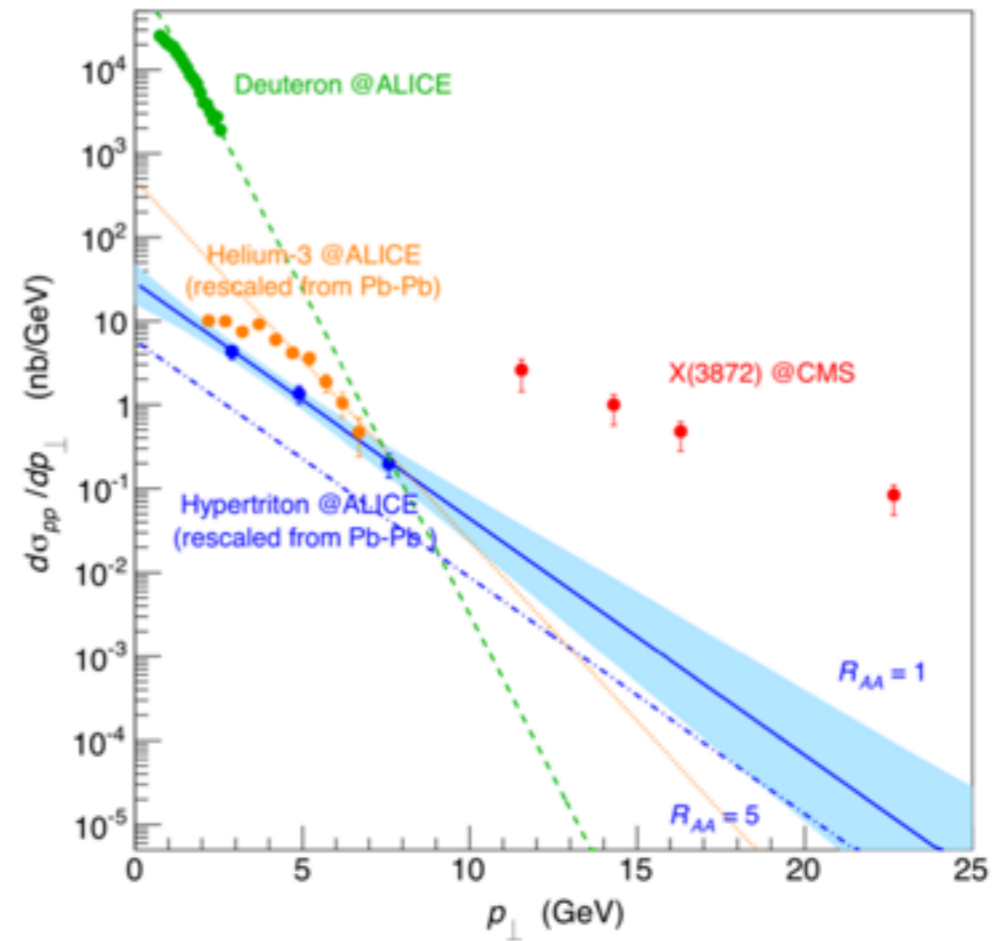
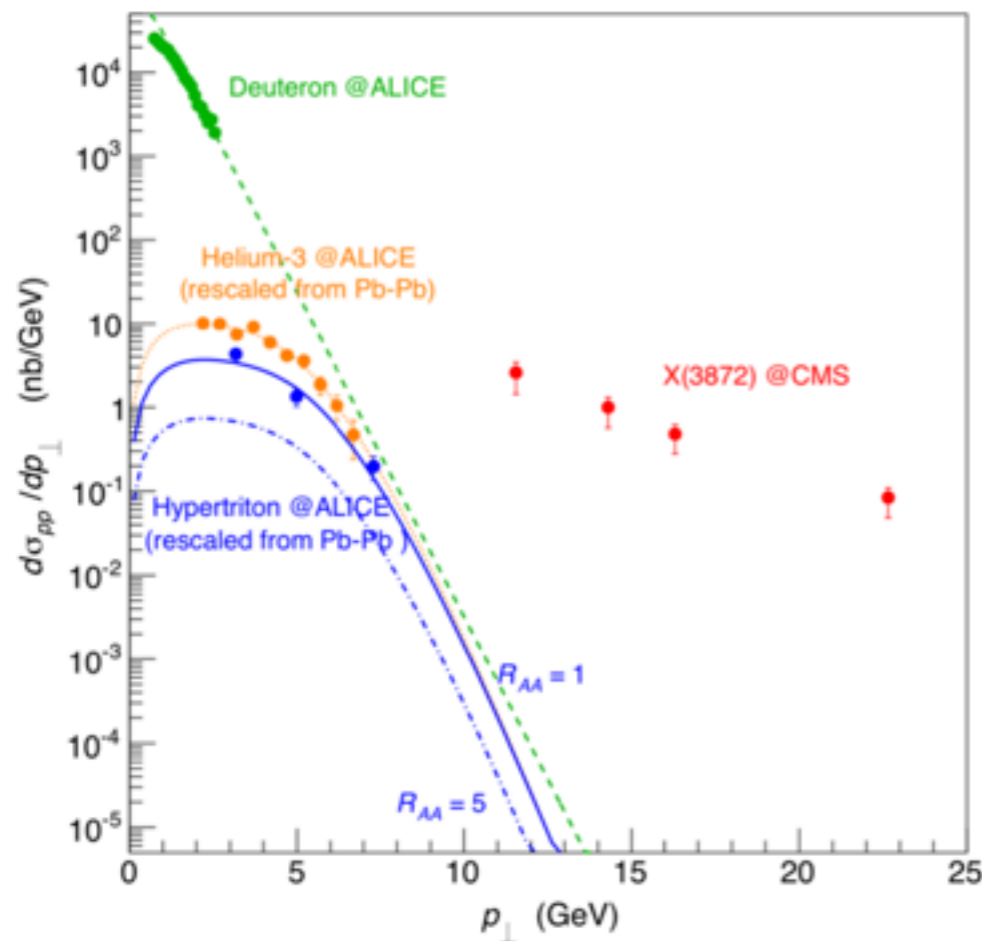


