Three Lextures on Exotic Hadrons

From Hidden Charm to Doubly Charmed Mesons

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Peking University Lecture 1: The Overall Panorama

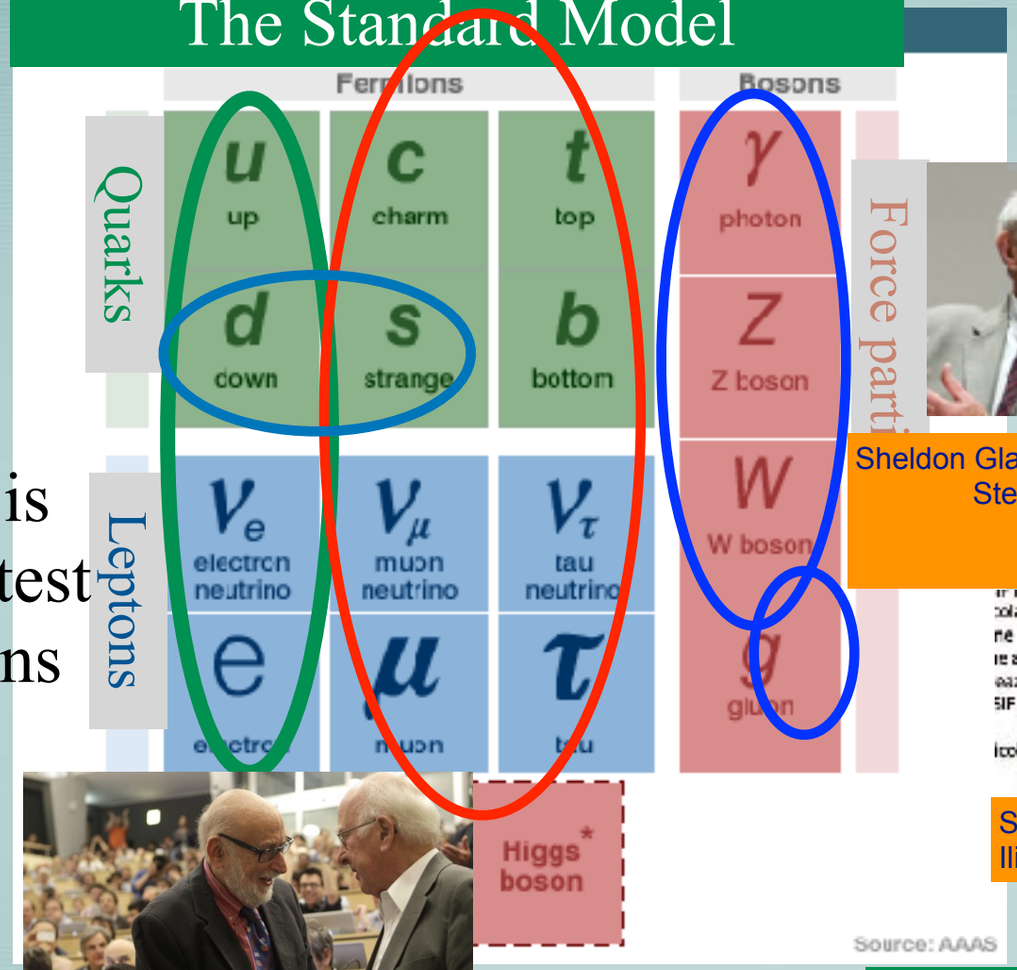
Constituents of matter and fundamental forces (after 2012)

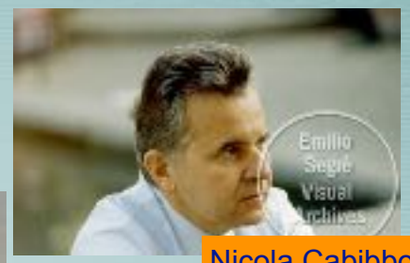


Murray Gell-Mann

Ordinary matter is made of the lightest quarks and leptons

The Standard Model





Nicola Cabibbo



Sheldon Glashow
Steven Weinberg
Abdus Salam
@ ICTP Trieste



Carlo Rubbia



Sheldon Glashow, John Iliopoulos, Luciano Maiani



Makoto Kobayashi , Toshihide Maskawa

Robert Englert e Peter Higgs



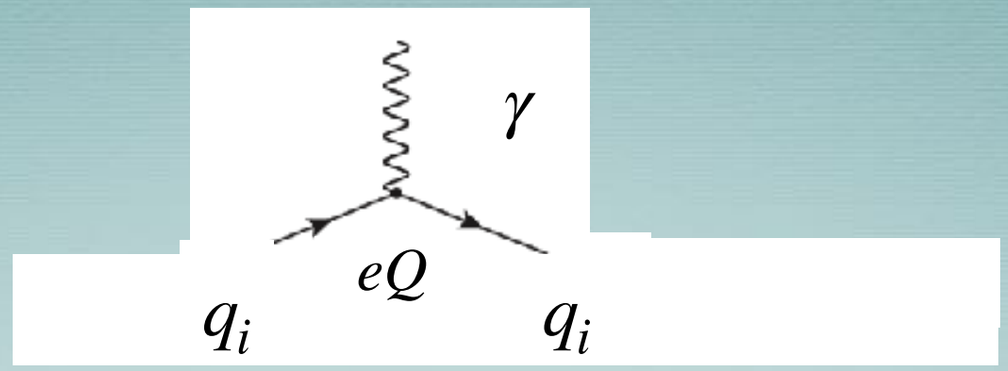
Heavier quarks are unstable: what is their role in the Universe?

Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free Gross&Wilczeck, Politzer (1973)

1. Gauge Theory of Particle Interactions (circa1972)

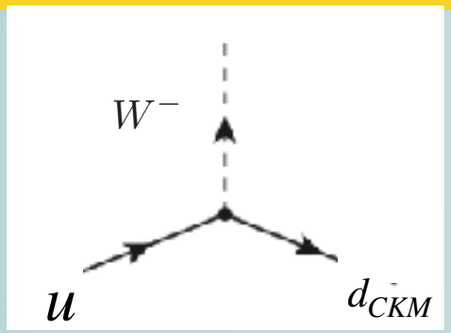
Quark and Leptons interact with 3 kinds of vector bosons, to produces Electromagnetic, Weak and Strong Interactions

E. M. INTERACTIONS= QED



WEAK INTERACTIONS (after GIM and CKM)

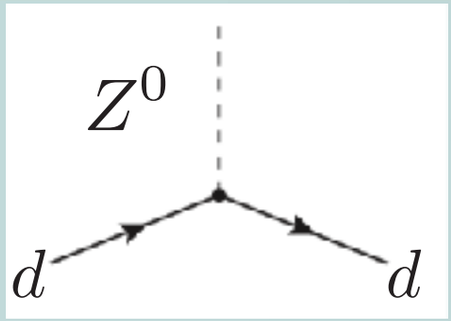
Quark-charged currents



$(c \to s_{CKM},\ t \to b_{CKM})$

$$\begin{bmatrix} d_{CKM} \\ s_{CKM} \\ b_{CKM} \end{bmatrix} = U_{CKM} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

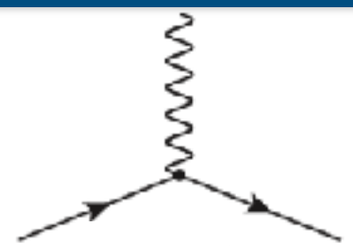
Quark-neutral currents



$(s \to s,\ \ b \to b)$

without GIM, $d + Z^0 \to s$: strangeness changing neutral currents would be allowed

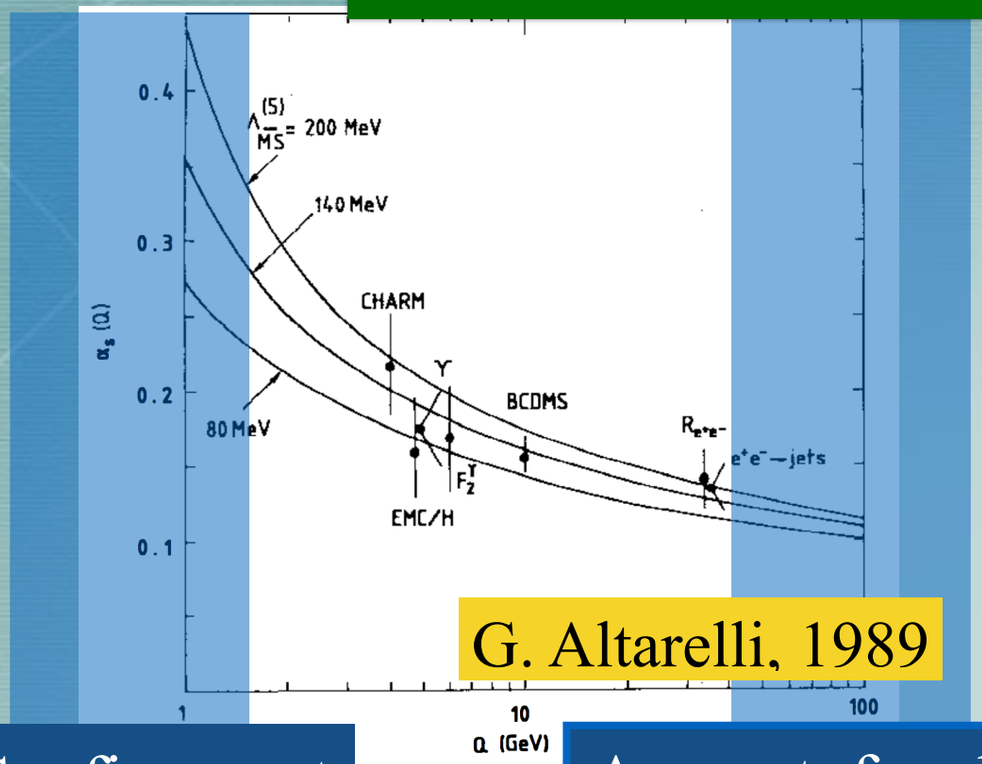
STRONG INTERACTIONS= COLOUR SU(3)



$q_i \qquad g_s\ \mathbf{T}^A_{ij} \qquad q_j \quad (A = 1,\ \ldots,\ 8)$

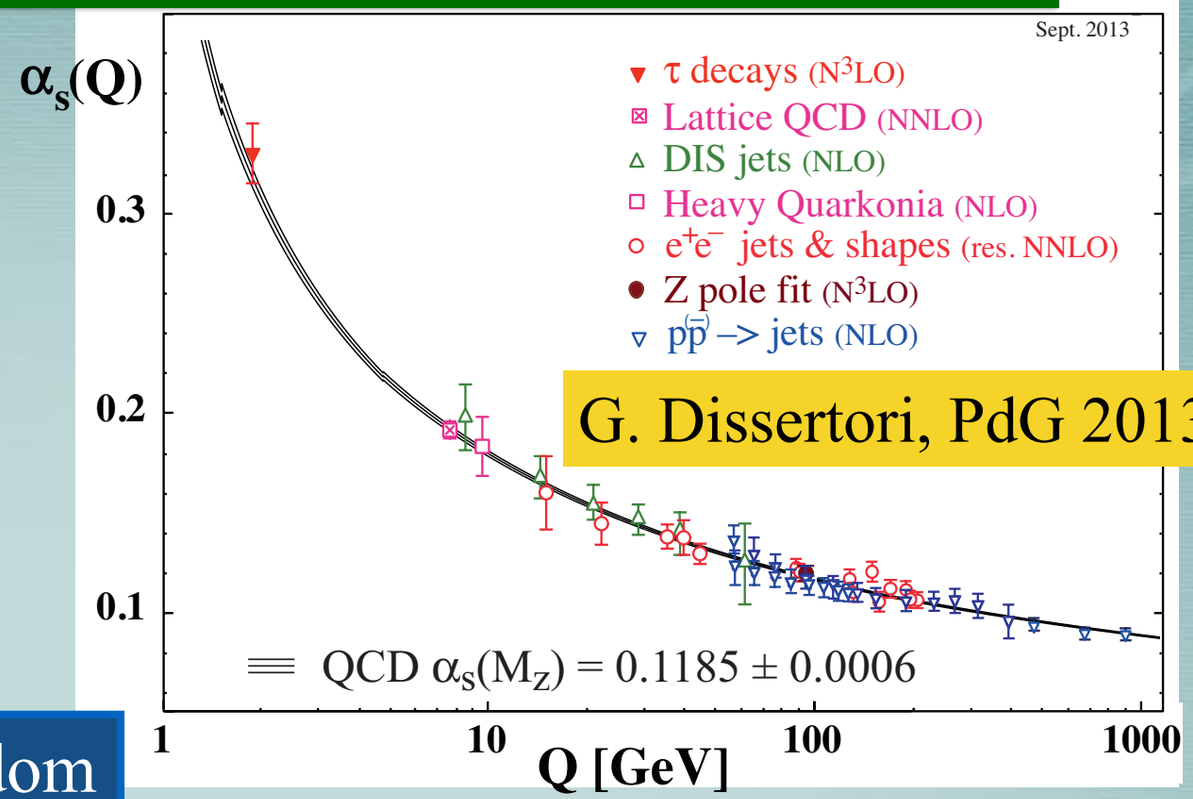
Quantum Chromo Dynamics is asymptotically free.
Critical parameter:
$\Lambda_{QCD} = 0.25$ GeV

QCD, Asymptotic Freedom and Heavy Quarks



G. Altarelli, 1989

Confinement



G. Dissertori, PdG 2013

Asympt. freedom

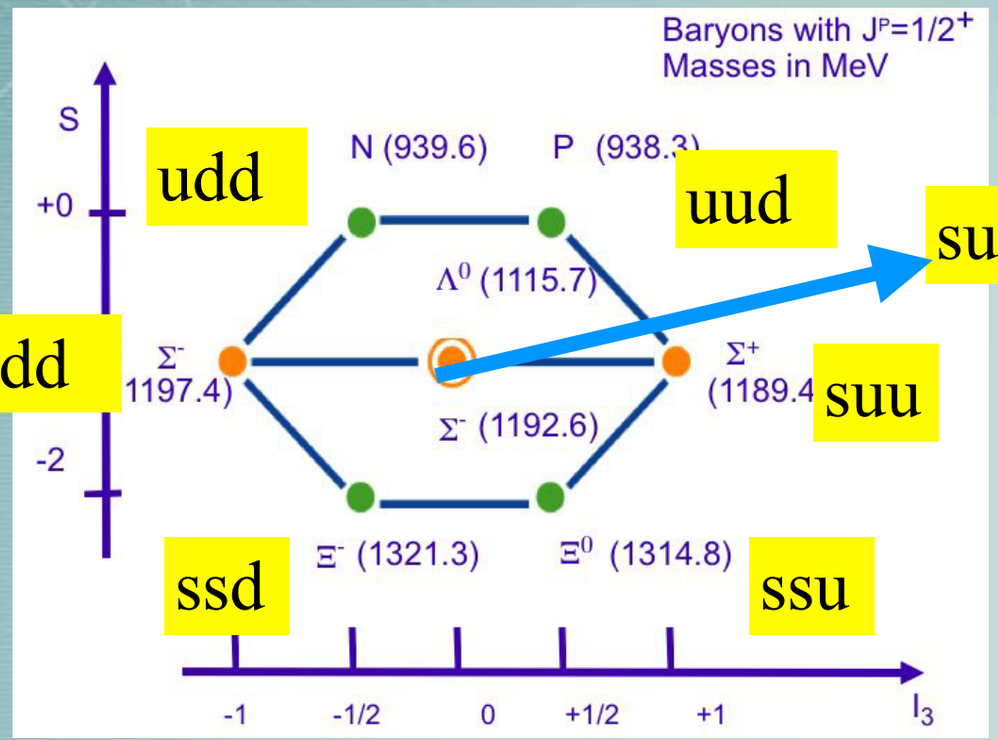
- At distances of order $M_{c,b}^{-1}$, QCD interaction is already reduced, to allow perturbation theory to be, at least, a good guide. T. Appelquist and H. D. Politzer, Phys. Rev. Lett. **34** (1975) 43
- This is what makes Charmonium Spectrum calculable, as anticipated by Appelquist and Politzer

