All-Heavy Tetraquarks: The Dynamical Diquark Model and Other Approaches

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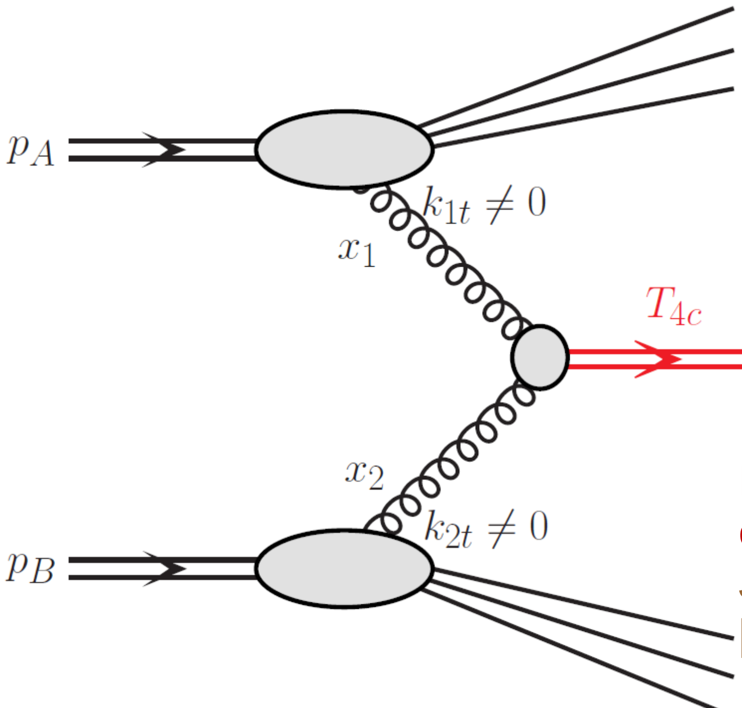
Although This Talk Is About Heavy Tetraquarks in General…

- In this talk, we focus on developments to study interesting structure observed by LHCb in the di-J/ψ channel [Sci. Bull. **65**, 1983 (2020)]
- After a false alarm of $b\bar{b}b\bar{b}$ state ($\rightarrow \mu^+\mu^-\mu^+\mu^-$) at 18.4 GeV using CMS data [http://meetings.aps.org/Meeting/APR18/Session/U09.6],
- LHCb [JHEP **10**, 086 (2018)] studied $\Upsilon(1S)\,\mu^+\mu^-$ and found no significant structures
- No structures reported yet in $b\bar{b}c\bar{c}$, $b\bar{c}b\bar{c}$, *etc*.

