Exotic hadrons with heavy quarks: experimental perspective

Tomasz Skwarnicki

Syracuse University, NY, USA

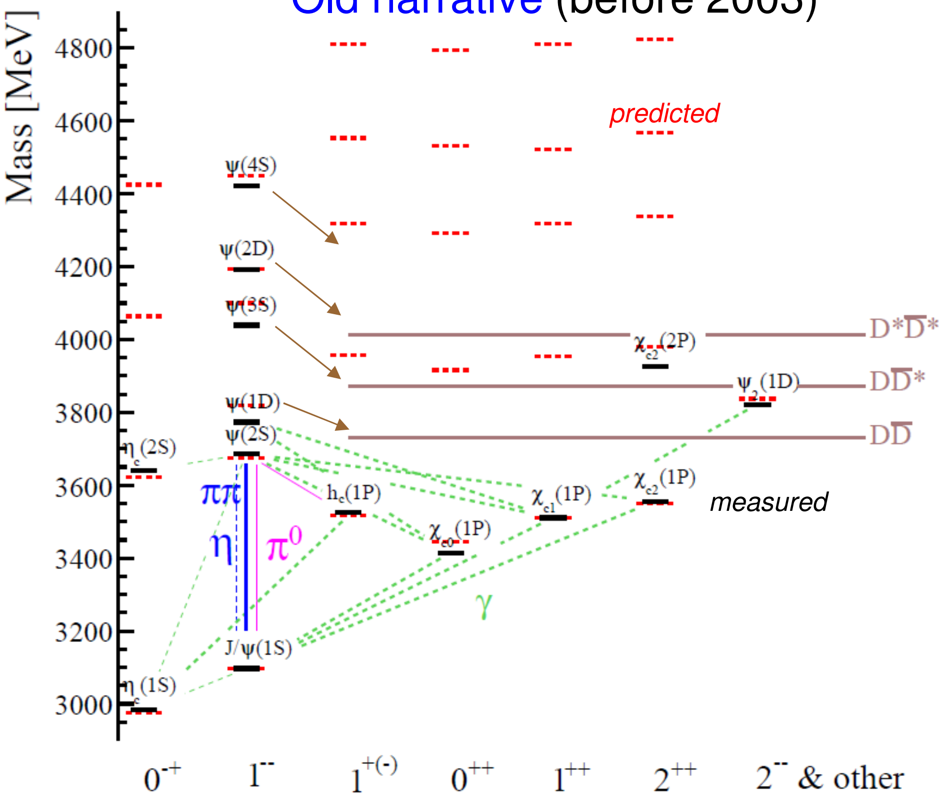
BOUND STATES
In strongly coupled systems

March 12, 2018 - March 16, 2018 • Florence, Italy
Galileo Galilei Institute for Theoretical Physics
Centro Nazionale INFN di Studi Avanzati

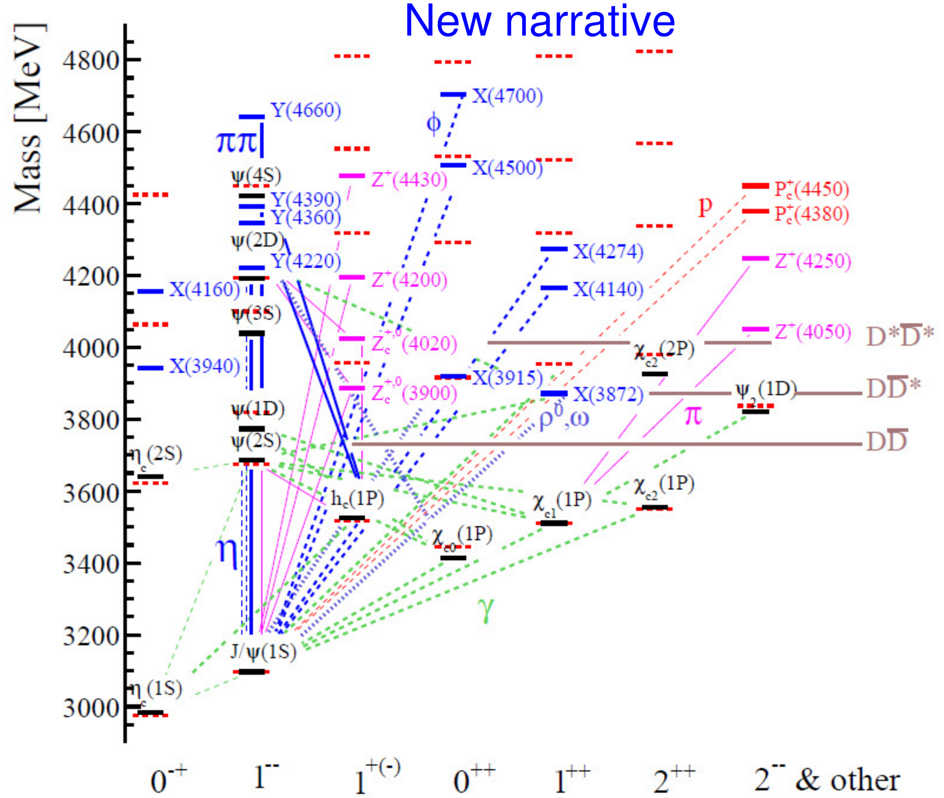
New particle Zoo: charmonium above flavor threshold

Above the flavor threshold: More exotic states than $c\bar{c}$ states!

Old narrative (before 2003)



New narrative



Figures from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Mesons are $(q\bar{q})$ bound states.

Mesons are **predominantly** $(q\bar{q})$ bound states below the open flavor threshold. **They are more complex structures above it,** and we have not yet understood them.

All excited light hadrons are above "the open flavor threshold"!

New particle Zoo: bottomonium above flavor threshold

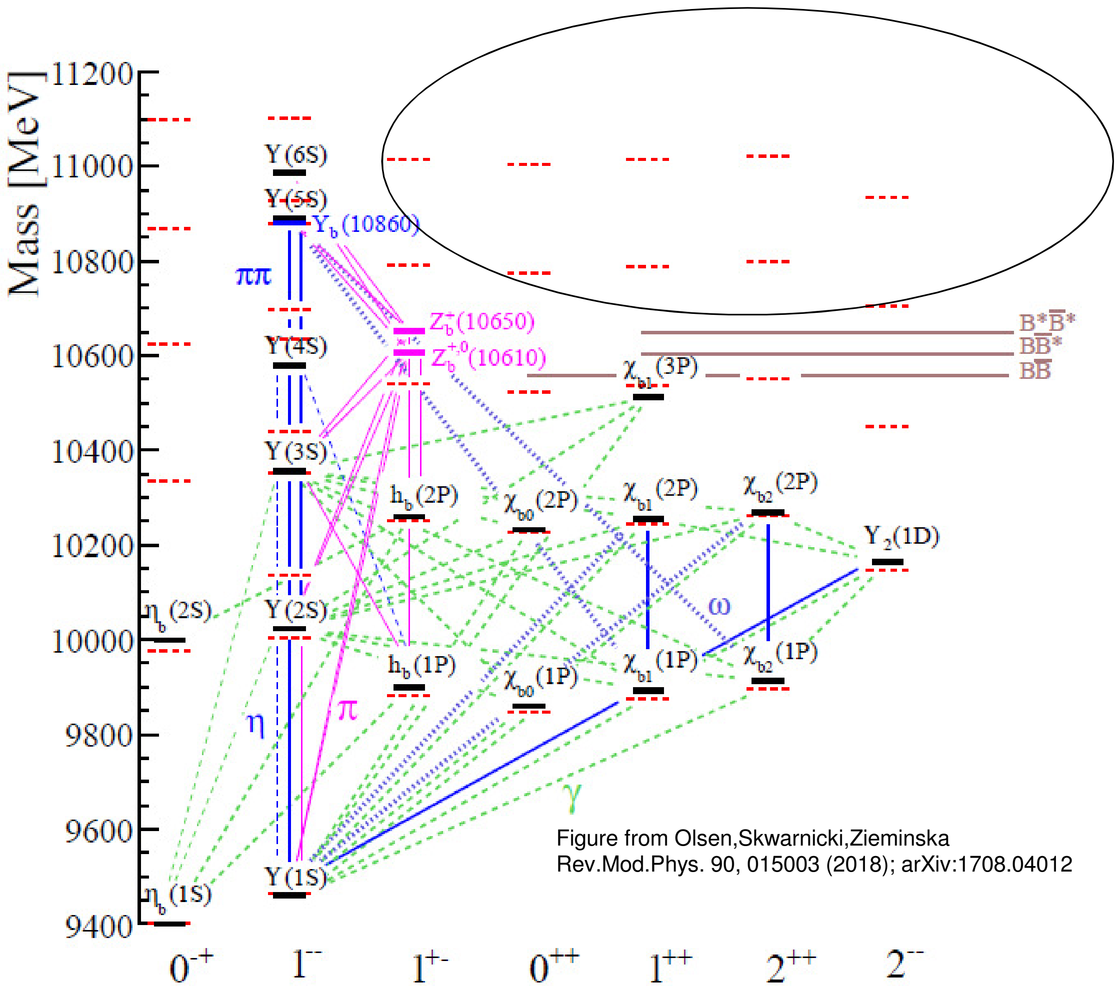


Figure from Olsen,Skwarnicki,Zieminska Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Difficult to explore experimentally:

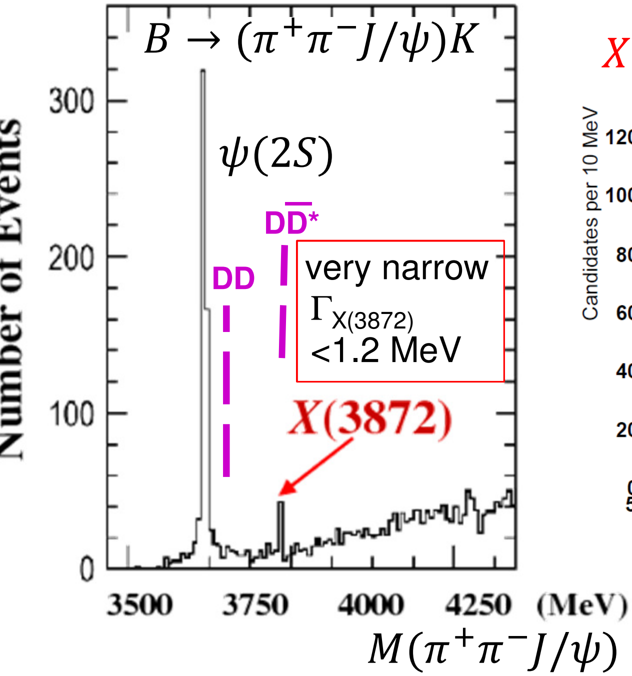
- Not accessible at B-factories
- Prompt production at LHC more promising but comes with **suppressed cross-section** $(m_b > m_c)$ and **very large combinatorial backgrounds** (huge particle multiplicities out of PV)
- $t \to bW$ at LHC does not produce secondary vertex unlike $b \to cW$ (much smaller backgrounds) since top is too short-lived
- Future high-energy e^+e^- collider?
  - ISR production from Higgs factory
  - Doubtful a dedicated high-luminosity e^+e^- machine to scan above Υ(6S) or produce $Z^0 \to b\bar{b}$ would ever be built

Charmonium near or above flavor threshold: back to complexity

Belle: Discovery of X(3872)

PRL 91, 262001 (2003)

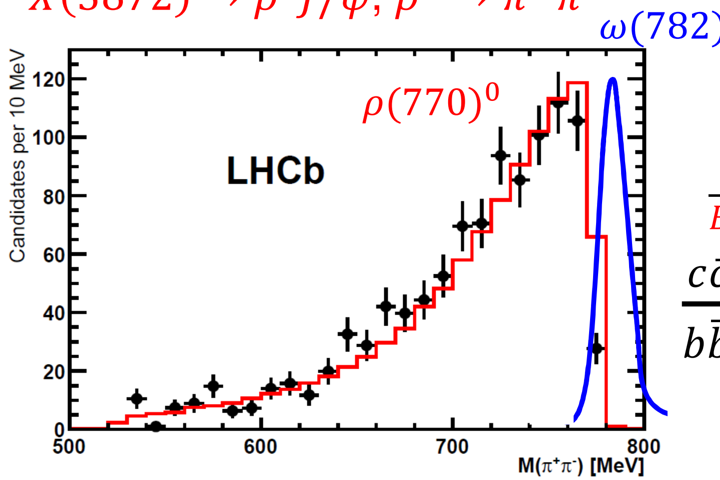
The most cited Belle paper (1441 citations)



No charged partner found: $I=0$.