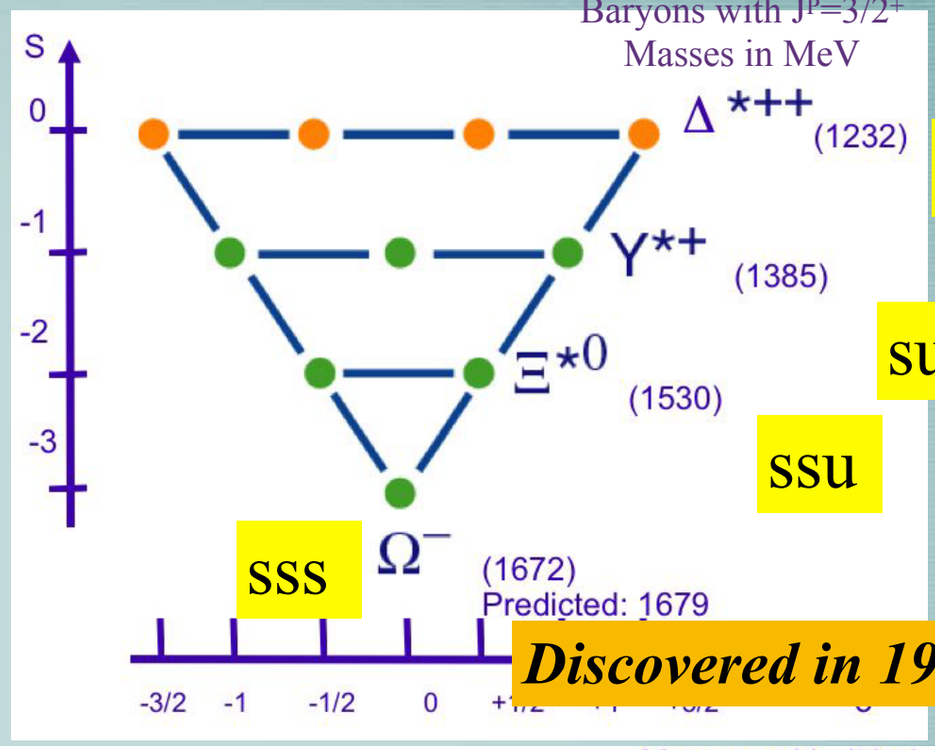
Heavy quarks ($m_Q >> \Lambda_{QCD}$):

- inclusive decays are calculable like deep inelastic processes;
- $c\bar{c}$ or $b\bar{b}$ bound states involve short distance forces: a calculable spectrum of charmonia/bottomonia;
- inside hadrons, $c\bar{c}$ or $b\bar{b}$ pairs are not easily created or destroyed:
- a hadron decaying into J/Ψ or Υ + … indicates a valence $c\bar{c}$ or $b\bar{b}$ pair
- ***heavy-quark counting is possible***.

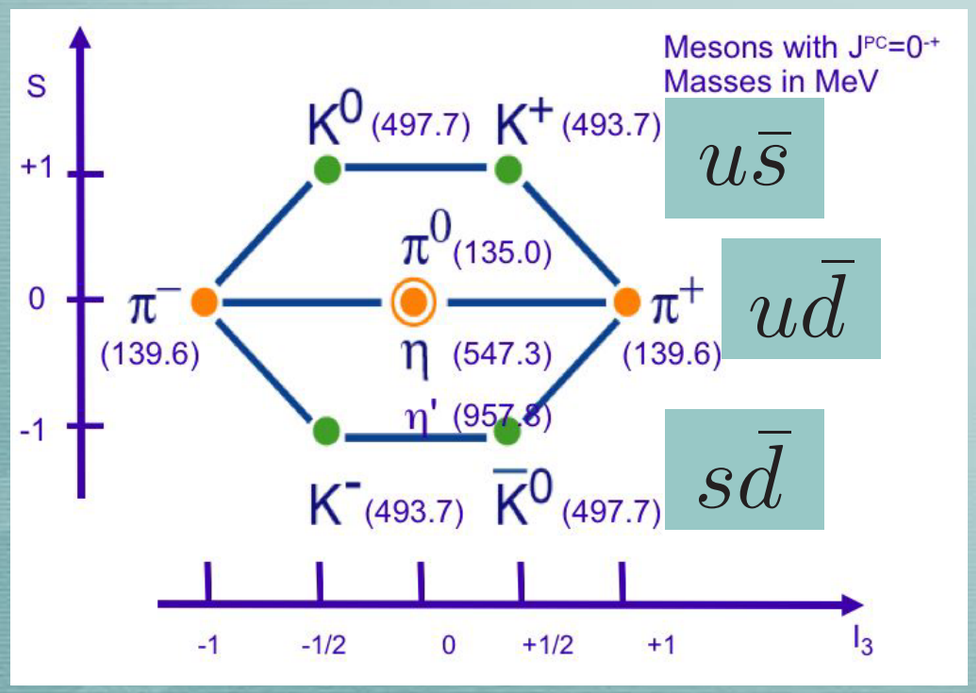
2. Quark composition of the lowest lying Baryons and Mesons

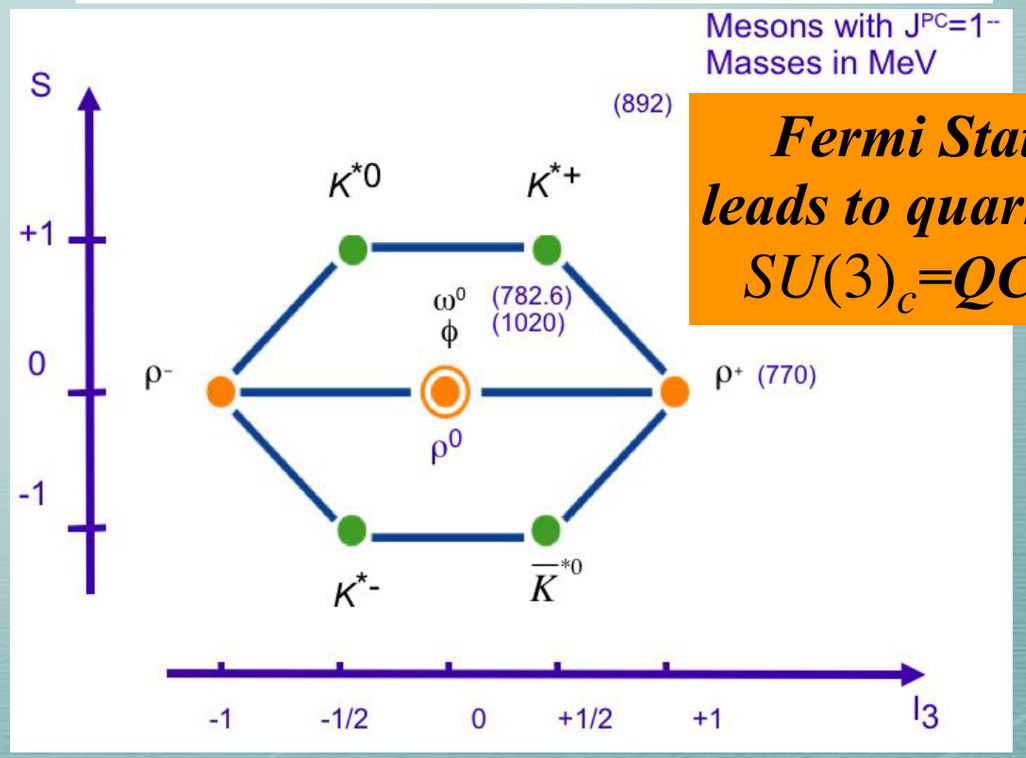
Multiplets of $SU(3)_{flavour}$ symmetry, broken by the mass difference $m_s - m_u \sim 150$ MeV.





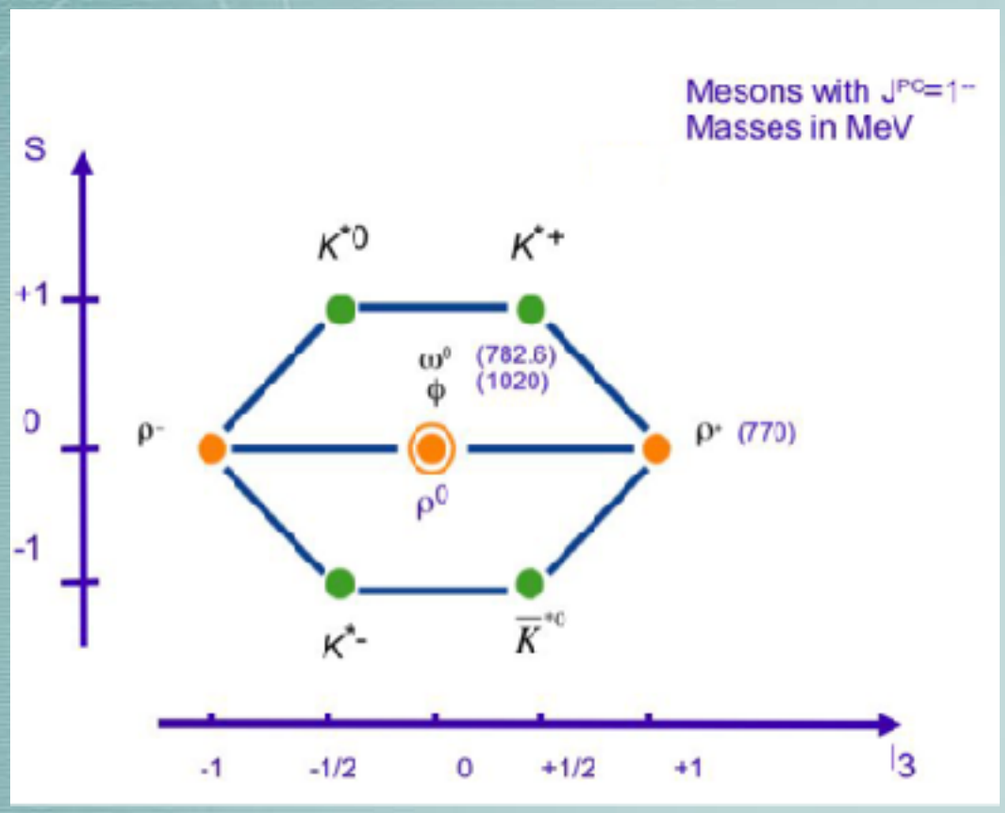
Discovered in 1964



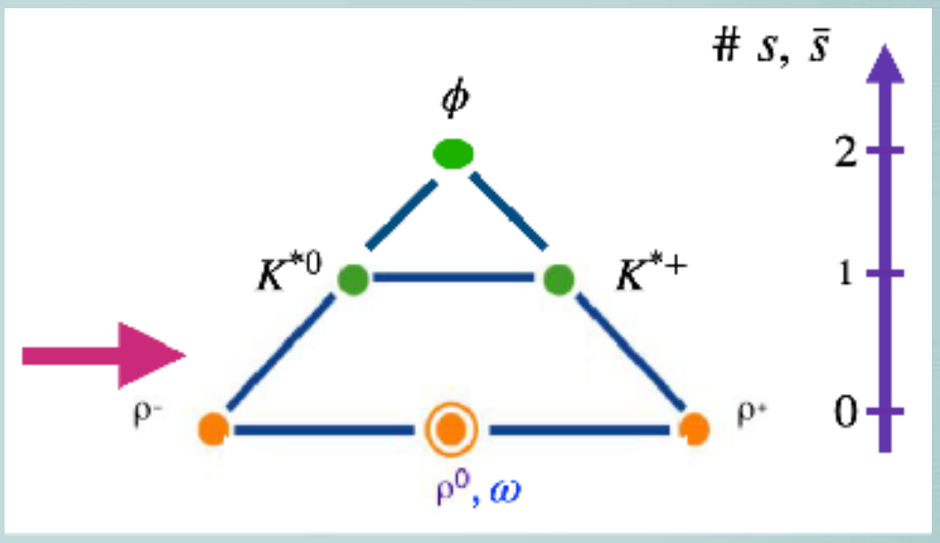


Fermi Statistics leads to quark colour $SU(3)_c$=QCD !!!!

Octet mesons vs number of strange quarks



can be plotted v.s. number of strange quarks/antiquarks



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

equal-spacing rule:

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

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.

3. Unanticipated charmonia X, Y, Z… and more

- ***Unanticipated, hidden charm/beauty resonances not fitting in predicted charmonium/bottomonium spectra have been observed.***

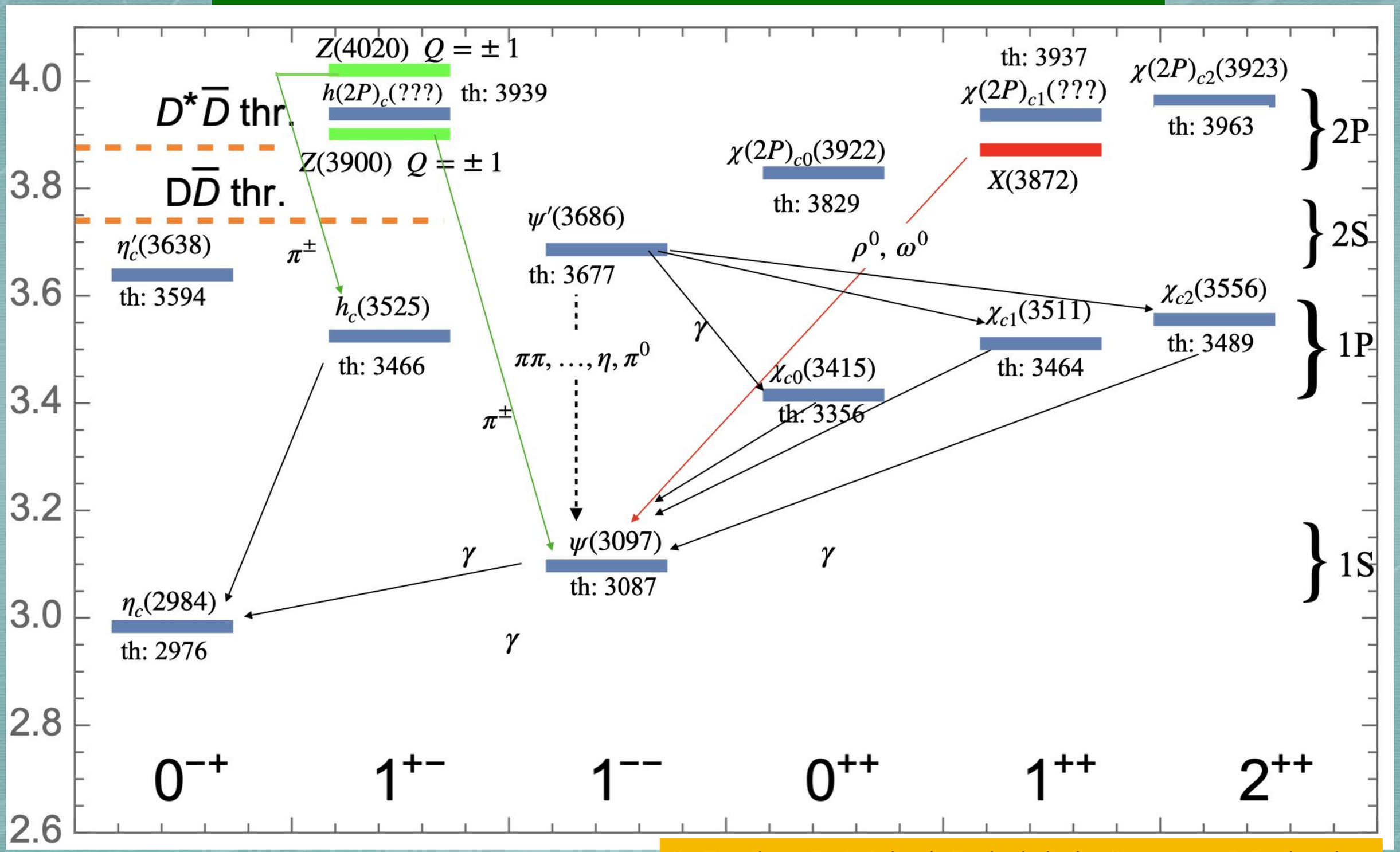
- **X**, e.g. *X*(3872): neutral, typically seen in $\Psi + 2\pi$, positive parity, $J^{PC} = 0^{++}, 1^{++}, 2^{++}$

- **Y**, e.g. Y(4260): neutral, seen in e^+e^- annihilation with *Initial State Radiation* (ISR):

$e^+e^- \to e^+e^- + \gamma_{ISR} \to Y + \gamma_{ISR}$, therefore $J^{PC} = 1^{--}$ (P-wave?)