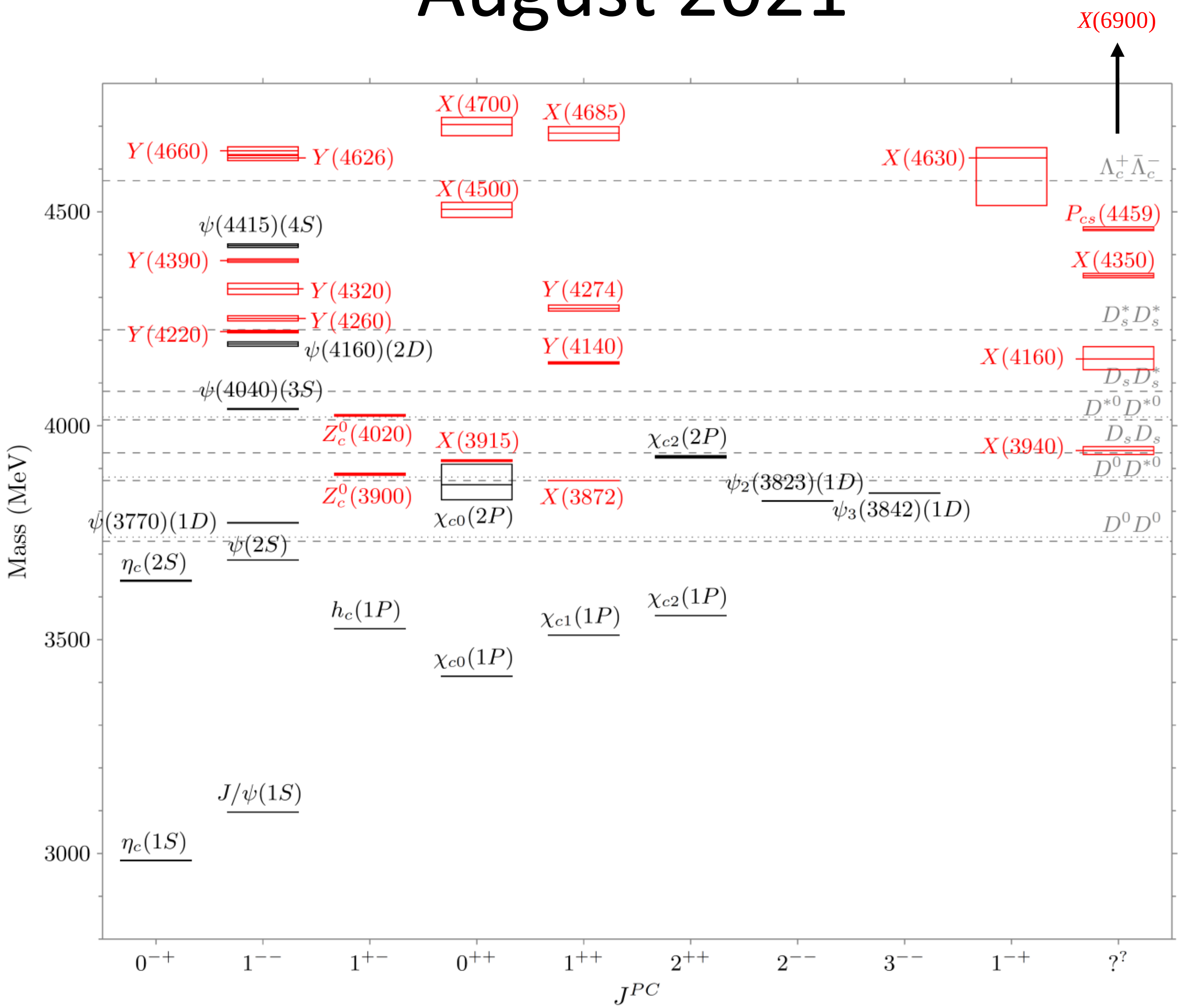
How All-Heavy Tetraquarks Are Made

- Mostly gluon-gluon fusion
  (but both single- and double-parton scattering important for nonresonant $Q\bar{Q}Q\bar{Q}$ production)
  [R. Maciuła, W. Schäfer, A. Szczurek, Phys. Lett. B **812**, 136010 (2021)]

