Compact Tetraquarks

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Are the New Particles Baryon-Antibaryon Nuclei?

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(Received 25 November 1974)

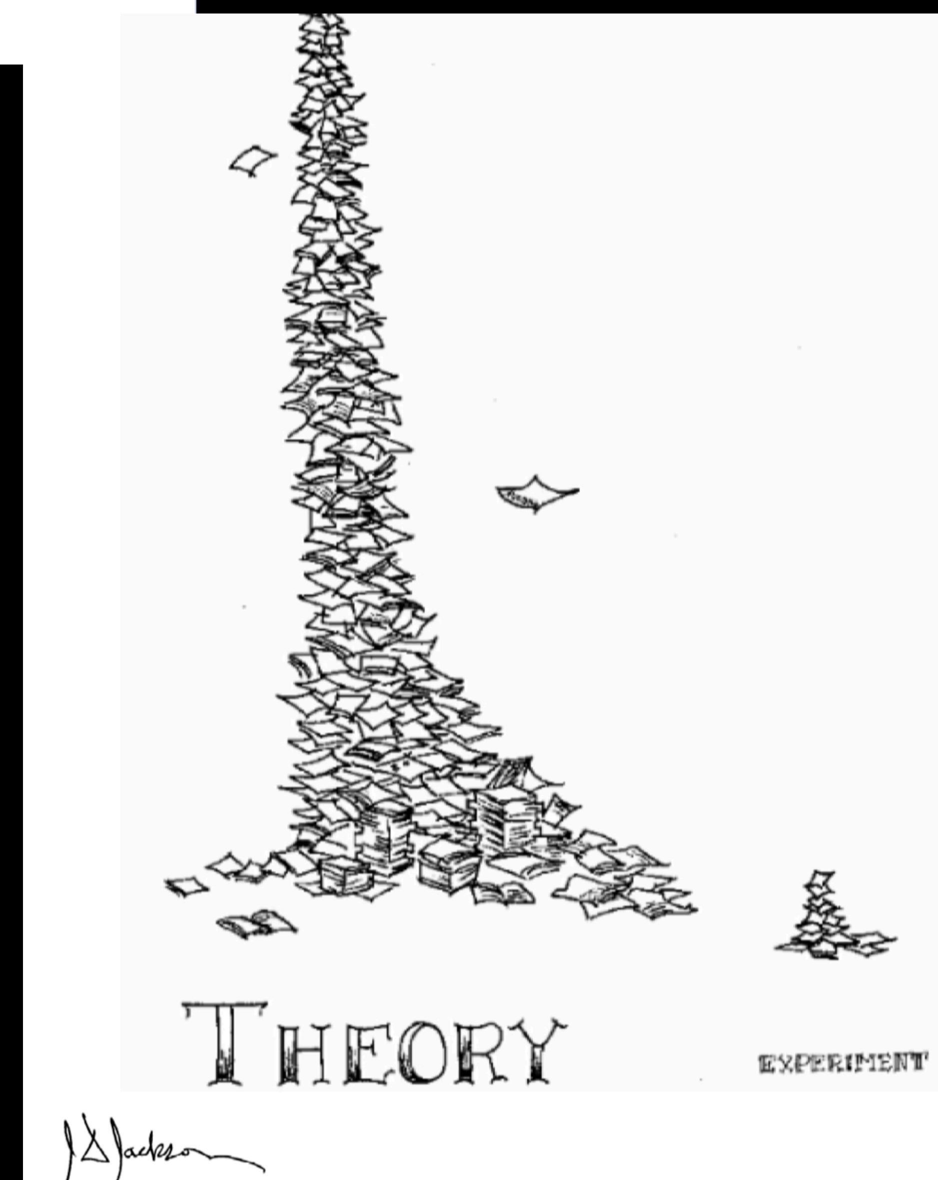
Baryon-antibaryon bound states and resonances could account for the new particles, as well as narrow states near nucleon-antinucleon threshold, which were reported earlier.

One of the first interpretations of J/psi

Interpretation of a Narrow Resonance in e^+e^- Annihilation*

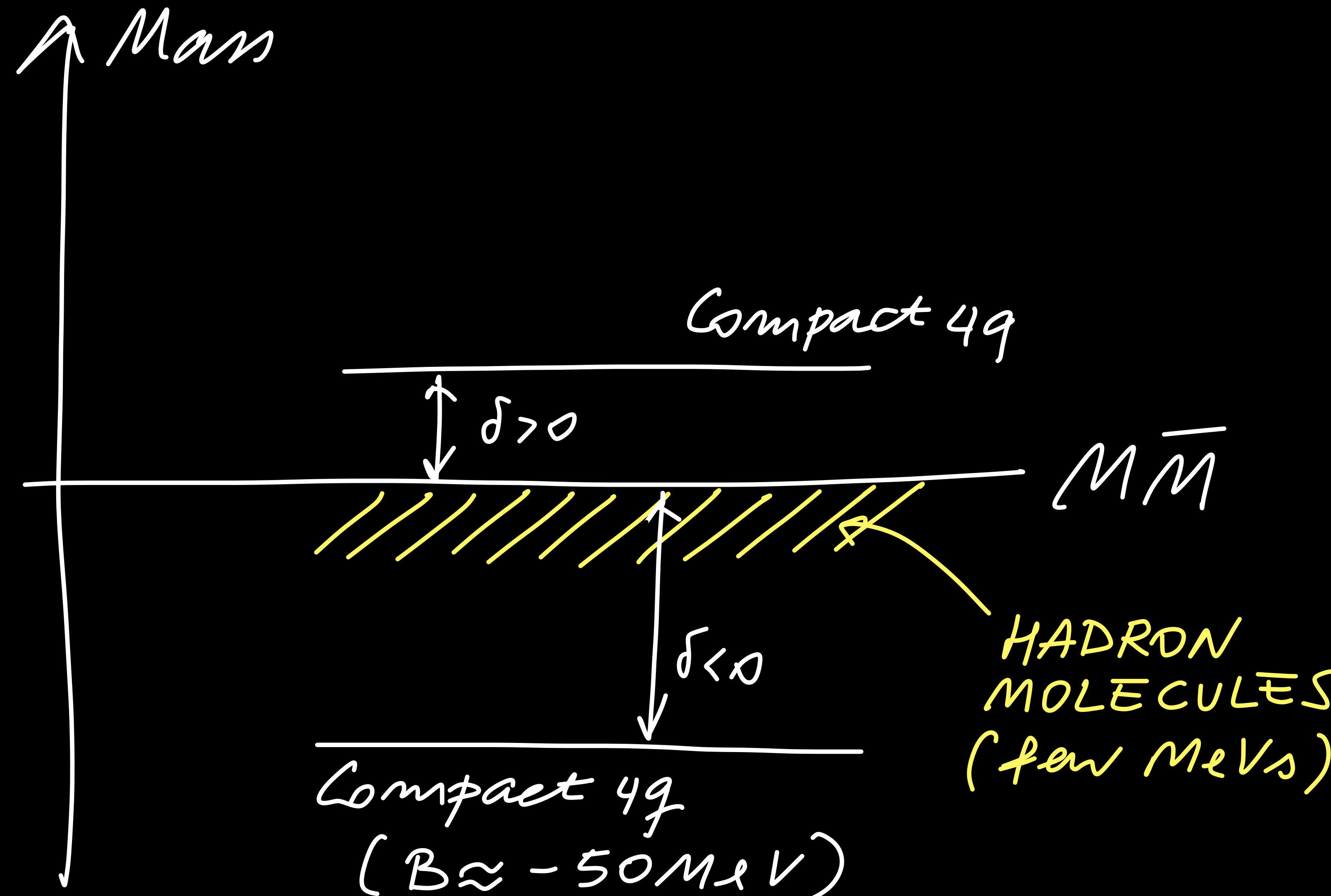
Julian Schwinger
University of California at Los Angeles, Los Angeles, California 90024
(Received 25 November 1974)

A previously published unified theory of electromagnetic and weak interactions proposed a mixing between two types of unit-spin mesons, one of which would have precisely the characteristics of the newly discovered neutral resonance at 3.1 GeV. With this interpretation, a substantial fraction of the small hadronic decay rate can be accounted for. It is also remarked that other long-lived particles should exist in order to complete the analogy with ρ^0, ω, and φ.



See C. Quigg's talk at CERN on the First 40 years of Charmonium 11-Nov-2014

Thresholds



For a review Esposito, Pilloni, ADP, Phys. Rept. 668 (2016) 1

X & Z Resonances

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

(in MeV)

Some hints by CMS of a $\Upsilon(1S)\Upsilon(1S)$ state with $\delta = -80\,\mathrm{MeV}$ — a 3σ signal to be confirmed.