- **Z**, e.g. Z(4430): typically $J^{PC} = 1^{+-}$, charged or neutral, 4 valence quarks manifest, mostly seen to decay in $\Psi + \pi$ and some in $h_c(1P) + \pi$;
  valence quarks: $c\bar{c}u\bar{d}$; Z_b also observed ($b\bar{b}u\bar{d}$).

Charmonium Spectrum, S and P waves.
Cornell Potential with first order relativistic corrections.

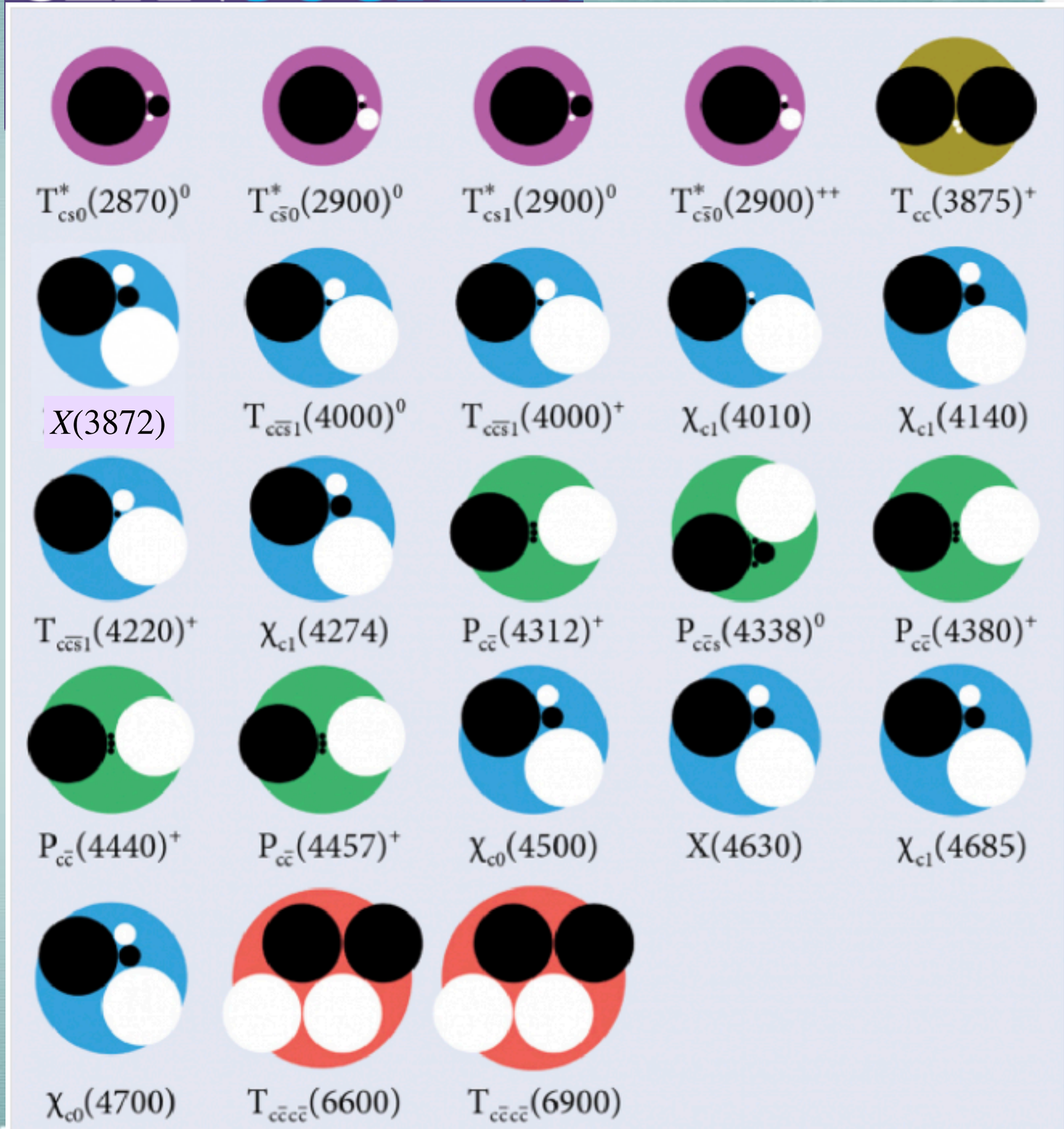


O. Benhar, L. Maiani, Relativistic Quantum Mechanics
Taylor & Francis (2024), Chapt. 18.

The first unexpected hadron , the $X(3872)$, was discovered by BELLE in 2003, confirmed by BABAR and seen in many other High Energy experiments.

Since then, a wealth of Exotic Hadrons have been observed, mesons and baryons that cannot be described by the classical Gell-Mann configurations ($q\bar{q}$) and (qqq).

CERN COURIER November-December 2024



Expected and Unexpected Charmonia in 2015

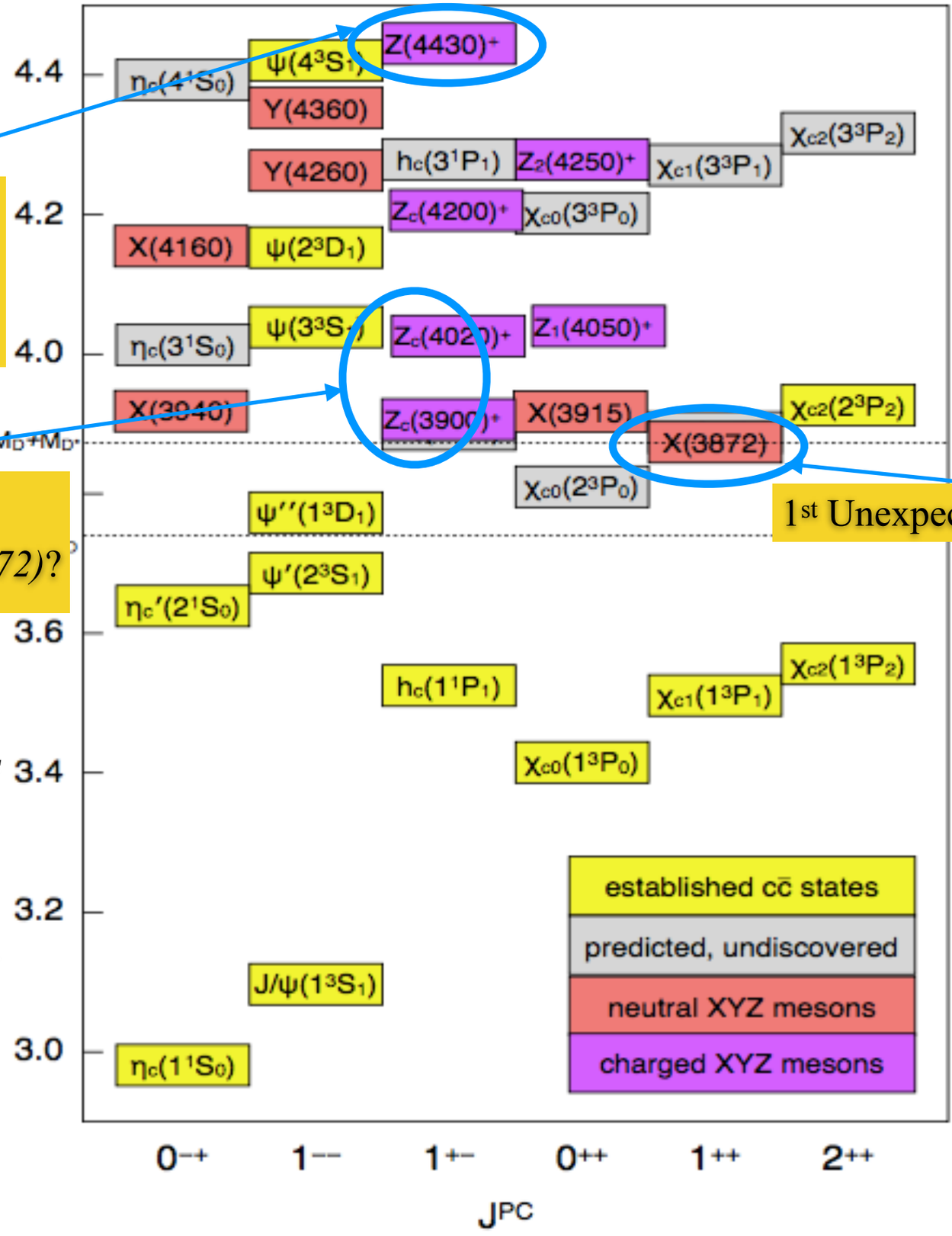
figure by:
S. L. Olsen (2015)
arXiv:1511.01589

2nd Unexpected (BELLE, 2008; doubts by BaBar; confirmed by LHCB, 2014)
first charged, a radial excitation?

3rd Unexpected (BES III, 2013):
ground state Tetraquarks with X(3872)?

$Z_c(3900) \to \pi^{\pm} J/\Psi$. *If interpreted as a new particle, it is unusual in that it carries an electric charge and couples to charmonium.*
BESII, Phys. Rev. Lett. **110** (2013) 252001

$Z_c(4020) \to \pi^{\pm} h_c$... *carries an electric charge and couples to charmonium*.
BESII, Phys. Rev. Lett. **111** (2013) 242001



1st Unexpected (BELLE, BaBar, 2003)

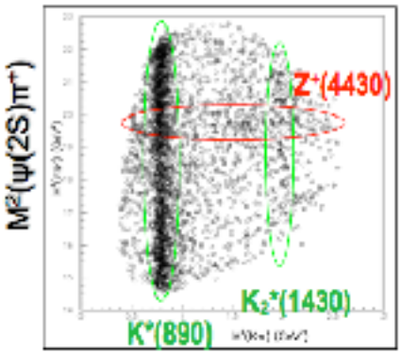
4. The saga of $Z^{\pm}(4430)$

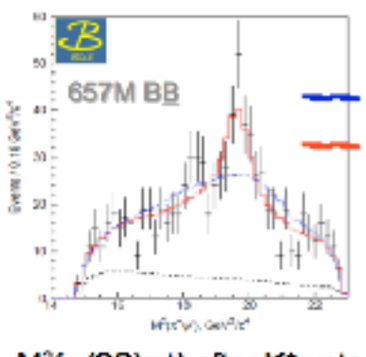
Belle observed $Z(4430)^{\pm}\to\psi(2S)\pi^{\pm}$

PRL100, 142001 (2008)

- Found in $\psi(2S)\pi^+$ from $B\to\psi(2S)\pi^+K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B\to\psi(2S)\pi^+K$
- $B\to\psi(2S)\pi^+K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^*\to K\pi^+$ resonances only

  all known $K^*\to K\pi^+$ and $Z^+\to\psi(2S)\pi^+$ ⇨ favored by data





Significance: 6.4σ

fit for model with K*'s only

fit for model with K*'s and Z

$$M = 4433\ ^{+15\,+19}_{-12-13}\ \text{MeV}$$

$$\Gamma = 107\ ^{+86+74}_{-43-53}\ \text{MeV}$$

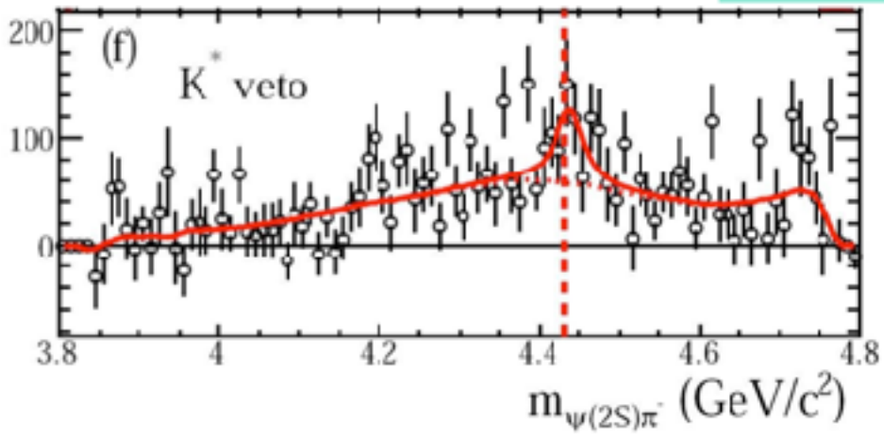
PRD80, 031104 (2009)

- [cu][cd] tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*\underline{D}_1(2420)$ molecule? should decay to $D^*\underline{D}^*\pi$

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BaBar doesn't see a significant $Z(4430)^+$

PRD79, 112001 (2009)



"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

$BF(B^0\to Z^+K)\times BF(Z^+\to\psi(2S)\pi^+) < 3.1\times10^{-5}$

Belle PRL: $(4.1\pm1.0\pm1.4)\times10^{-5}$

44

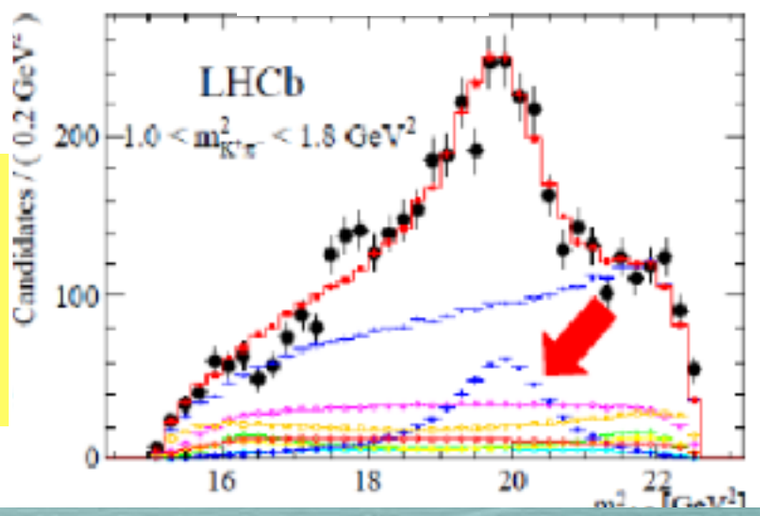
- Babar inserts in the fit all K* resonances
- is Belle effect due to K* reflections ???