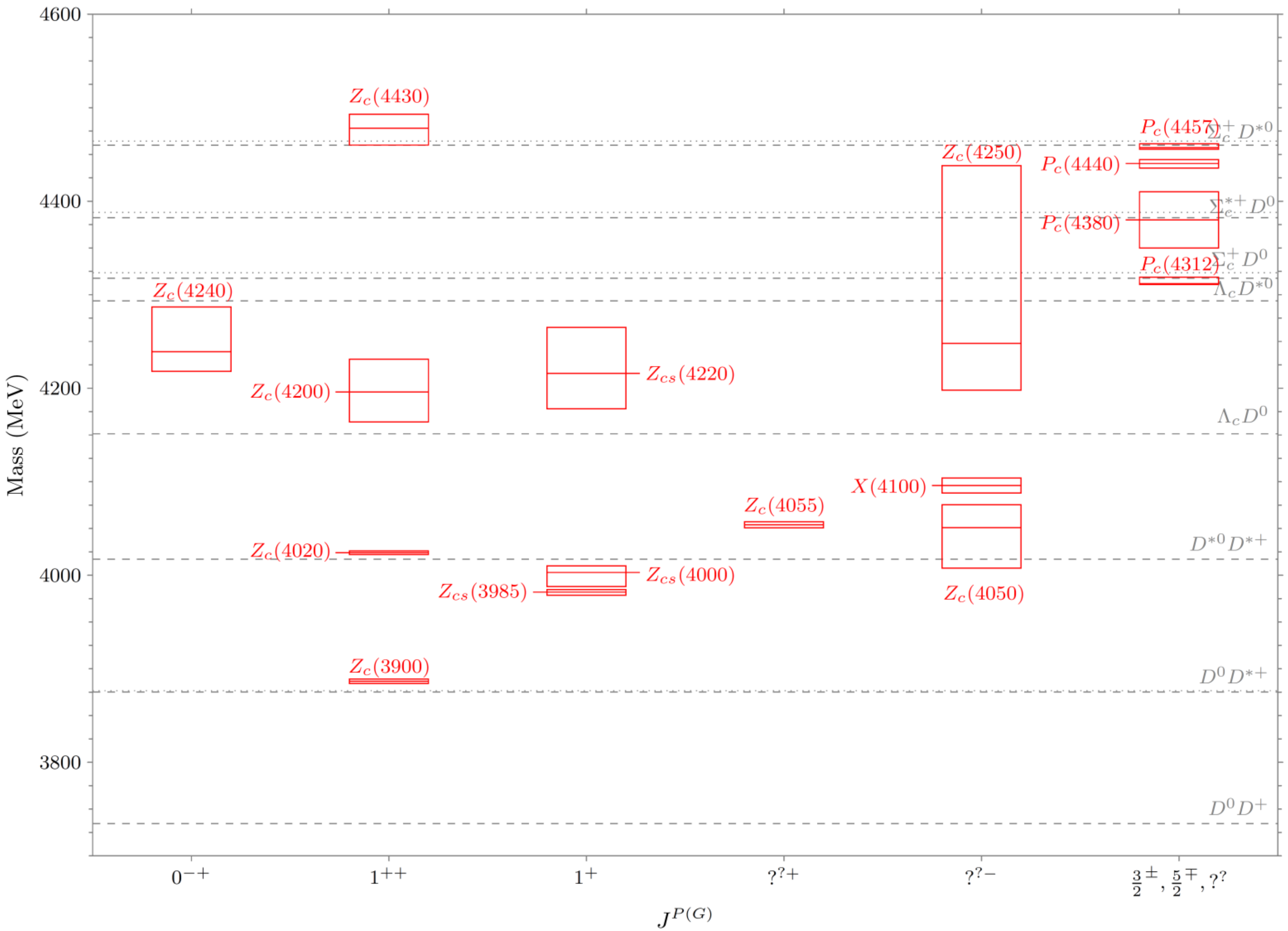


Production in heavy-ion collisions also possible:
J. Zhao, S. Shi, P. Zhuang [2009.10319]

