From Exotic Charmonia to $\mathcal{T}_{cc}$ and $\mathcal{T}_{bb}$

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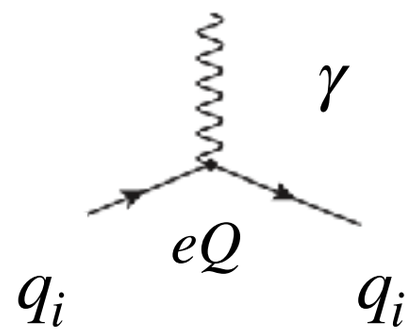
Introducing quarks to describe the known mesons and baryons, Murray Gell-Mann, in 1964, suggested the existence of further $qq\bar{q}\bar{q}$ mesons (tetraquarks) and $qq\bar{q}\bar{q}$ baryons (pentaquarks).

The firsty *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, $q\bar{q}$ and qqq, configurations.

I shall illustrate this new chapter of Particle Spectroscopy with a selection of results on the structure and symmetry pattern of the Exotic Hadrons, recent experimental discoveries and future perspectives.

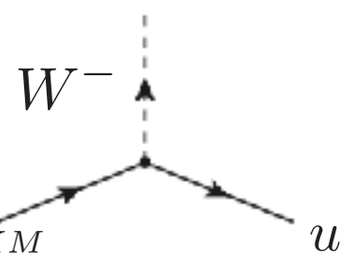
1. The Standard Theory of Particle Interactions

E. M. INTERACTIONS= QED



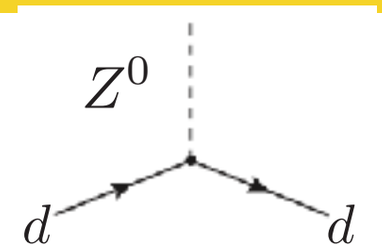
WEAK INTERACTIONS (after GIM and KM)

Quark-charged currents



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

Quark-neutral currents



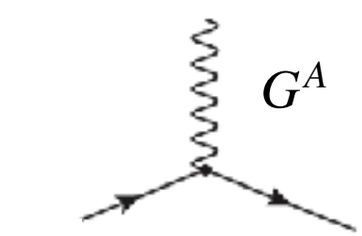
$(s \to s,\ b \to b)$

with d_C only, $d + Z^0 \to s$: strangeness changing neutral currents would be allowed

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

$$d_C = \cos\theta d + \sin\theta s,$$
$$\theta = \text{Cabibbo angle}$$

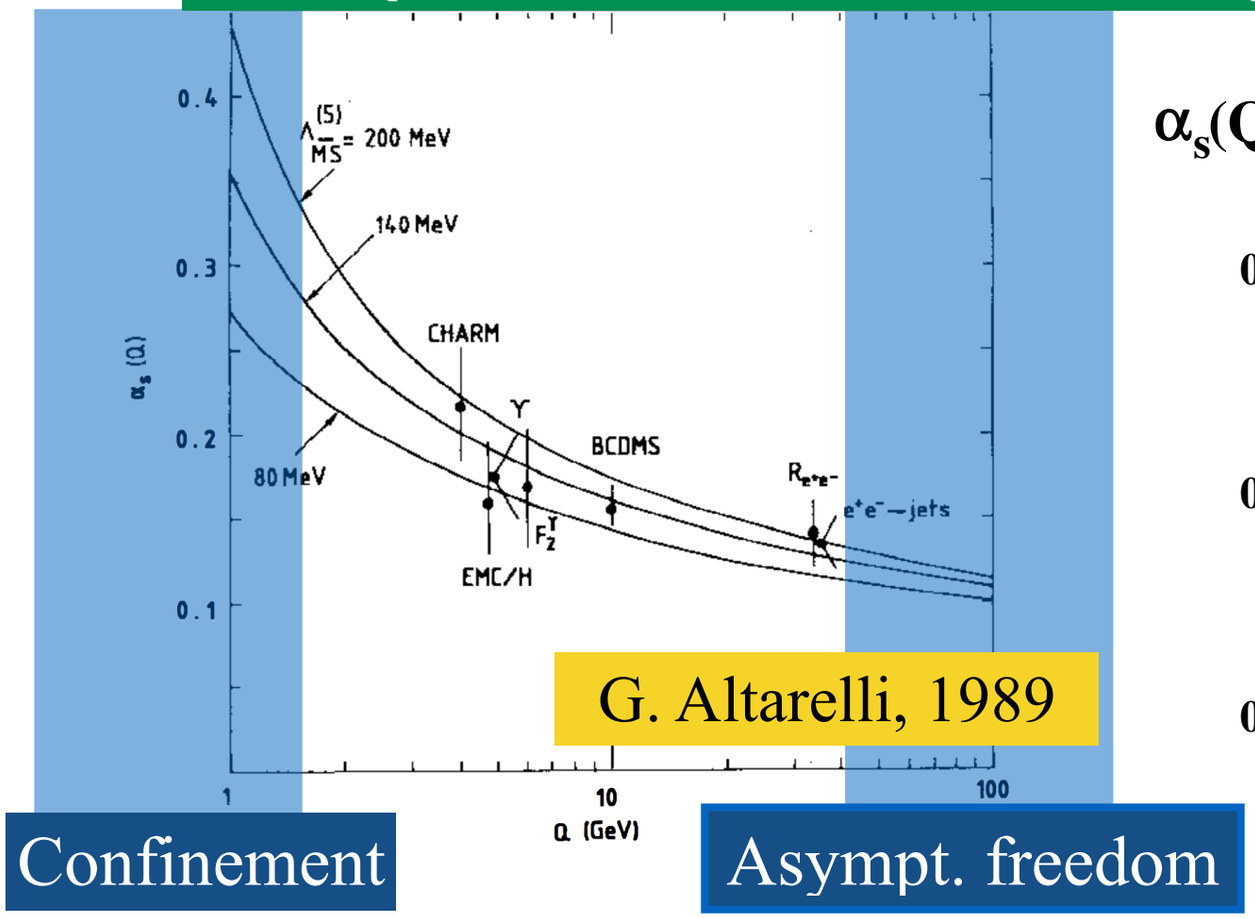
STRONG INTERACTIONS= COLOUR SU(3)

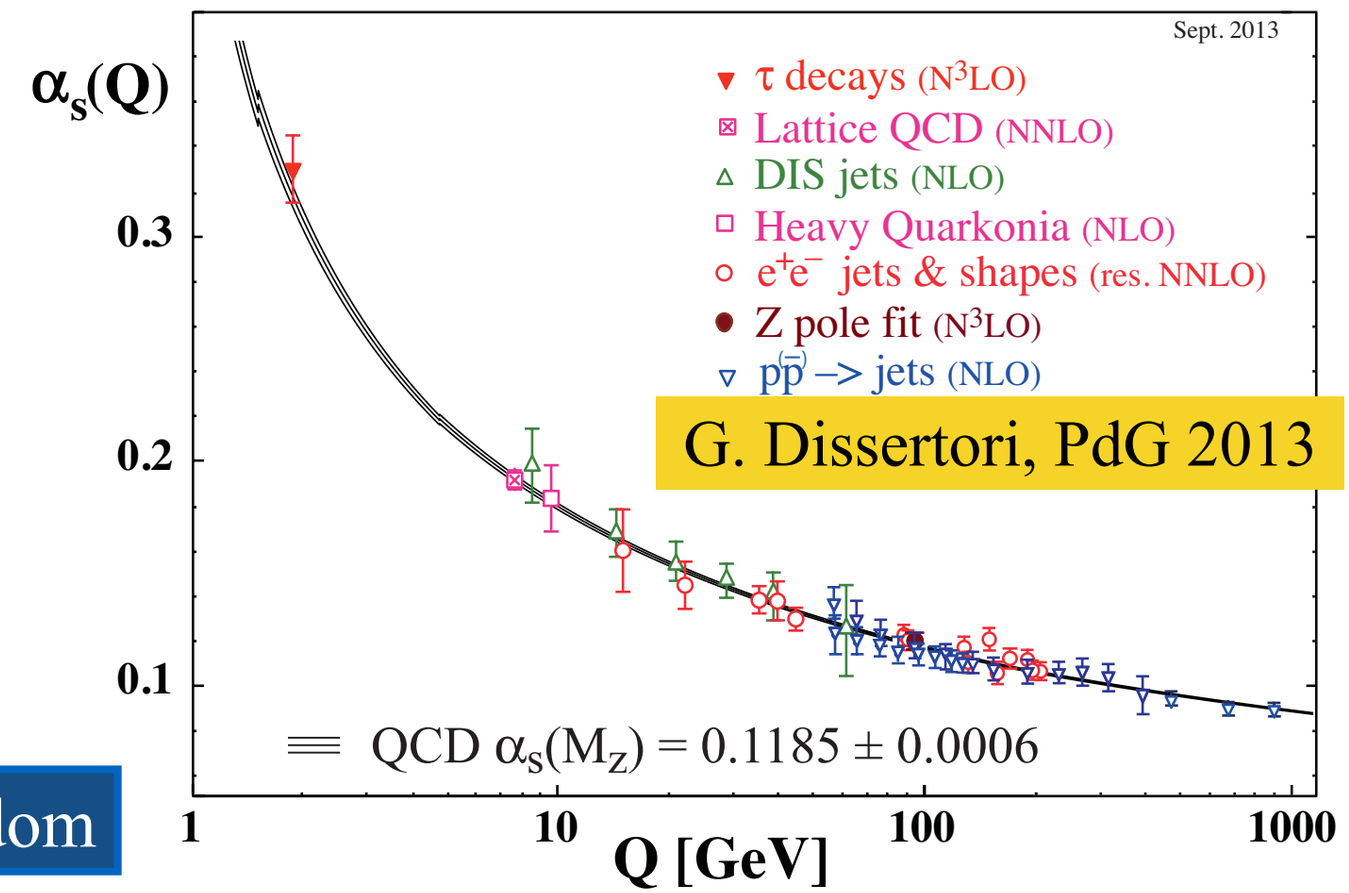


$q_i \quad g_s\, \mathbf{T}^A_{ij} \quad q_j \ (A = 1,\ \ldots,\ 8)$

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

QCD is the answer to (almost) any question





- QCD is asymptotically free
- quarks carry **color symmetry**, **SU(3)$_{\mathbf{col}}$**, and are confined inside **color singlet hadrons**,
- $\Delta^{(++)} = \epsilon^{\alpha\beta\gamma} u_\alpha^\uparrow u_\beta^\uparrow u_\gamma^\uparrow$: Fermi statistics is obeyed **Constituent Quarks**
- increasing q^2, quarks radiate gluons (the Altarelli-Parisi picture of scaling violations)
- at large q^2, we see quarks and neutral gluons as almost free partons. **QCD Partons**

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 $\Upsilon + \ldots$ indicates a valence $c\bar{c}$ or $b\bar{b}$ pair: ***heavy-quark counting is possible***.

2. Unanticipated charmonia X, Y, Z.. and more

- Hidden charm/beauty resonances not fitting in preedicted charmonium/bottomonium spectrum because of mass/decay properties or because charged.

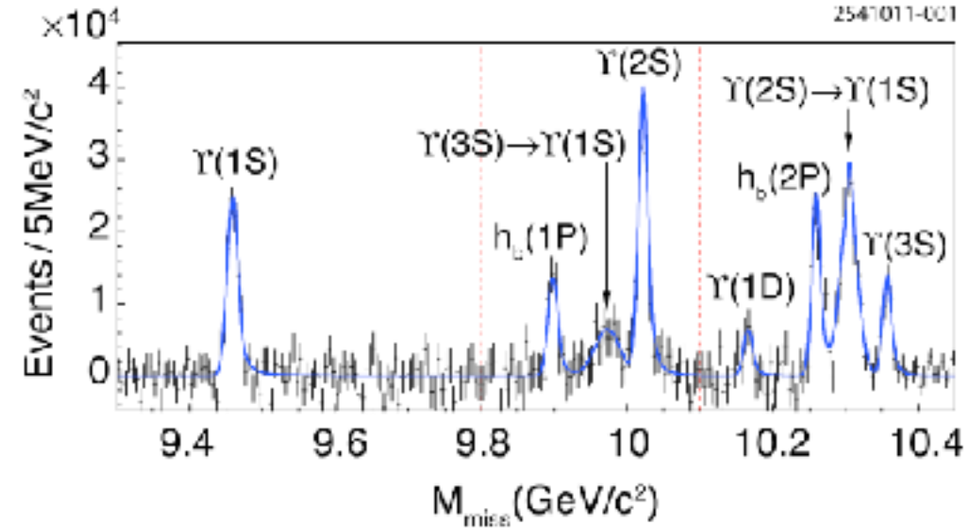


Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, M_{miss}, in e^+e^- collision

  - X, e.g. $X(3872)$: neutral, typically seen in Ψ + pions, 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 $J^{PC} = 1^{--}$,
  - Z, e.g. Z(4430): charged/neutral, typically positive parity, 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 observed ($b\bar{b}u\bar{d}$).

