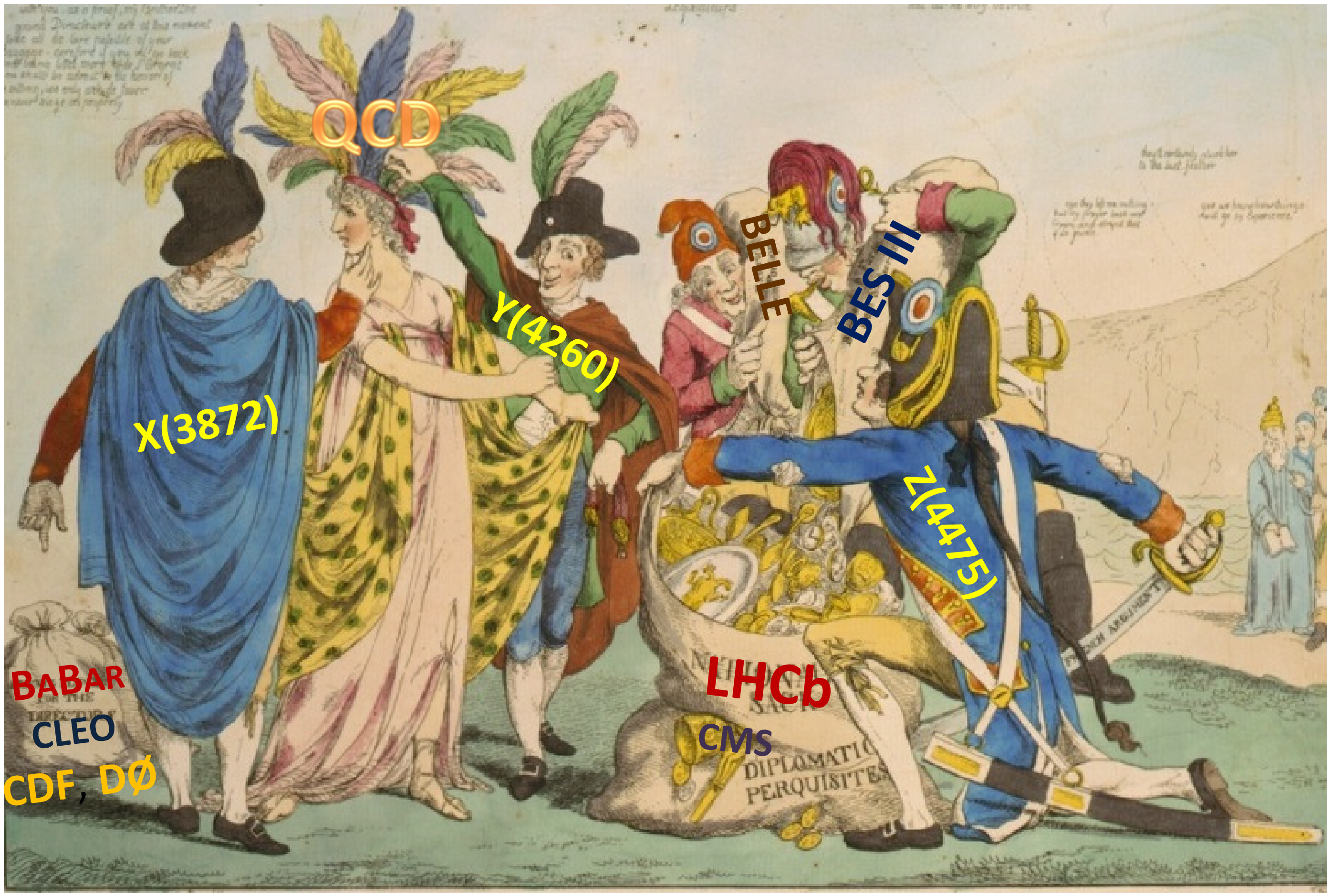
A New Dynamical Picture for Production and Decay of the XYZ Mesons



Richard Lebed

Arizona State University

CHARM 2015

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Outline

1) The forest of exotics *X,Y,Z*

2) How are the tetraquarks assembled?

3) A new dynamical picture for the *X,Y,Z*

4) Puzzles resolved by the new picture

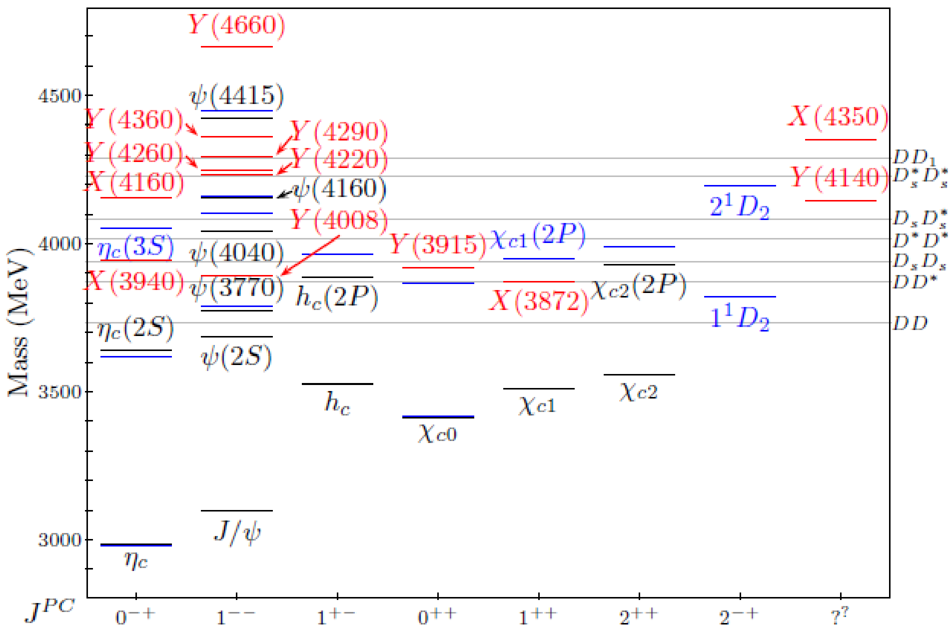
5) Next directions: Using constituent counting rules

