XYZ EXOTIC RESONANCES AT THE LHC

AD POLOSA (SAPIENZA UNIVERSITY)

X(3872)

2003 BELLE $B^+ \longrightarrow K^+ X(3872)$

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

QUANTUM NUMBERS: 1^{++}

— LATER OBSERVED ALSO IN $J/\psi\, \omega$

$$\mathcal{B}(X \to J/\psi\, \rho) \simeq \mathcal{B}(X \to J/\psi\, \omega)$$

WHAT IS THE ORIGIN OF THIS ISOSPIN VIOLATION?

— A REMARKABLE EXAMPLE OF FINE TUNING

$$M(X(3872)) \simeq M(D^0) + M(\bar{D}^{*0})$$

$$\simeq M(J/\psi) + M(\rho)$$

CONFIRMED BY BABAR, CDF, D0, CMS, ATLAS, BES

X(3872) AS A MOLECULE

— ATTRACTION in the $I=0$, $D\bar{D}^*$ CHANNEL due to π-exchange forces (repulsion in $I=1$!).

$X \sim$ A LOOSELY BOUND 'DEUSON' (Törnqvist)

FOR A PURE $I=0$ STATE

$$\frac{\alpha\,\Psi(D^0\bar{D}^{*0}) + \beta\,\Psi(D^+D^{*-})}{\sqrt{2}} \qquad \alpha=\beta=1$$

BUT, SINCE $D^0\bar{D}^{*0}$ IS LIGHTER THAN D^+D^{*-} BY ~ 8 MeV, the neutral component has higher weight: $\alpha > \beta$ — This brings in $I=1$ too. FINE!

"CHARGED MOLECULES WILL NOT BE OBSERVED" (2004)

[FOR AN EARLY ACCOUNT ON MOLECULAR CHARMONIUM DE RUJULA, GEORGI, GLASHOW PRL 38 (1977) 317]

CHARGED STATES

DURING THE LAST FEW YEARS THE FOLLOWING **CHARGED 1^{+-}** STATES HAVE BEEN DISCOVERED

$$Z_c^{\pm,0}(3900),\quad Z_c^{\pm,0}(4020),\quad Z_b^{\pm,0}(10610),\quad Z_b^{\pm,0}(10650)$$

WITH MASS VALUES **ABOVE** THE CORRESPONDING MESON-MESON THRESHOLDS:

$\delta =$	$+7.8$	$+6.7$	$+2.7$	$+1.8$ MeV
	$\bar{D}^0 D^{*+}$	$\bar{D}^{*0} D^{*+}$	$\bar{B}^0 B^{*+}$	$\bar{B}^{*0} B^{*+}$

— MOLECULES EVEN IN $I=1$ REPULSIVE CHANNELS?

— MOLECULES EVEN IF $\delta > 0$?!

way out
- Data analyses are wrong: $\delta < 0$ ...
- These states do not exist, they are CUSPS!
- Lattice does not have these states (C. Thomas et al.)

WHAT ABOUT THE $Z^+(4430)$ OBSERVED BY BELLE & LHCb?

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [1, 93] (>10), BaBar [94] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi) \ldots$	CDF [95, 96, 97] (11.6), D0 [98] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi) \ldots$	LHCb [99, 100, 101] (np), CMS [102] (np)	2012	Ok
				$Y(4260) \to \gamma\,(\pi^+\pi^- J/\psi)$	BESIII [103] (6.3)	2013	NC!
				$B \to K(\omega J/\psi)$	Belle [104] (4.3), BaBar [105] (4.0)	2005	NC!
				$B \to K(\gamma\, J/\psi)$	Belle [104, 106] (5.5), BaBar [107, 108] (3.6), LHCb [109] (> 10)	2005	Ok
				$B \to K(\gamma\, \psi(2S))$	BaBar [108] (3.5), Belle [106] (0.2), LHCb [109] (4.4)	2008	NC!
				$B \to K(D^0 \bar{D}^{*0})$	Belle [110, 111] (6.4), BaBar [112] (4.9)	2006	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	1^{+-}	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BESIII [113] (>8), Belle [114] (5.2), CLEO data [115] (>5)	2013	Ok
				$Y(4260, 4360) \to \pi^0(\pi^0 J/\psi)$	CLEO data [115] (3.5), BESIII [116] (10.4)	2013	Ok
				$Y(4260, 4390) \to \pi^-(\pi^+ h_c)$	BESIII [117] (2.1)	2013	NC!
				$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BESIII [118, 119] (18)	2013	Ok
				$Y(4260) \to \pi^0(D\bar{D}^*)^0$	BESIII [120] (>10)	2015	Ok
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4390) \to \pi^-(\pi^+ h_c)$	BESIII [117] (8.9)	2013	NC!
				$Y(4260, 4390) \to \pi^0(\pi^0 h_c)$	BESIII [121] (>5)	2014	NC!
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BESIII [122] (10)	2013	NC!
				$Y(4260) \to \pi^0(D^*\bar{D}^*)^0$	BESIII [123] (5.9)	2015	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [124, 125, 126] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^0(\pi^0\Upsilon(2S, 3S))$	Belle [127] (6.5)	2013	NC!
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [124, 125] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [128, 129] (9.3)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [124, 125, 126] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [124, 125] (16)	2011	Ok
				$\Upsilon(11020) \to \pi^-(\pi^+ h_b(1P))$	Belle [130] (3.3)	2015	NC!
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [128, 129] (8.1)	2012	NC!

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$\psi(3770)$	3773.13 ± 0.35	27.2 ± 1.0	1^{--}	$e^+e^- \to (D\bar{D})$	PDG [131]	1977	Ok
				$B \to K(D\bar{D})$	Belle [132, 133] (5.5), BaBar [112] (6.4)	2003	Ok
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	BES [134] (3), CLEO [135] (11.6)	2003	Ok
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [135] (3.4)	2005	NC!
				$e^+e^- \to (\eta J/\psi)$	CLEO [135] (3.5)	2005	NC!
				$e^+e^- \to (\phi \eta)$	CLEO [136] (5)	2005	NC!
				$e^+e^- \to (\gamma \chi_{c0,1})$	PDG [131]	2005	Ok
$\psi_2(3823)$	3822.2 ± 1.2	< 16	2^{--}	$B \to K(\gamma\chi_{c1})$	Belle [137] (3.8)	2013	NC!
or $X(3823)$				$e^+e^- \to \pi^+\pi^-(\gamma\chi_{c1})$	BESIII [138] (6.2)	2015	NC!
$X(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [139] (8), BaBar [140, 105] (19)	2004	Ok
or $Y(3940)$				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [141] (7.7), BaBar [142] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [143] (5.3), BaBar [144] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [145, 146] (6)	2005	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to$ (hadrons)	PDG [131]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	BESIII [147] (>10), Belle [148] (6.0)	2012	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [149] (5.0), BaBar [150] (1.1)	2008	NC!
$Z(4055)^+$	4054 ± 3.2	45 ± 13	$?^{?-}$	$Y(4360) \to \pi^-(\pi^+\psi(2S))$	Belle [151] (3.5)	2014	NC!
$X(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+30}_{-25}	1^{++}	$B^+ \to K^+(\phi J/\psi)$	CDF [152, 153] (5.0), Belle [154] (1.9),	2009	Ok
or $Y(4140)$					LHCb [155] (1.4), CMS [156] (>5),		
					D0 [157] (3.1), BaBar [158] (1.6),		
					LHCb [159, 160] (8.4)		
				$p\bar{p} \to (\phi J/\psi)\ldots$	D0 [161] (4.7)	2015	NC!
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to$ (hadrons)	PDG [131]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [148] (6.5), BESIII [162] (>5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [146] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+J/\psi)$	Belle [163] (6.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [149] (5.0), BaBar [150] (2.0)	2008	NC!
$Y(4260)$	4221.1 ± 2.5	47.7 ± 4.0	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	BaBar [164, 165] (8), CLEO [166, 167] (11),	2005	Ok
					Belle [168, 114] (15), BESIII [113, 169] (np)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [166] (5.1), BESIII [116] (np)	2006	Ok
				$e^+e^- \to (K^+K^- J/\psi)$	CLEO [166] (3.7)	2006	NC!
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [165] (np), Belle [114] (np)	2012	Ok
				$e^+e^- \to (\pi^+\pi^- h_c)$	BESIII [117, 170] (10)	2013	NC!
				$e^+e^- \to (\pi^0\pi^0 h_c)$	BESIII [121] (np)	2014	NC!
				$e^+e^- \to (\omega\chi_{c0})$	BESIII [171] (>9)	2014	NC!
				$e^+e^- \to (\gamma\,X(3872))$	BESIII [103] (6.3)	2013	NC!
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BESIII [113, 119] (>8), Belle [114] (5.2)	2013	Ok
				$e^+e^- \to (\pi^0 Z_c(3900)^0)$	BESIII [116, 120] (10.4)	2015	Ok
				$e^+e^- \to (\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [122, 117, 121, 123] (>10)	2013	Ok
$X(4274)$	$4273.3^{+19.1}_{-9.0}$	$56.2^{+13.8}_{-15.6}$	1^{++}	$B^+ \to K^+(\phi J/\psi)$	CDF [153] (3.1), LHCb [155] (1.0),	2011	NC!
or $Y(4274)$					CMS [156] (>3), D0 [157] (np),		
					LHCb [159, 160] (6.0)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [172] (3.2)	2009	NC!
$Y(4360)$	4341.2 ± 5.4	101.9 ± 9.3	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle [173, 151] (8), BaBar [174] (np)	2007	Ok
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	BESIII [169] (7.6)	2016	NC!
				$e^+e^- \to (\pi^+\pi^- \psi_2(3823))$	BESIII [138] (np)	2015	NC!
				$e^+e^- \to (\pi^0 Z_c(3900)^0)$	BESIII [116] (np)	2015	NC!
				$e^+e^- \to (\pi^- Z_c(4055)^+)$	Belle [151] (3.5)	2014	NC!