A new wave of Exotic Hadrons started in 2016:

- Hidden charm and Hidden strangeness seen, e.g. $X(4140) \to \Psi + \phi$, $J^{PC}=1^{++}$
- 4 charm tetraquarks seen as di-Ψ resonances by LHCb, e.g. $X(6900) \to \Psi + \Psi \to (\mu^+\mu^-)^2$
- Hidden charm- Open strangeness ($c\bar{c}u\bar{s}$), seen (last year!) by BES III: $Z_{cs}^{+}(3985) \to \Psi + K^{+}$ and by LHCb: $Z_{cs}^{+}(4003) \to \Psi + K^{+}$.
- Double charm tetraquark seen by LHCb: $\mathcal{T}_{cc}^{+}(3875) \to D^0 D^0 \pi^+$ (valence quarks: $cc\bar{u}\bar{d}$)

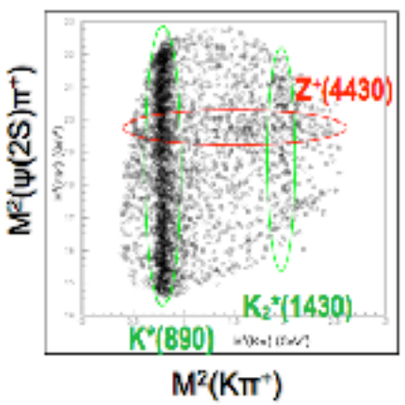
The saga of $Z^{\pm}(4430)$

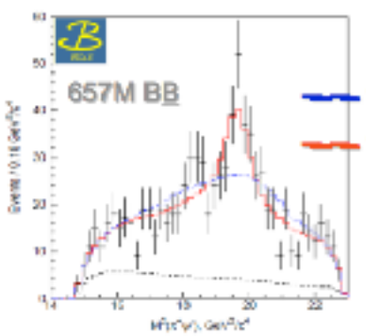
Belle observed $Z(4430)^{\pm}\to\psi(2S)\pi^{\pm}$

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





$M^2(\psi(2S)\pi^+)$ after K* veto

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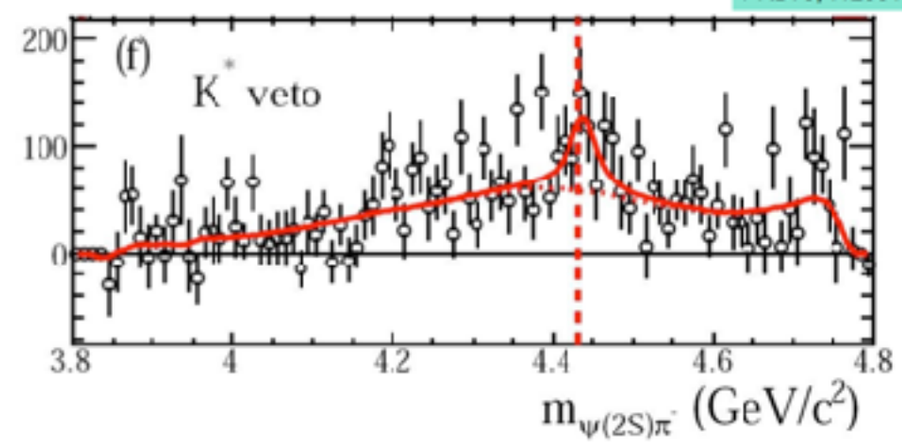
BaBar doesn't see a significant $Z(4430)^+$

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

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

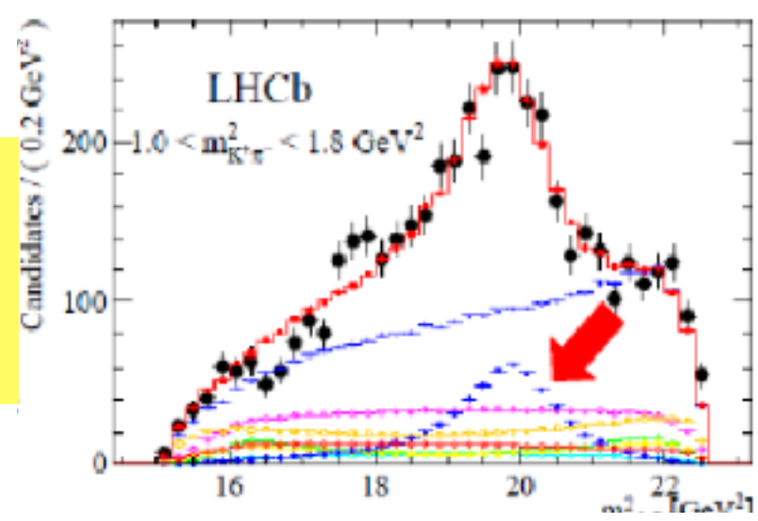
LHCB:

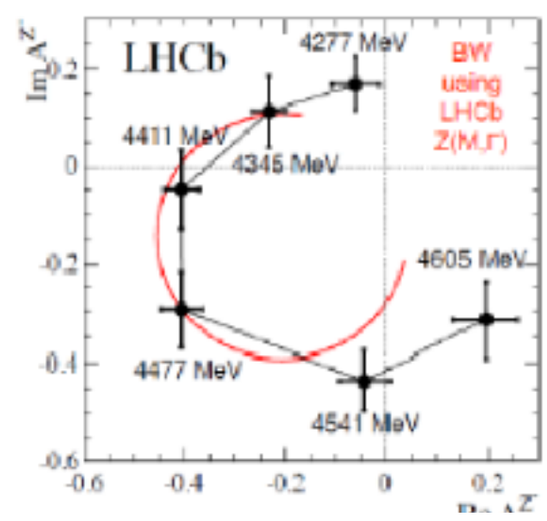
- confirms BELLE's observation of a bump

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

- Argand Plot shows 90^0 phase: Z is a genuine resonance

[PRL 112 (2014) 222002]

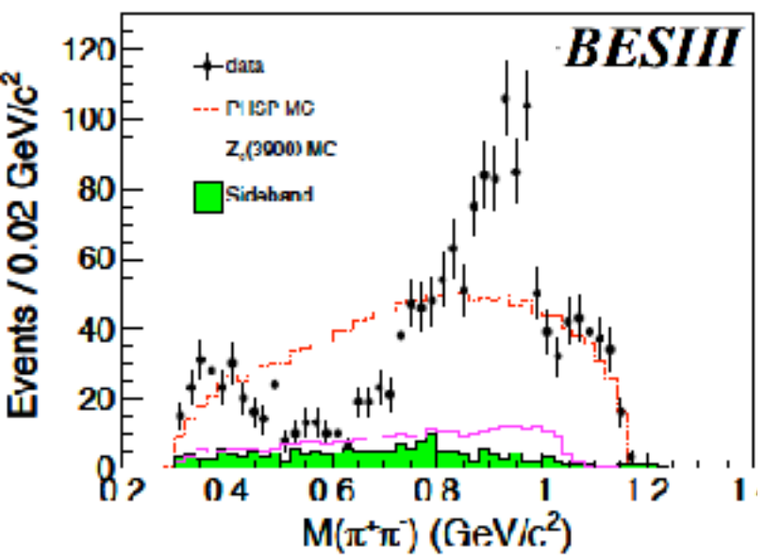


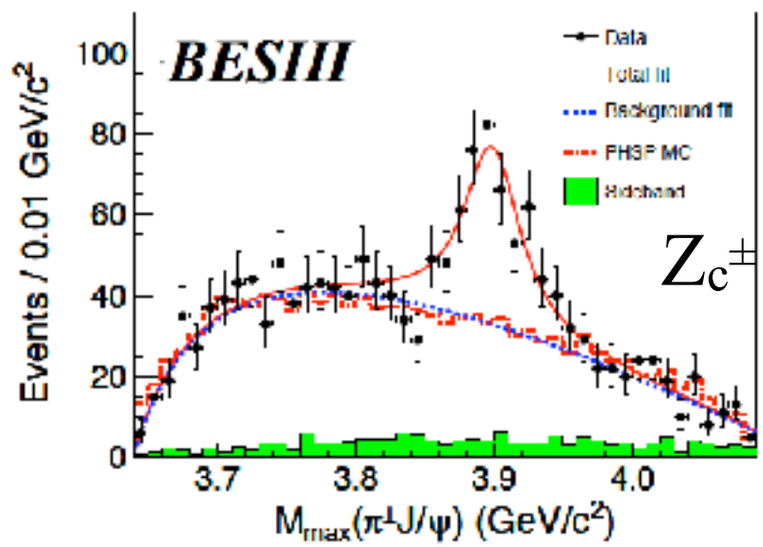


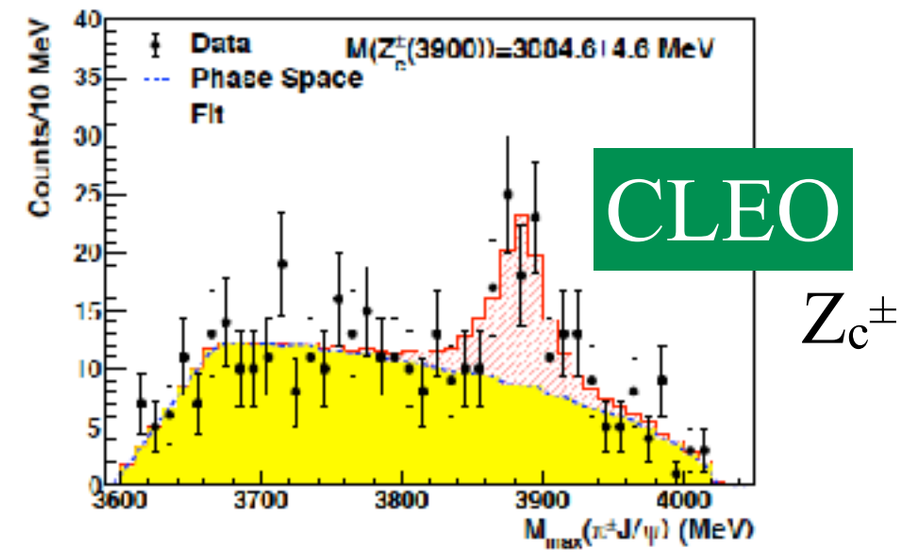
The unexpected $J^{PC}= 1^{--}$ resonance, Y(4260), and its unexpected $J^{PG}= 1^{++}$ descendants (2013)

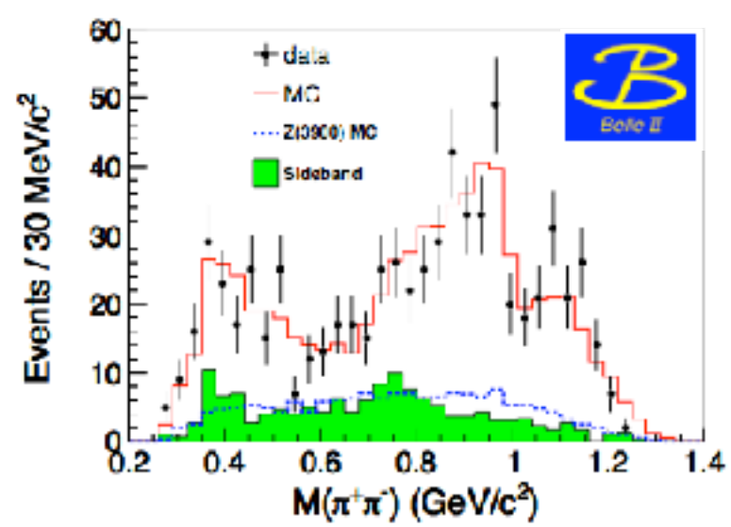
Observed by BES III, BELLE and CLEO:

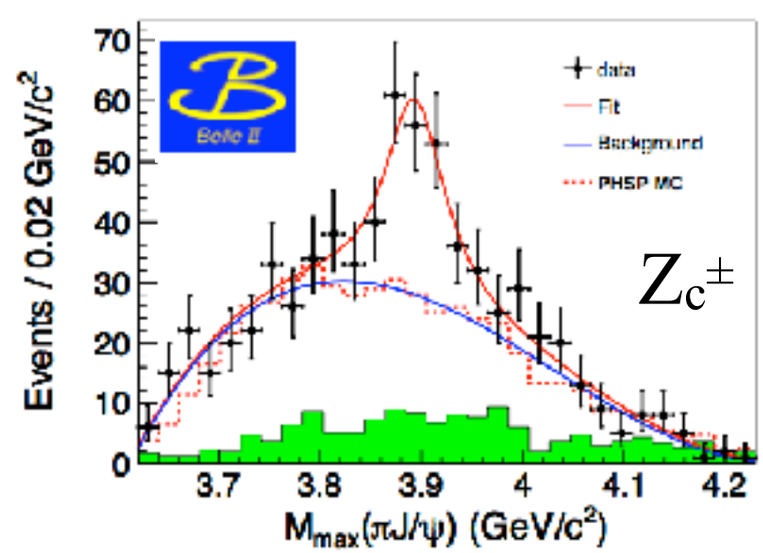
$Y(4260) \rightarrow \pi^{\pm} Z_c^{\mp}(3900) \rightarrow \pi^{+}\pi^{-}\Psi$ tetraquark de-excitation ?

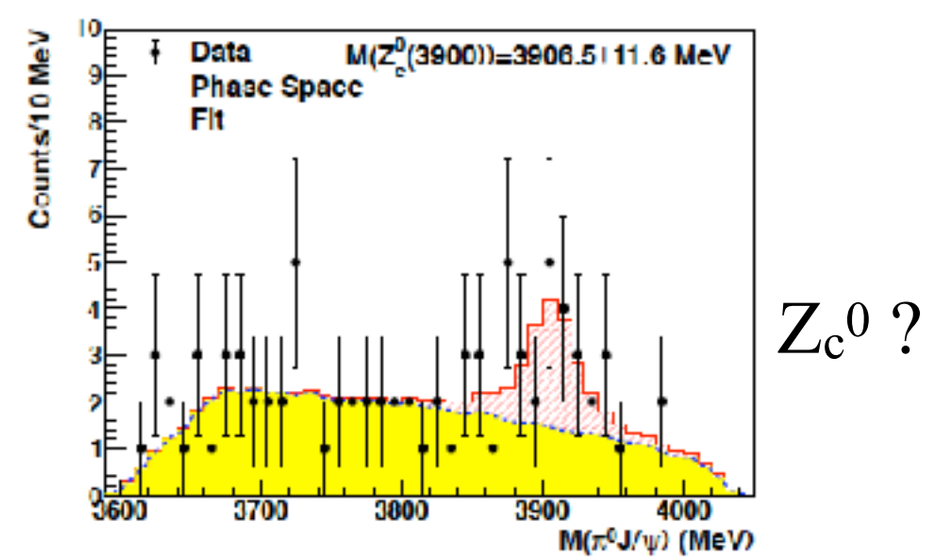












Z_c^0 ?

