EXOTIC SPECTROSCOPY

AD POLOSA
SAPIENZA UNIV. OF ROME.

X & Z RESONANCES

AMONG THE BEST ESTABLISHED STATES

	$X(3872)$ $D^0\bar{D}^{0*}$	$Z_c^{\pm,0}(3900)$ $\bar{D}^0 D^{*+}$	$Z_c^{\pm,0}(4020)$ $\bar{D}^{*0} D^{*+}$	$Z_b^{\pm,0}(10610)$ $\bar{B}^0 B^{*+}$	$Z_b^{\pm 0}(10650)$ $\bar{B}^{*0} B^{*+}$
δ	≈ 0	$+7.8$	$+6.7$	$+2.7$	$+1.8$

(VALUES IN MeV.)

$\sim$ EVERYONE AGREES THAT THEY ARE
$Q\bar{Q}q'\bar{q}$ HELD TOGETHER
or just CUSPS (??)

BINDING 4-QUARKS

SUPPOSE 4 QUARKS ARE PRODUCED (PROMPT OR IN SOME HEAVY MESON DECAY): $Q\bar{Q}q'\bar{q}$.

1) THEY FORM $Q\bar{q} + \bar{Q}q'$

2) THEY FORM $Q\bar{Q} + q'\bar{q}$

THE TWO MESONS FLY AWAY FROM EACH OTHER

3) THEY FORM $[Qq'] + [\bar{Q}\bar{q}]$

WHAT HAPPENS MAY DEPEND ON INITIAL CONDITIONS.

BINDING 4-QUARKS

SUPPOSE 4 QUARKS ARE PRODUCED (PROMPT OR IN SOME HEAVY MESON DECAY): $Q\bar{Q}\,q'\bar{q}$.

1) THEY FORM $Q\bar{q} + \bar{Q}q'$
2) THEY FORM $Q\bar{Q} + q'\bar{q}$

FLY AWAY

3) THEY FORM $[Qq'] + [\bar{Q}\bar{q}]$

3.1) THE TWO DIQUARKS ARE SQUEEZED IN A VOLUME $\lesssim 1\,fm^3$. THE SYSTEM MAY BE INDISTINGUISHABLE FROM 1) OR 2)

BINDING 4-QUARKS

SUPPOSE 4 QUARKS ARE PRODUCED (PROMPT OR IN SOME HEAVY MESON DECAY): $Q\bar{Q}q'\bar{q}$.

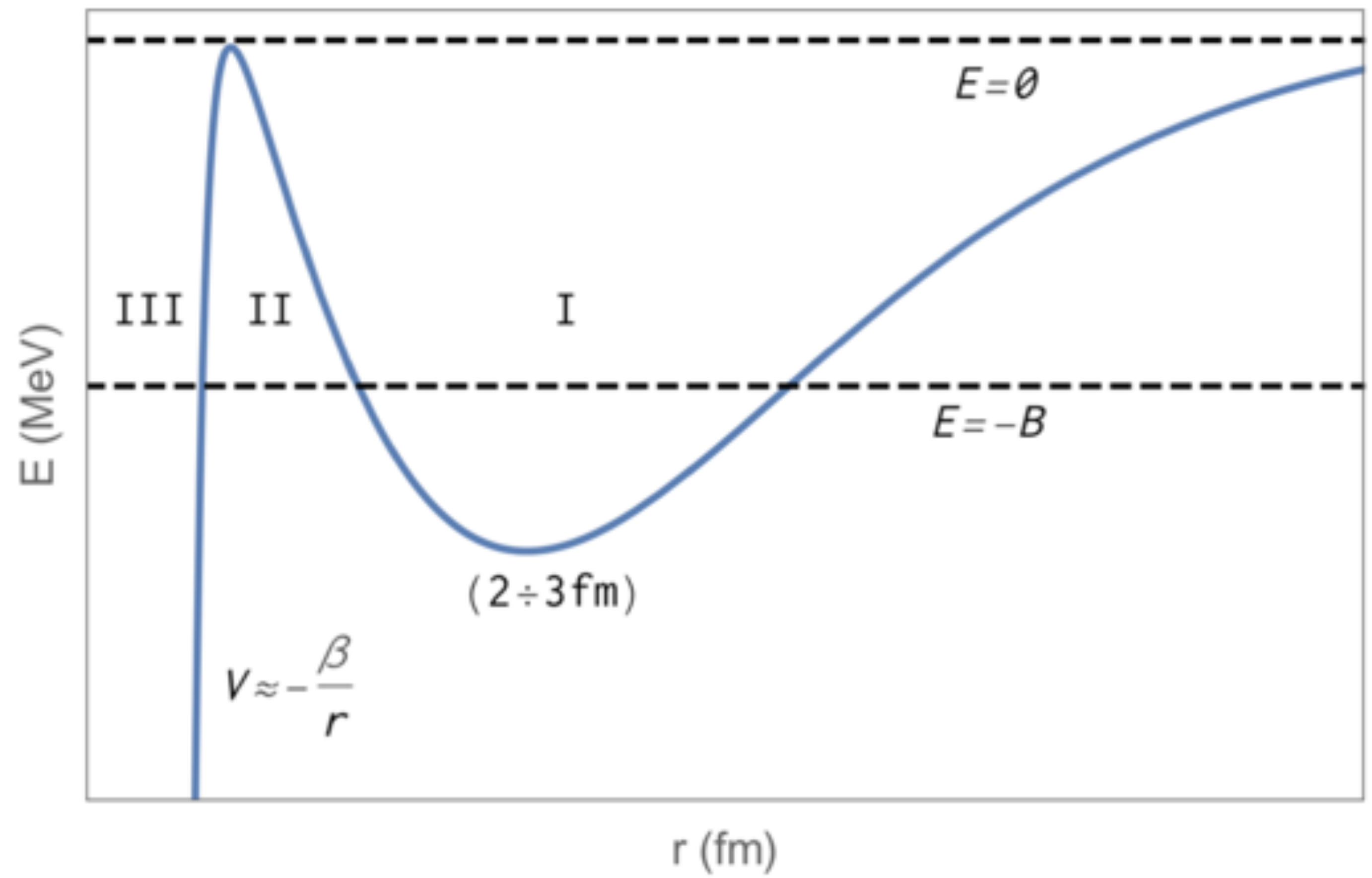
$$\left.\begin{array}{l}\text{1) THEY FORM } Q\bar{q} + \bar{Q}q' \\ \text{2) THEY FORM } Q\bar{Q} + q'\bar{q}\end{array}\right\} \text{FLY AWAY}$$

3) THEY FORM $[Qq'] + [\bar{Q}\bar{q}]$

3.1) THE TWO DIQUARKS ARE SQUEEZED IN A VOLUME $\lesssim 1\,fm^3$. THE SYSTEM MAY BE INDISTINGUISHABLE FROM 1) OR 2)

3.2) THE TWO DIQUARKS ARE SEPARATED IN SPACE...

HYPOTHETIC DIQUARK POTENTIAL



DISTANCE BETWEEN
TWO DIQUARKS

$$[Qq'] \xleftrightarrow[r]{\qquad\qquad} [\bar{Q}\bar{q}]$$

THE BARRIER IN II CAN MAKE THE TETRAQUARK METASTABLE.

A BARRIER?