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(4390)$	4391.6 ± 6.4	139.5 ± 16.1	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BESIII [170] (10)	2016	NC!
				$e^+e^- \to (\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [117, 121] (np)	2013	NC!
$\psi(4415)$	4421 ± 4	62 ± 20	1^{--}	$e^+e^- \to$ (hadrons)	PDG [131]	1976	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [148] (np), BESIII [162] (>5)	2013	NC!
				$e^+e^- \to (\omega \chi_{c2})$	BESIII [175] (10.4)	2015	NC!
				$e^+e^- \to (D\bar{D}_2^*(2460))$	Belle [176] (10)	2007	NC!
$Z(4430)^+$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [177, 178, 179] (6.4), BaBar [180] (2.4), LHCb [181, 182] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [163] (4.0)	2014	NC!
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	0^{++}	$B^+ \to K^+(\phi J/\psi)$	LHCb [159, 160] (6.1)	2016	NC!
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [173, 151] (5.8), BaBar [174] (5)	2007	Ok
				$e^+e^- \to (\Lambda_c^+ \bar{\Lambda}_c^-)$	Belle [183] (8.2)	2007	NC!
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B^+ \to K^+(\phi J/\psi)$	LHCb [159, 160] (5.6)	2016	NC!
$\Upsilon(4S)$	10579.4 ± 1.2	20.5 ± 2.5	1^{--}	$e^+e^- \to$ (hadrons)	PDG [131]	1985	Ok
				$e^+e^- \to (\pi^+\pi^- \Upsilon(1S, 2S))$	BaBar [184, 185] (>10), Belle [186, 187] (11.2)	2006	Ok
				$e^+e^- \to (\eta \Upsilon(1S))$	BaBar [185] (>11)	2008	Ok
				$e^+e^- \to (\eta h_b(1P))$	Belle [64] (11)	2015	Ok
$\Upsilon(10860)$	10891 ± 4	54 ± 7	1^{--}	$e^+e^- \to$ (hadrons)	PDG [131]	1985	Ok
				$e^+e^- \to (\pi^+\pi^- \Upsilon(1S, 2S, 3S))$	Belle [188, 125, 126] (>10)	2007	Ok
				$e^+e^- \to (\pi^0\pi^0 \Upsilon(1S, 2S, 3S))$	Belle [127] (np)	2013	Ok
				$e^+e^- \to (f_0(980) \Upsilon(1S))$	Belle [125, 127, 126] (>8)	2011	Ok
				$e^+e^- \to (f_2(1275) \Upsilon(1S))$	Belle [125, 127, 126] (np)	2011	NC!
				$e^+e^- \to (\eta \Upsilon(1S, 2S))$	Belle [189] (10)	2012	NC!
				$e^+e^- \to (K^+K^- \Upsilon(1S))$	Belle [188] (4.9)	2007	NC!
				$e^+e^- \to (\omega \chi_{b1,2}(1P))$	Belle [190] (12)	2014	Ok
				$e^+e^- \to ((\pi^+\pi^-\pi^0)_{\text{non-}\omega} \chi_{b1,2}(1P))$	Belle [190] (4.9)	2014	NC!
				$e^+e^- \to (\pi^+\pi^- \Upsilon_J(1D))$	Belle [189] (9)	2012	NC!
				$e^+e^- \to (\eta \Upsilon_J(1D))$	Belle [191] (np)	2014	NC!
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [125, 127] (>10)	2011	Ok
				$e^+e^- \to (B_s^* \bar{B}_s^*)$	Belle [192] (np)	2016	NC!
$\Upsilon(11020)$	$10987.5^{+11.0}_{-3.4}$	61^{+9}_{-28}	1^{--}	$e^+e^- \to$ (hadrons)	PDG [131]	1985	Ok
				$e^+e^- \to (\pi^+\pi^- \Upsilon(1S, 2S, 3S))$	Belle [193] (np)	2015	NC!
				$e^+e^- \to (\pi^\mp Z_b(10610, 10650)^\pm)$	Belle [130] (5.3)	2015	NC!

— IF $Z^{\pm}_{c,b}$ STATES ARE THERE, IT IS DIFFICULT TO ACCEPT THEM AS MOLECULES

— WHAT IS THE $Z^{+}(4430)$?

— CAN WE RISE SOME DOUBTS ON THE MOLECULAR NATURE OF $X(3872)$?

[FOR A REVIEW SEE ESPOSITO, PILLONI, P. Phys. Rept. 668 (2017)
ALI, LANG, STONE 1706.00610
LEBED, MITCHELL, SWANSON 1610.04528]

X(3872)

A $D^0(0^-)\,\bar{D}^{*0}(1^-)$ MOLECULE?

Suppose there is some $V(r)$ between D^0 & $\bar{D}^{*0}$

$$V(r) = -g\,\frac{e^{-r/r_0}}{r} \quad \text{with } r_0 \sim \frac{1}{m_\pi}$$

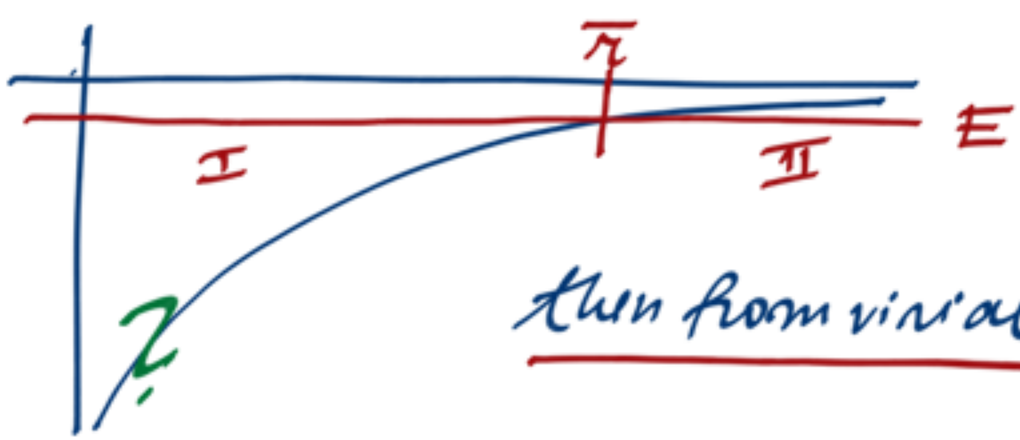
The VIRIAL THEOREM gives

$$2\langle T\rangle = \Big\langle \sum_{i=1}^{3} x_i \partial_i V \Big\rangle = \Big\langle r\frac{\partial}{\partial r} V(r)\Big\rangle$$

i.e.

