Flavour SU(3) symmetry, the new exotics $Z_{cs}(3085)$, $Z_{cs}(4003)$ and Y(4230) decays

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April 2, 2021

1. Hidden charm and beauty hadrons reveal *tetraquarks* and *pentaquarks*

- Heavy quark pairs are difficult to be created or destroyed by QCD forces inside hadrons.
- Hadrons electrically charged ***and*** featuring a $c\bar{c}$ or $b\bar{b}$ pair ***must*** contain additional light quarks, ***realising the hypothesis advanced by Gell-Mann in the Sixties***

M. Gell-Mann, A Schematic Model of Baryons and Mesons, PL **8**, 214, 1964

Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc.

- These are the exotic X, Y, Z mesons and the pentaquarks discovered over the last decade

There are, indeed, new valence quark configurations !!

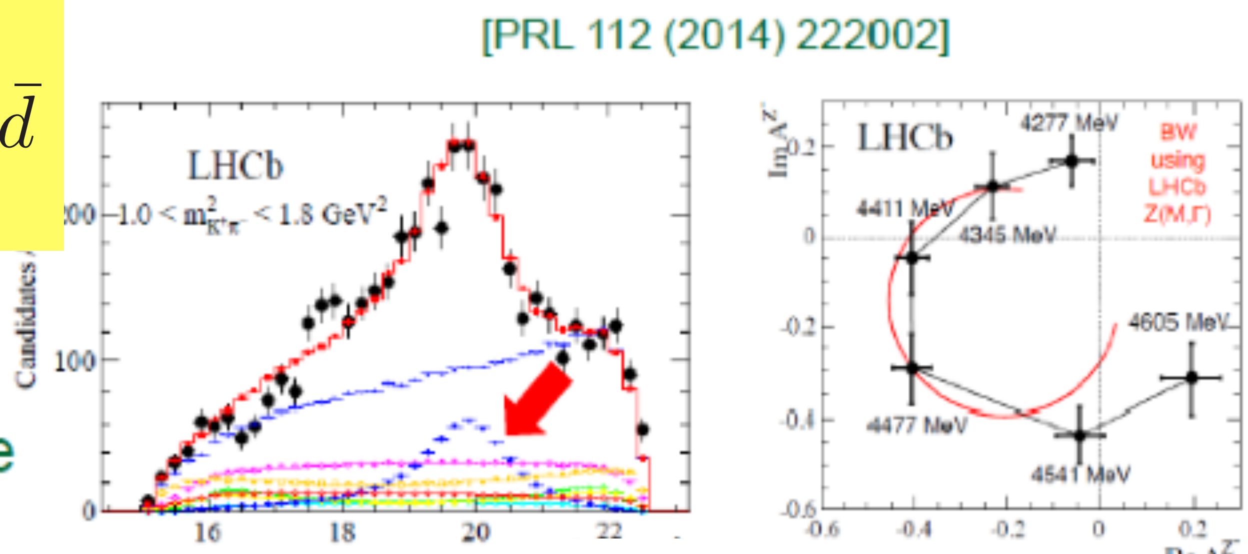
- First hypothesis of tetraquarks by R. Jaffe, as a model of the lightest scalar mesons
- Tetraquarks are more easy to identify at the increase of quark mass
- Hidden heavy flavors have been the first,
- hidden charm and open strangeness ***discovered now !!***
- The first, *unexpected charmonium* was the still controversial X(3872)
- Nearness to heavy pair threshold is to be expected, but the X(3872) is exceptionally close, we do not know yet if it is above or below the $D^0\bar{D}^{*0}$ threshold, within some 80 keV.

Explicit Tetraquarks

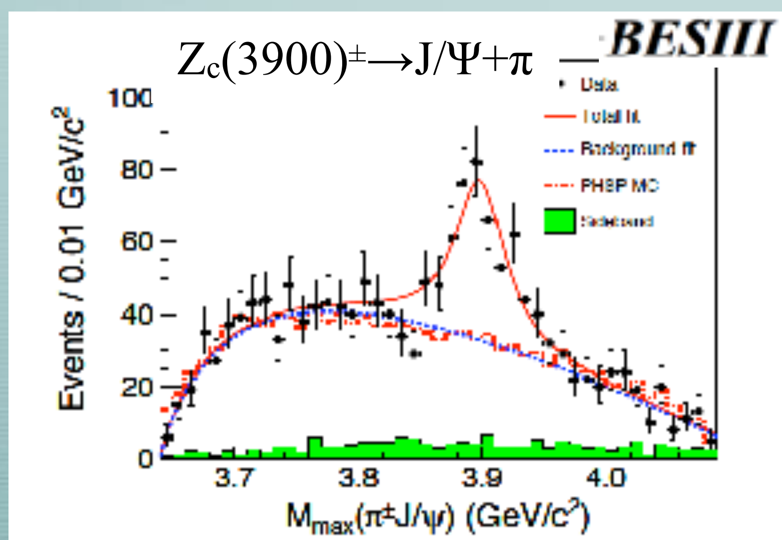
$Z_c(4430)^{\pm} \to J/\Psi + \pi$

valence quark composition: $c\bar{c}u\bar{d}$

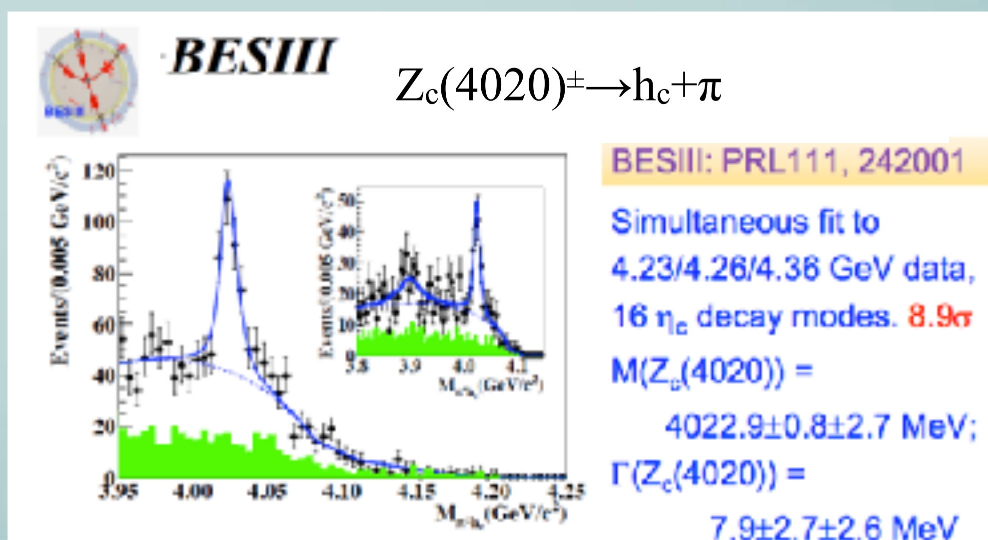
1. Confirm Belle's observation of 'bump'
2. Can NOT be built from standard states
3. Textbook phase variation of a resonance



$Z_c(3900)^{\pm} \to J/\Psi + \pi$



$Z_c(4020)^{\pm} \to h_c + \pi$



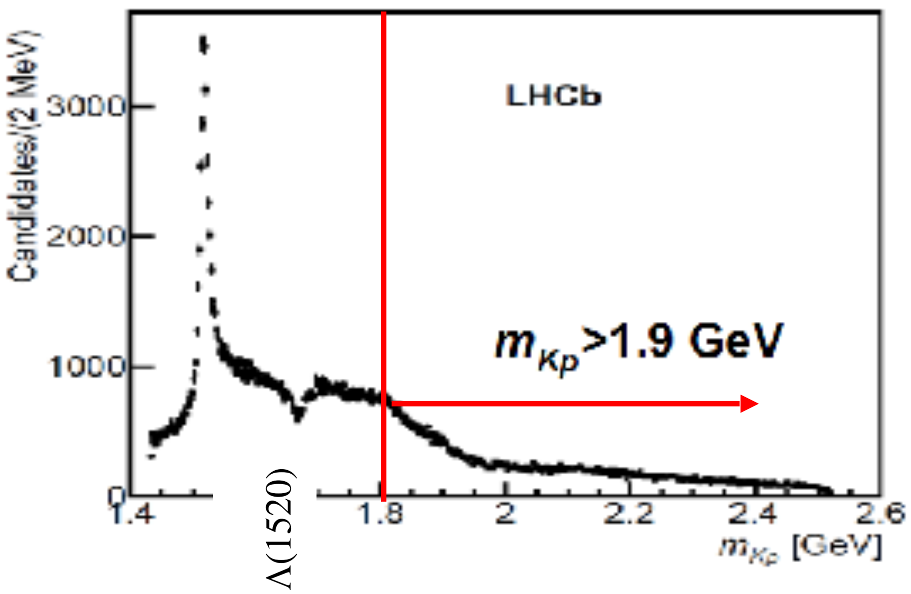
More, exotic valence quark configurations

$$\Lambda_b \to K^- + J/\psi + P$$

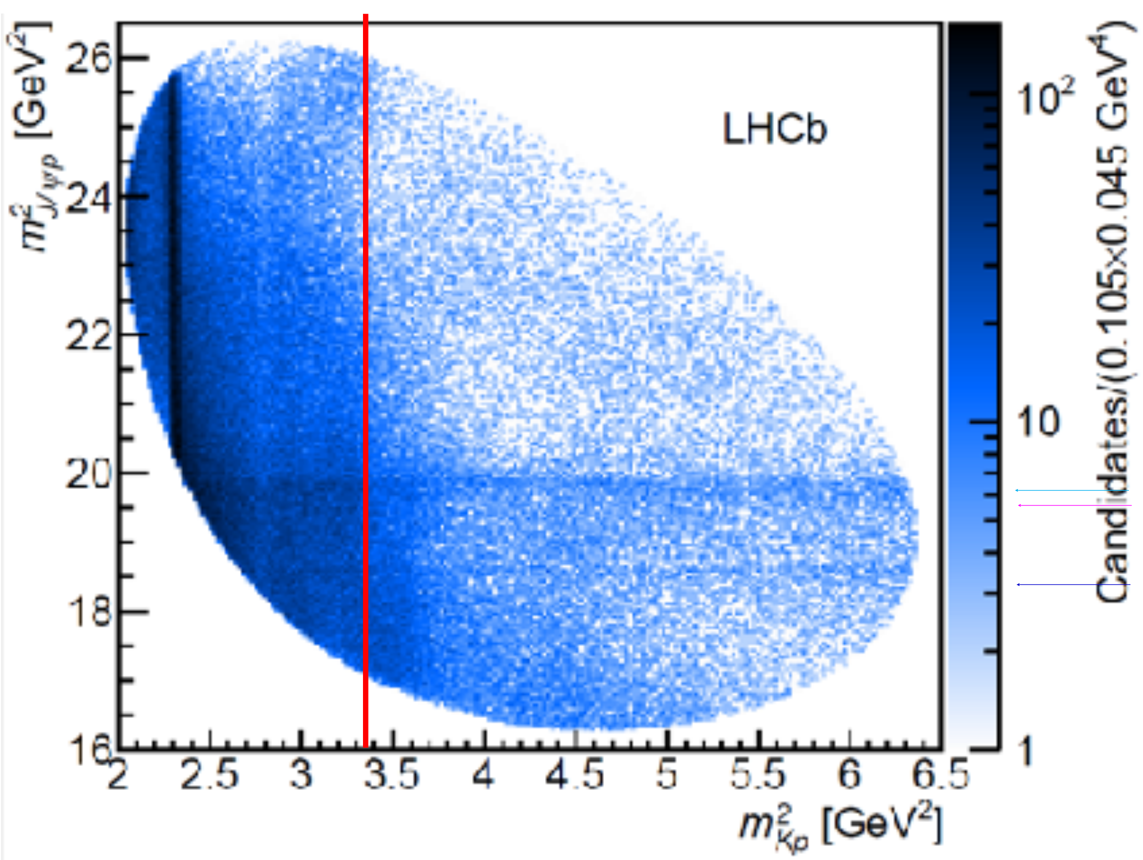
Narrow $P_c^+ \to J/\psi p$ peaks with Λ^* suppression

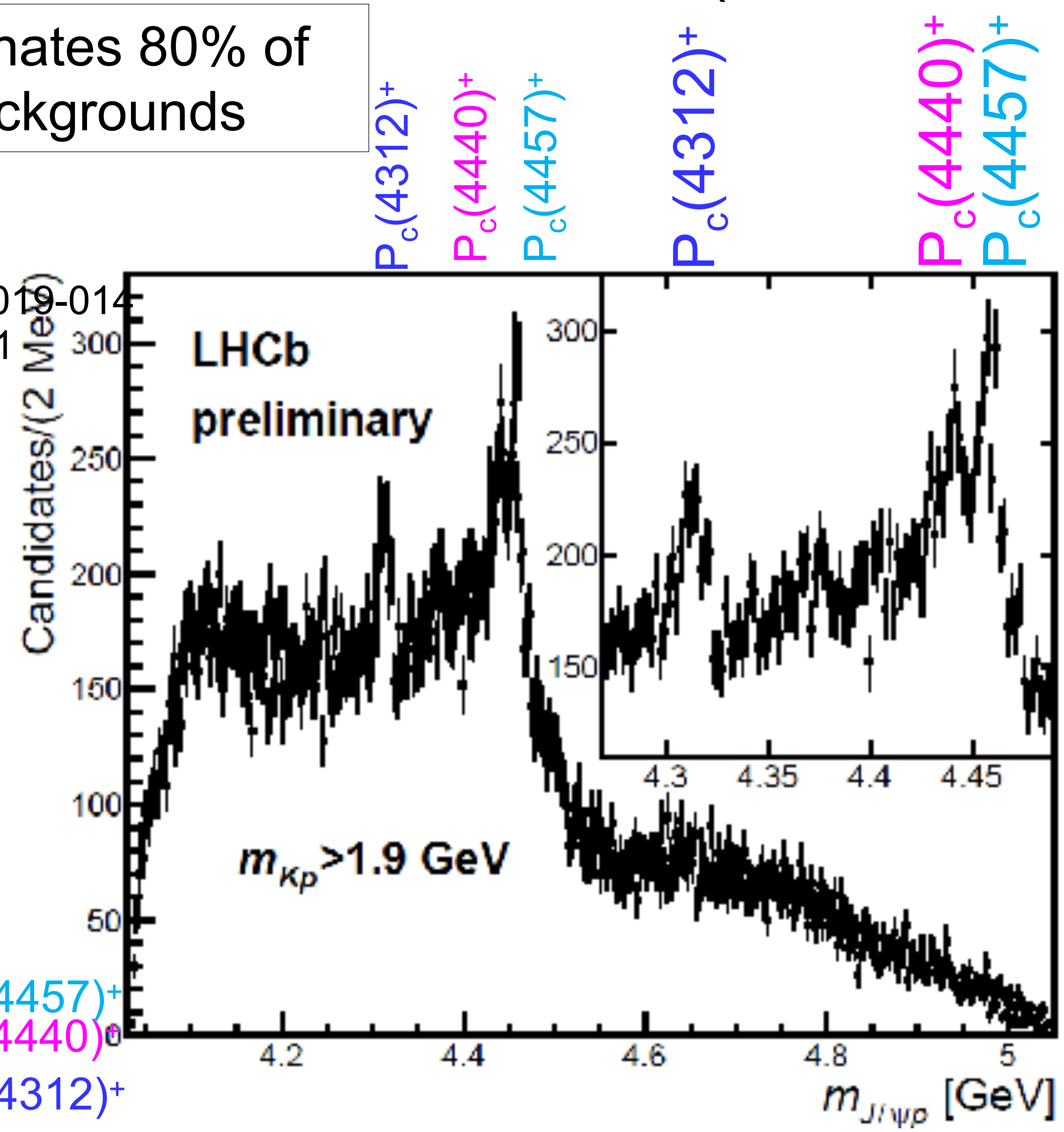
Mass resolution σ=2.3-2.7 (FWHM 5.4-6.4) MeV