Expected and Unexpected Charmonia

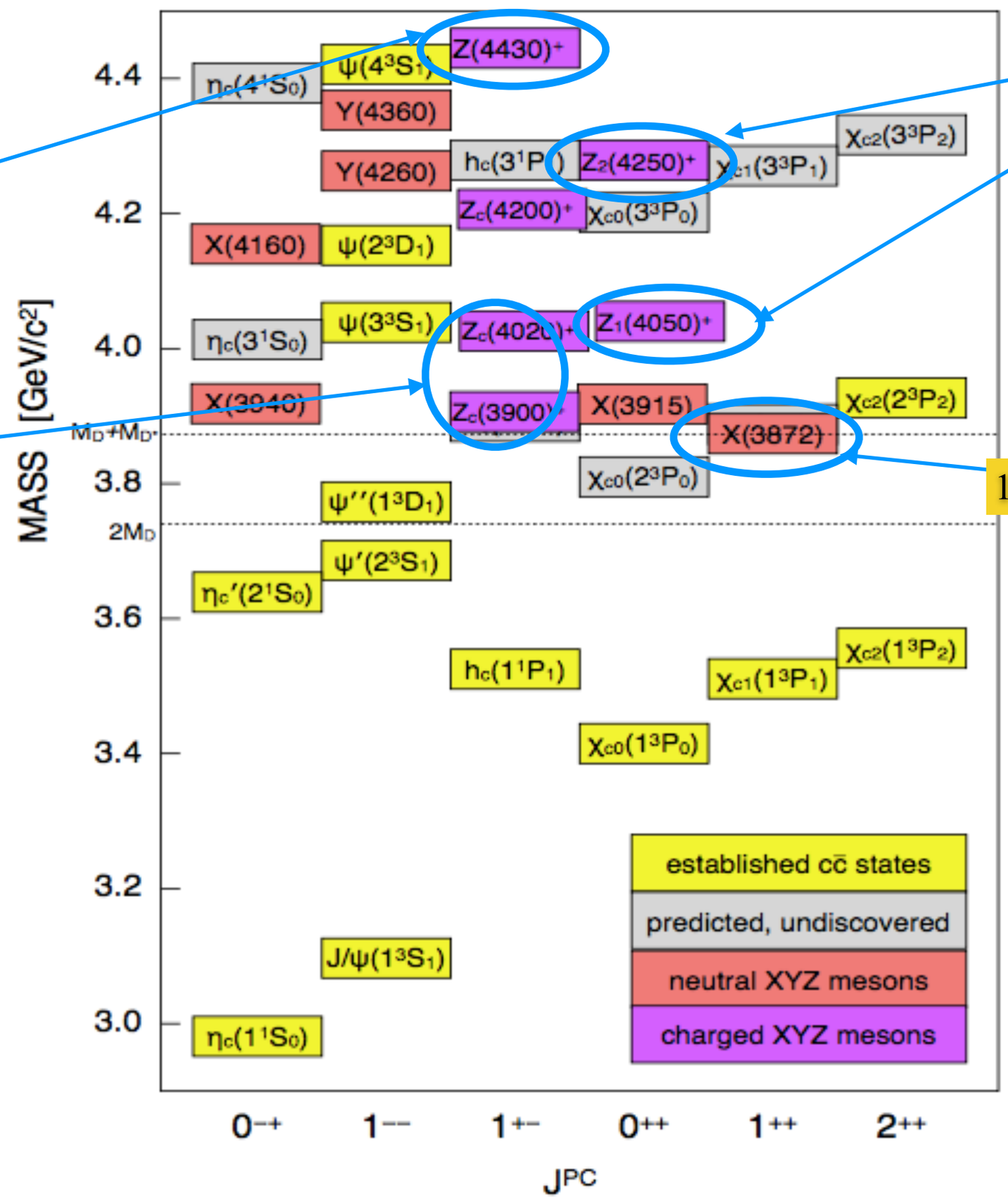
figure by:
S. L. Olsen (2015)
arXiv:1511.01589

2nd Unexpected (2007)
a radial excitation?

3rd Unexpected (2013):
a multiplet ground
state Tetraquarks?

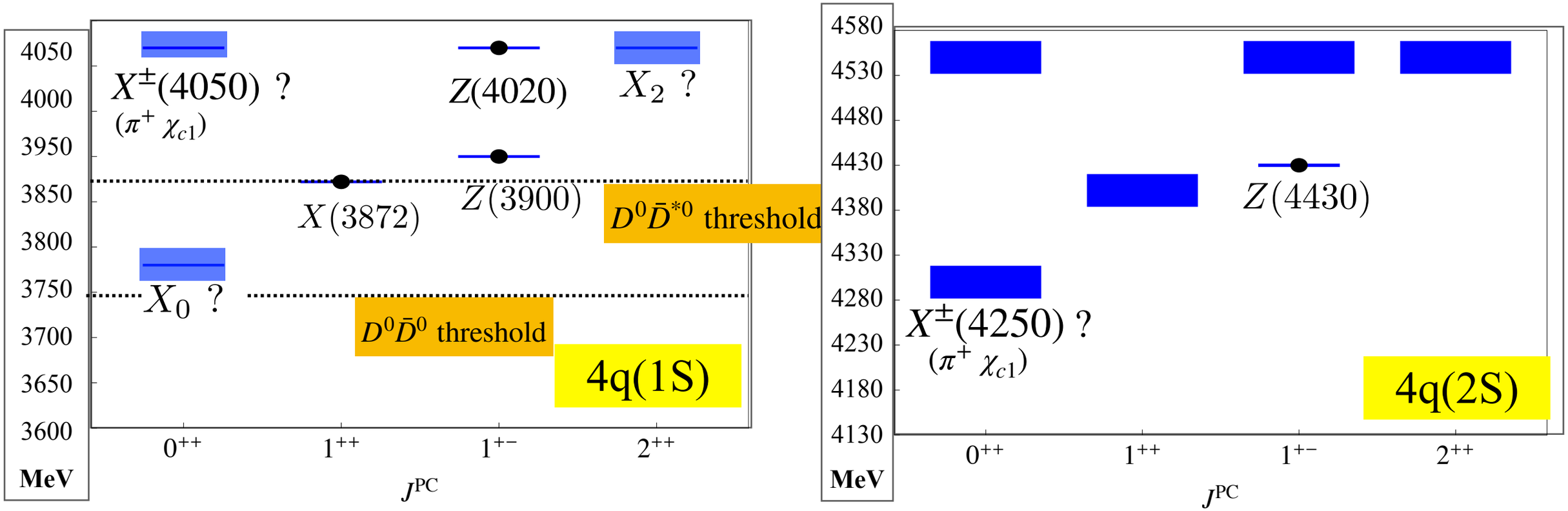
recent additions:
more than coincidence?
or
an almost filled multiplet?

1st Unexpected (2003)



Compact tetraquarks $[cq][\bar{c}\bar{q}']$: the first multiplets

- The spectrum of 1S ground states is characterised by two quantities:
  - the diquark mass, $m_{[cq]}$
  - the spin-spin interaction inside the diquark or the antidiquark, κ_{cq}.
- The first radially excited, 2S, states are shifted up by a common quantity, the radial excitation energy, ΔE_r expected to be mildly dependent on the diquark mass: $E_r(cq) \sim E_r(cs)$

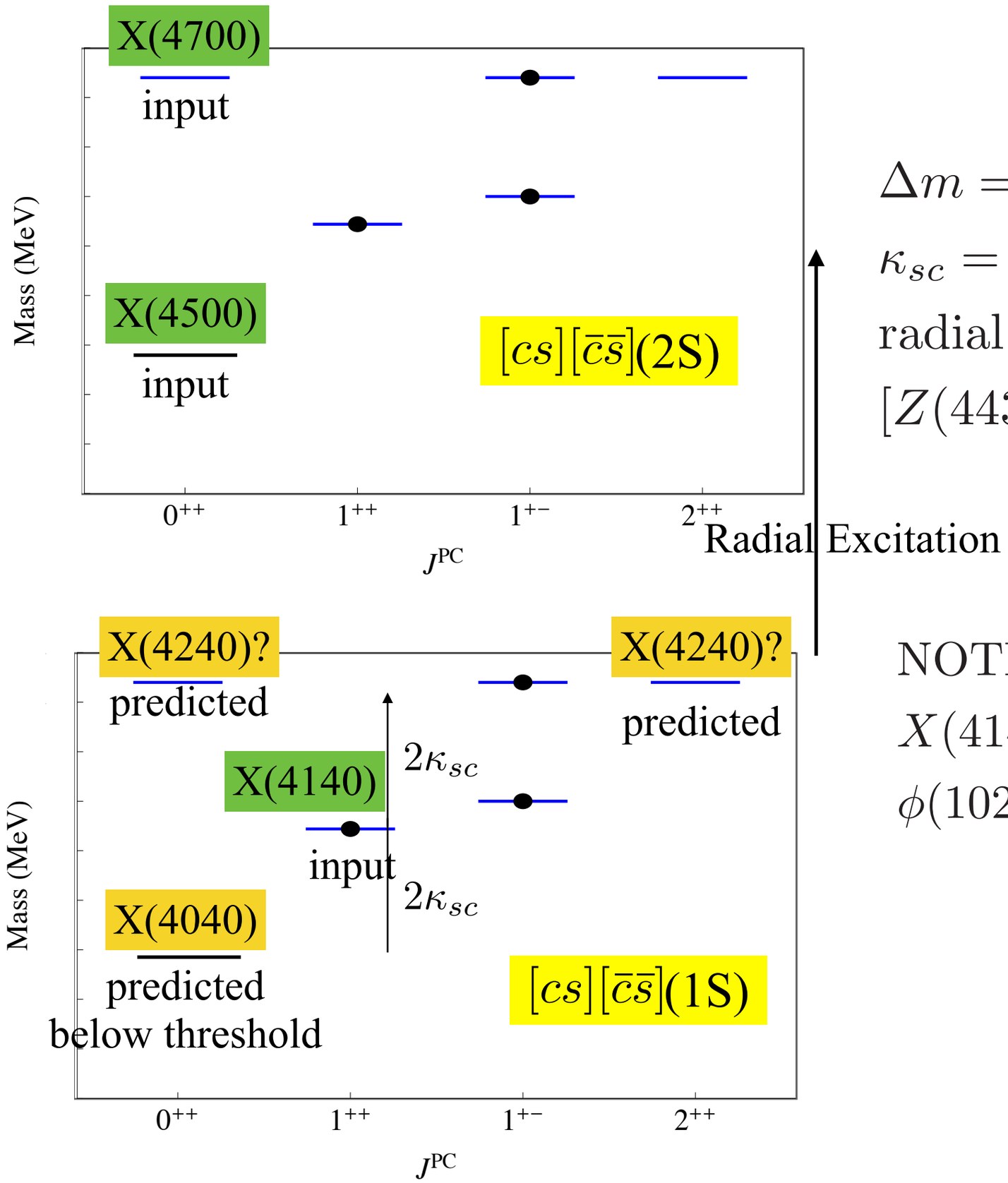


$$m_{[cq]} = 1980 \text{ MeV}$$

$$\kappa_{cq} = 67 \text{ MeV}$$

$$\Delta E_r(cq) = 530 \text{ MeV}$$

J/Ψ-φ structures and S-wave tetraquarks (2016)



$\Delta m = m_{cs} - m_{cq} = 129$ MeV;

$\kappa_{sc} = 50$ MeV ($\kappa_{qc} = 67$ MeV)

radial excit. = 460 MeV

$[Z(4430) - Z(3900) = 530$ MeV$]$

NOTE :

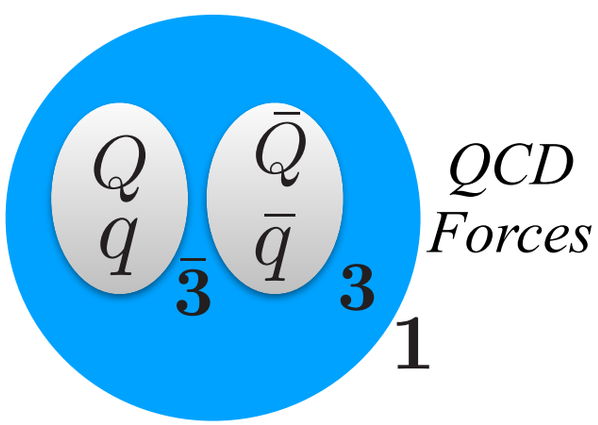
$X(4140) - X(3872) \sim 270$ MeV;

$\phi(1020) - \rho(770) \sim 244$ MeV

No consensus, yet

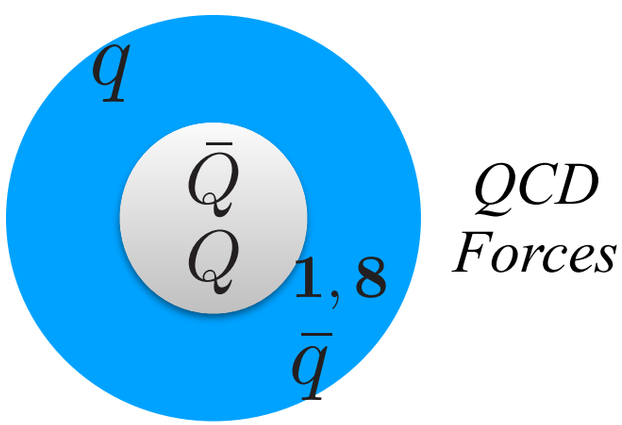
Hadron Molecule

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.