6) Conclusions

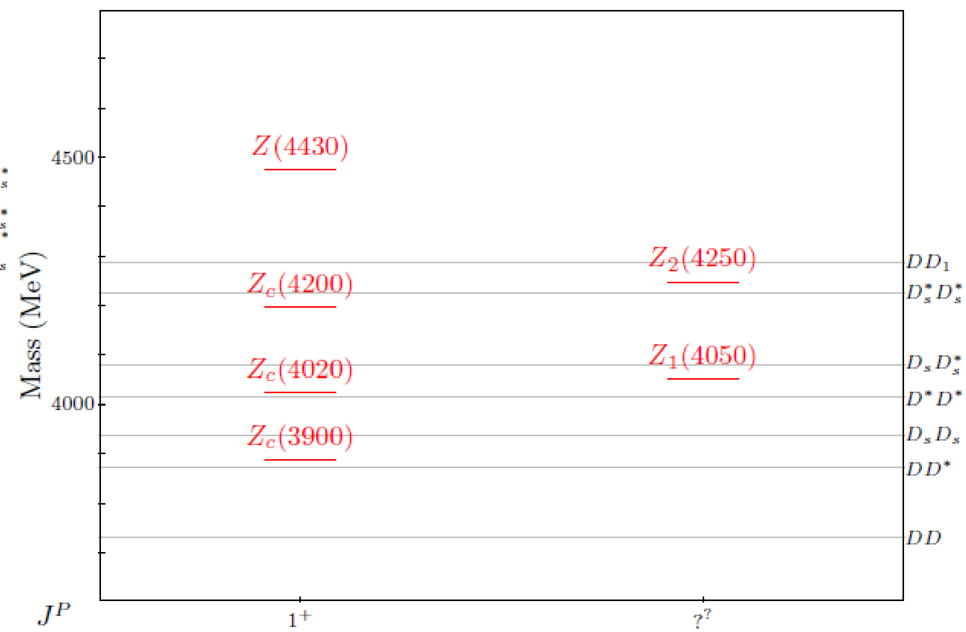
Charmonium: November 2014

Esposito *et al.*, 1411.5997

Neutral



Charged

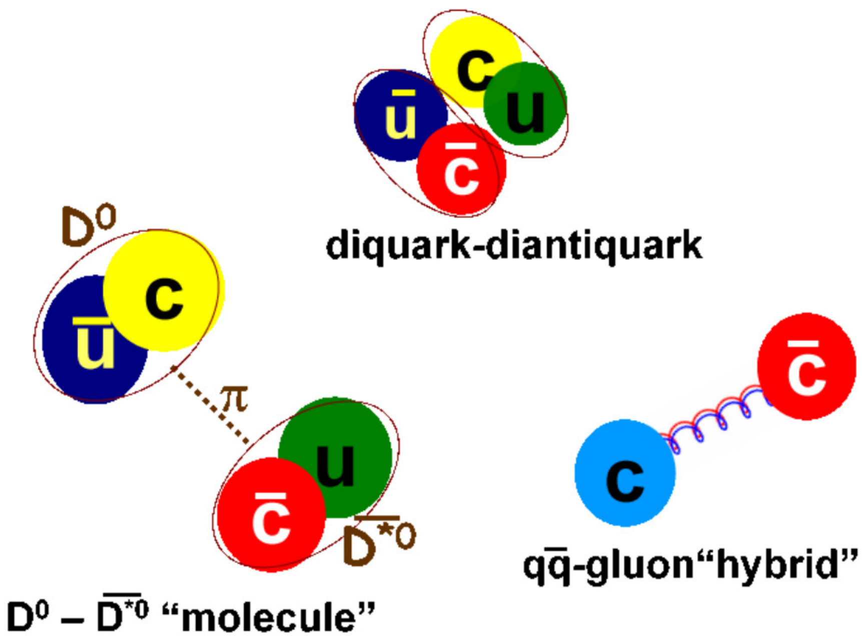


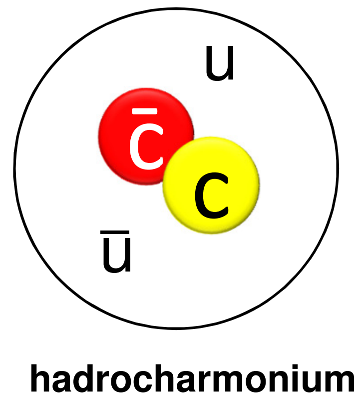
Black: Observed conventional $c\bar{c}$ states

Blue: Predicted conventional $c\bar{c}$ states

Red: Exotic $c\bar{c}$ states

How are tetraquarks assembled?





cusp effect:
Resonance created by rapid opening of meson-meson threshold

Image from Godfrey & Olsen,
Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

Trouble with the dynamical pictures

- Hybrids
  - Neutral states only; what are the *Z*'s?
  - Only certain quantum numbers (*e.g.*, $J^{PC} = 1^{++}$) easily produced
- Diquark and hadrocharmonium pictures
  - What keeps states from instantly segregating into meson pairs?
  - Diquark models tend to overpredict the number of bound states
  - Why wouldn't hadrocharmonium *always* decay into charmonium, instead of $D\bar{D}$?
- Cusp effect
  - Might be able to generate some resonances on its own, but >20 of them? And certainly not ones as narrow as $X(3872)$ ($\Gamma < 1.2$ MeV)

The hadron molecular picture

- Several *XYZ* states are *suspiciously* close to hadron thresholds
  - *e.g.*, $m_{X(3872)} - m_{D^{*0}} - m_{D^0} = -0.11 \pm 0.21$ MeV
- So we theorists have *hundreds* of papers analyzing the *XYZ* states as dimeson molecules
- But not all of them are!
  - *e.g.*, *Z*(4475) is a prime example
- Also, some *XYZ* states lie slightly *above* a hadronic threshold
  - *e.g.*, Y(4260) lies about 30 MeV above the $D_s^* \overline{D_s^*}$ threshold
  - How can one have a bound state with *positive* binding energy?

Prompt production

- If hadronic molecules are really formed, they must be very weakly bound, with very low relative momentum between their mesonic components
- They might appear in *B* decays, but would almost always be blown apart in collider experiments
- But CDF & CMS saw lots of them! [Prompt *X*(3872) production, σ≈30 nb]
  - CDF Collaboration (A. Abulencia *et al*.), PRL **98**, 132002 (2007)
  - CMS Collaboration (S. Chatrchyan *et al*.), JHEP **1304**, 154 (2013)
- Perhaps final-state interactions due to π exchange between D^0 and $\overline{D^{*0}}$?
  - P. Artoisenet and E. Braaten, Phys. Rev. D **81**, 114018 (2010); D **83**, 014019 (2011)
- Such effects can be significant, but do not appear to be sufficient to explain the size of the prompt production
  - C. Bignamini *et al*., Phys.Lett. B **228** (2010); A. Esposito *et al.*, J. Mod. Phys. **4**, 1569 (2013); A. Guerrieri *et al*., Phys. Rev. D **90**, 034003 (2014)

➢ Hadronic molecules may exist, but *X*(3872) does not seem to fit the profile

Amazing (well-known) fact about color:

- The short-distance color attraction of combining two color-$\mathbf{3}$ quarks into a color-$\overline{\mathbf{3}}$ diquark is *fully half as strong* as that of combining a $\mathbf{3}$ and a $\overline{\mathbf{3}}$ into a color singlet (*i.e.*, diquark attraction is nearly as strong as the confining attraction)