XYZ EXOTIC RESONANCES AT THE LHC

AD POLOSA (SAPIENZA UNIVERSITY)

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 ET AL. PRD 92 (2015)]
1508.00295

CHARGED STATES

DURING THE LAST FEW YEARS THE FOLLOWING CHARGED I^{\pm} STATES HAVE BEEN DISCOVERED

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

WITH MASS VALUES ABOVE THE CORRESPONDING MESON-MESON THRESHOLDS:

$$\begin{array}{cccc} \delta = & +7.8 & +6.7 & +2.7 & +1.8 \text{ MeV} \\ & \bar{D}^0 D^{*+} & \bar{D}^{*0} D^{*+} & \bar{B}^0 B^{*+} & \bar{B}^{*0} B^{*+} \end{array}$$

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

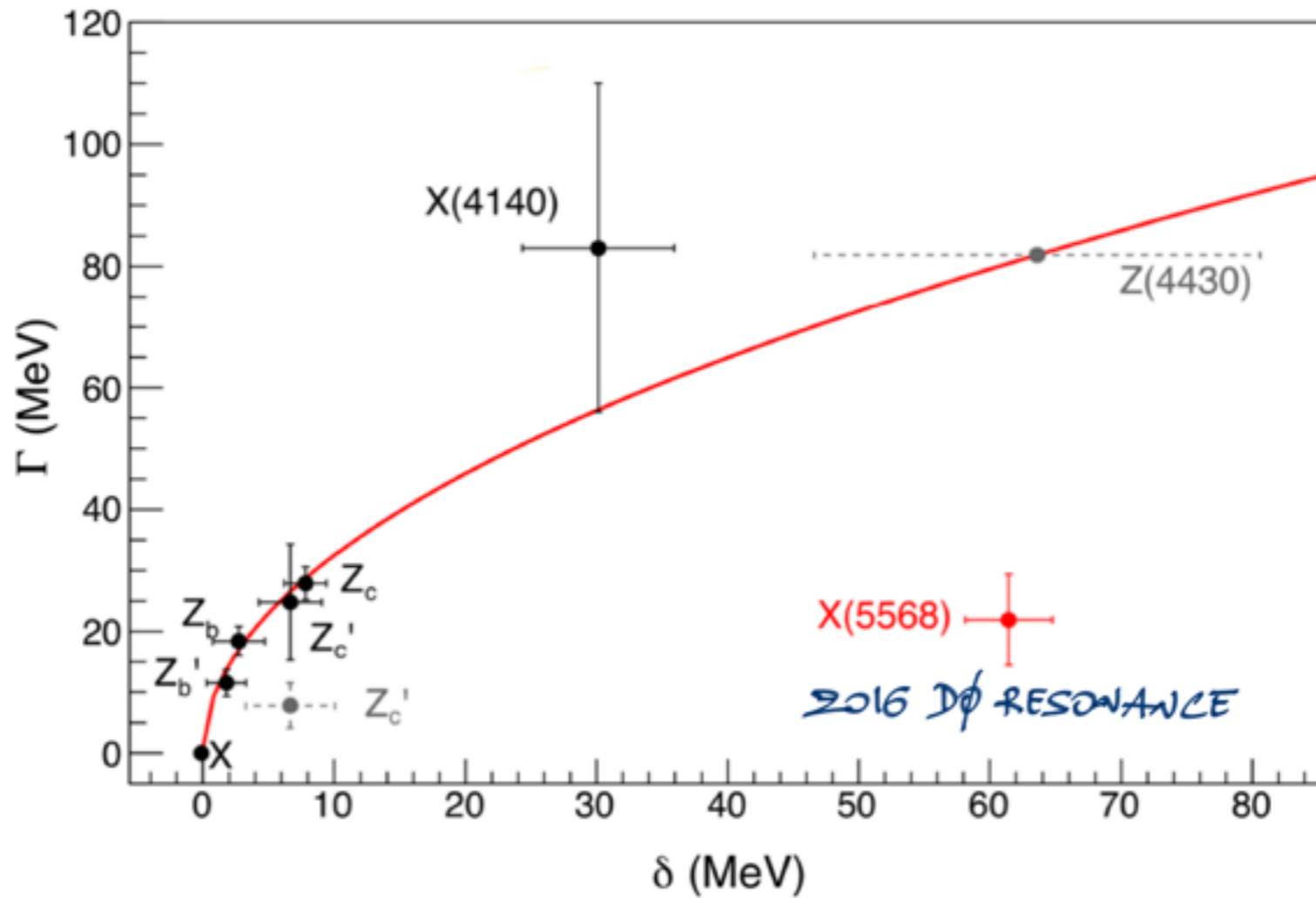
— MOLECULES EVEN IF $\delta > 0$?!