Eliminates 80% of backgrounds



LHCb-PAPER-2019-014
PRL 122, 222001





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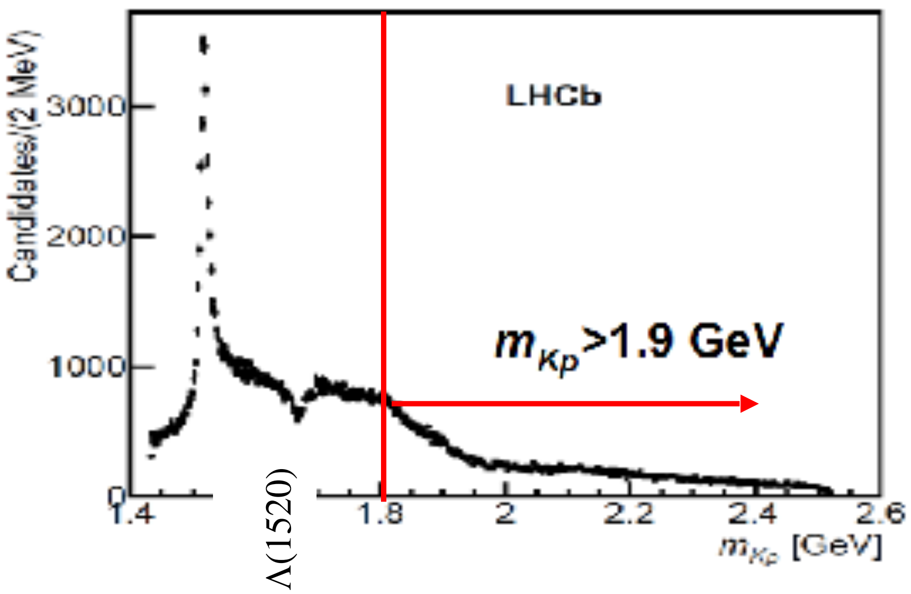

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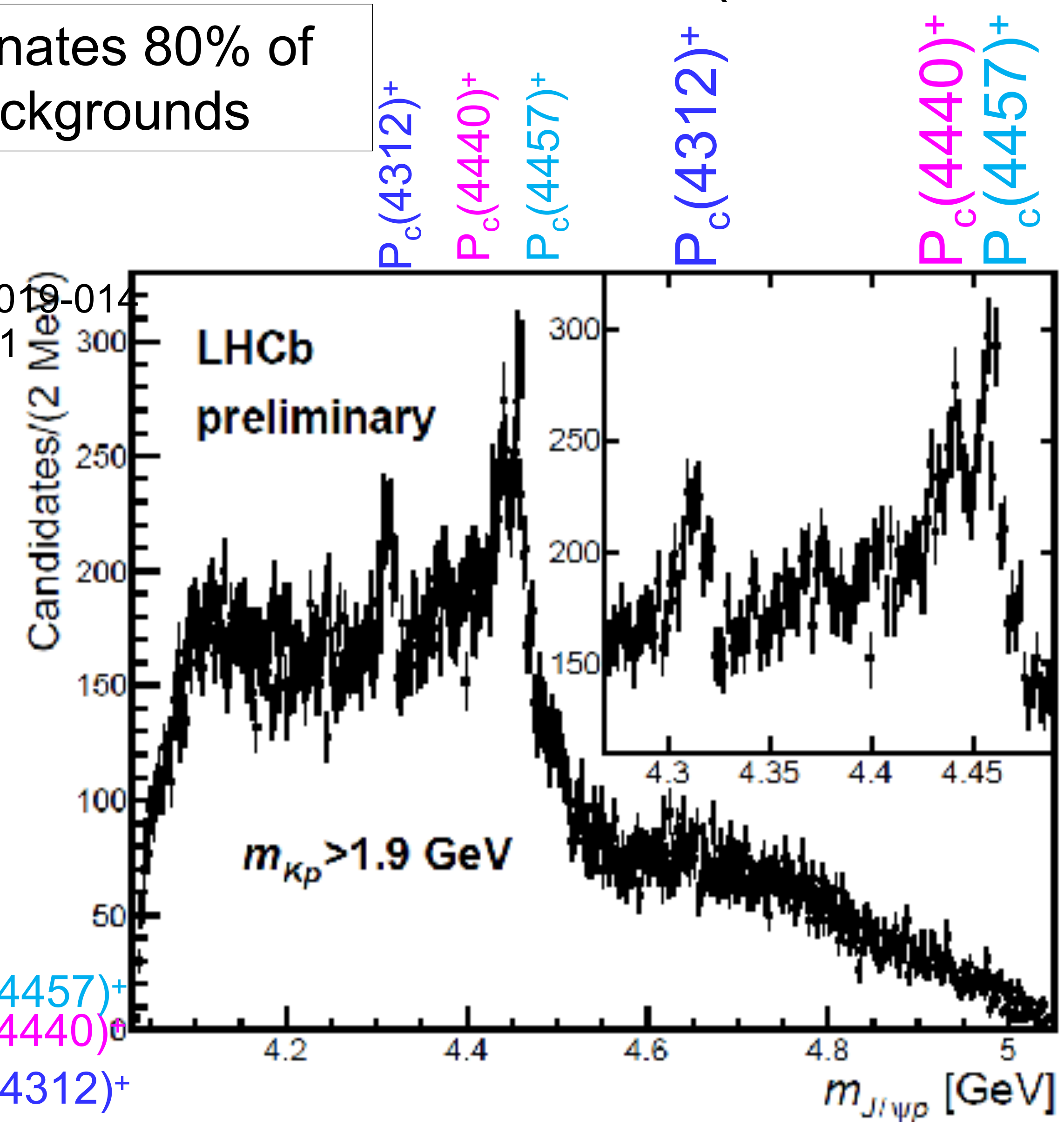
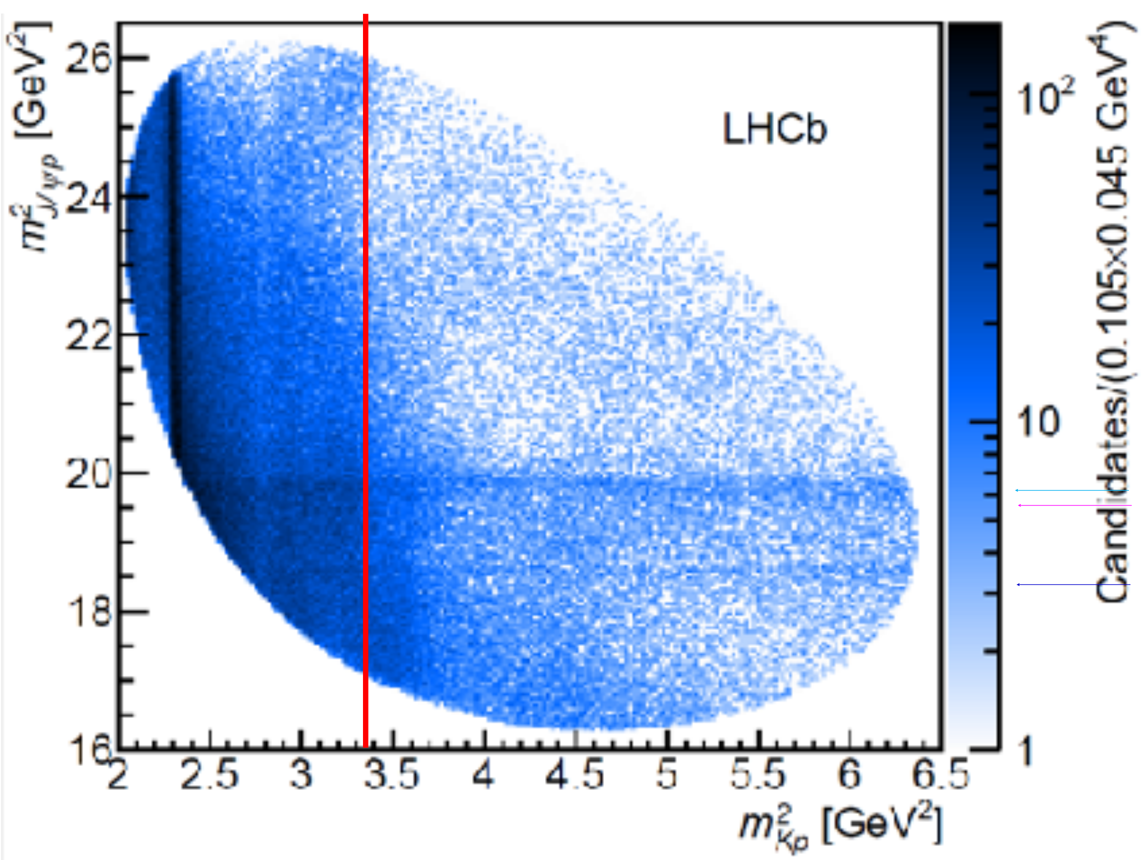
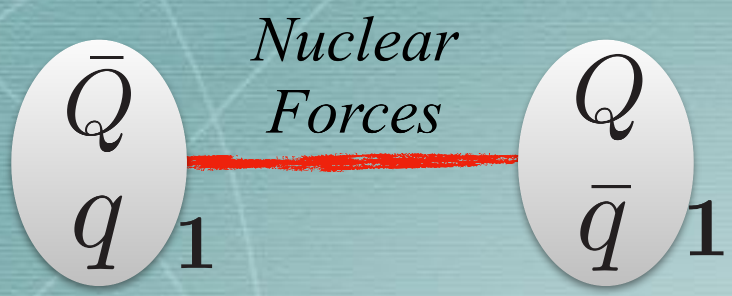




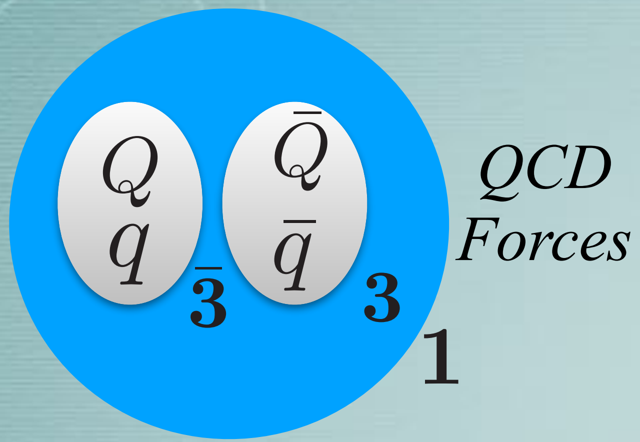
Pentaquarks: $\mathcal{P}^+ = c\bar{c}uud$

No consensus, yet



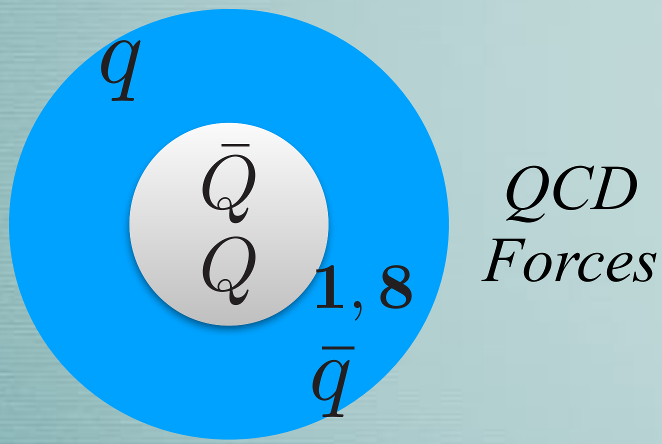
Hadron Molecule

F-K. Guo, C. Hanhart, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



Compact Diquark-Antidiquark

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71 (2005) 014028; **D 89** (2014) 114010.



HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

S. Dubynskiy, S. and M. B.Voloshin, Phys. Lett. **B 666**,(2008) 344.

E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. **D 90** (2014) 01404

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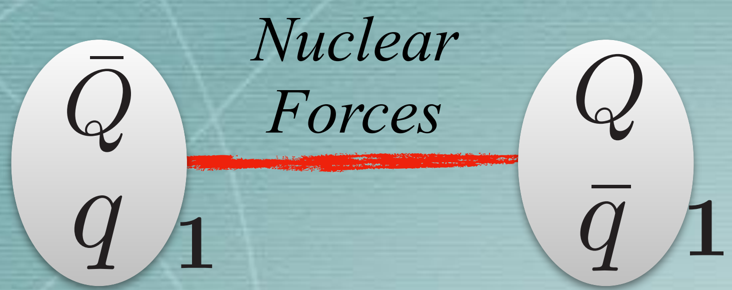

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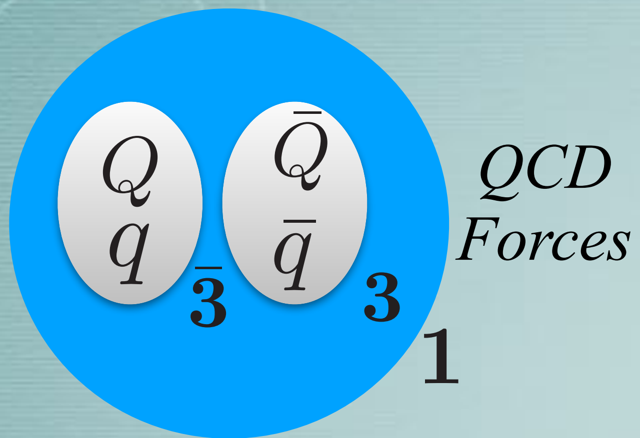

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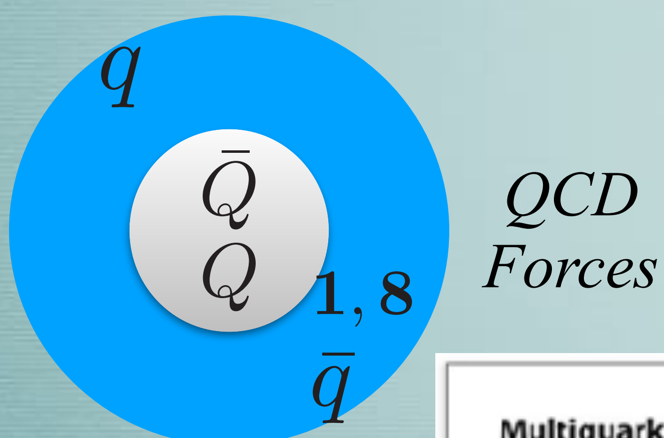

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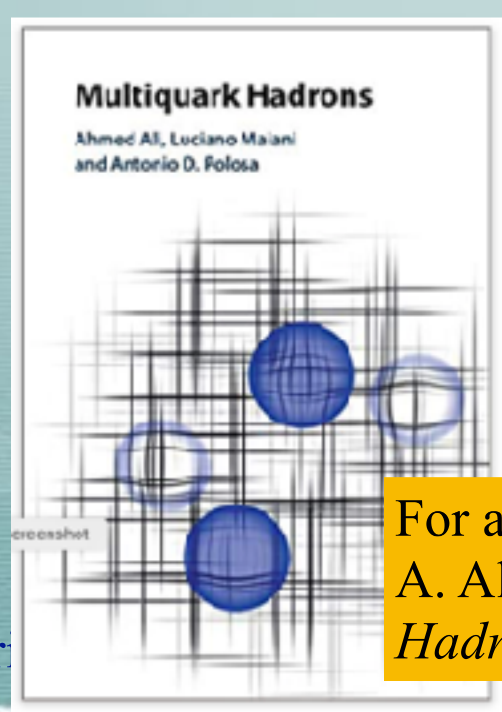


For a review, see:
A. Ali, L. Maiani and A.D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)

2. Exotic mesons: the *New Wave*

• Starting from 2016, new kinds of exotic hadrons have been discovered:

$J/\Psi\ \phi$ resonances, $di - J/\Psi$ resonances, open strangeness Exotics: $Z_{cs}(3082)$ and $Z_{cs}(4003)$

•No pion exchange forces can bind them as hadron molecules made by color singlet mesons: molecular models have to stand on the existence of "phenomenological forces" with undetermined parameters

• Not necessarily "just on threshold", no cusp behaviour..

• The New Exotics arise very naturally as $([cq]^{\bar{\mathbf{3}}}[\bar{c}\bar{q}']^{\mathbf{3}})_{\mathbf{1}}$ bound in color singlet

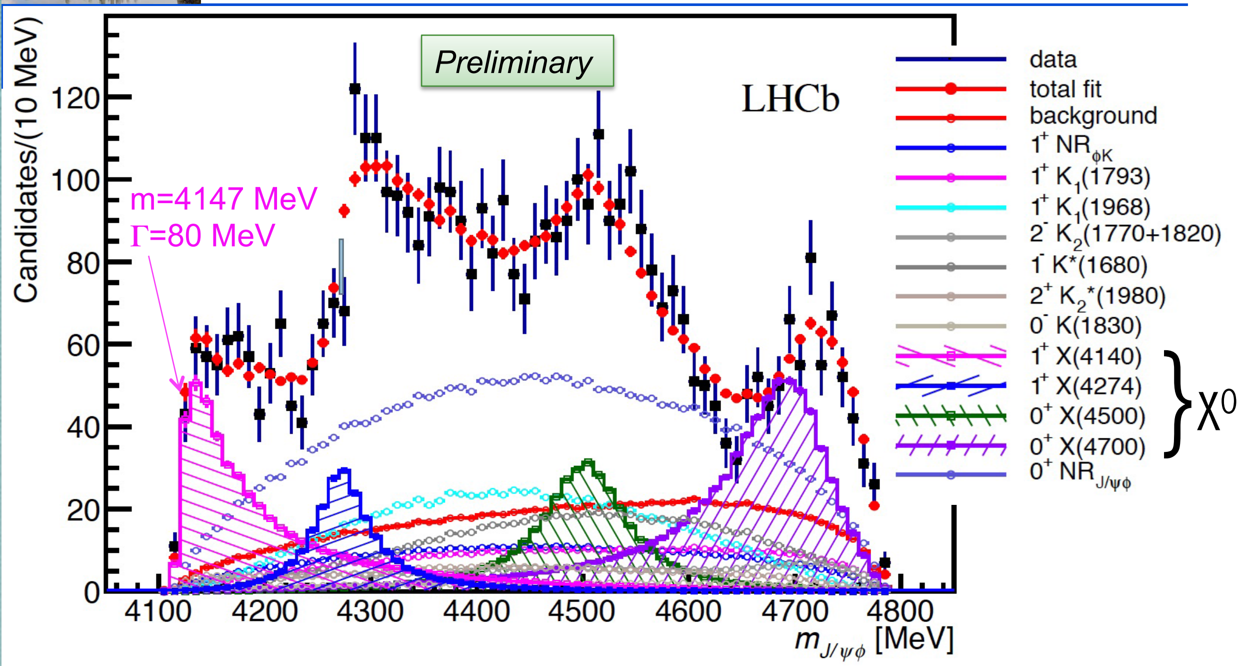
•The compact tetraquark model makes a firm prediction: hidden charm tetraquarks must form ***complete multiplets of flavor SU(3)***, with mass differences determined by the quark mass difference:

$$m_s - m_u = 120 - 150 \text{ MeV}.$$

• ***with $Z_{cs}(3082)$ and $Z_{cs}(4003)$ we can almost fill two tetraquark nonets with the expected scale of mass differences.***

The New Wave started with the discovery of $J/\Psi\ \phi$ resonances, LHCb 2016

Results of fit: m(J/ψϕ)



- 4 visible structures fit with BW amplitudes

28 Recontres de Blois, June 2, 2016

36

Results of fit

- J^P also measured all with >4σ significances

Particle	J^P	Signif-icance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	8.4 σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	1^+	6.0 σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	0^+	6.1 σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
X(4700)	0^+	5.6 σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$
NR	0^+	6.4 σ			$46 \pm 11^{+11}_{-21}$

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- J/Ψ φ mass distribution: four structures
- positive parity, J=0 and 1, positive charge conjugation
- X(4140) seen previously by CMS and by BELLE
- interpreted as $[cs][\bar{c}\bar{s}]$ tetraquarks

L. Maiani, A. Polosa, V. Riquer, Phys. Rev. D **94**, 054026 (2016)

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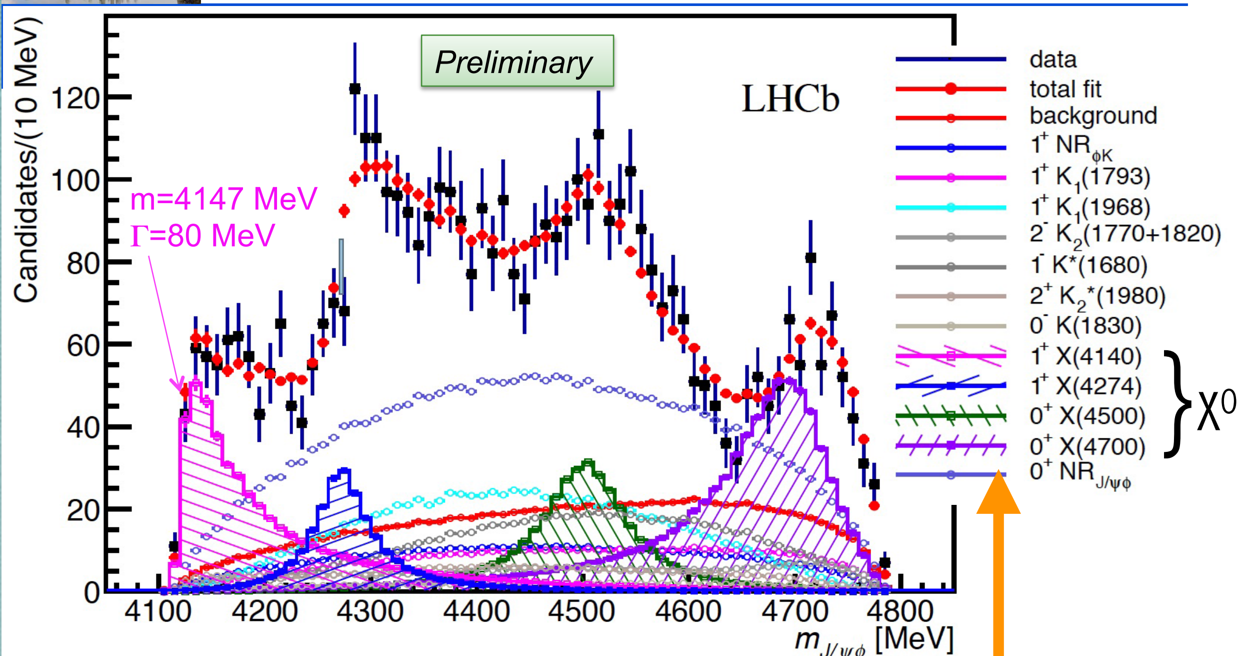

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$2M_{\Xi_c} \sim 4930$ MeV!!!

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di-J/\Psi resonances !!! LHCb November 2020

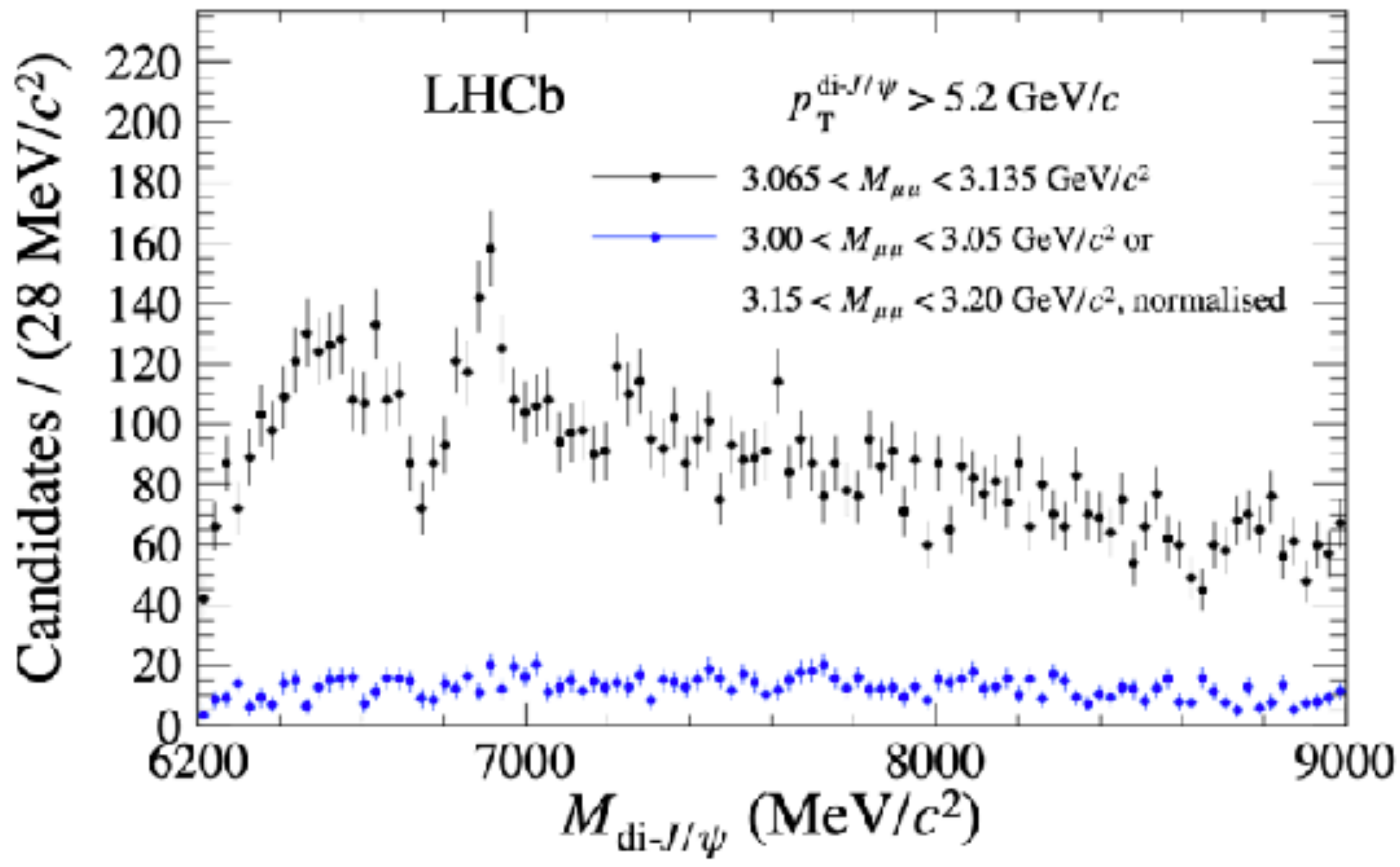

Figure 2: Invariant mass spectrum of J/ψ-pair candidates passing the $p_T^{\text{di-}J/\psi} > 5.2\,\text{GeV}/c$ requirement with reconstructed J/ψ masses in the (black) signal and (blue) background regions, respectively.