Isospin violating decay:

$X(3872) \to \rho^0 J/\psi,\ \rho^0 \to \pi^+\pi^-$



LHCb $J^{PC}=1^{++}$

$\chi_{c1}(2^3P_1)$?

$(\omega \to \pi^+\pi^-\pi^0)$

$$\frac{BR(X(3872) \to \omega J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 0.8 \pm 0.3$$

Suppression of isospin allowed $X(3872) \to \omega J/\psi$ can be blamed on phase-space $\Delta m = 774.8$ MeV

$$\frac{BR(X(3872) \to \gamma J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 0.27 \pm 0.08$$

$c\bar{c}$

$b\bar{b}$ $\Delta m = 795.2$ MeV

$$\frac{BR(\chi_{b1}(2^3P_1) \to \gamma \Upsilon(1^3S_1))}{BR(\chi_{b1}(2^3P_1) \to \omega \Upsilon(1^3S_1))} = 6.1 \pm 1.6$$

$\chi_{b1}(2^3P_1) \to \pi^+\pi^-\ \Upsilon(1^3S_1)$ not seen

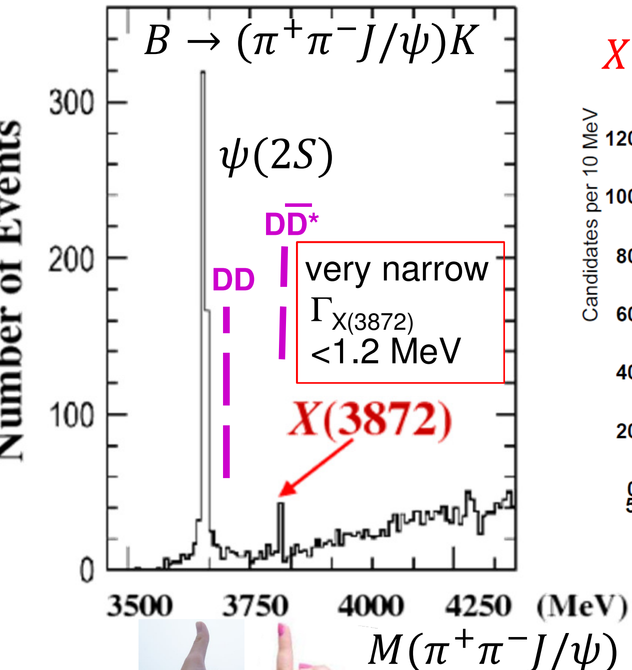
Enhancement of isospin violating $X(3872) \to \pi^+\pi^- J/\psi$ relative to radiative transitions rules out pure $\chi_{c1}(2^3P_1)$ interpretation

Charmonium near or above flavor threshold: back to complexity

Belle: Discovery of X(3872)

PRL 91, 262001 (2003)

The most cited Belle paper (1441 citations)

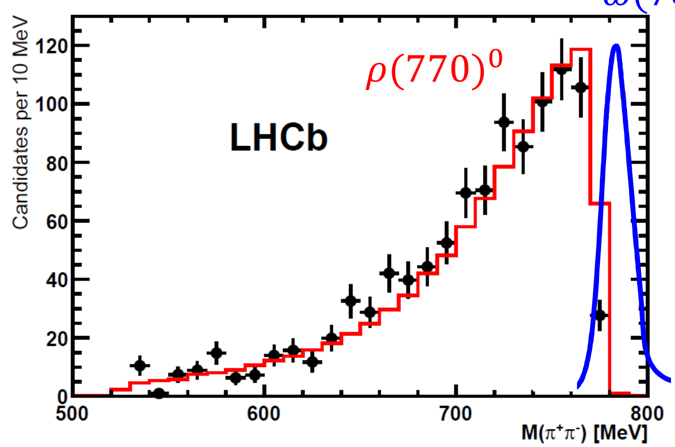


mesons are simple   *not at all!*

No charged partner found: I=0.

Isospin violating decay:

$X(3872) \to \rho^0 J/\psi,\ \rho^0 \to \pi^+\pi^-$



LHCb $J^{PC}=1^{++}$

$\chi_{c1}(2^3P_1)$?

$m_{X(3872)} \approx m_{D^0} + m_{D^{*0}}$
indistinguishable within the errors

molecule ?

8.2 ± 0.2 MeV below $m_{D^\pm} + m_{D^{*\pm}}$ ⇨ natural source of isospin violation

$(\omega \to \pi^+\pi^-\pi^0)$

$$\frac{BR(X(3872) \to \omega J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 0.8 \pm 0.3$$

Suppression of isospin allowed $X(3872) \to \omega J/\psi$ can be blamed on phase-space $\Delta m = 774.8$ MeV

$$\frac{BR(X(3872) \to \gamma J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 0.27 \pm 0.08$$

$c\bar{c}$

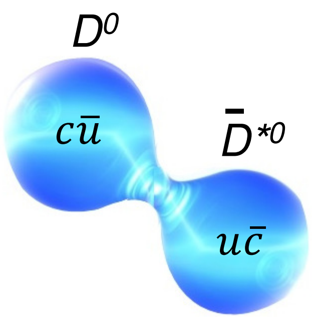
$b\bar{b}$ $\Delta m = 795.2$ MeV

$$\frac{BR(\chi_{b1}(2^3P_1) \to \gamma\Upsilon(1^3S_1))}{BR(\chi_{b1}(2^3P_1) \to \omega\Upsilon(1^3S_1))} = 6.1 \pm 1.6$$

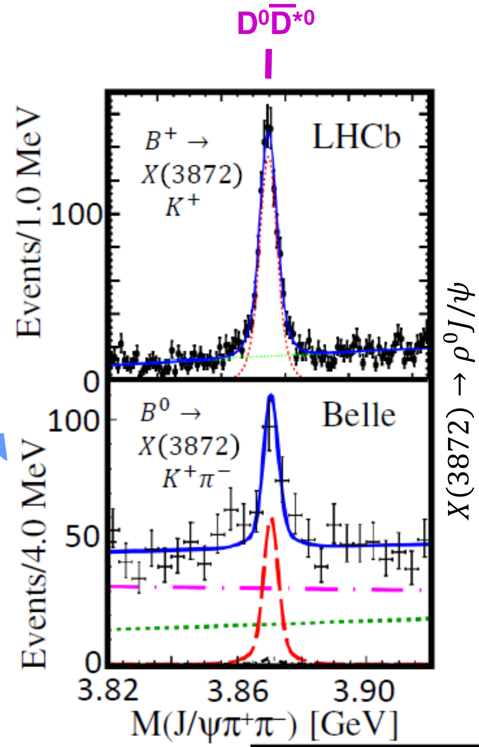
$\chi_{b1}(2^3P_1) \to \pi^+\pi^-\ \Upsilon(1^3S_1)$ not seen

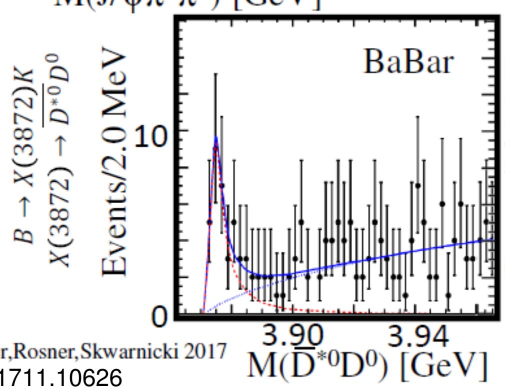
Enhancement of isospin violating $X(3872) \to \pi^+\pi^- J/\psi$ relative to radiative transitions rules out pure $\chi_{c1}(2^3P_1)$ interpretation

X(3872): molecular features



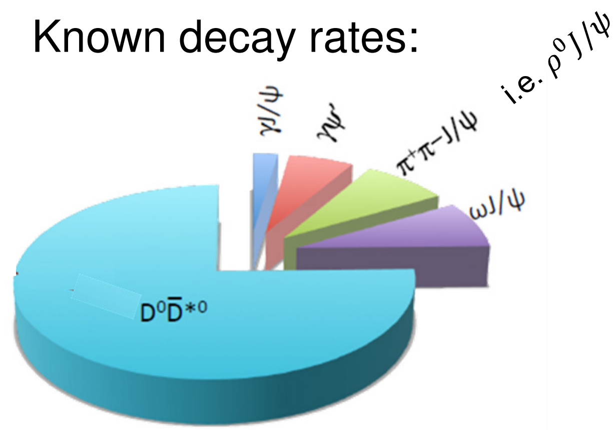
Narrow width in decays to $c\bar{c}$





Karliner,Rosner,Skwarnicki 2017
arXiv:1711.10626

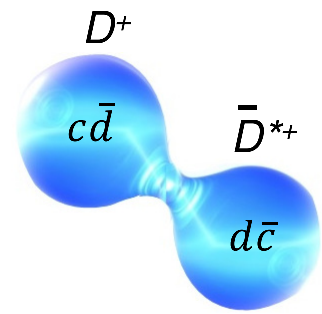
Known decay rates:



Huge fall-apart mode from the resonance tail above the $D^0\overline{D^{*0}}$ threshold

$0^- 1^-$ interacting in S-wave
compatible with $J^{PC}=1^{++}$

only small admixture of

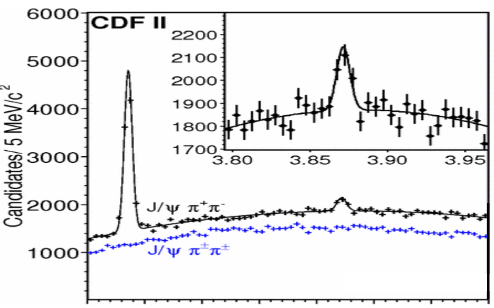


Enhanced isospin violating decays

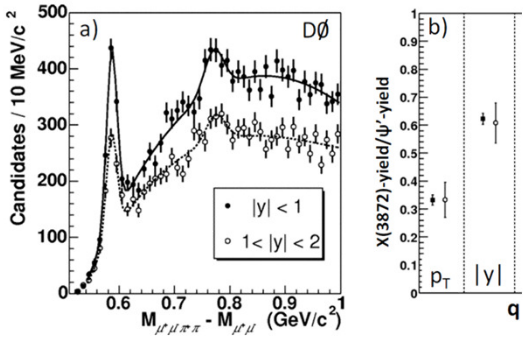
$X(3872) \to \rho^0 J/\psi$

Prompt production of X(3872)

$p\bar{p} \to X(3872) + \ldots$ @Tevatron

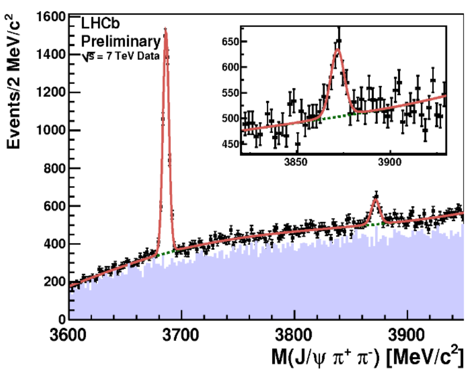


PRL **93**, 072001 (2004)

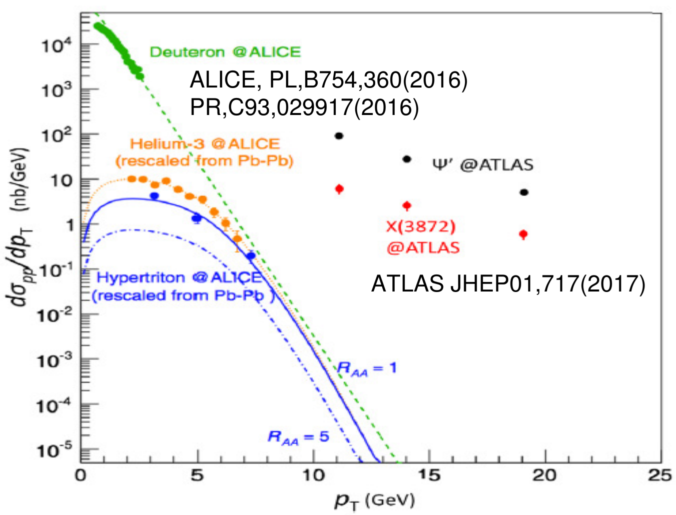


PRL **93**, 162002 (2004)

$pp \to X(3872) + \ldots$ @LHC



EPJ C72, 1972 (2012)



A. Esposito et al. (ATLAS data inserted by S.Olsen)

Dispute if large prompt production cross-section is compatible with molecular interpretation:

A. Esposito, A. L. Guerrieri, L. Maiani, F. Piccinini, A. Pilloni, A. D. Polosa, and V. Riquer PRD92, 034028 (2015)

M. Albaladejo, F.-K. Guo, C. Hanhart, Ulf-G. Meißner, J. Nieves, A. Nogga, Z. Yang, Chin.Phys.C41, 121001 (2017); arXiv:1709.09101

and

A. Esposito et al. arXiv:1709.09631

X(3872)/ψ(2S) production ratio nearly universal:

- in B decay modes
- prompt production in $p\bar{p}$ and pp including dependence on transverse momentum and rapidity

My own opinion:

- Strong evidence for compact component at short distances ($c\bar{c}$ or tetraquark?)
- Not necessarily incompatible with $D\bar{D}^*$ component at large distances

Radiative decays of X(3872)

LHCb NP B886 (2014) 665

phase-space:

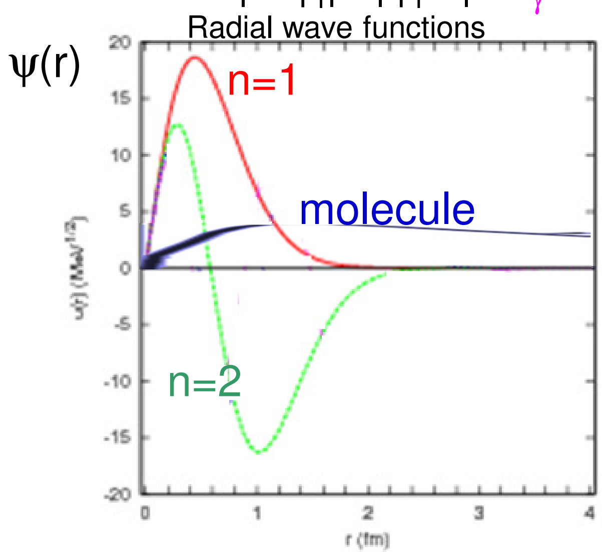
$$\frac{BR(X(3872)\to\psi(2S)\gamma)}{BR(X(3872)\to J/\psi(1S)\gamma)}$$

suspressed ← $\psi(2S)\gamma$; favored ← $J/\psi(1S)\gamma$

= 2.48±0.64±0.29 (>0 at 4.4σ)

by a factor of ~100!

BR ~ $|\langle\psi_f|\, r\, |\psi_i\rangle|^2\, E_\gamma^3$



Hard to find other mechanism to favor $\psi(2S)\gamma$ over $J/\psi(1S)\gamma$ other than 2P→ 2S

$|\langle 2S|\, r\, |2P\rangle|^2 \gg |\langle 1S|\, r\, |2P\rangle|^2$ — $\chi_{c1}(2^3P_{1++})$ ✓

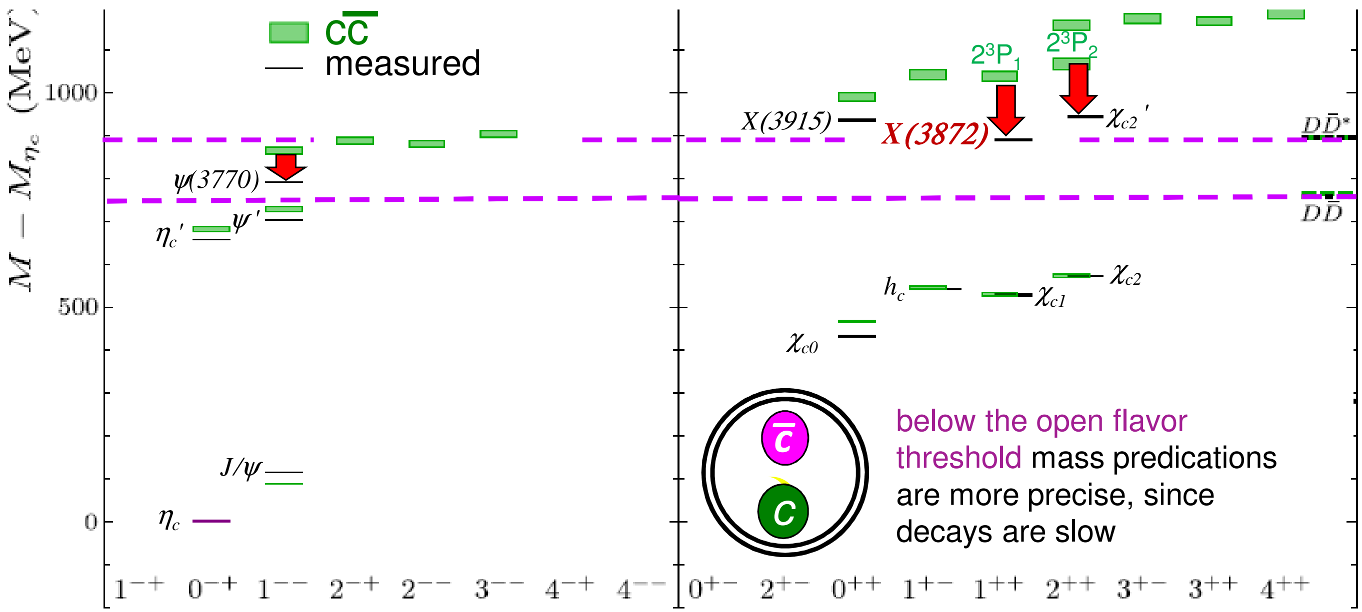
$|\langle 2S|\, r\, |mole.\rangle|^2 \ll |\langle 1S|\, r\, |mole.\rangle|^2$ — molecule ☐

My own opinion:

- Points to $c\bar{c}$ component of X(3872)
- Does not rule out $D\bar{D}^*$ component at large distances (F.-K. Guo et al., PL B742, 394 (2015); arXiv:1410.6712)

X(3872) mass vs $\chi_{c1}(2^3P_1)$ expectations

Hadron Spectrum Collaboration (LQCD m_π=240 MeV) **JHEP 1612, 089 (2016)**



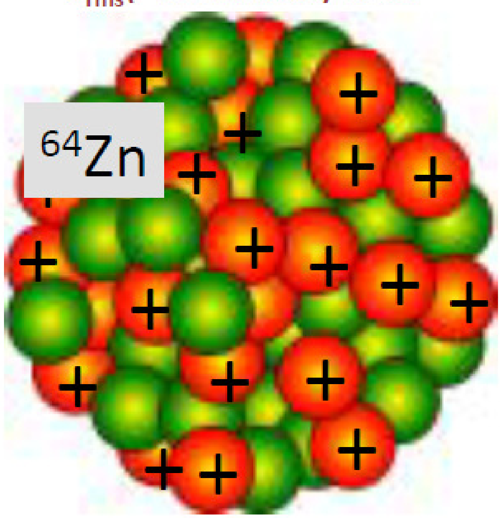
LQCD and potential models overestimate masses of excited charmonium states above the open flavor threshold, since they do not include large couplings to the decay channels

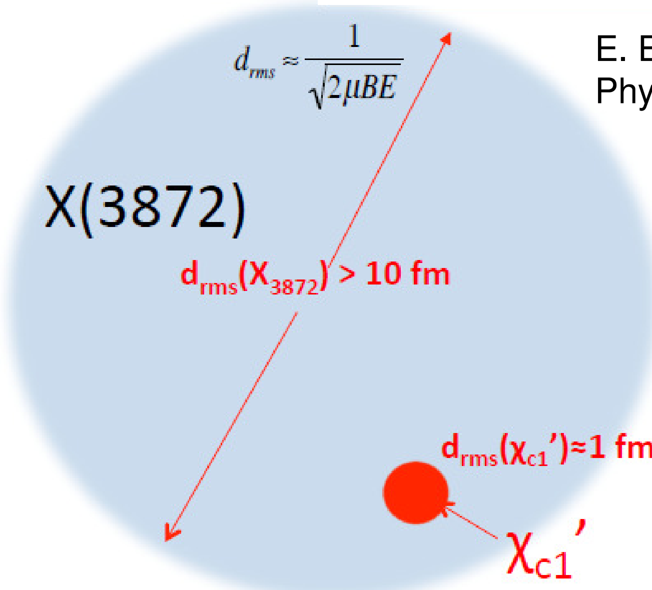
- The mass of X(3872) **is not** low compared to the expectations for $\chi_{c1}(2^3P_1)$ state!

Can a large molecule mix with a compact charmonium?

X(3872)-χ_{c1}' mixture ← pretty bizarre

$d_{rms}(^{64}Zn$ nucleus$) \approx 8$ fm





E. Braaten, J. Stapleton
Phys.Rev. D81, 014019 (2010)

$\text{Volume}(\chi_{c1}') / \text{Volume}(X_{3872}) \approx 10^{-3}$

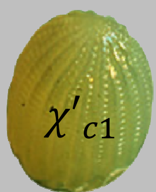
Discussion at Kolymbari 2017 workshop:

> It is not plausible for such a large molecular state to mix with such a compact charmonium state
>
> — Luciano Maiani

> For such a long-lived state as X(3872), even small overlap of wave functions can lead to mixing
>
> — Alex Bondar

Hadronic decay of a $q\bar{q}$ resonance

Thinking about a state oscillating back-and-fourth between $(c\bar{c})$ and $(c\bar{u}) - (\bar{c}u)$ is not necessarily the right picture. A different possibility:

$pp \to \cdots +$ 

then $\chi'_{c1} \to D^0\overline{D}^{*0}$

Adopted from Michael Pennington's slides at Modern Exotic Hadrons INT 15-60W workshop November 2015

Resonance decay

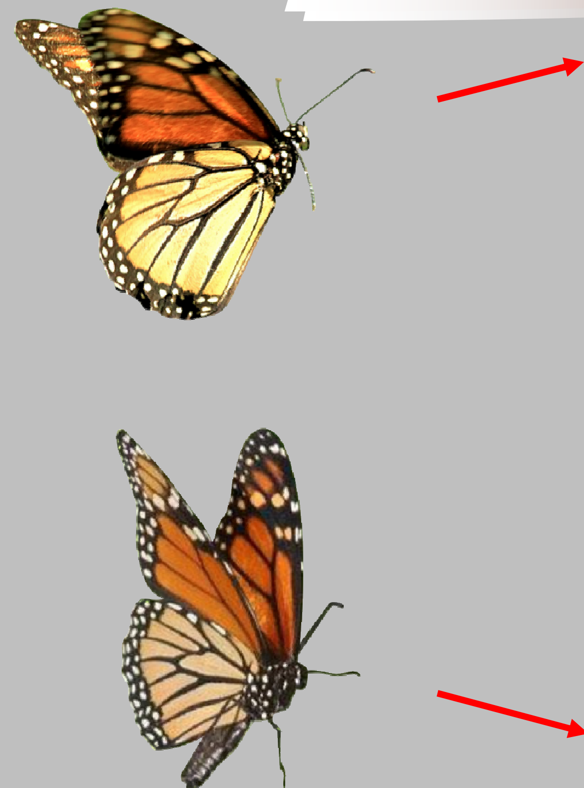
Resonance decay

Resonance decay

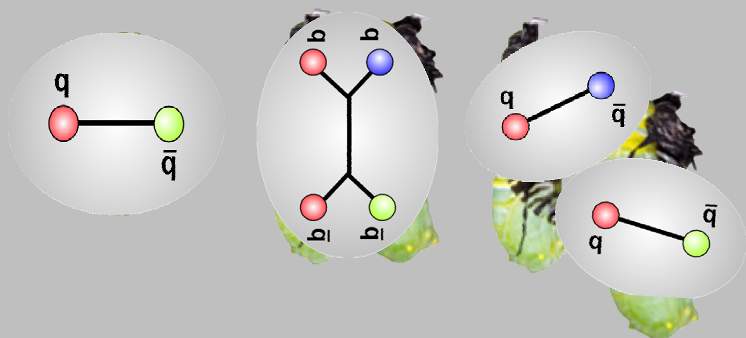
Resonance decay

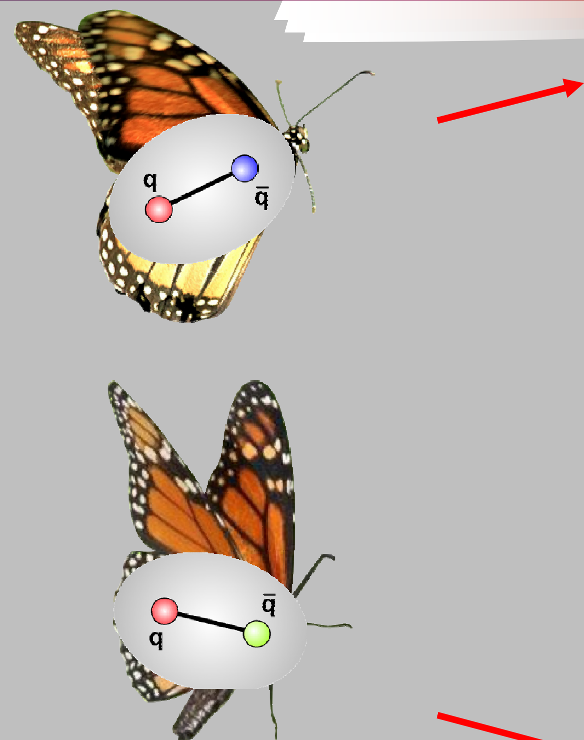
Resonance decay

Resonance decay



Resonance decay





Decaying $q\bar{q}$ meson resonance can go through tetraquark and/or molecular configurations.

