Hadron structure, spectroscopy and exotics at EIC and LHCb: the theory perspective

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Ordinary baryons and mesons

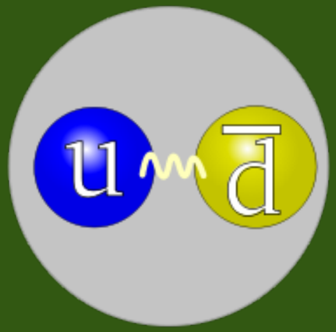
Described in terms of valence quark/antiquark degrees of freedom

QCD: gauge theory of the strong interaction

Its equations cannot be solved in the low-energy (non-perturbative) regime

Calculation of the hadron spectrum requires alternative approaches:

1. **Lattice QCD**
2. **Effective field theories**
3. **Quark models**



Quark (potential) model approach

Effective degree of freedom of constituent (valence) quark is introduced

Quark interaction → effective potential (OGE, GBE …)

OGE potential: Coulomb-like part + linear confining potential + spin forces

$$V(\mathbf{r}_1, \mathbf{r}_2) \approx -\frac{\alpha_\mathrm{S}}{r_{12}} + \beta r_{12} + V(\mathbf{S}_1, \mathbf{S}_2, \mathbf{L}_{12}, \mathbf{r}_{12})$$

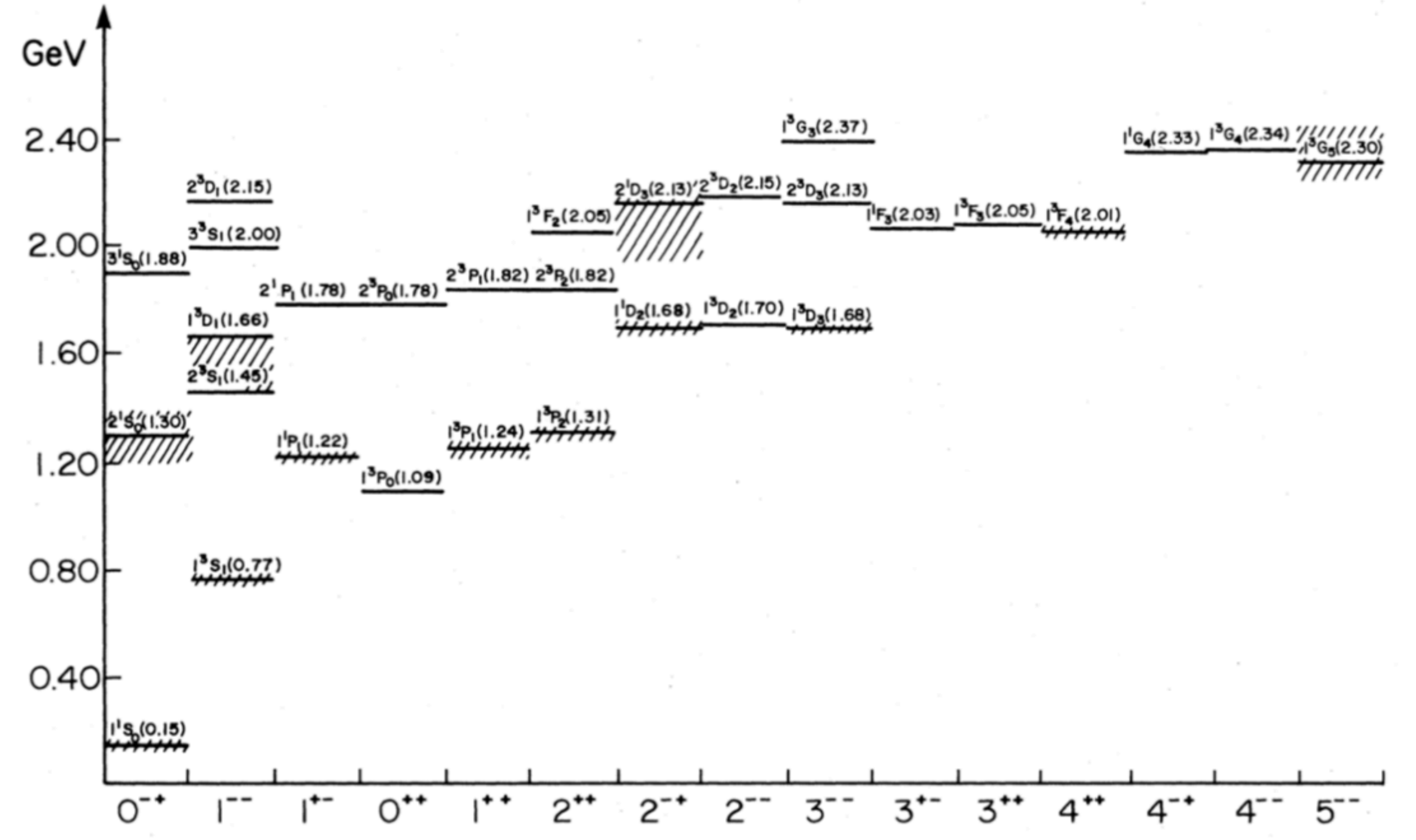
Lower part of baryon and meson spectra are reasonably well reproduced

Some problems

1. baryon missing resonances
2. emergence of exotic degrees of freedom?

Example: spectrum of isovector mesons

S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985)



Exotic hadrons

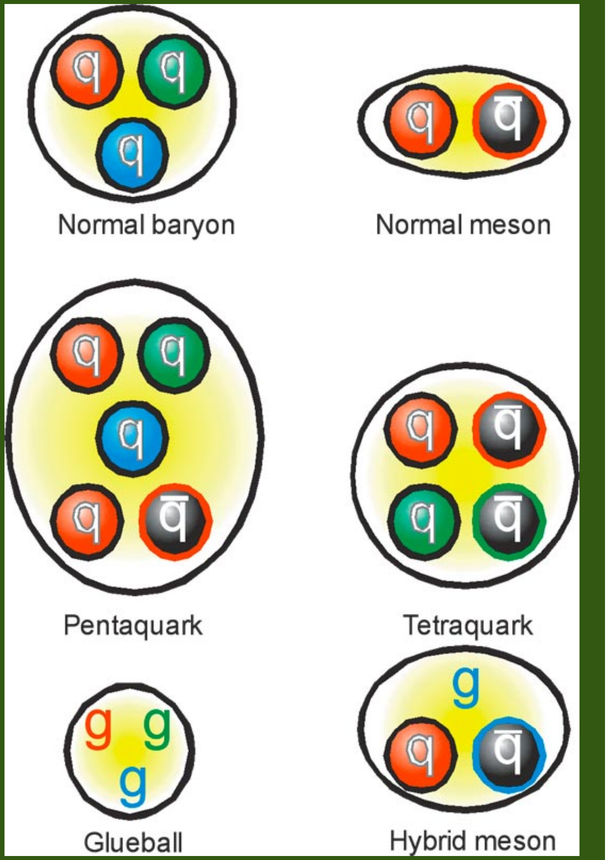
Exotic hadrons: meson and baryon states whose properties cannot be described in terms of q anti-q or qqq degrees of freedom only