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

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

LIFETIME

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



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

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



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

NEUTRAL AND CHARGED STATES CAN SIMPLY BE

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

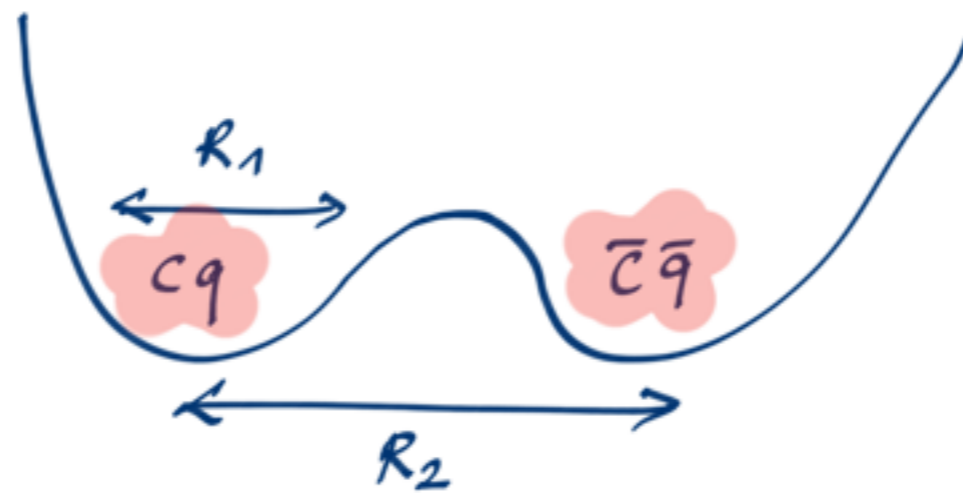
DIQUARK-ANTI-DIQUARK COMPOSITE STATES

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

PROBLEMS:

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

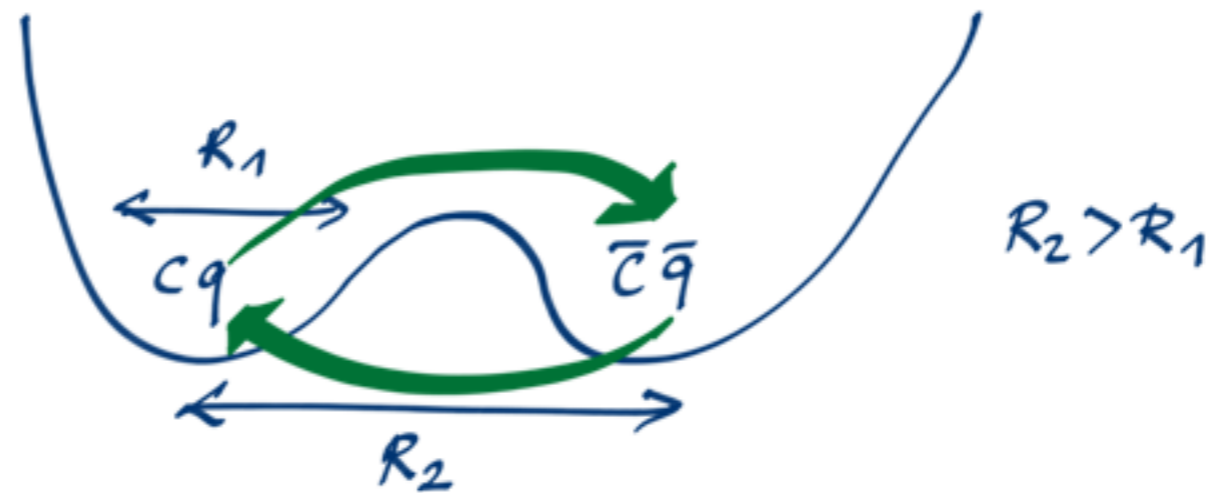
DIQUARK - ANTI DIQUARK STATES



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

[MAIANI ET AL, IN PREPARATION]

DIQUARK - ANTI DIQUARK STATES



THE TUNNELING OF THE HEAVY QUARK IS

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

WRT THE TUNNELING OF THE LIGHT QUARK.

This would explain why

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

ALSO DIQUARK $[cq]_3$ ARE LESS BOUND THAN $(c\bar{q})_1$, SO WE CAN EXPECT THAT

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

TETRAQUARK STATES

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

SPECTRUM

$$\underline{0^{++}} + \kappa$$

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

$$\underline{2^{++}} + \kappa$$

$$\underline{1^{++}}$$

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

$$\underline{0^{++}} - 3\kappa$$

TETRAQUARK STATES

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

SPECTRUM

$$\underline{0^{++}} + \kappa$$

$Z_c(4020)$

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

$$\underline{2^{++}} + \kappa$$

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

$X(3872)$ $Z_c(3900)$

$$\underline{0^{++}} - 3\kappa$$

TUNNELING

$$\Psi_D = [c u](x) [\bar{c} \bar{u}](y)$$

1. FIERZ COLOR $\Psi_D \sim (c(x) \bar{u}(y)) (\bar{c}(y) u(x))$
2. FIERZ SPIN & TUNNEL $y \leftrightarrow x, x \rightarrow y.$

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

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

WHEREAS

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

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

$c^\alpha(x) \sigma_2 \bar{u}_\alpha(x)$ & $\bar{c}_\beta(y) \sigma_2 \bar{u}^\beta(y)$
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 $\epsilon \approx 0$.

[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 ψ, ρ, ω).

THE DOUBLET GETS MIXED

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

$$X_{\bar{\ell}} = -\sin\theta X_u + \cos\theta X_d$$

**We find that X_u , X_d and X^\pm are almost degenerate states
(for an appropriate choice of λ) $X_u \sim X_d \sim X^\pm$**

X_u , X_d mix into X_l and X_h

**X_u can decay into DD^* , but this is not the case for X_d and X^\pm
—the latter two have only charmonium modes.**

The hyperfine splitting between X_u and X_d could eventually be resolved.

Why X^\pm has not (yet) been observed in $\psi\rho$?