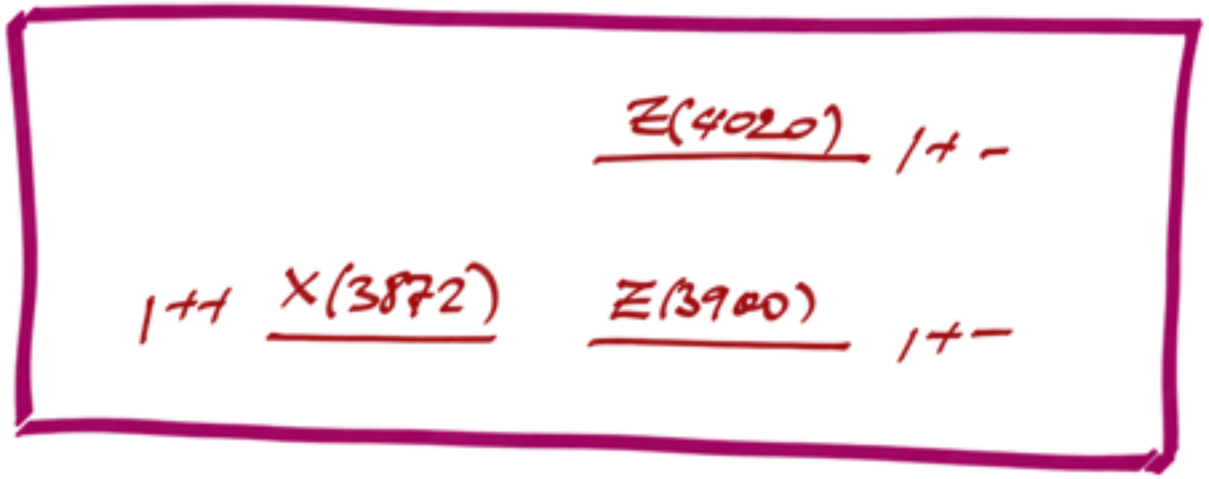
THERE IS NO BARRIER AT $L=0$!

HOWEVER

1) THE HAMILTONIAN

$$H = 2\kappa\left(S_{q} \cdot S_{Q} + S_{\bar{q}} \cdot S_{\bar{Q}} \right)$$

DESCRIBES VERY WELL THE PATTERN OF MASS



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

[ALSO NATURAL FOR A HADRON MOLECULE, BUT REMEMBER $\delta > 0$]

A BARRIER?

SUPPOSE THE ENERGY STORED IN THE 4 QUARKS IS DISTRIBUTED TO FORM A DIQUARK-ANTIDIQUARK SYSTEM

$$\boxed{E = \tilde{m}_1 + \tilde{m}_2 - B}$$

FALL APART

$E = m_1 + m_2 + \delta$

m_1 & m_2 meson masses

$\tilde{m}_1$ & $\tilde{m}_2$ diquark masses.

VERY BROAD STATES

BARRIER

LIGHT QUARKS SWAP THROUGH THE BARRIER

$$\tau \propto e^{-2\sqrt{2m_q |B|}\,\ell}$$

NARROW STATES

FINAL STATES

$$\boxed{\begin{aligned} \Gamma &\approx \frac{\pi^5}{2a^3}\,\frac{(\tilde{m}|B|)^{3/2}}{m_q\, m^{3/2}}\,\mathcal{T}\,\sqrt{\delta} \\ &= A(a, m, \tilde{m}, B)\sqrt{\delta} \end{aligned}}$$

Rewrite A in terms of $\mathcal{F}$ (leaving aside numerical constants which appear both in Z_c/Z_b decays)

$$\mathcal{F}_Q = \frac{(\tilde{m}|B|)^{3/2}}{\ell_Q^3\, m^{3/2}}\,\mathcal{R}_Q^{-1}\,\exp\left(-2\sqrt{2m_Q|B_Q|\ell_Q}\right)$$

taken from data

ARE THERE ANY SOLUTIONS TO THE EQUATION?

$$\boxed{\mathcal{F}_Q = \mathcal{F}_c}$$

FINAL STATES : DATA

$$\frac{\Gamma(X \to \psi\rho)}{\Gamma(X \to DD^*)} = \frac{p_{\psi\rho}}{p_{DD^*}} \mathcal{R}_c$$

$$\frac{\Gamma(Z_b' \to \Upsilon(1S)\pi)}{\Gamma(Z_b' \to B^* B^*)} = \frac{p_{\Upsilon\pi}}{p_{B^*B^*}} \mathcal{R}_b$$

$$\boxed{\mathcal{R}_c^{exp} \sim 10^{-3} \; ; \; \mathcal{R}_b^{exp} \sim 10^{-4}}$$

FOR US

$$\boxed{\mathcal{R}_Q \equiv \left[\frac{\exp(-\sqrt{2 m_Q |B|} \ell)}{\exp(-\sqrt{2 m_q |B|} \ell)} \right]^2}$$

FINAL STATES

$$\boxed{\begin{aligned}\Gamma &\approx \frac{\pi^5}{2a^3}\,\frac{(\tilde{m}\,|B|)^{3/2}}{m^{5/2}}\,T\,\sqrt{\delta}\\ &= A(a, m, \tilde{m}, B)\,\sqrt{\delta}\end{aligned}}$$

Rewrite A in terms of $\mathcal{F}$ (leaving aside inessential numerical constants)

$$\mathcal{F}_Q = \frac{(\tilde{m}\,|B|)^{3/2}}{\ell_Q^3\, m^{5/2}}\,\mathcal{R}_Q^{-1}\,\exp\left(-2\sqrt{2m_Q|B_Q|\ell_Q}\right)$$

taken from data

ARE THERE ANY SOLUTIONS TO THE EQUATION?

$$\boxed{\mathcal{F}_Q = \mathcal{F}_c}$$

CONSTANT A?

WE USE THE CONSTITUENT QARK MASS VALUES (MeV)