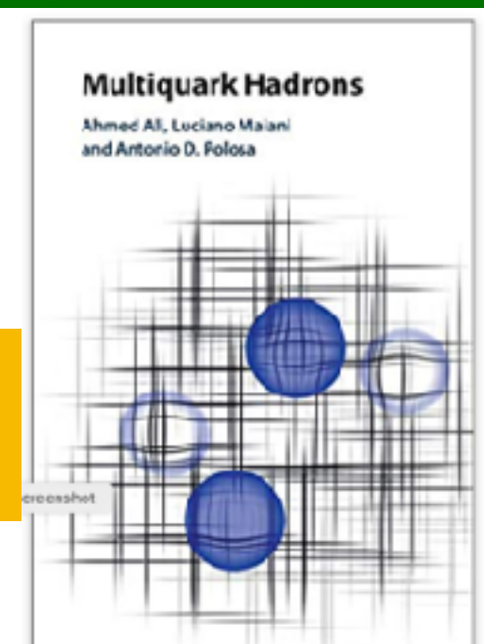


HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

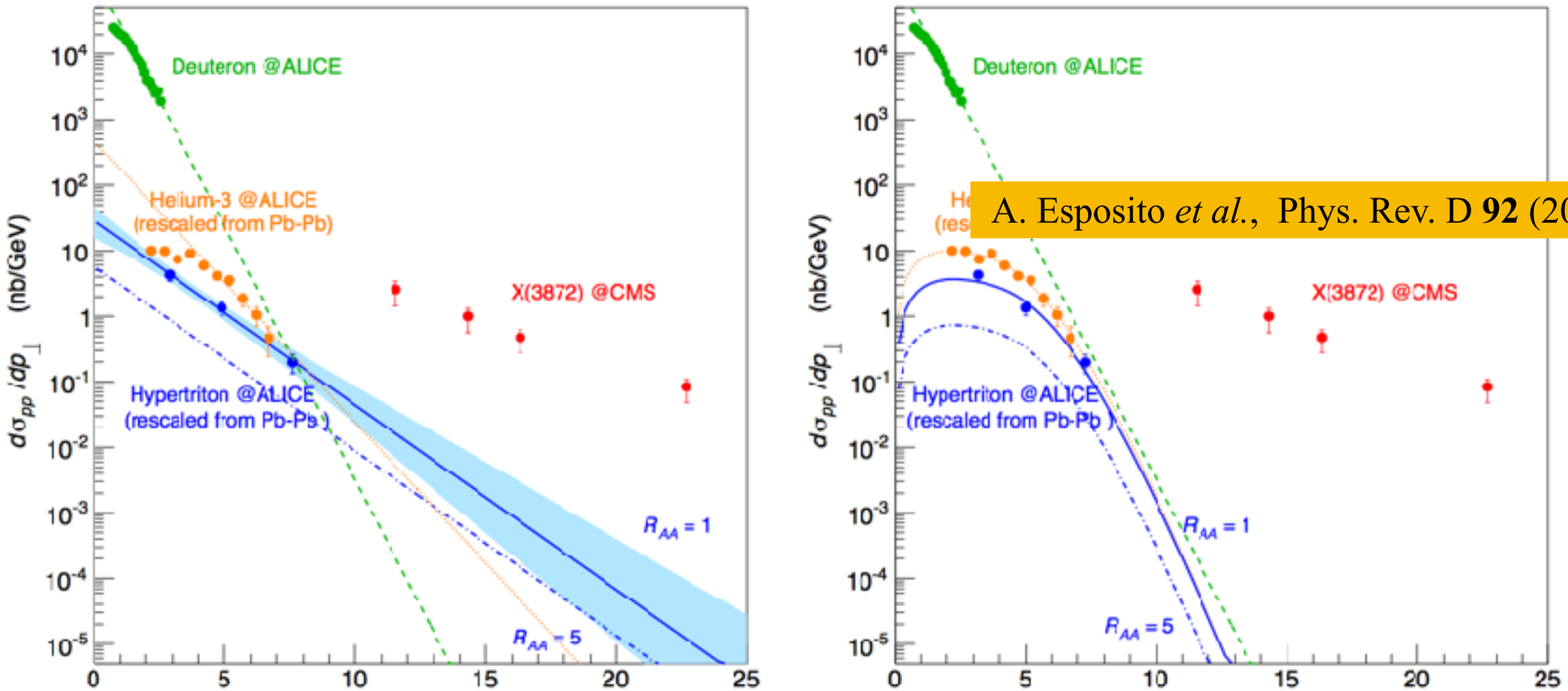
S. Dubynskiy, S. and M. B.Voloshin, Phys. Lett. **B 666**,(2008) 344.

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

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



In most cases Exotic Hadrons are produced in the decay of Beauty Mesons or Baryons but, for X(3872), production from unelastic reactions at large p_T has been observed (by CMS). This gives an important clue about its structure



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

Rescaling from Pb-Pb ALICE cross sections to p-p CMS cross section is done with: Glauber model (**left panel**) and blast-wave function (**right panel**}) (R_{AA} or R_{CP} =1)

- There is a vast difference in the probability of producing X(3872) and that of producing light nuclei, true "hadronic molecules", in high energy collisions
- high energy production of suspected exotic hadrons from quark-gluon plasma in HI collisions at colliders can be very effective tool to discriminate different models
- a long list of suspects: $f_0(980)$, X(3872), $Z^{\pm}(3900)$, $Z^{\pm}(4020)$, $Z^{\pm}(4430)$, X(4140)….

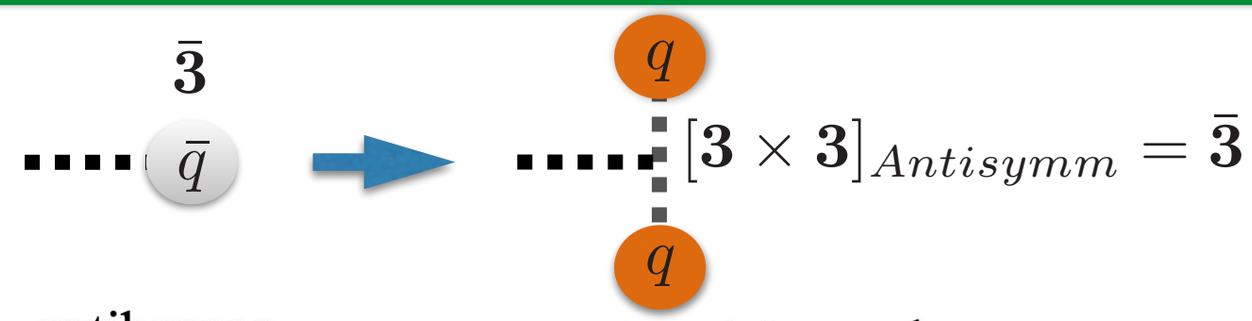
can molecule be saved by mixing with charmonium?

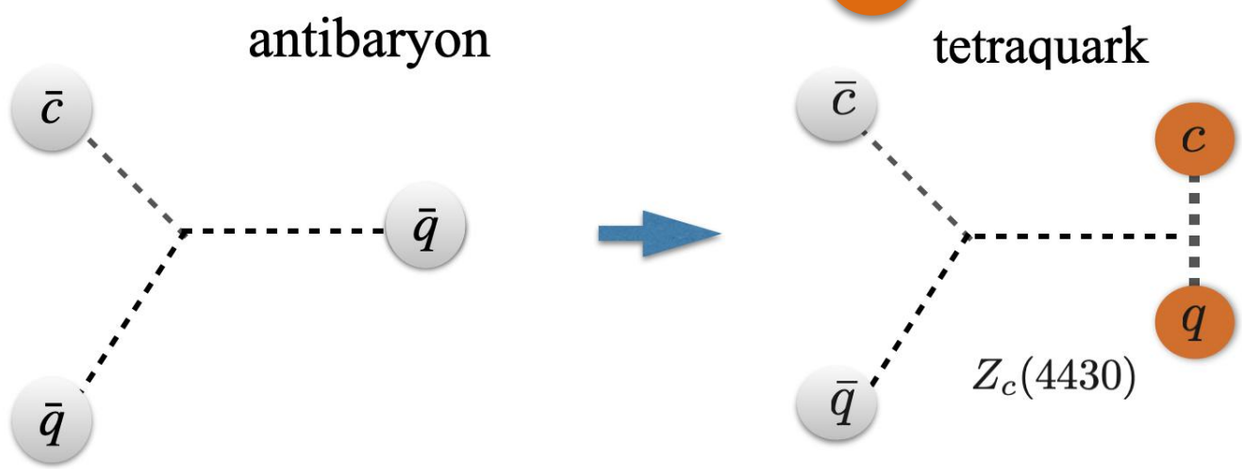
3. Generating multiquark hadrons in QCD

Classic configs:

New objects can be made by the substitution: antiquark → diquark

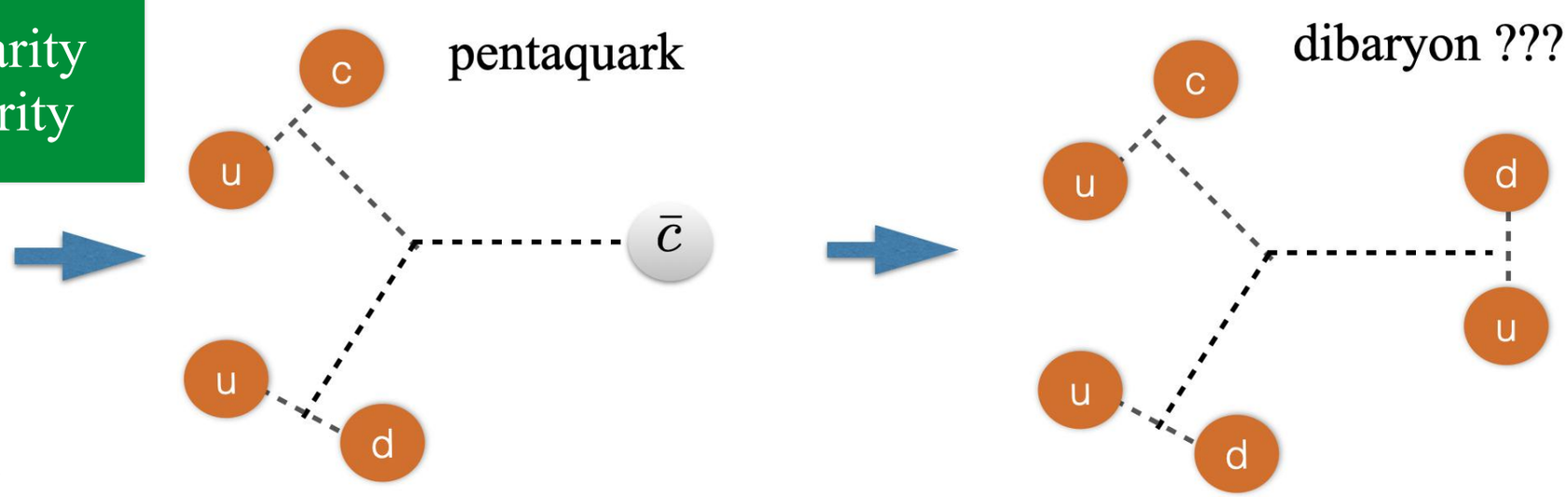
QCD rule:





S-wave positive parity: X, Z
P-wave negative parity: Y

Pentaquarks:
S-wave: negative parity
P-wave: positive parity



Lowest lying Spectroscopic series (color singlets) in 3 colours QCD

• Spectroscopic series depend upon the number of colors: ***with 2 colours*** we have only $q\bar{q}$ mesons and qq "baryons" : all extra states must be molecules.

• Multiquark states can be formulated in arbitrary number of colours, N,

• ***With 3 colours***, from baryons qqq we generate ***three spectroscopic series***: tetraquarks, pentaquarks and dibaryons, all in different flavours.

• BELLE, BESIII, LHCb have produced well established examples of (valence) tetra- and pentaquarks, no dibaryon has bee seen thus far.