**Probably because it is assumed that $\Gamma(X^0 \rightarrow \psi\rho^0) \sim \Gamma(X^+ \rightarrow \psi\rho^+)$
but this may not be the case.**

X_u and X_d QUASI-DEGENERATE

$$\frac{\Gamma(B^0 \rightarrow KX, X \rightarrow \psi\omega)}{\Gamma(B^0 \rightarrow KX, X \rightarrow \psi\rho)} = R^{00} = \frac{\Gamma(B^0 \rightarrow X_e, X_e \rightarrow \psi\omega) + (l \rightarrow h)}{\Gamma(B^0 \rightarrow X_e, X_e \rightarrow \psi\rho) + (l \rightarrow h)}$$

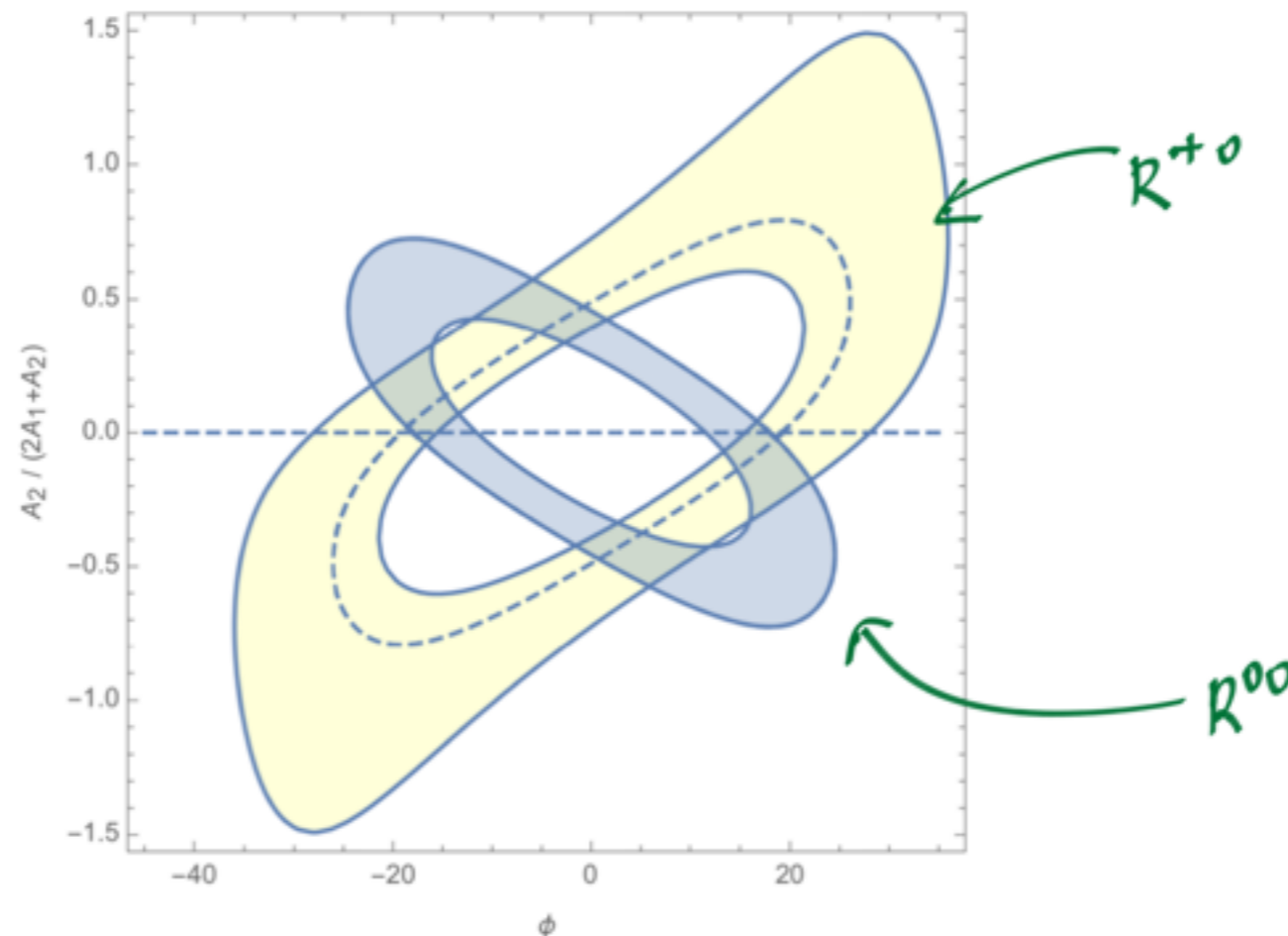
$$\stackrel{\text{EXP.}}{=} 1.4 \pm 0.6$$

AT THE SAME TIME WE CAN KEEP BELOW 1
THE RATIO

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

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

X_u and X_d QUASI-DEGENERATE



$$A_2 \propto R^{0+}$$

$$\Theta_{\text{mix}} = 45^\circ - \varphi$$

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_u & X_d NEITHER OF WHICH IS

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

— WHY ARE STATES CLOSE TO MESON-MESON THRESHOLDS?

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

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

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

THE Z_c 's & Z_b 's

RECALL

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

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

SIMILARLY

$$Z_c \sim \frac{\beta}{\sqrt{2}} (D^0 \bar{D}^{*0} - D^{*0} \bar{D}^0) + c \underbrace{D^{*0} \times \bar{D}^{*0}}_{\text{phase space forbidden.}}$$

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

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

OPEN QUESTIONS

— $Z_c^{\pm,0}, Z_c^{\prime\pm,0}$ IN B DECAYS?

— $Z_c^{\pm,0}, Z_c^{\prime\pm,0}$ IN PROMPT pp COLLISIONS?

[Same question for Z_c 's]

FINAL STATES LIKE $J/4 \pi^+$ SHOULD BE FEASIBLE.

— Which resolution can be needed to measure the mass of the X^0 in $D\bar{D}^{*0}$ and in $J/4 p$?