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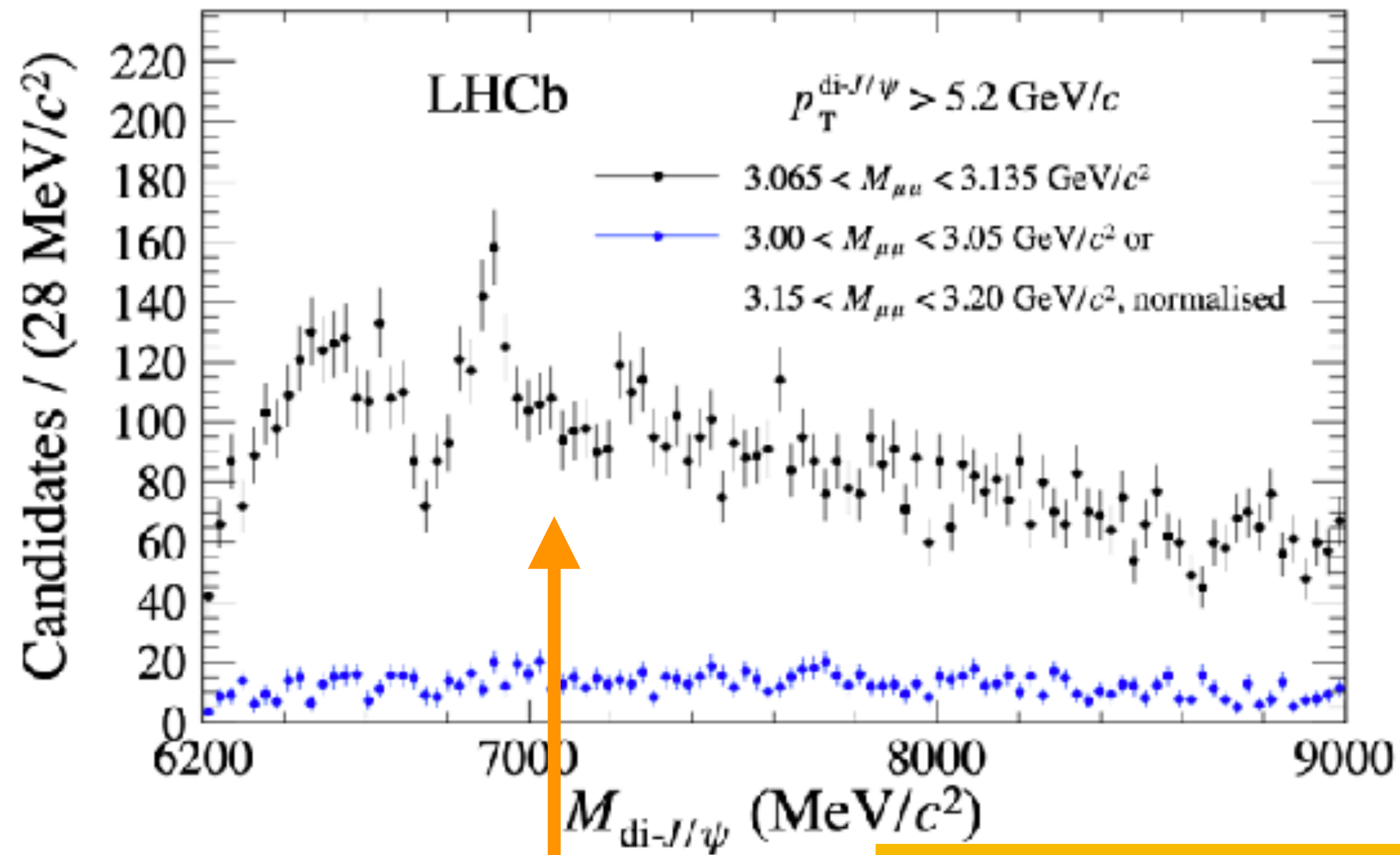

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- Baryon-antibaryon molecule? $\Xi_{cc} = [ccu]$

$2M_{\Xi_{cc}} \sim 7242$ MeV!!!

Open Strangeness

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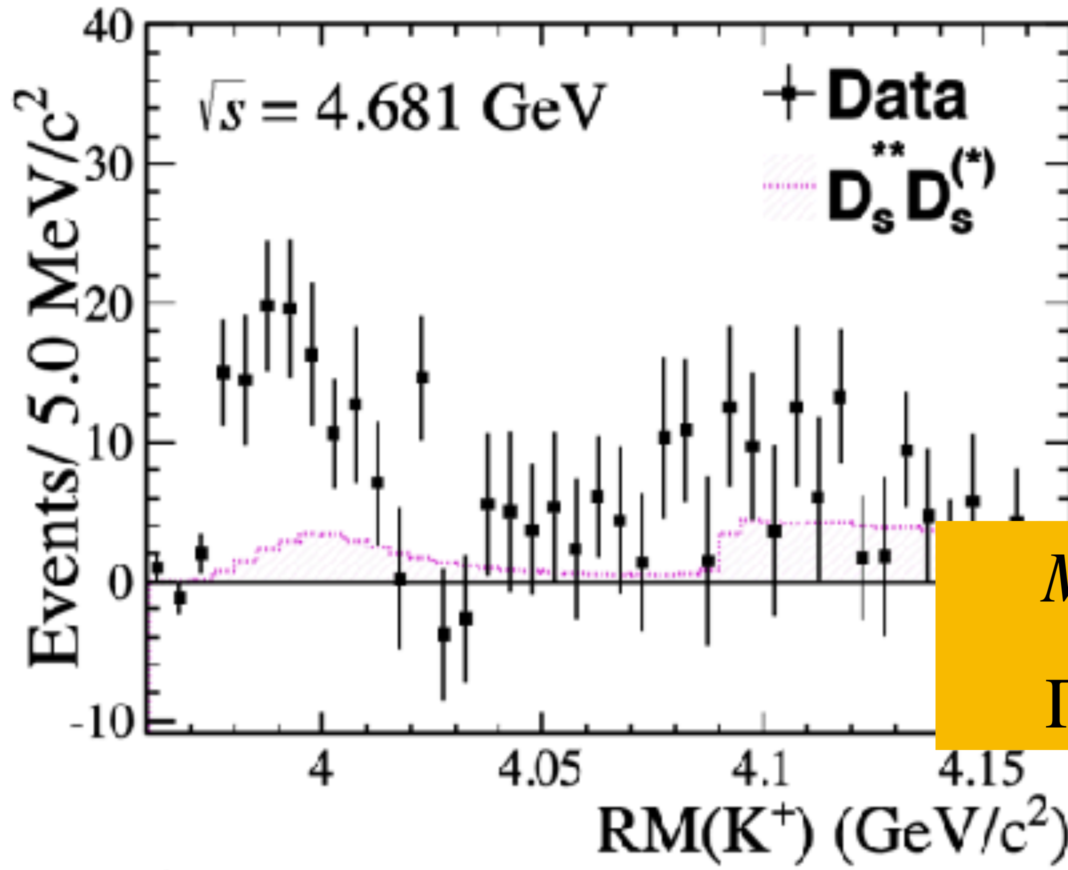

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FIG. 4. The K^+ recoil-mass spectrum in data at $\sqrt{s} = 4.681$ GeV after subtraction of the combinatorial backgrounds.

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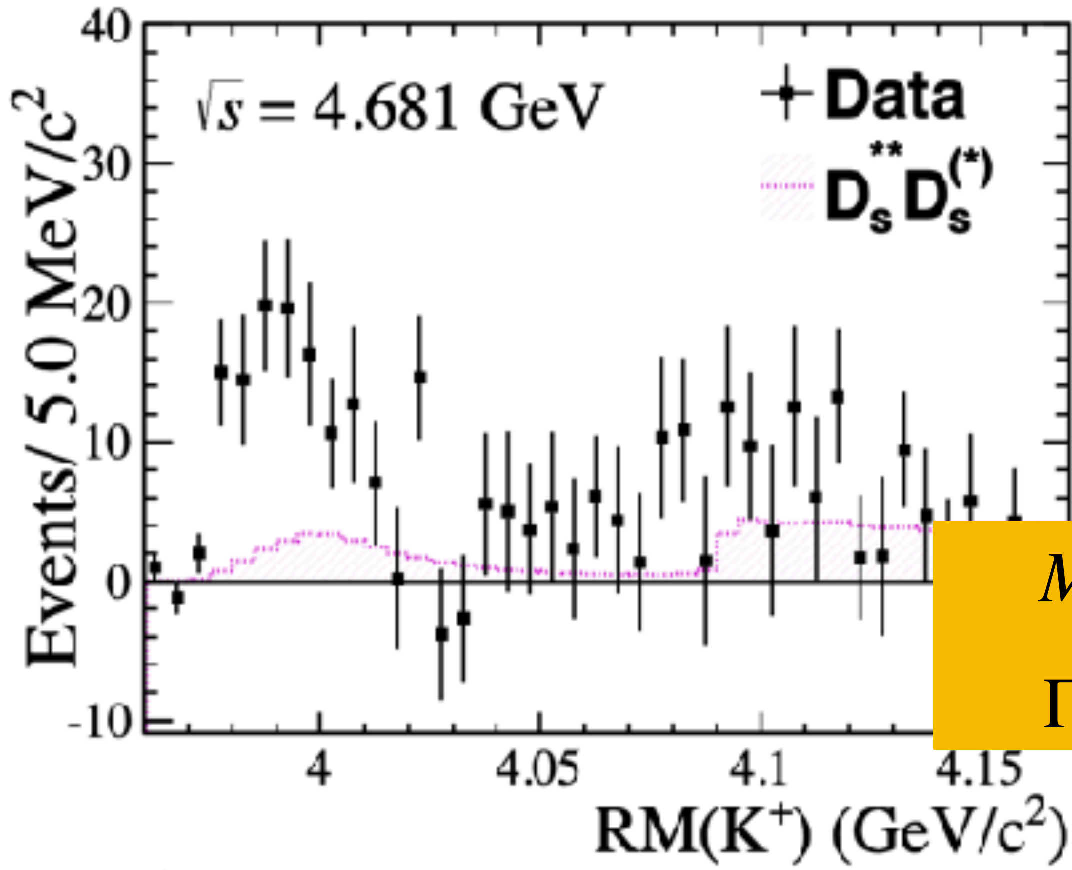

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$\Xi_c^+ = [csu]$, $\bar{\Sigma}_c^{--} = [\bar{c}\bar{u}\bar{u}]$

$M_{\Xi_c} + M_{\bar{\Sigma}_c} \sim 4923$ MeV!!!

LHCb:

The decay: $B^+ \to J/\Psi\ \phi\ K^+$

displays exotic resonances in two channels:

$J/\Psi\ \phi\ (X_{s\bar{s}} = [cs][\bar{c}\bar{s}])$ and

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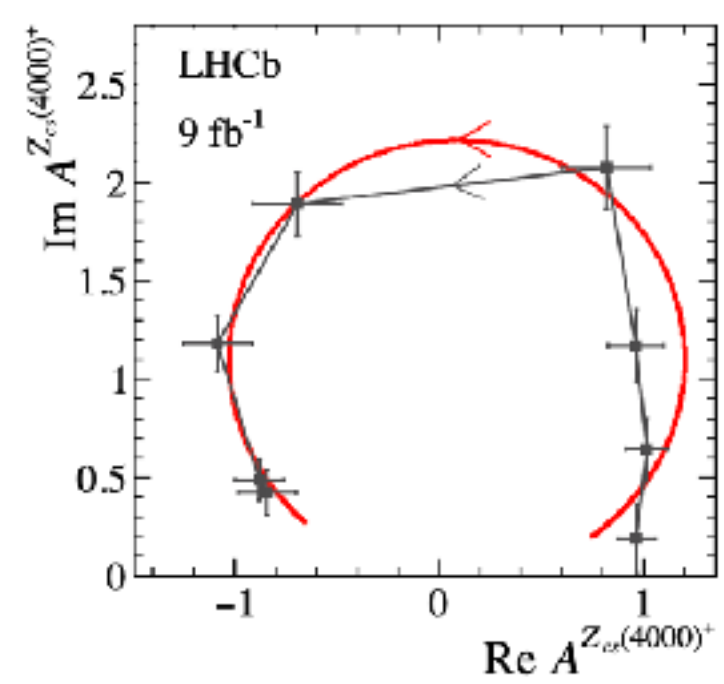
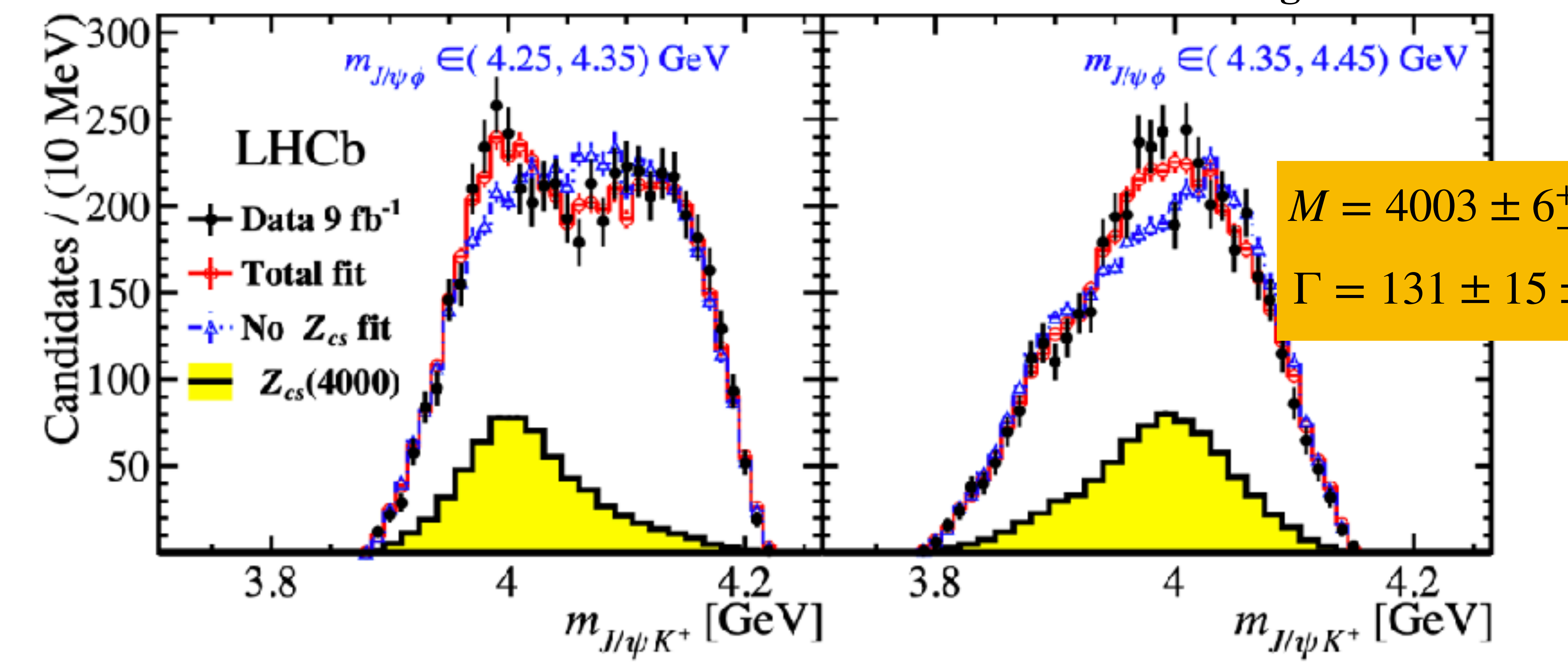