$$m_c = 1710 \quad m_b = 5043$$

$$\tilde{m}_c = 1976 \quad \tilde{m}_b = 5315$$

$$-B_c = M_X - 2\tilde{m}_c \approx -100$$

$$l_c = 2\,fm \text{ (see the barrier)}$$

Require $B_b \approx 2.5\, B_c$

We find then

$$A_b = A_c$$

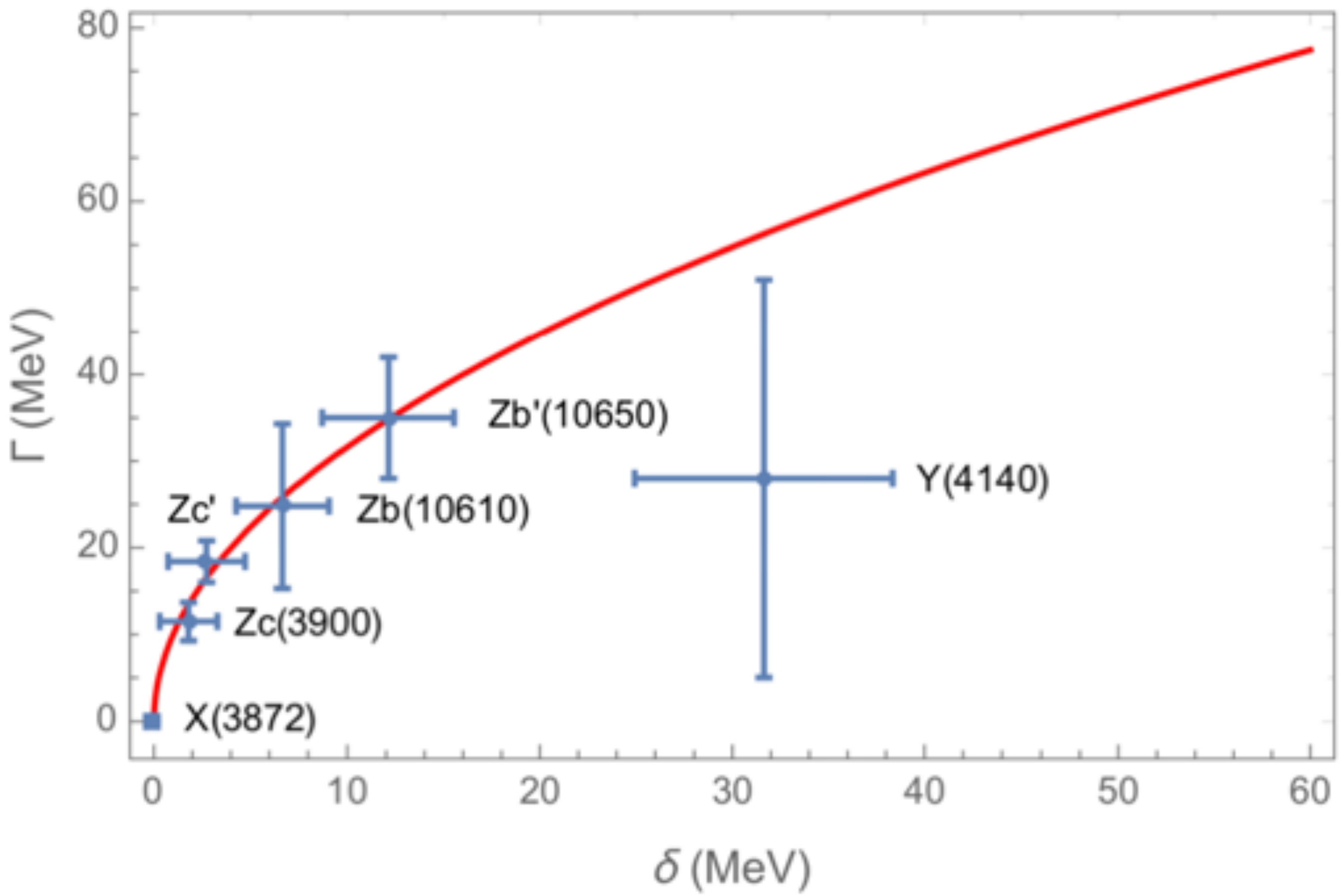
provides that

$$l_b \cong 0.8\, l_c$$

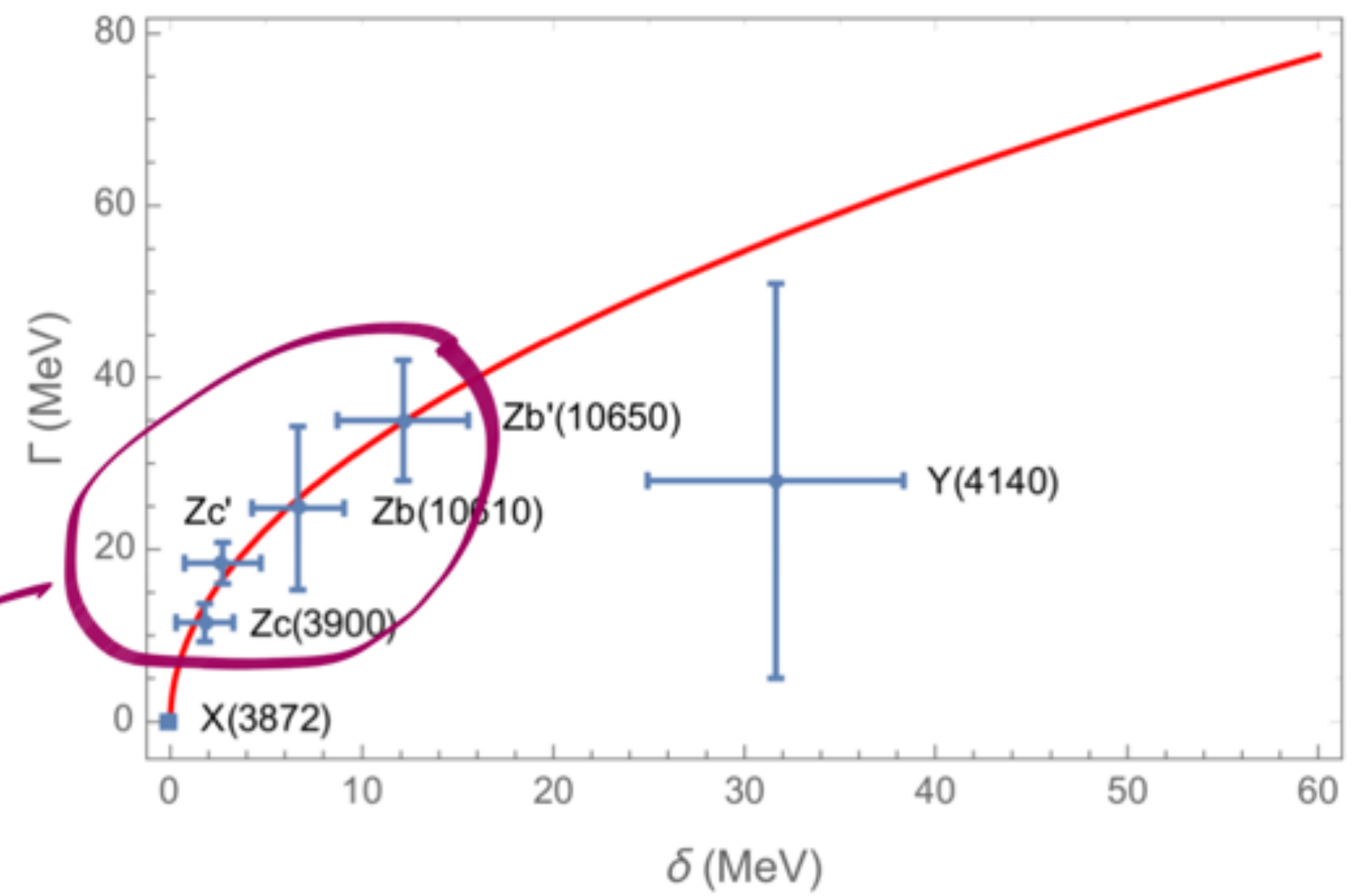
$$\boxed{\text{THUS } \Gamma = A\sqrt{\delta}}$$

WITH CONSTANT A...

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



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



Z_c & Z_b with same A.

[OBSERVED ORIGINALLY BY
ESPOSITO, PILLONI, ADP
PLB 758 (2016) 292]

OTHER CONSEQUENCES

THE TETRAQUARK IS A TWO - SCALES SYSTEM

1) THE SIZE OF A DIQUARK $\tilde{\ell}$

2) THE SIZE OF THE DIQUARK-ANTIDIQUARK BOUND STATE ℓ

$$\lambda = \ell/\tilde{\ell} > 1$$

AN APPROPRIATE CHOICE OF λ GIVES

$$\boxed{M(X_u) - M(X_d) \simeq 0}$$

[Maiani - ADP - Riquer
PLB778 (2018) 247
1803.06883]

X_u - X_d DEGENERACY

BECAUSE OF THIS DEGENERACY

1) X_d & $X^{\pm}$ HAVE ONLY CHARMONIUM DECAY MODES ($D^+\bar{D}^{*-}$, $D^+\bar{D}^{*0}$ TOO HEAVY)

2) X_u & X_d GET MIXED

$$X_1 = c_\phi \frac{X_u + X_d}{\sqrt{2}} + s_\phi \frac{X_u - X_d}{\sqrt{2}}$$

$$X_2 = -s_\phi \frac{X_u + X_d}{\sqrt{2}} + c_\phi \frac{X_u - X_d}{\sqrt{2}}$$

Mass eigenstates in the isospin basis.

$X^{\pm}$ should be found only in $\psi\rho/\omega$ modes.

The prejudice is that $\Gamma(X^0 \to \psi\rho^0) \simeq \Gamma(X^+ \to \psi\rho^+)$

COMPARISON TO DATA

$$R^0(B^0) = \frac{B^0 \to K^0 X^0 \to K^0 + 3\pi}{B^0 \to K^0 X^0 \to K^0 + 2\pi} = 1.4 \pm 0.6$$

$$R^0(B^+) = \frac{B^+ \to K^+ X^0 \to K^+ + 3\pi}{B^+ \to K^+ X^0 \to K^+ + 2\pi} = 0.7 \pm 0.4$$

ISOSPIN VIOLATING MODES

$$R^-(B^0) = \frac{B^0 \to K^+ X^- \to K^+ + \rho^-}{B^0 \to K^0 X^0 \to K^0 + \rho^0}$$

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

MODES WITH $X^\pm$

$$R^-(B^0) \overset{!}{<} 1$$
$$R^+(B^+) \overset{!}{<} 0.5$$

exclusions.