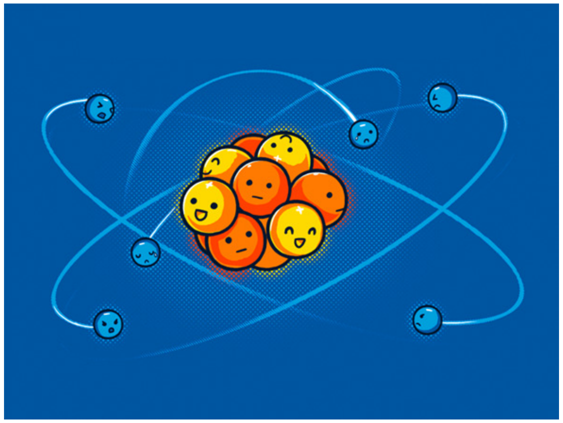
- Just as one computes a spin-spin coupling,
$$\overrightarrow{s_1} \cdot \overrightarrow{s_2} = \frac{1}{2}\left[(\overrightarrow{s_1} + \overrightarrow{s_2})^2 - \overrightarrow{s_1}^2 - \overrightarrow{s_2}^2\right],$$
from two particles in representations 1 and 2 combined into representation 1+2,

- The generic rule in terms of quadratic Casimir C_2 of representation R is $\frac{1}{2}[C_2(R_{1+2}) - C_2(R_1) - C_2(R_2)]$; this formula gives the result stated above

A new tetraquark picture

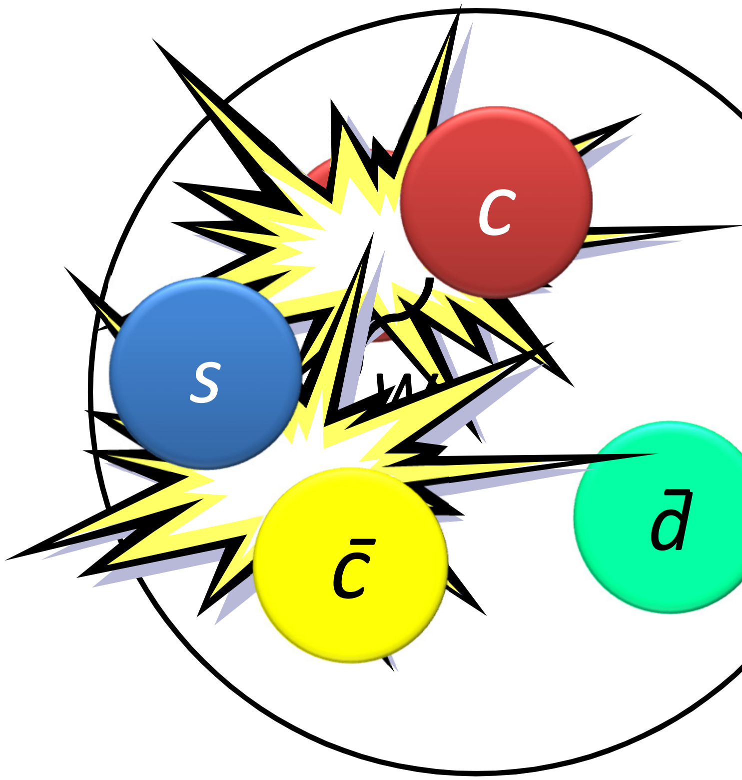
Stanley J. Brodsky, Dae Sung Hwang, RFL
Physical Review Letters **113**, 112001 (2014)

- CLAIM: At least some of the observed tetraquark states are bound states of diquark-antidiquark pairs
- BUT the pairs are not in a static configuration; they are created with a lot of relative energy, and rapidly separate from each other
- Diquarks are not color singlets! They are in either a $\overline{\mathbf{3}}$ (attractive) or a $\mathbf{6}$ (repulsive) and cannot, due to confinement, separate asymptotically far
- They must hadronize via large-*r* tails of mesonic wave functions, which suppresses decay widths
- Want to see this in action? Time for some cartoons!



Nonleptonic $\bar{B}^0$ meson decay

B.R.~22%

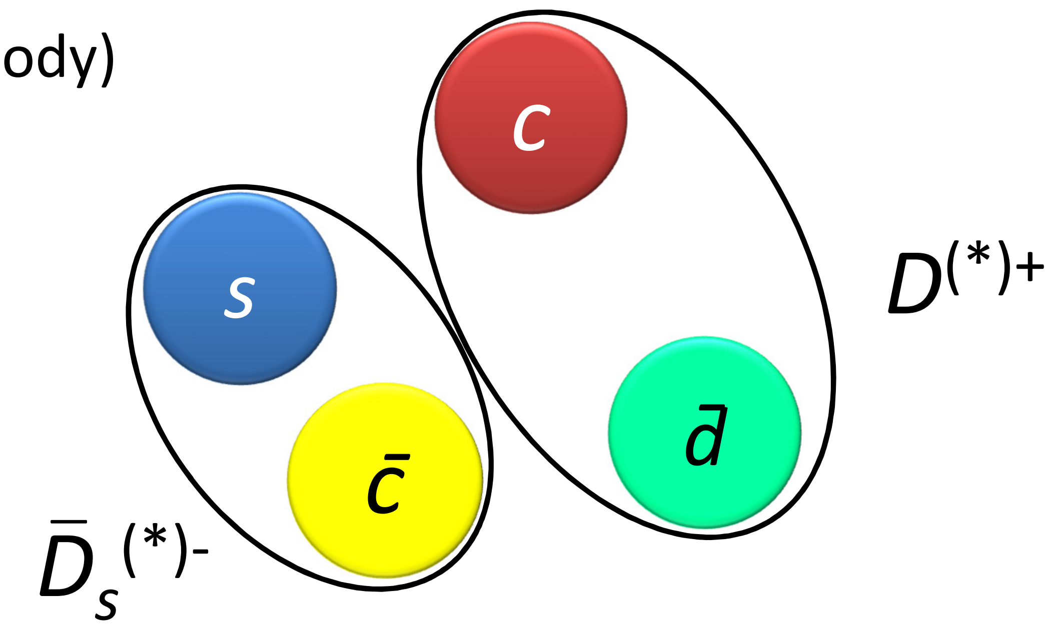


Powerpoint version containing animations available by request, richard.lebed@asu.edu

What happens next?
Option 1: Color-allowed

B.R.~5%

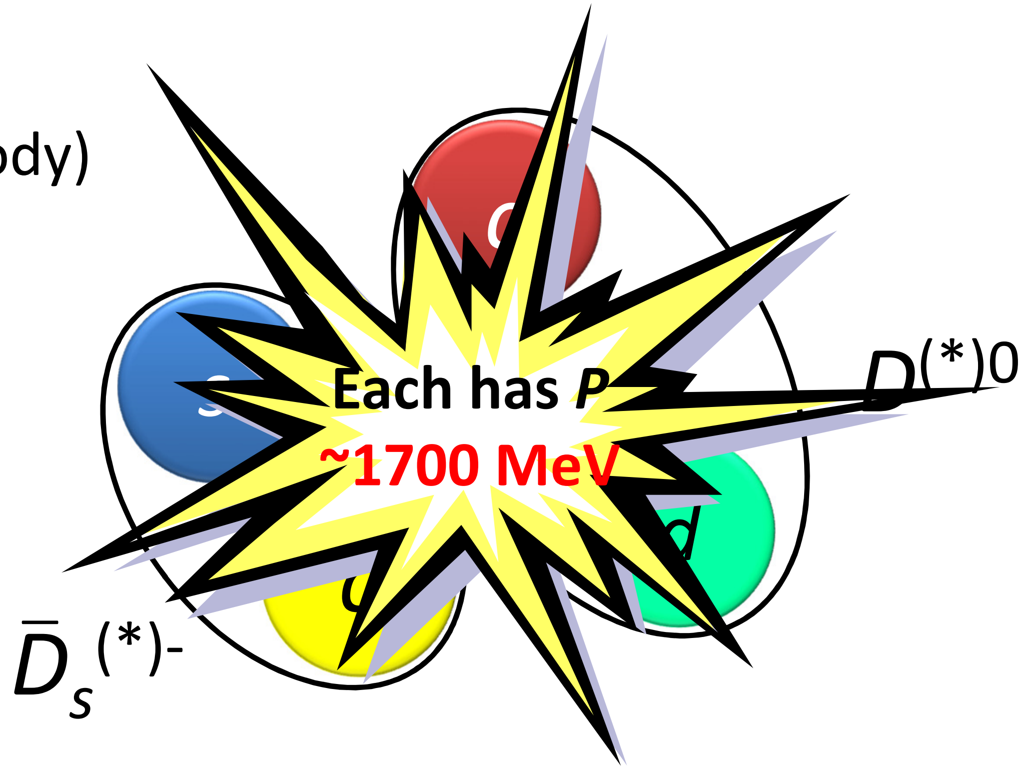
(& similar 2-body)