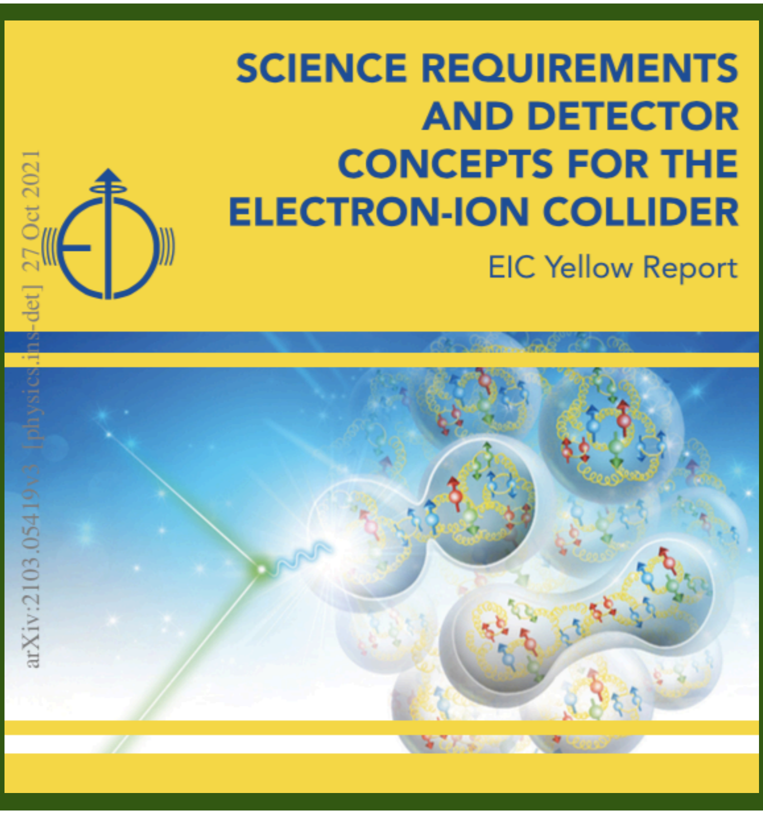
Multiquark states:

1. Baryons made up of more than 3 valence quarks → pentaquarks or exaquarks
2. Mesons made up of more than a quark-antiquark pair → tetraquarks

Hybrid mesons/baryons: hadrons made up of qqq or q anti-q valence quarks plus gluonic degrees of freedom

Glueballs: particles consisting of gluonic degrees of freedom only

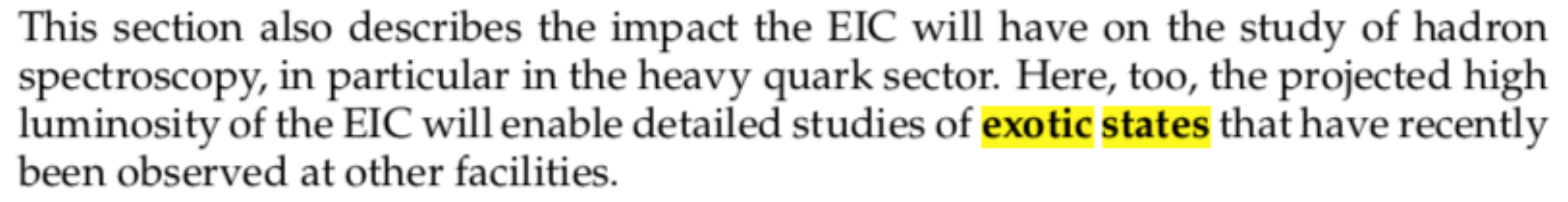




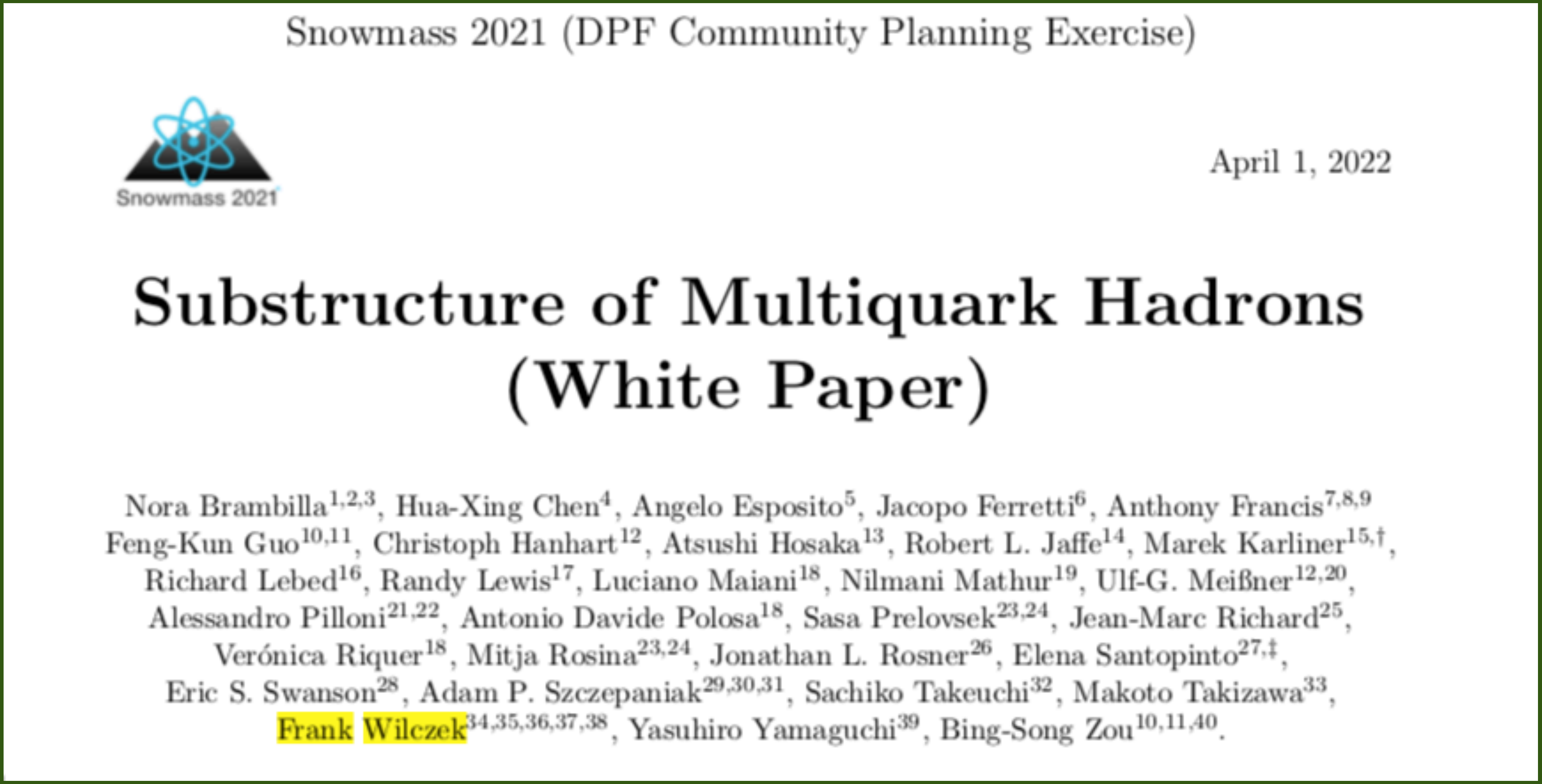
SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

arXiv:2103.05419v3 [physics.ins-det] 27 Oct 2021



This section also describes the impact the EIC will have on the study of hadron spectroscopy, in particular in the heavy quark sector. Here, too, the projected high luminosity of the EIC will enable detailed studies of **exotic states** that have recently been observed at other facilities.