TWO AMPLITUDES

$$\underbrace{\bar b\, d}_{B^0} \longrightarrow \bar c \;\; c\bar s + (d\bar d \vee u\bar u) + d$$

if K is formed from $\bar s$ + spectator d : A_1

" " " " " " + "sea" d : A_2

$$\mathrm{Amp}(B^0 \to X_d K^0) \sim A_1 + A_2$$

$$\mathrm{Amp}(B^0 \to X_u K^0) \sim A_1$$

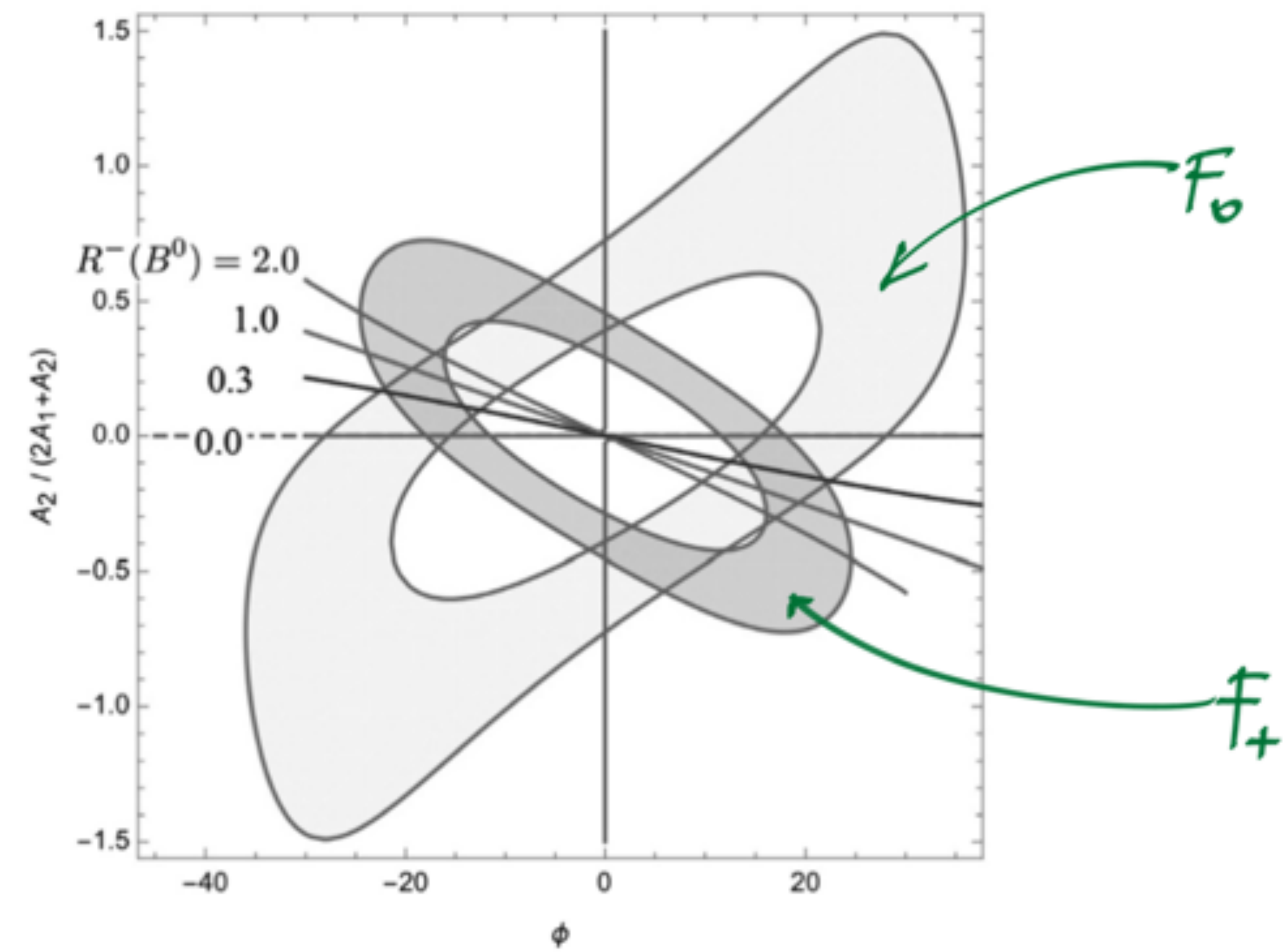
$$\mathrm{Amp}(B^0 \to X^- K^+) \sim A_2$$

$$\bar c + \overbrace{c\bar s}^{K^+} + d$$

$$\underbrace{\bar u \;\; d}_{X^-} \;\; u$$

Similarly for B^+

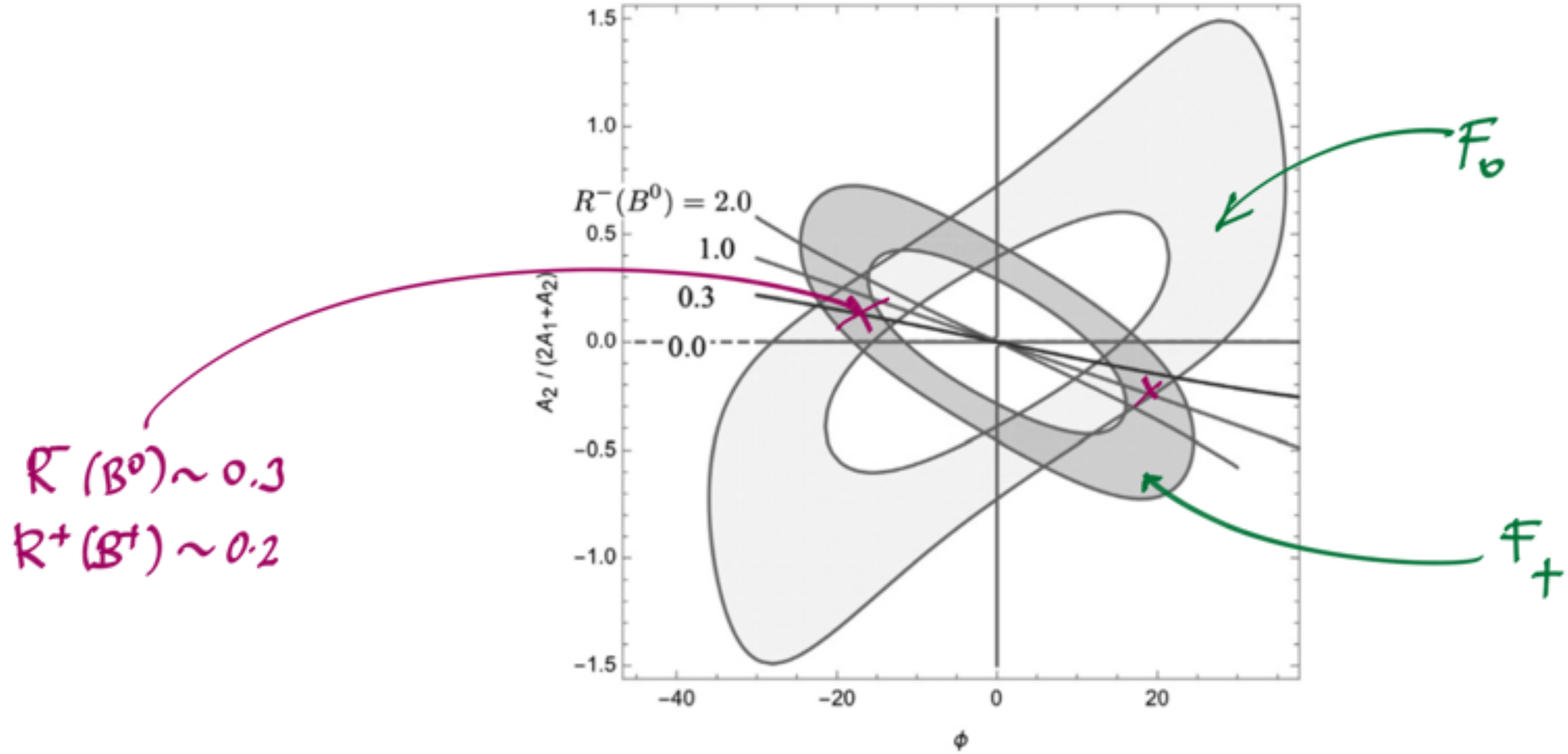
OTHER CONSEQUENCES



$$R^0(B^0) = \frac{I=1}{I=0} \propto F_0\left(\phi, \frac{A_2}{2A_1+A_2}\right)\frac{p_\rho}{p_\omega}$$

$$R^0(B^+) \propto F_+\left(\phi, \frac{A_2}{2A_1+A_2}\right)\frac{p_\rho}{p_\omega}$$

OTHER CONSEQUENCES



OVERLAP REGIONS CORRESPOND TO PARAMETERS (ϕ, A_1, A_2) REPRODUCING EXPERIMENTAL VALUES FOR BOTH F_+ & F_0.

HOWEVER SOLUTIONS WITH $\phi \approx 0^\circ$ HAVE $R^-(B^0) \simeq 2$ — excluded.