$M(X_{\ell}) - M(X_{\ell'})$ could be ≈ 0 , but this is worth being investigated.

— What about the X_{ℓ}^0 ($> B^0 \bar{B}^{*0}$)?

- IF $Z_{c,b}^+$ 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) 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' (Törzsgrit)

FOR A PURE $I=0$ STATE

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

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 RUIJLA, GEORGI, GLASHOW PRL 38 (1977) 317]

X(3872)

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

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

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

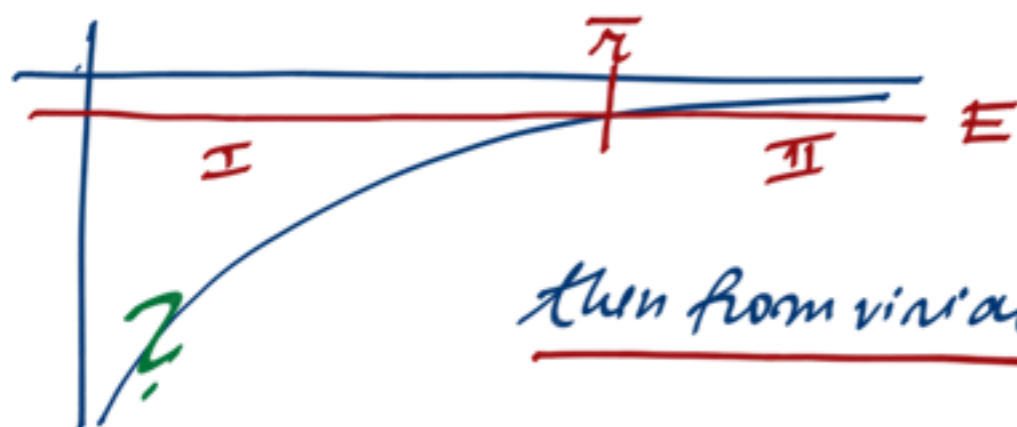
The VIRIAL THEOREM gives

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

i.e.

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

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

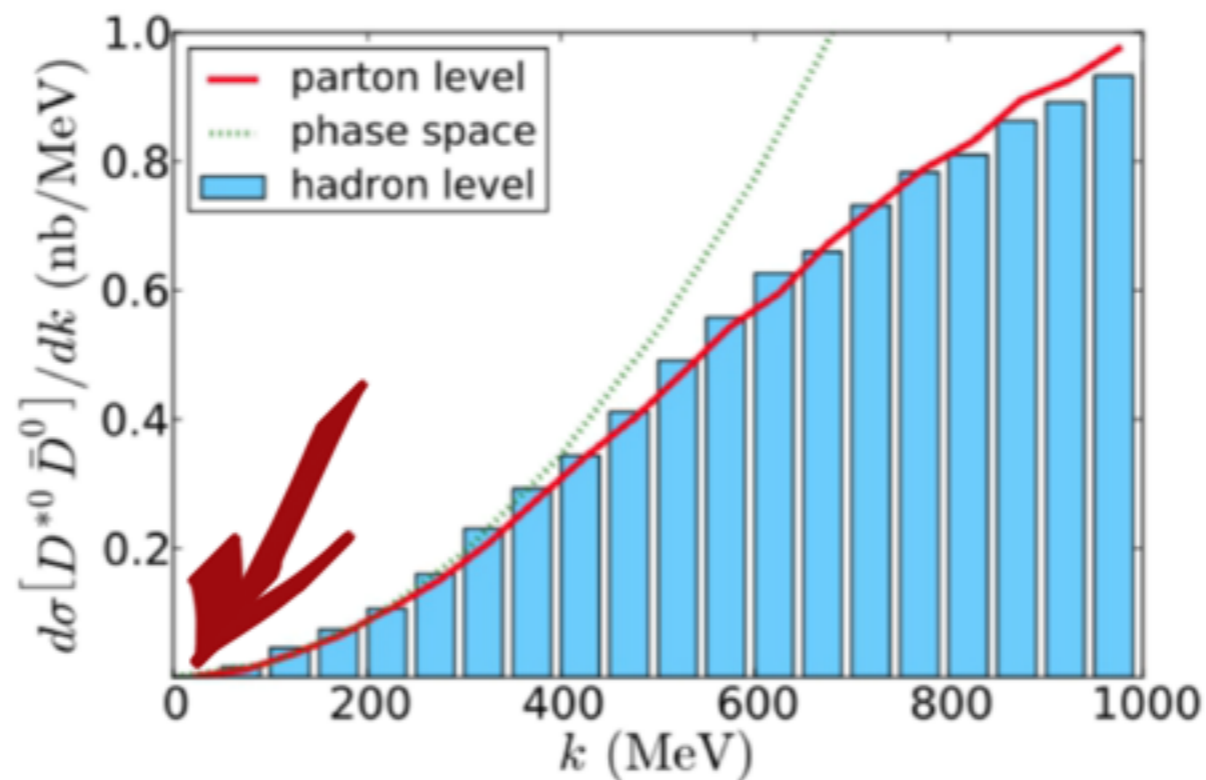


FOR SHALLOW BOUND STATES

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

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

X PRODUCTION AT HADRON COLLIDERS



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

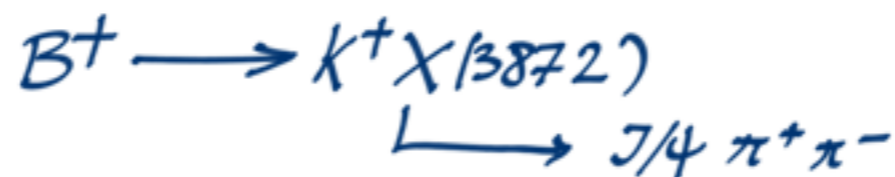
FROM ARTOISENET & BRAATEN PRD 81 (2010) 014013

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

backup

X(3872)

2003 BELLE



QUANTUM NUMBERS: 1^{++}

— LATER OBSERVED ALSO IN $J/4 \omega$

$$\mathcal{B}(X \rightarrow J/4 \rho) \simeq \mathcal{B}(X \rightarrow J/4 \omega)$$

WHAT IS THE ORIGIN OF THIS ISOSPIN VIOLATION?