Snowmass 2021 (DPF Community Planning Exercise)

April 1, 2022

Substructure of Multiquark Hadrons (White Paper)

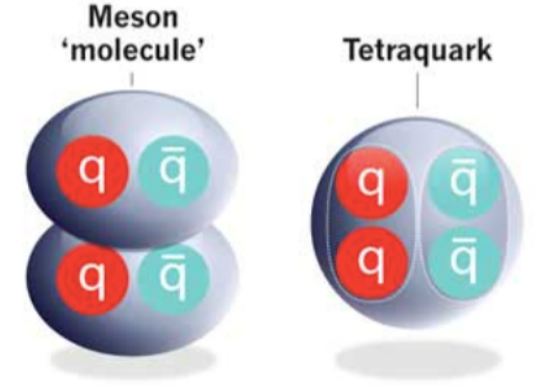
Nora Brambilla[1,2,3], Hua-Xing Chen[4], Angelo Esposito[5], Jacopo Ferretti[6], Anthony Francis[7,8,9]
Feng-Kun Guo[10,11], Christoph Hanhart[12], Atsushi Hosaka[13], Robert L. Jaffe[14], Marek Karliner[15,†],
Richard Lebed[16], Randy Lewis[17], Luciano Maiani[18], Nilmani Mathur[19], Ulf-G. Meißner[12,20],
Alessandro Pilloni[21,22], Antonio Davide Polosa[18], Sasa Prelovsek[23,24], Jean-Marc Richard[25],
Verónica Riquer[18], Mitja Rosina[23,24], Jonathan L. Rosner[26], Elena Santopinto[27,‡],
Eric S. Swanson[28], Adam P. Szczepaniak[29,30,31], Sachiko Takeuchi[32], Makoto Takizawa[33],
Frank Wilczek[34,35,36,37,38], Yasuhiro Yamaguchi[39], Bing-Song Zou[10,11,40].

Exotic meson candidates (hidden-charm sector)

Tetraquarks: bound states of four valence quarks/ antiquarks [R. L. Jaffe, Phys. Rev. D 15, 267 (1977)]

Combine 4 quarks in terms of 2-quark substructures:

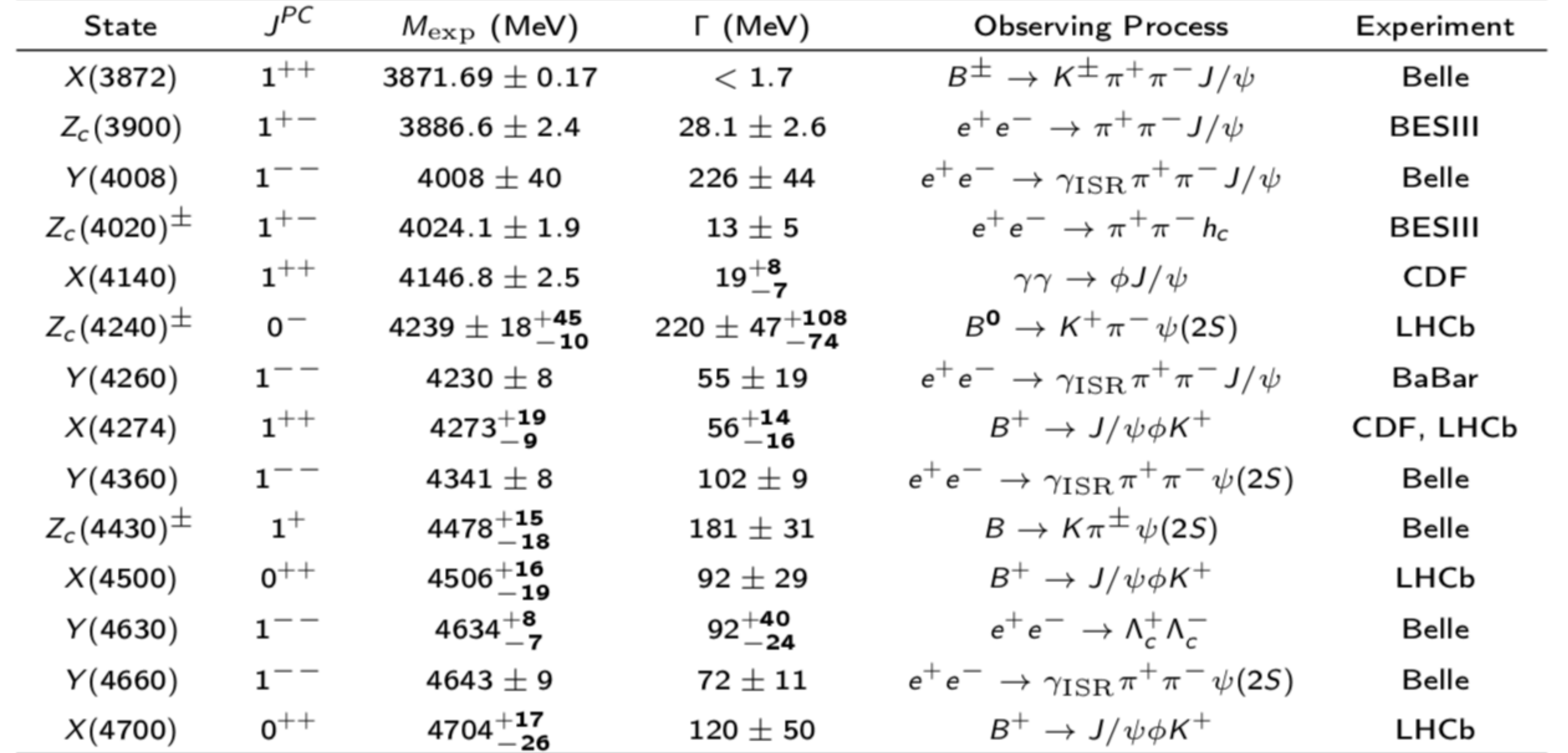
1. **Compact tetraquark model**
2. **Meson-meson molecular model**
3. **Hadro-charmonium model**



Possible mixing between (*q* anti-*q*) and (*q* anti-*q* *q* anti-*q*) components: Unquenched quark model (UQM)

Several candidates in the hidden-charm (*q* anti-*q* *c* anti-*c*) sector

Exotic meson candidates (hidden-charm sector)



