN, PLB639 (06)272)

How to solve this problem?

X(3872) as a mixed charmonium 4-quark state

Matheus, Navarra, MN, Zanetti: PRD80 (09)

$$J_\mu^q(x) = \sin(\theta) j_\mu^{(4q)}(x) + \cos(\theta) j_\mu^{(2q)}(x)$$

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$$j^{(4q)}_\mu(x) = \frac{1}{\sqrt{2}}\Big[\Big(\bar{q}_a(x)\gamma_5 c_a(x)\bar{c}_b(x)\gamma_\mu q_b(x)\Big) - \Big(\bar{q}_a(x)\gamma_\mu c_a(x)\bar{c}_b(x)\gamma_5 q_b(x)\Big)\Big]$$

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$m_X = (3.77 \pm 0.18)$ GeV

$5^0 \leq \theta \leq 13^0$

Compatible with the experimental X(3872) mass

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$m_X = (3.77 \pm 0.18)$ GeV

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Compatible with the experimental X(3872) mass

Belle II

$$\frac{\mathcal{B}(X \to J/\psi\,\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3 \;\rightarrow\; j_\mu^X(x) = \cos\alpha J_\mu^u(x) + \sin\alpha J_\mu^d(x)$$

$\alpha \sim 20°$

Decay width $X \rightarrow J/\psi\pi^+\pi^-\pi^0$

$\Gamma = (9.3 \pm 6.9)$ MeV, $5^0 \leq \theta \leq 13^0$

X(3872) as a mixed charmonium 4-quark state

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m_X = (3.77 ± 0.18) GeV

$5^0 \leq \theta \leq 13^0$

Compatible with the experimental X(3872) mass

Belle II

$$\frac{\mathcal{B}(X \to J/\psi\, \pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi \pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3 \;\rightarrow\; j_\mu^X(x) = \cos\alpha J_\mu^u(x) + \sin\alpha J_\mu^d(x)$$

$\alpha \sim 20°$

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Γ = (9.3 ±6.9) MeV, $5^0 \leq \theta \leq 13^0$

Decay width $X \rightarrow J/\psi\ \gamma$

MN, Zanetti: PRD82 (10)

Belle II

$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} = 0.14 \pm 0.05$$

$$5^0 \leq \theta \leq 13^0$$

⬇

$$\frac{\Gamma(X \to J/\psi\ \gamma)}{\Gamma(X \to J/\psi\ \pi^+\pi^-)} = 0.19 \pm 0.13$$

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$$\frac{\Gamma(X \to J/\psi\,\gamma)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} = 0.19 \pm 0.13$$

Production rate $B^+ \to X(3872)K^+$

Matheus, MN, Zanetti: PLB702 (11)

$$5^0 \leq \theta \leq 13^0 \;\Rightarrow\; \mathcal{B}(B \to X(3872)K) = (1.00 \pm 0.68) \times 10^{-5}$$

$$\mathcal{B}(B^\pm \to K^\pm X(3872)) < 3.2 \times 10^{-4}$$

Decay width $X \to J/\psi\ \gamma$

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$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} = 0.14 \pm 0.05$$

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$$\mathcal{B}(B^\pm \to K^\pm X(3872)) < 3.2 \times 10^{-4}$$

- X(3872) is probably a mixed multiquark state with a χ_{c1} state

Conclusions

X(3872) ➜ mixture χ_{c1} and a 4-quark state

$Z_c^+(3900)$ ➜ $J^P=1^+$ tetraquark state

$Z_c^+(4430)$ ➜ first radial excitation of $Z_c^+(3900)$

- Z^+ states need confirmation. A bump in the spectra does not indicate, necessarily, the existence of a state

Y(4260) ➜ mixture of charmonium and a 4-quark state

Y(4660) ➜ tetraquark quark state $[cs][\bar{c}\bar{s}]$

Thank you!