— A REMARKABLE EXAMPLE OF FINE TUNING

$$M(X(3872)) \simeq M(D^0) + M(\bar{D}^{*0})$$
$$\simeq M(J/4) + M(\rho)$$

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

Charged $Z_c(3900)$

Found in $Y(4260) \rightarrow Z_c^\pm(3900) \pi^\mp \rightarrow J/\psi \pi^\pm \pi^\mp$

Exotic charged charmonium-like state!

$$G = G_\pi C_{J/\psi} =$$

$$= -1(-1) = +1$$

$$P = +1 \text{ (S-wave)}$$

$\Rightarrow Z_c^0$ has $J^{PC} = 1^{+-}$

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

BESIII, arXiv:1303.5949

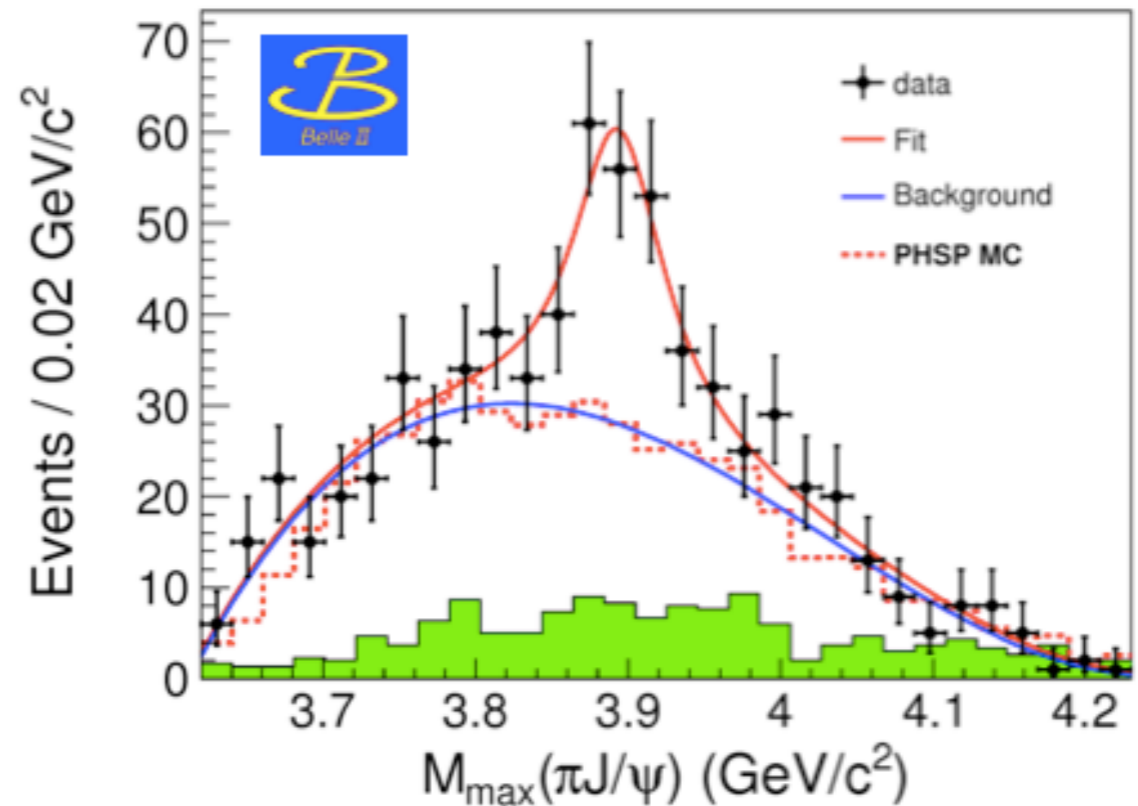
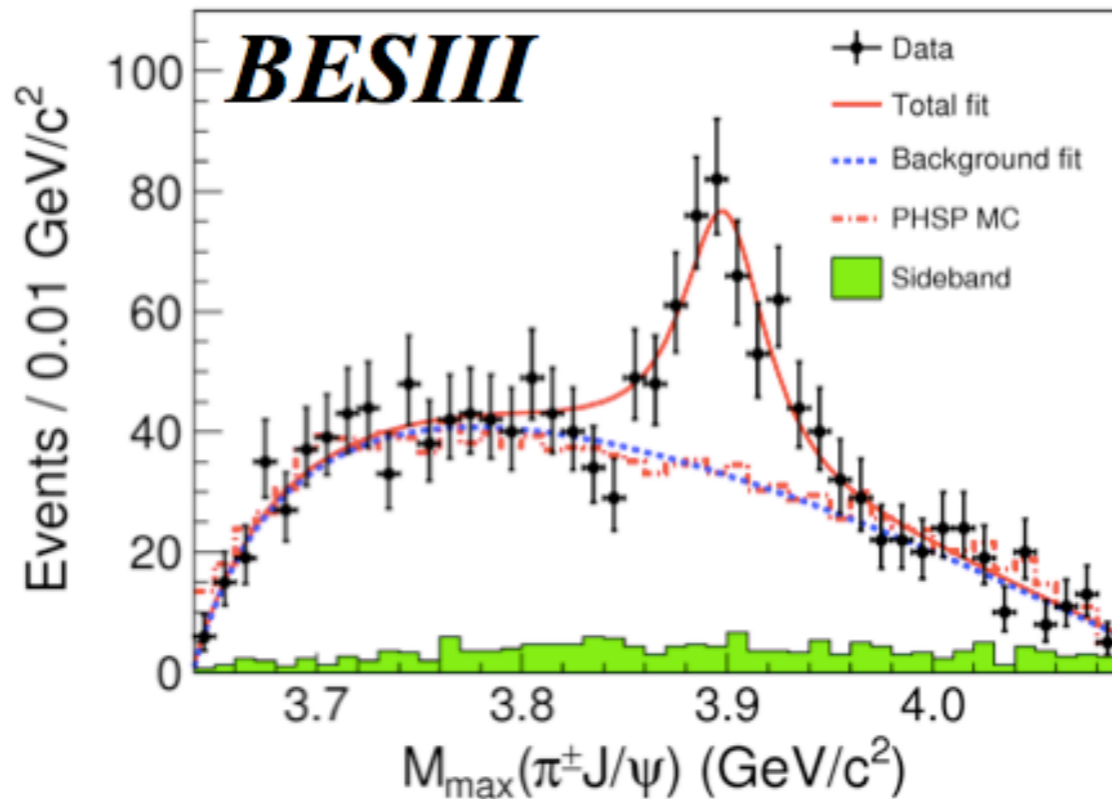
$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$