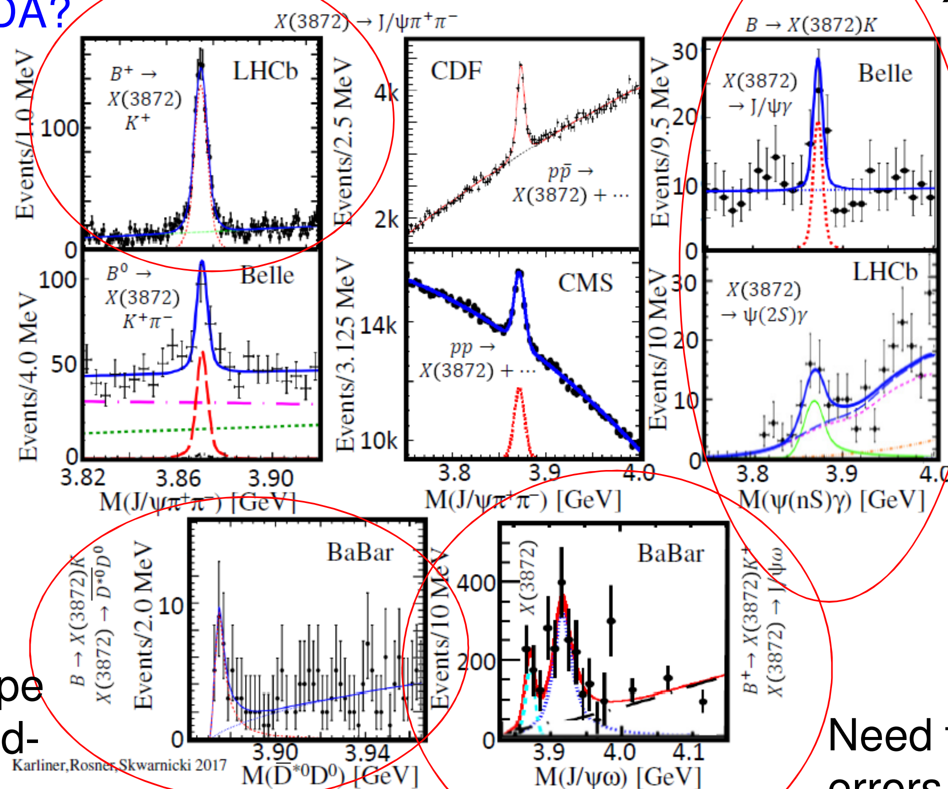
This can sometimes lead to

Dynamically generated state;
an extra pole in the scattering matrix

Experimental prospects for X(3872)

Mass and natural width of X(3872)

LHCb,PANDA?



Need to improve statistical errors on radiative decays of X(3872)

LHCb,Belle-II

Verify BES-III
$e^+e^- \to Y(4260) \to \gamma X(3872)$

Look for:
$X(3872) \to \pi^+\pi^-, \pi^0\pi^0\chi_{c1}(1P)$
since
$BR(\chi_{b1}(2P) \to \pi^+\pi^-, \pi^0\pi^0\chi_{b1}(1P))$
$=(0.9 \pm 0.1)\%$

Belle-II, LHCb

Study line shape in $D\overline{D}^*$; coupled-channel line-shape fit LHCb,Belle-II

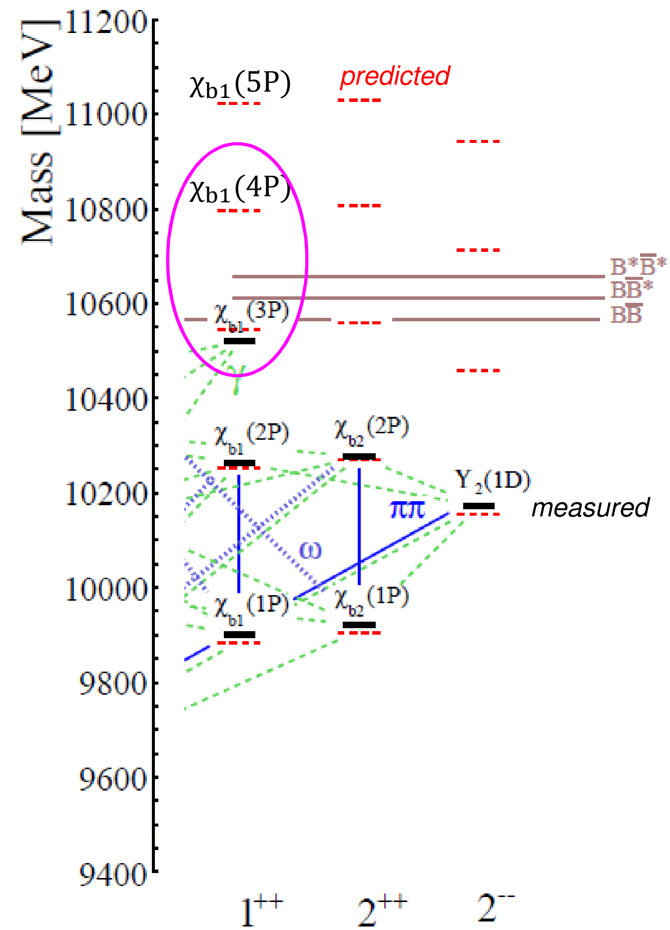
Need to improve statistical errors on X(3872)→ $\omega J/\psi$
(clarify 2nd peak: X(3915))

LHCb,Belle-II

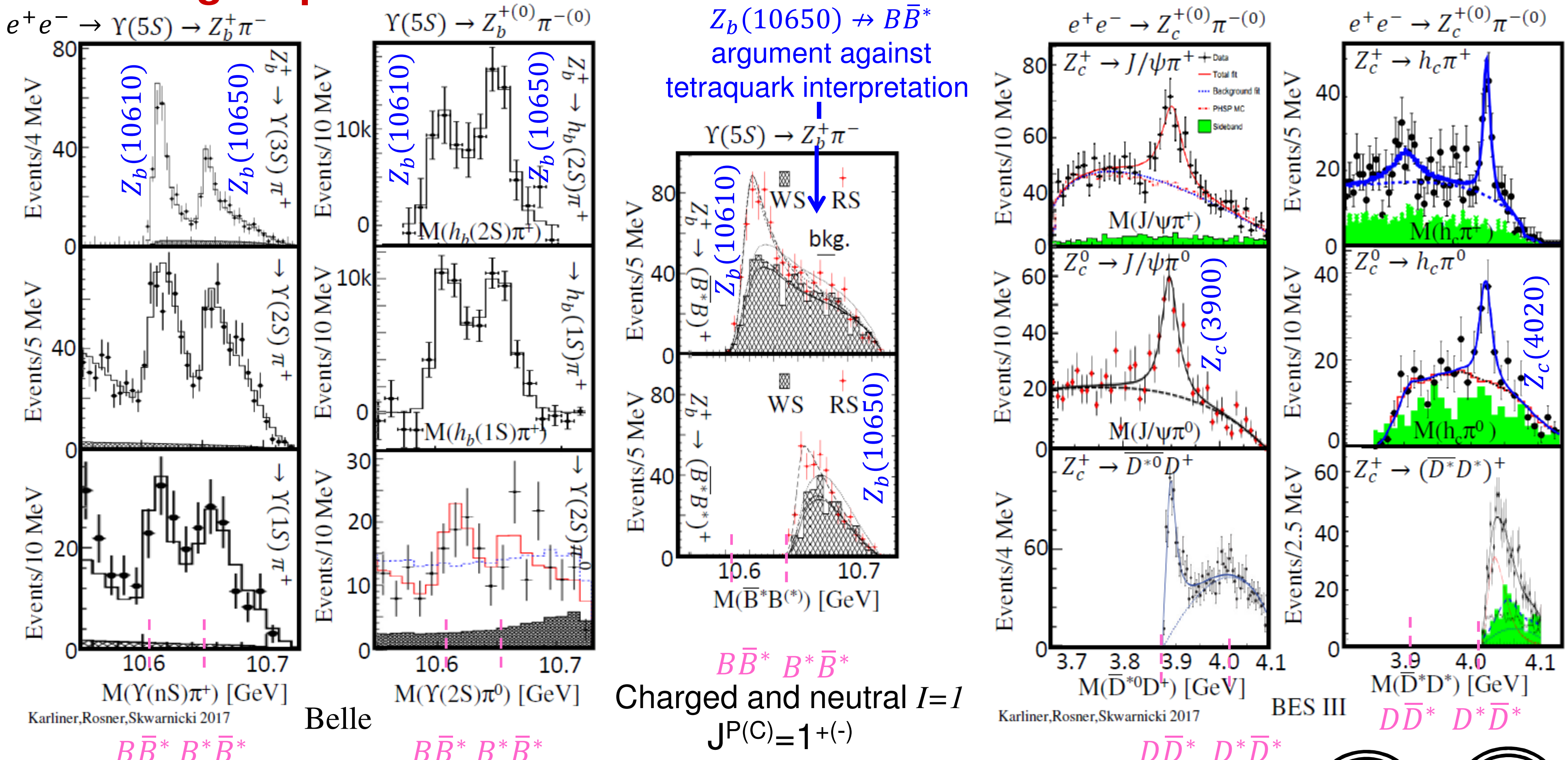
More production mechanisms, decay modes …
+ CMS, ATLAS, ALICE? …

X(3872), so far, in unique!

- The only exotic charmonium-like candidate which shows up consistently in many different productions mechanism, accompanying well-behaved $c\bar{c}$ state $-\ \psi(2S)$, and detected in many different decays modes
- If coincidence of $\chi_{c1}(2^3P_1)$ with the $D^0\overline{D}^{0*}$ threshold is responsible for it, then there is no narrow analog of it in bottomonium
- Any other states like this, with conventional $q\bar{q}$ and exotic properties mixed in?



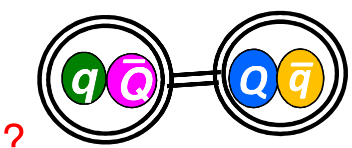
Charged quarkonium-like near-threshold states



No confusion with quarkonia states (charge!).

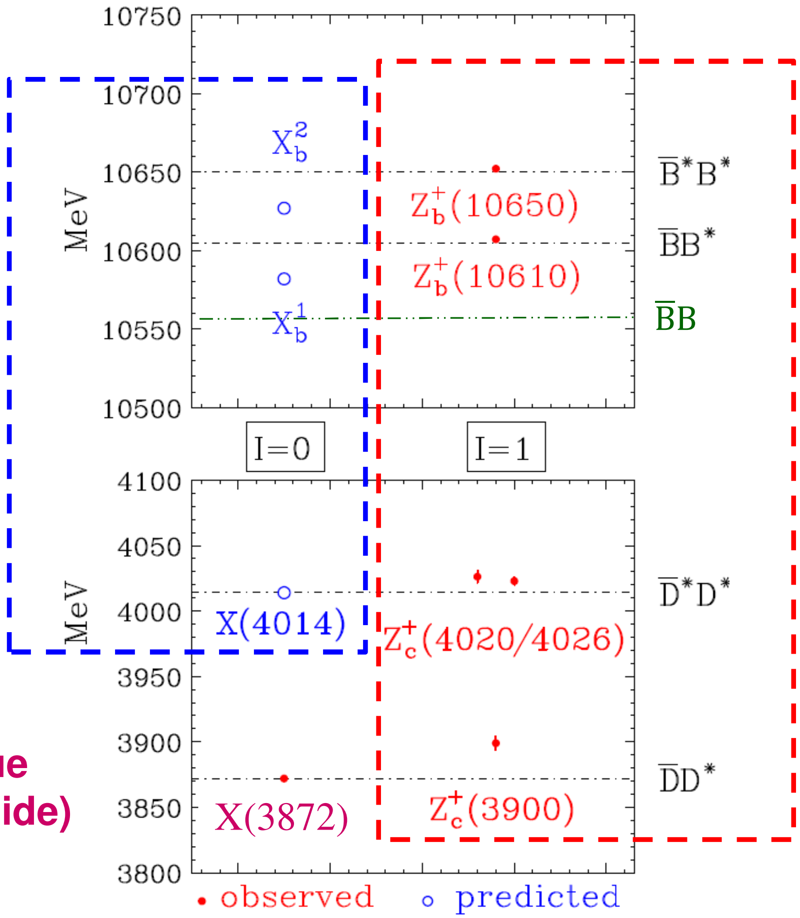
Near thresholds. Relatively narrow. Large fall-apart rates. Observable rates to quarkonia.