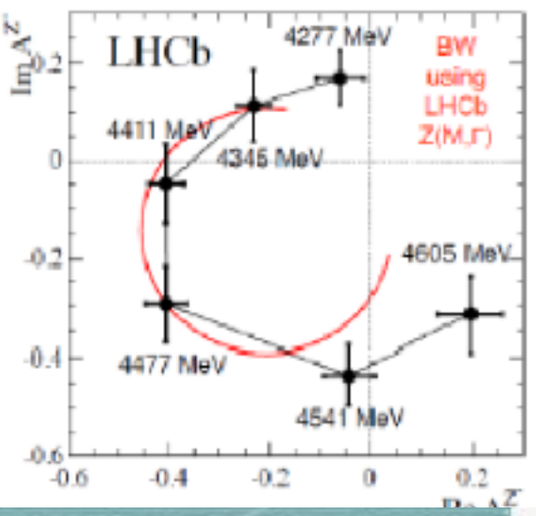
LHCB (2014):

- confirms BELLE's observation of a bump, $J^{PC} = 1^{+-}$

- CANNOT be built as a molecule of standard states: D^*D_1= in S-wave may have J=1 but has negative parity.
  - A genuine resonance

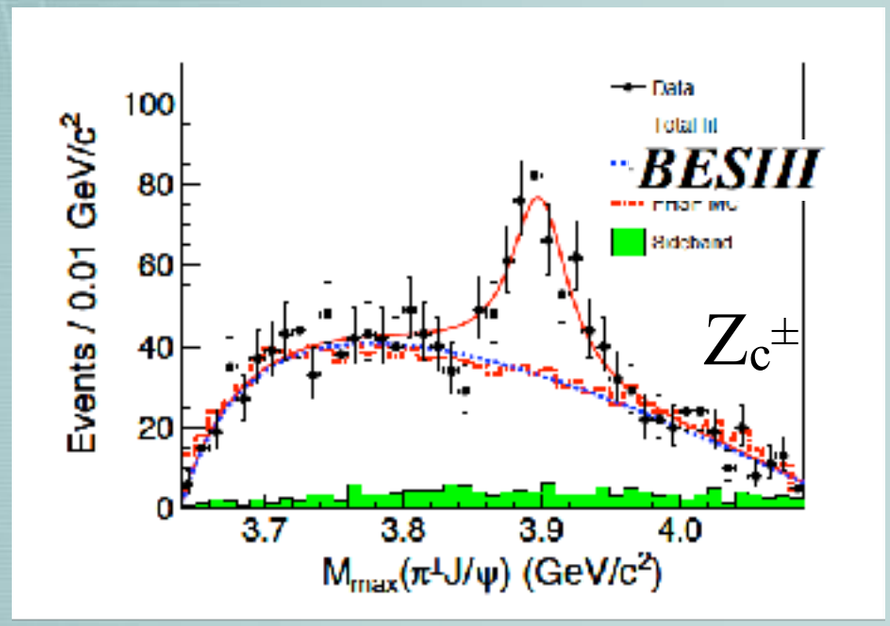
[PRL 112 (2014) 222002]

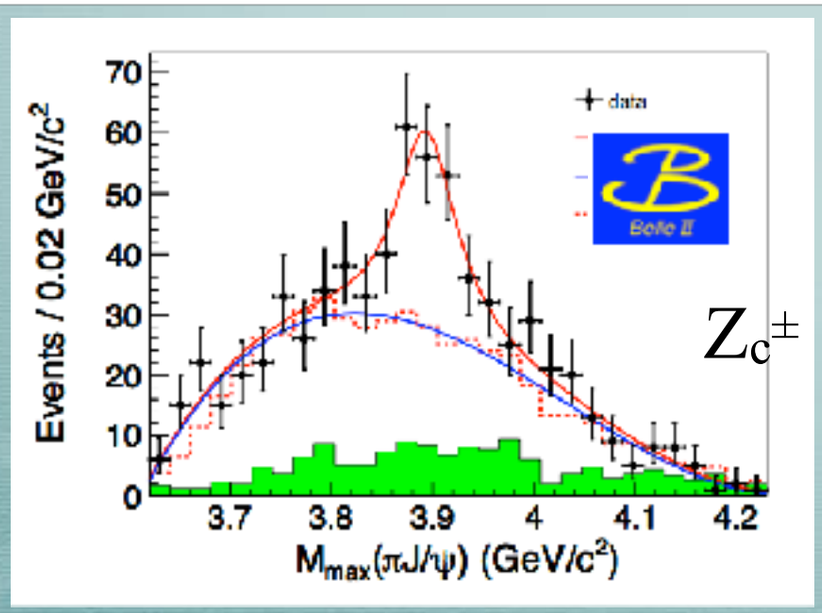




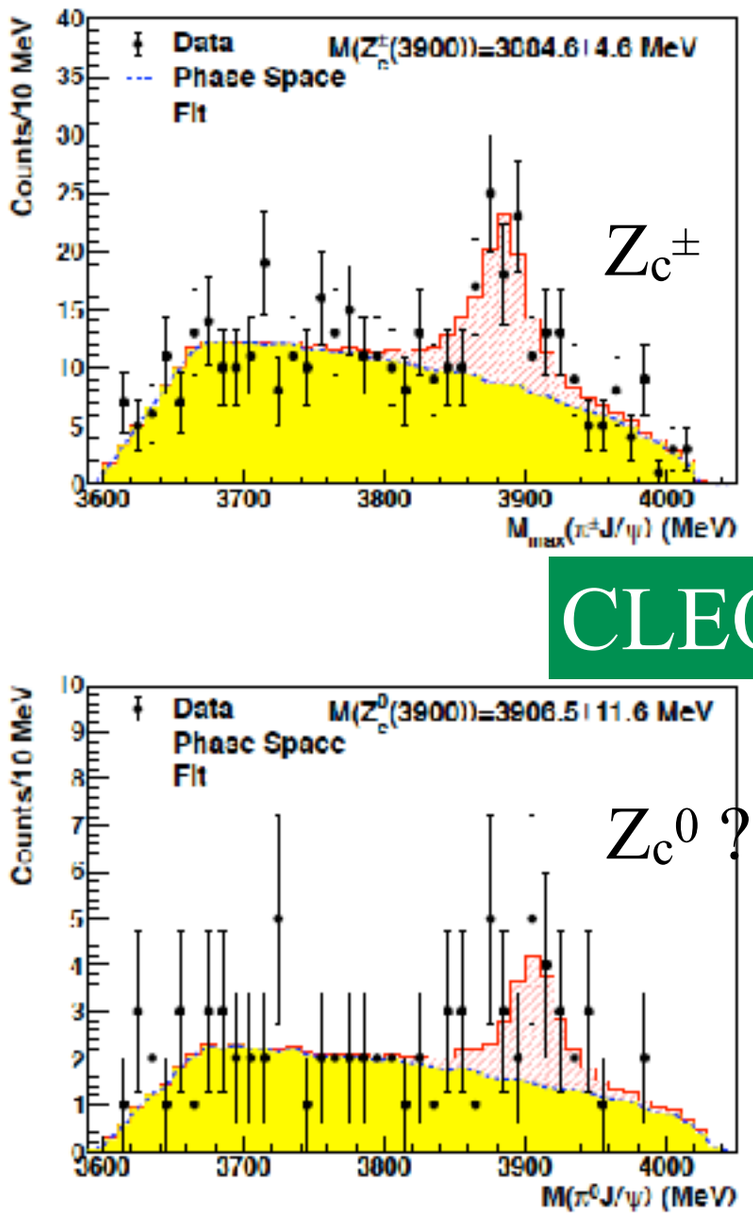
Observed by BES III, BELLE and CLEO:
$Y(4260) \to \pi^{\pm} Z_c^{\mp}(3900) \to \pi^+\pi^-\Psi$

The unexpected $J^{PC}= 1^{--}$ resonance, Y(4260), and its unexpected $J^{PG}= 1^{++}$ descendants (2013)





CLEO



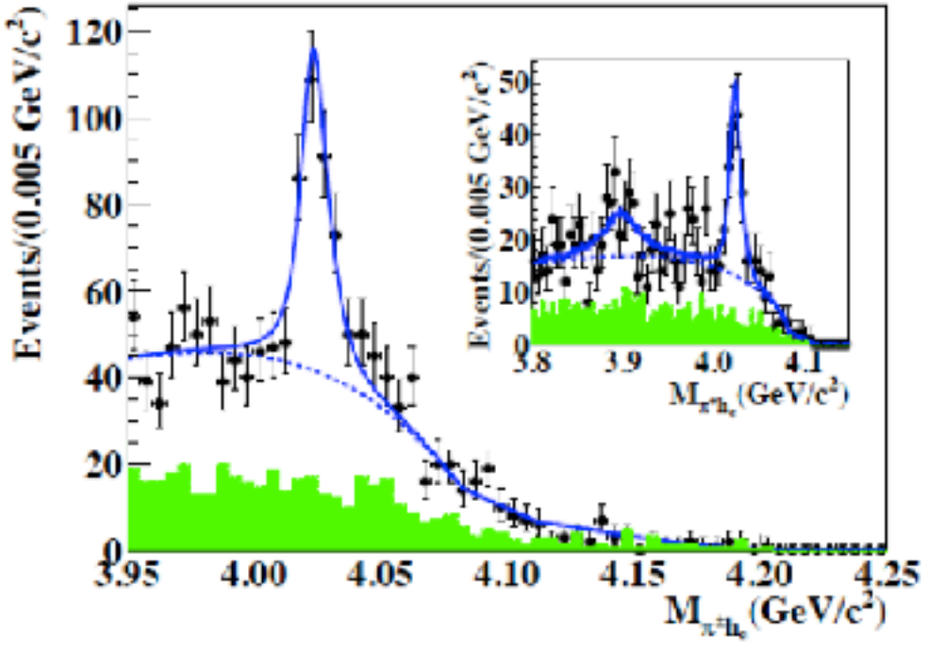
A second Z=Z(4020) (2013)

- seen in $D^*\bar{D}^*$, with a hint of the presence of the Z(3900) in $h_c+\pi$ spectrum

Note: $h_c(1P) = \bar{c}c$ with : $n = 1,\ L = 1,\ S_{c\bar{c}} = 0$

$$J^{PC}(h_c) = 1^{+-}$$

$e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^+\pi^- h_c(1P)$



BESIII: PRL111, 242001

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes. 8.9σ

$M(Z_c(4020)) =$ $4022.9\pm0.8\pm2.7$ MeV;

$\Gamma(Z_c(4020)) =$ $7.9\pm2.7\pm2.6$ MeV

Close to $\bar{D}^*D^*$ threshold

$\sigma(e^+e^- \rightarrow \pi Z_c \rightarrow \pi^+\pi^- h_c)$:

$8.7\pm1.9\pm2.8\pm1.4$ pb @ 4.230 GeV

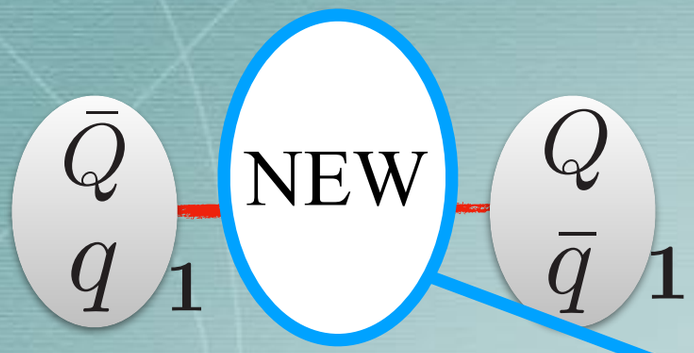
$7.4\pm1.7\pm2.1\pm1.2$ pb @ 4.260 GeV

$10.3\pm2.3\pm3.1\pm1.6$ pb @ 4.360 GeV

Significance: 8.9σ [$Z_c(4020)$]

No significant $Z_c(3900)$ (2.1σ)

Twenty years after X(3872) discovery, there is no consensus yet on the internal structure of Exotic Hidden Charm hadrons

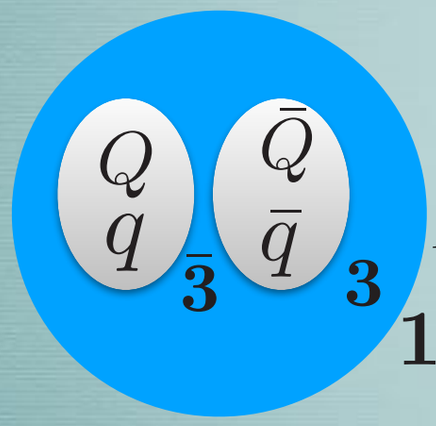


Hadron Molecule

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

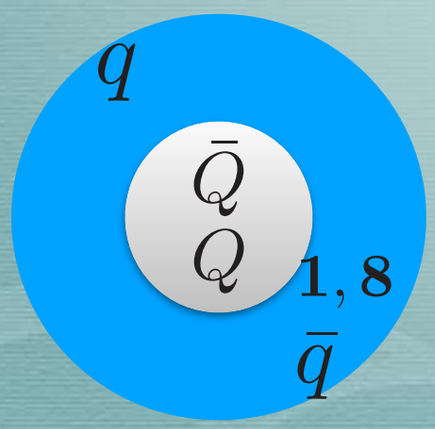
Contact meson interactions in chiral Effective Field Theory

Z. H. Zhang *et al.*, arXiv:2404.11215 [hep-ph]



Compact Diquark-Antidiquark bound by QCD interactions

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



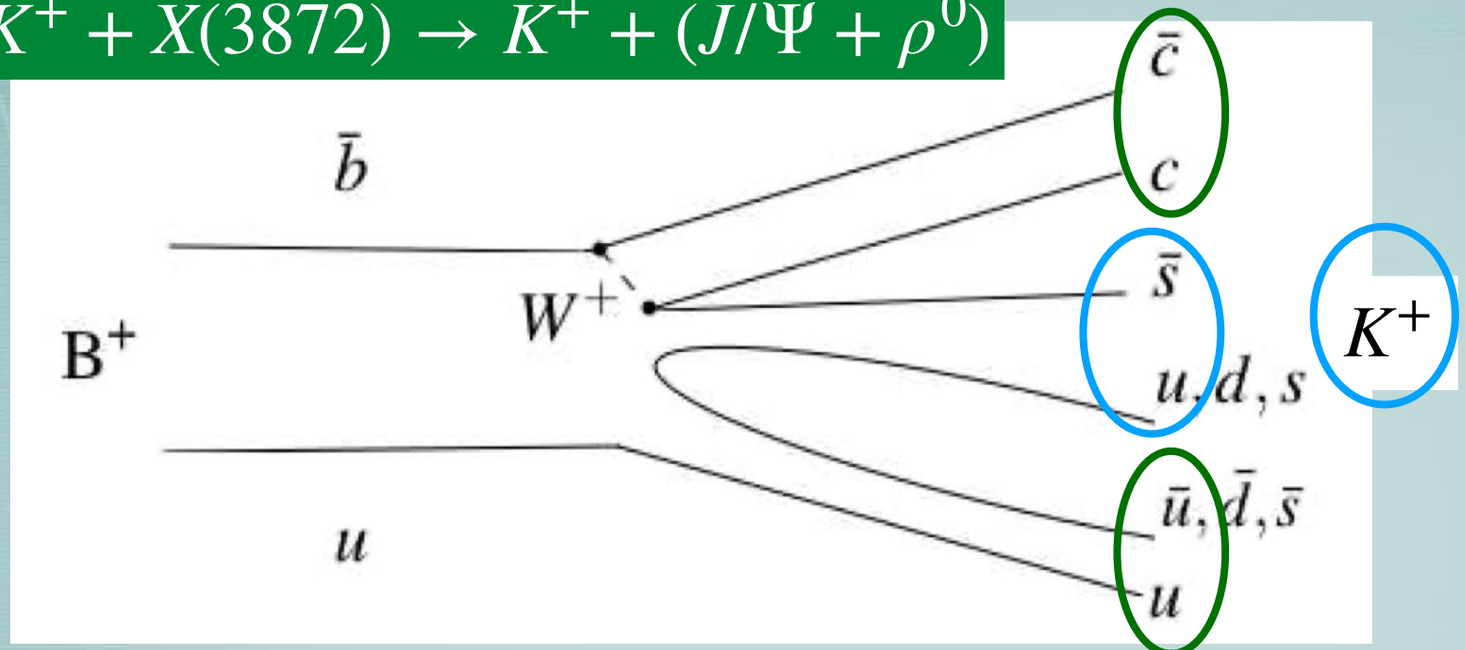
HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