$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

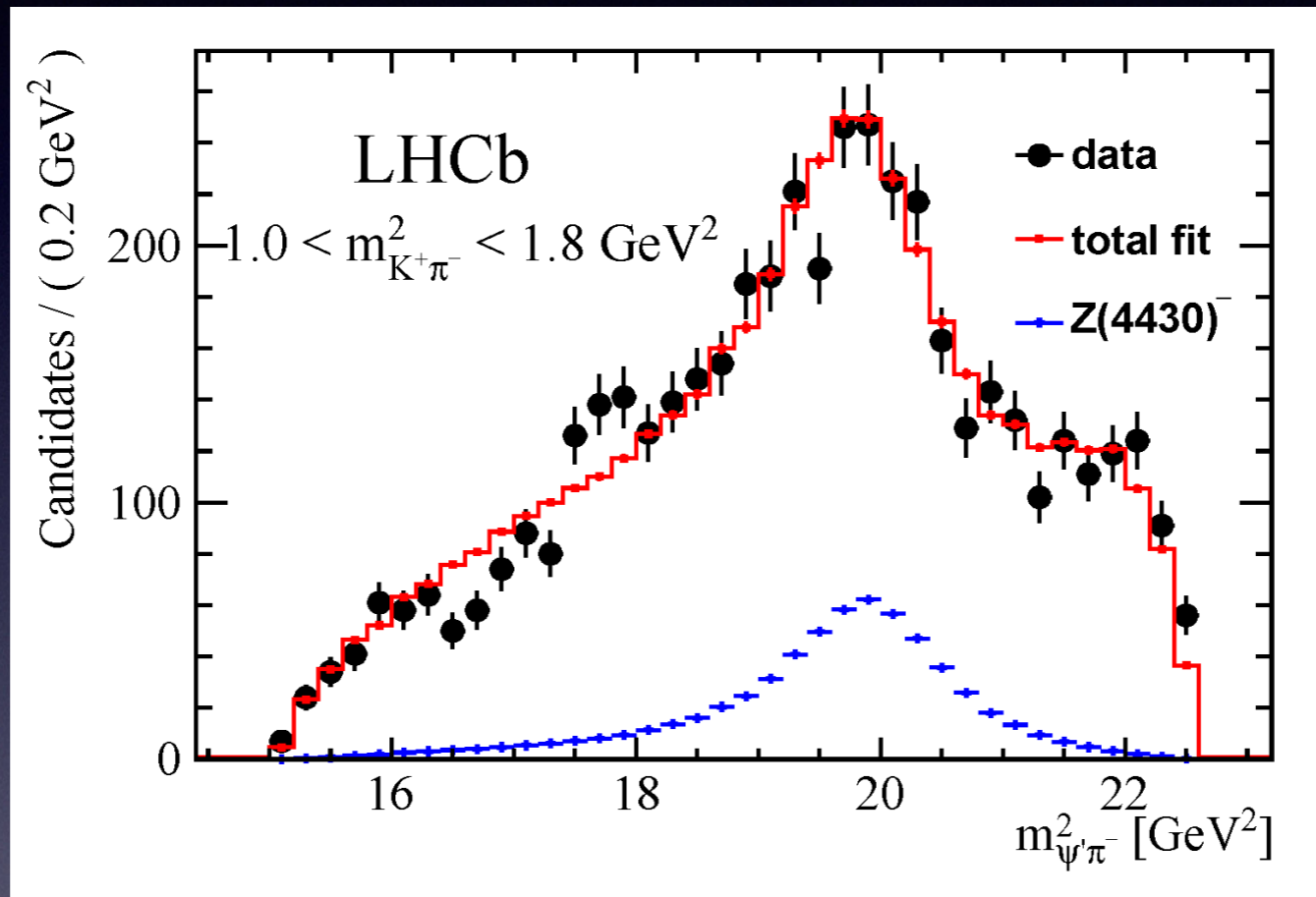
Belle, arXiv:1304.0121

$$M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$$

$$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$$



Z(4430)⁻ at LHCb | April 2014



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

Signal: 13.9σ

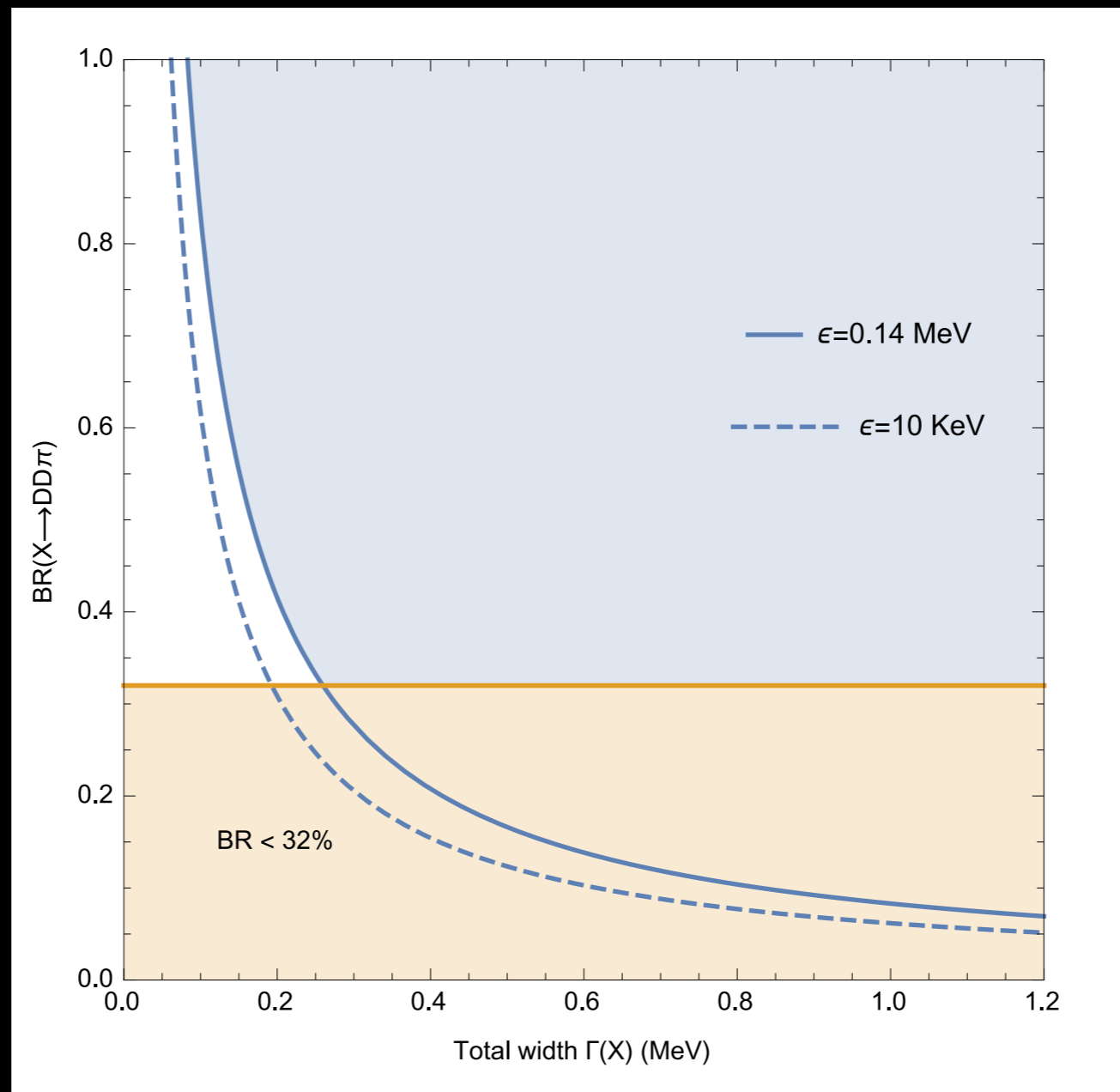
Other assignments ruled out at 9.7σ