LHCb:
Argand's Plot of $Z^+_{cs}(4003)$

LHCb: $Z^+_{cs}(4003)$
March 2021



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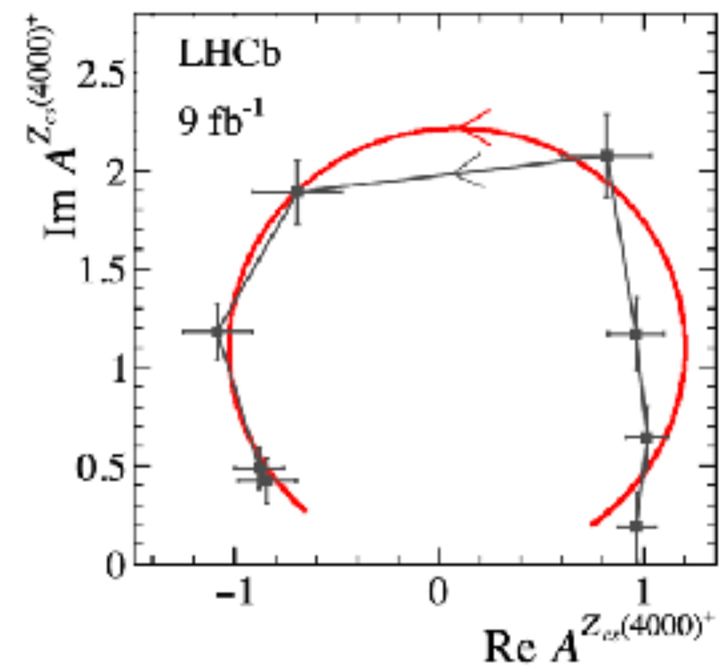

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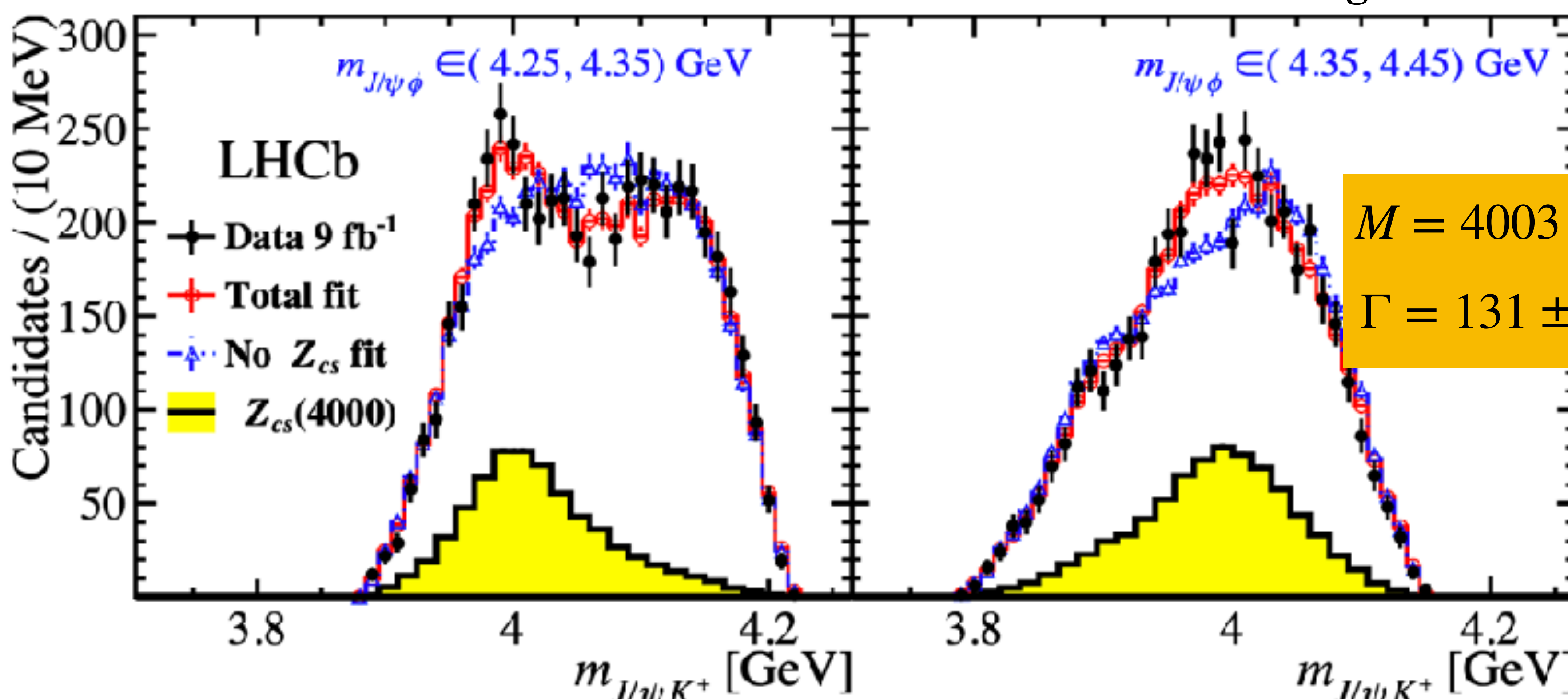

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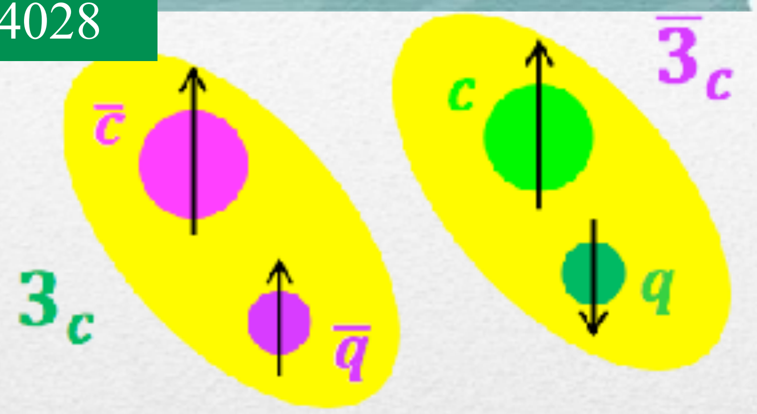
LHCb and BES III see two DIFFERENT particles !!!

3. Tetraquark constituent picture of unexpected quarkonia

L.Maiani, F.Piccinini, A.D.Polosa and V.Riquer, Phys. Rev. D 71 (2005) 014028



- [cq] in color $\bar{\mathbf{3}}$, $[cq]_{S=0,1}[\bar{c}\bar{q}']_{S=0,1}$ I=1, 0
- S-wave: positive parity
- total spin of each diquark, S=1, 0
- neutral states may be mixtures of isotriplet and isosinglet

- mass splitting due to spin-spin interactions (e.g. the non-relativistic costituent quark model

The S-wave, $J^P=1^+$ charmonium tetraquarks

- in the basis $\left|s,\bar{s}\right\rangle_J$

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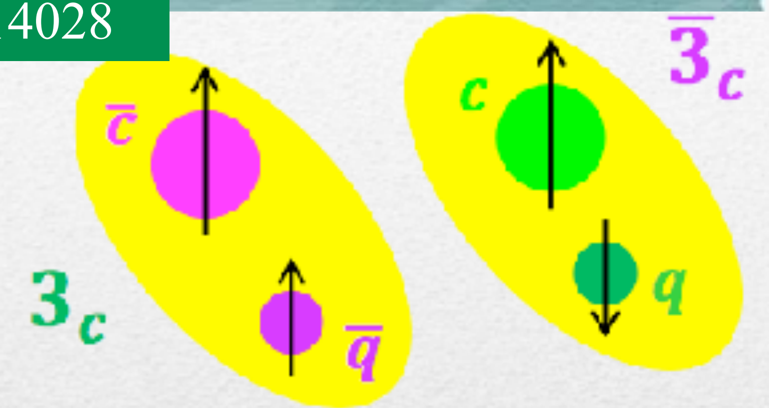

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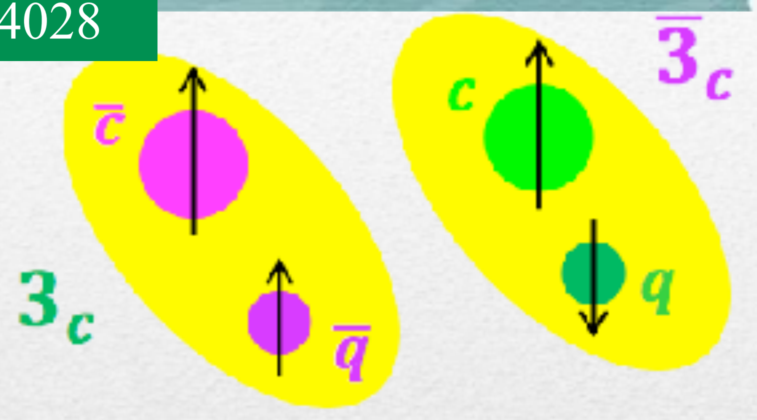

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X(3872)=X_1
Z(3900), Z(4020)=lin. combs. of Z&Z' that diagonalize H
X(3940)=X_2 ??

Tetraquark constituent picture of di-J/Ψ resonances

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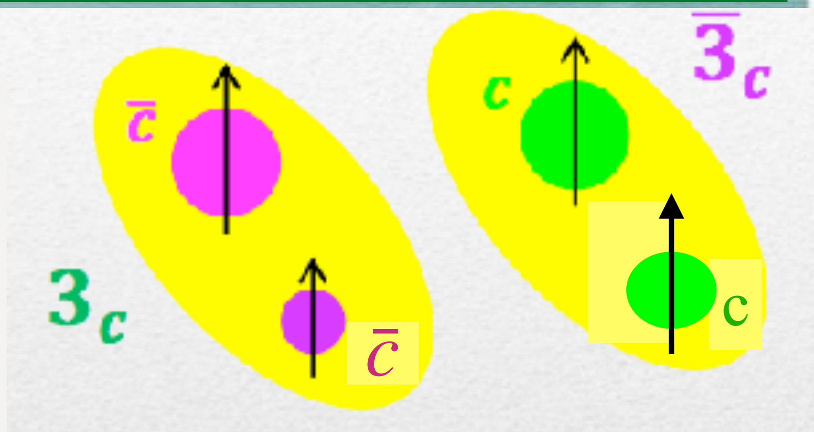


- [cc] in color $\bar{\mathbf{3}}$

$$[cc]_{S=1}[\bar{c}\bar{c}]_{S=1}$$

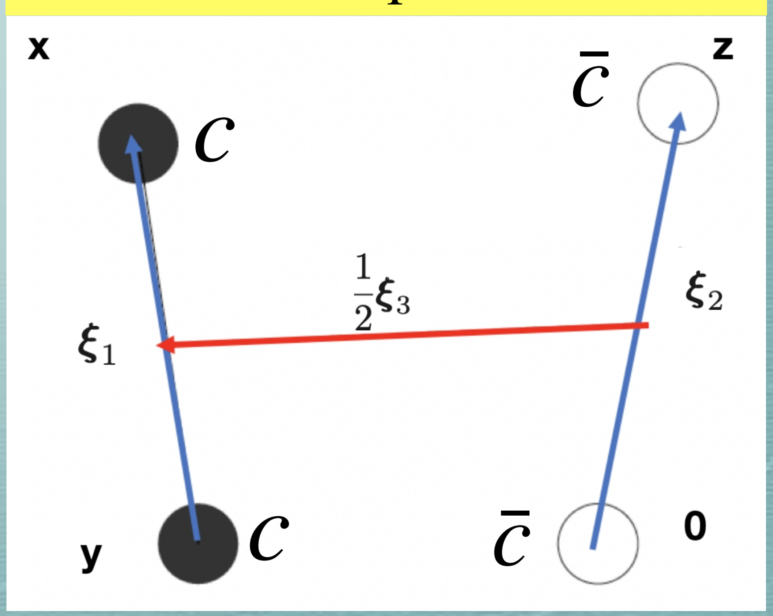
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)
- S-wave: positive parity

S-wave, fully charm tetraquarks

- C=+1 states: $J^{PC} = 0^{++},\ 2^{++}$, decay in $2\ J/\psi,\ 2\ \eta_c,\ 2\ \chi_{c0}(1P),\ 2\ \chi_{c1,2}(1P),\ D\bar{D}$
- C= -1 states: $J^{PC} = 1^{+-}$, decays in $J/\psi + \eta_c,\ D\bar{D}$