Heavy-light tetraquarks

4 quarks $Q\bar{Q}q\bar{q}$ produced in a volume V can alternatively

1 — $(Q\bar{q})+(\bar{Q}q)$
$(Q\bar{Q})+(q\bar{q})$
form two <u>free</u> mesons

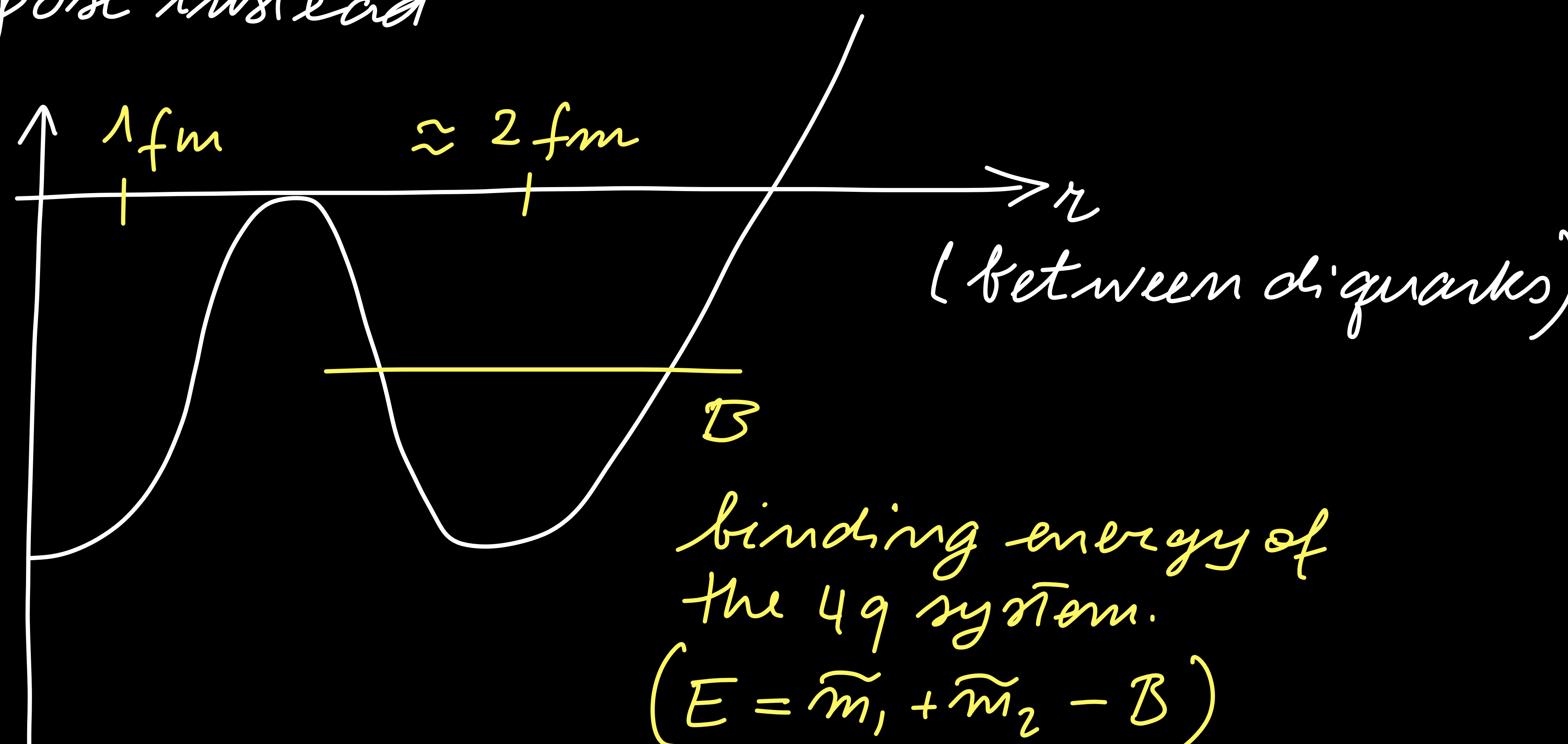
2 — $[Qq]_{\bar{3}}[\bar{Q}\bar{q}]_{3}$ form a compact tetraquark.

3 — $(Q\bar{q})(\bar{Q}q)$ with $B \approx -$few MeVs!

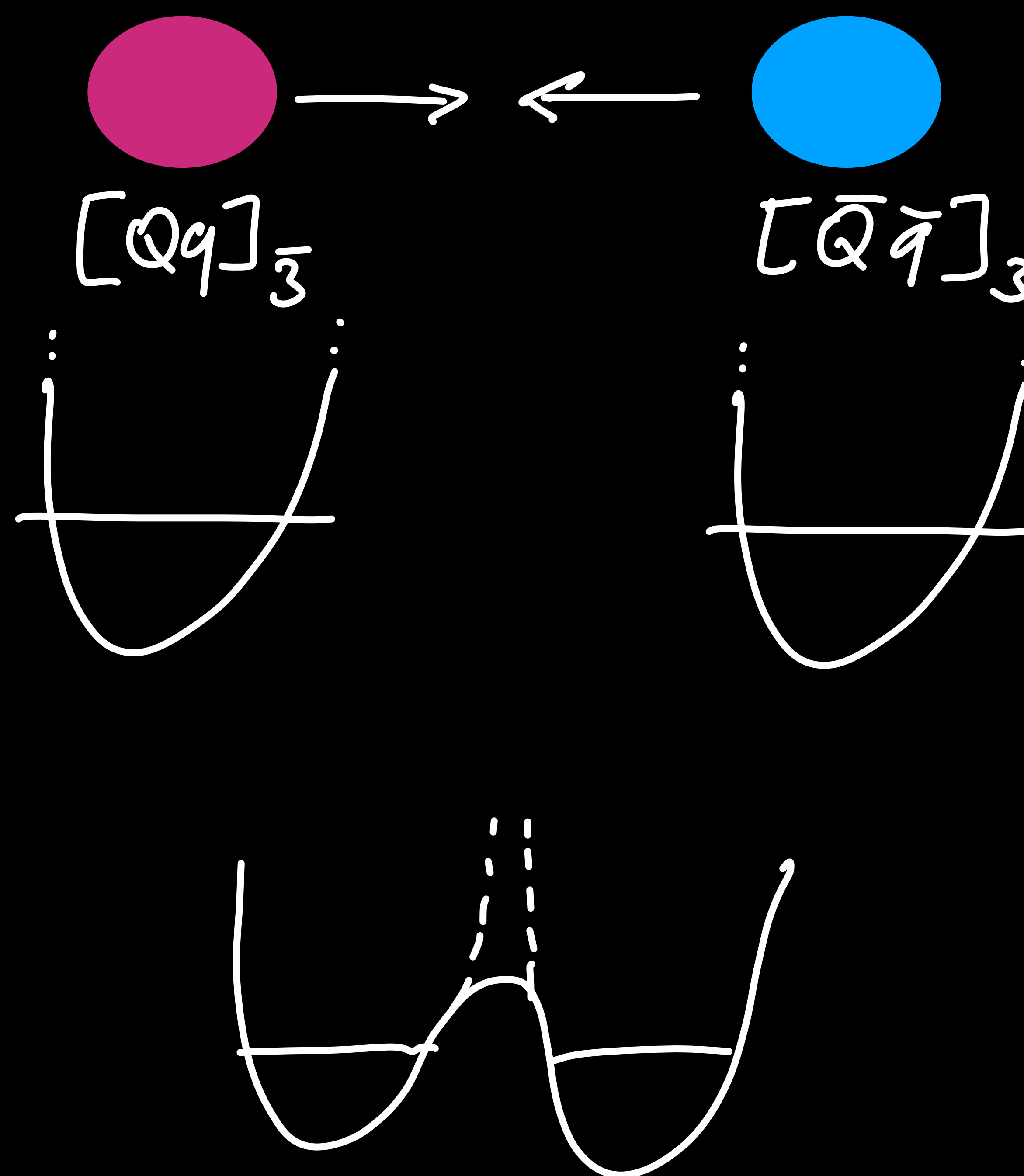
Separated Diquarks

If $[Qq]_{\bar{3}}[\bar{Q}\bar{q}]_3$ is squeezed in a standard hadron size the color can Fierz into $(Q\bar{q})+(\bar{Q}q)$.

Suppose instead



Separated Diquarks



Metastable Tetraquarks

The barrier makes the system metastable -
The TRANSPARENCY factor

$$T \propto e^{-2\sqrt{2m|B|}\,\ell}$$

suggests that, being $m_q < m_Q$, an higher rate is expected for $(Q\bar{q})+(\bar{Q}q)$ decays wrt $(Q\bar{Q})+(q\bar{q})$ decays.

Indeed

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

Spin-Spin interactions

The Hamiltonian

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

has predicted the mass spectrum

1^{+-} ——— $Z_c(4020)$

$X(3872)$ ——— 1^{++} $\qquad$ 1^{+-} ——— $Z_c(3900)$

i.e. 1 — the quasi-degeneracy of 1^{++} and 1^{+-}

2 — the gap $Z_c - Z_c'$

Maiani, Piccinini, ADP, Riquer PRD89 (2014) 114010 — PRD71 (2005) 014028

Spin-Spin interactions

The Hamiltonian

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

SUGGESTS THAT DIQUARK & ANTIDIQUARK ARE SEPARATED IN SPACE, otherwise one should include other terms

$$\vec{S}_Q\cdot\vec{S}_{\bar{q}},\quad \vec{S}_Q\cdot\vec{S}_{\bar{Q}},\quad \vec{S}_{\bar{Q}}\cdot S_q,\quad \vec{S}_q\cdot\vec{S}_{\bar{q}}$$

as required by the constituent quark model.