What happens next?
Option 1: Color-allowed

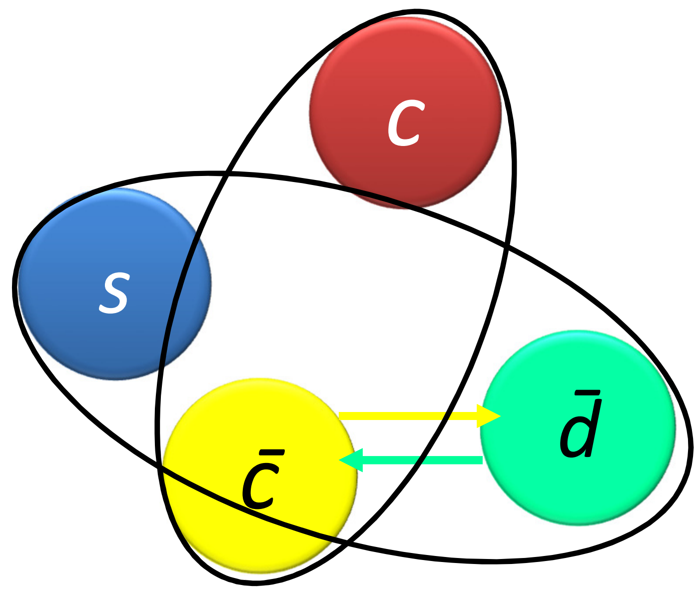
B.R.~5%

(& similar 2-body)