$$\langle H\rangle = -\langle T\rangle + \frac{g}{r_0}\langle e^{-r/r_0}\rangle$$

$$= -\frac{\langle p^2\rangle}{2m} + \frac{g}{r_0}\exp\left(-\frac{\langle r\rangle}{r_0}\right)$$

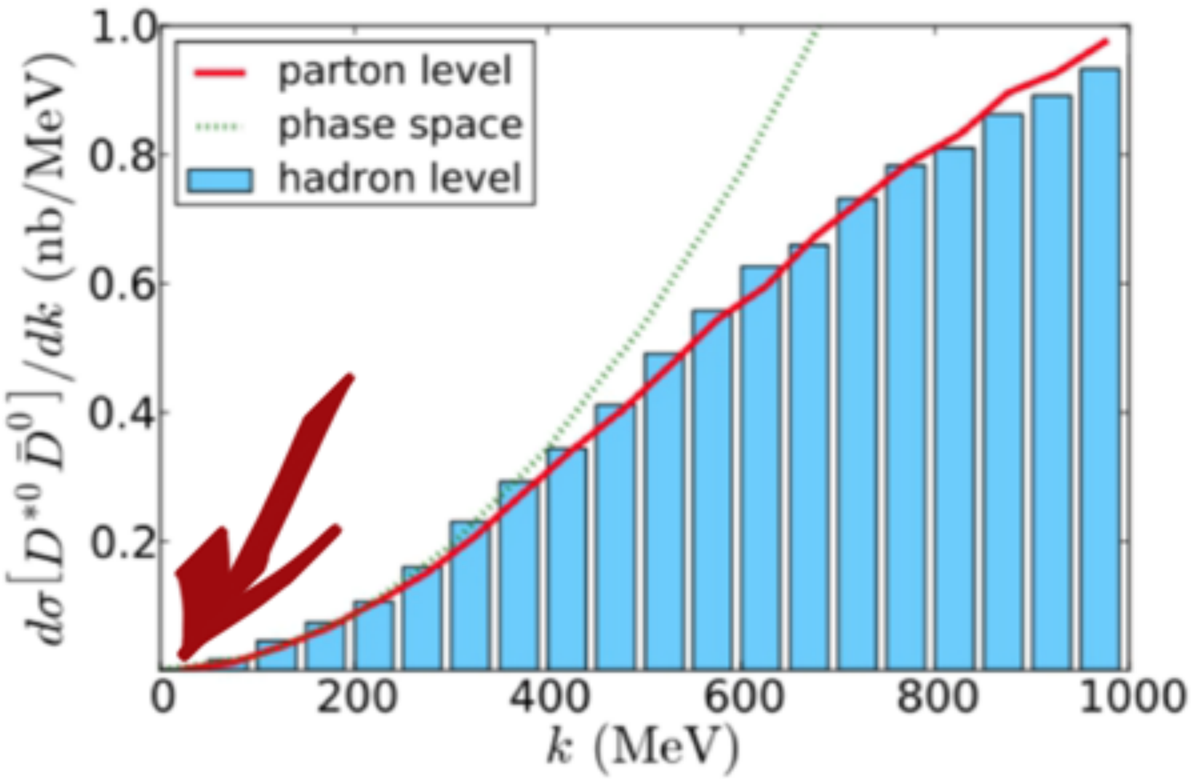


FOR SHALLOW BOUND STATES

$$\langle r\rangle \approx \frac{1}{\sqrt{2m|E|}} \approx 10\,fm \gg r_0$$

then from virial: $\sqrt{\langle p^2\rangle} \simeq 2m\,|E| \simeq 20\,MeV$

X PRODUCTION AT HADRON COLLIDERS

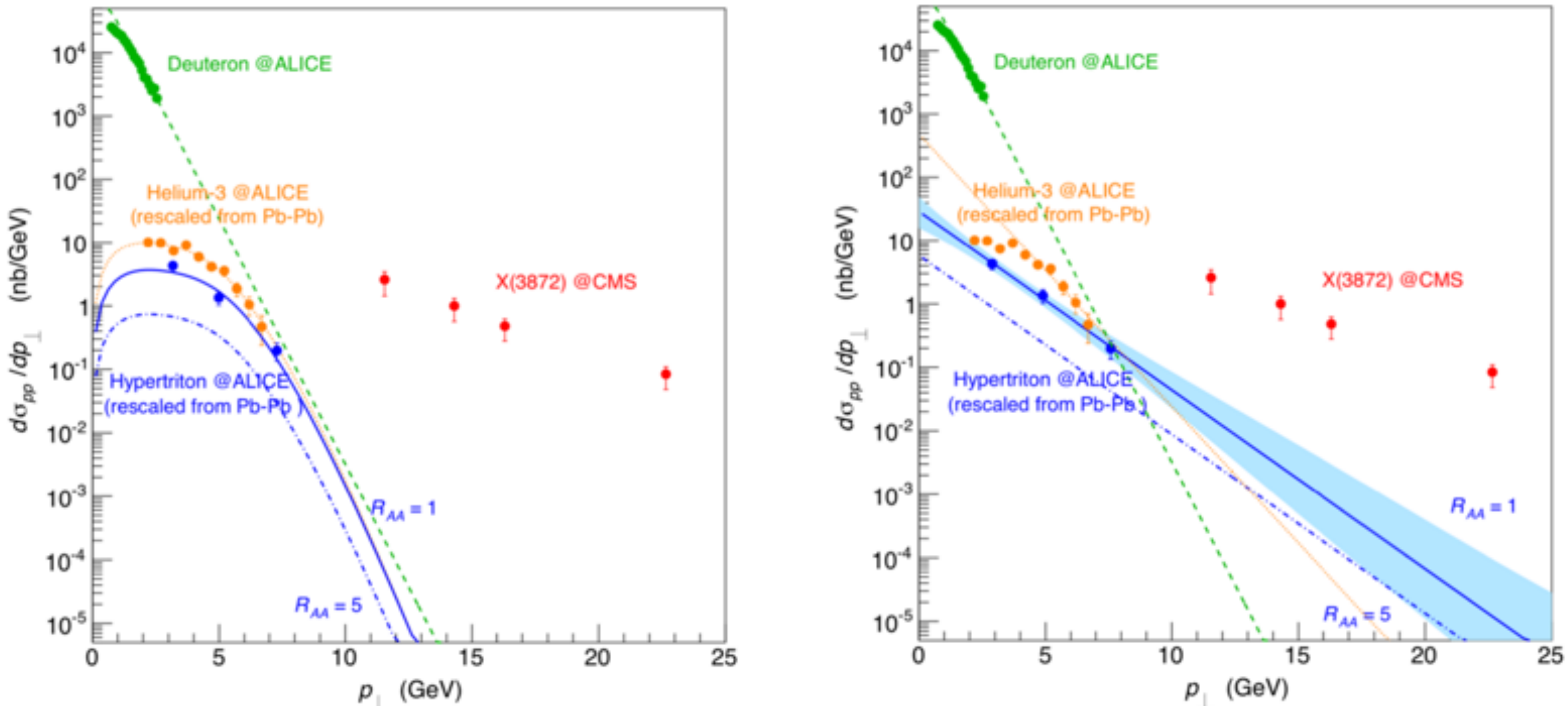


$p_T(D^{*0}\bar{D}^0) > 5$ GeV and $|y(D^{*0}\bar{D}^0)| < 0.6$
in $p\bar{p}$ @ 1.96 TeV

[FROM ARTOISENET & BRAATEN PRD 81 (2010) 014013

SAME RESULTS FOUND BY
BIGNAMINI & AL. PRL 103 (2009) 162001]

X PRODUCTION AT HADRON COLLIDERS



THE X PRODUCTION DOES NOT SEEM COMPARABLE TO THAT OF 'REAL' HADRON MOLECULES.

(what about other states in pp ?)