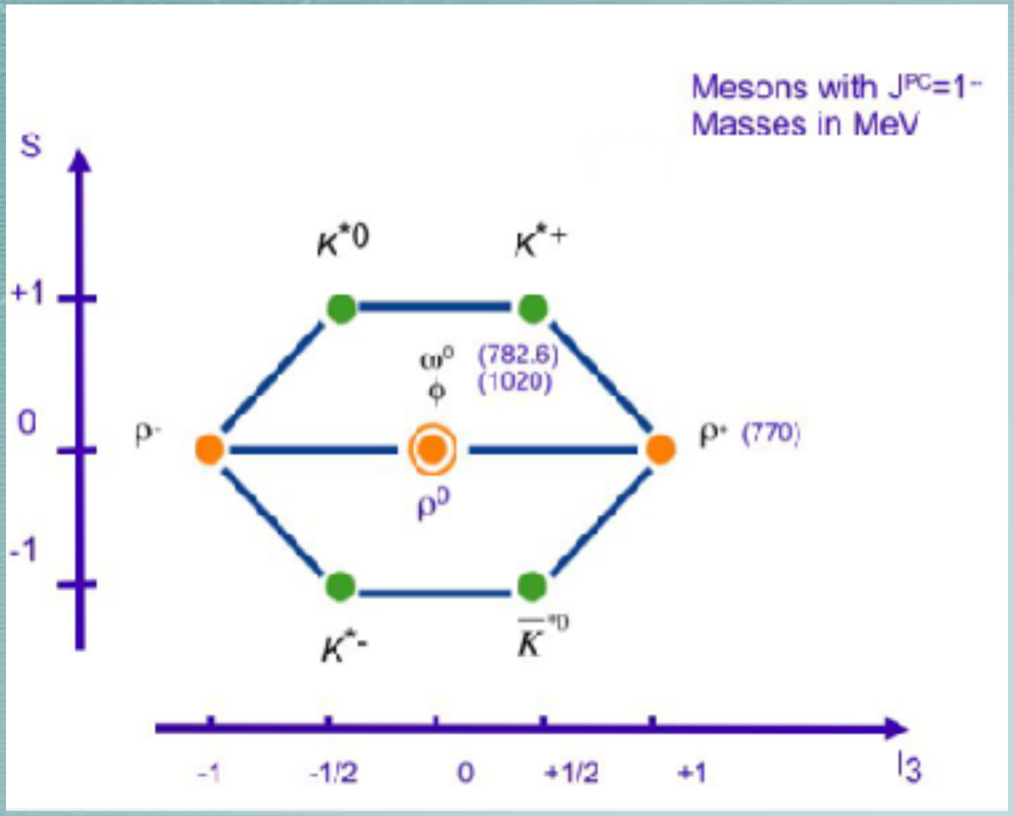
- mass spectrum can be computed (see e.g. M.A.Bedolla, J.Ferretti, C.D.Roberts and E.Santopinto, arXiv:1911.00960 [hep-ph]:
  - QCD inspired potential (Coulomb+linear potential), gaussian wave functions in the three Jacobi coordinates, $\xi_1,\ \xi_2,\ \xi_3$
- Urgent: measure Spin-Parity of the resonances in the spectrum

Jacobi coordinates in the tetraquark



4. Hidden charm tetraquarks make Flavour SU(3) nonets

classical SU(3) nonet



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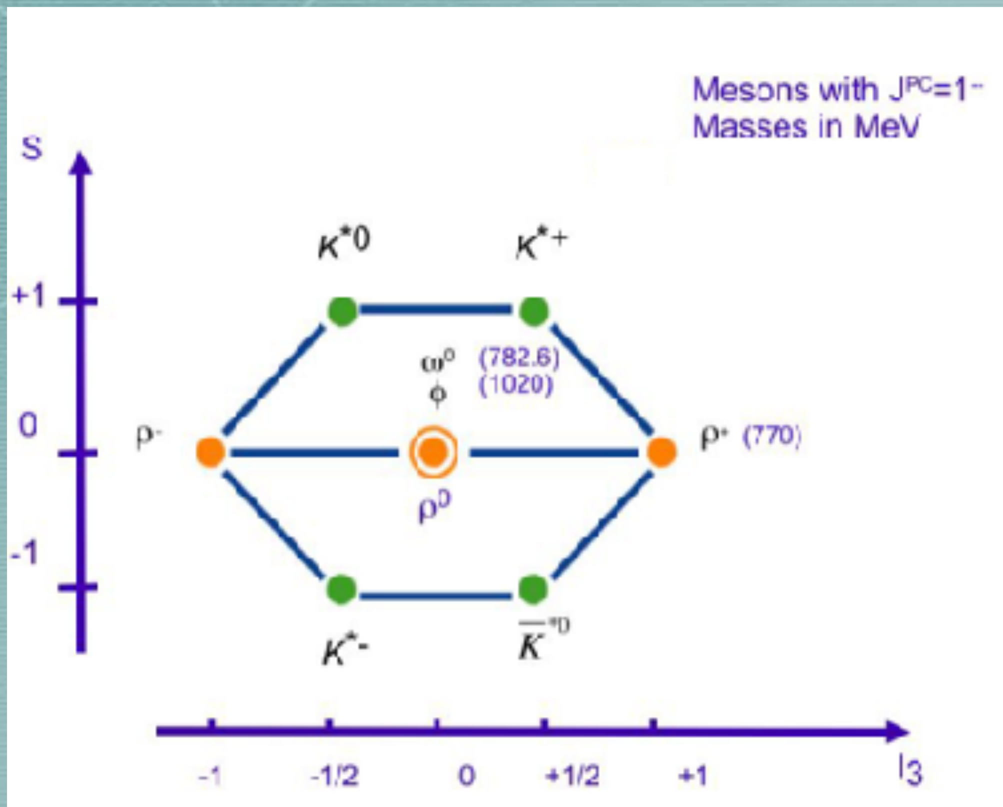
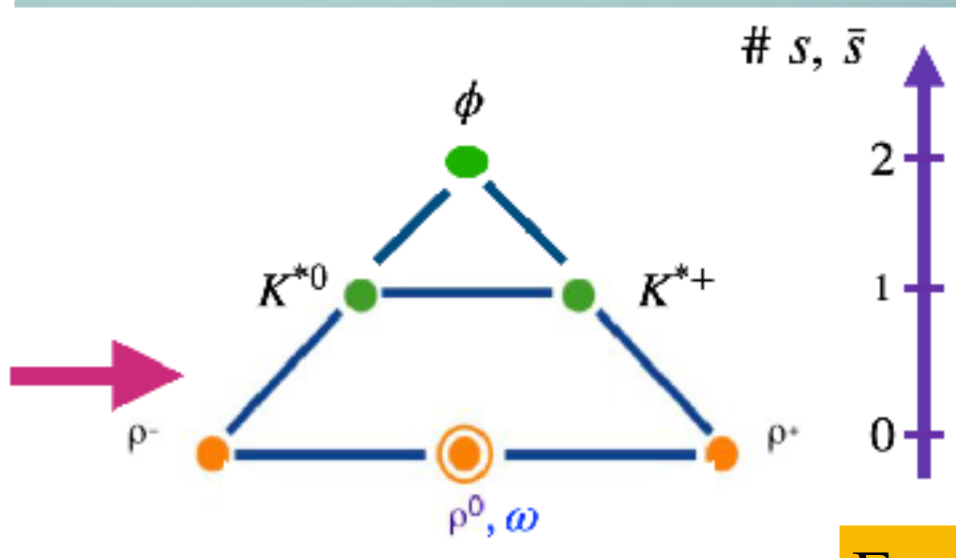


can be plotted v.s. number of strange quarks



Nonet Mixing:
mass differences
$\propto (n_s + n_{\bar{s}})(m_s - m_u)$

Equal Spacing rule, e.g.:

$$\frac{\rho(775) + \phi(1020)}{2} - K^*(892) \sim 6 \text{ MeV}$$

$$\phi(1020) - \rho(775) \sim 244 \text{ MeV}$$

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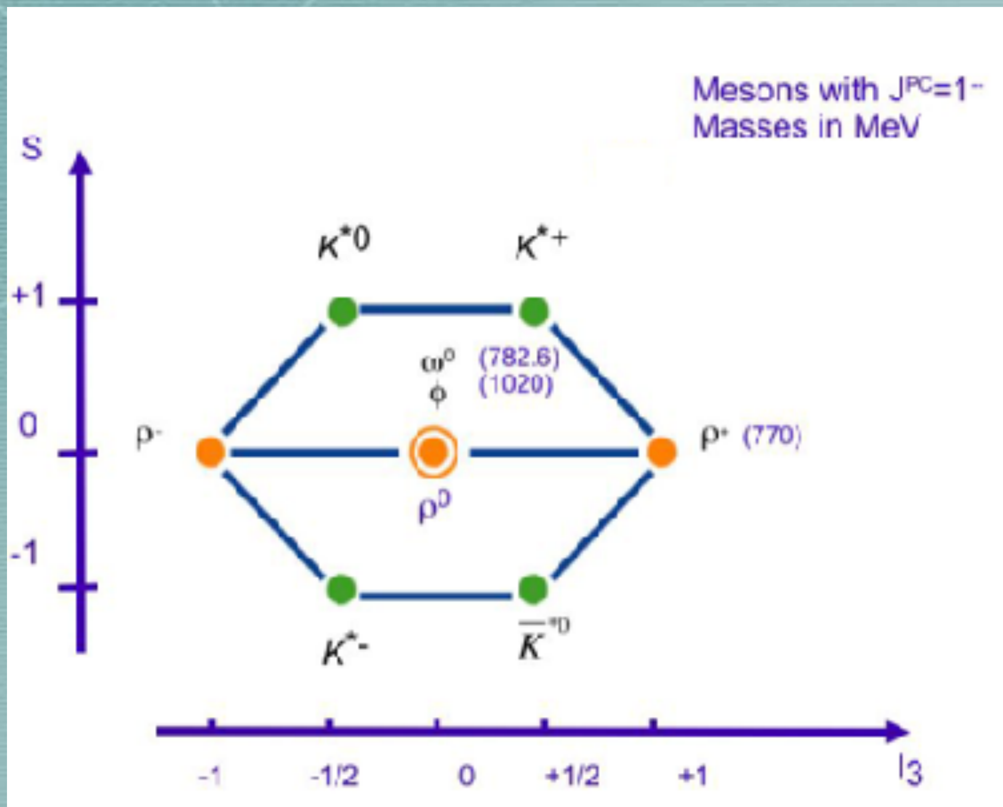

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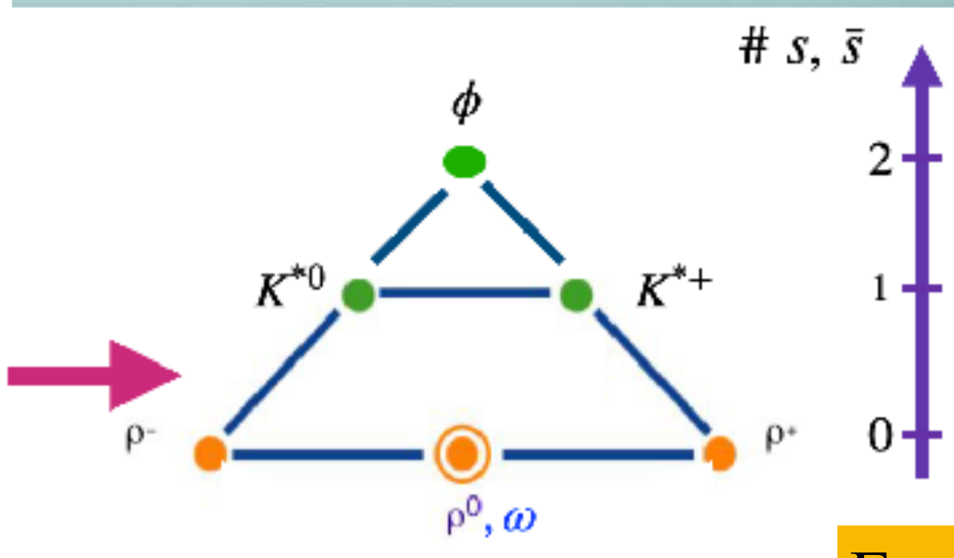

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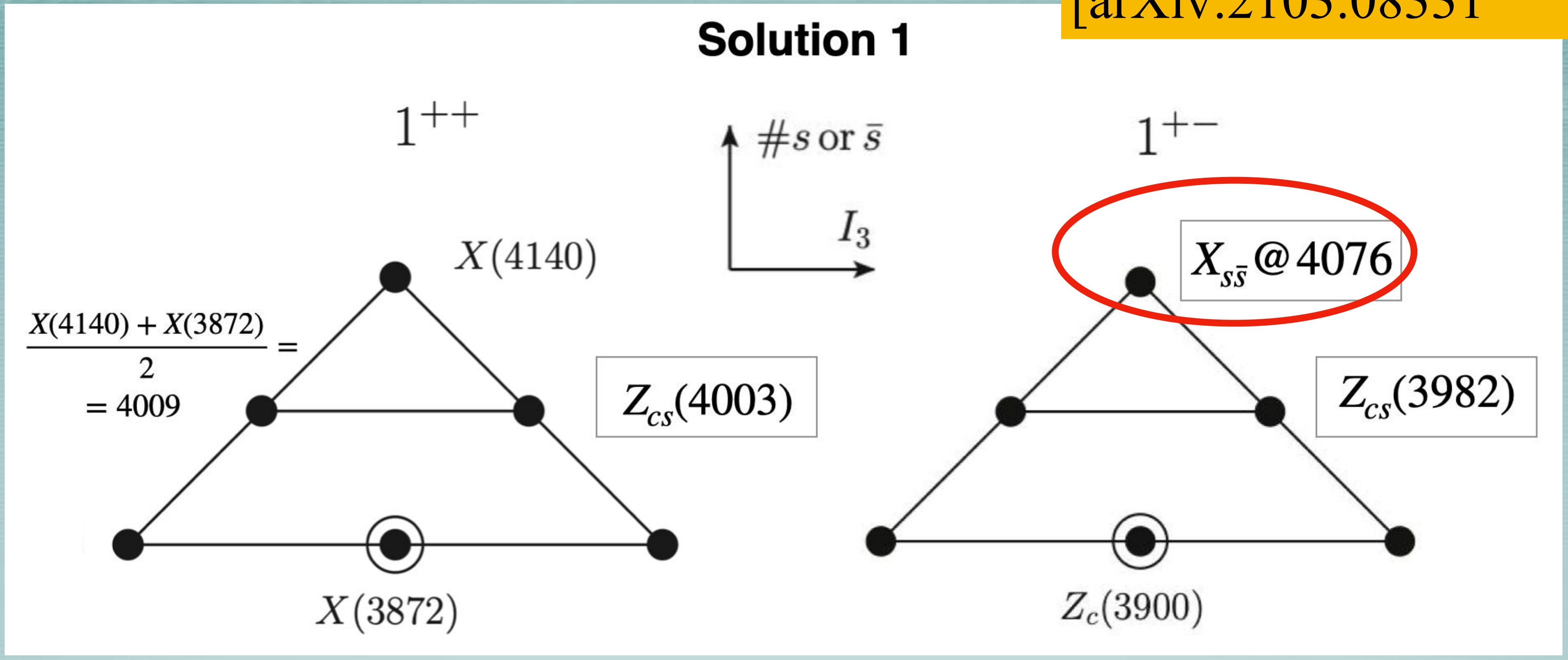
The lightest $J^P = 1^+$ tetraquarks fall into two different nonets