What happens next?
Option 2: Color-suppressed

B.R.~2.3%

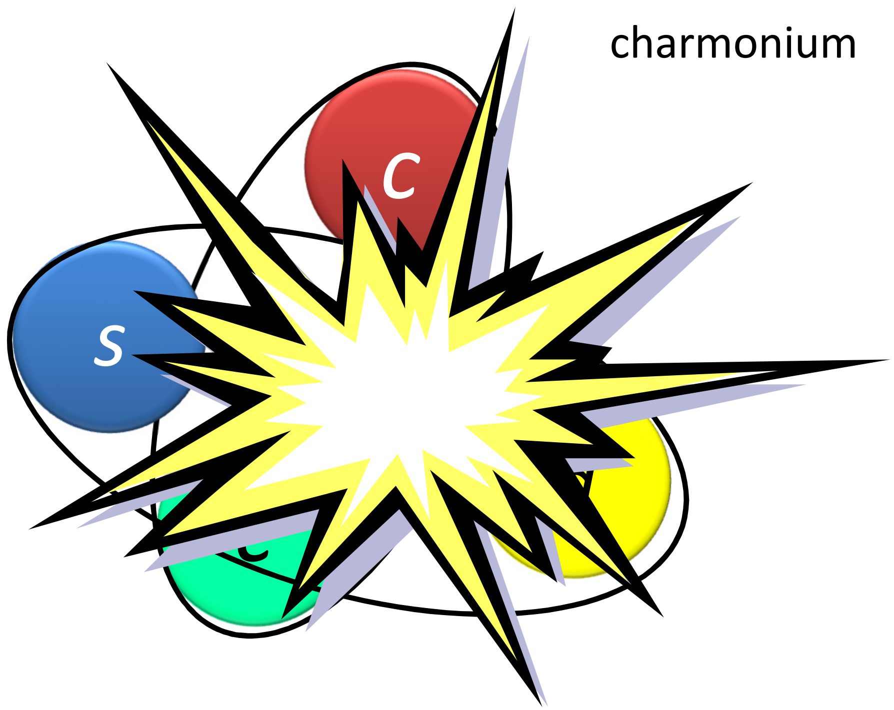


What happens next?
Option 2: Color-suppressed

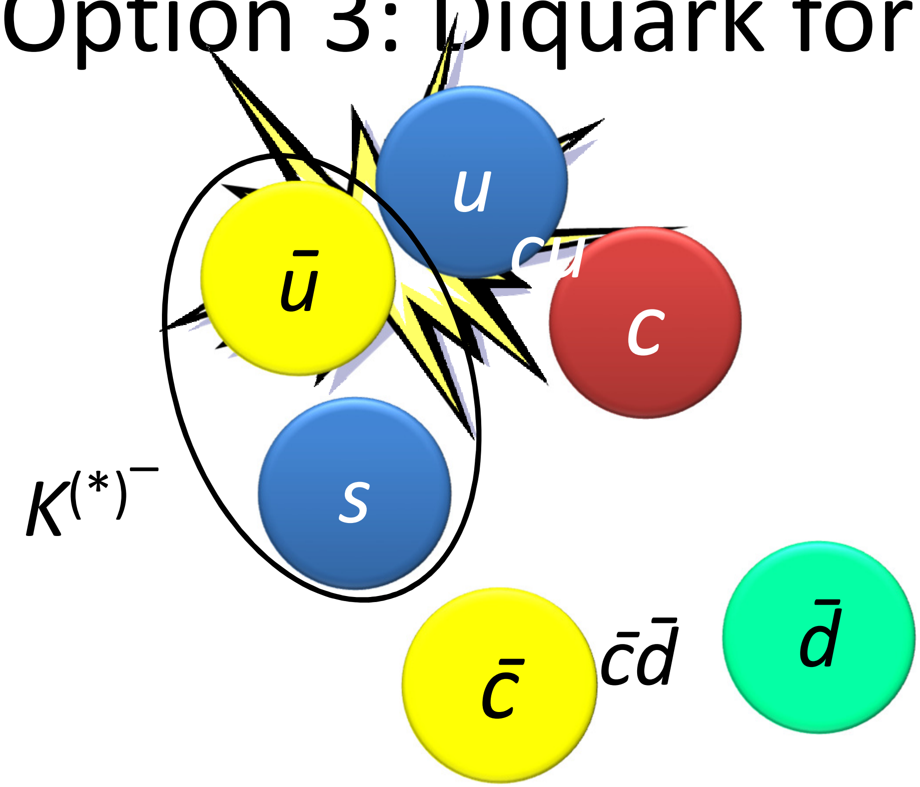
B.R.~2.3%

$\bar{K}^{(*)0}$

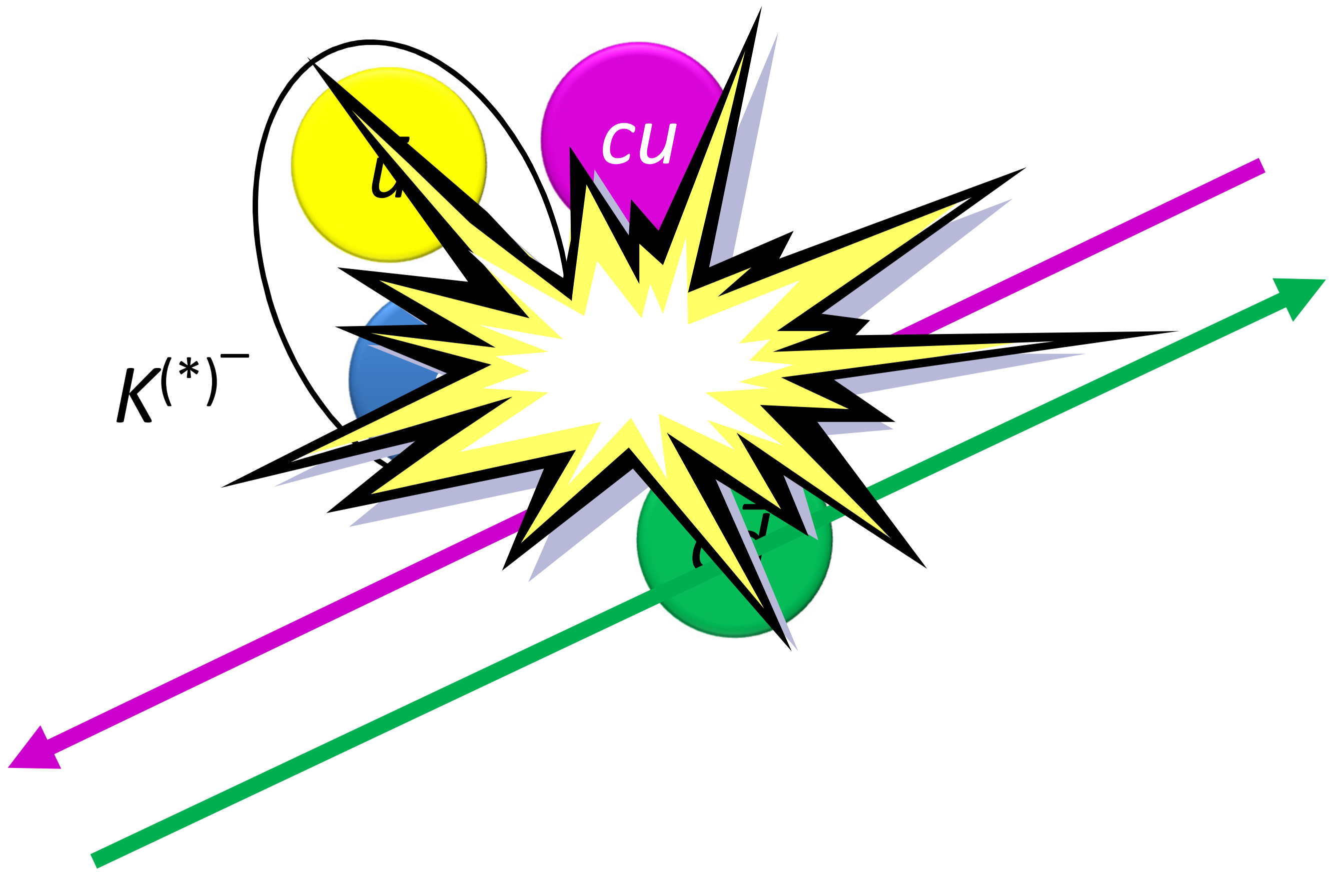
charmonium



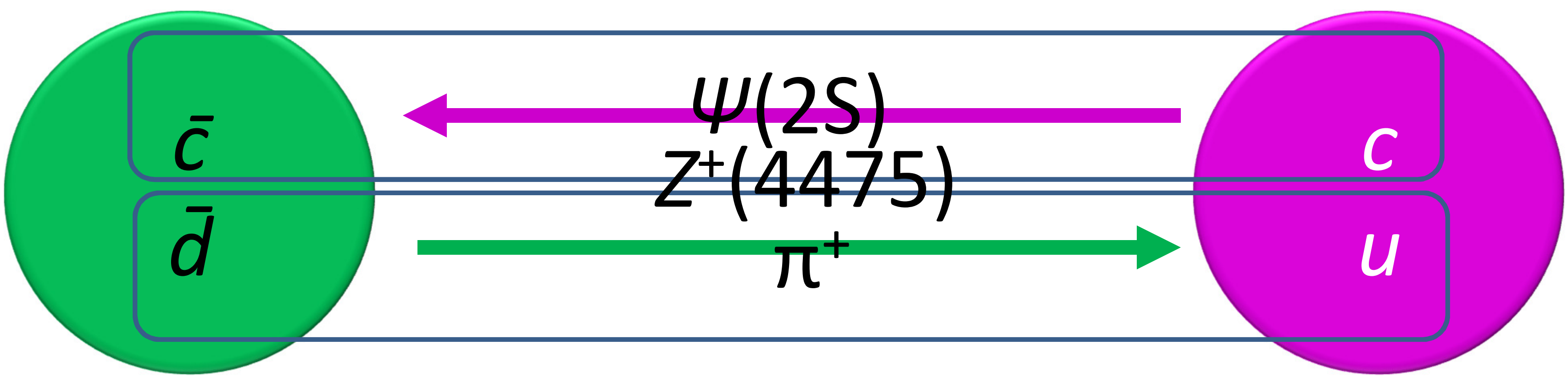
What happens next?
Option 3: Diquark formation