[FROM ESPOSITO & AL. PRD 92 (2015)]
1508.00295

NEUTRAL <u>AND</u> CHARGED STATES CAN SIMLPY BE

$$[Qq][\bar{Q}\bar{q}]$$

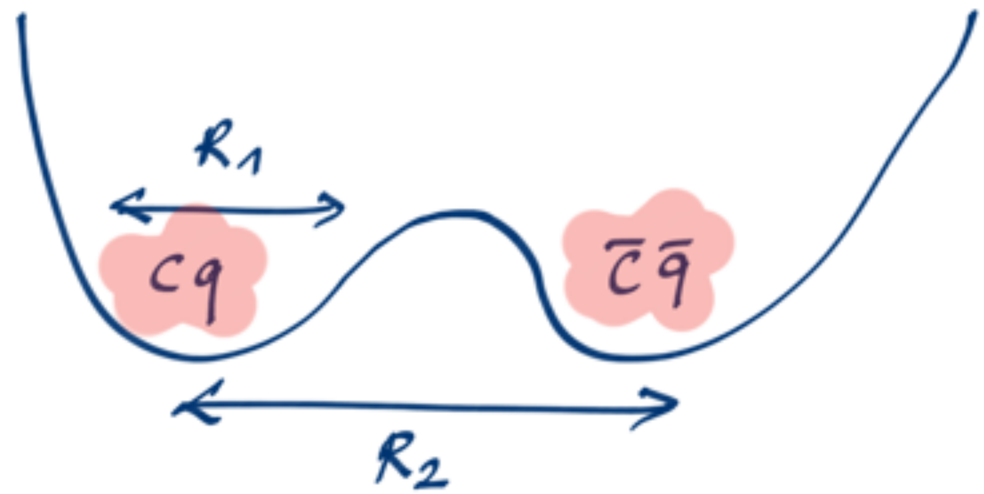
DIQUARK-ANTIDIQUARK COMPOSITE STATES

WOULD EXPLAIN NATURALLY THE EXISTENCE OF CHARGED STATES AND THEIR DECAYS, e.g. $Z_c^+ \to J/\psi\, \pi^+$

PROBLEMS:

- WHY $X^{\pm}(3872)$ STATES ARE ABSENT?
- HOW TO EXPLAIN THE ISOSPIN VIOLATION PATTERN?
- WHY ARE STATES CLOSE TO MESON-MESON THRESHOLDS?
- WHY $\mathcal{B}(X \to \psi\rho) \ll \mathcal{B}(X \to D^0 \bar{D}^{*0})$?

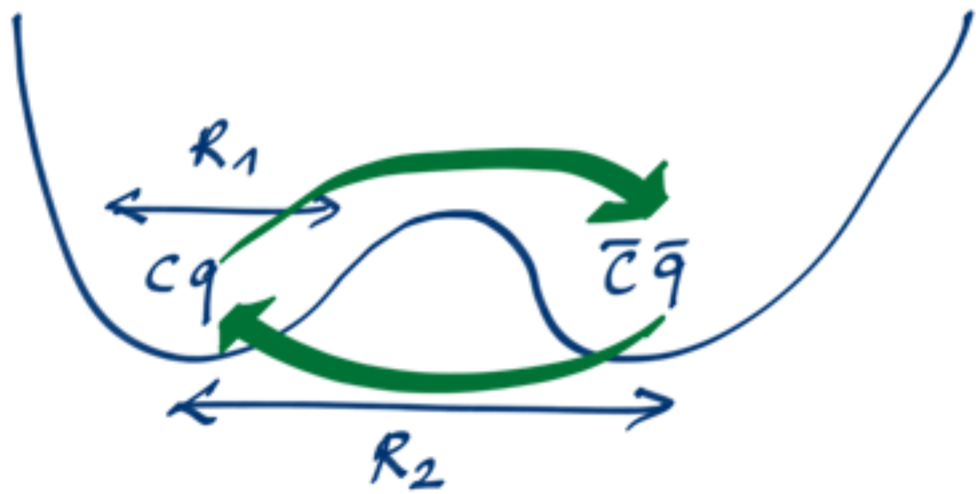
DIQUARK - ANTIDIQUARK STATES



$$\lambda = R_2/R_1 > 1$$

[MAIANI ET AL, IN PREPARATION]

DIQUARK-ANTIDIQUARK STATES



$R_2 > R_1$

THE TUNNELING OF THE HEAVY QUARK IS

$$\exp(-\sqrt{2M_Q})$$

WRT THE TUNNELING OF THE LIGHT QUARK.

This would explain why

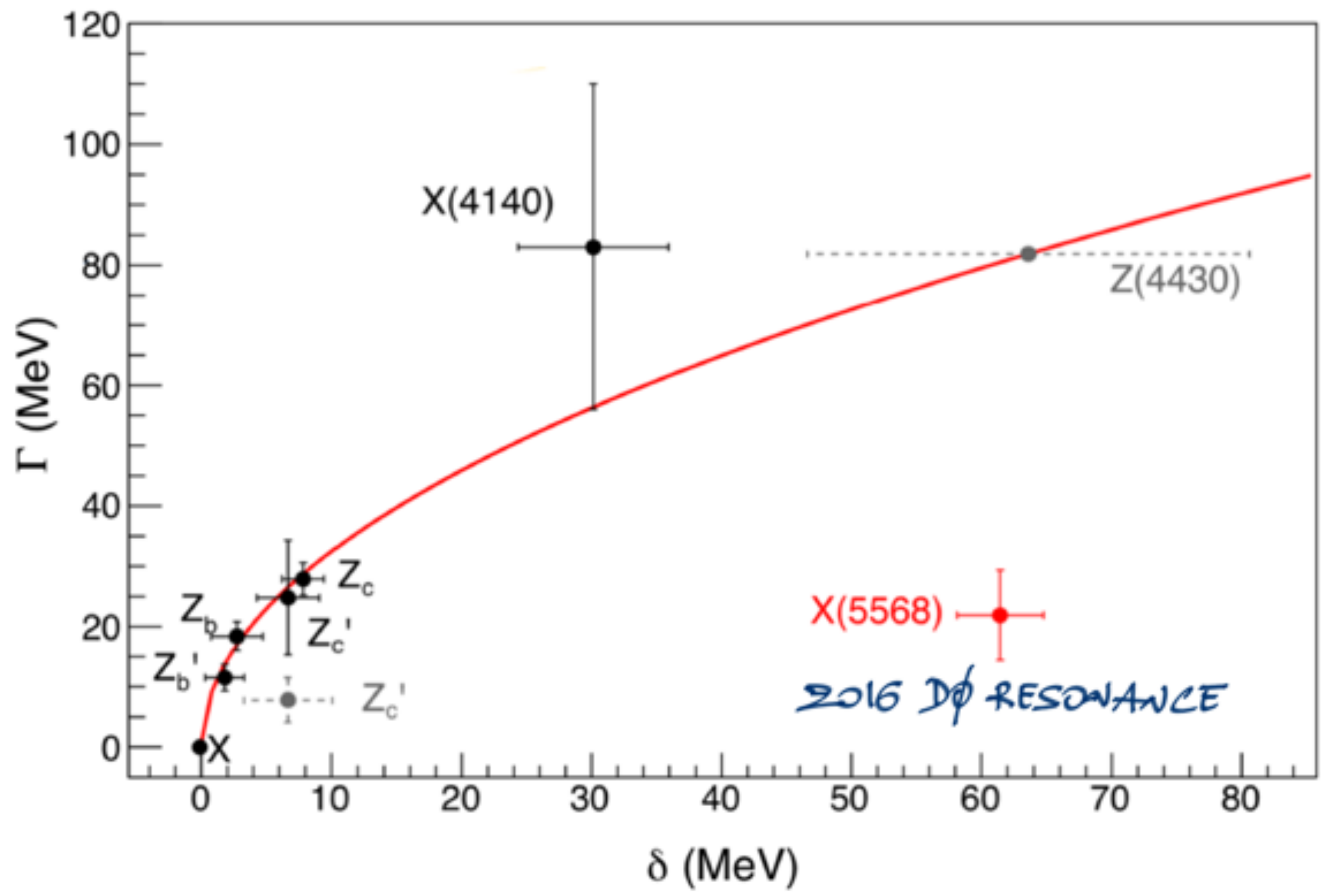
$$\mathcal{B}(X \to D^0 \bar{D}^{*0}) > \mathcal{B}(X \to J/\psi\, \rho)$$