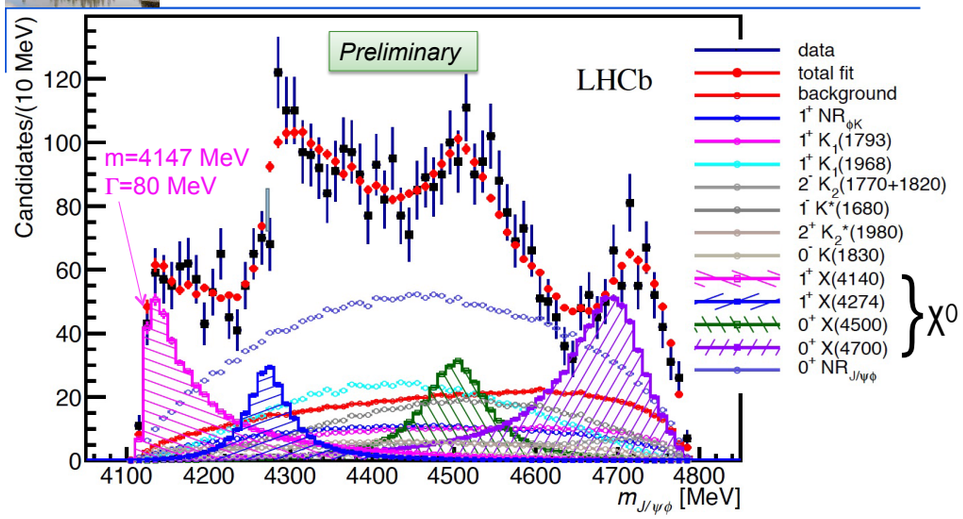
• A recent lattice QCD calculation shows a deeply bound 6 b-quarks dibaryon: $\Omega_{bbb}\Omega_{bbb}$, $E_B = -\,89^{+16}_{-12}$ MeV

N. Mathur et al. ArXiv:2205.02862

4. Exotics: the New Wave

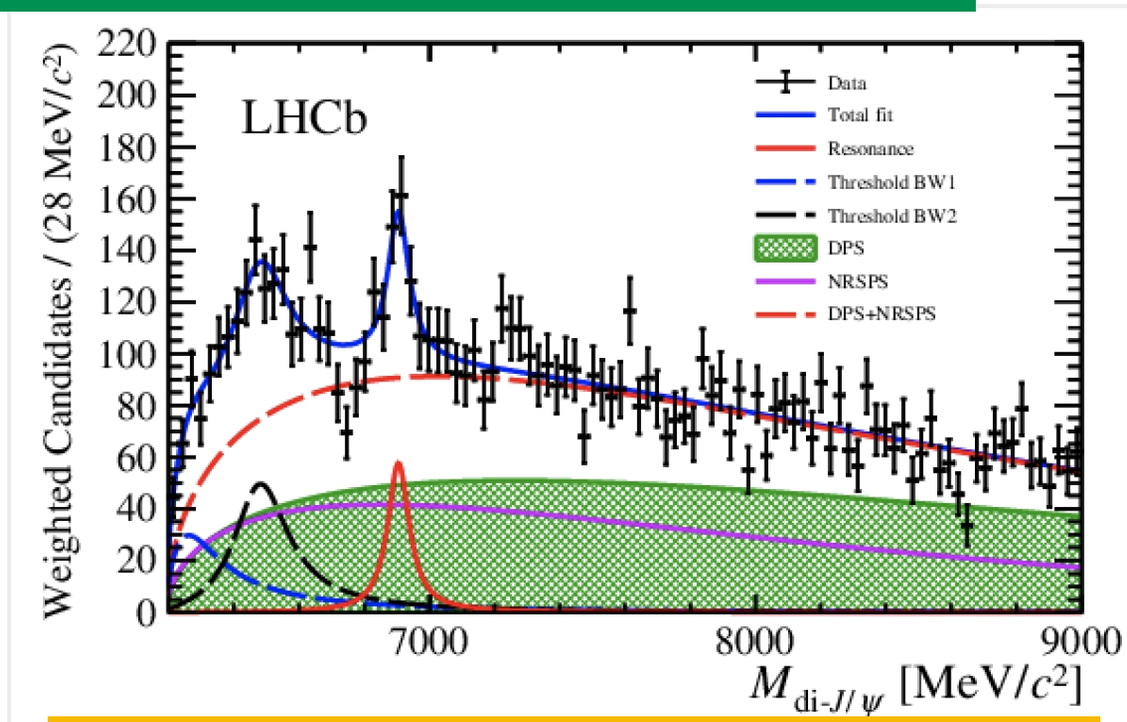
$B^+ \to K^+ + X(4140) \to K^+ + \phi\ \Psi$, etc.

Results of fit: m(J/ψϕ)



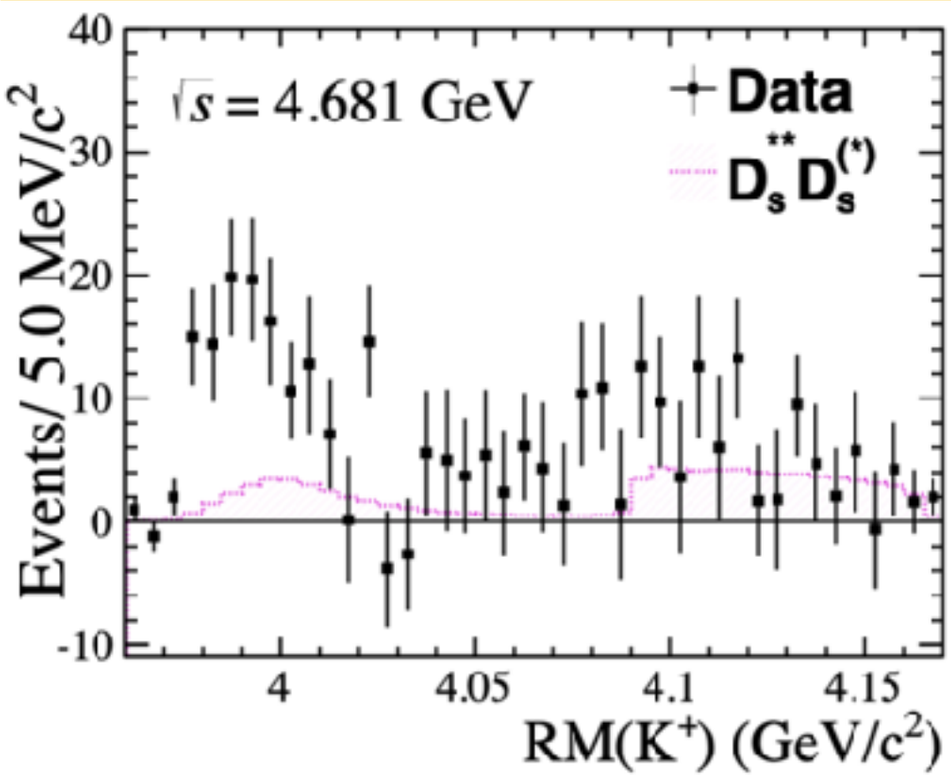
- 4 visible structures fit with BW amplitudes

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

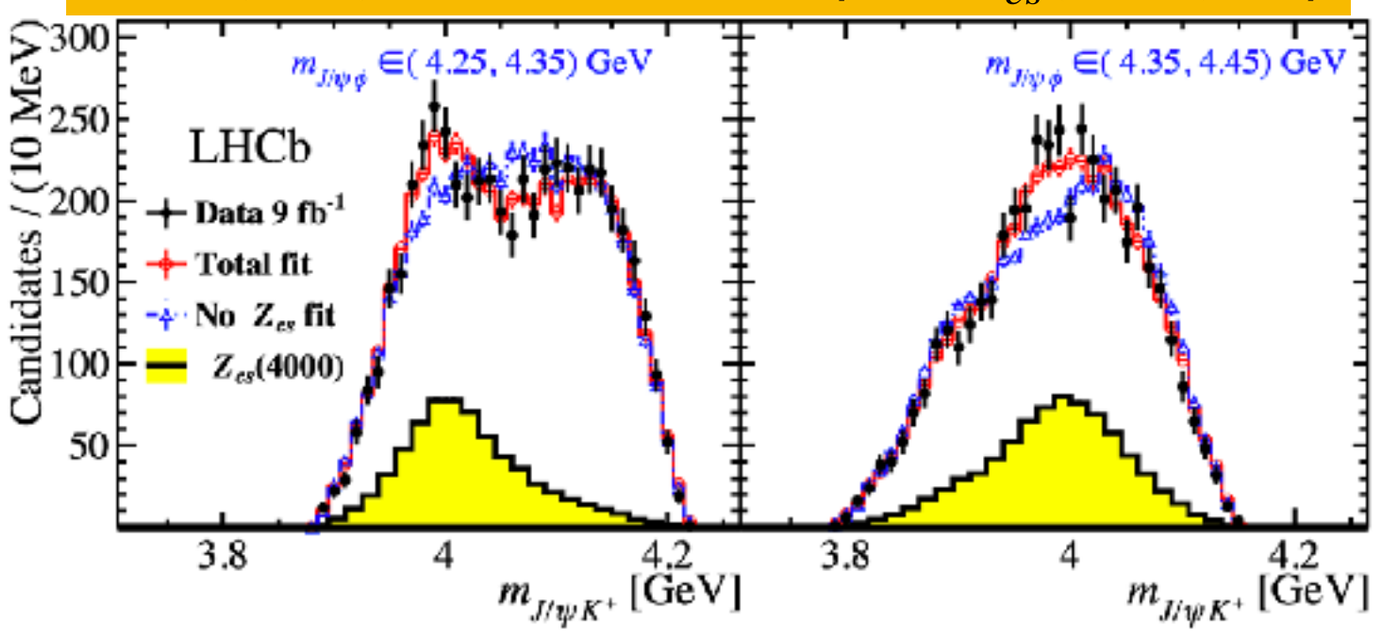


LHCb (2020): di-Ψ resonance(s) spectrum

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



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



new wave (cont'd)

- 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 could bind them as hadron molecules made by color singlet mesons
- molecular models applied to the new hadrons have to stand on the existence of "phenomenological forces" with undetermined parameters
- The New Exotics arise very naturally as $([cq]^{\mathbf{3}}[\bar{c}\bar{q}']^{\mathbf{3}})_{\mathbf{1}}$ 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

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

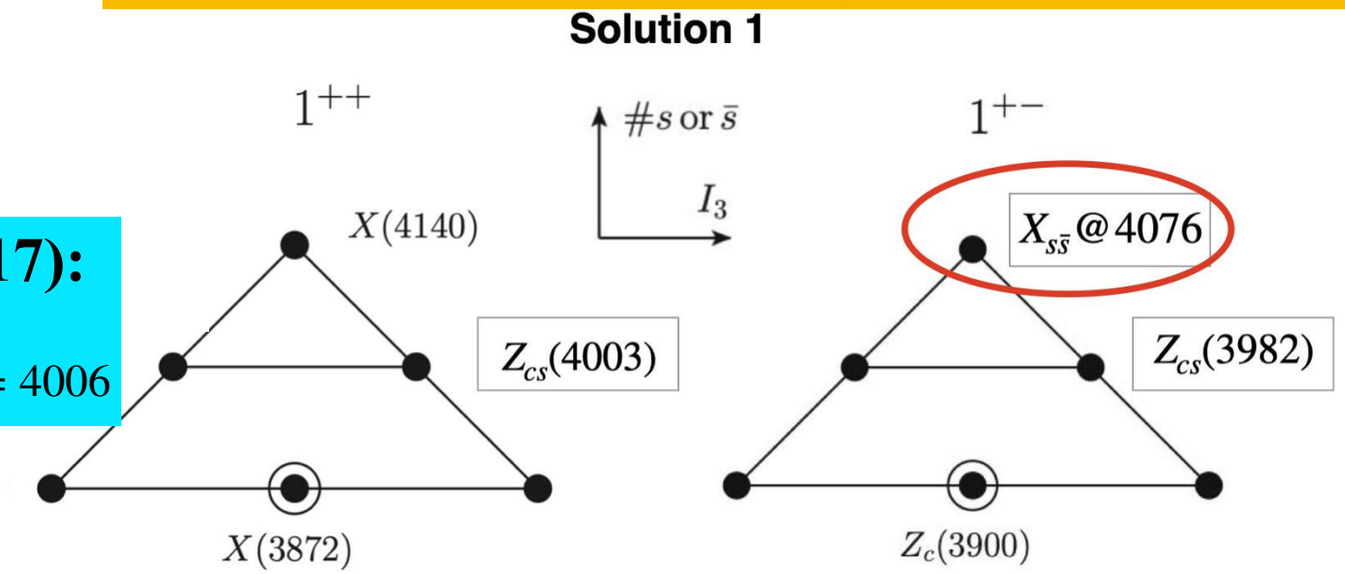
with $Z_{cs}(3082)$ and $Z_{cs}(4003)$ we can almost fill two tetraquark nonets with the expected scale of mass differences

Two nonets: Solution 1 (preferred)

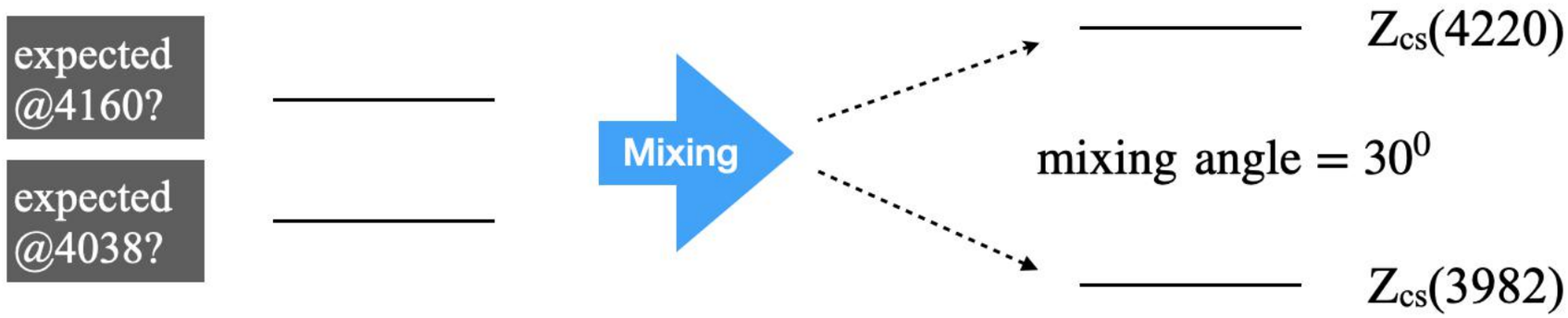
L. Maiani, A. D. Polosa and V. Riquer, Sci. Bull. **66** (2021), 1616, arXiv:2103.08331

Predicted (2017):

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



- There is a ***third nonet*** associated to $Z_c(4020)$, $J^{PC}=1^{+-}$: a third Z_{cs} is required, Mass=4150 - 4170
- ***LHCb sees a $Z_{cs}(4220)$, $J^P=1^+$or 1^-: is it too heavy ?*** A bold proposal:



A well defined shopping list towards completion:

- $X_{s\bar{s}}$, $M=4076$ (Sol. 2 : 4121), decays: $\eta\psi$, $\eta_c\ \phi$, $D_s^*\bar{D}_s$ (if phase space allows)
- the I=1 partner of X(3872), decays: $X^+\to J/\psi\ \rho^\pm\to J/\psi\ \pi^+\pi^0$
- the I=0 partners of $Z_c(3900)$ and $Z_c(4020)$, possibly decaying into: $J/\psi+f_0(500)$ (aka $\sigma(500)$)

5. Molecule or compact ? the QCD framework (following Weinberg's argument about deuteron, PRL 1965)

- We know that QCD produces hidden charm, confined hadron states: charmonia, $D^*\bar{D} + \bar{D}^*D$.