State	J^{PC}	$M_{\rm exp}$ (MeV)	Γ (MeV)	Observing Process	Experiment
$X(3872)$	1^{++}	3871.69 ± 0.17	< 1.7	$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$	Belle
$Z_c(3900)$	1^{+-}	3886.6 ± 2.4	28.1 ± 2.6	$e^{+}e^{-} \to \pi^{+}\pi^{-}J/\psi$	BESIII
$Y(4008)$	1^{--}	4008 ± 40	226 ± 44	$e^{+}e^{-} \to \gamma_{\rm ISR}\pi^{+}\pi^{-}J/\psi$	Belle
$Z_c(4020)^{\pm}$	1^{+-}	4024.1 ± 1.9	13 ± 5	$e^{+}e^{-} \to \pi^{+}\pi^{-}h_c$	BESIII
$X(4140)$	1^{++}	4146.8 ± 2.5	19^{+8}_{-7}	$\gamma\gamma \to \phi J/\psi$	CDF
$Z_c(4240)^{\pm}$	0^{-}	$4239 \pm 18^{+45}_{-10}$	$220 \pm 47^{+108}_{-74}$	$B^{0} \to K^{+}\pi^{-}\psi(2S)$	LHCb
$Y(4260)$	1^{--}	4230 ± 8	55 ± 19	$e^{+}e^{-} \to \gamma_{\rm ISR}\pi^{+}\pi^{-}J/\psi$	BaBar
$X(4274)$	1^{++}	4273^{+19}_{-9}	56^{+14}_{-16}	$B^{+} \to J/\psi\phi K^{+}$	CDF, LHCb
$Y(4360)$	1^{--}	4341 ± 8	102 ± 9	$e^{+}e^{-} \to \gamma_{\rm ISR}\pi^{+}\pi^{-}\psi(2S)$	Belle
$Z_c(4430)^{\pm}$	1^{+}	4478^{+15}_{-18}	181 ± 31	$B \to K\pi^{\pm}\psi(2S)$	Belle
$X(4500)$	0^{++}	4506^{+16}_{-19}	92 ± 29	$B^{+} \to J/\psi\phi K^{+}$	LHCb
$Y(4630)$	1^{--}	4634^{+8}_{-7}	92^{+40}_{-24}	$e^{+}e^{-} \to \Lambda_c^{+}\Lambda_c^{-}$	Belle
$Y(4660)$	1^{--}	4643 ± 9	72 ± 11	$e^{+}e^{-} \to \gamma_{\rm ISR}\pi^{+}\pi^{-}\psi(2S)$	Belle
$X(4700)$	0^{++}	4704^{+17}_{-26}	120 ± 50	$B^{+} \to J/\psi\phi K^{+}$	LHCb

The *X(3872)* [also known as $\chi_{c1}(3872)$]

Discovered by Belle in *B* meson decays (2003).
$J^{PC} = 1^{++}$ quantum numbers; narrow width (< 1 MeV)

Mass problem

Experimental mass is 3871.68 ± 0.17 MeV [PDG]
Incompatible with QM predictions → $\mathcal{O}$(3.95 GeV)
***X(3872)* is also very close to *D* bar-*D** threshold**

X(3872) is thus not a (pure) charmonium state

Several interpretations

1. ***D* bar-*D** meson-meson molecule**
2. **Compact tetraquark**
3. **(*c* anti-*c*) core plus 4-quark components (*c* anti-*c* *u* anti-*u* ± *c* anti-*c* *d* anti-*d*) due to threshold effects**

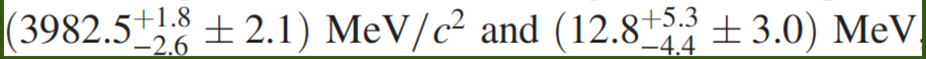
To discriminate among the different interpretations:

1. **Study of the decay modes**
2. **Experimental search for new *c* anti-*c* mesons to complete the $\chi_c(2P)$ multiplet**

Experimental discovery of Z_{cs} tetraquarks

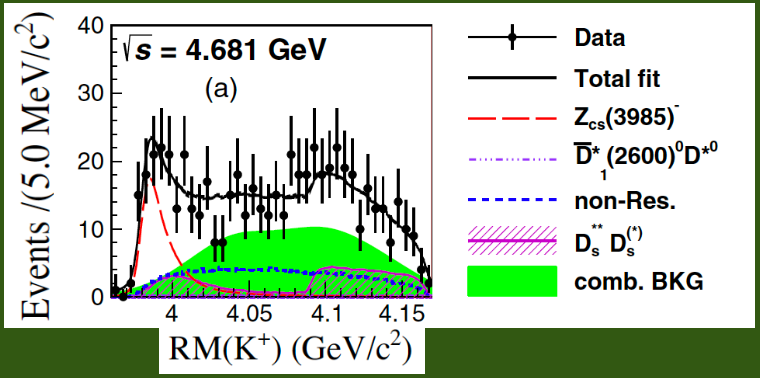
$Z_{cs}(3985)^-$ (c anti-c s anti-u) was discovered by BESIII [Phys. Rev. Lett. 126, 102001 (2021)] (5.3 σ statistical significance)

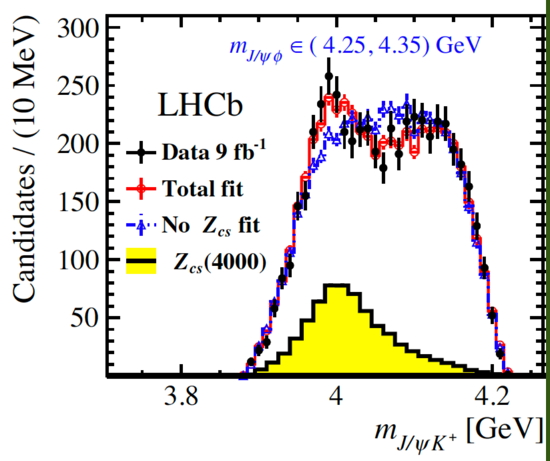
Mass and width are, respectively:


$(3982.5^{+1.8}_{-2.6} \pm 2.1)$ MeV$/c^2$ and $(12.8^{+5.3}_{-4.4} \pm 3.0)$ MeV

$Z_{cs}(4003)^+$ (c anti-c u anti-s) was discovered by LHCb [Phys. Rev. Lett. 127, 082001 (2021)] (15 σ statistical significance)


$4003 \pm 6^{+4}_{-14}$ MeV, a width of $131 \pm 15 \pm 26$ MeV





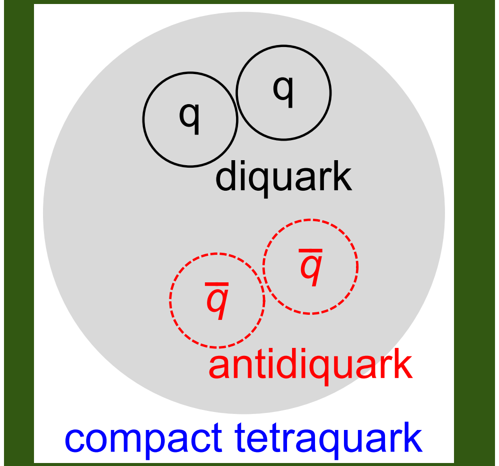
Tetraquarks in the diquark-antidiquark model