Neutral charmoniumlike sector, August 2021



Charged charmoniumlike sector, August 2021

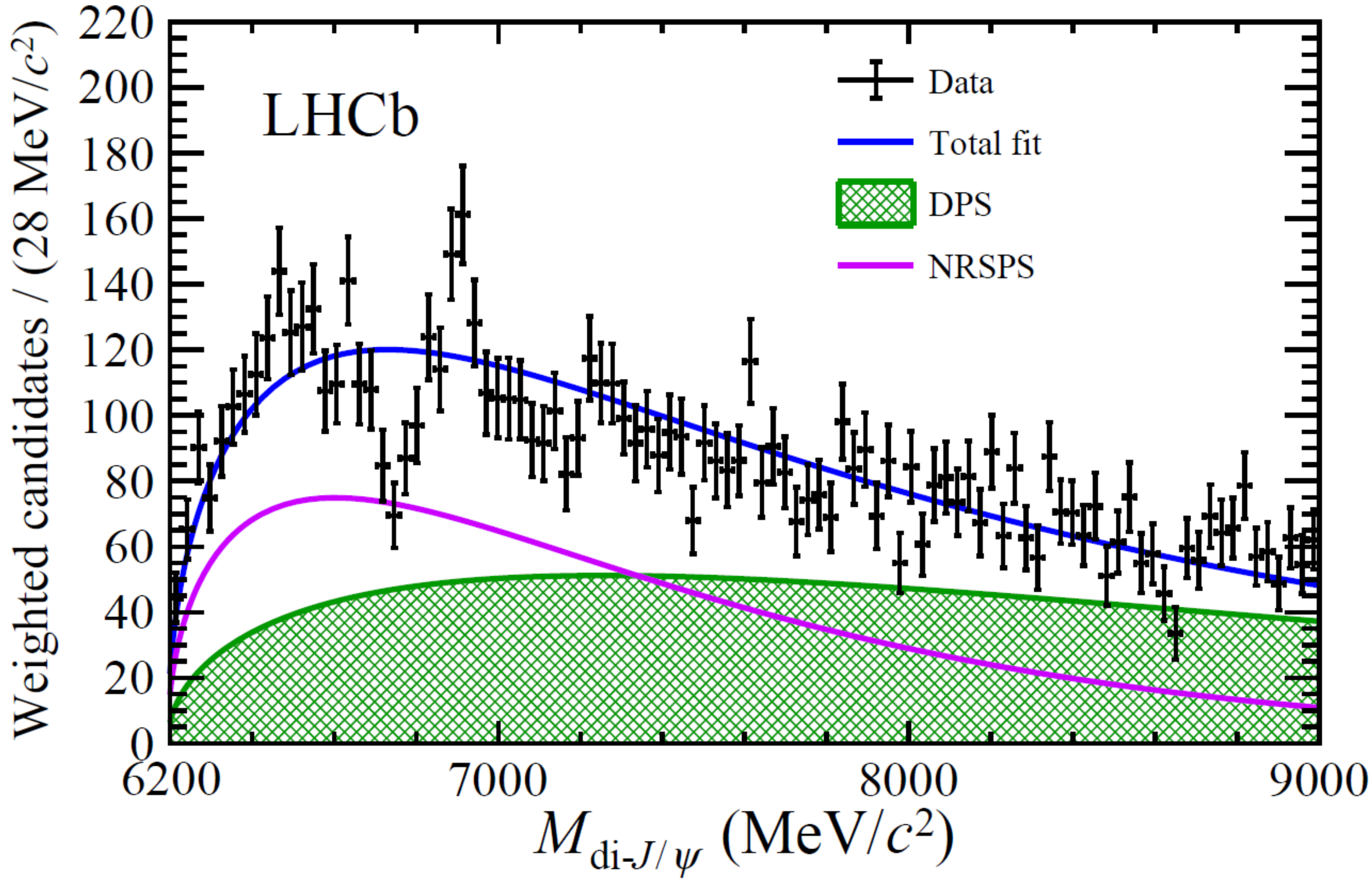


The heavy exotics scorecard: August 2021

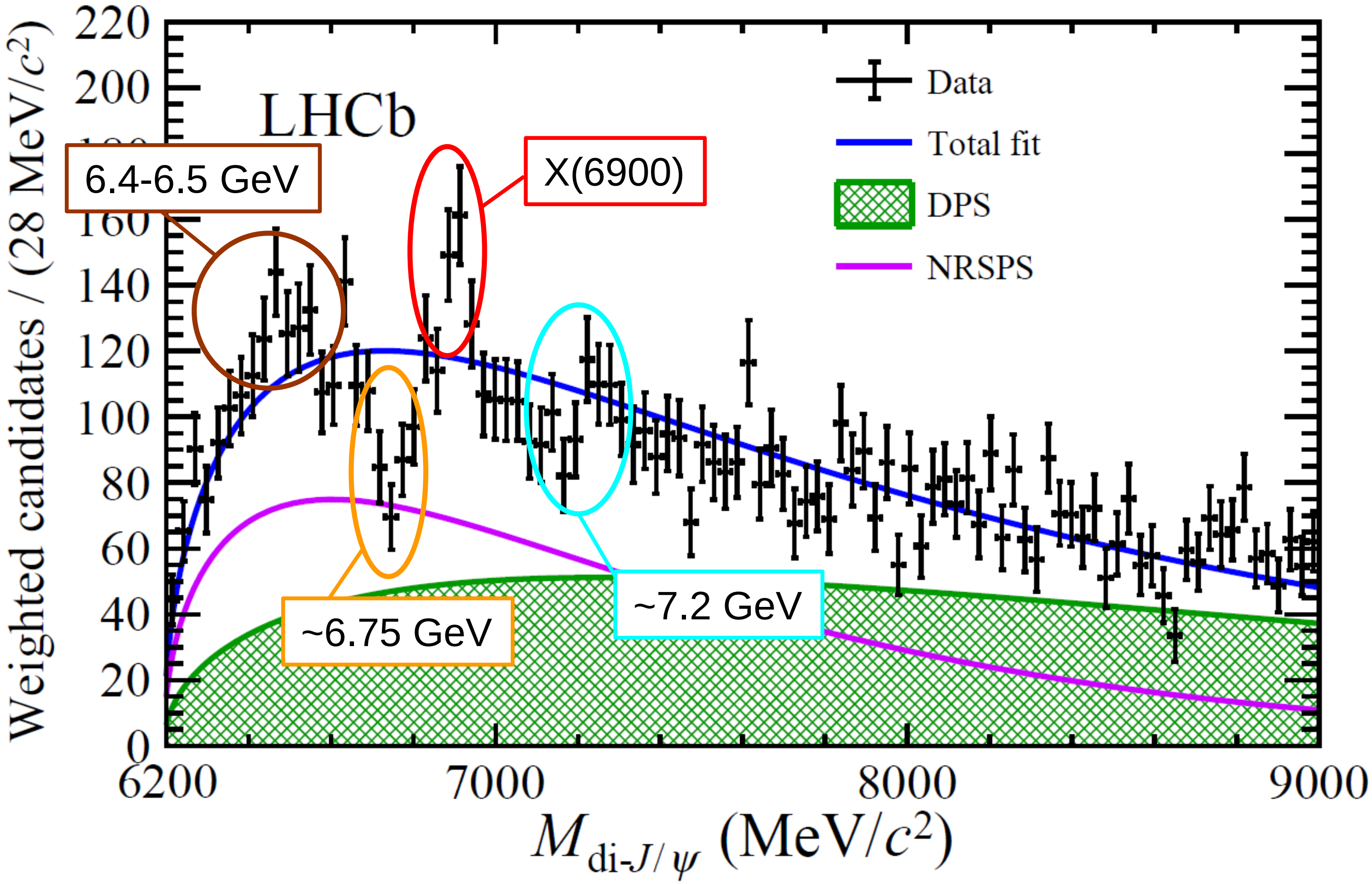
- **51** observed exotics
  - 41 in charmoniumlike sector (incl. pentaquarks)
  - 1 decaying to di-J/ψ
  - 5 in the (much less explored) bottomonium sector
  - 1 with a single *b* quark (and an *s*, a *u*, and a *d*)
  - 2 with a single *c* quark (and an *s*, a *u*, and a *d*)
  - 1 with two *c* quarks
- **15** established [PDG] (& none of other 36 disproved)
- My naïve count estimates over 100 more exotics are waiting to be discovered