First observed by BELLE in 2007 and not confirmed by BaBar at that time

Binding energy and decay rates

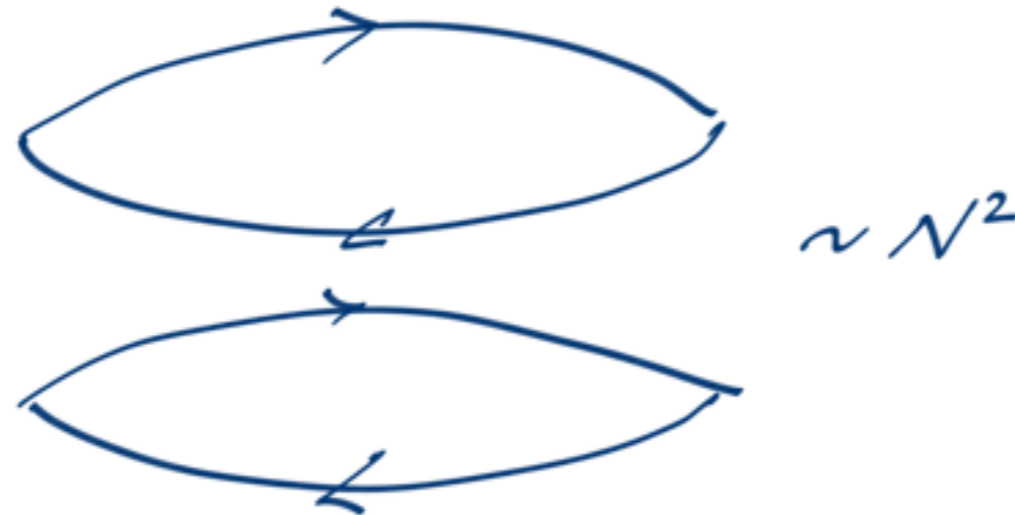
$$B \simeq \frac{G^4}{512 \pi^2} \frac{m^5}{(m_a m_b)^4}$$

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



TETRAQUARKS & $1/N$ EXPANSION

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



(THIS WOULD MEAN THAT ψ_m & ψ_a 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))