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

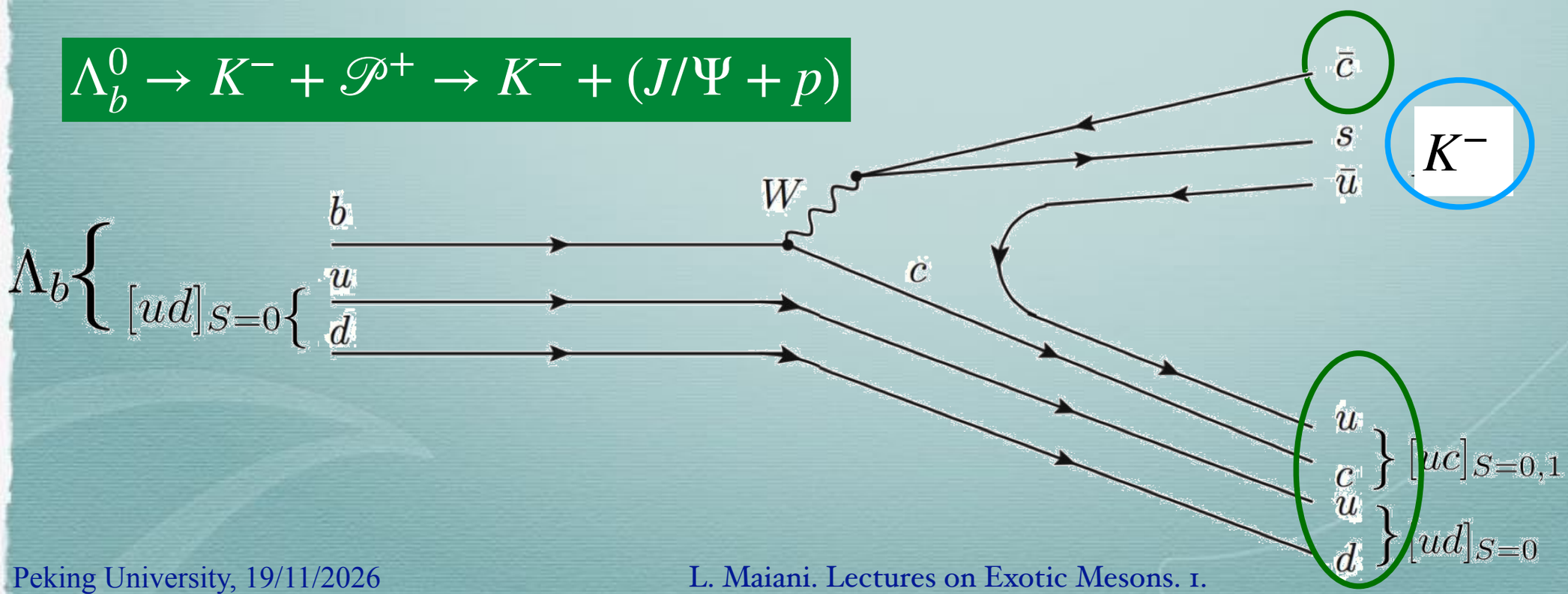
E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. **D 90** (2014) 01404

5. Basic reactions:
Many Exotic Hadrons have been found in the weak decays of Beauty-Mesons and Baryons

$$B^+ \to K^+ + X(3872) \to K^+ + (J/\Psi + \rho^0)$$



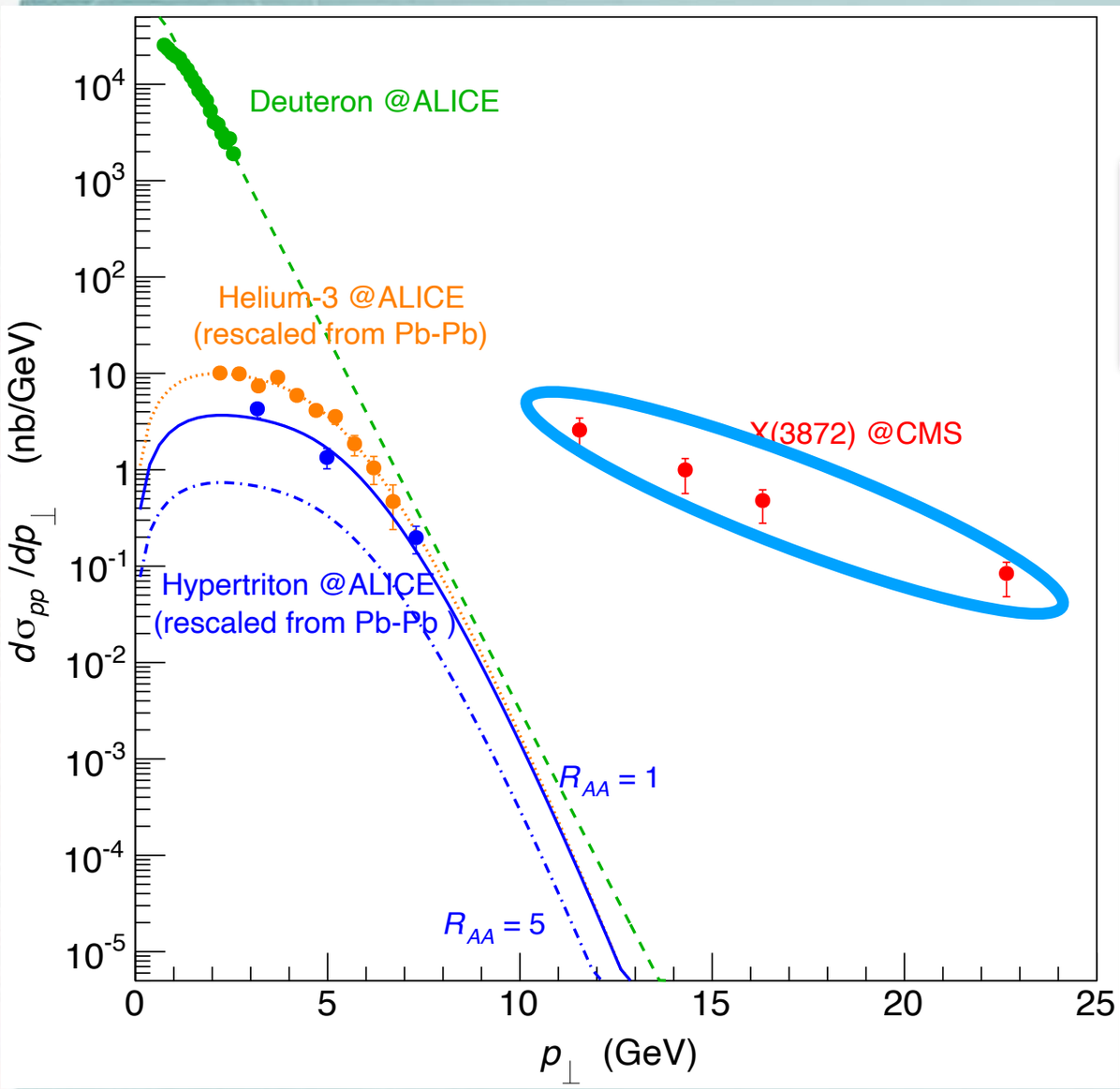
$$\Lambda_b^0 \to K^- + \mathscr{P}^+ \to K^- + (J/\Psi + p)$$



High Energy, large angle production

- $X(3872)$ is produced promptly in pp high energy, large transverse momentum collisions, $\sigma \sim \sigma(\psi')$

Pb-Pb ALICE cross sections rescaled to p-p CMS with Glauber model(with R_{AA} or R_{CP} =1)



A. Esposito *et al*. Phys. Rev. D **92** (2015) 3, 034028

Collective effects in Pb-Pb (e.g.quark-gluon plasma) **enhance nuclear cross sections** and therefore **reduce the cross section rescaled to p-p**.

- At high p_{perp} there is a vast difference in probability between X(3872) and light nuclei, the true "hadronic molecules",
- high energy production of suspected exotic hadrons in p-p and Heavy Ion colliders is a very effective tool to discriminate different models
- a long list of suspects: $f_0(980)$, X(3872), Z(3900), Z(4020), Z(4430), X(4140)…

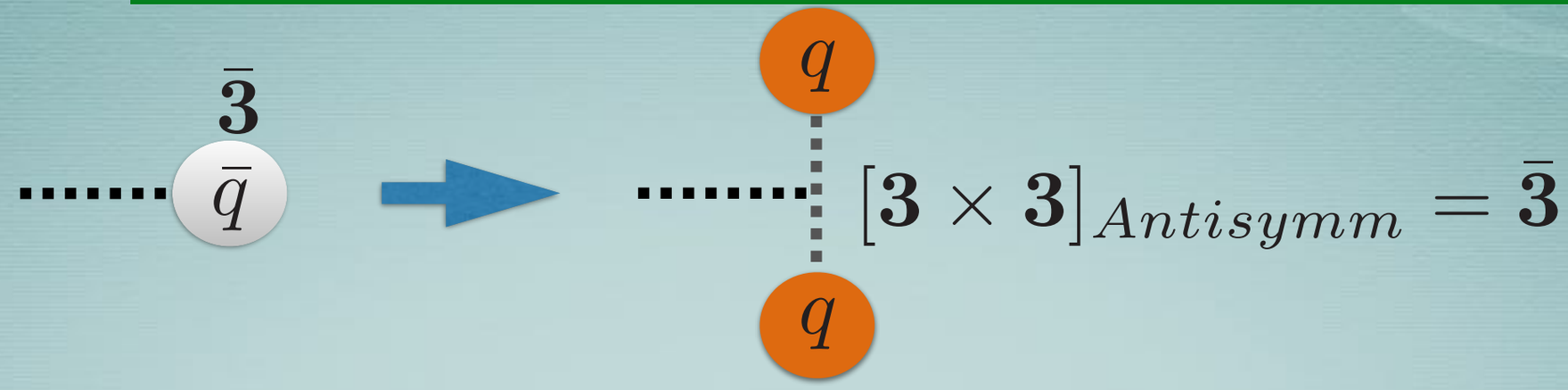
Can mixing with charmonium save the molecule?

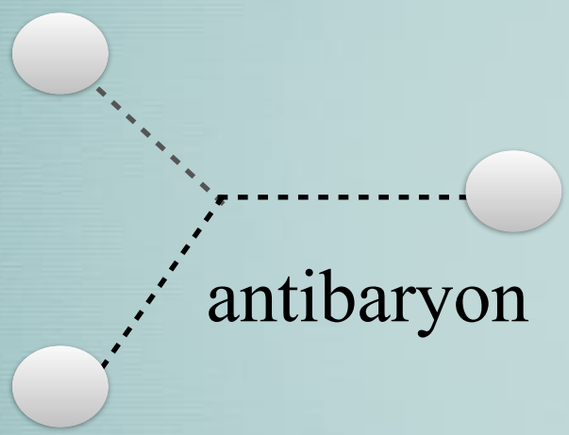
Are tetraquark ***possible***?

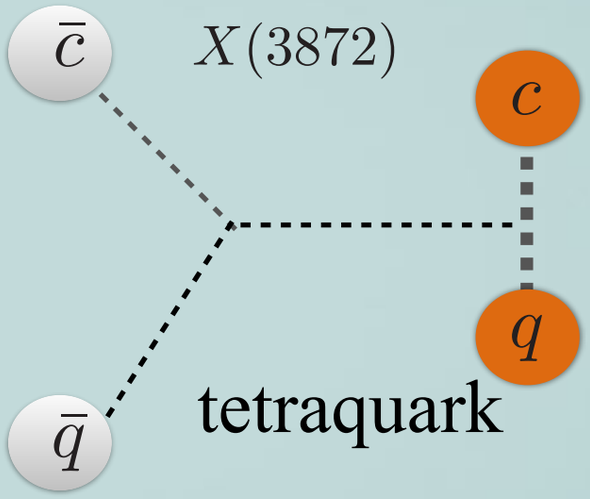
Color forces in diquark are attractive in color 3-bar

Replacing: antiquark → $\bar{\mathbf{3}}$ diquark makes new objects

rule:

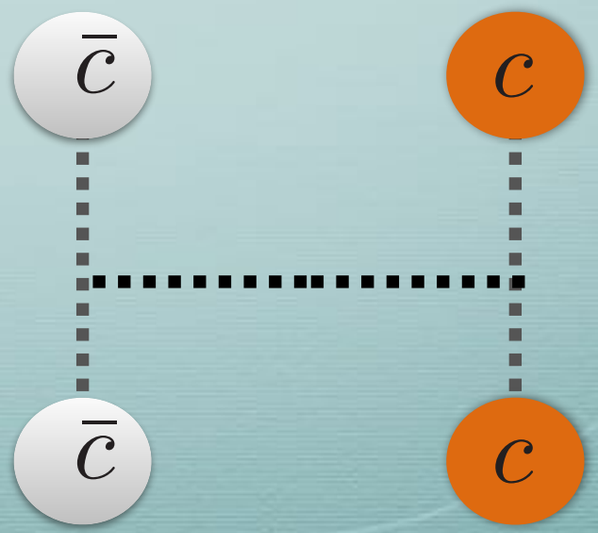






S-wave states: positive parity, X Z
L=1 states: negative parity, Y

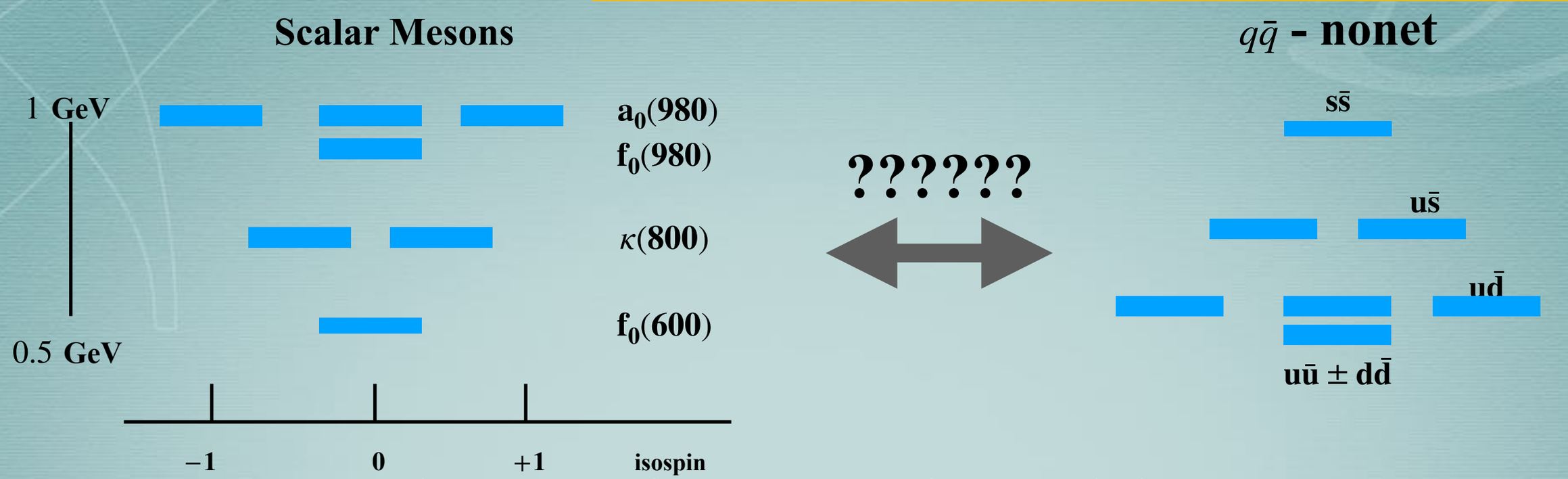




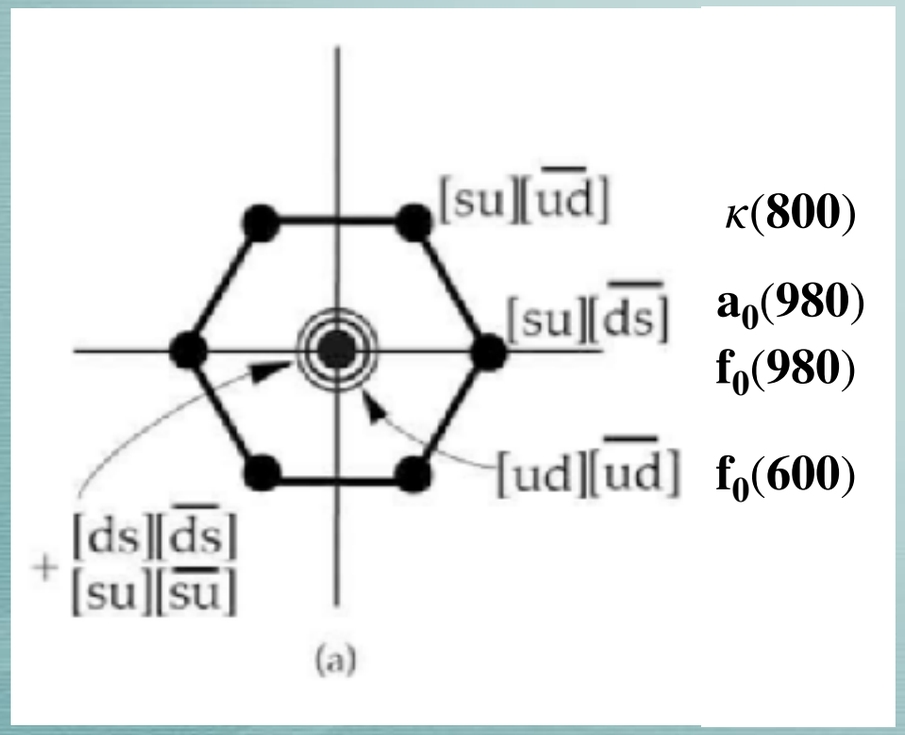
S or P-waves all-charm tetraquark

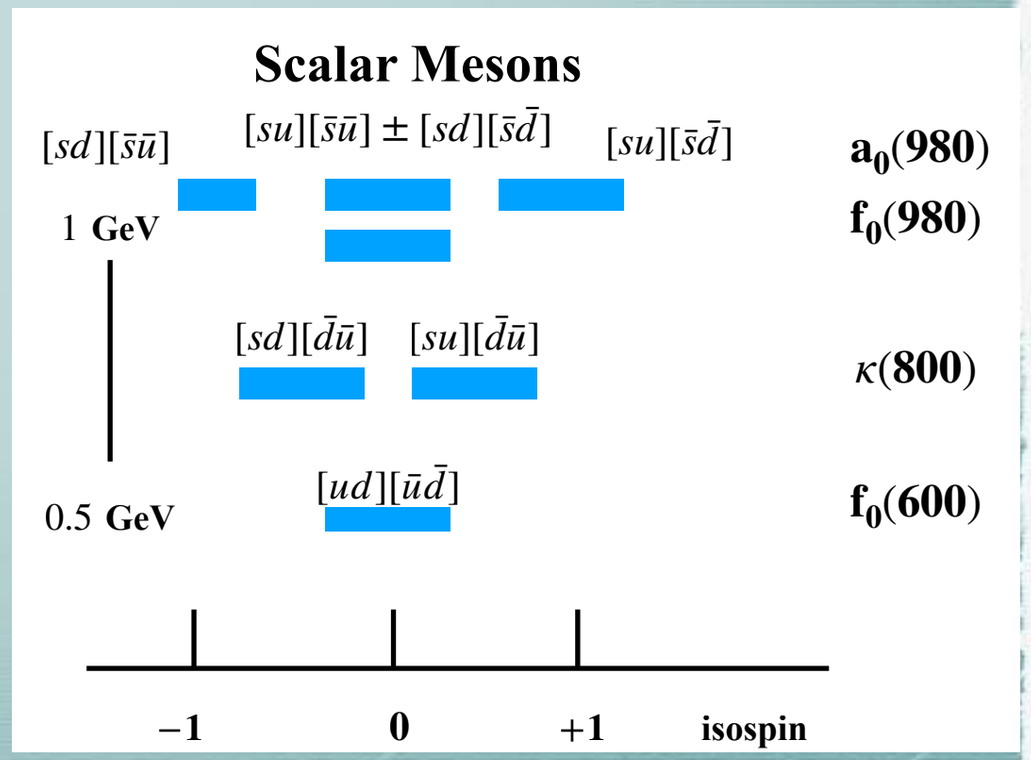
6. Light Scalar Mesons and Tetraquarks

R.L. Jaffe, Phys. Rev. D15 (1977) 267; ibidem D15 (1977), 281



Antisymmetric tetraquarks work better





To avoid states with I=2, Jaffe assumes that only *good diquarks* (colour $\bar{\mathbf{3}}$, $S_{qq} = 0$) do bind

7. The *New Wave*

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

-$J/\Psi\ \phi$ resonances, $[cs][\bar{c}\bar{s}]$, $di-J/\Psi$ resonances, $[cc][\bar{c}\bar{c}]$

-open strangeness Exotics: $Z_{cs}(3985)$ and $Z_{cs}(4003)$, $[cs][\bar{c}\bar{u}]$

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

• The New Exotics arise very naturally as $([cq]^{\bar{\mathbf{3}}}[\bar{c}\bar{q}']^{\mathbf{3}})_{\mathbf{1}}$ or $([cc]^{\bar{\mathbf{3}}}[\bar{c}\bar{c}]^{\mathbf{3}})_{\mathbf{1}}$ i.e. diquark-antidiquark 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 $m_s - m_u$.

Charm-strange exotics

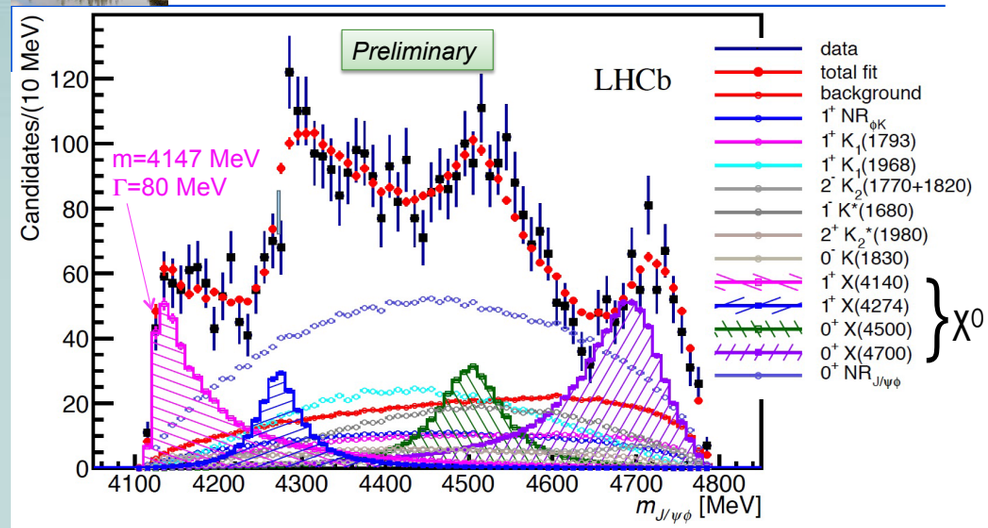
Hidden charm and strangeness and charm-strange tetraquarks have provided crucial steps forward.

LHCb (2016): $\Psi\ \phi$ resonances (***2016***)

$B^+ \to K^+ + X(4140) \to K^+ + \phi\ \Psi$, etc .

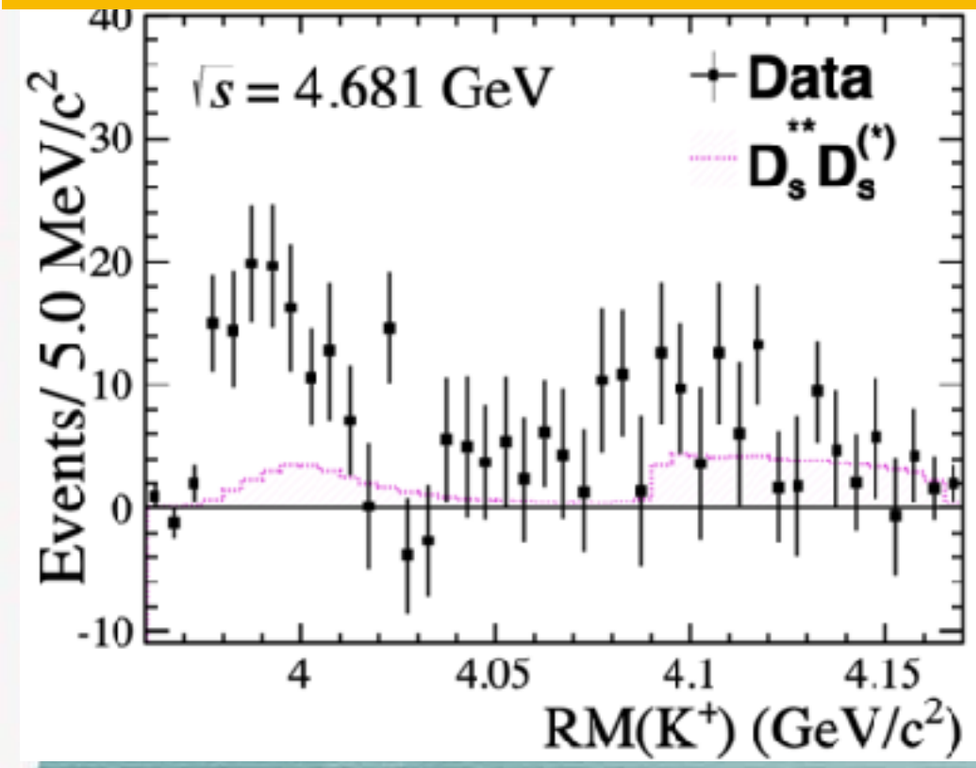


Results of fit: m(J/ψϕ)

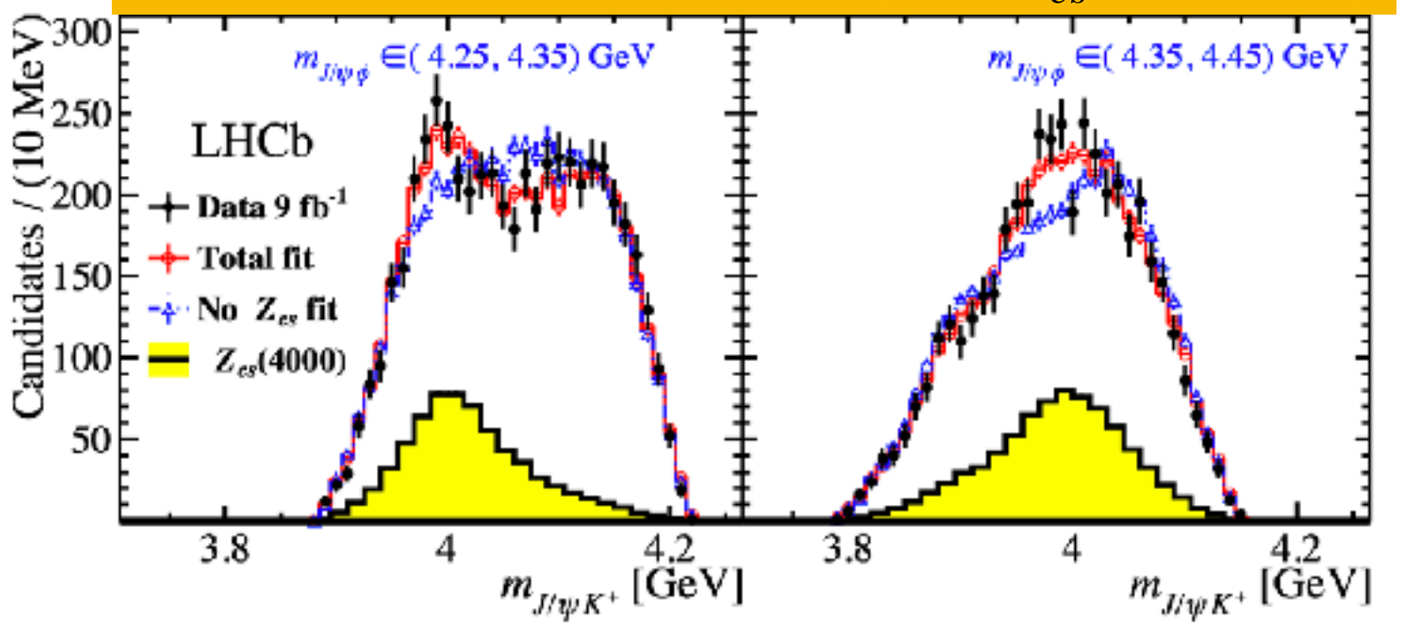


- 4 visible structures fit with BW amplitudes

BES III (***2021***): $e^+e^- \to K^+ + Z_{cs}^-(3985) \to K^+(D_s^{*-}D^0 + D_s^-D^{*0})$



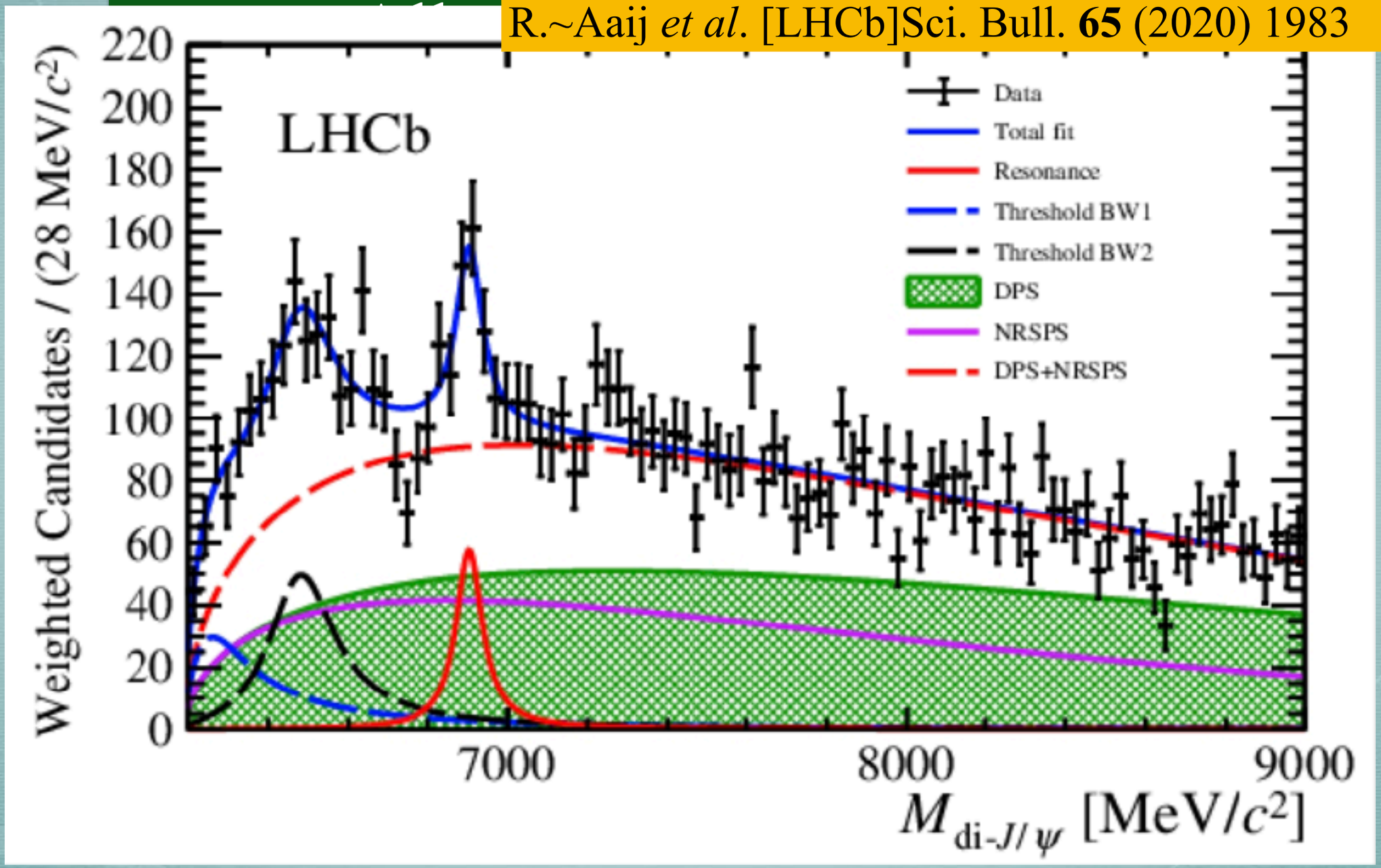
LHCb (***2021***): $B \to \Psi + K^+ + \phi \to Z_{cs}(4003) + \phi$



The incompatible values for the widths reported by AAIJ 2021E and ABLIKIM 2021G indicates the existence of two separate states. ***LHCb reports evidence of a third state*** $Z_{cs}(4220)$

Nov. 10, 2020: First observation of 4-muon, all-charm: 2 J/Ψ resonances!!