The Plot That Launched 100 Theory Papers

LHCb Collaboration, Sci. Bull. **65**, 1983 (2020) [2006.16957]



The Eye Immediately Notices…



The Most Important Apparent Features

- $X(6900)$, the only obvious peak, lies about $700\ \mathrm{MeV}$ above $2m_{J/\psi}$ but is likely not wider than the ρ ($\lesssim 200\ \mathrm{MeV}$, & perhaps much narrower)
- A $c\bar{c}c\bar{c}$ state, if a *traditional* di-meson molecule, would be bound through exchanging conventional charmonium—which for expected $\leq O(10\ \mathrm{MeV})$ molecular binding energies is ***very far*** off mass shell
- Typical $c\bar{c}$ mean charge radii from potential models:

  $1S$: $0.35\ \mathrm{fm}$ $1P$: $0.63\ \mathrm{fm}$ $2S$: $0.78\ \mathrm{fm}$

  $\Longrightarrow J/\psi$ exchange in particular would be very short-ranged
- So what about *nontraditional* di-meson molecules?
  - Pomeron (multi-gluon) exchanges [C. Gong *et al.*, 2011.11374]
  - Soft gluons hadronizing into light-meson exchanges (π, K) [X.-K. Dong *et al.*, 2107.03946]

The Most Important Apparent Features

- J^{PC} for $J/\psi(1^{--})$ identical boson pair restricted: $C = +$ and:
  $0^{++}, 2^{++}$ (S wave), $0^{-+}, 1^{-+}, 2^{-+}$ (P wave)
- J^{PC} for system made of cc and $\bar{c}\bar{c}$ identical fermion pairs also restricted:
  In their S wave: [color-$\bar{\mathbf{3}}$, spin-1] or [color-$\mathbf{6}$, spin-0]

History of $c\bar{c}c\bar{c}$ Theory Studies

- 11 November 1974: Discovery of J/ψ
  [J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974);
  J. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974)]
- First di-J/ψ theory paper: Y. Iwasaki, Prog. Theor. Phys. **54**, 492 (1975) (**!**)
- **5** theory papers in the **1980**s, **1** in the **1990**s, **3** in the **2000**s
  ("All the states are unbounded and consequently rather uninteresting")
- **2010**: First physics from LHC. Very soon afterwards pointed out that:
  Lots of $gg \longrightarrow J/\psi$-$J/\psi$ being produced, and can be reconstructed by LHCb:
  [A. Berezhnoy, A. Likhoded, A. Luchinsky, and A. Novoselov,
  Phys. Rev. D **84**, 094023 (2011); **86**, 034004 (2012)]
- And then…nothing else until **2016**,
  and **12** papers from then until the middle of **2020**