SOLUTIONS WITH $\phi \gtrsim \pm 20^\circ$ HAVE $R^-(B^0) \lesssim 2$.

PRESENT LIMIT IS $R^-(B^0) \lesssim 1$ & $R^+(B^+) \lesssim 0.5$

REMARKS

1. Why $X^{\pm}(3872)$ seem to be absent?

   Because the A_2 amplitude can be very small, for certain values of ϕ

2. Where does the ϕ mixing comes from?

   Even a very small $q\bar{q}$ annihilation amplitude in the tetraquark could produce sizeable mixing if $M(X_u) \simeq M(X_d)$

3. Where does the $X_u - X_d$ degeneracy comes from?

   If the tetraquark is a system with two length scales, l and $\bar{l}$, their ratio can be chosen so as $M(X_u) \simeq M(X_d)$

REMARKS

4. Why two length scales?

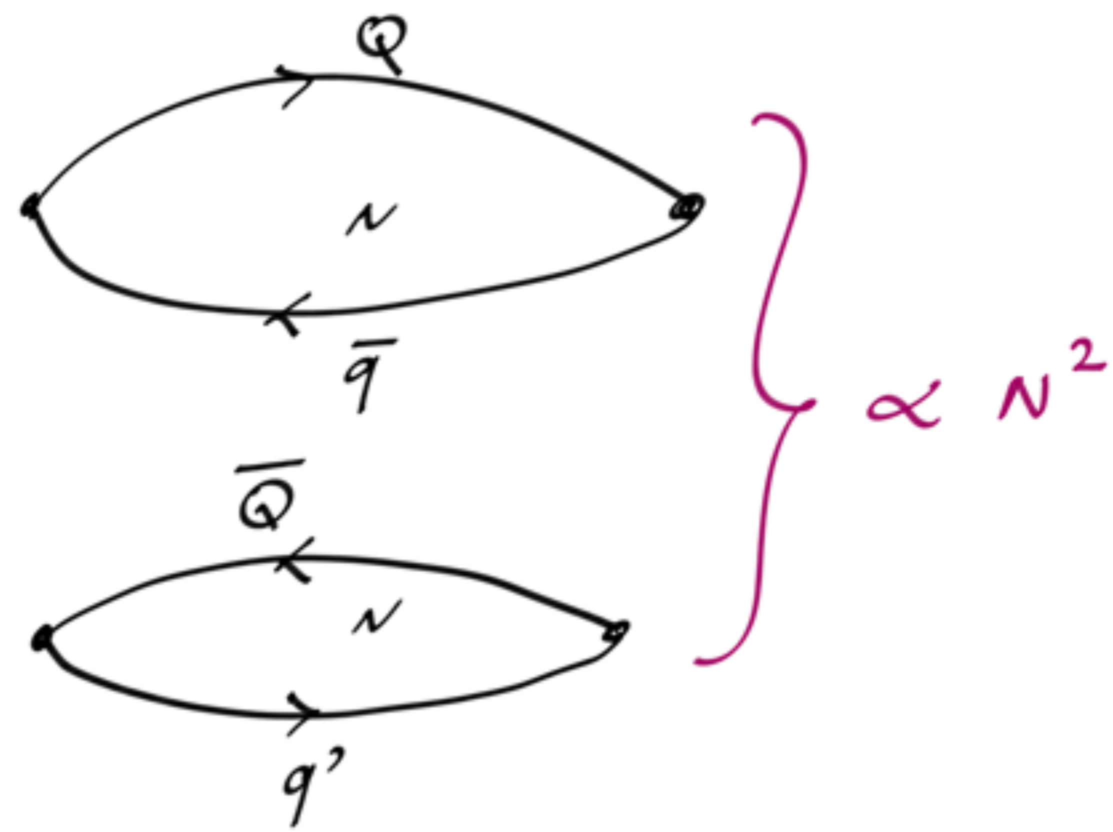
   Because it seems that there is an effective repulsion at very short distances of the diquark-antidiquark pair.

5. Other clues on this repulsion?

   - Spin-Spin interactions work as if tetraquarks were segregated at some distance apart.
   - Tunneling disfavours $\psi/\rho/\omega$ decays
   - A fit $\Gamma = A\sqrt{\delta}$ works for both Z_c and Z_b resonances.

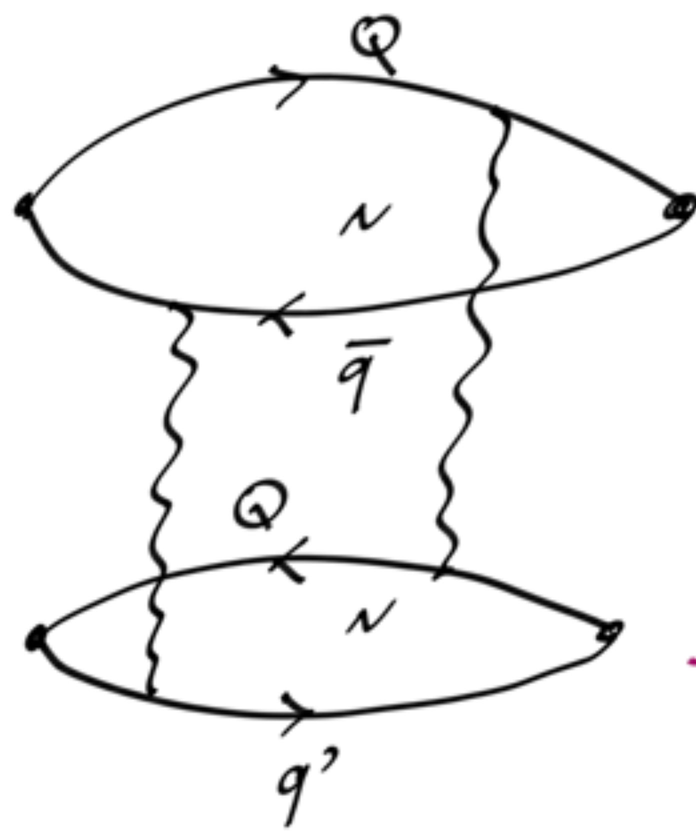
THE LARGE-N EXPANSION & TETRAQUARKS

S. WEINBERG PRL 110 (2013) 261601



THE LARGE-N EXPANSION & TETRAQUARKS

S. WEINBERG PRL 110 (2013) 261601

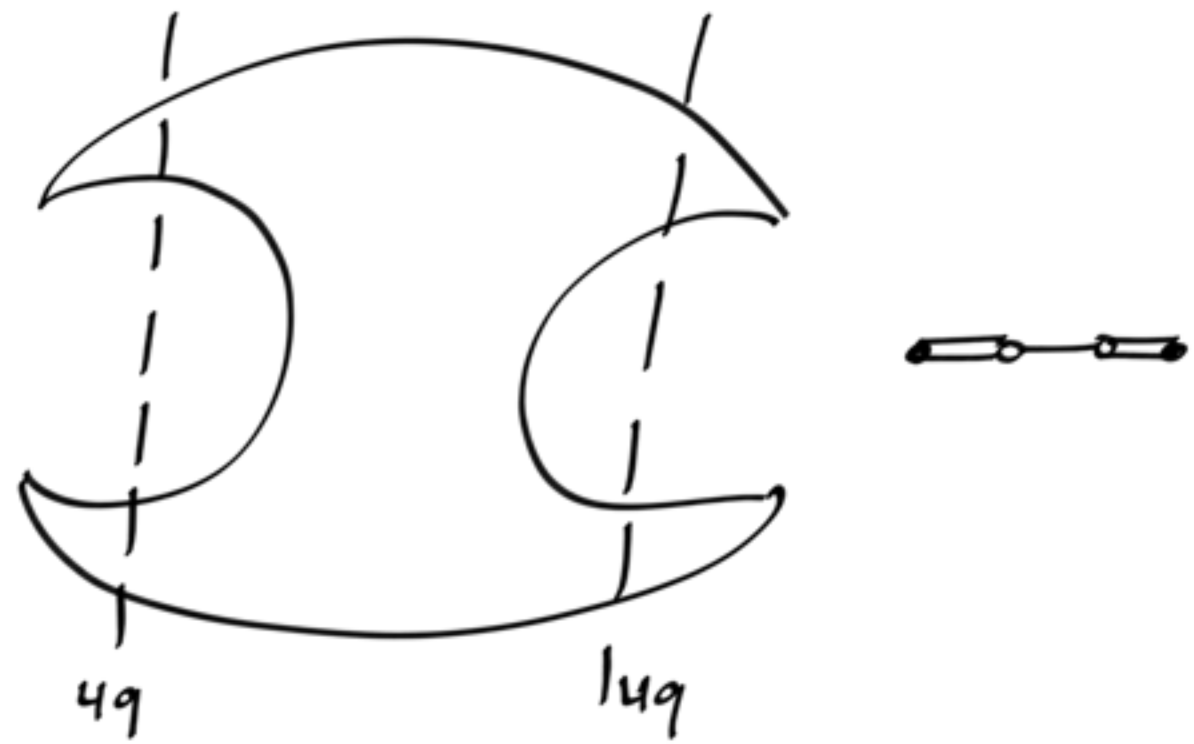


$$\propto N^2 \times \left(\frac{1}{\sqrt{N}}\right)^2$$

FOR LARGE N ($N \to \infty$) THE DIAGRAM W/ NO GLUONS WINS —— FALL APART DECAY OF THE TETRAQUARK. (COLEMAN, WITTEN)