⇨ Molecular states? Tetraquarks interacting with meson-meson thresholds?



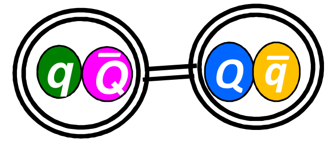
Quarkonium-like near-threshold mesons

If X(3872) exists thanks to the coincidence of 2^3P_1 $c\bar{c}$ and of the $D^0\bar{D}^{*0}$ threshold, then these may not exist



Picture from Marek Karliner

X(3872) is unique (see previous slide)



The only clear "spectroscopy" emerging from XYZ states so far

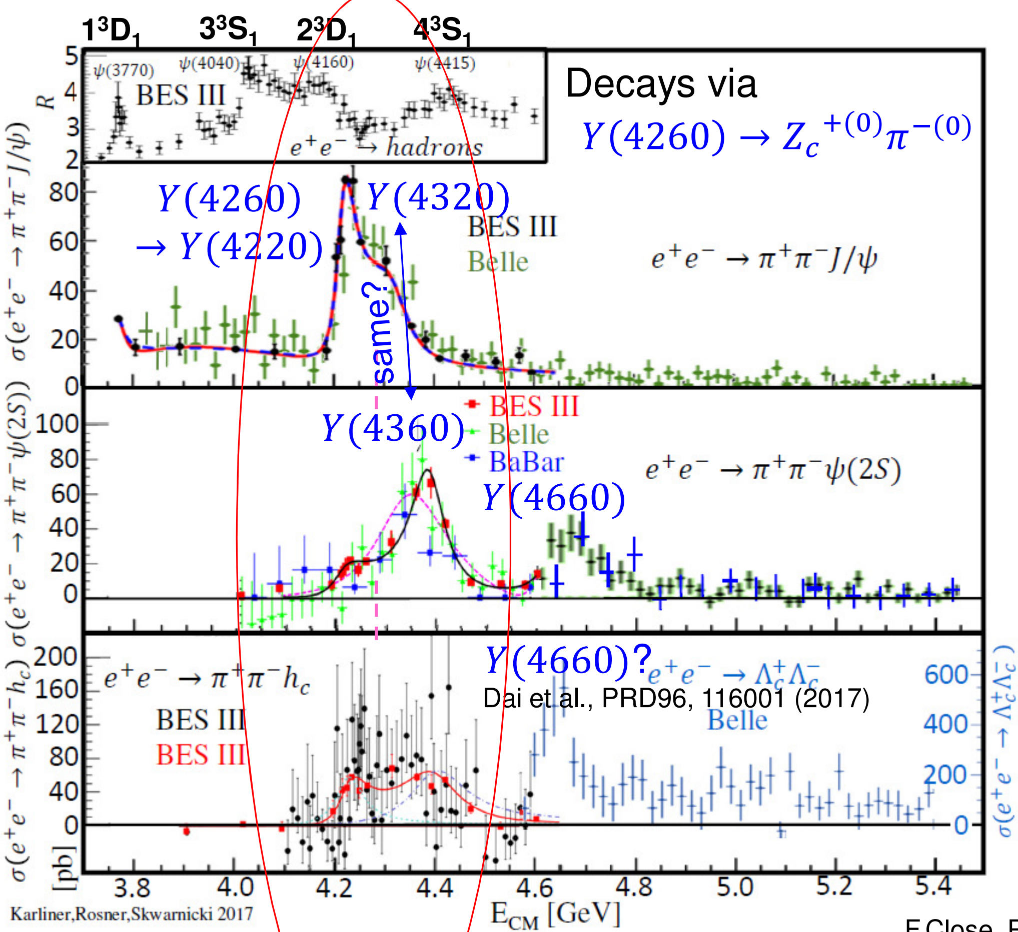
No sign of such states at $D\bar{D}$ and $B\bar{B}$, hints at forces dominated by π exchange

Many molecular candidates among light, and heavy-light mesons and baryons:
$0^{++} a_0(980)$, $f_0(980)$ $[K\bar{K}]$,
$1^{++} f_1(1420)$ $[K\overline{K^*}]$, $\frac{1}{2}^-$ $\Lambda(1405)$ $[KN]$,
$0^+ D^*_{s0}(2317)$ $[D\bar{K}]$, $1^+ D_{s1}(2460)$ $[D^*\bar{K}]$

Alternative viewpoint: tightly bound tetraquarks
A. Ali, L. Maiani, A. Polosa, V. Riquer, PRD91, 017502 (2015)

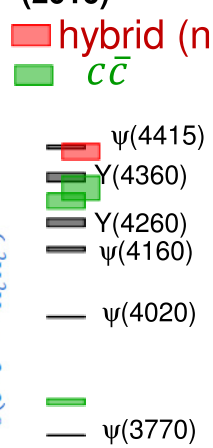
For a broader review see: "Hadronic molecules",
F-K. Guo, C. Hanhart, Ulf-G. Meißner, Q. Wang, Q. Zhao, B-S. Zou, Rev.Mod.Phys. 90,15004 (2018); arXiv:1705.00141

Anomalous charmonium-like vector states

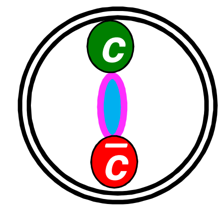


- $Y(4220)$ and $Y(4320/4360)$ do not align with $c\bar{c}$ states
- Γ_{ee} widths suppressed by $10^{2\text{-}3}$
- $\Gamma_{\pi\pi\psi}$ widths huge

Hadron Spectrum Collaboration (LQCD m_π=240 MeV)
JHEP 1612, 089 (2016)



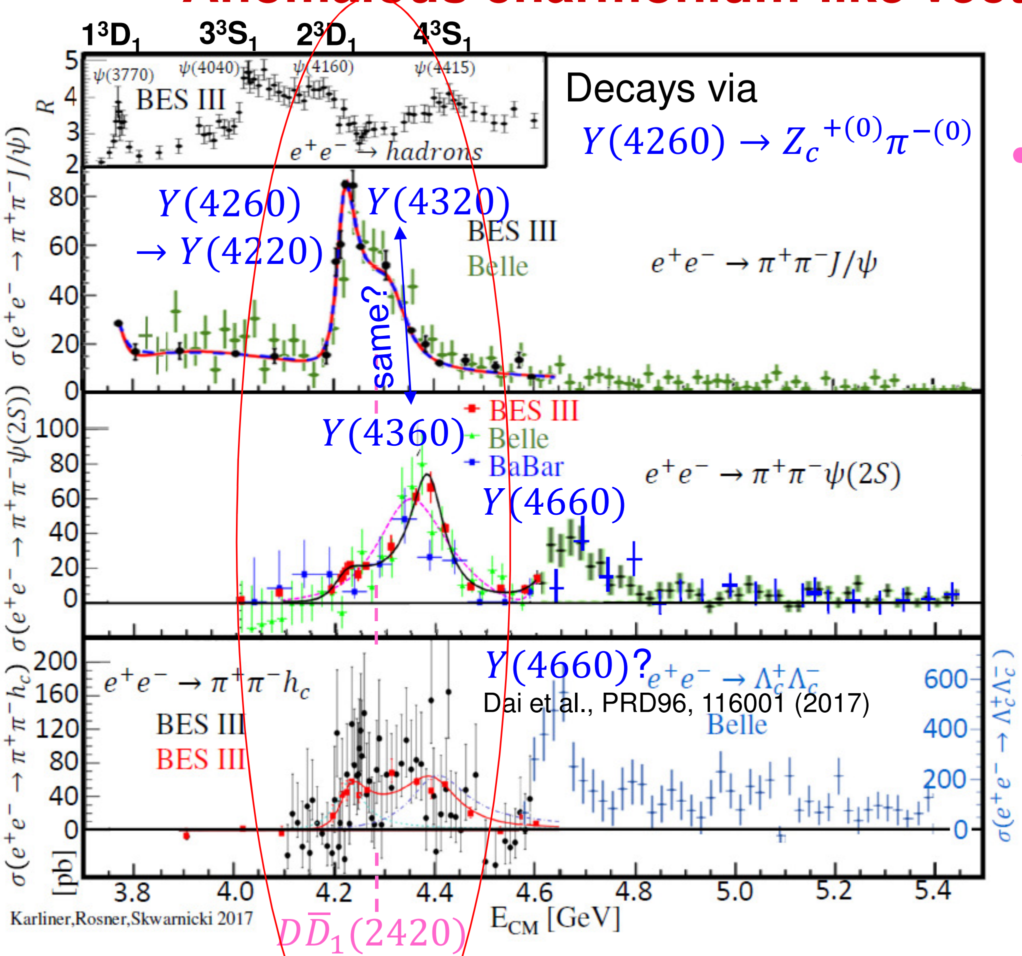
- **Hybrid-charmonium ?**



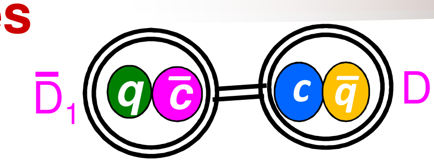
- Masses not too far from the predicted 1^{--} hybrid by the lattice QCD:
  - Only one 1^{--} hybrid expected in this mass range
  - ψ(4020),ψ(4160),ψ(4415) not well reproduced by lattice
- Γ_{ee} suppressed by a spin-flip needed to produce cc in S=0 configuration
- ππψ can proceed via DD** rescattering
- However, expected to decay to $DD^{(*)}\pi$, but not observed [CLEO-c PR D80, 072001(2009)]

F.Close, P.Page PL B628, 215 (2005)
E.Kou, O.Pene, PL B631, 164 (2005)
S-L. Zhu, PL B625, 212 (2005)
P.Guo, A.Szczepaniak G.Galata, A.Vassallo, E.Santopinto PRD78, 056003 (2008) …

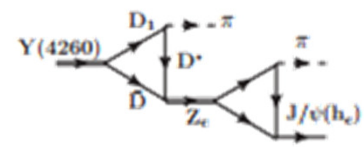
Anomalous charmonium-like vector states



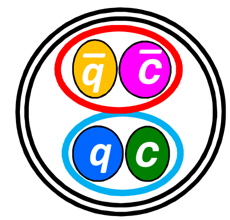
$Y(4220)$ -60 MeV binding? [$Y(4360)$ +40 MeV]



- $D\bar{D}_1(2420)$ **molecule** Q.Wang, C.Hanhart, Q.Zhao, **PRL 111 (2013) 132003**

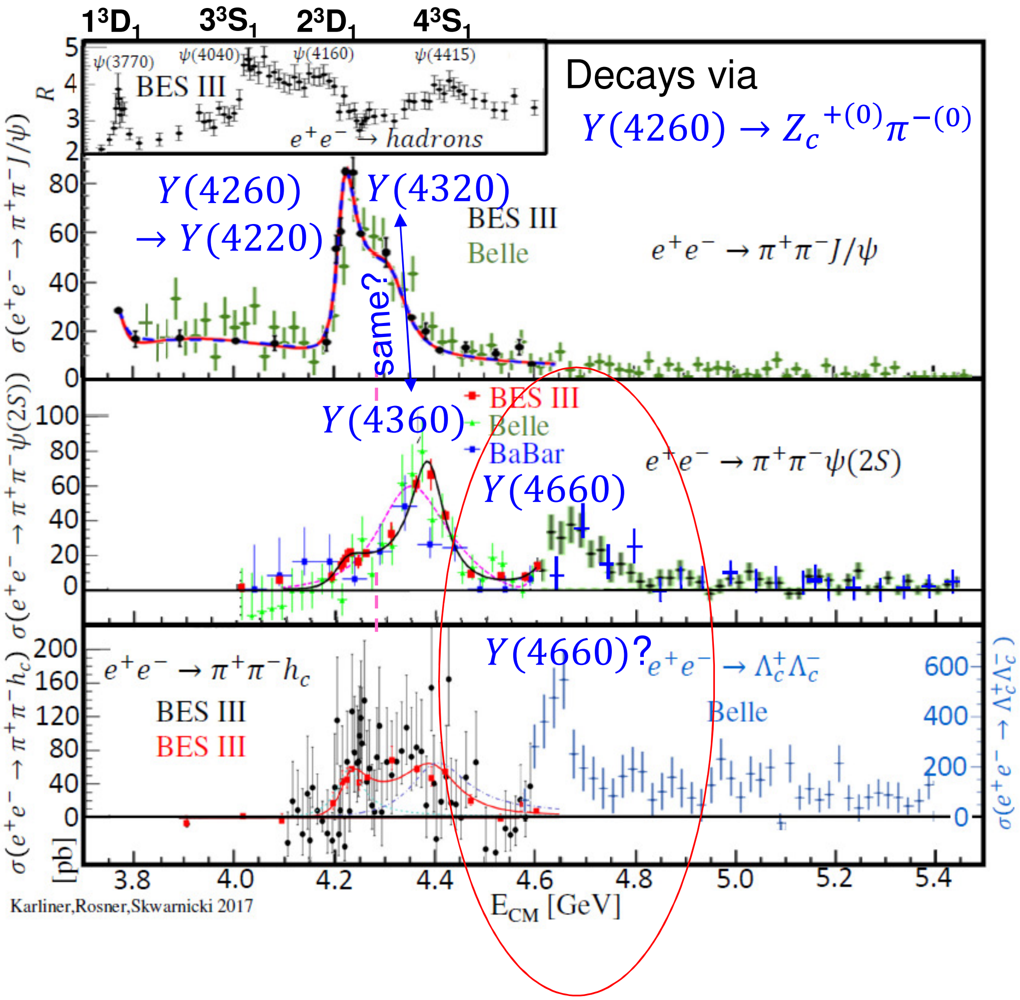


Asymmetric shape: M.Cleven, Q.Wang, F.K. Guo, C. Hanhart, U-G. Meißner, Q. Zhao, **PRD90 (2014) 074039**