R.~Aaij *et al*. [LHCb]Sci. Bull. **65** (2020) 1983



8. Flavour Symmetry of Compact Tetraquarks

- QCD interactions are approximately symmetric under flavour SU(3) so diquark-antidiquark states must fall in complete SU(3) flavour multiplets, with mass differences determined by the quark mass difference

$$m_s - m_{u,d}$$

We have identified particles that can be assigned to 3 different multiplets:

- Hidden Charm $(\bar{c}cq_1\bar{q}_2)$, $SU(3)_f$: $\mathbf{8} \oplus \mathbf{1}$
- Single Charm $[(\bar{c}\bar{q}_1)_{S=0}(q_2q_3)_{S=0}]$, $J^P = 0^+$, $SU(3)_f$: $\mathbf{3} \oplus \bar{\mathbf{6}}$
- Double Charm (Beauty) $[(cc)_{S=1}(\bar{q}_1\bar{q}_2)_{S=0}]$, $J^P = 1^+$, $SU(3)_f$: $\mathbf{3}$

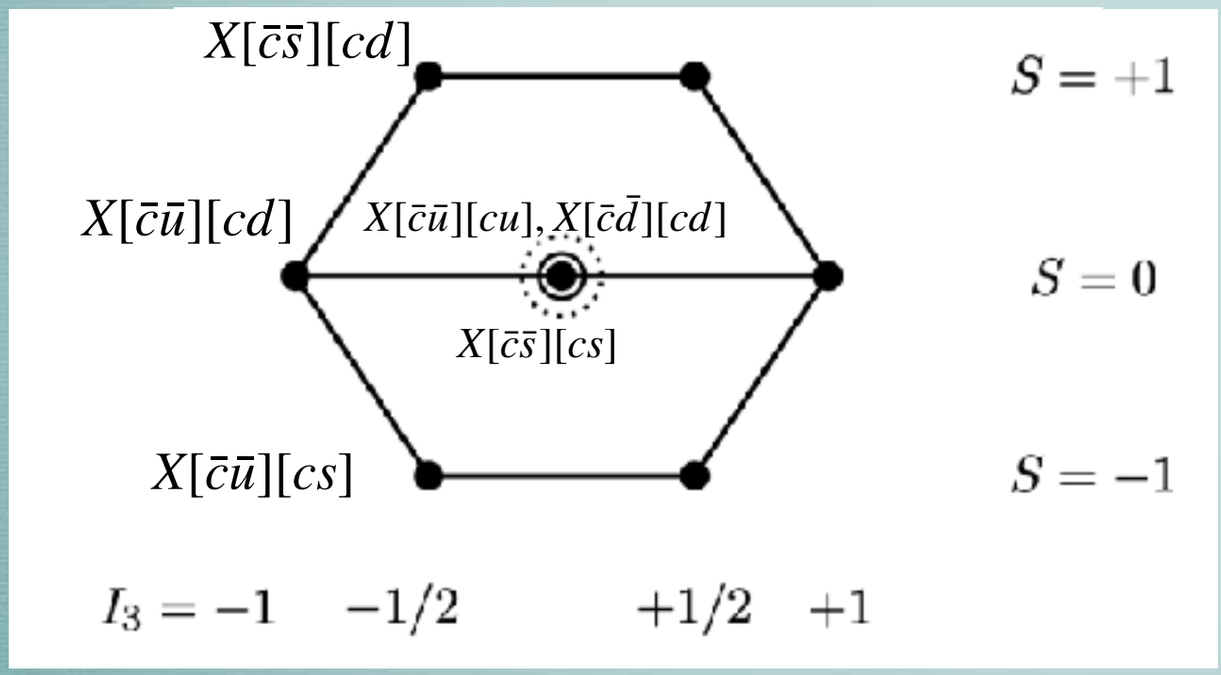
With $Z_{cs}(3082)$, $Z_{cs}(4003)$, $Z_{cs}(4220)$ we can almost fill three tetraquark nonets with the expected scale of mass differences

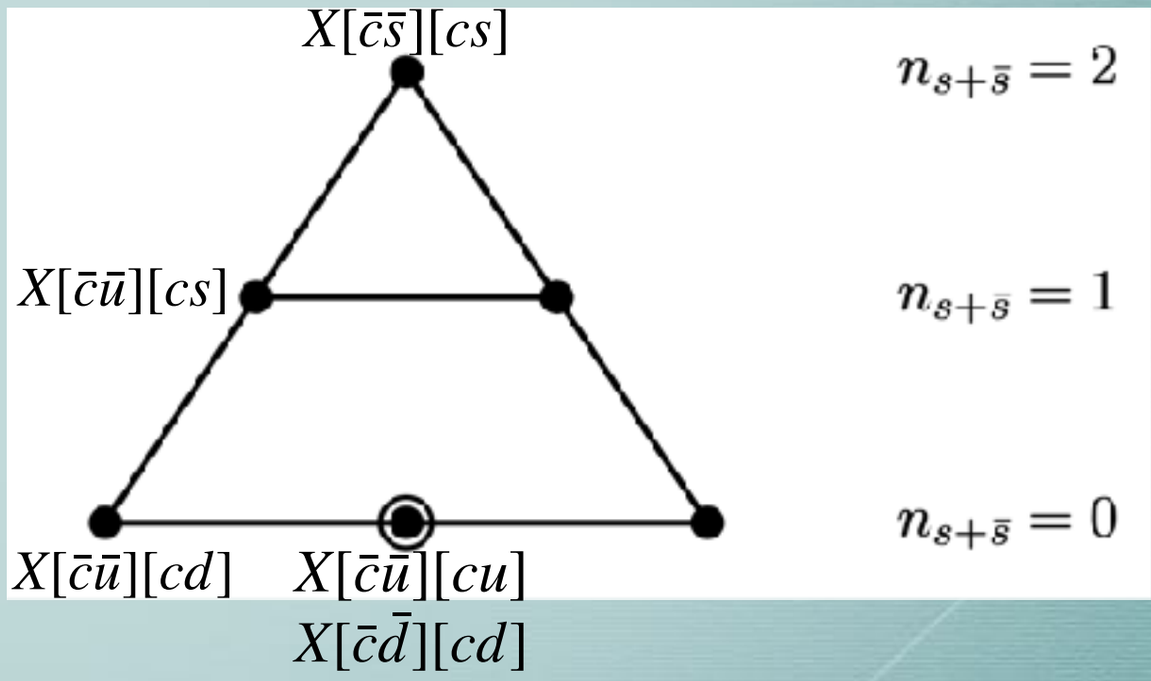
The same happens with the three states of Scalar , Single Charm Tetraquarks recently discovered by LHCb

We may produce estimates of mass and decay modes of the missing partners

Hidden Charm Tetraquarks form ***nonets of flavor SU(3)*** with mass differences determined by the quark mass difference $m_s - m_{u,d}$

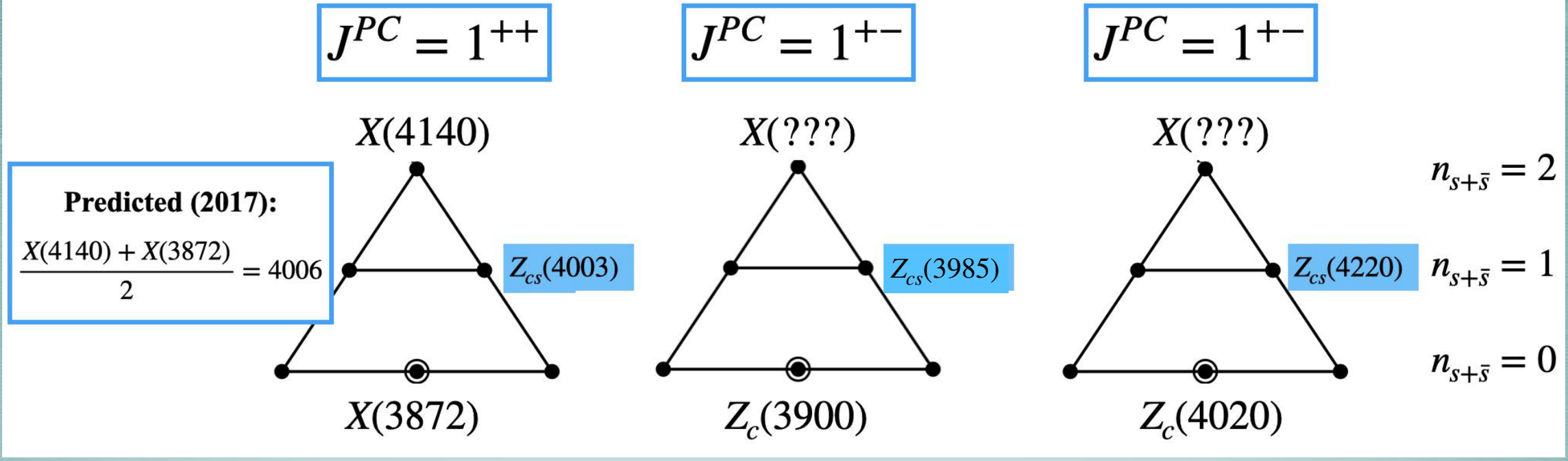
with $Z_{cs}(3082)$, $Z_{cs}(4003)$, $Z_{cs}(4220)$ we can almost fill three tetraquark nonets with the expected scale of mass differences



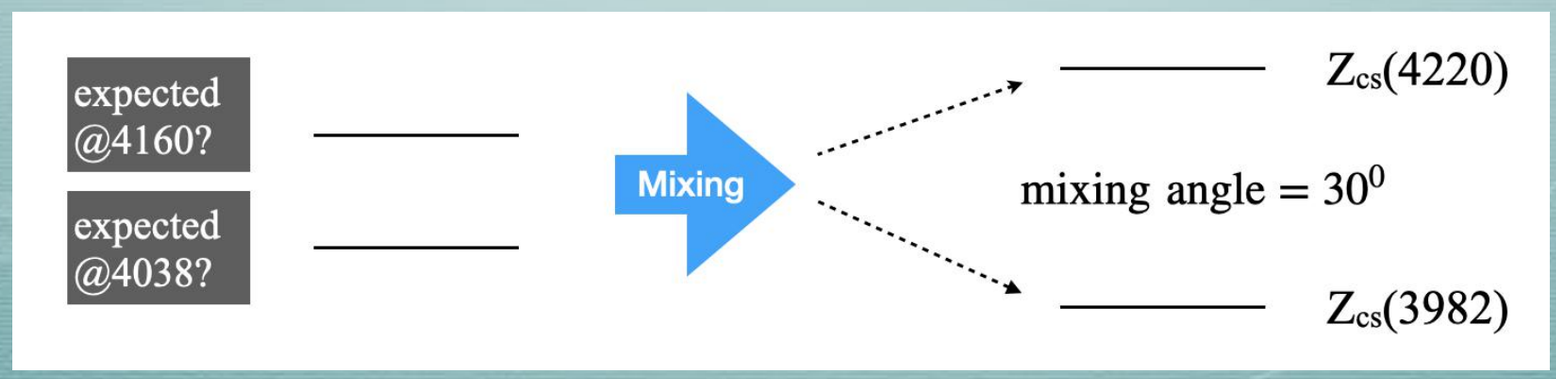


- Nonet multiplets can be also represented in function of the total number of $s + \bar{s}$ quarks;
- octet breaking implies ***the equal spacing rule*** of the masses in the ladder.

L. Maiani, A. D. Polosa and V. Riquer, Sci. Bull. **66** (2021), 1616, arXiv:2103.08331

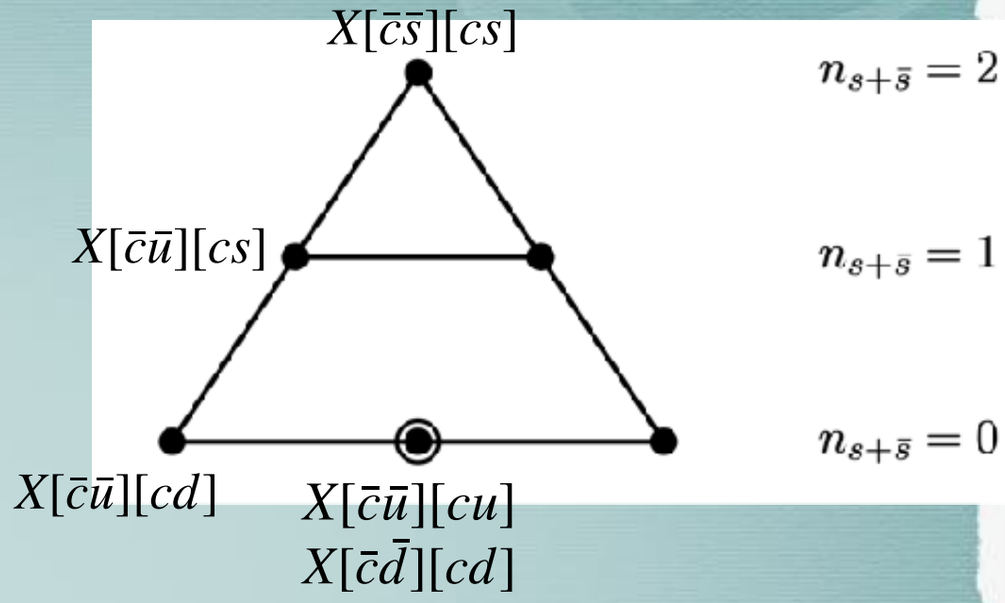


- $Z_{cs}(3982)$, to be associated to the $Z_{cs}(3982)$, $J^{PC} = 1^{+-}$nonet, is lighter than expected and $Z_c(4220)$, to be associated to the nonet of $Z_c(4020)$ is heavier than expected.
- The discrepancy can be explained by a mixing of the two nonets with the same quantum numbers, given that mixing implies a widening of the unmixed levels.
- Indeed, a mixing angle of $\sim 30^0$ would bring the unmixed masses in line with the mass difference observed for the $X(3892)$, 1^{++} nonet.