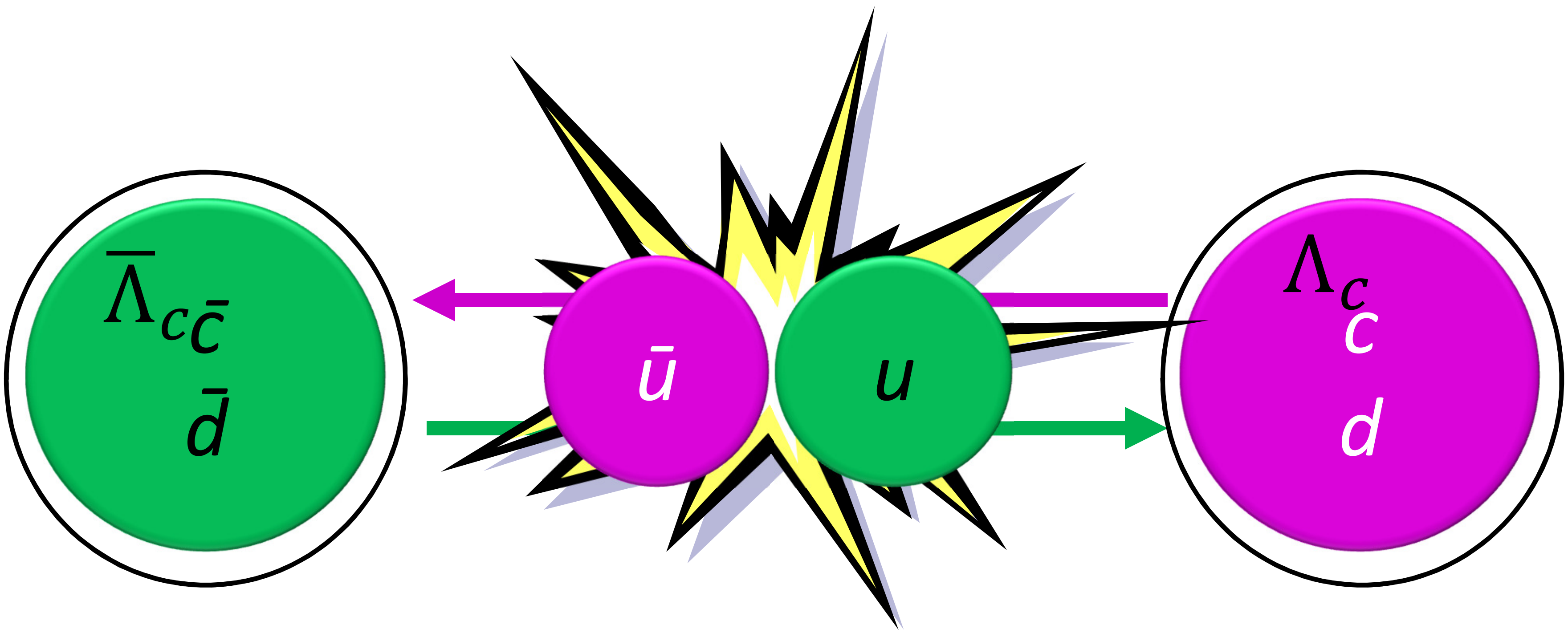
What happens next?
Option 3: Diquark formation



Driven apart by kinematics,
yet bound together by confinement,
our star-crossed diquarks
must somehow hadronize as one



Why doesn't this just happen?
It's called *baryonium*



It *does* happen, as soon as the threshold $2M_{\Lambda_c} = 4573$ MeV is passed

The lightest exotic above this threshold, $X(4632)$, decays into $\Lambda_c + \overline{\Lambda}_c$

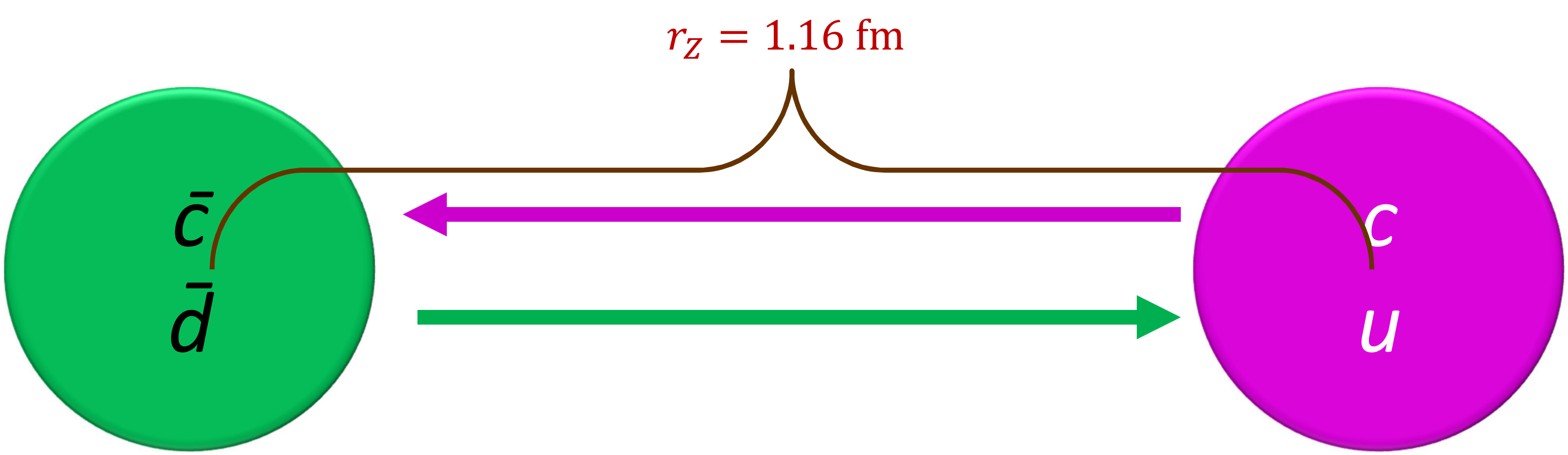
How far apart do the diquarks actually get?

- Since this is still a $\mathbf{3} \leftrightarrow \overline{\mathbf{3}}$ color interaction, just use the Cornell potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_{cq}^2}\left(\frac{\sigma}{\sqrt{\pi}}\right)^3 e^{-\sigma^2 r^2}\mathbf{S}_{cq}\cdot\mathbf{S}_{\overline{cq}},$$

[This variant: Barnes et al., PRD **72**, 054026 (2005)]

- Use that the kinetic energy released in $\overline{B}^0 \longrightarrow K^- + Z^+(4475)$ converts into potential energy until the diquarks come to rest
- Hadronization most effective at this point (WKB turning point)