- X(3872) & X(4140) (the lowest $J/\Psi\ \phi$ resonance) belong to one ($J^{PC} = 1^{++}$) nonet, as indicated by the mass difference:
$$Z_c(4140) - X(3872) = 275 \text{ MeV}$$
- $Z_c(3900)$ needs a second ($J^{PC} = 1^{+-}$) nonet
- $Z_{cs}(3985)$ and $Z_{cs}(4003)$ almost completely fill them…

Two solutions

L. Maiani, A. D. Polosa and V. Riquer, [arXiv:2103.08331



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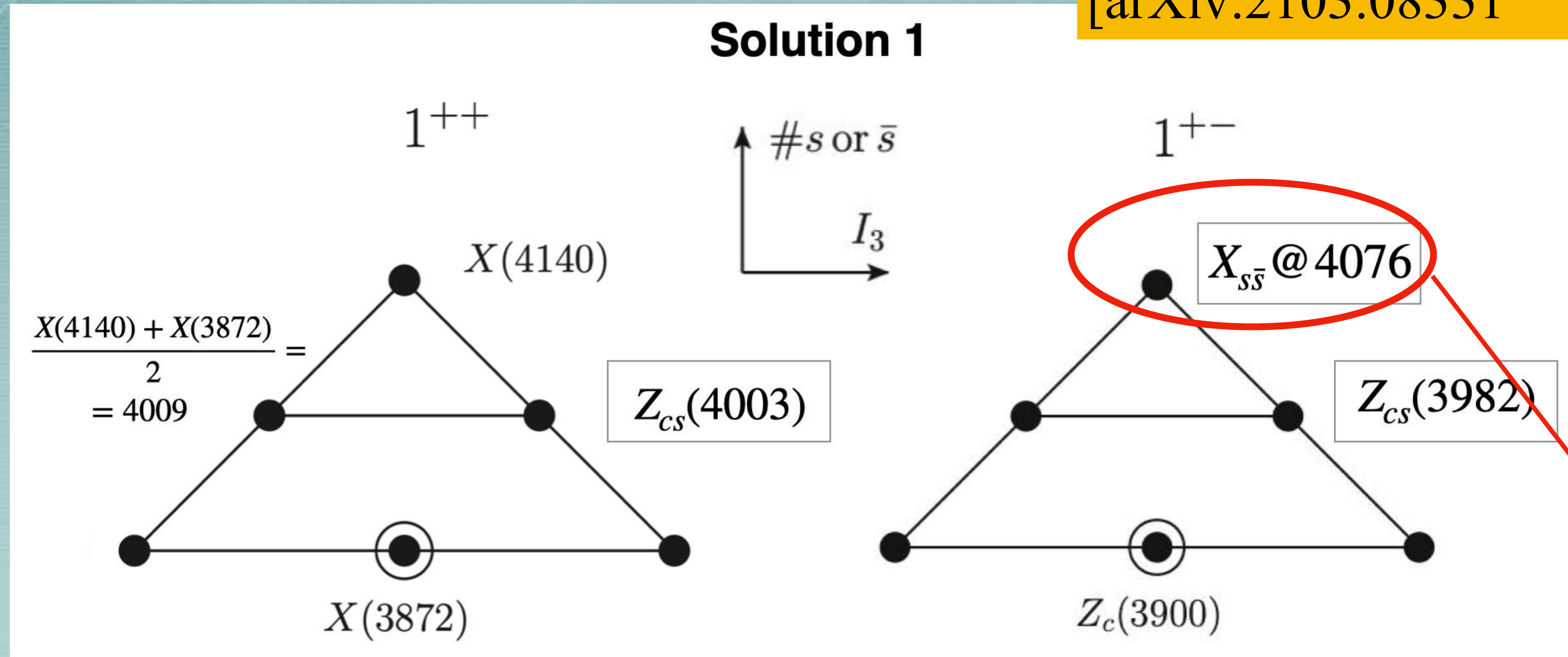
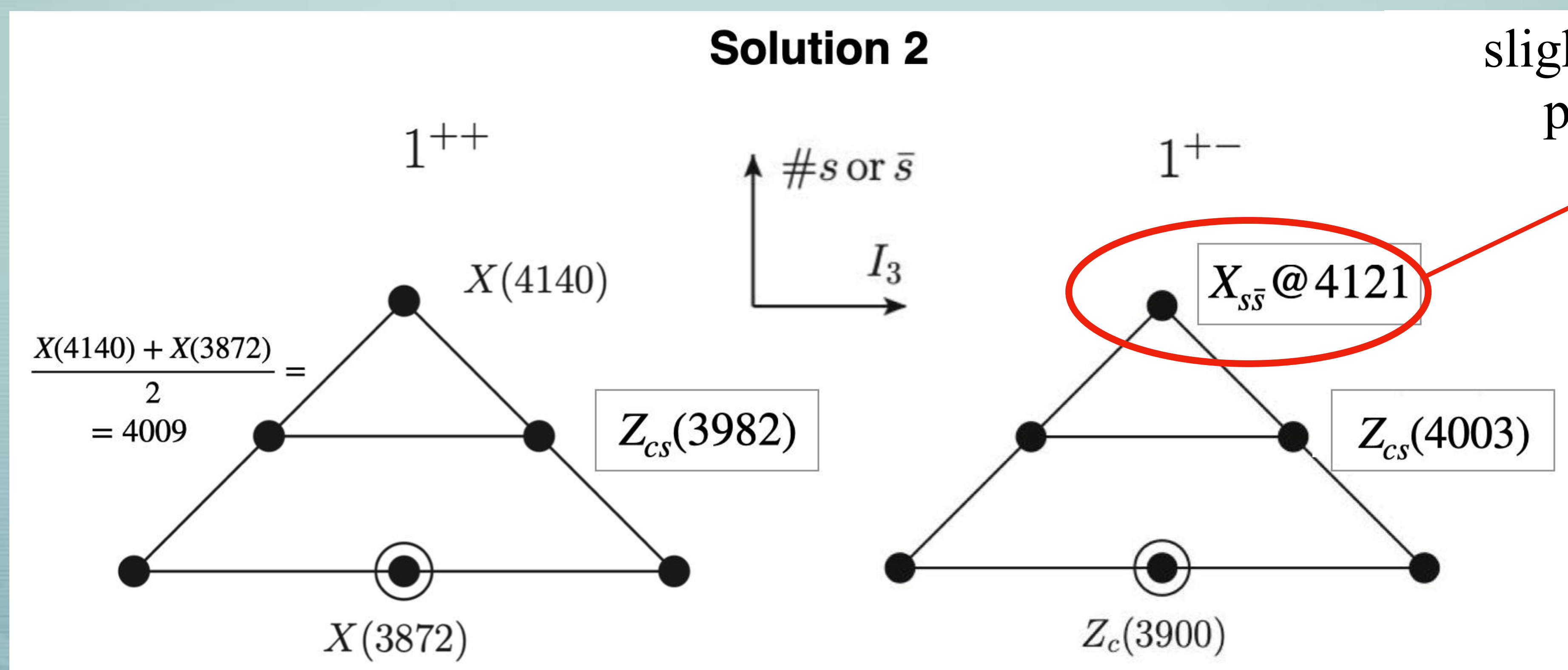


slightly different predictions



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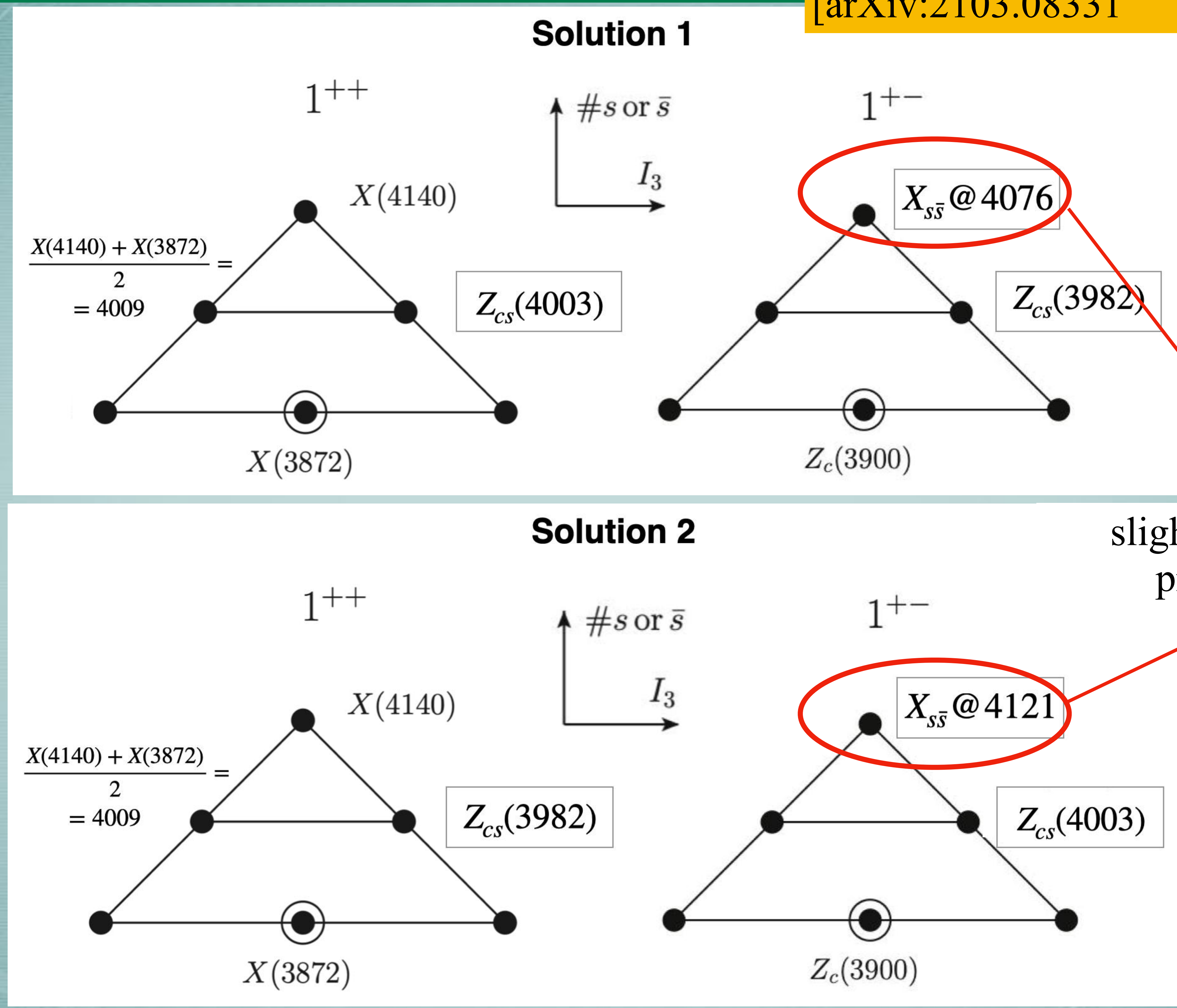

slightly different predictions

Solution 1 is favoured. The scale of the mass differences is in line for both

a well identified shopping list

- $X_{s\bar{s}}$, $M = 4076$ or 4121, decays: $\eta_c\ \phi$, $D_s^*\bar{D}_s$:
- The nonet of $Z_c(4020)$, $J^{PC} = 1^{+-}$, requires a third Z_{cs} at 4150-4170 MeV;
- LHCb indeed sees a $Z_{cs}(4220)$, $J^P = 1^+$or 1^-, which may be too heavy
- the I=1 partners of X(3872), decaying into $J/\Psi + \rho^\pm$
- the I=0 partners of $Z_c(3900)$ and $Z_c(4020)$, possibly decaying into $J/\Psi + f_0(500)$(aka $\sigma(500)$).

Radiative and Pionic Decays of Y(4230)

L. Maiani, A. D. Polosa and V. Riquer, arXiv:2103.14356

- Have been studied by BESIII in e^+e^- annhilation:

$$e^+e^- \to Y(4230) \to \pi + Z_c(3900)/Z_c(4020) \text{ or } \gamma + X(3872)$$

Ref.	Z(Mass)	$\sqrt{s}$ (GeV)	$e+e \to Y(4230) \to \dots$	Q-value	σ (pb)
PRL 115[20]	$Z_c(3885)$	4.226	$\pi^0 Z_c^0 \to \pi^0(D\bar{D}^* + c.c.)^0$	197	77 ± 21
PRD 92[21]	$Z_c(3885)$	4.23	$[\pi^+ Z_c^- + c.c.] \to [\pi^+(D\bar{D}^*)^- + c.c.]$	197	141 ± 14
PRL 112 [22]	$Z_c(4020)$	4.26	$[\pi^+ Z_c^- + c.c.] \to [\pi^+(D^*\bar{D}^*)^- + c.c.]$	65	$(0.65 \pm 0.11)\cdot$ $\cdot(137 \pm 17) =$ $= 89 \pm 19$
PRL 115 [23]	$Z_c(4020)$	4.23	$\pi^0 Z_c^0 \to \pi^0(D^*\bar{D}^*)^0$	65	62 ± 12
PRL 115[24]	$X(3872)$	4.226	$\gamma X \to \gamma\pi^+\pi^- J/\psi$	$--$	$0.27 \pm 0.09 \pm 0.12$
PRD100[25]			γX	354	$5.5^{+2.8}_{-3.6}$
2011.07855[2]	$Z_{cs}(3982)$	4.681	$K^+ Z_{cs}^- \to K^+(D_s^{*-}D^0 + D_s^- D^{*0})$	199	4.4 ± 0.9

TABLE I: e^+e^- annhilation cross sections into exotic hadrons, determined by BES III in the $Y(4230)$ region.