ALSO DIQUARK $[cq]_{\bar{3}}$ ARE LESS BOUND THAN $(c\bar{q})_1$, SO WE CAN EXPECT THAT

$$M([cq]_{\bar{3}}[\bar{c}\bar{q}]_3) \gtrsim M((c\bar{q})_1(\bar{c}q)_1)$$

LIFETIME

INDEED THE TOTAL WIDTH OF X, Z_c, Z_b STATES APPEARS TO BE DOMINATED BY THEIR DECAYS INTO CLOSE MESON-MESON THRESHOLDS



$$\Gamma = A\sqrt{\delta}$$

[ESPOSITO & AL. PLB 758 (2016) 292]

→ $A = (10.3 \pm 1.3)\,\mathrm{MeV}^{1/2}$ $\chi^2/\mathrm{DOF} = 1.2/5$

TETRAQUARK STATES

$$H \approx 2\kappa\left(\vec{S}_q \cdot \vec{S}_Q + \vec{S}_{\bar{q}} \cdot \vec{S}_{\bar{Q}}\right)$$

SPECTRUM

0^{++} $+\kappa$ 1^{+-} $+\kappa$ 2^{++} $+\kappa$

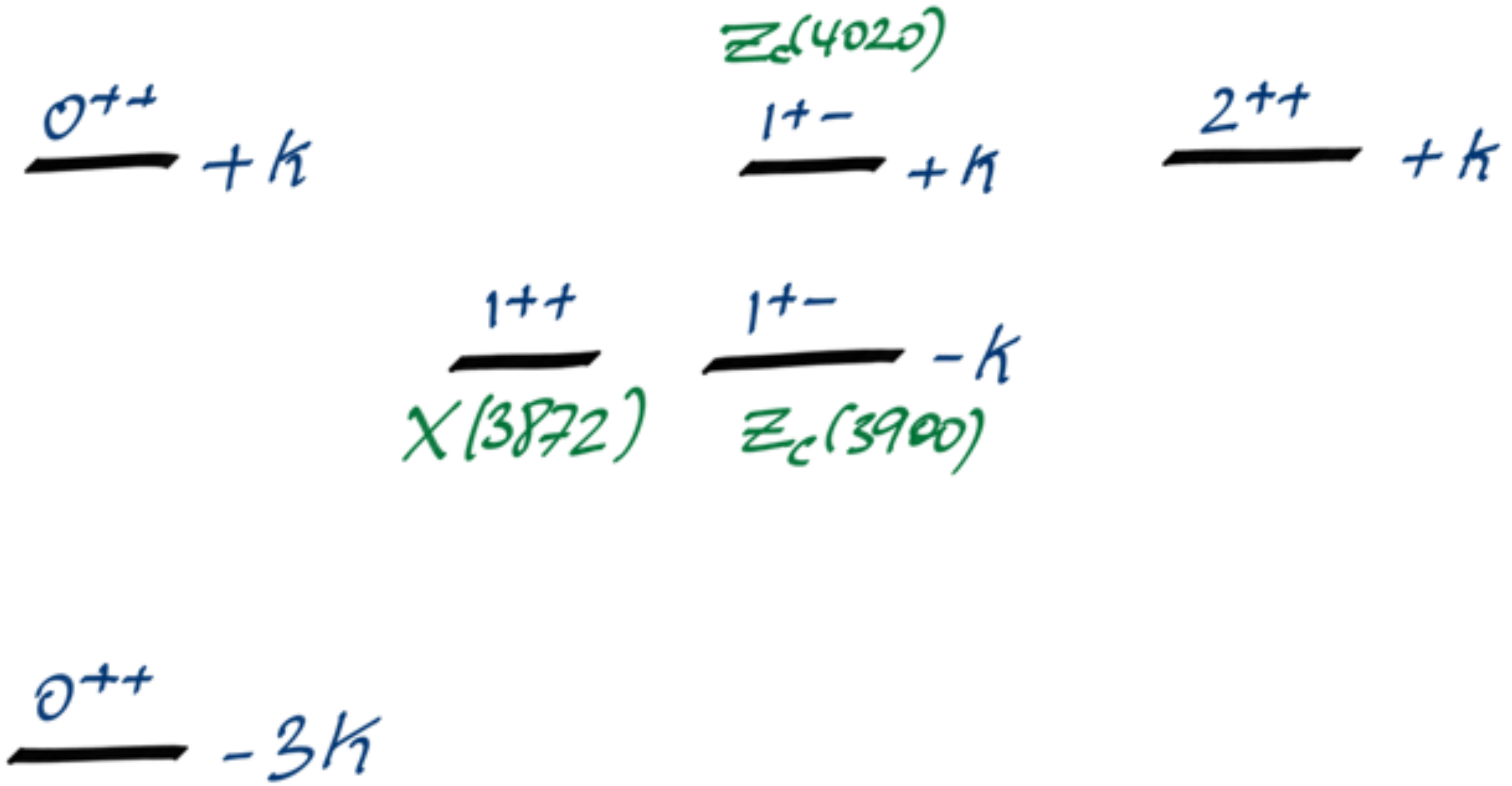
1^{++} 1^{+-} $-\kappa$

0^{++} -3κ

TETRAQUARK STATES

$$H \approx 2\kappa\left(\vec{S}_q \cdot \vec{S}_Q + \vec{S}_{\bar{q}} \cdot \vec{S}_{\bar{Q}}\right)$$

SPECTRUM



TUNNELING

$$\psi_D = [cu](x)\,[\bar c \bar u](y)$$

1. FIERZ COLOR $\psi_D \sim \big(c(x)\,\bar u(y)\big)\big(\bar c(y)\,u(x)\big)$
2. FIERZ SPIN & TUNNEL $y \mapsto x,\ x \to y$.

$$X_u = \frac{[cu]_0[\bar c\bar u]_1 + [cu]_1[\bar c\bar u]_0}{\sqrt{2}}$$

$$X_u \sim \frac{A}{\sqrt{2}}\left(D^0\bar D^{*0} - \bar D^0 D^{*0}\right)$$

WHEREAS

$$X_d \sim \frac{A}{\sqrt{2}}\left(D^+\bar D^{*-} - D^{*+}\bar D^-\right)$$

When by D^0 and $\bar D^{*0}$ we mean here

$c^\alpha(x)\,\sigma_2\,\bar u_\alpha(x)$ & $\bar c_\beta(y)\,\sigma_2\vec\sigma\,u^\beta(y)$

and so on.

X_u and X_d QUASI-DEGENERATE

WE RECONSIDERED THE PROBLEM OF THE DETERMINATION OF THE

$$M(X_u) - M(X_d) = \epsilon$$

MASS DIFFERENCE FINDING THAT AN APPROPRIATE CHOICE OF $\lambda = R_2/R_1$ COULD GIVE $\epsilon \simeq 0$.

[MAIANI ET AL. IN PREPARATION]

THUS WE HAVE A (X_u^0, X_d^0) QUASI-DEGENERATE DOUBLET (WITH X_d ALLOWED TO DECAY ONLY INTO $\psi\,\rho, \omega$) –

THE DOUBLET GETS MIXED

$$X_\ell = \cos\theta\, X_u + \sin\theta\, X_d$$

$$X_h = -\sin\theta\, X_u + \cos\theta\, X_d$$

X_u and X_d QUASI-DEGENERATE

$$\frac{\Gamma(B^0 \to KX, X \to 4\omega)}{\Gamma(B^0 \to KX, X \to 4\rho)} = R^{00} = \frac{\Gamma(B^0 \to X_\ell, X_\ell \to 4\omega) + (\ell \to h)}{\Gamma(B^0 \to X_\ell, X_\ell \to 4\rho) + (\ell \to h)}$$