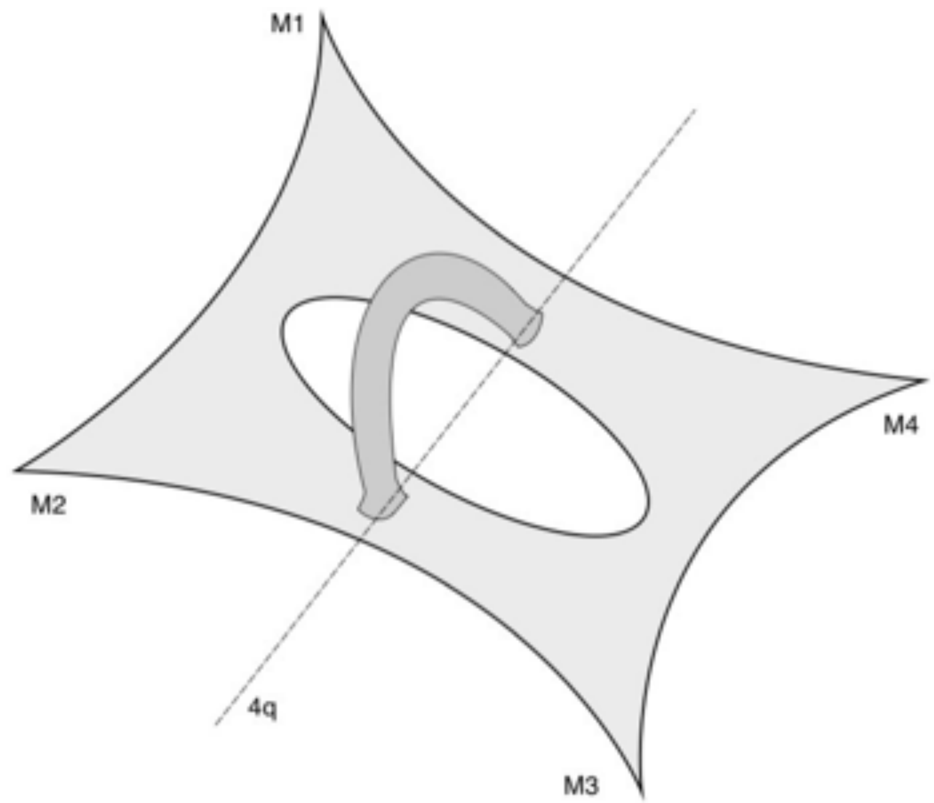
THE LARGE-N EXPANSION & TETRAQUARKS

S. WEINBERG PRL 110 (2013) 261601

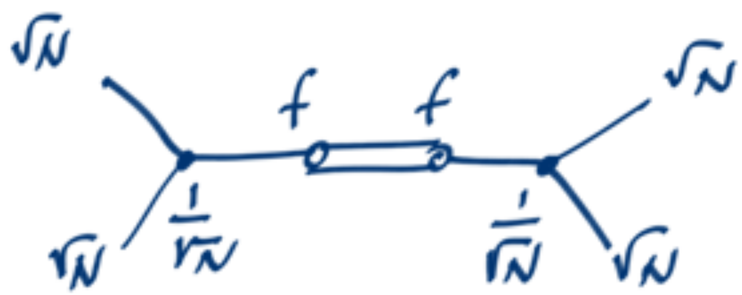


"IF THERE IS A TETRAQUARK MESON POLE IN THE CONNECTED PART OF THE PROPAGATOR WHAT DIFFERENCE DOES IT MAKE IF ITS RESIDUE IS SMALLER WRT THE DISCONNECTED PART?"

NON PLANAR DIAGRAMS



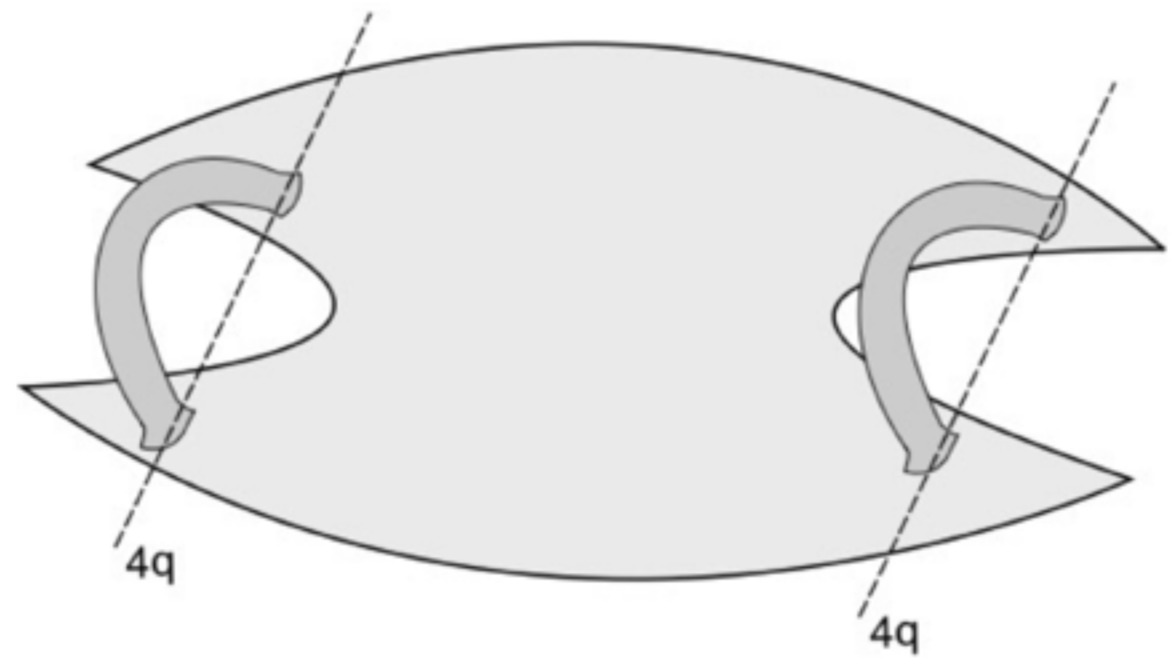
$$N^{\alpha} = N^{2-L-2H} = N^{2-2-2} = \frac{1}{N^2}$$