History of $c\bar{c}c\bar{c}$ Theory Studies

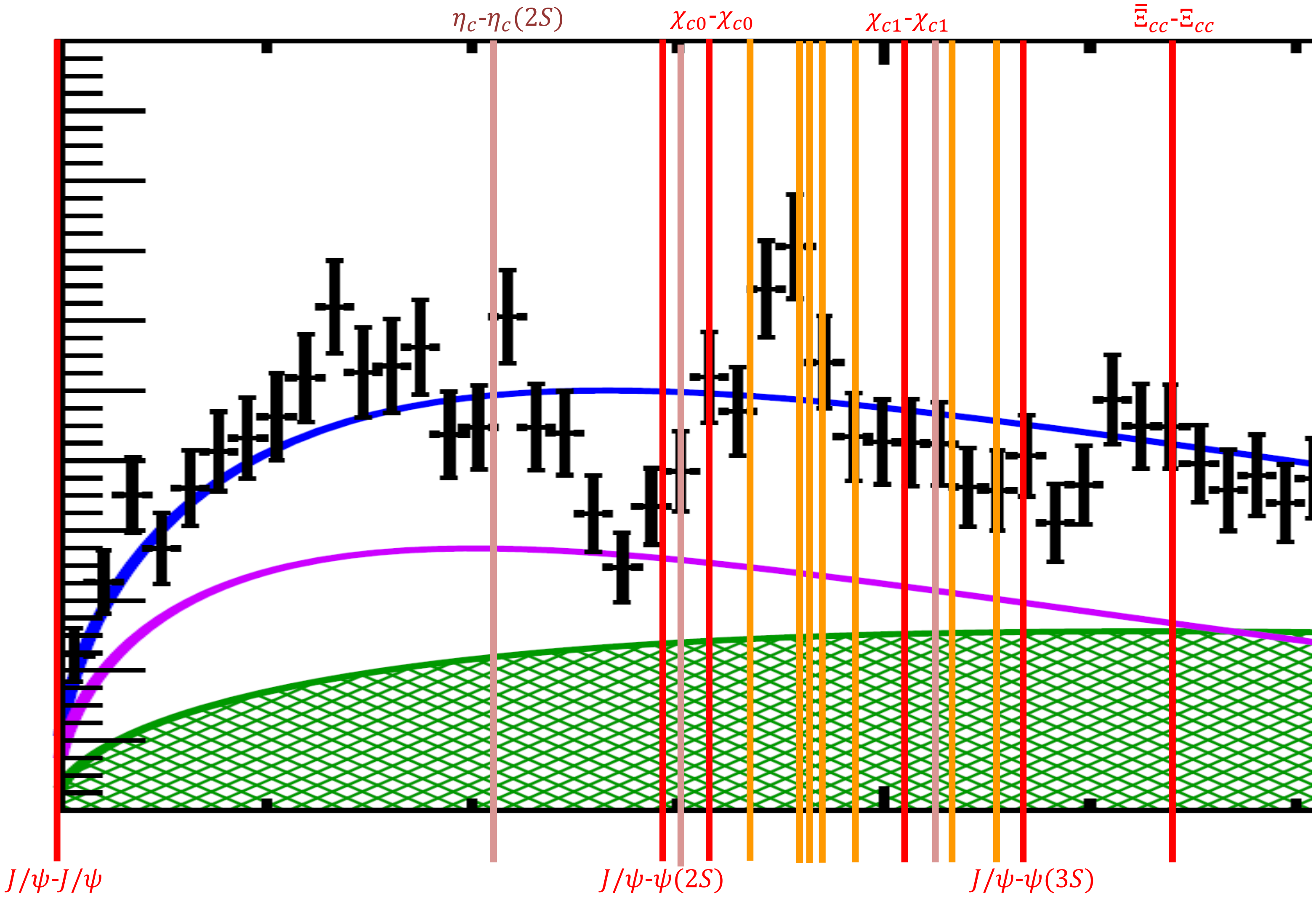
- **16 June 2020**: CERN-LHC Seminar, Liupan An (LHCb Collaboration), "Latest Results on Exotic Hadrons at LHCb"
- Then **8** more theory papers just in the following two weeks
- **30 June 2020**: Posting of arXiv:2006.16957, R. Aaij *et al.* (LHCb Collaboration), Sci. Bull. **65**, 1983 (2020), "Observation of Structure in the J/ψ-pair Mass Spectrum"
- Since then: **53** theory papers posted on arXiv discussing $c\bar{c}c\bar{c}$ structure (as of 21 August 2021)

What Has Been Tried?

(with apologies to the many authors whose names are not listed here!)

- String junction model
- Quark model, chromomagnetic interactions
- Quark potential model
- Chiral quark model
- Diquark model
- Effective theory with light-meson exchanges
- Threshold effects with coupled charmonium channels
- Threshold effects plus compact tetraquark
- QCD sum rules
- Lattice
- Regge phenomenology, including Pomeron exchange
- Holography
- Spin-chain (Bethe Ansatz) algebraic methods
- $X(6900)$ might even be a Higgs-like boson!