??? Do confined tetraquarks exist??

- Suppose we switch off the interactions between confined hadrons. The space of possible hidden charm st is made by two components
  - discrete energy states: charmonia and possibly tetraquarks: $|C><C| + |T><T|$
  - continuum charmed meson pairs: $|D^*\bar{D}(\alpha)><D^*\bar{D}(\alpha)|$

Completeness relation: $<X|X> = 1 = Z + \int d\alpha \; |<X|D^*\bar{D}(\alpha)>|^2,$

$$Z = |<X|C>|^2 + |<X|T>|^2$$

There are ***two regimes***

- Z=0: corresponds to a pure molecular state: X results from $D^* - \bar{D}$ interactions only (like the deuteron = pn)
- $Z \neq 0$: some compact, discrete state ***must*** exist: could it be charmonium only?
- unlike charmonium states, X decays violate isospin: $\Gamma(\Psi\rho) \sim \Gamma(\Psi\omega)$

so that:

- $Z \neq 0$ ➜***Tetraquark with X quantum numbers exists***.

How can we know?

S. Weinberg, Phys.Rev. **137**, (1965) B672

- The key is the $D^*\bar{D}$ scattering amplitude, f, that near threshold (k=center of mass momentum~0) can be parametrised as $f^{-1} = k\cot\delta(k) - ik = -\kappa_0 + \frac{1}{2}r_0k^2 - ik + \ldots$
- in presence of a shallow, below-threshold, resonance Weinberg finds:

$$\kappa_0^{-1} = 2\frac{1-Z}{2-Z}\kappa^{-1} + O(1/m_\pi);\ \ r_0 = -\frac{Z}{1-Z}\kappa^{-1} + O(1/m_\pi)$$

$\kappa^{-1} = \sqrt{2\mu B}$, $B = M(D^*) + M(D) - M(X)$ (the "binding energy")

- in the molecular case (Z=0) one has $r_0 = O(1/m_\pi)$
- ….and, for attractive potentials, one can show that ***the unspecified part*** $O(1/m_\pi)$ ***is positive***: $\boxed{r_0 > 0}$

This result is stated as solution to a problem given in the book of Landau and Lifshitz, *Quantum Mechnics;*
H.Bethe, 1949, gives a concise demonstration, see A. Esposito *et al*. Phys. Rev. **D 105** (2022), L031503

X and $\mathcal{T}_{cc}$ lineshape: from Breit-Wigner to scattering lengths

R. Aaij *et al*. (LHCb), PRD **102**, (2020) 092005

- Consider $D^{*0}\bar{D}^0$scattering above threshold. If there is a resonance slight below, the amplitude takes the Breit-Wigner form

$$f = -\frac{\frac{1}{2}g_{\mathrm{BW}}^2}{E - m_{\mathrm{BW}} + \frac{i}{2}g_{\mathrm{BW}}^2 k} \quad \text{(A)}$$

- for E= $\dfrac{k^2}{2\mu}$ and small k, the BW reduces to the scattering amplitude

$$f = \frac{1}{\cot\delta(k) - ik} = \frac{1}{-\kappa_0 + \frac{1}{2}r_0 k^2 - ik + \ldots} \quad \text{(B)}$$

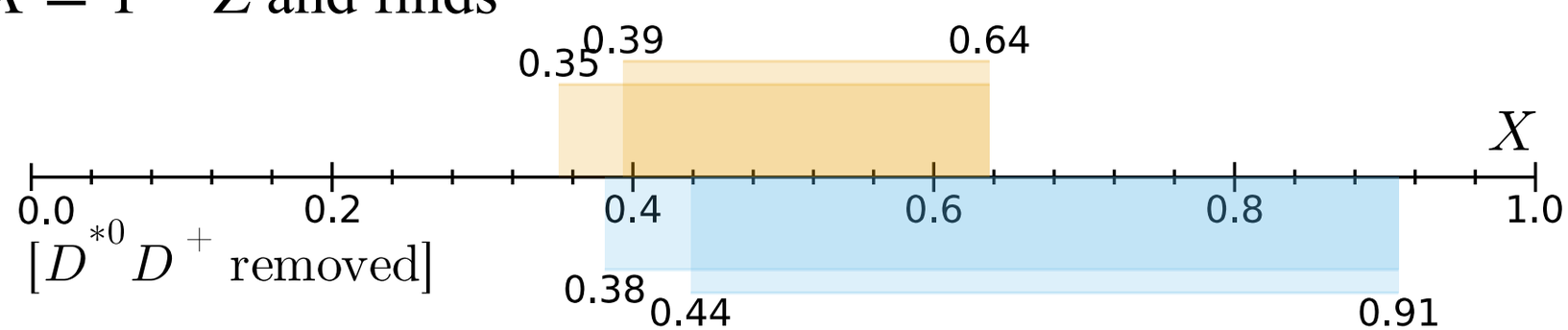
- from the parameters of the line-shape (A) we can determine κ_0 and r_0 in (B)
- for X(3872), taking into account the experimental errors, the effective radius is found to be in the range

A. Esposito *et al*. Phys. Rev. **D 105** (2022).

$$X(3872): -1.6\ \mathrm{fm} > r_0 > -5.3\ \mathrm{fm}$$

V. Baru et al., arXiv:2110.07484

- a similar analysis can be done for $\mathcal{T}_{cc}$. M Mikhasenko (Arxiv:2203.04622v1) defines: $X = 1 - Z$ and finds



X=1-Z

$0.65 > Z > 0.36$

$0.62 > Z > 0.09$

The value of Z

- From previous Weinberg formulae, we derive

$$Z = \frac{-r_0\kappa}{1 - r_0\kappa}$$

- Z is often identified with the admixture of the molecule with the compact (tetraquark) state and for small Z one would say that X is "essentially" a molecule

- However, the interpretation of Z as mixing coefficient, ***holds true in the free theory only***. With interaction, the state vector corresponding to the compact state may be renormalized and the strenght of Z looses its meaning.

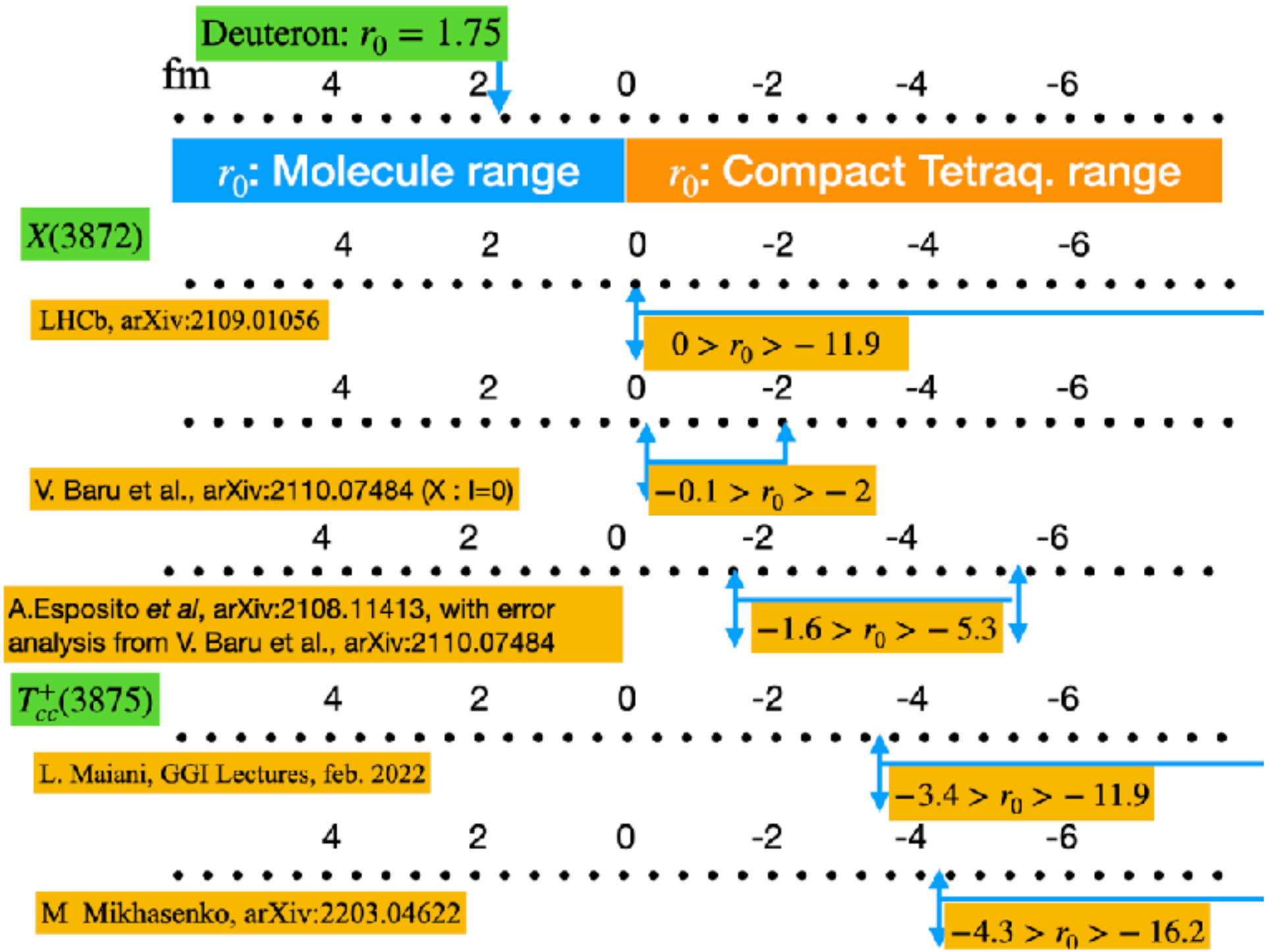
- What counts is that Z is non vanishing, indicating that ***there are***, in the Hilbert space, discrete states, different from the D D* continuum, to which X has a non-vanishing projection. This is stated clearly in Weinberg's paper:

  - *the true token that the deuteron is composite is an effective range r_0 small and positive rather than large and negative*

  - *an elementary deuteron would have* 0<Z<1.

- 0 < Z < 1 does not say anything about the existence of bound states in the inter-hadron $D^*\bar{D}$ potential, i.e. molecules: the interaction could be driven by the compact state only and be consistent with no bound molecule at all.

My Summary about r_0

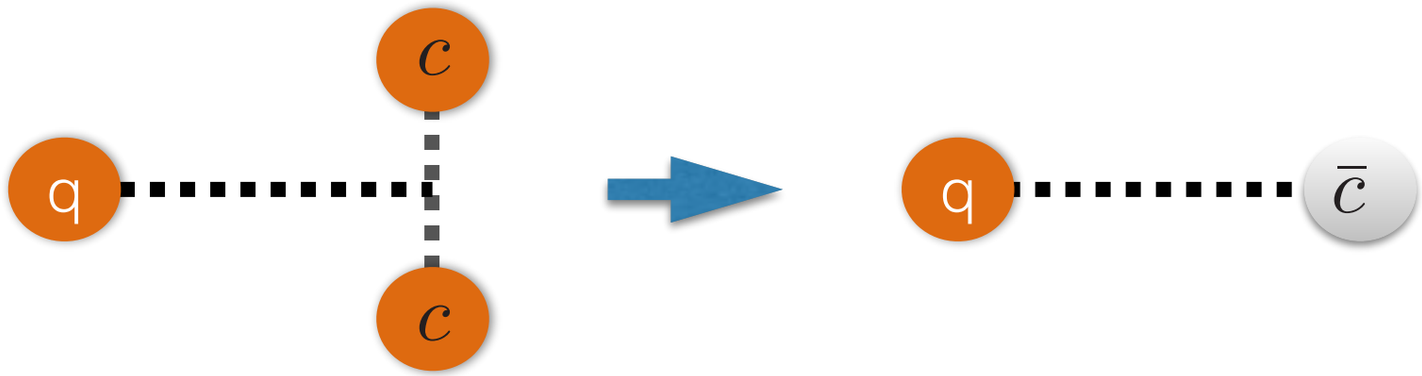


No consensus yet, but we are on a very promising road.
Stay tuned!!

6. The new sensation: doubly heavy baryons and doubly heavy tetraquarks

Single heavy-doubly heavy quark symmetry: M. Savage, M. B. Wise, PLB 248,1990; N. Brambilla, A. Vairo and T. Rosch, PRD 72, 2005; T. Mehen, arXiv:1708.05020v3

- Doubly heavy baryons are related to single quark heavy mesons:



- QCD forces are mainly spin independent, so there is an approximate symmetry relating masses of DH baryons to SH mesons: e.g. $M(\Xi^*_{cc}) - M(\Xi) = \frac{3}{4}(M(D^*) - M(D))$
- Doubly heavy tetraquarks have been anticipated long ago.