Maiani, Piccinini, ADP, Riquer PRD89 (2014) 114010 — PRD71 (2005) 014028

Decay through the barrier

$$\frac{d\Gamma}{d\Omega}(\alpha\to\beta) = (2\pi)^4 \rho \left(\frac{K' E_1' E_2'}{E}\right) |M_{\beta\alpha}|^2$$

$$\rho \approx \frac{1}{\langle R\rangle^3} \approx \left(\sqrt{2\tilde{m}B}\right)^3$$

$$E = E_\alpha = E_\beta = (m_1 + m_2 + \delta)$$

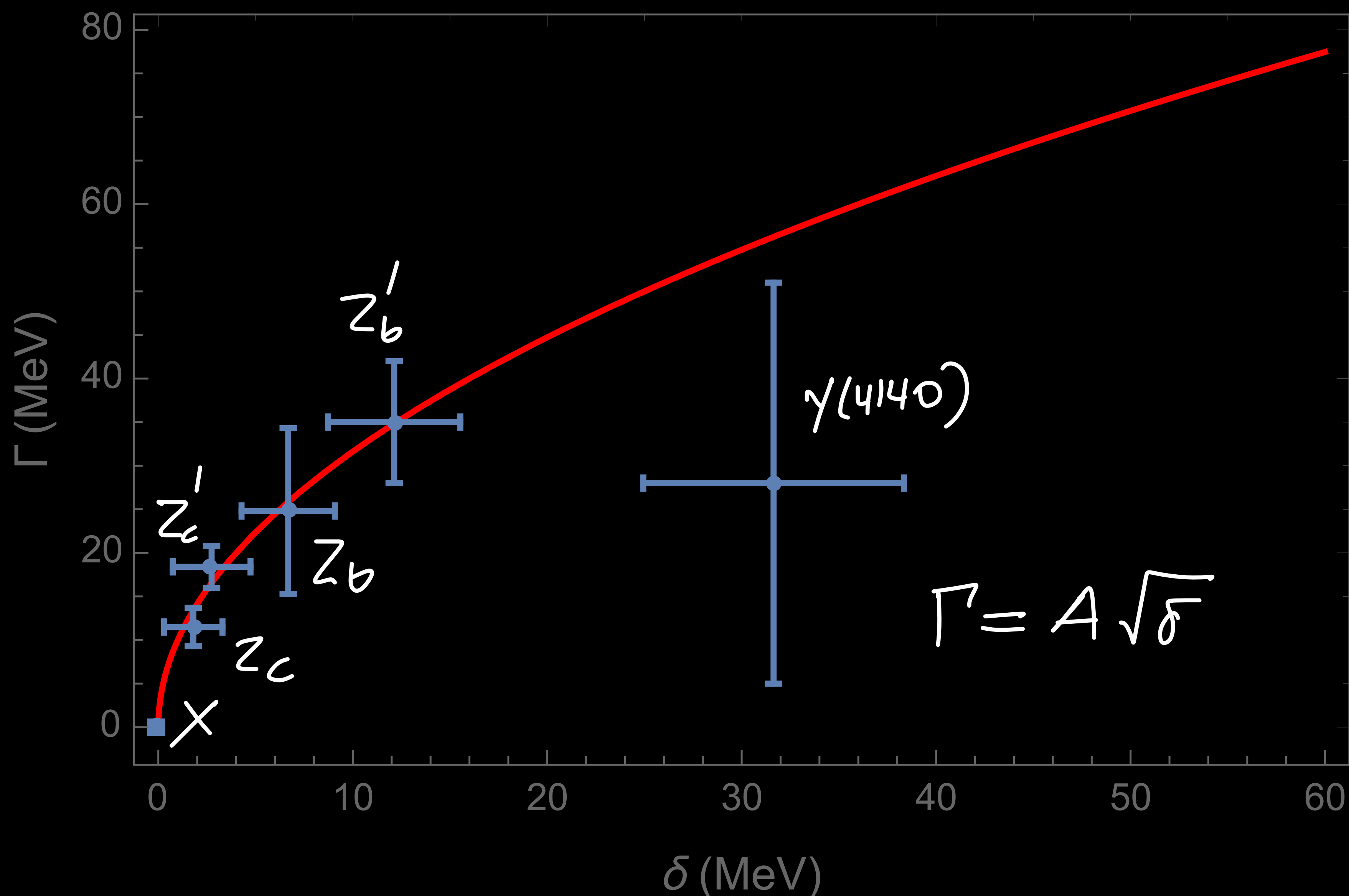
$m_{1,2}$ = meson masses

$\tilde{m}_{1,2}$ = diquark masses

$\delta > 0$ & $\delta \ll m_{1,2}$

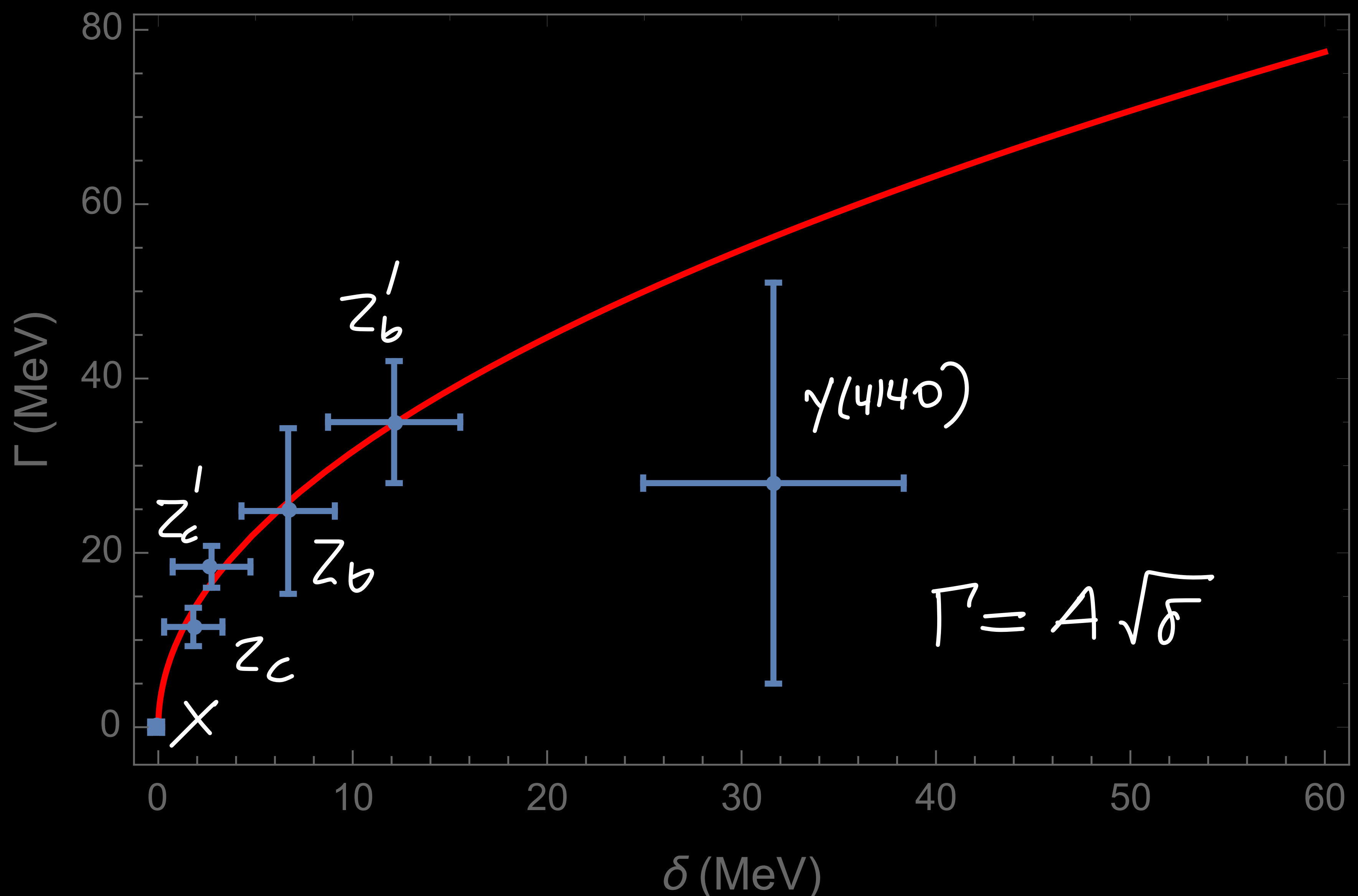
$$\Gamma \approx \left[\frac{\pi}{2}^5 \left(\frac{\tilde{m}B}{m}\right)^{3/2} \frac{T}{m_q}\right]\sqrt{\delta} \quad \text{for } m_1 \approx m_2 \simeq m.$$