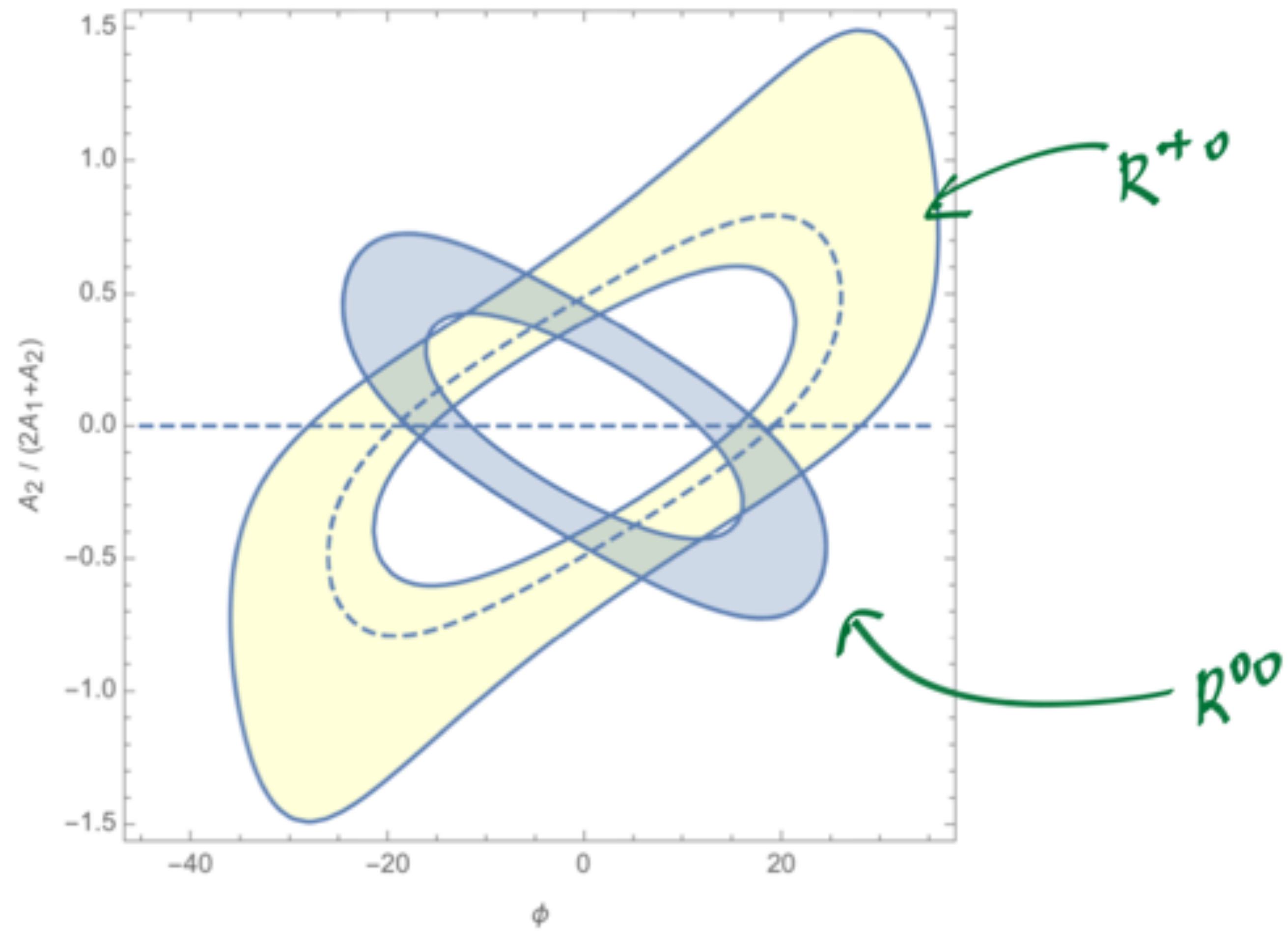
$$\stackrel{\text{EXP.}}{=} 1.4 \pm 0.6$$

AT THE SAME TIME WE CAN KEEP BELOW 1 THE RATIO

$$\frac{\Gamma(B^0 \to X^+, X^+ \to 4\rho^+)}{\Gamma(B^0 \to X^0, X^0 \to 4\rho^0)} = R^{0+}$$

ISOSPIN VIOLATION AND NON-OBSERVATION OF X^+ CAN LIVE TOGETHER.

X_u and X_d QUASI-DEGENERATE



$A_2 \propto R^{0+}$

$\theta_{mix} = 45° - \varphi$

R^0 & R^+ fixed on expt data (with errors)

WE CAN KEEP A_2 VERY LOW...

[MAIANI & AL, IN PREPARATION]

— WHY $X^{\pm}(3872)$ STATES ARE ABSENT?

THE A_2 AMPLITUDE CAN BE VERY SMALL

— HOW TO EXPLAIN THE ISOSPIN VIOLATION PATTERN?

WE HAVE X_ℓ & X_h NEITHER OF WHICH IS

$$\frac{X_u + X_d}{\sqrt{2}} \quad !$$

— WHY ARE STATES CLOSE TO MESON-MESON THRESHOLDS?

STRONG INT IN $\bar{3}_c$ ARE HALF AS STRONG AS 1_c

— WHY $\mathcal{B}(X \to \psi\rho) \ll \mathcal{B}(X \to D^0 \bar{D}^{*0})$?

BECAUSE OF $\exp(-\sqrt{2M_H})$ IN BARRIER PENETRATION

THE Z_c's & Z_b's

RECALL

$$X_u \sim \frac{A}{\sqrt{2}}\left(D^0\bar{D}^{*0} - D^{*0}\bar{D}^0\right)$$

$$X_d \sim \frac{A}{\sqrt{2}}\left(D^+\bar{D}^{*-} - D^{*+}\bar{D}^-\right)$$

SIMILARLY

$$Z_c \sim \frac{B}{\sqrt{2}}\left(D^0\bar{D}^{*0} - D^{*0}\bar{D}^0\right) + C\, D^{*0}\times\bar{D}^{*0}$$

The nontrivial dependence of BARRIER PENETRATION FACTORS FROM LIGHT QUARK SPINS ALLOWS $Z_c \to DD^*$.

phase space forbidden.

Z_C HAS NOT (YET?) BEEN OBSERVED IN B DECAYS.
WE COULD HAVE $\varphi \gtrsim 0$ ($\theta \simeq 45°$) SO THAT Z_e & Z_h CORRESPOND TO $I=0$ & $I=1$, AND SIZEABLE $R^{0\pm}$ (as well as $R^{\pm\mp}$).

OPEN QUESTIONS

- $Z_c^{\pm,0}$, $Z_c'^{\pm,0}$ IN B DECAYS ?

- $Z_c^{\pm,0}$, $Z_c'^{\pm,0}$ IN PROMPT pp COLLISIONS ?

  [Same question for Z_b's]

  FINAL STATES LIKE $J/\psi\,\pi^+$ SHOULD BE FEASIBLE.

- Which resolution can be reached to measure the mass of the X^0 in $D^0\bar{D}^{*0}$ and in $J/\psi\,\rho$? $M(X_\ell) - M(X_h)$ could be $\simeq 0$, but this is worth being investigated.

- What about the X_b^0 ($> B^0\bar{B}^{*0}$) ?

backup

courtesy of A Pilloni

Charged $Z_c(3900)$

Found in $Y(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp} \to J/\psi\,\pi^{\pm}\,\pi^{\mp}$

Exotic charged charmonium-like state!

$$G = G_\pi C_{J/\psi} = \\ = -1(-1) = +1$$
$$P = +1\ (S - \text{wave})$$
$$\Rightarrow Z_c^0 \text{ has } J^{PC} = 1^{+-}$$