- **Tetraquark (diaquarkonium)** L.Maiani, F. Piccinini, A. Polosa, V. Riquer, PR D89, 114010 (2014):
  - Tetraquark→tetraquark transitions: Y(4260)→Z_c(3900)π, Y(4260)→X(3872)γ (possibly observed by BESIII)

Anomalous charmonium-like vector states



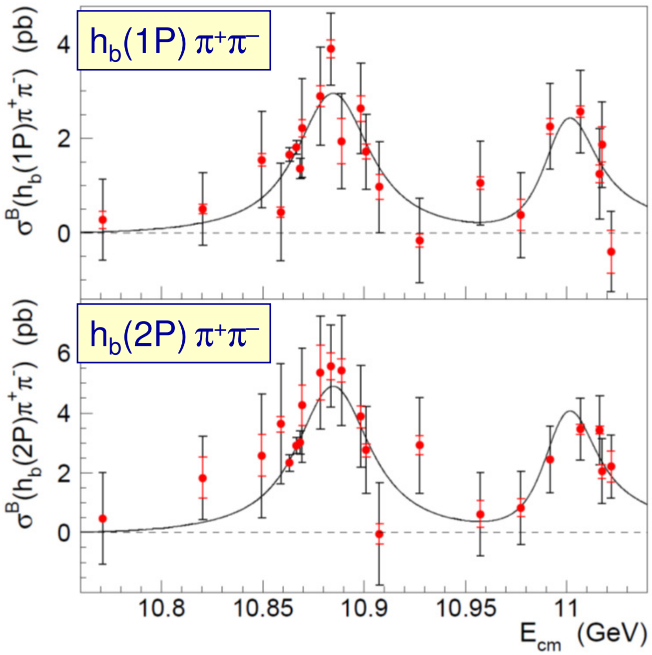
Y(4660): the same or different state in $e^+e^- \to \pi^+\pi^-\psi(2S)$ and $e^+e^- \to (\gamma)\ \Lambda_c^+\Lambda_c^-$

Dai et al., PRD96, 116001 (2017)

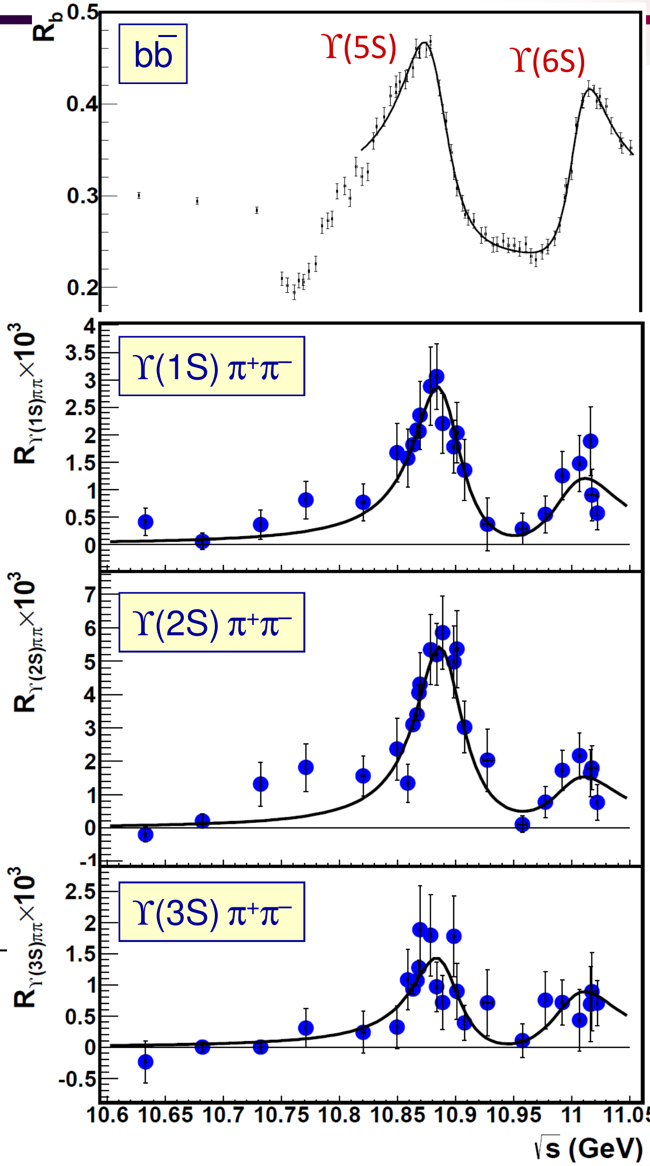
- $\psi(5^3S_1)$ or $\psi(6^3S_1)$?
- tetraquark?
- baryonium (see G.C.Rossi's talk!) ?

G.C. Rossi, G. Veneziano, NP B123, 507 (1977)!

Anomalous behavior of 1^{--} states above open bottom threshold



PRL117,142001(2016)
PRD93,011101(2016)



$e^+e^- \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ and $h_b(1P,2P)\,\pi^+\pi^-$ proceed via $\Upsilon(5S)$, $\Upsilon(6S)$

Unlike in charmonium!

However, $\Upsilon(5S)$, $\Upsilon(6S) \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ widths are 100 larger than $\Upsilon(3S)$, $\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-$

OZI-rule violation

Also widths for $\Upsilon(5S)$, $\Upsilon(6S) \to h_b(1P)$, $h_b(2P)\,\pi^+\pi^-$ are comparable, but require heavy quark spin flip

HQSS violation

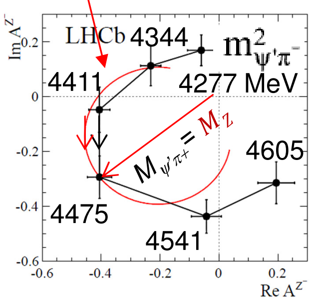
Like in charmonium!

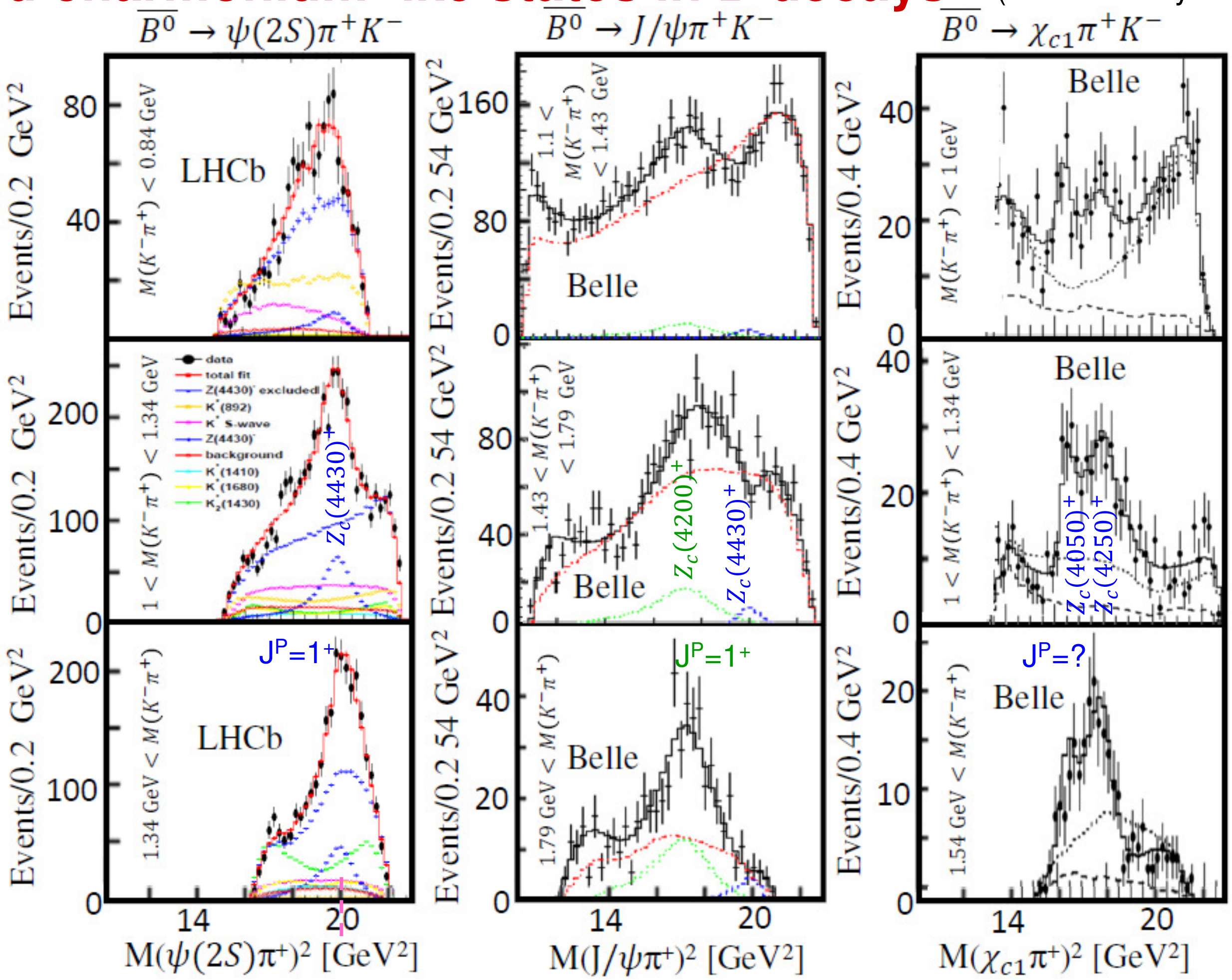
Charged charmonium-like states in B decays

(dominated by $K^{*0} \to \pi^+ K^-$ resonances)

Breit-Wigner amplitude

$$\frac{1}{M_Z^2 - m_{\psi'\pi^+}^2 - i M_Z \Gamma_Z}$$





$D\overline{D}(2S)$

$\Gamma_{Z(4430)}$=181±31 MeV

$\Gamma_{D(2600)}$=104±20 MeV

$\Gamma_{Z(4200)}=370^{+100}_{-150}$ MeV

$Z_c(4200)^+$, $Z_c(4050)^+$, $Z_c(4250)^+$ await confirmation

$Z_c(3900)^+$ and $Z_c(4020)^+$ observed in $e^+e^- \to \pi^- Z_c^+$, not observed in $B \to K\, Z_c^+$, (and vice versa).
Sensitivity to production mechanism, points to hadron-level interactions.