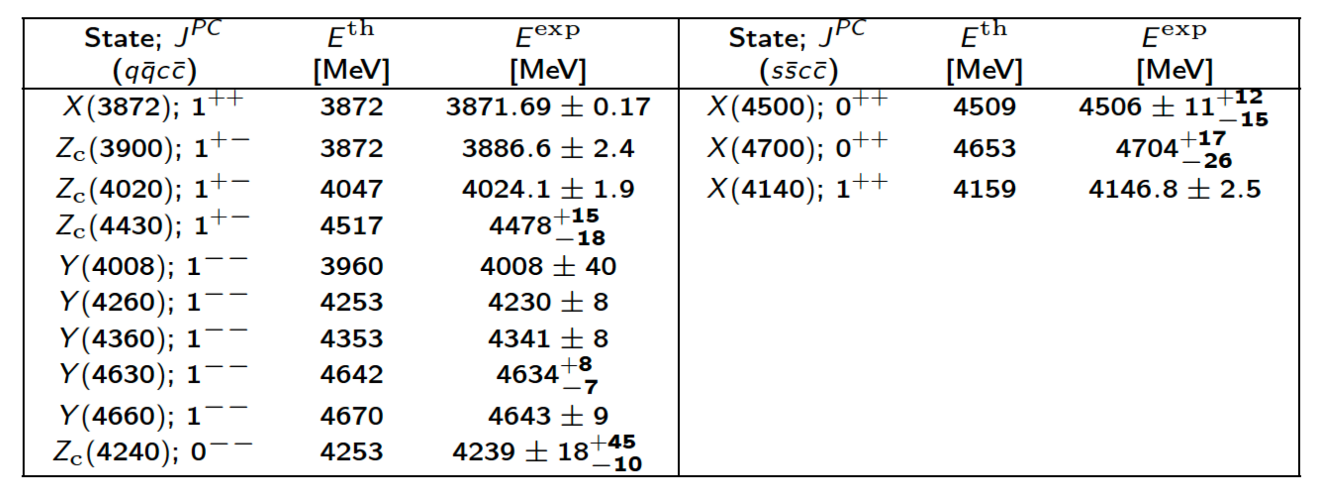
M. Naeem Anwar, J. Ferretti and E. Santopinto, PRD **98**, 094015 (2018)

Spectrum of suspected XYZ hidden-charm tetraquarks calculated in the relativized tetraquark (diquark-antidiquark) model

$$H = E_0 + \sqrt{q^2 + m_D^2} + \sqrt{q^2 + m_{\bar{D}}^2} + V_{conf} + V_{OGE}$$

Hamiltonian contains OGE + confining potential. The parameters are fitted to XYZ tetraquark candidates





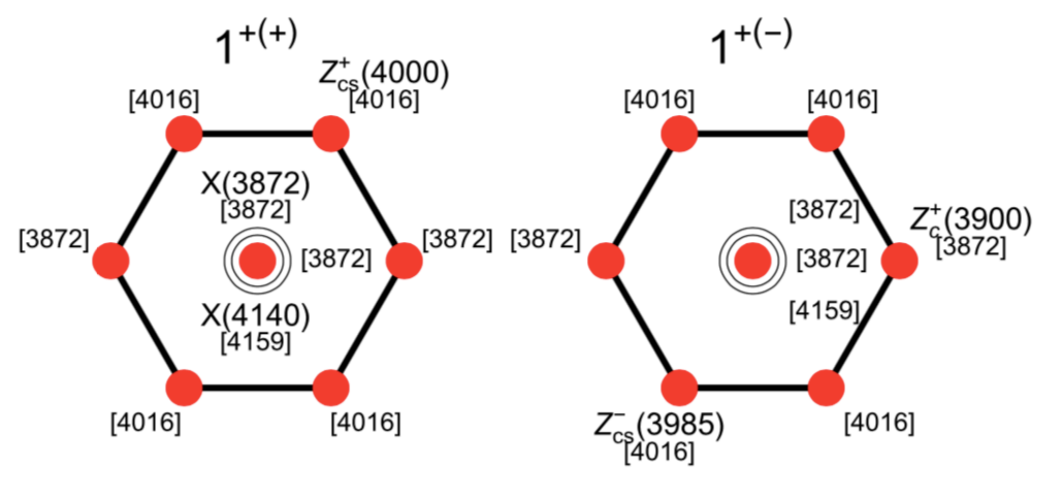
State; J^{PC} ($q\bar{q}c\bar{c}$)	$E^{\rm th}$ [MeV]	$E^{\rm exp}$ [MeV]	State; J^{PC} ($s\bar{s}c\bar{c}$)	$E^{\rm th}$ [MeV]	$E^{\rm exp}$ [MeV]
$X(3872)$; 1^{++}	3872	3871.69 ± 0.17	$X(4500)$; 0^{++}	4509	$4506 \pm 11^{+12}_{-15}$
$Z_c(3900)$; 1^{+-}	3872	3886.6 ± 2.4	$X(4700)$; 0^{++}	4653	4704^{+17}_{-26}
$Z_c(4020)$; 1^{+-}	4047	4024.1 ± 1.9	$X(4140)$; 1^{++}	4159	4146.8 ± 2.5
$Z_c(4430)$; 1^{+-}	4517	4478^{+15}_{-18}			
$Y(4008)$; 1^{--}	3960	4008 ± 40			
$Y(4260)$; 1^{--}	4253	4230 ± 8			
$Y(4360)$; 1^{--}	4353	4341 ± 8			
$Y(4630)$; 1^{--}	4642	4634^{+8}_{-7}			
$Y(4660)$; 1^{--}	4670	4643 ± 9			
$Z_c(4240)$; 0^{--}	4253	$4239 \pm 18^{+45}_{-10}$			

Several XYZ exotics are accommodated

Hidden-charm tetraquarks in the diquark-antidiquark model

M. Naeem Anwar, J. Ferretti and E. Santopinto, PRD **98**, 094015 (2018) [only tetraquarks with null strangeness]
J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020) [tetraquarks with a strangeness content]
J. Ferretti and E. Santopinto, arXiv:2111.08650, accepted on Sci. Bull. [SU(3) flavor tetraquark multiplets]

If the light (q anti-q, with $q = u$, d or s) and heavy (c anti-c) degrees of freedom are somehow decoupled because of their large mass difference, then the tetraquark multiplet structure is provided by the light component (c anti-c being in flavor singlet) → emergence of SU(3)$_f$ multiplets in the hidden-charm sector.



Spectrum of Z_{cs} states predicted almost a year prior to the experimental discovery by using the SU(3) flavor symmetry in JHEP **04**, 119 (2020)

JHEP **04**, 119 (2020) cited by the LHCb and BESIII experimental papers on the Z_{cs} findings

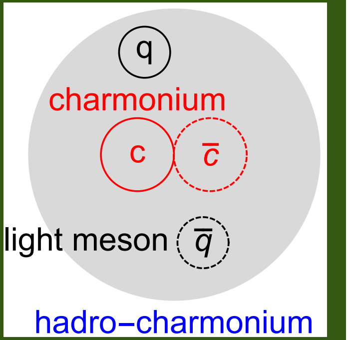
Cited by the PDG 2021 (update)!

Compact tetraquark multiplets. Theoretical predictions (in square brackets) for the masses are compared to the experimental data (when available). **By C = ±1 nonets we refer to the sign of charge conjugation of the neutral-non-strange members.**

Hadro-charmonium (hadro-quarkonium) model

The idea of the hadro-charmonium model was introduced by Dubynskiy and Voloshin in Phys. Lett. B **666**, 344 (2008).