Tetraquark widths



Interestingly charm and beauty resonances have all the same A –

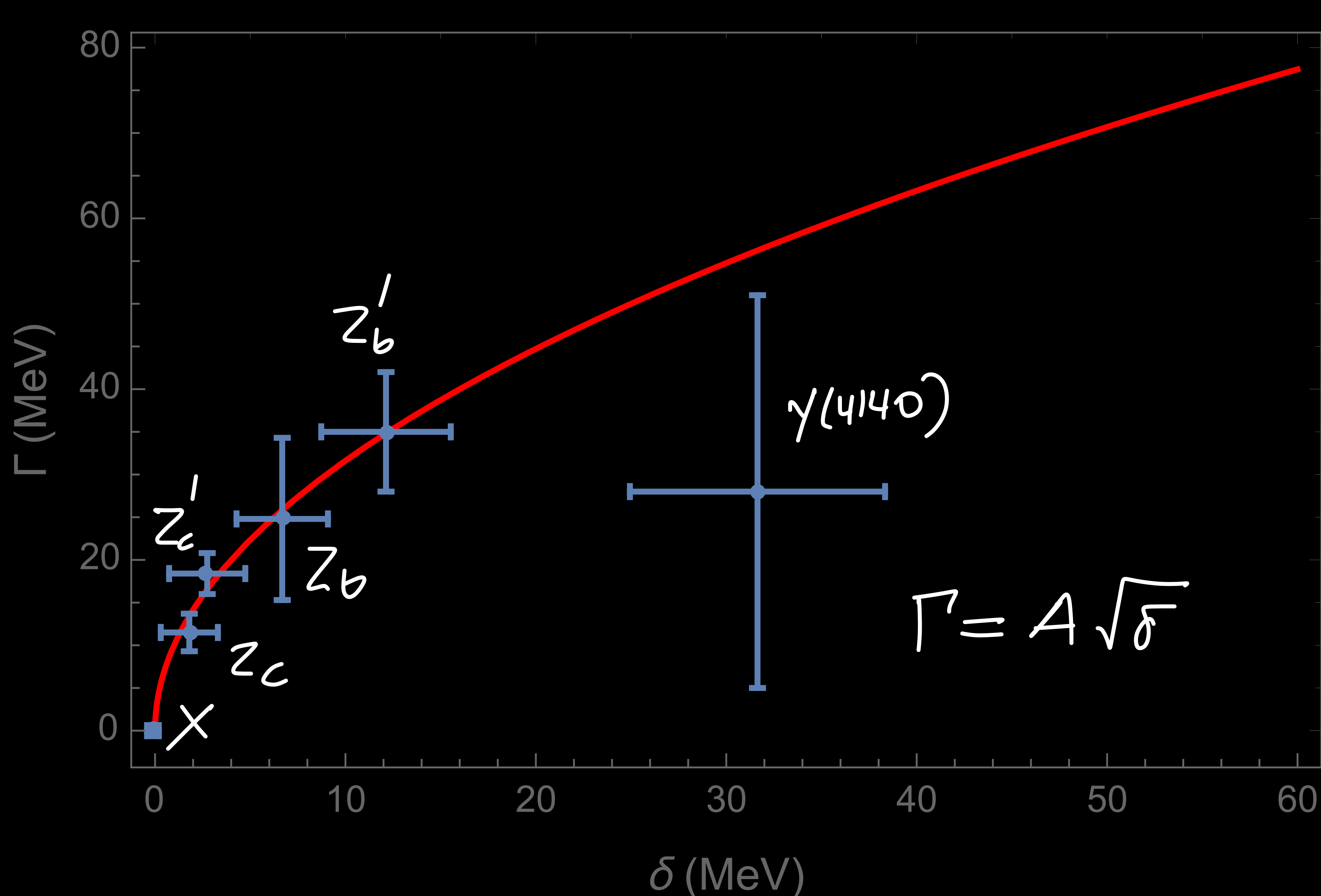
Tetraquark widths



THIS REQUIRES

$$\left.\begin{array}{l} B_b \simeq 5\, B_c \\ \ell_b \simeq 0.5\, \ell_c \end{array}\right\}$$ in previous formula.

Tetraquark widths



Phase space only would predict

$$\Gamma = \frac{\sqrt{\delta}}{m^{3/2}} |Amp|^2$$

Two scales for tetraquarks

Tetraquarks are characterized by two scales

1 — The size of the diquark-antidiq. bound state ℓ

2 — The size of the diquark $\tilde{\ell}$

$$\lambda = \ell/\tilde{\ell} \gtrsim 3$$

In PLB 778 (2018) 247 (Maiani, ADP, Riquer) it is shown that

$$M(X_u) - M(X_d) = f(\lambda)$$

Taking into account the effect of electrostatic, e.m. hyperfine and strong hyperfine interactions.

Two scales for tetraquarks

$\lambda = 1$ Electrostatic repulsion in the (anti)diquarks is almost compensated by the electrostatic attraction between diquark and antidiquark.

$\lambda = 3$ Electrostatic repulsion dominates and the mass difference gets reduced

$$\boxed{M(X_u) \simeq M(X_d) \text{ at } \lambda \simeq 3}$$

Maiani, ADP, Riquer PLB778 (2018) 247

Xu-Xd quasi-degeneracy

$$X_d = [cd][\bar{c}\bar{d}] \longrightarrow \underset{D^+}{(c\bar{d})} + \underset{D^{*-}}{(\bar{c}d)}$$

$$X_u = [cu][\bar{c}\bar{u}] \longrightarrow \underset{D^0}{(c\bar{u})} + \underset{\bar{D}^{*0}}{(\bar{c}u)}$$

$$M(X_u) \simeq M(D^0) + M(\bar{D}^{*0}) < M(D^+) + M(D^{*-})$$

[by ≈ 8 MeV]

$$\Longrightarrow \quad X_d \not\rightarrow D^+ D^{*-}$$

$$X^+ = [cu][\bar{c}\bar{d}] \longrightarrow \underset{D^+}{(c\bar{d})} + \underset{\bar{D}^{*0}}{(\bar{c}u)}$$

[$\gtrsim 5$ MeV wrt $D^0 \bar{D}^{*0}$]

$$\Longrightarrow \quad X^+ \not\rightarrow D^+ \bar{D}^{*0}$$

B decays to X

$$B^0 = \bar{b} d \longrightarrow \bar{c} + c\bar{s} + (d\bar{d} \text{ or } u\bar{u}) + d$$

A_2

A_1

$$\text{Amp}(B^0 \to X_u K^0) \sim A_1$$
$$\text{Amp}(B^0 \to X_d K^0) \sim A_1 + A_2$$
$$\text{Amp}(B^0 \to X^- K^+) \sim A_2$$

Similarly for B^+

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

Mixing

The quasi-degeneracy $M(X_u) \simeq M(X_d)$ implies that EVEN A SMALL $q\bar{q}$ ANNIHILATION AMPLITUDE INSIDE $4q$ CAN PRODUCE A SIZEABLE MIXING

$$
\begin{cases}
X_1 = X_u \cos\phi + X_d \sin\phi \\
X_2 = -X_u \sin\phi + X_d \cos\phi
\end{cases}
$$

$$
\mathrm{Amp}(B^0 \to K X_1) \sim \cos\phi\, A_1 + \sin\phi\, (A_1 + A_2)
$$

$$
\mathrm{Amp}(B^0 \to K X_2) \sim -\sin\phi\, A_1 + \cos\phi\, (A_1 + A_2)
$$

X decays to charmonium

$$B \to K X$$
$$\quad \hookrightarrow J/\psi + 3\pi/2\pi$$

can proceed through

$$|Amp(B \to K \psi \rho)|^2 = |Amp(B \to K X_1 \to K \psi \rho)|^2 +$$
$$+ |Amp(B \to K X_2 \to K \psi \rho)|^2$$

where e.g.

$$Amp(B \to K X_1 \to K \psi \rho) =$$
$$= Amp(B \to K X_1) \underbrace{Amp(X_1 \to \psi \rho)}_{\cos\phi - \sin\phi}$$