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

- The possibility has been raised that the $I = 0$, $J^P = 1^+$, $\mathcal{T}^+_{cc} = bb\bar{u}\bar{d}$ be stable under strong and e.m. decays

  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.

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

  L. Maiani, A. D.Polosa and V. Riquer, Phys. Rev. **D100** (2019) 074002,

- and in Lattice QCD

  see later for Reffs.

Radiography of the double beauty tetraquark

Born-Oppenheimer approximation in 3 steps:

- take the b quarks as fixed sources at distance R;
- find V_{BO}= energy of the bound state of light quarks in presence of the b quarks;
- solve Schroed. equation of b quarks with potential $V_{BO}(R)+V_{bb}(R)$.

For $R \to +\infty$ $V_{BO}(R)$ vanishes in both cases: why not confined?

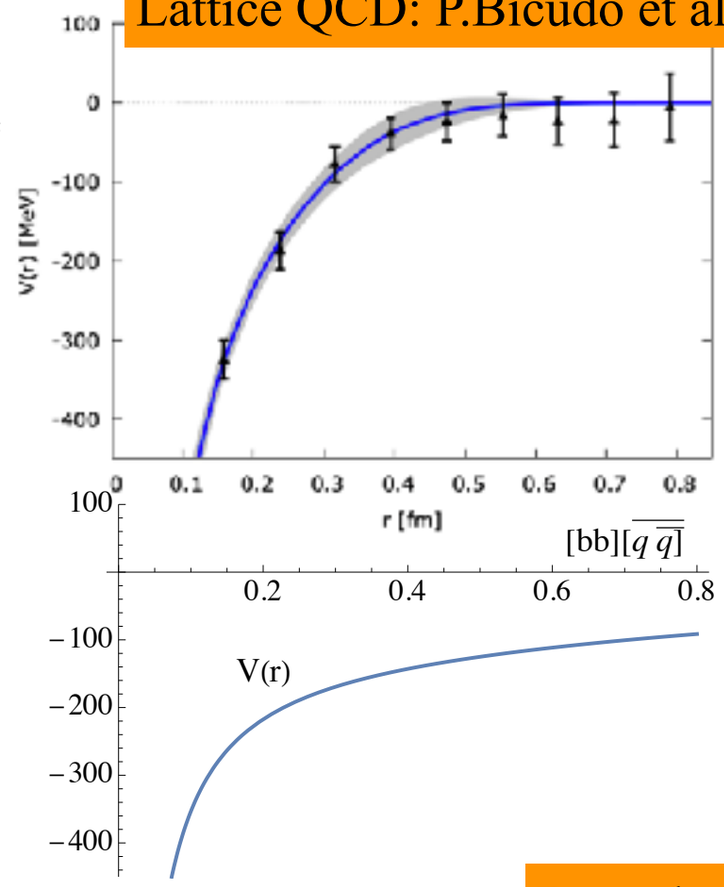
- at ∞, each b quark is screened by a $\bar{q}$: the state is a superposition of

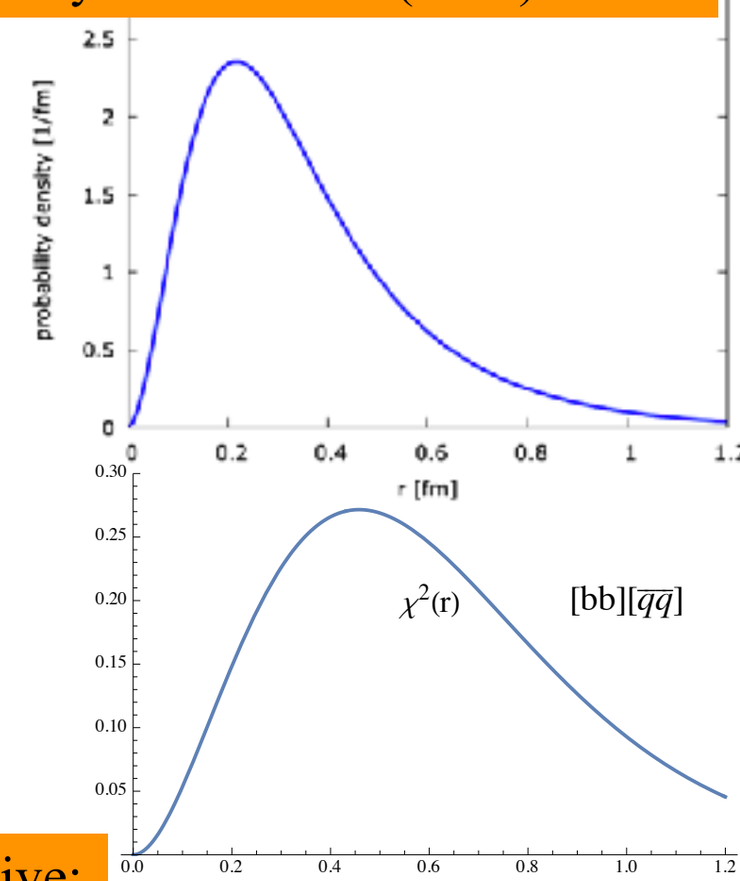
$B_{color\ 8} - B_{color\ 8}$ and $B_{color\ 1} - B_{color\ 1}$

- but in $B_{color\ 8} - B_{color\ 8}$ color can be screened by soft gluons from vacuum
- ***the asymptotic state is $B_{color\ 1} - B_{color\ 1}$ with vanishing interaction at $R \to \infty$***

- Projection of the lattice $\bar{q}\bar{q}$ result over Dd (yellow) or BB (blue) gives a picture of the space arrangement of light quarks at a given bb distance, R
- Mainly $[bb]_{\bar{3}}[\bar{q}\bar{q}]_{3}$ at the peak of the bb wave function ~0.2 fm.

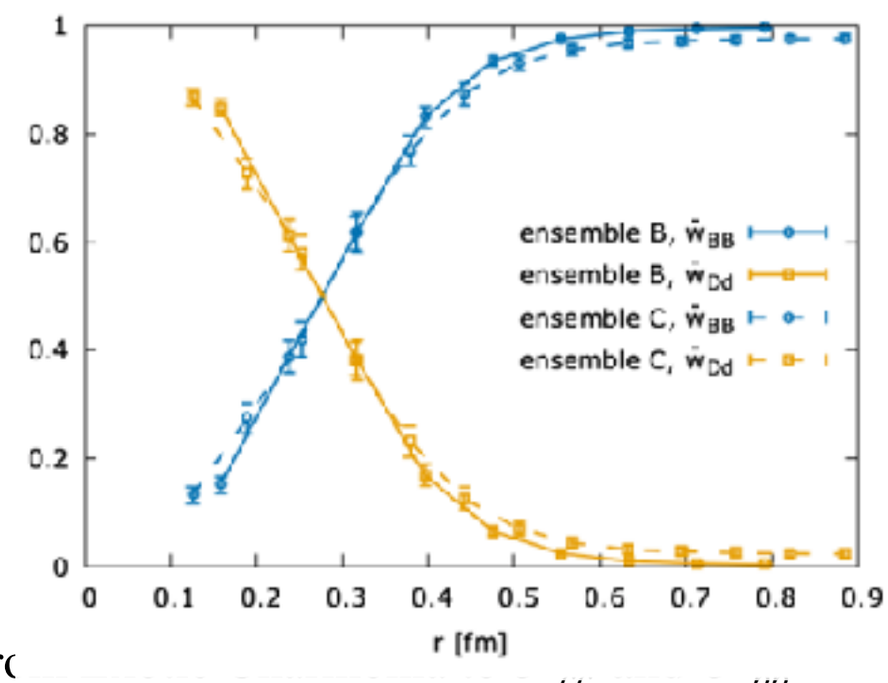
Lattice QCD: P.Bicudo et al. Phys. Rev. **D 103** (2021) 114506





Perturbative:

L. Maiani, A. D.Polosa and V. Riquer, PR D**100** (2019) 074002



← $B_1 B_1$ = Meson-Meson

Lattice QCD

← $Dd = [bb][\bar{q}\bar{q}]$

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

- There are recent estimates of the mass of of the lightest, double heavy tetrquarks, that may indicate that the I=0, $bb\bar{u}\bar{d}$ tetraquark may be stable.We give in the table below 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
- ***BO revised***: L. Maiani, A. Pilloni, A. D. Polosa and V.~Riquer, [arXiv:2208.02730 [hep-ph]]

$QQ\bar{u}\bar{d}$	BO revised [1]	K. and R.[2]	E. and Q.[3]	L.[4]	Lattice QCD
$cc\bar{u}\bar{d}$	$+136(+119)$	$+140$	$+102$	$+39$	-23 ± 11 Junn. *et al.*[5]
$bb\bar{u}\bar{d}$	$-1.8(-9.7)$	-170	-121	-75	-143 ± 34 Junn.[5] *et al.* $-143(1)(3)$ Francis *et al.*[6] $-82 \pm 24 \pm 10$ Leskovec *et al.*[7] -13^{+38}_{-30} P.Bicudo *et al.*[8]

[1] L. Maiani,et al. (2022) [2]M. Karliner and J. L. Rosner (2017). [3] E. J. Eichten and C. Quigg, (2017); [4] S. Q. Luo et al. (2017)

Lattice QCD:

[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.

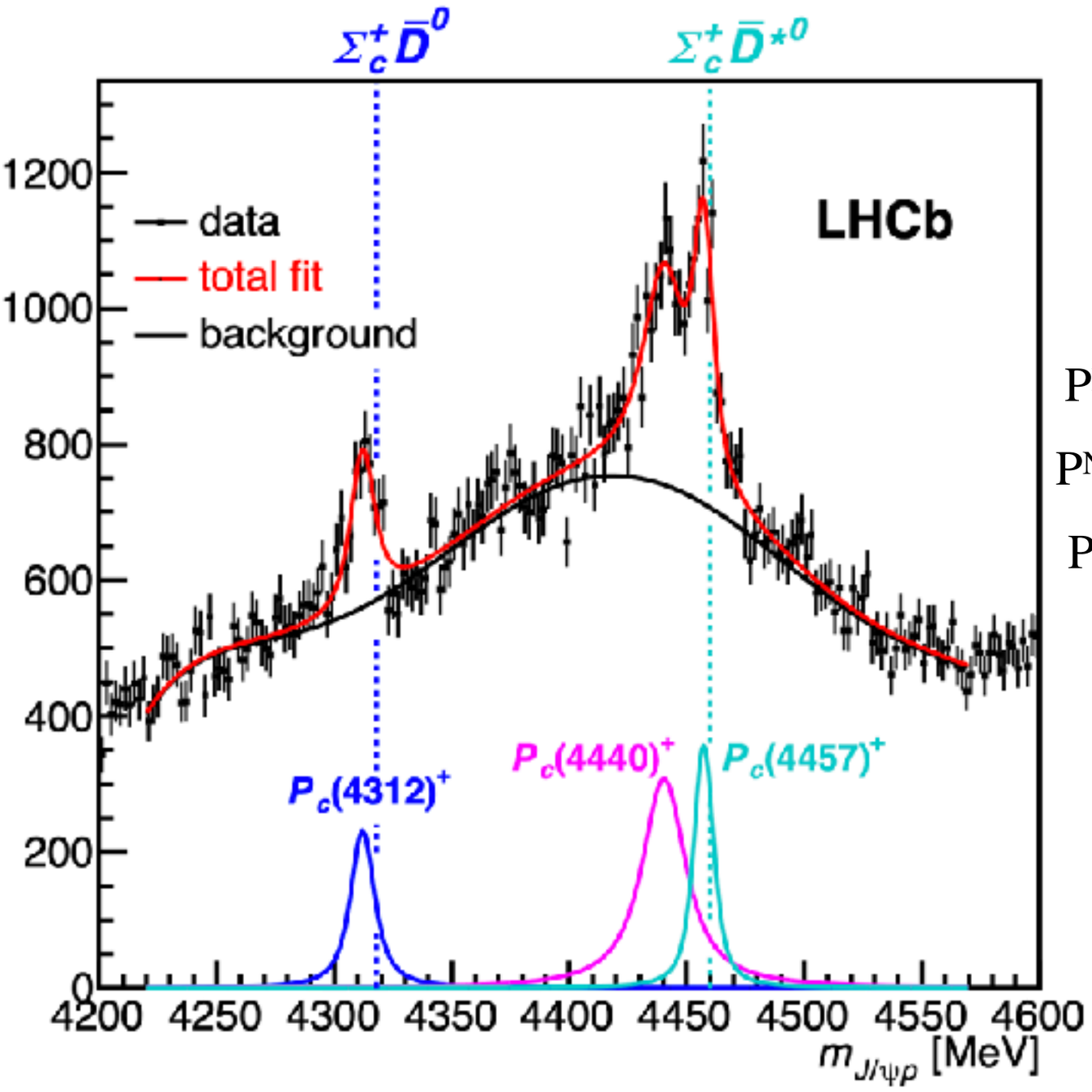
Born-Oppenheimer approximation:

- Estimate of $\mathcal{T}_{cc}$ mass close to the observed mass:

$$M(\mathcal{T}^{BO}_{cc}) = 3871(3854) \leftrightarrow \text{LHCb} : \mathcal{T}^{+}_{cc}(3875)$$