In the hadro-charmonium picture a colorless heavy quarkonium “kernel”, *Q* anti-*Q*, interacts with a larger light quark “shell”, *q* anti-*q* or *qqq*, through Multiple gluon-exchange forces (the QCD analogue of van der Waals forces between molecules)



Tetraquarks and pentaquarks in the hadro-charmonium model

J. Ferretti, Phys. Lett. B 782, 702 (2018)

J. Ferretti, E. Santopinto, M. Naeem Anwar and M.A. Bedolla, Phys. Lett. B **789**, 562 (2019)

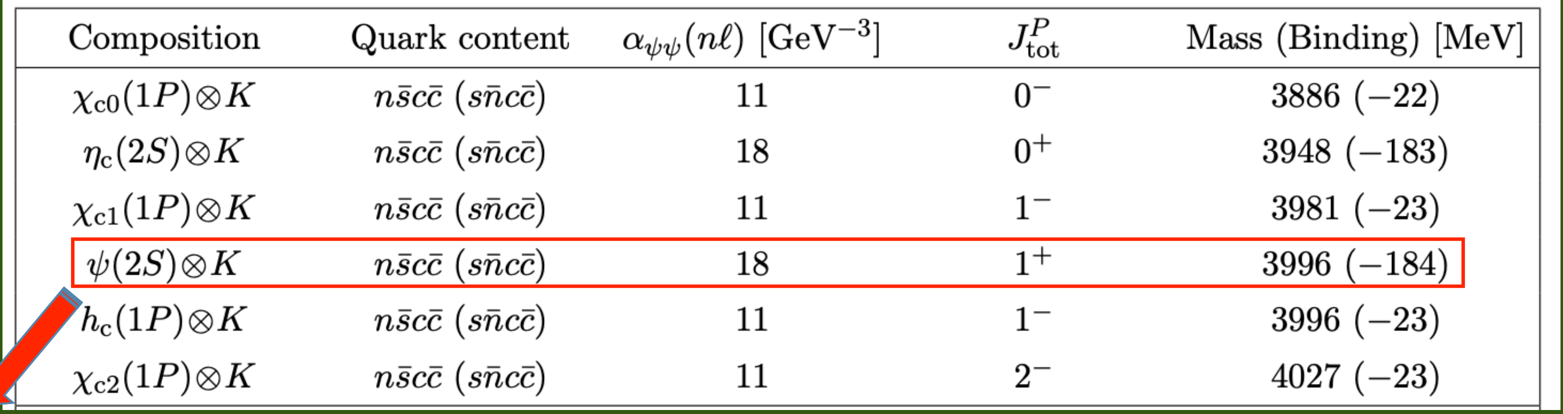
J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020)

$$H_{\rm hc} = M_\psi + M_\chi + V_{\rm hc}(r) + T_{\rm hc}$$

M_ψ = charmonium mass
M_χ = light baryon/meson mass
$T_{\rm hc}$ = kinetic energy
$V_{\rm hc}$ = hadro-charmonium potential

Tetraquark Z_{cs} states in the hadro-charmonium model

J. Ferretti and E. Santopinto, JHEP **04**, 119 (2020); arXiv:2111.08650, accepted on Sci. Bull.

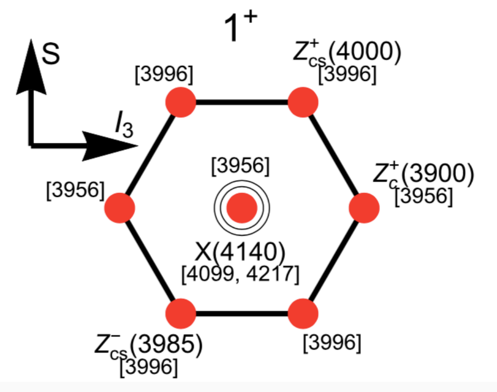


Composition	Quark content	$\alpha_{\psi\psi}(n\ell)$ [GeV^{-3}]	$J^P_{\rm tot}$	Mass (Binding) [MeV]
$\chi_{c0}(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	0^-	3886 (−22)
$\eta_c(2S)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	18	0^+	3948 (−183)
$\chi_{c1}(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	1^-	3981 (−23)
$\psi(2S)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	18	1^+	3996 (−184)
$h_c(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	1^-	3996 (−23)
$\chi_{c2}(1P)\otimes K$	$n\bar{s}c\bar{c}$ ($s\bar{n}c\bar{c}$)	11	2^-	4027 (−23)

Z_{cs}(3985) & Z_{cs}(4003)

Spectrum of Z_{cs} states predicted almost a year prior to the experimental findings by using SU(3) flavor symmetry

JHEP 04, 119 (2020) cited by the LHCb and BESIII experimental papers on the Z_{cs} findings



1^+ hadro-charmonium multiplet

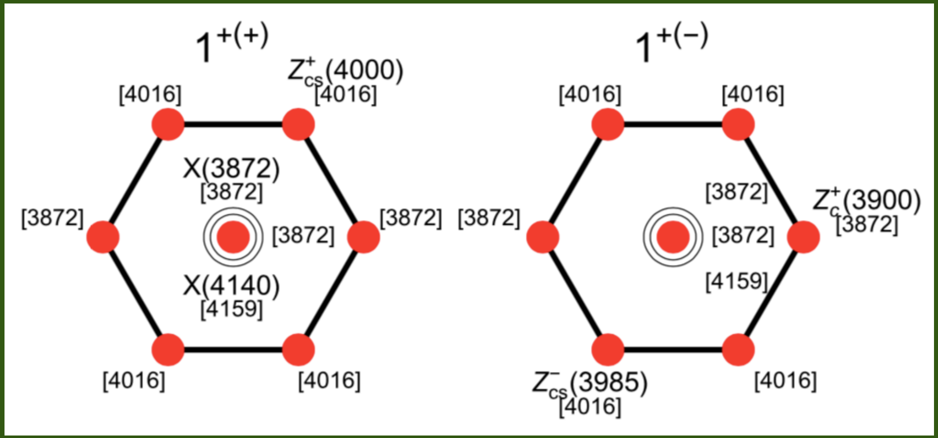
SU(3) flavor hidden-charm tetraquark nonets

J. Ferretti and E. Santopinto, arXiv:2111.08650, accepted on Sci. Bull.

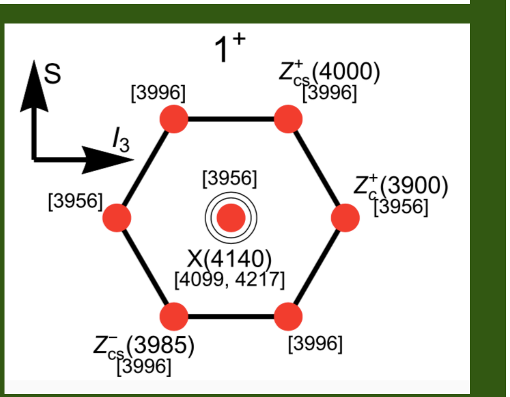
In the compact tetraquark model there are two multiplets with $J^P = 1^+$ → one can accommodate each of the Z_{cs} states (characterized by very different decay widths) in a different multiplet

In the hadro-charmonium model there is only one multiplet with $J^P = 1^+$ → either the two Z_{cs} states belong to the same multiplet (unlikely) OR the two Z_{cs} states have a different nature (e.g. one is hadro-charmonium and the other is a molecular state)

Possibility to use the tetraquark multiplet structure (in combination with predictions for the decay widths, production cross-sections …) to discriminate among the different interpretations



1^+ tetraquarks: compact tetraquark (upper panel) VS hadro-charmonium model (lower panel) interpretations



Fully-heavy tetraquarks in the diquark-antidiquark model

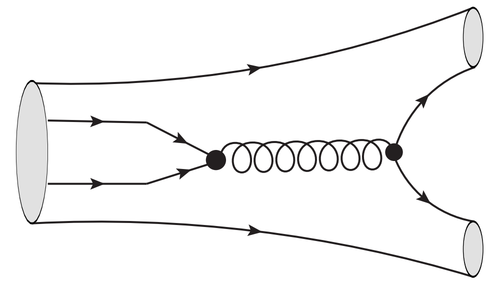
M. Naeem Anwar, J. Ferretti, F.-K. Guo, E. Santopinto and B.-S. Zou, EPJC **78**, 647 (2018)

- Ground-state 4*c* and 4*b* tetraquark masses calculated in the diquark-antidiquark model AND in a non relativistic QM with Coulomb interaction
- First predictions for the 4*c* and 4*b* decay widths.