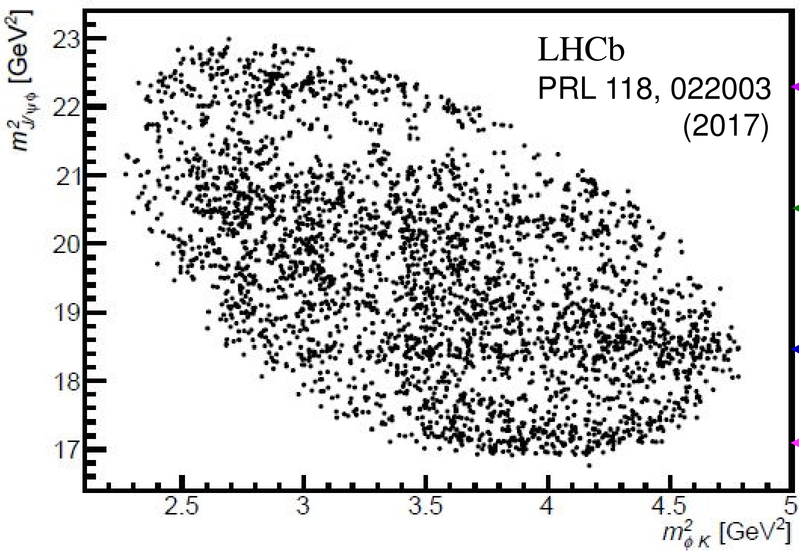
No clear explanations.

- Too broad to be molecular bound states?
- No tetraquark model can accommodate all of them.
- Rescattering effects?
- Artifacts of complicated amplitude analyses?

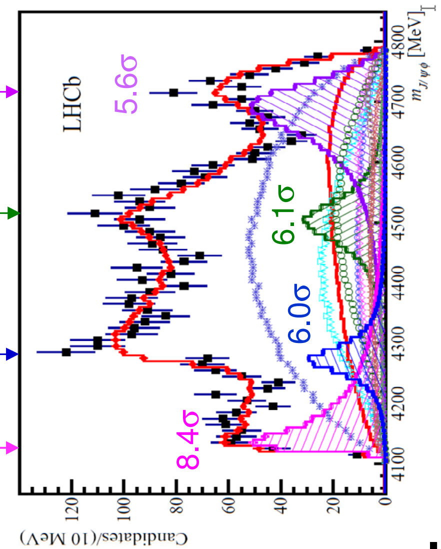
$B^- \to J/\psi\,\phi\,K^-$

6D amplitude analysis

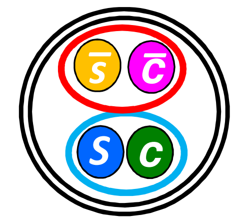
LHCb PRL118, 022003 (2017)
PRD95, 012002 (2017)



X(4700)→ J/ψφ
X(4500)→ J/ψφ
X(4274)→ J/ψφ
X(4140)→ J/ψφ



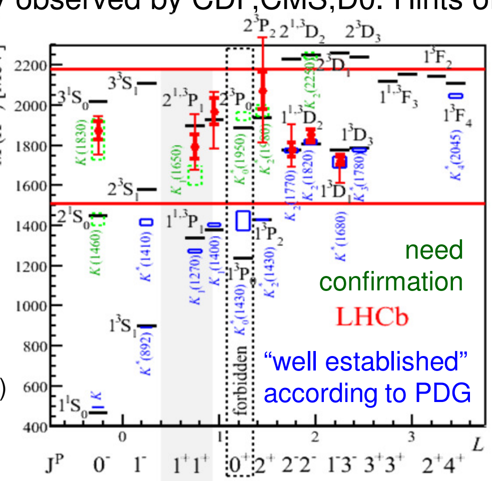
Tetraquarks or $D_s\bar{D}_s$ molecules



X(4140) was previously observed by CDF,CMS,D0. Hints of X(4274) in CDF data.

Many heavy $K^{*+} \to \phi K^+$ observed

$B^+ \to J/\psi\,\phi\,K^+$

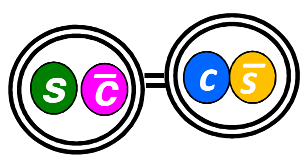


QM predicted
Godfrey-Isgur,
PRD 32, 189 (1985)

No η-exchange

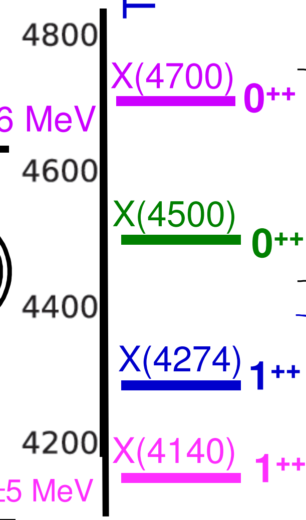
$D_{s0}^{+}D_{s0}^{*-}$ +69±26 MeV

Plenty of other thresholds, but no matching J^{PC} numbers



No π-exchange forces!

η-exchange OK $D_s^+D_s^{*-}$ +66±5 MeV



Postdiction by L.Maiani, A.D.Polosa, V. Riquer PRD94, 054026 (2016)
Possibly radially excited 0^{++} tetraquarks. However, only one 1^{++} state with color triplet diquarks.

F. Stancu, J.Phys. G37, 075017 (2010)
Predicted two 1^{++} tetraquarks in this mass range (S=0,1 diquarks in color triplet and sextet)

Prompt production of X → J/ψφ states ?

Inclusive analysis at Tevatron

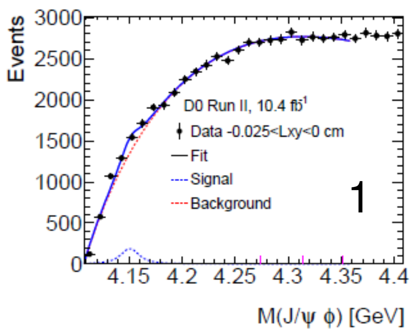
D0 PRL 115, 232001 (2015)

$p\bar{p} \to (J/\psi\ \phi) + \ldots$

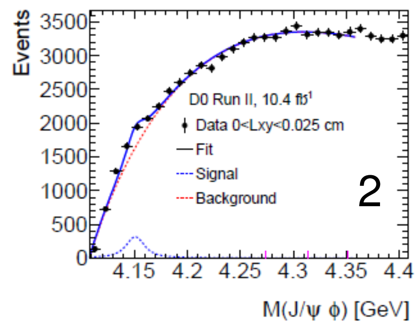
$J/\psi \to \mu^+\mu^-$

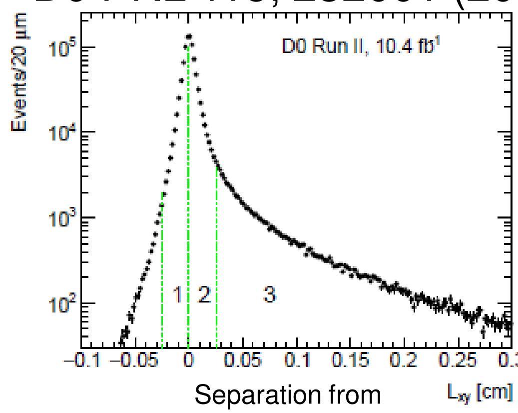
$\phi \to K^+K^-$

Prompt production



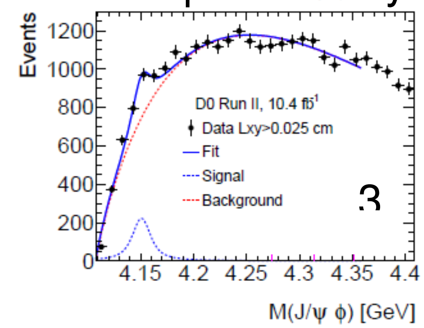
Prompt production + b-quark decays





Separation from the primary vertex

From b-quark decays

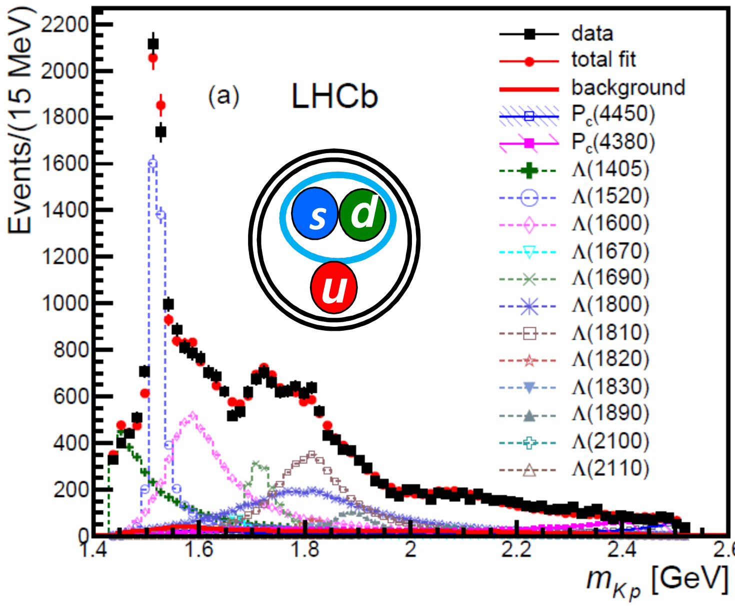


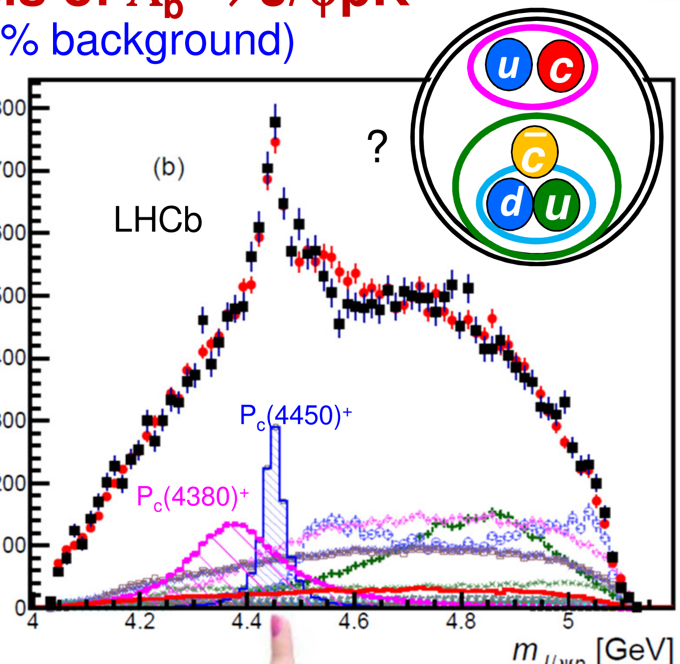
- D0 claims a significant (4.7σ) shoulder near 4140 MeV in promptly produced J/ψφ candidates.
- Caution is advisable:
  - D0 measured here: $\Gamma = 16.3 \pm 5.6 \pm 11.4$ MeV,
  - Later LHCb measured $\Gamma = 83 \pm 21^{+21}_{-14}$ MeV, and claimed 3 other J/ψ φ states (only one promptly produced?)
  - D0 has no particle ID (no K/π separation) and has not demonstrated that the presumed X(4140) signal is associated with a φ peak in $M(K^+K^-)$
  - The claim of significant prompt X(4140) signal relies on proper subtraction of the huge background. Ad hoc assumption about the background shape ($f(m) \sim m(m^2/m^2_{th}-1)^{\alpha} e^{-m\beta}$), without any evaluation of systematics.
  - No word from the experiments better equipped to see such signal (CDF at Tevatron, LHCb at LHC)
- **X(3872) is the only exotic hadron candidate which has been confirmed to be produced promptly.**

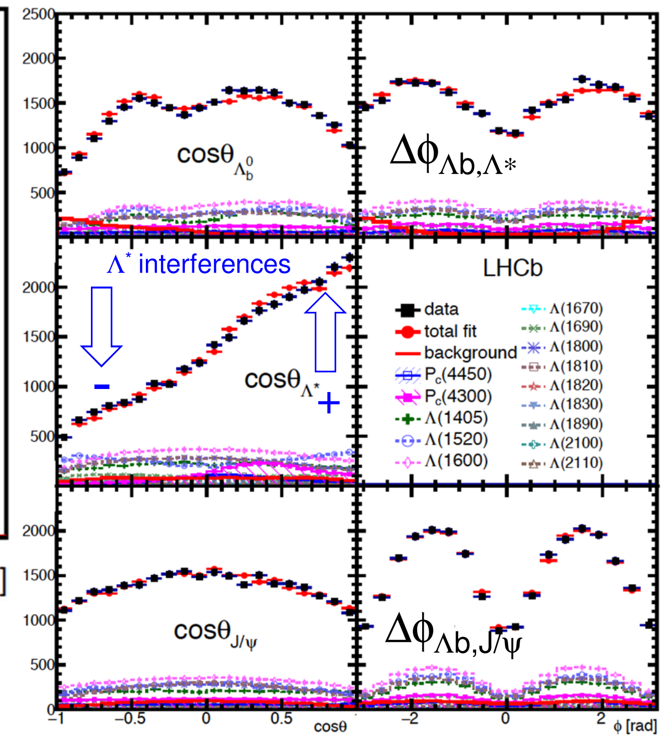
LHCb: 6D amplitude analysis of $\Lambda_b \to J/\psi p K^-$