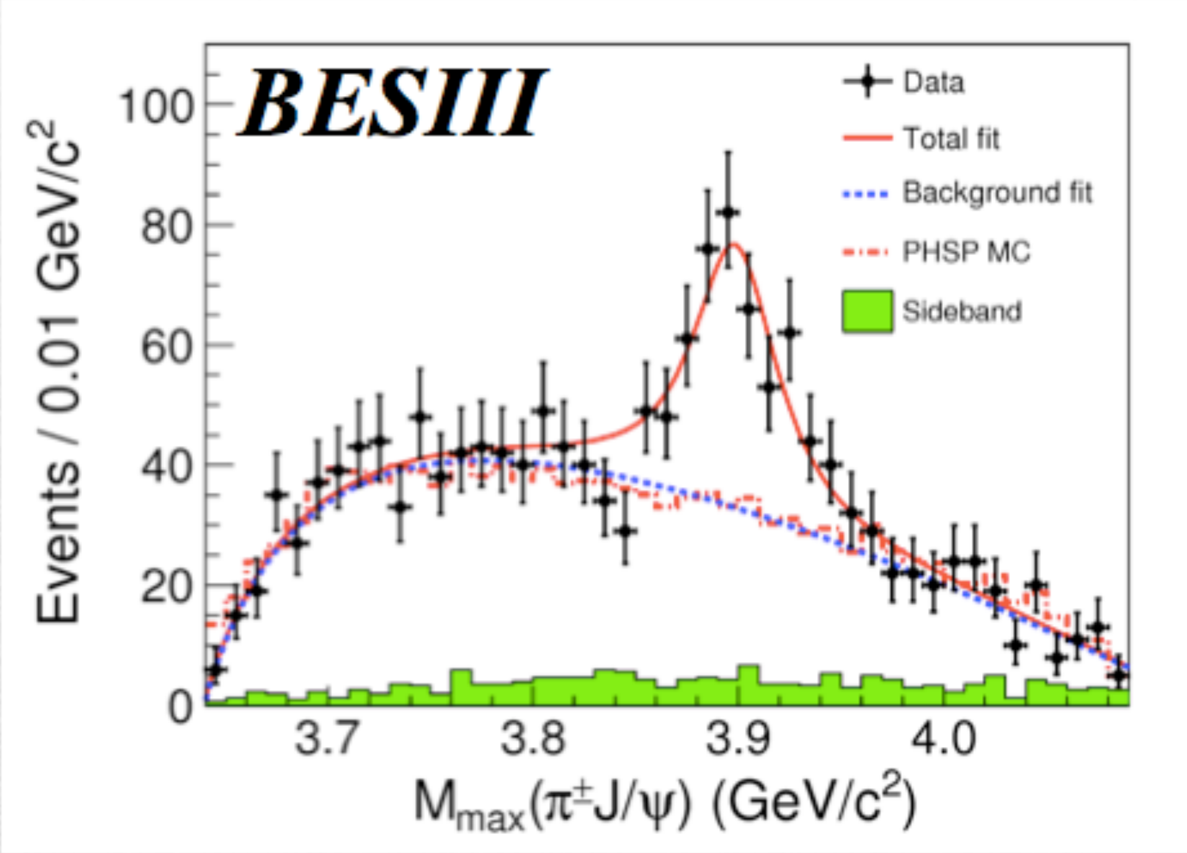
$$I^G J^{PC} = 1^+ 1^{+-}$$

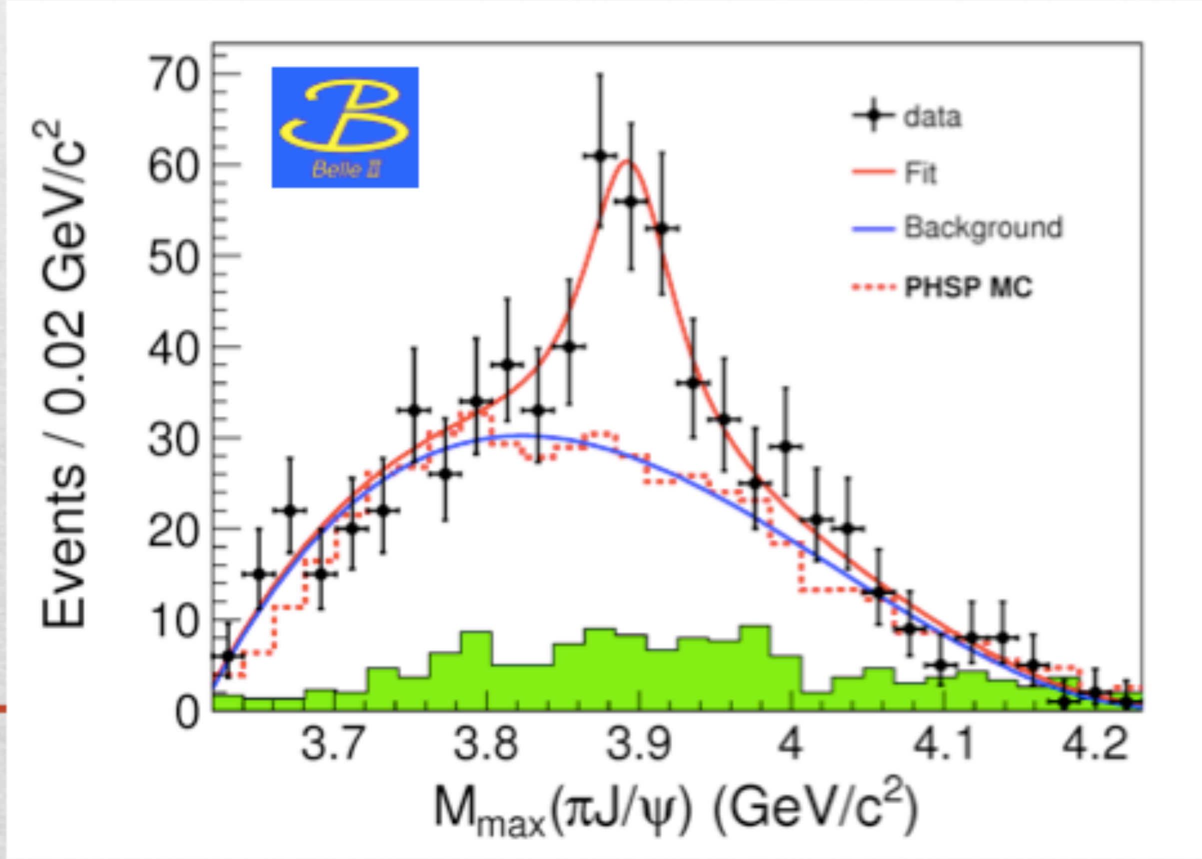
BESIII, arXiv:1303.5949

$M = 3899.0 \pm 3.6 \pm 4.9$ MeV
$\Gamma = 46 \pm 10 \pm 20$ MeV

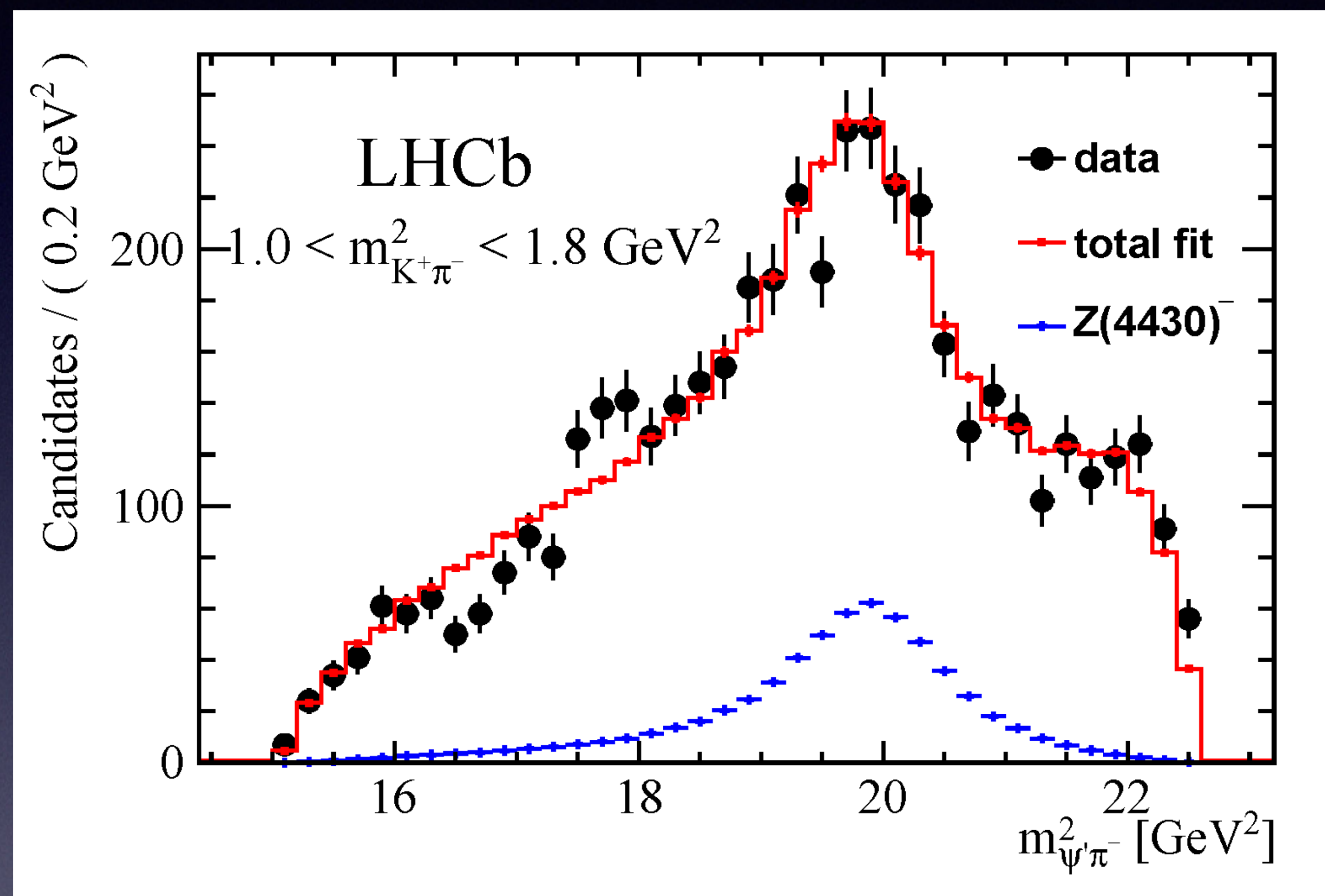
Belle, arXiv:1304.0121

$M = 3894.5 \pm 6.6 \pm 4.5$ MeV
$\Gamma = 63 \pm 24 \pm 26$ MeV





Z(4430)$^-$ at LHCb | April 2014



$$B \to K^+(\psi(2S)\pi^-)_{J^{PG}=1^{++}}$$

Signal: 13.9 σ

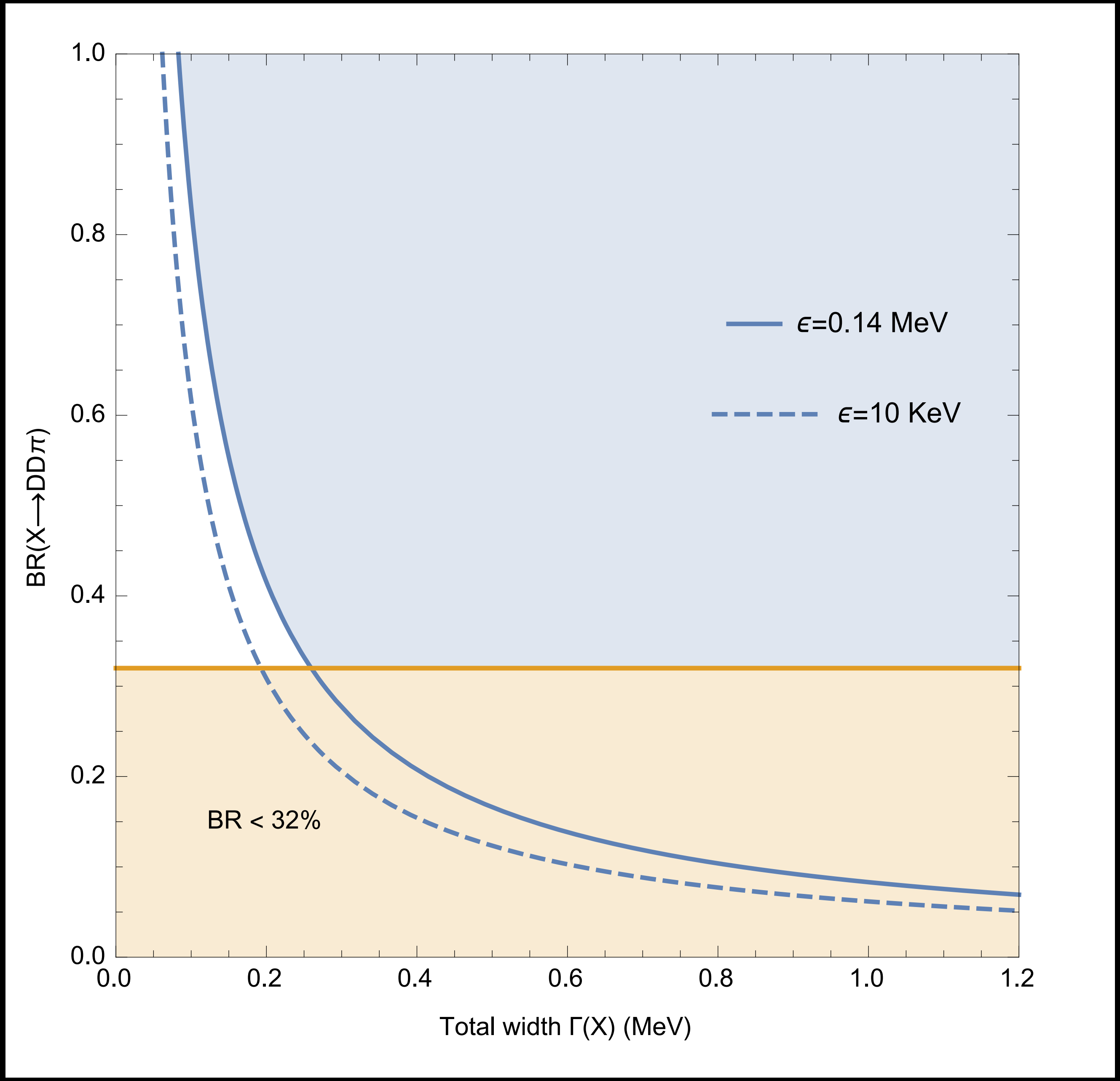
Other assignments ruled out at 9.7σ

First observed by BELLE in <u>2007</u> and <u>not confirmed by BaBar at that time</u>