$$N f^2 \sim \frac{1}{N^2}$$

$$f \sim \frac{1}{N\sqrt{N}}$$

NON PLANAR DIAGRAMS



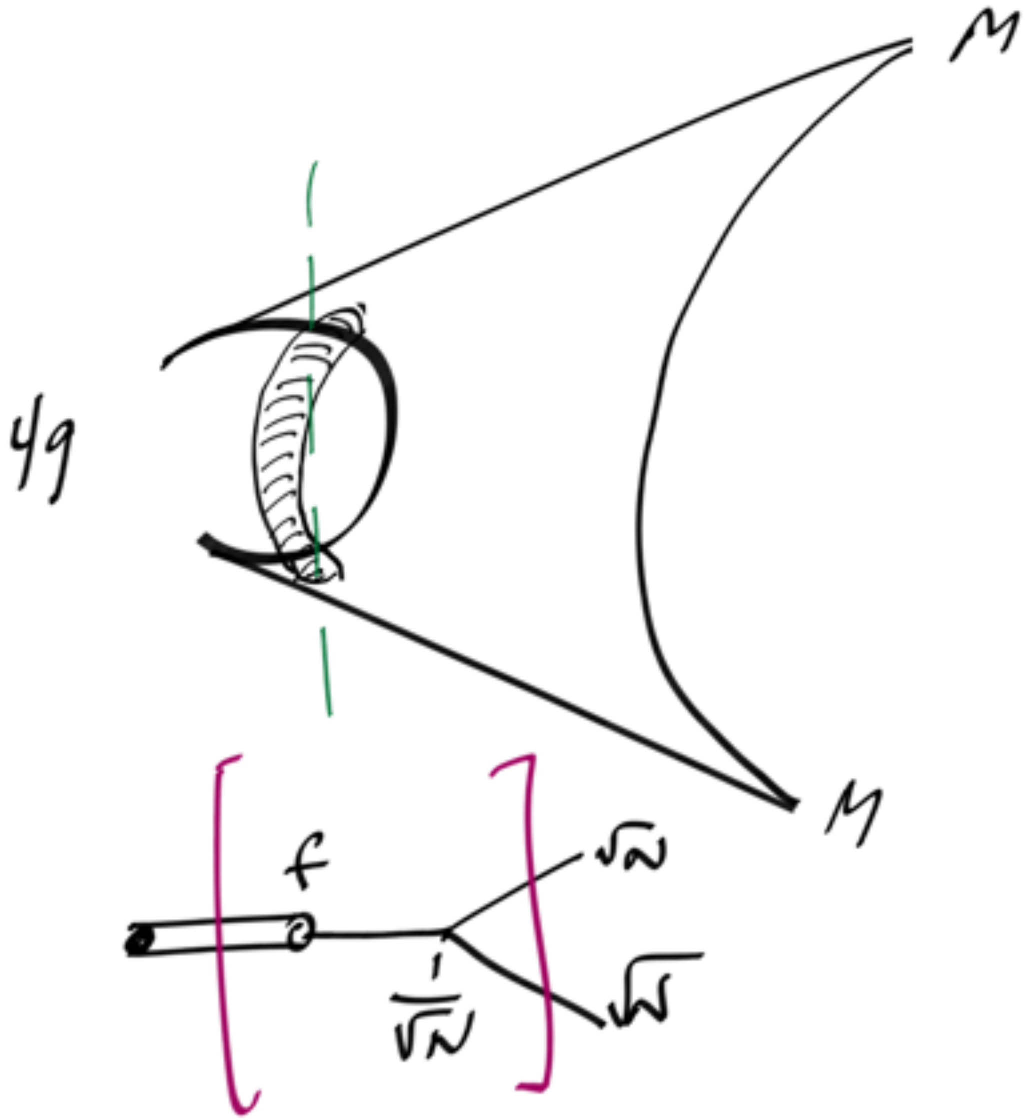
$$N^{2-2-2H} = N^{2-1-4} = N^{-3}$$

$$f_{4q}^2 \frac{1}{N^3} \sim \frac{1}{N^3}$$

$$f_{4q} \sim N^0$$

[OBSERVED IN MAIANI, ADP, RIQUER JHEP 1606 (2016) 160
& 1803.06883]

DECAY



$$g \sim f \frac{1}{\sqrt{N}} = \frac{1}{N^2}$$

TETRAQUARKS CAN BE VERY NARROW

Auxiliary slides

X(3872)

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

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

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

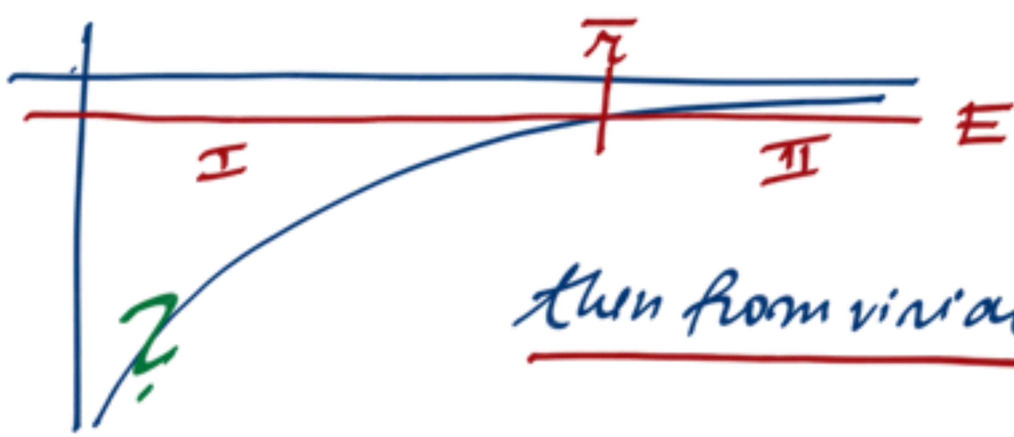
The VIRIAL THEOREM gives

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

i.e.