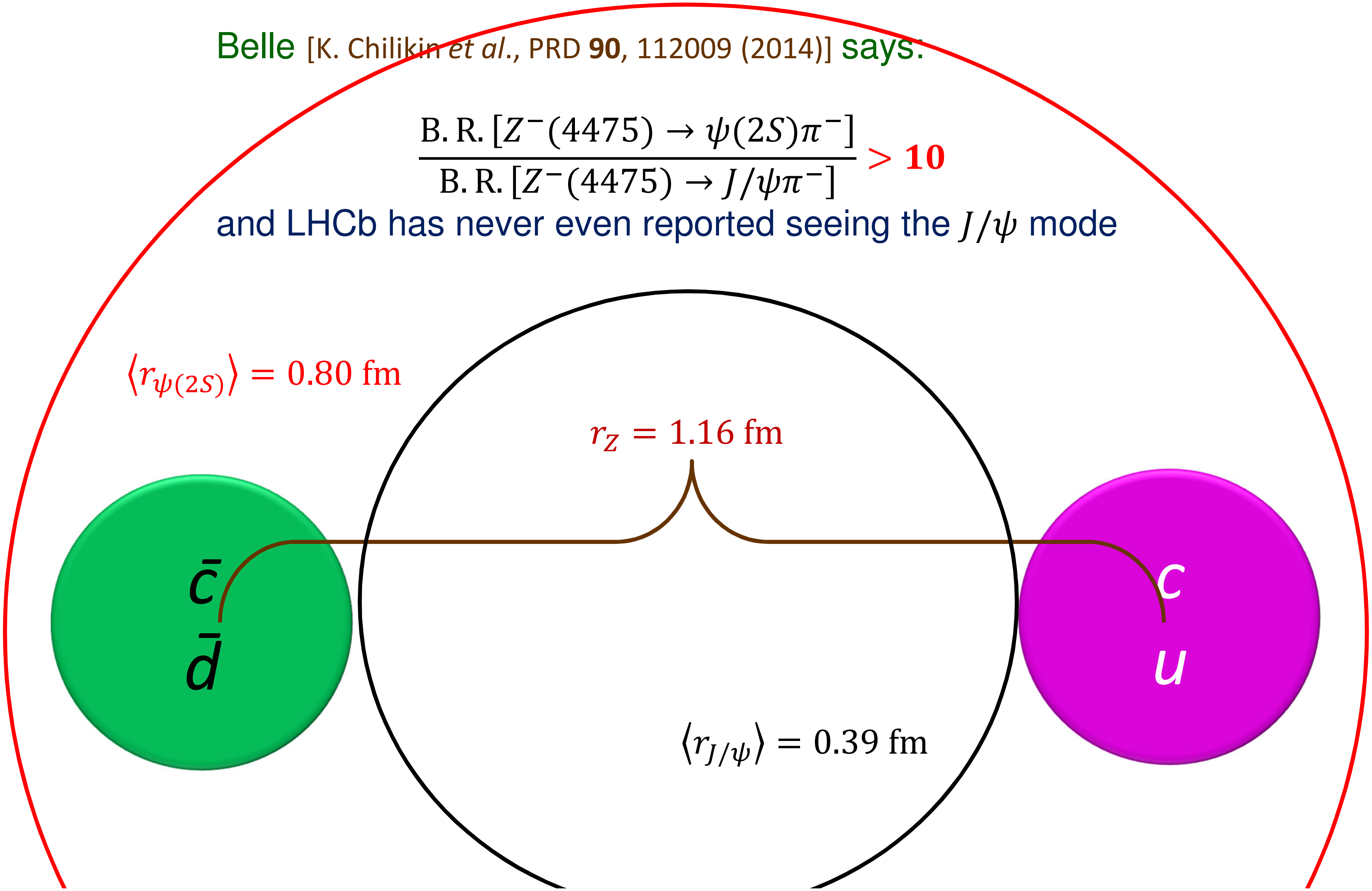


Fascinating $Z(4475)$ fact:

Belle [K. Chilikin *et al.*, PRD **90**, 112009 (2014)] says:

$$\frac{\mathrm{B.R.}\,[Z^-(4475) \to \psi(2S)\pi^-]}{\mathrm{B.R.}\,[Z^-(4475) \to J/\psi\pi^-]} > \mathbf{10}$$

and LHCb has never even reported seeing the J/ψ mode



The large-*r* wave function tails and resonance widths

- The simple fact that the diquark-antidiquark pair is capable of separating further than the typical mean size of ordinary hadrons before coming to rest implies:
  - The hadronization overlap matrix elements are suppressed, SO
  - The hadronization rate is suppressed, SO
  - The width is smaller than predicted by generic dimensional analysis (*i.e.*, by phase space alone)
- *e.g.*, $\Gamma[Z(4475)] = 180 \pm 31 \text{ MeV}$ (*cf.* $\Gamma[\rho(770)] = 150 \text{ MeV}$)
- But why would these diquark-antidiquark states behave like resonances at all?

For one thing,

- Diquark-antidiquark pairs create their own bound-state spectroscopy [L. Maiani *et al.*, PRD **71** (2005) 014028]

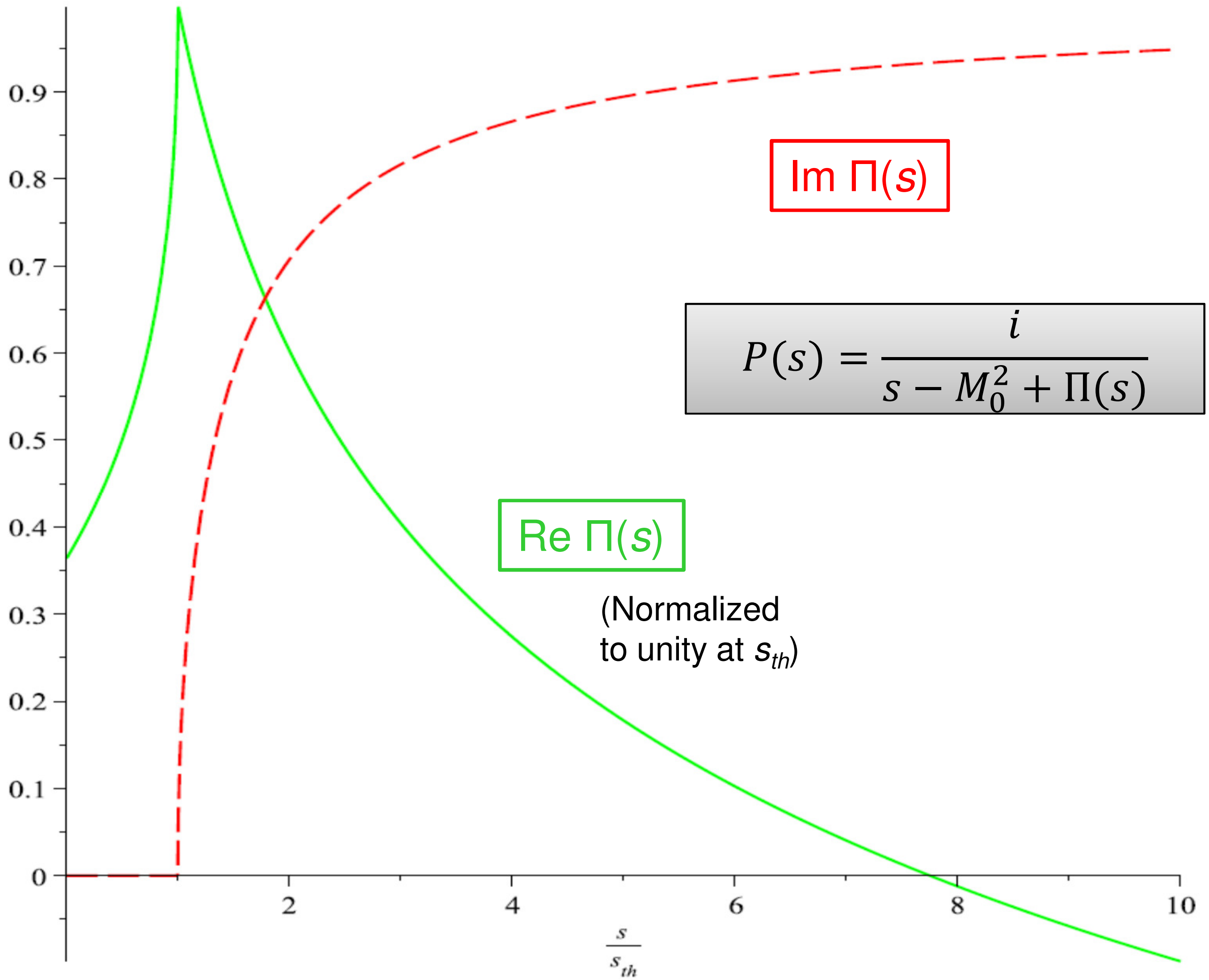
- Original 2005 version predicts states with quantum numbers and multiplicities not found to exist, but a new version of the model [L. Maiani *et al.*, PRD **89** (2014) 114010] appears to be much more successful