  Decays proceed via *Q* anti-*Q* annihilation into a gluon (*Q* = *c* or *b*)

  Γ(4*b* → hadrons) = *O*(50 MeV)

  Γ(4c → hadrons) = *O*(100 MeV)



Decays of (*Q Q* anti-*Q* anti-*Q*) into mesons M_1 M_2

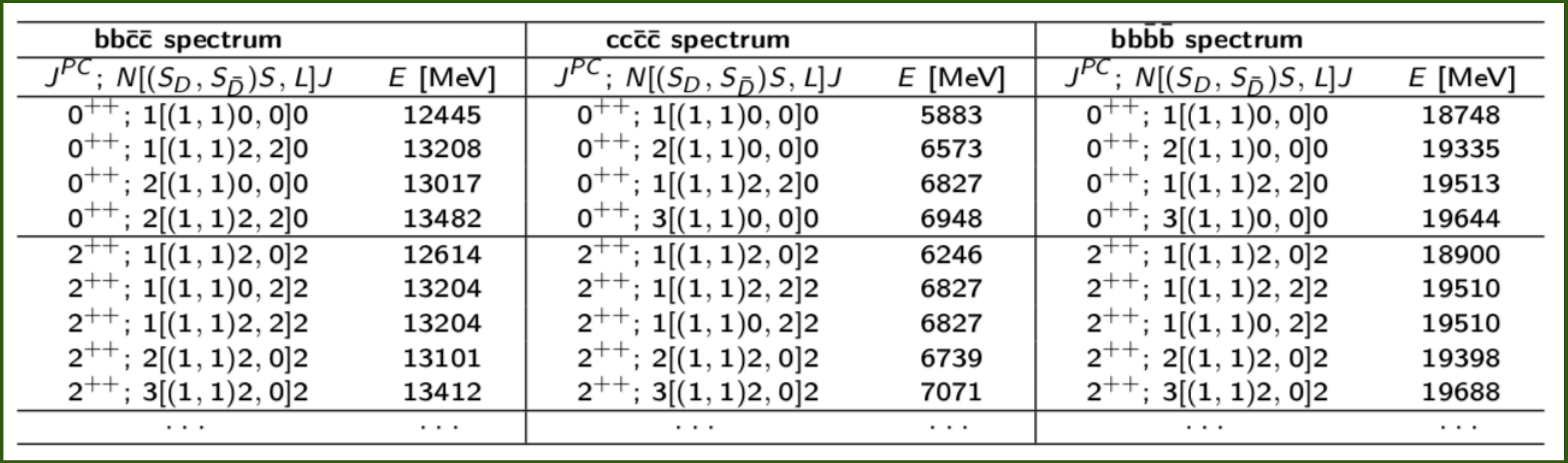
- Predictions compatible with the experimental data for the width of the X(6900) fully-c tetraquark: Γ[X(6900)] = 80 ± 19 MeV

  R. Aaij *et al*. [LHCb Collaboration], Sci. Bull. **65**, 1983 (2020)
- **This article was cited by LHCb twice**:

  1. [JHEP **10**, 086 (2018)], search for the GS 4*b* tetraquark in 4*b* → 4 muons
  2. [Sci. Bull. **65**, 1983 (2020)], discovery of the X(6900) 4*c* tetraquark

Spectrum of fully-heavy tetraquarks

M.A. Bedolla, J. Ferretti, C.D. Roberts and E. Santopinto, EPJC **80**, 1004 (2020)



$bb\bar{c}\bar{c}$ spectrum		$cc\bar{c}\bar{c}$ spectrum		$bb\bar{b}\bar{b}$ spectrum	
J^{PC}; $N[(S_D, S_{\bar{D}})S, L]J$	E [MeV]	J^{PC}; $N[(S_D, S_{\bar{D}})S, L]J$	E [MeV]	J^{PC}; $N[(S_D, S_{\bar{D}})S, L]J$	E [MeV]
0^{++}; 1[(1, 1)0, 0]0	12445	0^{++}; 1[(1, 1)0, 0]0	5883	0^{++}; 1[(1, 1)0, 0]0	18748
0^{++}; 1[(1, 1)2, 2]0	13208	0^{++}; 2[(1, 1)0, 0]0	6573	0^{++}; 2[(1, 1)0, 0]0	19335
0^{++}; 2[(1, 1)0, 0]0	13017	0^{++}; 1[(1, 1)2, 2]0	6827	0^{++}; 1[(1, 1)2, 2]0	19513
0^{++}; 2[(1, 1)2, 2]0	13482	0^{++}; 3[(1, 1)0, 0]0	6948	0^{++}; 3[(1, 1)0, 0]0	19644
2^{++}; 1[(1, 1)2, 0]2	12614	2^{++}; 1[(1, 1)2, 0]2	6246	2^{++}; 1[(1, 1)2, 0]2	18900
2^{++}; 1[(1, 1)0, 2]2	13204	2^{++}; 1[(1, 1)2, 2]2	6827	2^{++}; 1[(1, 1)2, 2]2	19510
2^{++}; 1[(1, 1)2, 2]2	13204	2^{++}; 1[(1, 1)0, 2]2	6827	2^{++}; 1[(1, 1)0, 2]2	19510
2^{++}; 2[(1, 1)2, 0]2	13101	2^{++}; 2[(1, 1)2, 0]2	6739	2^{++}; 2[(1, 1)2, 0]2	19398
2^{++}; 3[(1, 1)2, 0]2	13412	2^{++}; 3[(1, 1)2, 0]2	7071	2^{++}; 3[(1, 1)2, 0]2	19688
...	...	...	...	...	...