$$(\rho^0 = u\bar{u} - d\bar{d})$$

X decays to charmonium

Let's introduce

$I=0$ amplitude $2A_1+A_2 \equiv 2\alpha$ $(J/\psi\ 3\pi)$

$I=1$ amplitude $A_2 \equiv 2\beta$ $(J/\psi\ 2\pi)$

$$A_1 = \alpha - \beta$$

Then

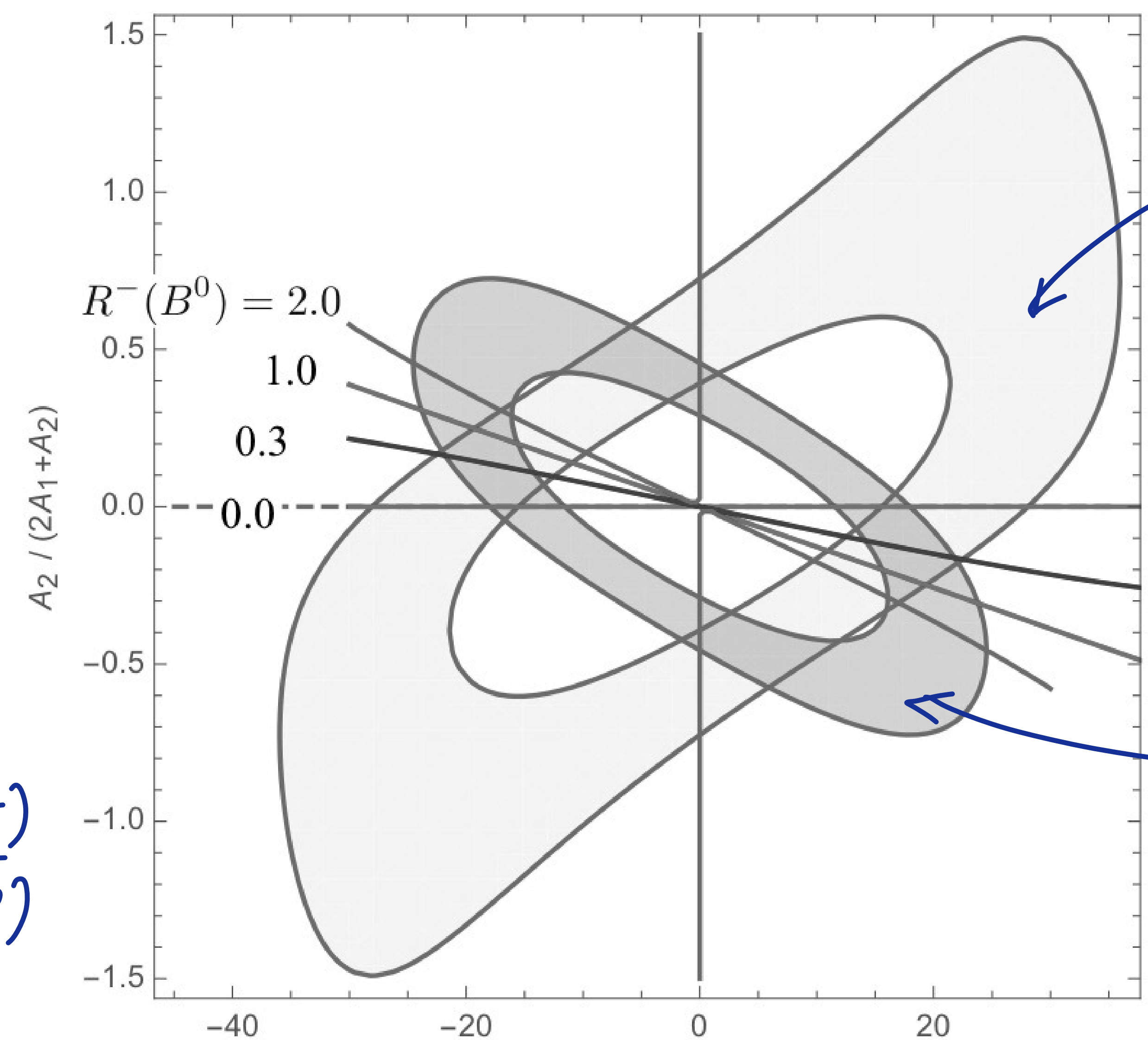
$$R(B^0) \equiv \frac{\Gamma(B^0 \to KX \to K\psi\omega)}{\Gamma(B^0 \to KX \to K\psi\rho)} = \frac{p_\rho}{p_\omega} F_0\left(\theta, \frac{\beta}{\alpha}\right)$$

$[1.4 \pm 0.6]$

$$R(B^+) \equiv \frac{\Gamma(B^+ \to K^+X \to K^+\psi\omega)}{\Gamma(B^+ \to K^+X \to K^+\psi\rho)} = \frac{p_\rho}{p_\omega} F_+\left(\theta, \frac{\beta}{\alpha}\right)$$

$[0.7 \pm 0.4]$

X decays to charmonium



F_0

F_0 & F_+ from data.

F_+

$R^-(B^0) \equiv$

$$\equiv \frac{\Gamma(B^0 \to K^+ X^- \to K^+ \psi \rho^-)}{\Gamma(B^0 \to K^0 X^0 \to K^0 \psi \rho^0)}$$

$$\theta = \frac{\pi}{4} - \phi$$

X decays to charmonium

Experimental exclusion is

$$R^-(B^0) < 1$$

indeed it can be much smaller than that.

Similarly for $R^+(B^+)$ [PLB 778 (2018) 247]

MORE REFINED ANALYSES OF

$B \to K^+ \psi \rho^-$ CHANNELS & SIMILAR

$\hookrightarrow \pi^- \pi^0$

COULD TEST THESE CONCLUSIONS _

Maiani, ADP, Riquer PLB778 (2018) 247

Tunneling

Consider

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

$$\xrightarrow[\text{Fiery.}]{} \left(c(x)\bar{u}(y)\right)\left(\bar{c}(y)u(x)\right)$$

We still need to bring $\bar{u}(y) \to \bar{u}(x)$ and $u(x) \to u(y)$. This involves TUNNELING the barrier between diquarks. This MAY PROVIDE DYNAMICAL FACTORS IN FRONT OF THE VARIOUS TERM OF THE FIERZ REARRANGED EXPRESSION.

Tunneling

Consider

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

$$\xrightarrow[\text{Fiery.}]{} \left(c(x)\bar{u}(y)\right)\left(\bar{c}(y)u(x)\right)$$

Take for example

$$\Psi = [c^\alpha \sigma_2 u^\beta](x)[\bar{c}_\beta \sigma_2 \vec{\sigma} \bar{u}_\alpha](y)$$

$$\longrightarrow A\,[c^\alpha(x)\sigma_2 \bar{u}_\alpha(x)][\bar{c}_\beta(y)\sigma_2\vec{\sigma}u^\beta(y)]$$

$$-\ B\,[c^\alpha(x)\sigma_2\vec{\sigma}\bar{u}_\alpha(x)][\bar{c}_\beta(y)\sigma_2 u^\beta(y)]$$

$$+\,iC\,[c^\alpha(x)\sigma_2\vec{\sigma}\bar{u}_\alpha(x)]\times[\bar{c}_\beta(y)\sigma_2\vec{\sigma}u^\beta(y)]$$

A, B, C = non-pert. coefficients associated to different barrier penetration amplitudes for different light quark spin config.

Tunneling

So we got

$$\Psi = A\, D^0 \bar{D}^{*0} - B\, D^{*0} \bar{D}^0 + i C\, D^{*0} \times \bar{D}^{*0}$$

$$\equiv \Psi_1 = [cu]_0 [\bar{c}\bar{u}]_1$$

Similarly

$$\Psi_2 = [cu]_1 [\bar{c}\bar{u}]_0 =$$

$$= B\, D^0 \bar{D}^{*0} - A\, D^{*0} \bar{D}^0 - i C\, D^{*0} \times \bar{D}^{*0}$$

Then

$$Z_c = \frac{1}{\sqrt{2}} \left([cu]_0 [\bar{c}\bar{u}]_1 - [cu]_1 [\bar{c}\bar{u}]_0 \right)$$

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

IF $A \neq B \Rightarrow Z_c \to D^0 \bar{D}^{*0}$ ($D^{*0} \bar{D}^{*0}$ BEING SUPPR.)

Summary

1 – Why $X^{\pm}$ seem to be absent

Because A_2 can be very small for certain values of ϕ

2 – Where does the mixing ϕ come from?

From the quasi-degeneracy $X_u \simeq X_d$

3 – Where does this degeneracy come fom?

The $4q$ is a two-scales system and $M(X_u) - M(X_d) = f(\lambda)$ where $\lambda = \ell / \tilde{\ell}$

4 – Why $\ell \leq \tilde{\ell}$?

Short distance repulsion between diquarks

Summary

5- What is suggesting such a repulsion?

— Spin-Spin interactions work as if diquark where segregated at some distance

— Tunneling disfavours $4\rho/\omega$ decays

— The width formula

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

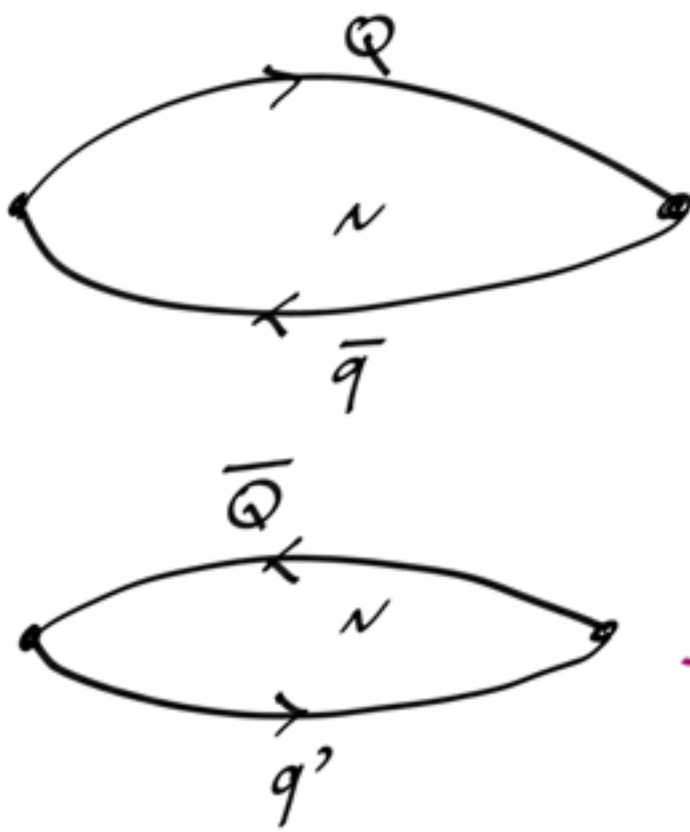
works for Z_c's, Z_b's & X as can be understood with a tunneling process.

Open questions

- Z_c, Z_c' in B decays?
- Z_c, Z_c' in prompt collisions?
- Which resolution can be reached to measure the mass of X^0 in $D\bar{D}^*$ and $\psi\rho$?
- What about the $\Upsilon(1S)\Upsilon(1S)$ state with $\delta \cong -80$ MeV?