The Relevant Charmonium Thresholds



Any Solid Conclusions/Consensus?

- $\boldsymbol{X(6900)}$ seems to be genuine resonance, even within the presence of multiple threshold effects that might explain other $c\bar{c}c\bar{c}$ structure:
  [*e.g.,* X.-K. Dong *et al*., Phys. Rev. Lett. **126**, 132001 (2021);
  Z.-H. Guo and J.A. Oller, Phys. Rev. D **103**, 034024 (2020)]
- Others [*e.g.*, J.-Z. Wang, X. Liu, and T. Matsuki, Phys. Rev. D **103**, L071503 (2021)] suggest $X(6900)$ itself might be generated by χ_{c0}-χ_{c1} threshold
- Virtually all models predict ground-state $1S$ resonances to be much lower than $X(6900)$, typically from 6.0-6.4 GeV (ever since Iwasaki [1975])
- So then, is $X(6900)$ ...
  a $1P$ state (*e.g.*, M.-S. Liu *et al*., 2006.11952)
  or a $2S$ state [*e.g.*, J.F. Giron and RFL, Phys. Rev. D **102**, 074003 (2020);
  M. Karliner and J.L. Rosner, Phys. Rev. D **102**, 114039 (2020)]?
  (Measuring parity will answer this question)

Any Solid Conclusions/Consensus?

- **The broad structure around $\mathbf{6400\text{-}6500\ MeV}$** is about the upper limit of where models predict ground-states ($1S$) to occur
[*e.g.,* B.-C. Yang, L. Tang, and C.-F. Qiao, Eur. Phys. J. C **81**, 324 (2021);
Z. Zhao *et al*., Phys. Rev. D **103**, 116207 (2021)]
- LHCb's Model I [Sci. Bull. **65**, 1983 (2020)]:
Broad structure is a superposition of (at least) two resonances
- And what do we mean by "$1S$", which suggests a 2-body description?
Since molecules are problematic for $c\bar{c}c\bar{c}$, and no good thresholds are in the $6400\text{-}6500$ MeV range, then diquark $(cc)_{\bar{\mathbf{3}}}(\bar{c}\bar{c})_{\mathbf{3}}$ structure is natural
- But not everyone agrees!
C. Deng, H. Chen, J. Ping, Phys. Rev. D **103,** 014001 (2021) note that
6-$\bar{6}$ attraction stronger than $\bar{3}$-3 (despite quark repulsion in a 6 diquark!),
and find that the ground states mix both configurations,
but that $\bar{3}$-3 dominates excited states

Any Solid Conclusions/Consensus?

- **The dip around $\mathbf{6750\ MeV}$** suggests destructive interference with $X(6900)$
- LHCb's Model II [Sci. Bull. **65**, 1983 (2020)]:
  Interference between broad $6400\text{-}6500\ \mathrm{MeV}$ structure and a resonance
- χ_{c0}-χ_{c0} threshold effect?
  [*e.g.*, M. Karliner and J.L. Rosner, Phys. Rev. D **102**, 114039 (2020)]?
- If $X(6900)$ is $2S$ ($P = +$),
  then $6750\ \mathrm{MeV}$ is where $1P$ states ($P = -$) expected
  [*e.g.*, Giron & RFL]
  But of course $P = +$ and $P = -$ configurations do not have interference with each other
  Again, determining the parity of these events is crucial

Any Solid Conclusions/Consensus?

- LHCb [Sci. Bull. **65**, 1983 (2020)] notes **structure near $\mathbf{7200\ MeV}$**
- Open-flavor decays of $c\bar{c}c\bar{c}$ first allowed at $\bar{\Xi}_{cc}$-Ξ_{cc} $(ccu)(\bar{c}\bar{c}\bar{u})$ threshold, $7242.4(1.0)$ MeV
- Likely no observably narrow $c\bar{c}c\bar{c}$ structures above this point
- Giron & RFL:
  "where the color flux tube breaks in a diquark model"
- J. Sonnenschein and D. Weissman, Eur. Phys. J. C **81**, 1 (2021):
  "where new string junctions become possible in a holographic model"

How Many States?