- Stable Double Beauty tetraquarks ? still possible but not so clear
- Searching for $\mathcal{T}_{cc}, I = 1$ around DD/D^*D thresholds ***is essential!!***

7. Pentaquarks



Three non strange pentaquark lines:

$P^N(4312)$: $M = 4311.9 \pm 0.7 + 6.8$, $\Gamma = 9.8 \pm 2.7 + 3.7$

$P^N(4440)$: $M = 4440.3 \pm 1.3 + 4.1$, $\Gamma = 20.6 \pm 4.9 + 8.7$

$P^N(4457)$: $M = 4457.3 \pm 0.6 + 4.1$, $\Gamma = 6.4 \pm 2.0 + 5.7$

$\Lambda_b \to J/\Psi + p + K^-$, R.~Aaij et al. [LHCb], Phys. Rev. Lett. **122** (2019) 222001, arXiv:1904.03947 [hep-ex]

In addition two (three ?) strange pentaquark lines seen

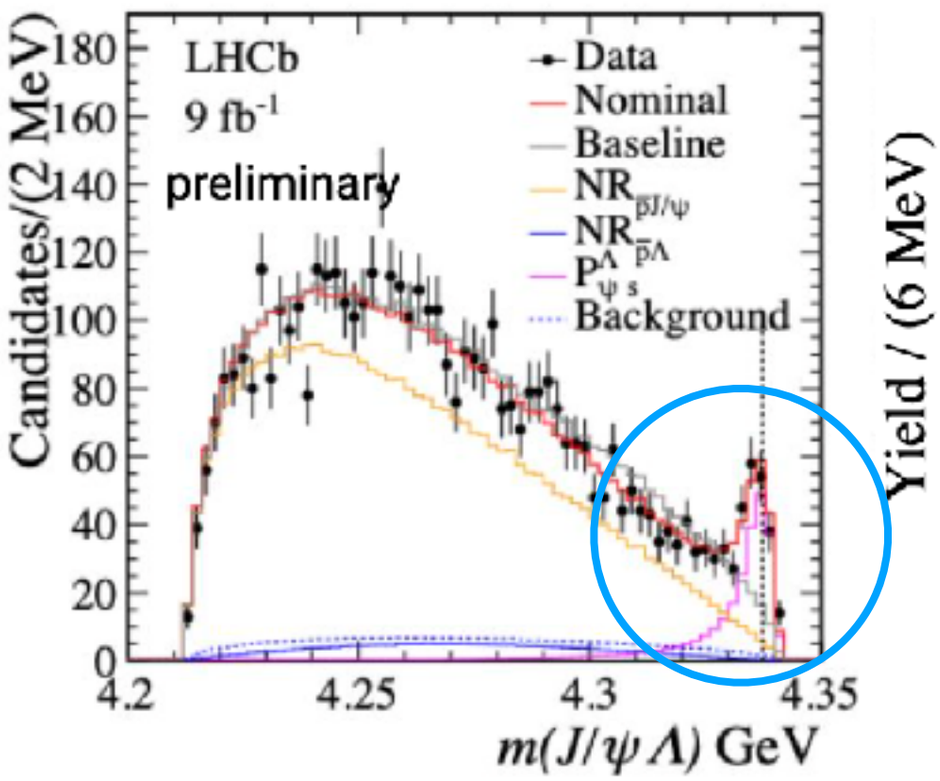
$B^- \to J/\Psi + \Lambda + \bar{p}$, LHCb Paper 2022-031,

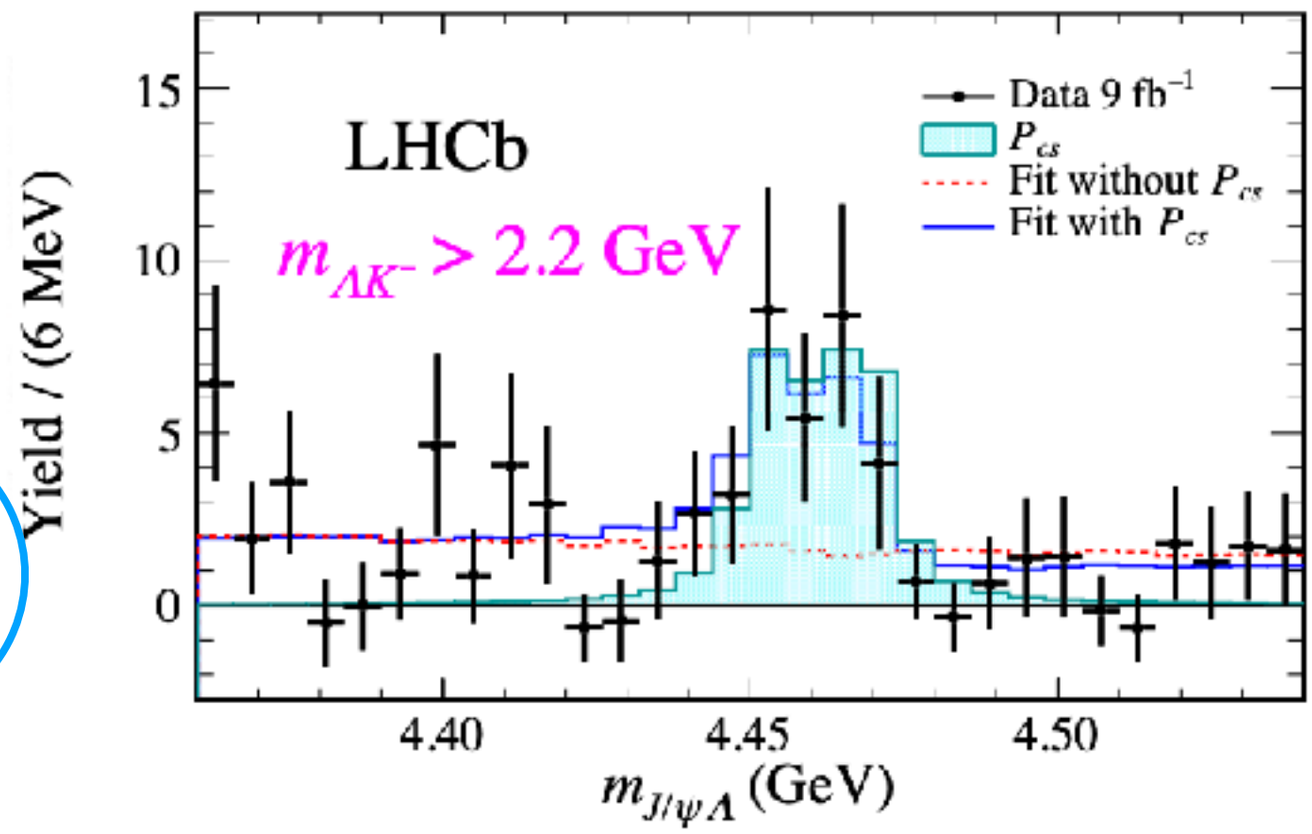
R.Aaij *et al.* [LHCb], Sci. Bull. **66** (2021), 1278; arXiv:2012.10380

P^{Λ} (4338) : M = 4338.2 ± 0.7 MeV, Γ=7.0±1.2MeV

P^{Λ} (4455) : M = 4454.9 ± 2.7 MeV, Γ = 7.5 ± 9.7 MeV

P^{Λ} (4468) : M = 4467.8 ± 3.7 MeV, Γ = 5.2 ± 5.3 MeV





Theory

1. *Molecules?*

- Non strange Pentaquarks : $\Sigma_c - \bar{D}^0$ (spin 1/2), $\Sigma_c - \bar{D}^{*0}$ (spin 1/2, 3/2)
- Strange Pentaquarks : $\Xi_c - \bar{D}^0$ (spin 1/2), $\Xi_c - \bar{D}^{*0}$ (spin 1/2, 3/2)

Karliner & Rosner arXiv:2207.07581

2. *Compact Pentaquarks ?*

Maiani, Polosa, Riquer, in preparation

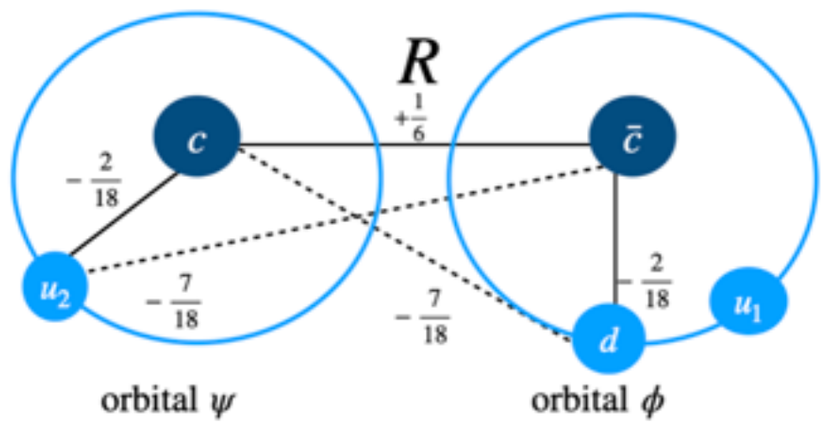
- We consider non strange Pentaquark in the Born-Oppenheimer approximation, with $\bar{c}\ [cu]\ [ud] \to [(\bar{c}c)_8 \times (uud)_8]_1$,
- To extend to a full flavour SU(3) multiplet one must consider the restrictions due to Fermi Statistics to the configurations of ***three light quarks in colour octet***
- We consider the exchange of colour, coordinates and flavour $\times$ spin (summarised in the $SU(6) \supset SU(3)_f \times SU(2)_{spin}$ symmetry)
- We find that full quark antisymmetry is reached for ***two*** flavour-spin configurations: $\mathbf{8}_{1/2} + \mathbf{10}_{3/2} = \mathbf{56}$ or $\mathbf{1}_{3/2} + \mathbf{8}_{1/2} = \mathbf{20}$.
- In both case, the ground state is in $\mathbf{8}_{1/2}$. Combining with with $c\bar{c}$ spin= 0,1, this geves rise to three Pentaquark octets: $2 \times \mathbf{8}_{1/2} + \mathbf{8}_{3/2}$
- We ***predict three lines***, corresponding to pentaquark decays: $\mathscr{P}^{(S=0)} \to J/\Psi + p$ or to: $\mathscr{P}^{(S=-1)} \to J/\Psi + \Lambda$, as observed
- decays $\mathscr{P}^{(S=-1)} \to J/\Psi + \Sigma$ and $\mathscr{P}^{(S=-2)} \to J/\Psi + \Xi$ are also predicted, e.g.:

$$\Omega_b^-(bss) \to J/\Psi + \Xi^- + K_S;\ B^-(b\bar{d}) \to J/\Psi + \Xi^0 + \bar{\Sigma}^-$$

- The two alternatives (**56** or **20**) would be distinguished by presence or absence of Pentaquarks decaying into spin 3/2 resonances, e.g. : $\mathscr{P}^* \to J/\Psi + \Delta^{++} \to J/\Psi + p + \pi^+$

Born-Oppenheimer approximation for QCD, in a nutshell

- $c(x_A)$, $\bar{c}(x_B)$ are treated as sources at fixed position (distance R) and fixed color ($\mathbf{8}_{\mathrm{SU(3)\ colour}}$)
- find the energy eigestate of the light particles $\epsilon(x_A, x_B))$
- in molecular physics one assumes light particles in orbitals around the sources
- we do the same in QCD, as in the figure



- Solve the Schroedinger equation for $c(0) - \bar{c}(x)$ with potential $V(x) = V_{c\bar{c}}(x) + \epsilon(0,\ x)$
- the eigenvalue, E, is the energy of the whole system

Preparing for Panda

- Panda could provide an additional source of high resolution results on exotic states produced by direct formation
- In particular, a high resolution study of X(3872) and related decay channel could shed light to the greatest challenges of multiquark theory of exotics:
    1. is the X(3872) line split into two almost degerate tetraquarks $X_u = [cu][\bar{c}\bar{u}]$, $X_d = [cd][\bar{c}\bar{d}]$, with $\Delta M \leq 1$ MeV?
    2. does the charged partner $X^+ \to J/\Psi + \rho^+ \to J/\Psi + \pi^+ + \pi^0$ exists?

(1.) is compatible with the present LHCb resolution,

for (2.) the present information is limited to:

$$R = \frac{\Gamma(B^0 \to K^+ + X^- \to K^+ + \ J/\psi + \pi^- + \pi^0)}{\Gamma(B^0 \to K^0\, X(3872) \to K^+ + J/\ \psi + \pi^- + \pi^+)} < 1 \text{ (PdG)},$$

we estimate: $R = 0.6 - 0.3$

In conclusion….

- ***First class results on Exotic Hadrons have been obtained in the last decade by BELLE, BES III and LHCb***
- ***The nex decade will see substantial progress by the same collaborations, with upgraded detectores, and with the start of Panda***

- 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.
- Lineshape analyses of both $X(3872)$ and $\mathcal{T}_{cc}^{+}(3875)$ seem to indicate negative values of r_0.
- Much remains to be done, to produce more precise data and to search for still missing particles, to complete the flavour multiples required by QCD bound, multiquark Exotics.
- Among the missing particles:
  - $X(3872)^{+}$, isX(3872) split into two lines: $X(3872) \rightarrow X_u + X_d$?
  - $\mathcal{T}_{cc}^{++}(?)$, $\mathcal{T}_{\bar{b}\bar{b}}^{-}(?)$
- many other states are still missing, with well defined mass and decay modes as discussed before.
- Quantum numbers of Pentaquarks and of $di - J/\Psi$
- Exotic hadrons produced in hadron collisions at large p_T: are there other, besides X(3872)?

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

so much accomplished, and so much more left to do (Winston Churchill)