THE LARGE-N EXPANSION & TETRAQUARKS

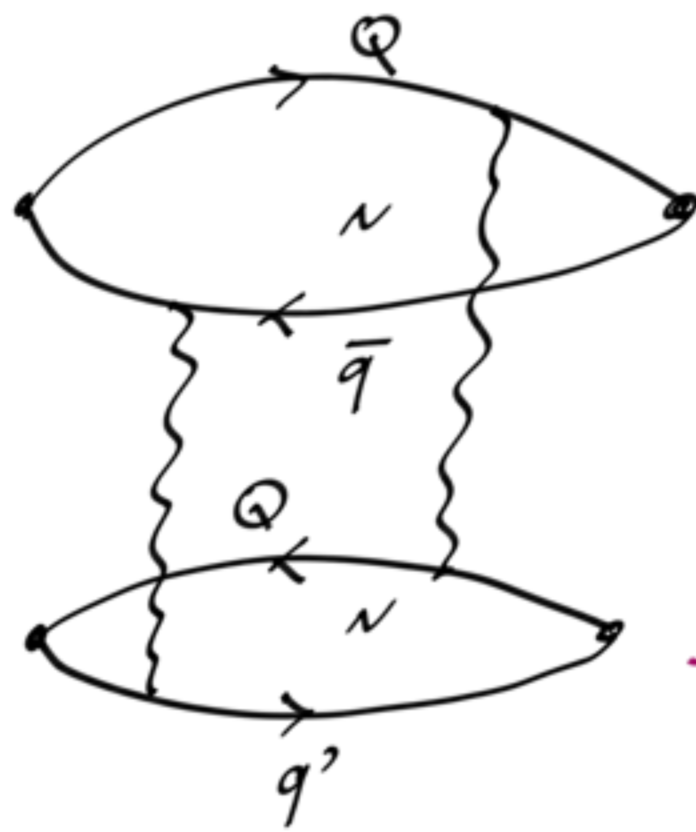
S. WEINBERG PRL 110 (2013) 261601



$\propto N^2$

THE LARGE-N EXPANSION & TETRAQUARKS

S. WEINBERG PRL 110 (2013) 261601

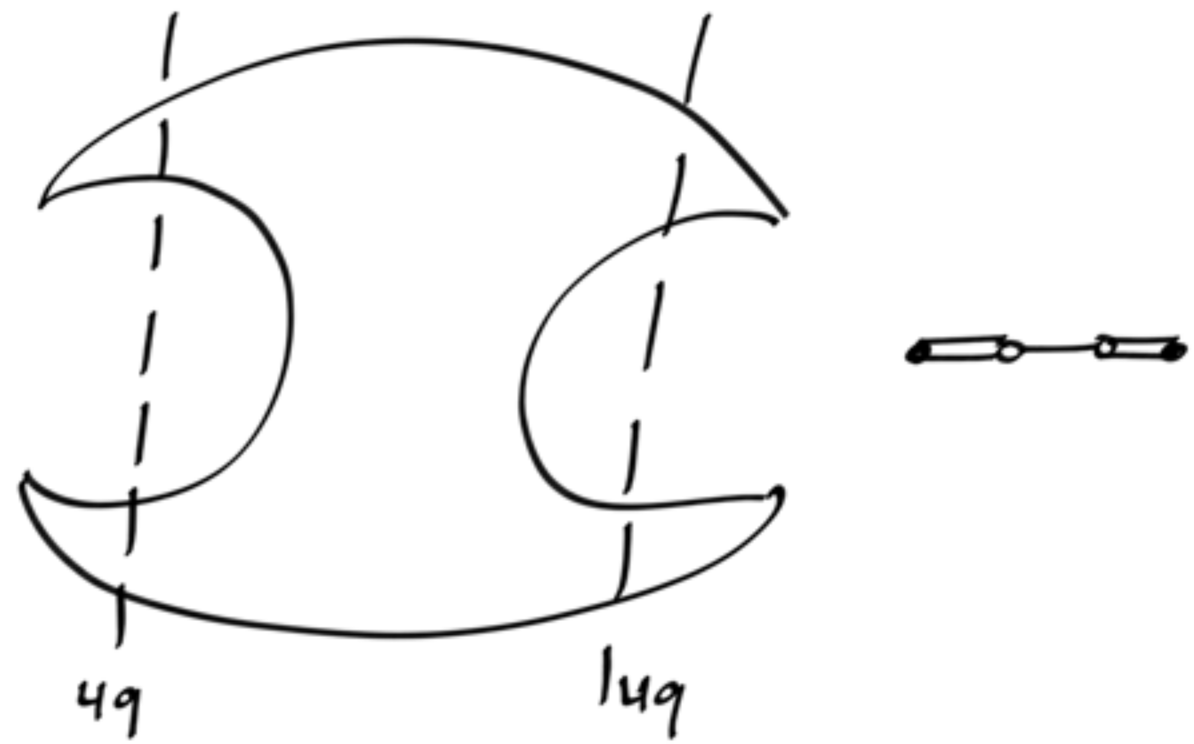


$\propto N^2 \times \left(\frac{1}{\sqrt{N}}\right)^2$

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

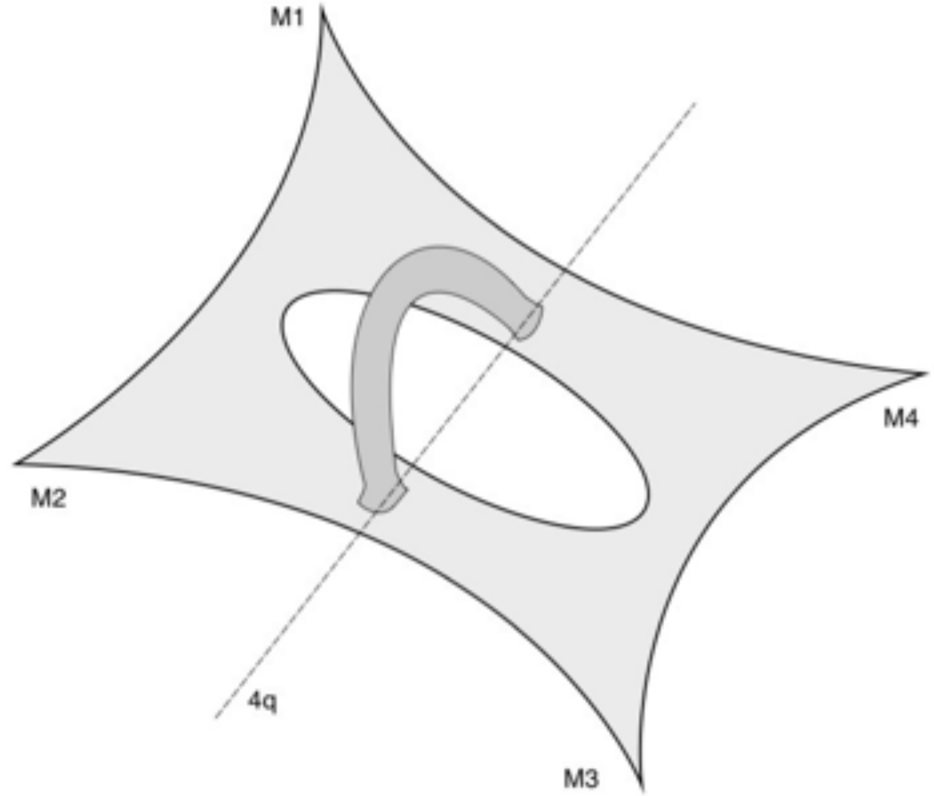
THE LARGE-N EXPANSION & TETRAQUARKS

S. WEINBERG PRL 110 (2013) 261601

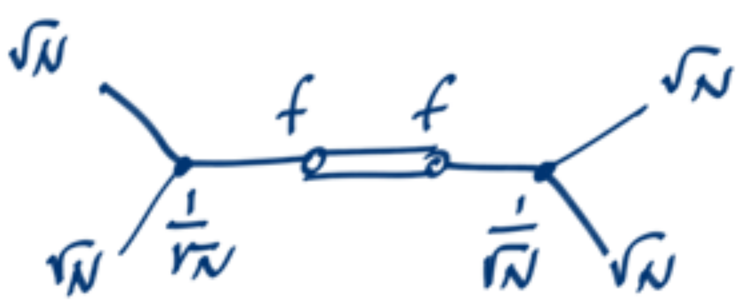


"IF THERE IS A TETRAQUARK MESON POLE IN THE CONNECTED PART OF THE PROPAGATOR WHAT DIFFERENCE DOES IT MAKE IF ITS RESIDUE IS SMALLER WRT THE DISCONNECTED PART?"