Missing particles to complete the hidden charm nonets, $J^P = 1^+$

The shopping list towards completion of the ***hidden charm nonets***:



- two $X_{[\bar{c}\bar{s}][cs]}$, expected at:

$M \sim 4170$ for $Z_c(3900)$ and $M \sim 4290$ for $Z_c(4020)$

with decays: $\eta\psi$, $\eta_c\,\phi$, $D_s^*\bar{D}_s$ (threshold: 4080 MeV)

- the I=1 partner of X(3872), with decay:

$$X^+ \to J/\psi\,\rho^\pm \to J/\psi\,\pi^+\pi^0 \text{ with the bounds:}$$

$$0.057 < R_{2\pi}^{(0+,00)} = \frac{\Gamma(B^0 \to K^+X^- \to K^+\psi\,\pi^0\pi^-)}{\Gamma(B^0 \to K^0X(3872) \to K^0\psi\,\pi^+\pi^-)} < 0.50$$

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

- the I=0 partners of $Z_c(3900)$ and $Z_c(4020)$, possibly decaying into:

$$J/\psi + f_0(500) \text{ (aka } \sigma(500))$$

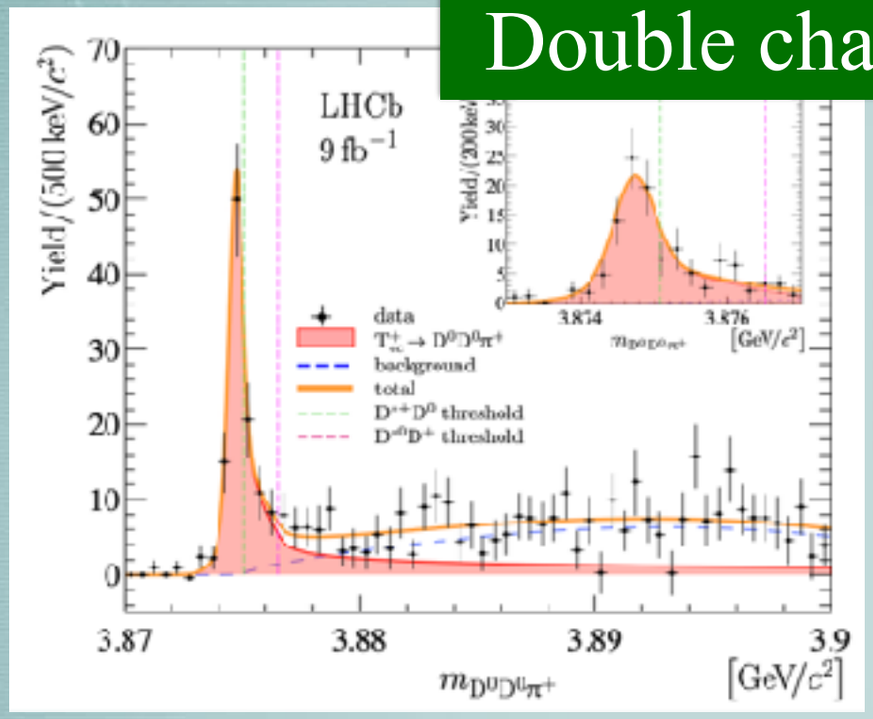
Only few particles are missing, in well defined mass regions and with identified decay modes.

9. Doubly heavy baryons and doubly heavy tetraquarks

- Doubly heavy tetraquarks, $[cc][\bar{u}\bar{d}]$, have been anticipated long ago.

Esposito, M. Papinutto, A. Pilloni, A. D. Polosa, and N. Tantalo, Phys. Rev. D88, 054029 (2013)

Double charm tetraquark $[cc][\bar{u}\bar{d}]$



LHCb arXiv:2109.01056v2

Mass : $D^{*0}D^{+} = 3876.5$ MeV $(c\bar{u})_{s=1} + (c\bar{d})_{s=0}$

Mass : $D^{*+}D^{0} = 3875.1$ MeV $(c\bar{d})_{s=1} + (c\bar{u})_{s=0}$

M. Karliner and J. L. Rosner, PRL **119** (2017) 202001. E. J. Eichten and C. Quigg, PRL **119** (2017) 202002.; S. Q. Luo et al. Eur. Phys. J. C **77** (2017) 709.

Double Beauty tetraquarks may be stable for the strong interactions !!

- extended calculations of $\mathcal{T}_{cc}$, $\mathcal{T}_{cb}$ and $\mathcal{T}_{bb}$ mass in the Born-Oppenheimer approximation have been presented: analytics and in Lattice QCD

The limit of large heavy quark mass

- ***Most clearly stated by Eichten and Quigg***:

  -in the large mass limit, the heavy quarks go to short distance, where the coulomb-like QCD potential dominates

  -the QQ binding energy is then given by the QCD Rydberg, so that:

$$Q_{\text{value}} = M(T) - 2M(P) = -\frac{1}{2}(\frac{2}{3}\alpha_s)^2 \bar{M}_Q + \mathcal{O}(m, M^{-1})$$

  -P is the pseudoscalar $(Q\bar{q})$ meson

  -$\bar{M}_Q$ the reduced mass of the QQ pair

  -Large rest masses cancel in the Q value

- for $\bar{M}_Q$ large enough $T = (QQ\bar{q}\bar{q})$ is stable against strong as well as electromagnetic decays into $PP + \gamma$.
- ***Is b quark mass heavy enough for stability?***

The mass of the lightest double heavy tetraquarks can be computed!

- Recent estimates of the mass of the lightest, double heavy tetraquarks indicate that the I=0, $bb\bar{u}\bar{d}$ tetraquark ***could be stable***. The table below gives a comparison of different theoretical results.
- ***Q-value is taken with respect to PS-PS threshold (not V-PS!)*** $M(D^*) - M(D) = 140$ MeV

$QQ'\bar{u}\bar{d}$	BO(2023)[1]	K&R(2017)[2]	E&Q(2017)[3]	Luo(2017)[4]	Lattice QCD
$cc\bar{u}\bar{d}$	+136 (+111)	+140	+102	+39	-23 ± 11 Junn. et al.[5]
$cb\bar{u}\bar{d}$	+72 (+48)	−11	+83	−108	$+8 \pm 23$ Francis et al [6]
$bb\bar{u}\bar{d}$	−8 (−38)	−170	−121	−75	-143 ± 34 Junn. *et al.*[5] $-143(1)(3)$ Francis *et al.*[6] $-82 \pm 24 \pm 10$ Leskovec *et al.*[7] -13^{+38}_{-30} Bicudo *et al.* [8]

Q values in MeV for decays into meson+meson+γ obtained with string tension 1/4 k (in parentheses string tension k). Models used in K&R (2017), E&Q (2017), Luo (2017) are different elaborations of the constituent quark model, more details are found in the original references. In the last column the lattice QCD results.

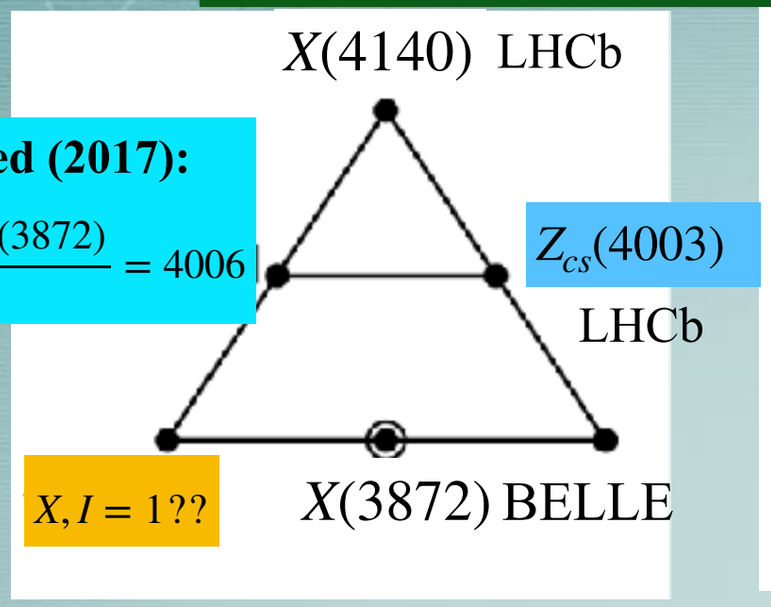
[1] L. Maiani *et al*. (2023) [2]M. Karliner and J. L. Rosner (2017). [3] E. J. Eichten and C. Quigg, (2017); [4] S. Q. Luo et al. (2017)

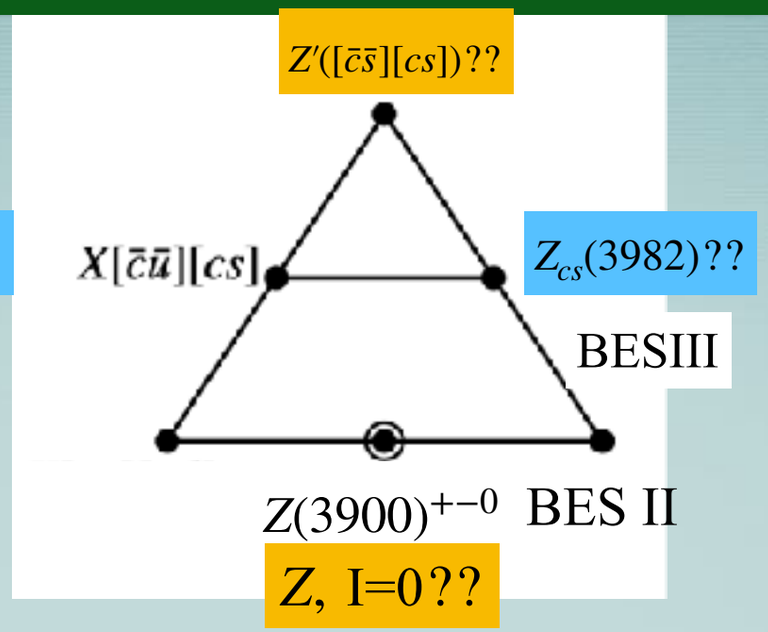
[5] Junnarkar *et al*. Phys. Rev. **D 99** (2019) 034507; [6] Francis *et al*. Phys. Rev. Lett. **118** (2017), Phys. Rev. **D 99** (2019); [7] L. Leskovec *et al*. Phys. Rev. **D 100** (2019) 014503; [8] P. Bicudo *et al*. (BO in lattice QCD) Phys. Rev. **D 103** (2021) 114506.

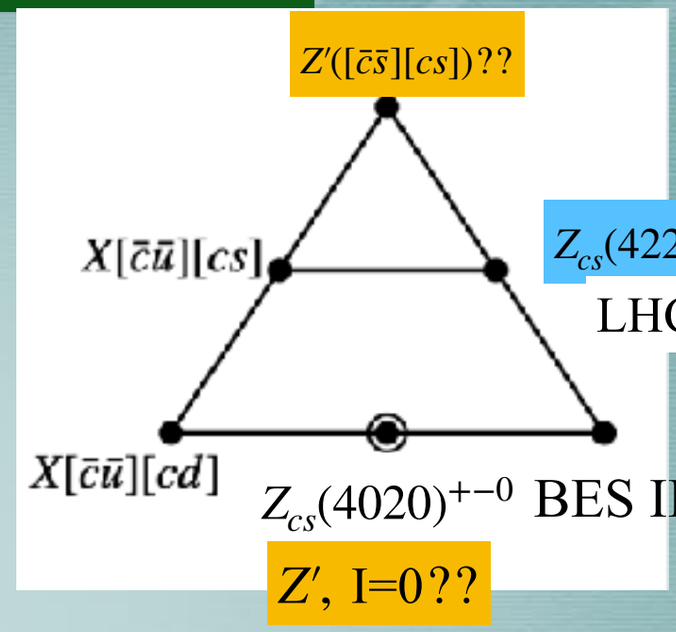
Summing Up

Predicted (2017):

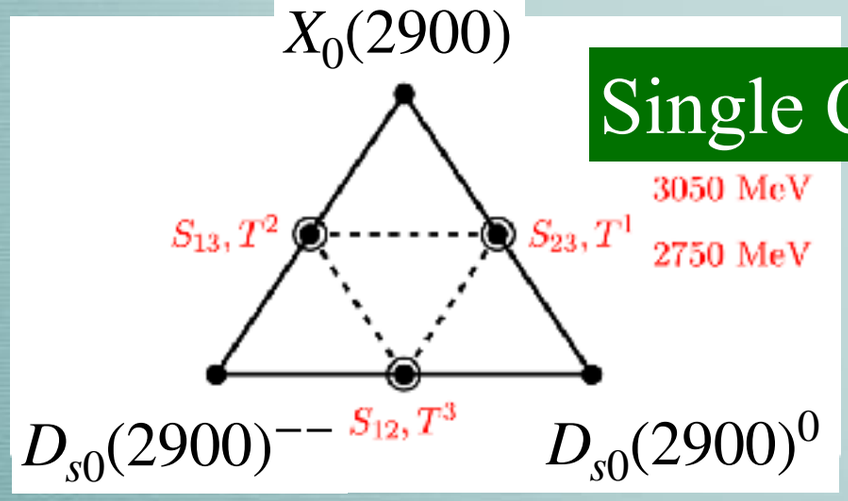
$$\frac{X(4140)+X(3872)}{2}=4006$$





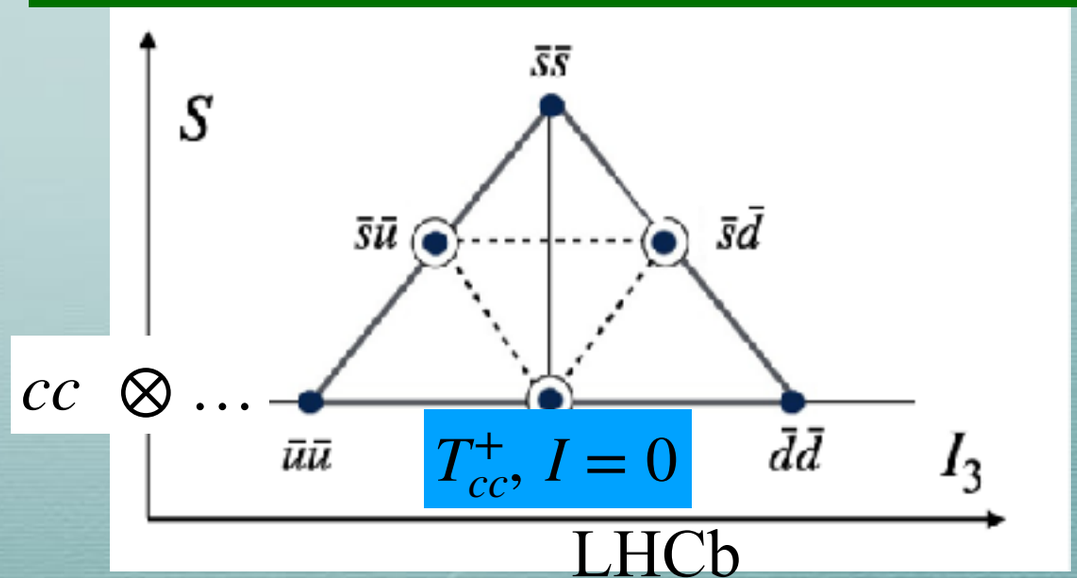


Hidden Charm. : $\mathbf{8 \oplus 1}$



Single Charmed, $J^P = 0^+ : \mathbf{3} \oplus \bar{\mathbf{6}}$

Doubly Charmed: $J = 1^+ : \mathbf{3},\ J = 0^+ : \bar{\mathbf{6}}$



Final questions (to LHCb and BESIII)

- Are $Z_{cs}(3985)$ and $Z(4003)$ two different states? is there a third $Z_{cs}(4220)$?
- Can X^+ near $X(3872)$ be found in B decays?
- can we find the missing partners of the $\mathbf{3} \oplus \bar{\mathbf{6}}$, (n=2) Open Charm multiplet:

$[\bar{c}\bar{s}][sd]_{(n=2)}(3050) \to \bar{D}^- \eta,\ \bar{D}_s^- K^0,\ \bar{D}^{*-} \phi, \ldots$

$[\bar{c}\bar{u}][ud]_{(n=2)}(2750),\ [\bar{c}\bar{d}][ud]_{(n=2)} \to \bar{D}\pi, \ldots$

Hidden charm: complete nonets ?

Open charm and strangeness: Complete $\bar{\mathbf{3}} \oplus \mathbf{6}$?

- LHCb has used efficiently the channel $B \to (J/\Psi)\ \phi\ K + \ldots$ to study $X_{ss}(4140)$ etc.., and Z_{cs} etc. of SU(3) nonet tetraquarks…
- Can the study of $B \to \bar{D}_s\ D\ \phi$ channel be similarly used to study single charm $[\bar{c}\bar{s}]_{S=1}[ss]_{S=0}$, $J^P = 1^+$ tetraquarks of the interesting $\mathbf{15} \oplus \mathbf{3}$, $J^P = 1^+$ multiplet ?
- Reconsider K-like states which decay into $K\ \phi$ (e.g. $K_1(2650)$), therefore unlikely to be $(s\bar{q})$ excited Kaons: could they be zero-charm $[\bar{u}\bar{s}][ss]$ tetraquarks?

Open strangeness ?

- ***Tough orders***: more luminosity, better energy definition, detectors with exceptional qualities… a lot of work…
- ***Close exchange between theory and experiments*** is essential…

Let it continue !