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

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

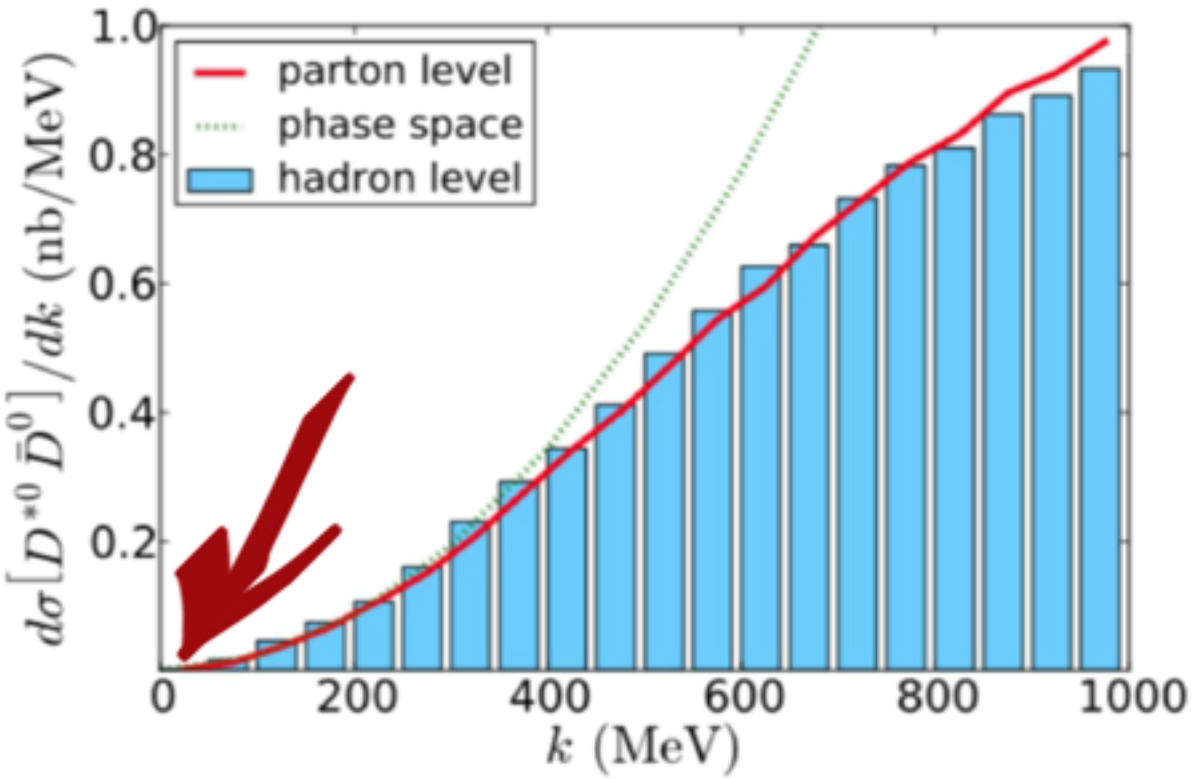


FOR SHALLOW BOUND STATES

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

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

X PRODUCTION AT HADRON COLLIDERS

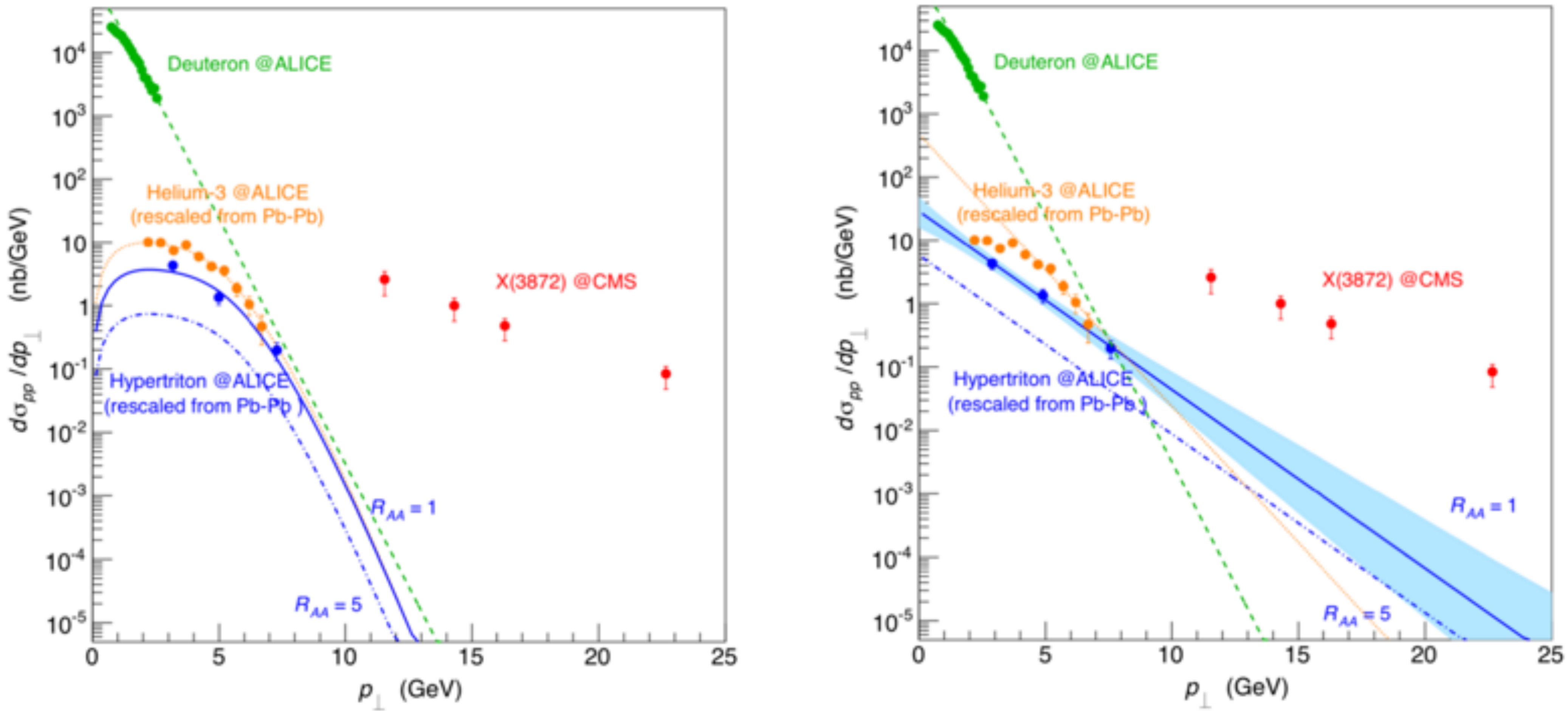


$p_T(D^{*0}\bar{D}^0) > 5$ GeV and $|y(D^{*0}\bar{D}^0)| < 0.6$
in $p\bar{p}$ @ 1.96 TeV

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

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

$$Z_c \sim \underbrace{\frac{B}{\sqrt{2}}}_{\text{The nontrivial dependence of barrier penetration factors from light quark spins allows } Z_c \to DD^*.}\left(D^0\bar{D}^{*0} - D^{*0}\bar{D}^0\right) + \underbrace{C\, D^{*0}\times\bar{D}^{*0}}_{\text{phase space forbidden.}}$$

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

26/10/2017

Annecy18

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]

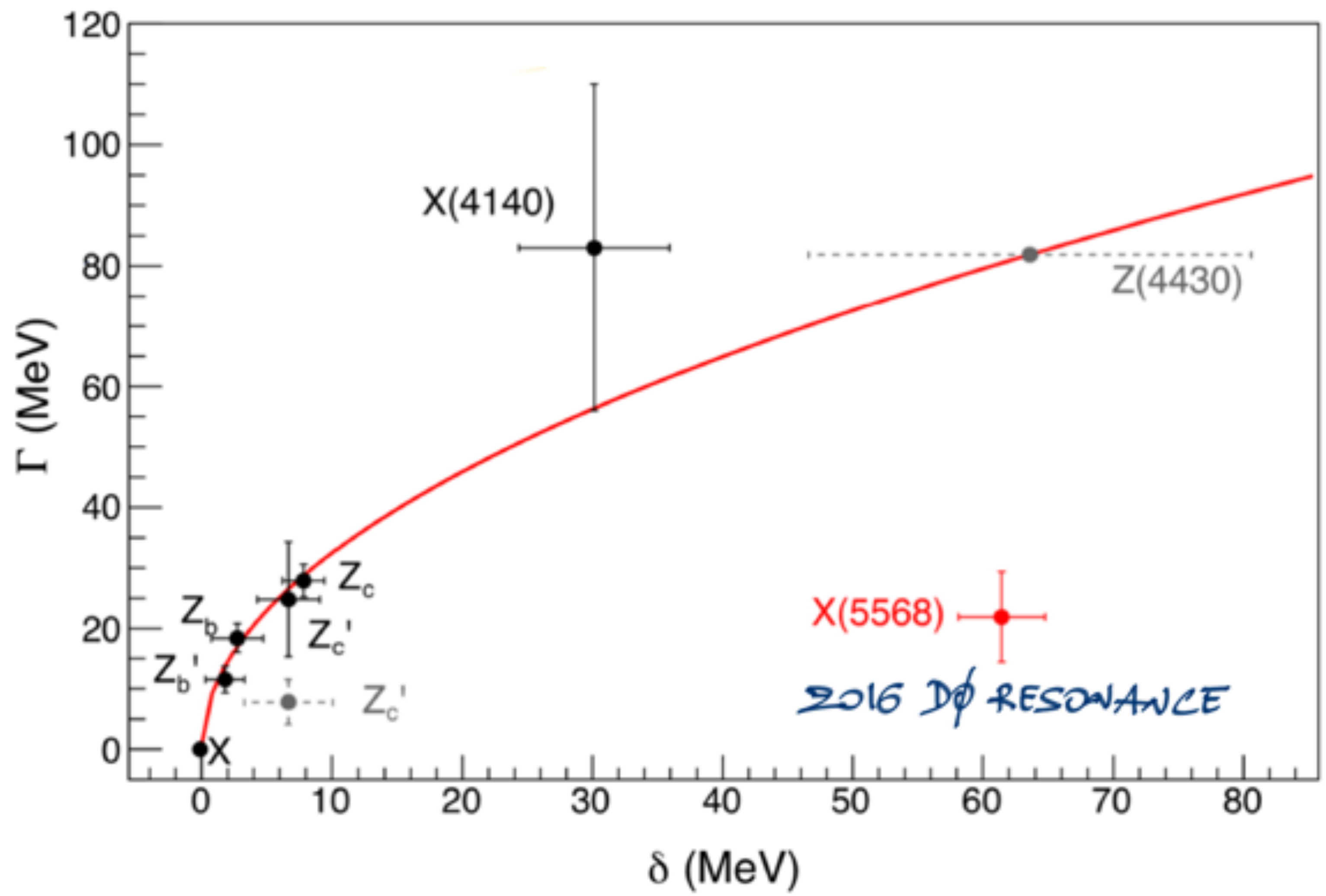
FINAL STATES LIKE $J/\psi\,\pi^+$ SHOULD BE FEASIBLE.

— 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 ($\to B^0\bar{B}^{*0}$) ?

LIFETIME

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



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

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

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