NON PLANAR DIAGRAMS



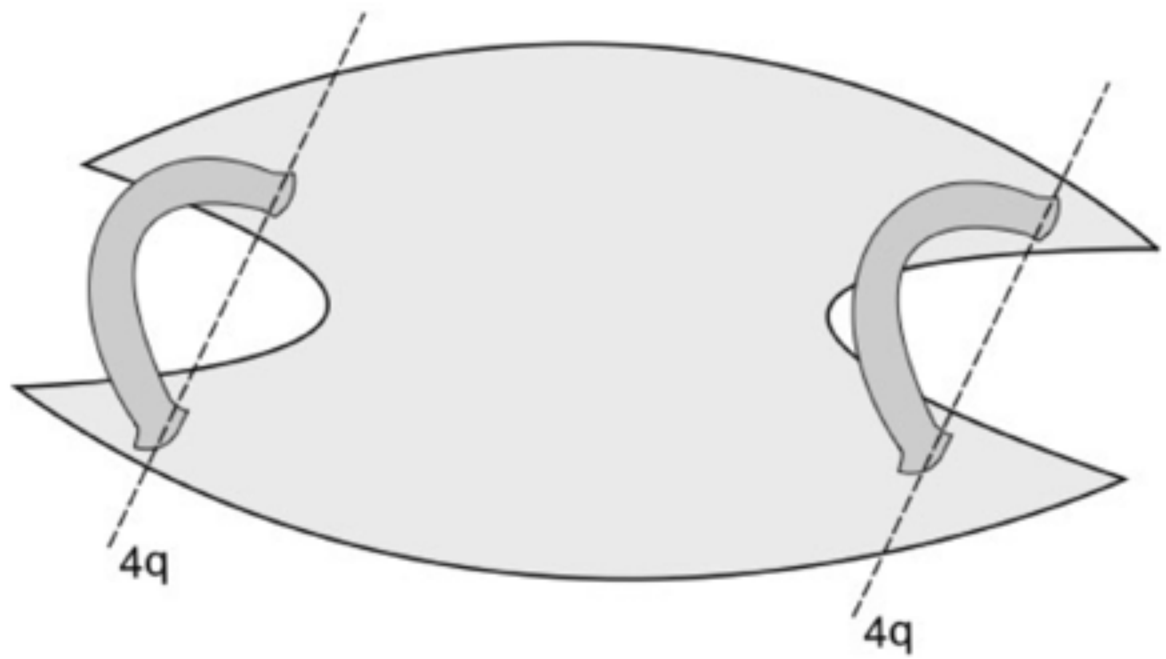
$$N^{\alpha} = N^{2-L-2H} = N^{2-2-2} = \frac{1}{N^2}$$



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

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

NON PLANAR DIAGRAMS



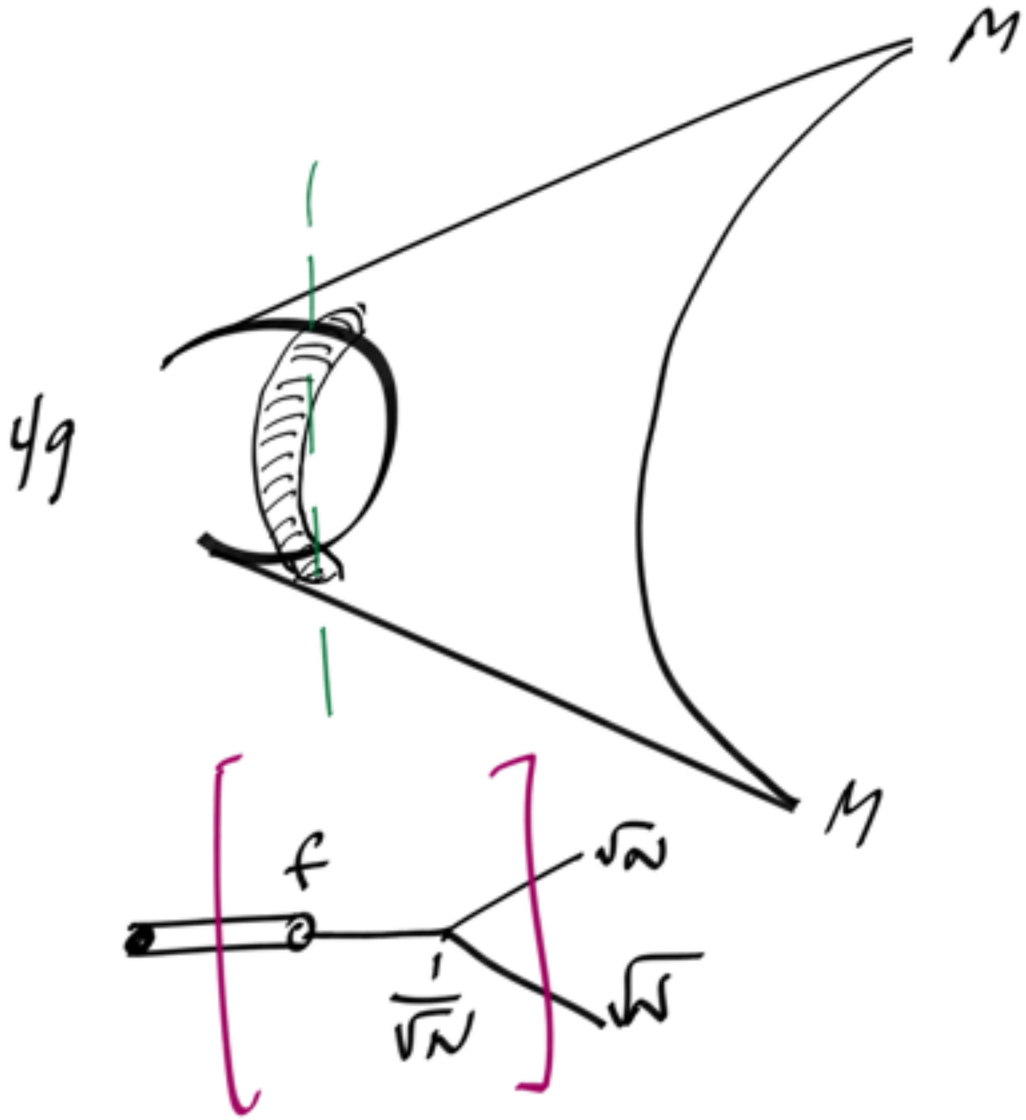
$$N^{2-2-2H} = N^{2-1-4} = N^{-3}$$

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

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

[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 & $\bar{D}^{*0}$

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

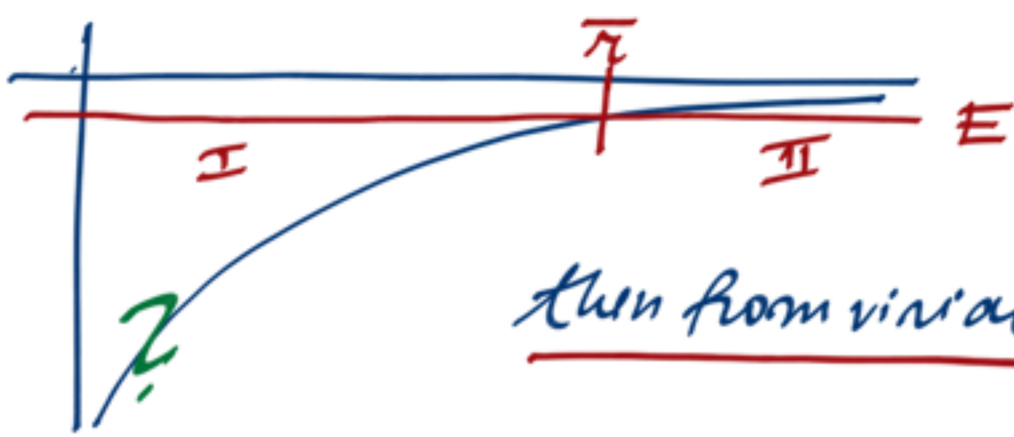
The VIRIAL THEOREM gives

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

i.e.