Spectrum of fully-heavy tetraquarks in the compact tetraquark (diquark-antidiquark) model (continues)

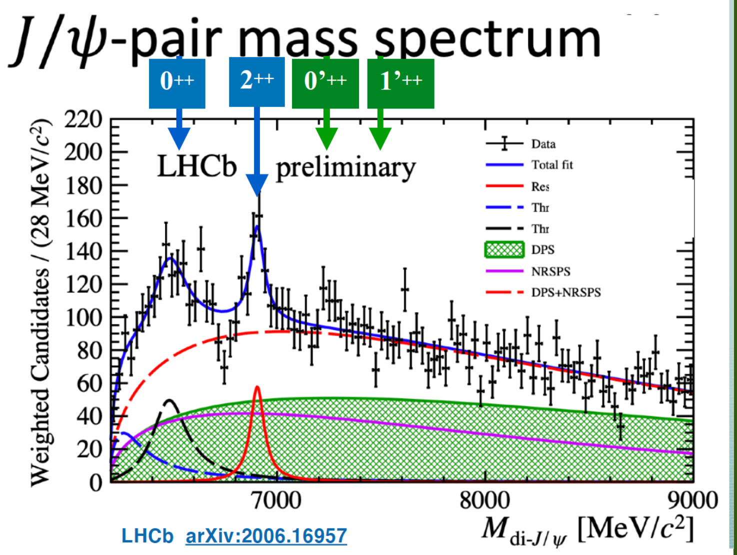
A rich spectrum, with orbital and radial excitations, is predicted

This article was cited by the LHCb paper [Sci. Bull. **65**, 983 (2020)], on the discovery of the X(6900) 4*c* tetraquark

Total widths and mass spectrum

C. Becchi, J. Ferretti, A. Giachino, L. Maiani and E. Santopinto, Phys. Lett. B **811**, 135952 (2020)

- Total widths are proportional to the ratio: $\xi = |\Psi_T(0)|^2 / |\Psi_{J/\Psi}(0)|^2$
- We determine ξ from the diquark-antidiquark model



LHCb arXiv:2006.16957

Science Bulletin, Volume 65, Issue 23, 1983 (2020)

$$\xi = 4.6 \pm 1.4$$

$$\Gamma(2^{++}) = (97 \pm 30)\ \text{MeV}$$

Widths are computed by using the formula:

$$\Gamma = |\Psi_T(0)|^2 \cdot |\mathbf{v}| \cdot \sigma(c\bar{c} \to f)$$

Computed widths are in perfect agreement with LHCb experimental results

Paper appeared on the arXiv before LHCb discovery

EIC goals

See e.g. the EIC Yellow Report, arXiv:2103.05419

EIC will study important topics, including:

1. The parton structure of hadrons

How the global properties nucleon spin and nucleon mass are understood in terms of contributions from quarks and gluons.

2. The multidimension imaging of nucleons, nuclei and mesons

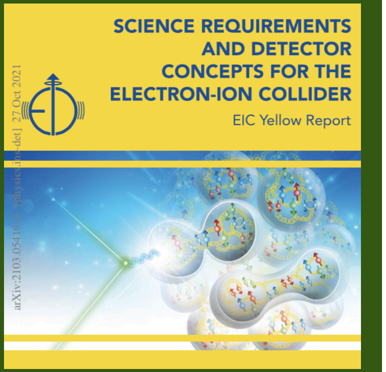
Imaging in position space comes through form factors and GPDs (generalized parton distributions); TMDs (transverse momentum dependent parton distributions) quantify the 3D parton structure of hadrons in momentum space.

3. Nucleon structure

Effect of binding of nucleons on nuclear parton distributions; spatial distributions of partons in a nucleus via diffractive or exclusive processes.

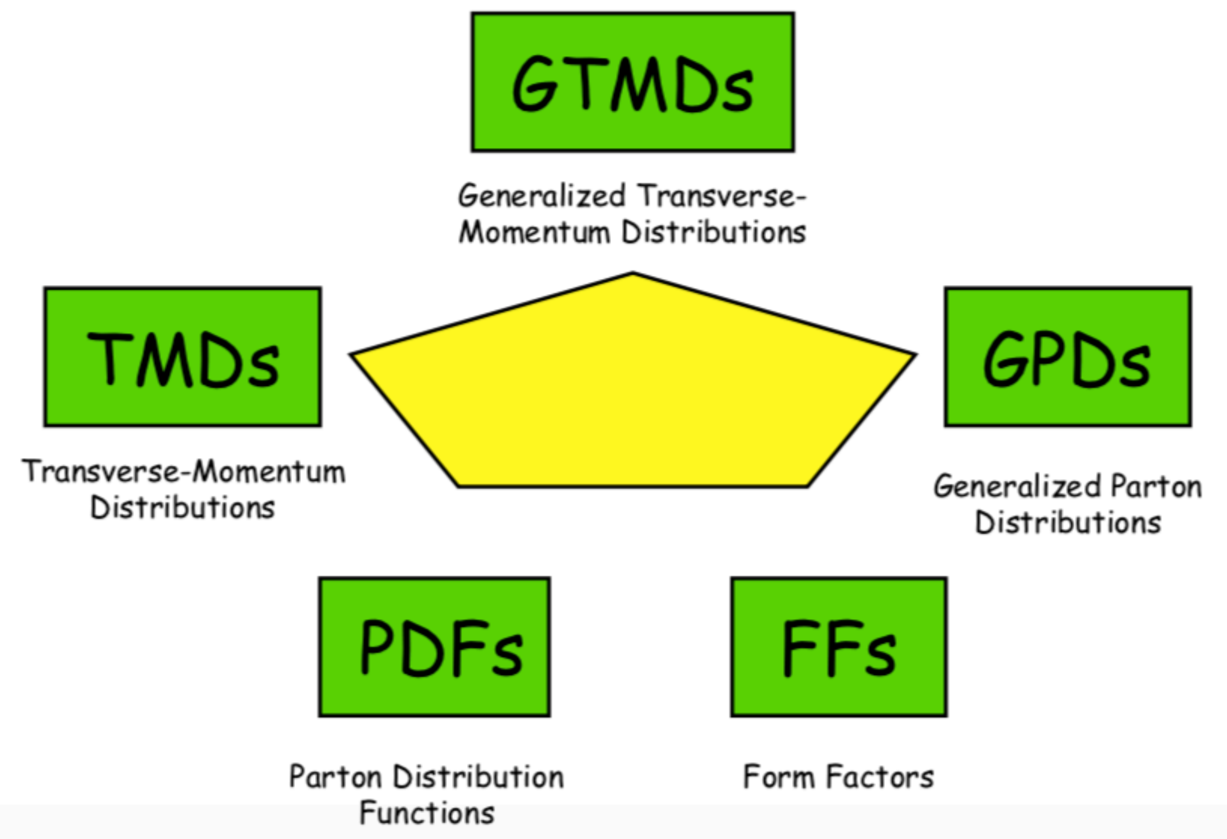
4. The mechanisms of hadronization

Study of hadronization mechanisms production in lepton-hadron collisions, including parton fragmentation, threshold production, string-breaking, and coalescence or recombination.



SCIENCE REQUIREMENTS
AND DETECTOR
CONCEPTS FOR THE
ELECTRON-ION COLLIDER
EIC Yellow Report

Parton distributions



GTMDs

Generalized Transverse-Momentum Distributions

TMDs

Transverse-Momentum Distributions

GPDs

Generalized Parton Distributions

PDFs

Parton Distribution Functions

FFs

Form Factors

Conclusions

- The field of exotic hadron spectroscopy and structure is a hot one
- There is a new discovery every 2/3 months by several experiments (LHCb, BESIII, Belle …)

- In the last three years I have predicted in advance several exotic states: $X(6900)$, Z_{cs} states
- Four of my papers have been cited by the discovery papers of BESIII and LHCb
- One of my papers cited by the PDG 2021 (update)

Thank you for your attention!