Binding energy and decay rates

$$B \simeq \frac{G^4}{512\,\pi^2}\frac{m^5}{(m_a m_b)^4}$$

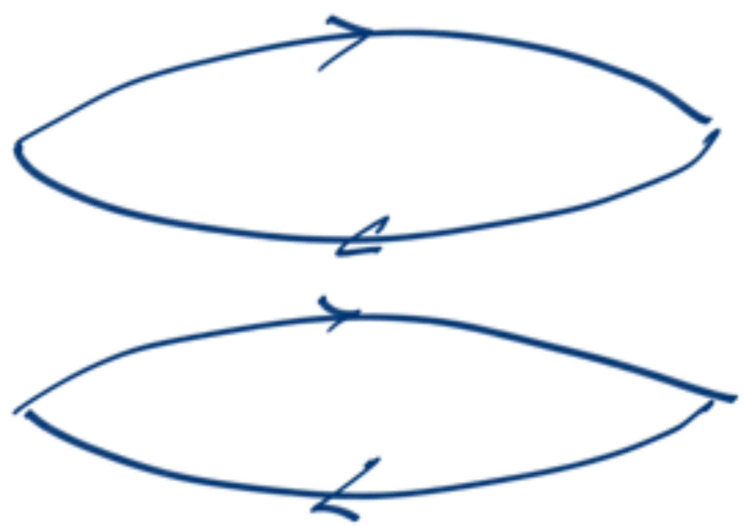
$$\mathcal{B}(X \to DD\pi)\cdot\Gamma(X) \sim G^2 \sim \sqrt{B}$$



ADP
1505.03083 PLB

TETRAQUARKS & 1/N EXPANSION

TETRAQUARK CORRELATORS FOR $N \to \infty$ REDUCE TO DISCONNECTED MESON-MESON PROPAGATORS (WITTEN NPB 160 (1979))



$\sim N^2$

(THIS WOULD MEAN THAT Ψ_m & Ψ_d ARE INDISTINGUISHABLE!)

IF CONNECTED TETRAQUARK CORRELATORS DEVELOP A POLE, IT WILL BE IRRELEVANT IF ITS RESIDUE IS SUBLEADING WRT DISCONNECTED PARTS (WEINBERG PRL 110 (2013))