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

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

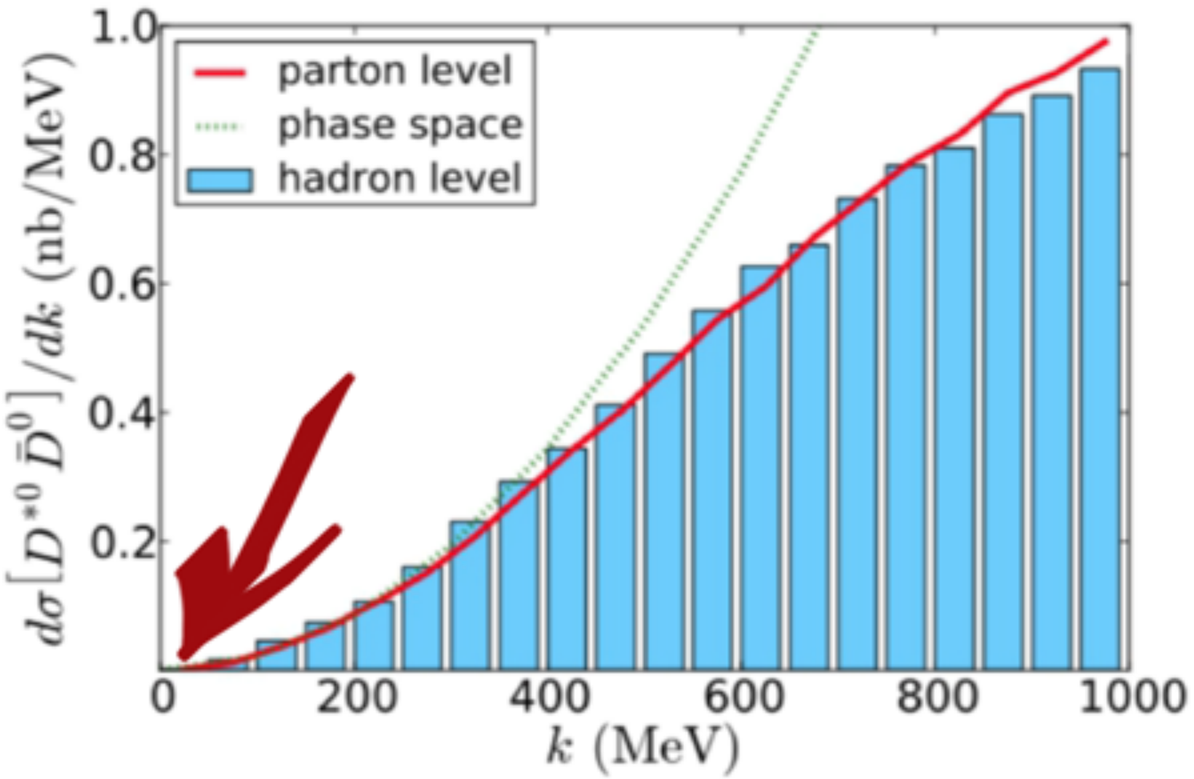


FOR SHALLOW BOUND STATES

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

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

X PRODUCTION AT HADRON COLLIDERS

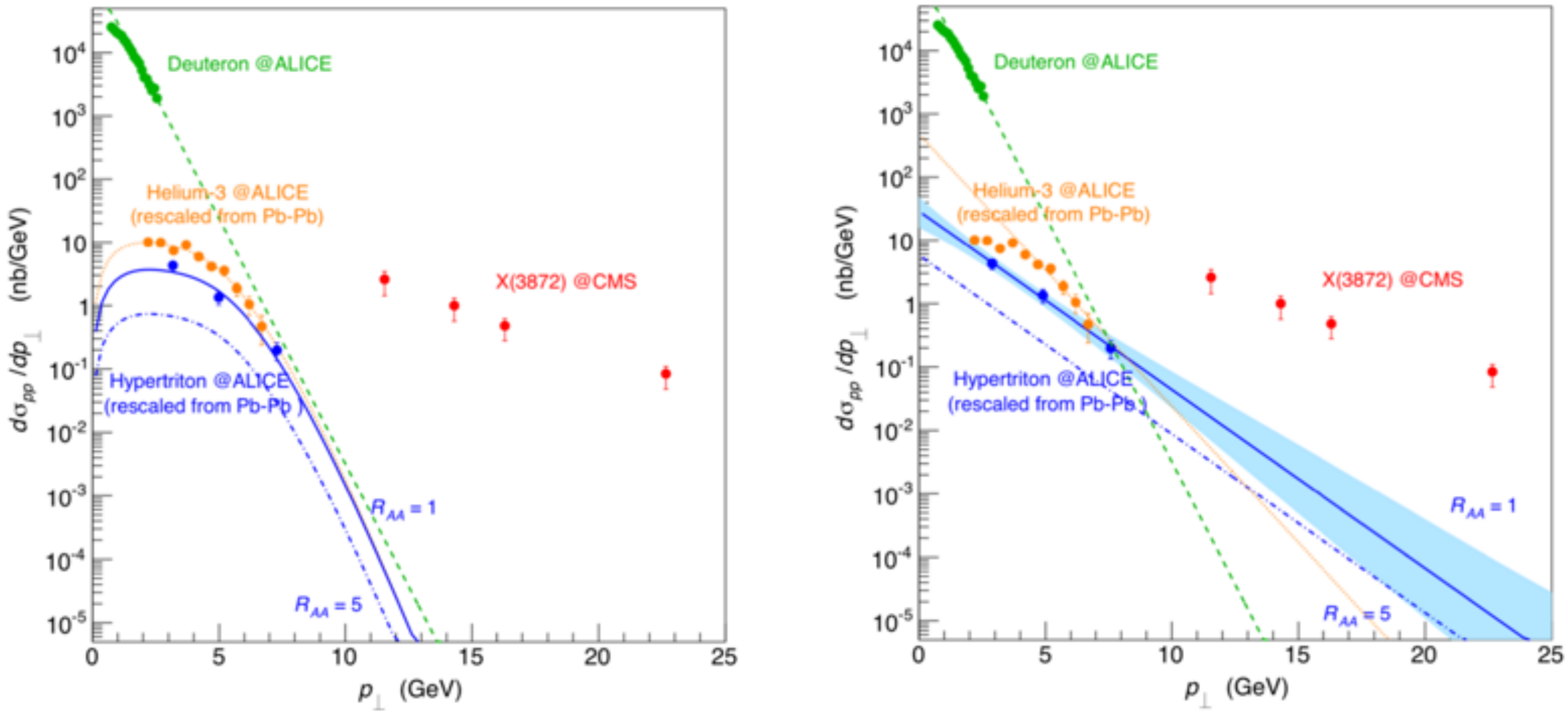


$p_T(D^{*0}\bar{D}^0) > 5$ GeV and $|y(D^{*0}\bar{D}^0)| < 0.6$
in $p\bar{p}$ @ 1.96 TeV

FROM ARTOISENET & BRAATEN PRD 81 (2010) 014013

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

X PRODUCTION AT HADRON COLLIDERS



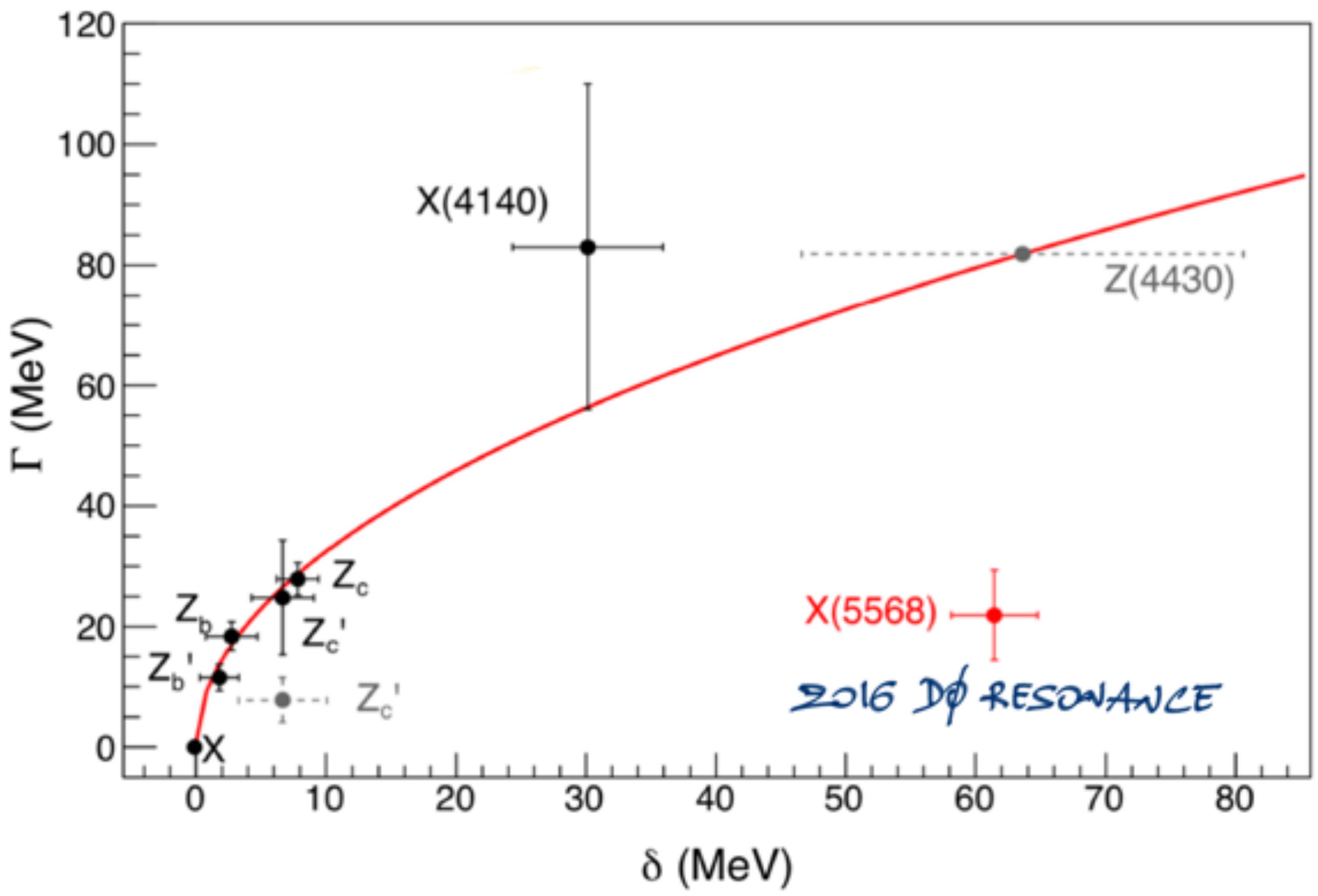
THE X PRODUCTION DOES NOT SEEM COMPARABLE TO THAT OF 'REAL' HADRON MOLECULES.

(what about other states in pp?)

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

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]

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

cc* mixing

$$\boxed{\Psi = Z_1\, \Psi_{D\bar{D}^*} + Z_2\, \Psi_{\chi_{c1}(2P)}}$$

(predicted but not yet observed radial excitation)

TO EXPLAIN PROMPT PRODUCTION NEED

$$\underline{Z_2 = 28 \div 44\%}$$

(Meng et al. PRD <u>96</u> (2017) 074014)

THE PROB. THAT A χ_{c1} CONFIG. IS FOUND IN A MOLECULE IS

$$P = V\,|\Psi(0)|^2 = (1\,fm)^3 \left(\frac{1}{10\,fm}\right)^3 = 10^{-3}$$

which apparently clashes with Z_2 ...