- the cross section at the peak is

$$\sigma_{\text{peak}}(e^+e^- \to Y(4230) \to f) = \frac{12\pi}{M_Y^2}\frac{\Gamma_e\Gamma_f}{\Gamma^2} \qquad \Gamma(Y(4230)) = (56.0 \pm 3.6 \pm 6.9)\ \text{MeV}$$

- Assume Y has a valence quark composition $[cu][\bar{c}\bar{u}]$ or $[cd][\bar{c}\bar{d}]$, then:

- the photon is emitted from the light quark or antiquark:
  $q \to q + \gamma$, same for q̄,

coupling = $e\ Q_{u,d}$, $\frac{e^2}{4\pi} = \frac{1}{137}$

- pionic decay arises from the elementary transitions
- $u \to d\ \pi^+$ or $\bar{d} \to \bar{u}\ \pi^+$ (and similar for π^- and π^0)
- the pion couples to the axial current:

$$\mathscr{H}_I^\pi = \frac{g}{f_\pi}\ \bar{q}\gamma\gamma_5(\nabla \mathbf{M})q,\ f_\pi = 132 \text{ MeV}$$

where M is the meson SU(3) matrix

- The same transitions are operative in

$D^* \to \gamma/\pi + D\ \ (\Delta L = 0)$

and $D_1 \to \pi\ D^*\ (\Delta L = 1)$

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo,
R. Gatto, F. Feruglio and G.Nardulli,
Phys. Rept. **281**, 145(1997).

Is quark dynamics the same in mesons and tetraquarks ?

- the ratio $R_\Gamma = \dfrac{\Gamma(Y4230) \to \pi^0 Z_c(3900))}{\Gamma(Y(4230) \to \gamma X(3872))}$ depends only on g (the dependence upon wave functions cancel out)

- setting:

$$R_\Gamma = R_\sigma = \frac{\sigma(e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0(D\bar{D}^* + c\,.\,c.)^0)}{\sigma(e^+e^- \to \gamma X(3872))} \sim 14$$

we find:

$$Y \to \pi Z/\gamma X : g = 1.0\,^{+0.6}_{\;0.3}$$

compared to

- $D^* \to D\pi : g \sim 0.56$
- $D_1 \to D^*\pi : g = 0.61 \pm 0.8$

Not so different !

Charge conjugation for SU(3) nonets

•A charge conjugation quantum number can be given to each self conjugate SU(3) multiplet according to

$$\mathscr{C} T \mathscr{C} = \eta_T \tilde{T},\ \tilde{T} = \text{transpose matrix},\ \eta_T = \pm 1$$

- η is the sign taken by neutral members, but it can be attributed to all members of the multiplet.
- η =-1 is given to the electromagnetic current while $\eta_Y = -1,\ \eta_{K,\pi} = +1$
- In the exact SU(3) limit, η is conserved in strong and electromagnetic decays.
- Selection Rules: exact SU(3) or first order in m_s-m_u
- Y Decay:

$$\mathscr{H}_I \propto \text{Tr}[Y[M,X]]\ (\eta_X = +1),\ \mathscr{H}_I \propto \text{Tr}[Y\{M,Z\}] \quad (\eta_Z = -1)$$

- Z_{cs}, X_{cs} decay:

$$\mathscr{H}_I = \lambda\mu\ \psi\ (\text{Tr}\{Z,M\})\ ([\mu] = \text{mass}),\ = \lambda\ \mu\ [Z^-_{cs}\ (\psi K^+) + c\,.\,c.]$$

$$\mathscr{H}_I = \lambda\ i\psi\ \text{Tr}([\epsilon_8[X,M]]) \sim \lambda\ (m_s - m_u)\ i[X^-_{cs}\ (\psi K^+) - c\,.\,c.]$$

Isospin and Flavour SU(3) Selection Rules

Isospin:

- $Y(I=0) \nrightarrow \pi^{\pm,0}X^{\mp,0}$;
- $Y(I=1) \to \pi^+X^- - \pi^-X^+$;
- $Y(I=0) \to \pi^+Z_c^- + \pi^-Z_c^+ + \pi^0Z_c^0$, same for Z_c';

SU(3)

- $Y(I=0,1)$ or $Y([cs][\bar{c}\bar{s}]) \to (K^+X_{cs}^- - c\,.\,c.)$ and $(K^+Z_{cs}^- + c\,.\,c.)$;
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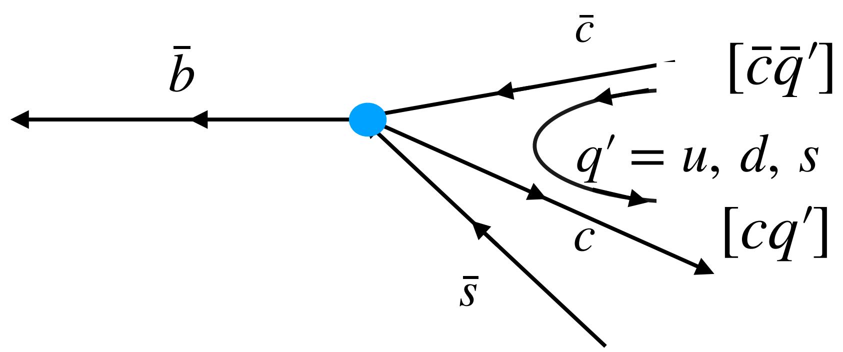
BES III should see in his spectrum two more Z_{cs} :
$Z_{cs}(4003)$ and the Z_{cs} associated to the nonet of $Z_c(4020)$

The LHCb way

- The main process: $B^+ \to K^+ \, \phi \, J/\Psi$

L. Maiani, A. D. Polosa and V. Riquer

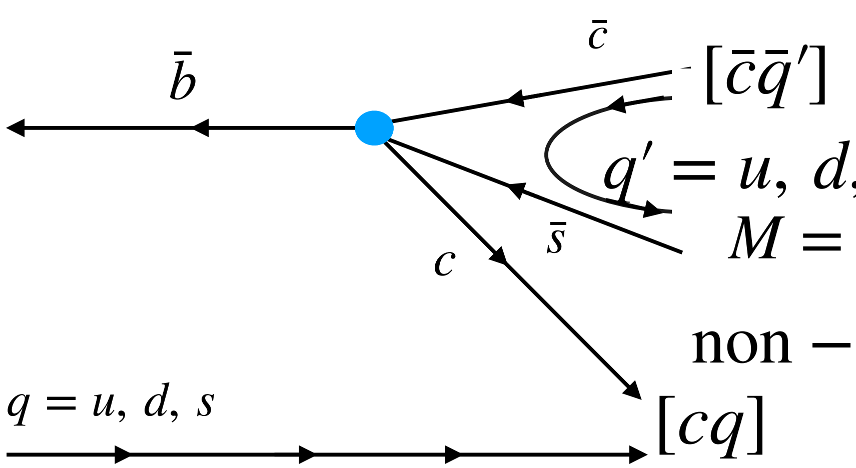
- B decays into meson + tetraquark are described by two quark diagrams:



$$\text{diagonal Tetraq. only} = X_{u,\,d,\,s}$$

$$M = (\bar{s}q) = K^+,\, K^0, \phi$$

(a)



$$M = (\bar{s}q') = K^+,\, K^0,\, \phi$$

$$\text{non - diagonal Tetraq. possible} = X_{u\bar{d},u\bar{s},\dots}$$

(b)

e.g.

$$B^+ \to K^+ + X_u/X_d/X_s$$
$$B^+ \to \phi + X_{us}$$

10

Originate from the weak decay

$$\bar{b} \to \bar{c} + (c + \bar{s})$$

The strange antiquark may form a meson with
(a) the spectator quark
(b) a quark from the sea

diagonal tetraqs. are formed with K+
strange tetraqs. with ϕ

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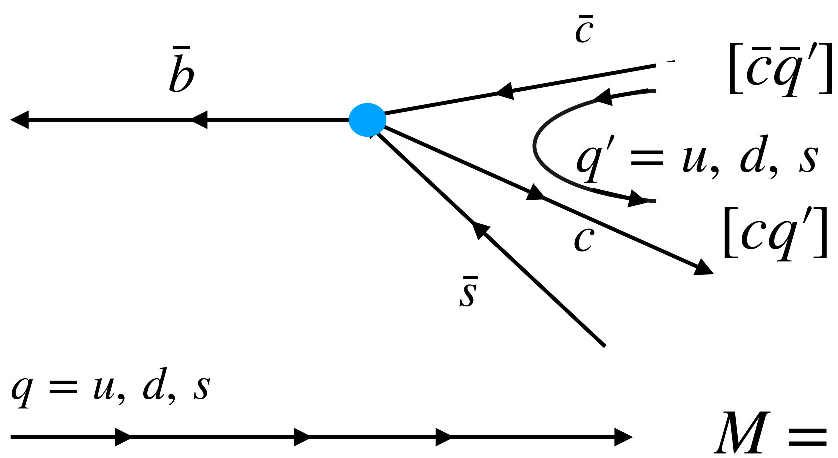

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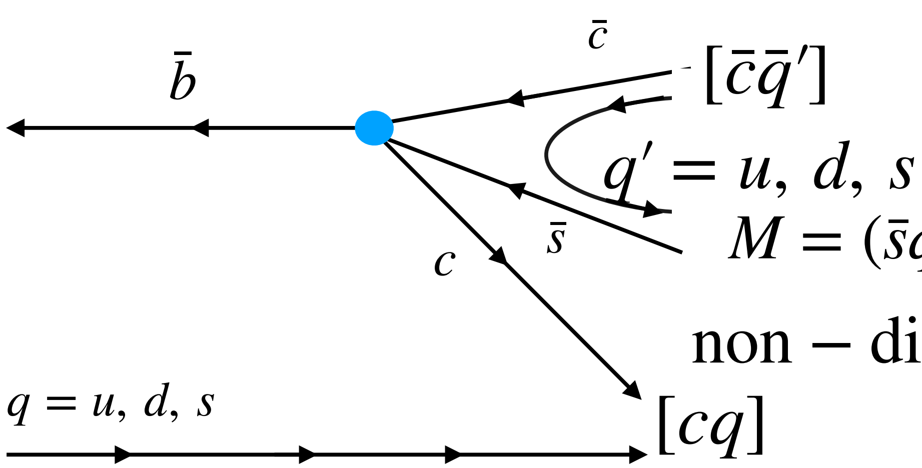

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X has been abundantly seen
Is there a selection rule discriminating Z nonet vs X's ?

The $X^{\pm}$ puzzle

- $X^+([cu][\bar{c}\bar{u}])$ and X^- must exist, not far from 3872 MeV !
- expected decays: $X^+ \to D^0\bar{D}^{*+} + c.c.,\ J/\Psi + \pi^+\pi^0$
- the first channel may be below thresold, the second must exist
- There is only a very old limit by BABAR:

$$R_{2\pi}^{-} = \frac{Br(B^0 \to K^+X(3872)^- \to K^+J/\psi\ \pi^0\pi^-)}{Br(B^0 \to K^0X(3872) \to K^0J/\psi\ \pi^+\pi^-)} < 1$$

- From more recent data on B^+, B^0 and B^0_s decays, we derive the bounds

L. Maiani, A. D. Polosa and V. Riquer, Phys. Rev. **D 102** (2020), 034017

$$0.05 < R_{2\pi}^{-} = \frac{Br(B^0 \to K^+X(3872)^- \to K^+J/\psi\ \pi^0\pi^-)}{Br(B^0 \to K^0X(3872) \to K^0J/\psi\ \pi^+\pi^-)} < 0.57$$

- Can we afford a new try?

On the *not so bright* side…

- $\Gamma \propto q^5$: the decay $Y(4230) \to \pi Z_c(4020)$ is strongly suppressed
- rate would be OK if the signal comes from the next line, Y(4320): is it possible?
- the $J/\Psi\ \phi$ resonance X(4274) is classified by LHCb as $J^P = 1^+$, but for color 3 diquarks, there may be only one $J^P = 1^+$, which is X(4140). Could there be also color 6 ***diquarks quarks*** as suggested

J. Wu, et al., Phys. Rev. **D 94**, 094031(2016)

(but no evidence color of color 6 diquarks from lattice calculations)

- Can we exclude that the X(4274) signal consists of two almost degerate lines with $J^+ = 0^+$, $J^P = 2^+$?

In conclusion….

- The existence of exotic SU(3) flavour multiplets, with a characteristic scale of symmetry breaking is a distinctive prediction of compact tetraquarks.
- The newly found strange exotics are close in mass, like X(3872) and Z_c(3900), and fit into their nonets: a clear score in favour.
- Decays: $Y(4230) \to \gamma\, X(3872)$ and $\pi\, Z(3900)$ are consistent with D* and D1 decays
- $Y \to \pi\, Z(4020)$???? needs clarification
- Much remains to be done, to produce more precise data and to search for still missing particles, some with well defined mass and decay modes
- it is a ***tough order***: more luminosity, better energy definition, detectors with exceptional qualities… a lot of work…
- a much closer exchange between theory and experiment is needed
- like the exchange that took place in the sixties and seventies, and led to the quark picture of mesons and baryons.

Starting in 1957, a new generation of film Directors, in France and Italy, proposed a completely new way of making movies…
the were called
La Nouvelle Vague
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Similarly, we assist now to the discovery of a completely New Wave of Exotic Hadrons…

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Like La Nouvelle Vague of film directors

Let us follow the Wave
and face the challenges !!