  - *e.g.*, *Z*(4475) is radial excitation of *Z*(3900); *Y* states are *L*=1 color flux tube excitations

And furthermore,

- The presence of nearby hadronic thresholds can attract nearby diquark resonances: *Cusp effect*

The Cusp



$$P(s) = \frac{i}{s - M_0^2 + \Pi(s)}$$

Example cusp effects

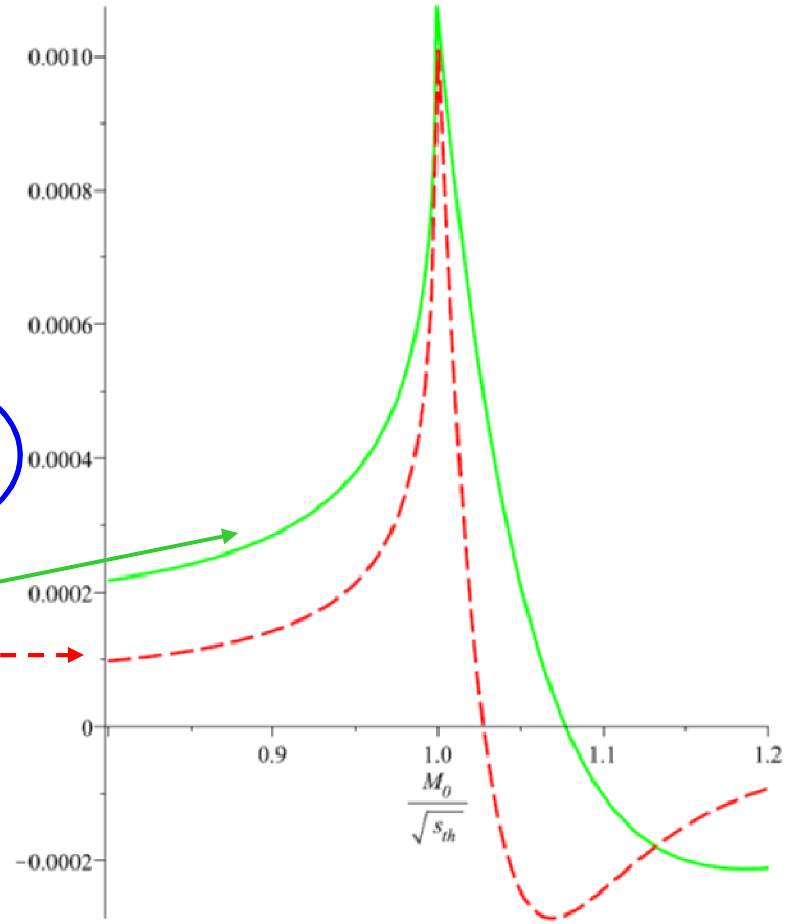
S. Blitz & RFL, arXiv:1503.04802

(accepted to appear in PRD)

M_0: Bare resonant pole mass
S_{th}: Threshold s value [here (3.872 GeV)^2]
M_{pole}: Shifted pole mass

Relative size of pole shift (about 0.12% near S_{th}, or 5 MeV)

$$\frac{M_{pole} - M_0}{\sqrt{s_{th}}}$$



At the charm scale, a cusp from an opening diquark pair threshold is more effective than one from a meson pair!

How closely can cusps attract thresholds?

- Consider the *X*(3872), with $\Gamma < 1.2$ MeV
  - Recall $m_{X(3872)} - m_{D^{*0}} - m_{D^0} = -0.11 \pm 0.21$ MeV
  - Also,
$$m_{X(3872)} - m_{J/\psi} - m_{\rho^0_{peak}} = -0.50 \text{ MeV}$$
$$m_{X(3872)} - m_{J/\psi} - m_{\omega_{peak}} = -7.89 \text{ MeV}$$
  - Bugg [J. Phys. G **35** (2008) 075005]:
    X(3872) is far too narrow to be a cusp alone—
    Some sort of resonance must be present
  - Several channels all open up very near 3.872 GeV
  - ➢ All contribute to a big cusp that can drag diquark-antidiquark resonance from perhaps 10's of MeV away to become the *X*(3872)

What determines cusp shapes?

- Mesons: Traditional phenomenological exponential form factor:

$$F_{\rm mes}^2(s) = \exp\left(-\frac{s-s_{th}}{\beta^2}\right),$$

where β is a typical hadronic scale (~0.5-1.0 GeV)

- High-energy (s) processes, or when large-s tails of form factors important (as in dispersion relations): Use ***constituent counting rules***
[Matveev *et al*., Lett. Nuovo Cim. **7**, 719 (1973); Brodsky & Farrar, PRL **31**, 1153 (1973)]

- In hard processes in which constituents are diverted through a finite angle, each virtual propagator redirecting them contributes a factor $1/s$ (or $1/t$)

➢ Form factor $F(s)$ of particle with 4 quark constituents scales as

$$F_{\rm diq}(s) \sim \left(\frac{\alpha_s}{s}\right)^3 \rightarrow F_{\rm diq}(s) = \left(\frac{s_{th}}{s}\right)^3$$

Can the counting rules be used for cross sections as well?

- With *ease*: S. Brodsky and RFL, arXiV:1505.00803
- Exotic states can be produced in threshold regions in e^+e^- (BES, Belle), electroproduction (JLab 12), hadronic beam facilities (P̄ANDA at FAIR, AFTER@LHC) and are best characterized by cross section ratios
- Two examples:

1) $$\frac{\sigma(e^+e^-\to Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\to\mu^+\mu^-)} \propto \frac{1}{s^6} \text{ as } s\to\infty$$

2) $$\frac{\sigma(e^+e^-\to Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\to\Lambda_c(cud)+\bar{\Lambda}_c(\bar{c}\,\bar{u}\bar{d}))} \to const \text{ as } s\to\infty$$

  - Ratio numerically smaller if Z_c behaves like weakly-bound dimeson molecule instead of diquark-antidiquark bound state due to weaker meson color van der Waals forces

Conclusions

- For the 20 or so exotic states (*X*, *Y*, *Z*) that have thus far been observed, all of the popular physical pictures for describing their structure seem to suffer some imperfection
- We propose an entirely new dynamical picture based on a diquark-antidiquark pair rapidly separating until forced to hadronize due to confinement
- Then several problems, *e.g.*, the widths of *X*, *Y*, *Z* states and their couplings to hadrons, become much less mysterious
- The latest work exploits a cusp effect from diquark pairs, and constituent counting rules. But much more remains to be explored!