- If both $\bar{3}$ and 6 diquarks both allowed, one finds a *lot* of states [M.A. Bedolla, J. Ferretti, C. Roberts, and E. Santopinto, Eur. Phys. J. C **80**, 1004 (2020)]:
  17 with $C = +$ & $J \leq 2$ predicted below $\bar{\Xi}_{cc}$-Ξ_{cc} threshold (see next slide)
- Adopt minimal ansatz, of $\bar{3}$ diquarks only: about half as many states
  Take spin couplings to be large only within diquarks
  [Defining properties of **dynamical diquark model**: Giron & RFL]:
  All S wave multiplets: **3** degenerate states 0^{++}, 2^{++} (and 1^{+-})
  In P wave multiplets: **7** states (**3** with $C = +$),
  equal-spacing mass rule
  if tensor couplings negligible

J^{PC}	ΔM_{LS}	ΔM_T
1^{--}	$-3V_{LS}$	$-\frac{28}{5}V_T$
0^{-+}	$-2V_{LS}$	$-8V_T$
1^{-+}	$-V_{LS}$	$+4V_T$
2^{--}	$-V_{LS}$	$+\frac{28}{5}V_T$
1^{--}	$0V_{LS}$	$0V_T$
2^{-+}	$+V_{LS}$	$-\frac{4}{5}V_T$
3^{--}	$+2V_{LS}$	$-\frac{8}{5}V_T$

$cc\bar{c}\bar{c}$		
J^{PC}	$N[(S_D, S_{\bar{D}})S, L]J$	E^{th} [MeV]
0^{++}	$1[(1,1)0,0]0$	5883
0^{++}	$2[(1,1)0,0]0$	6573
0^{++}	$1[(1,1)2,2]0$	6835
0^{++}	$3[(1,1)0,0]0$	6948
0^{++}	$2[(1,1)2,2]0$	7133
0^{++}	$3[(1,1)2,2]0$	7387
1^{+-}	$1[(1,1)1,0]1$	6120
1^{+-}	$2[(1,1)1,0]1$	6669
1^{+-}	$1[(1,1)1,2]1$	6829
1^{+-}	$3[(1,1)1,0]1$	7016
1^{+-}	$2[(1,1)1,2]1$	7128
1^{+-}	$3[(1,1)1,2]1$	7382
1^{--}	$1[(1,1)0,1]1$	6580
1^{--}	$1[(1,1)2,1]1$	6584
1^{--}	$2[(1,1)0,1]1$	6940
1^{--}	$2[(1,1)2,1]1$	6943
1^{--}	$3[(1,1)0,1]1$	7226
1^{--}	$3[(1,1)2,1]1$	7229
0^{-+}	$1[(1,1)1,1]0$	6596
0^{-+}	$2[(1,1)1,1]0$	6953
0^{-+}	$3[(1,1)1,1]0$	7236
1^{++}	$1[(1,1)2,2]1$	6832
1^{++}	$2[(1,1)2,2]1$	7130
1^{++}	$3[(1,1)2,2]1$	7384
2^{++}	$1[(1,1)2,0]2$	6246
2^{++}	$1[(1,1)2,2]2$	6827
2^{++}	$1[(1,1)0,2]2$	6827
2^{++}	$2[(1,1)2,0]2$	6739
2^{++}	$3[(1,1)2,0]2$	7071
2^{++}	$2[(1,1)2,2]2$	7125
2^{++}	$2[(1,1)0,2]2$	7126
2^{++}	$3[(1,1)2,2]2$	7380
2^{++}	$3[(1,1)0,2]2$	7380

Some Parting Thoughts

- Desperately need J^P information to disentangle spectrum
- An excellent suggestion: Look at J/ψ-$\psi(2S)$ spectrum
  [*e.g.*, J.-M. Richard, Sci. Bull. **65**, 1954 (2020);
  Q.-F. Cao *et al.*, Chin. Phys. C **45**, 093113 (2021)], even though its threshold is 700 MeV higher, and $\psi(2S)$ production is lower than that of J/ψ
  Also note that BESIII sees different Y states via J/ψ or $\psi(2S)$ decays
- gg producing J/ψ is $C = +$; is there much ggg ($C = -$) production?
  Could find 1^{+-} resonance via J/ψ-η_c, although η_c harder to reconstruct
  [but note B.R.($\eta_c \to p\bar{p}$) = 1.45×10^{-3}]
  Alternately, J/ψ-χ_{cJ} also has $C = -$, but less phase space ($> \ 6512 \text{ MeV}$)
- And don't forget about $c\bar{c}b\bar{b}$ and $b\bar{b}b\bar{b}$ production!
  $c\bar{c}b\bar{b}$ (*e.g.*, J/ψ-Υ) should have more resonances:
  evades identical fermions constraint
  → Important tests of quark flavor universality

Backup slides