26,007±166 Λ_b^0 (plus 5.4% background)

LHCb PRL 115, 072001 (2015)







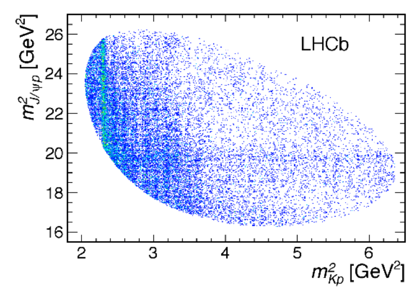
- Only better established Λ^* states have been used (fixed M,Γ)

State	Mass (MeV)	Width (MeV)	Sig.
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	12σ
$P_c(4380)^+$	4380 ±8±29	205±18±86	9σ

- Best fit has $J^P=(3/2^-, 5/2^+)$

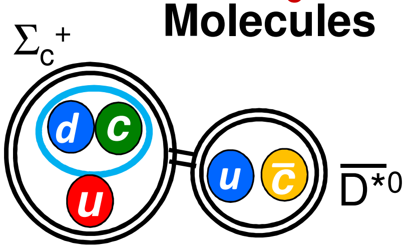
~~*simplicity of baryons*~~

However, J^P not well determined.
Large systematic effects due to the Λ^* model
[see Nathan Jurik, Ph.D. thesis, Syracuse 2016]



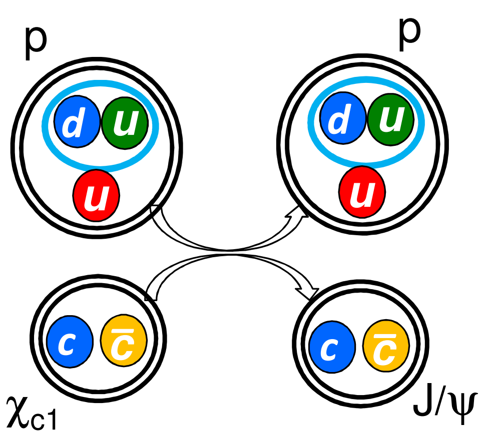
Interpretations of $P_c(4450)^+$, $P_c(4380)^+$

Molecules

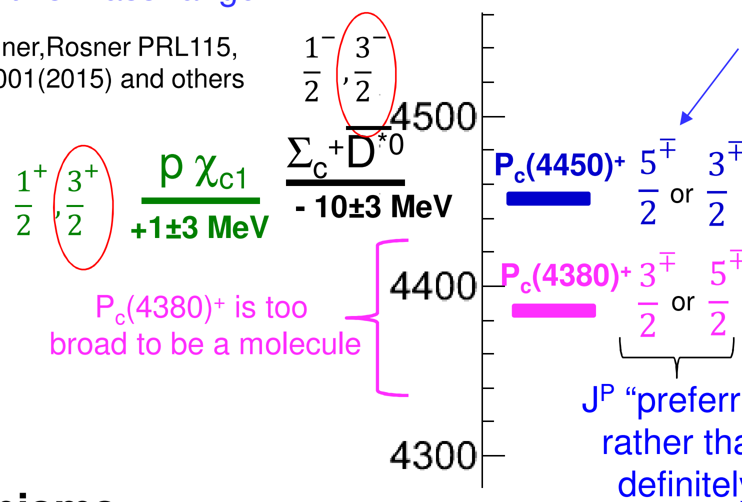


No $\frac{5}{2}^{\pm}$ molecules in this mass range

Karliner,Rosner PRL115, 122001(2015) and others



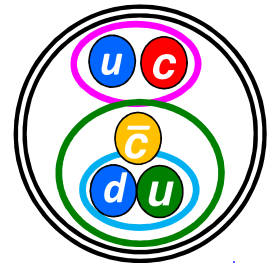
Realistic **rescattering mechanisms (cusps, triangle anomalies)** have the same J^P selection rules as realistic molecular models (must happen in S-wave)



$P_c(4380)^+$ is too broad to be a molecule

J^P "preferred" rather than definitely determined

Tightly-bound penataquark



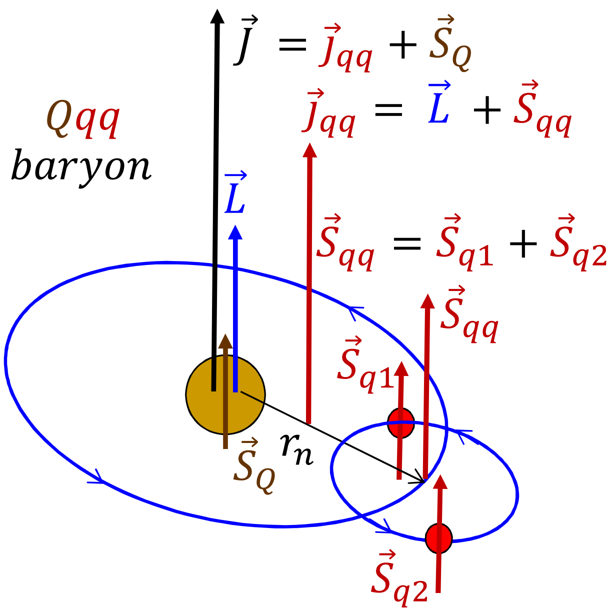
Can accommodate $\frac{5}{2}^{\pm}$ when at least one diquark in $S=1$ state

Maiani et al PLB749, 289 (2015) and many others

Such mass difference and the opposite parity can be explained by $\Delta L=1$ and $\Delta S=1$

It is crucially important to better determine quantum numbers of the P_c^+ states!

Heavy-light-light baryons



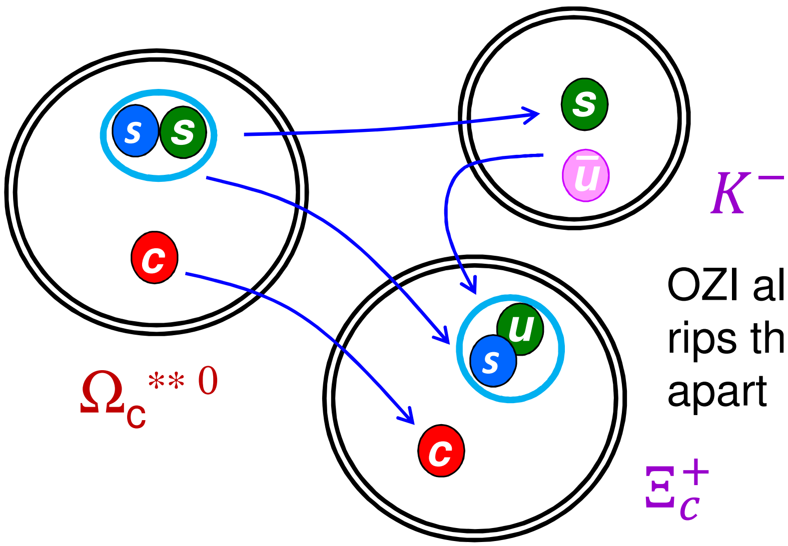
In usual diaquark model: $S_{qq}=0,1$

$n_{qq}=1$ $\vec{L}_{qq}=0$

Scalar and axial-vector diquarks

- Qqq baryons are a perfect place to study diquark structures as the heavy quark spin decouples from light quark spins
- QCD motivated diquarks need to be in the ground state, $n_{qq}=1$, $L_{qq}=0$,which eliminates a large number of possible excitations:
  - States can be labeled with ***n*,*L*** of the diquark orbiting around the heavy quark, which will be a dominant effect in mass
  - The main mass level hierarchy like among mesons!
- Diaquark spin S_{qq} can be 0 or 1 (scalar and axial vector diquarks):
  - Since quarks are light (relativistic), and the diquark is in $L_{qq}=0$ state, their hyperfine mass splitting $\vec{S}_{q1} \cdot \vec{S}_{q2}$ can be large.
- Also important is fine structure from $\vec{L} \cdot \vec{S}_{qq}$ couplings
- Small hyperfine structure from $\vec{j}_{qq} \cdot \vec{S}_Q$

Why the $\Omega_c^{**\,0}$ states observed by LHCb are narrow?

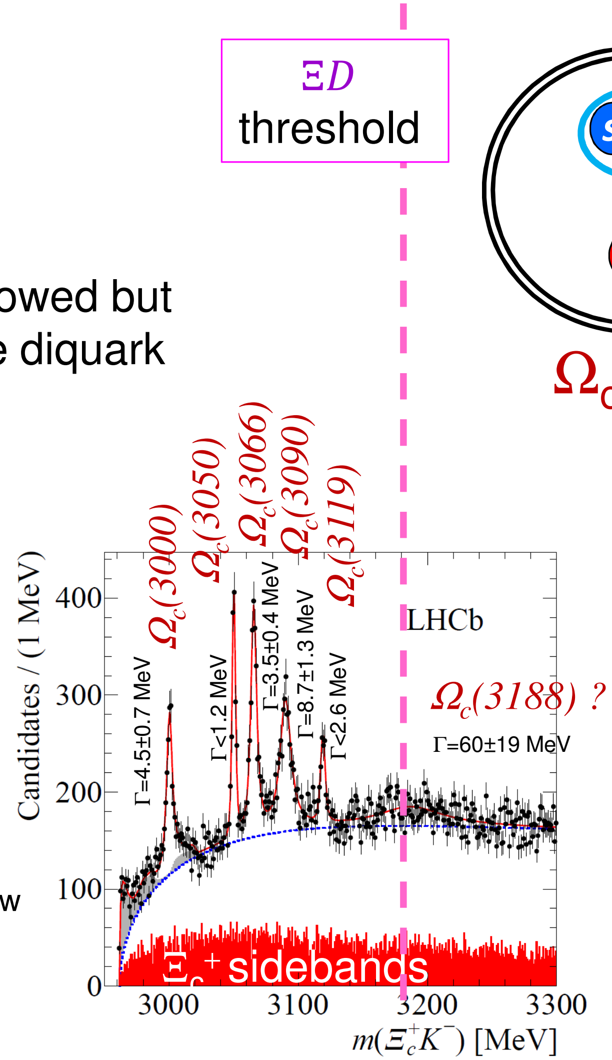


OZI allowed but
rips the diquark
apart

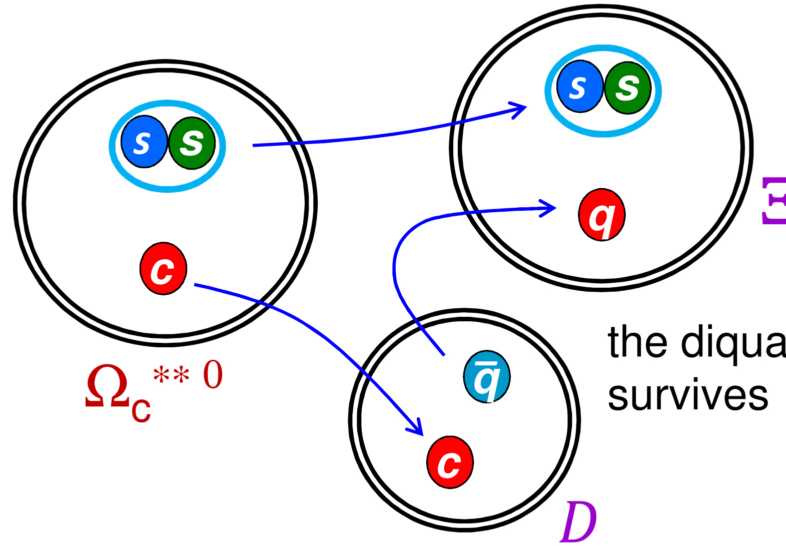
LHCb PRL 118, 182001 (2017).

$\Omega_c^{**\,0} \to \Xi_c^+ K^-$

(Strong decay)



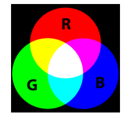
Significance of
each of the narrow
resonances
> 10σ

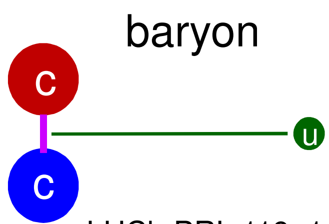


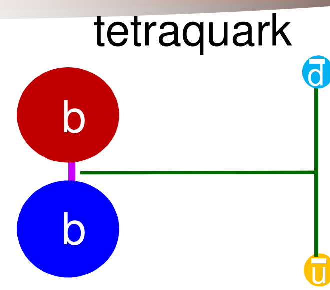
the diquark
survives

The narrow states
observed by LHCb
are likely 1P and 2S
of c-(ss diaquark)

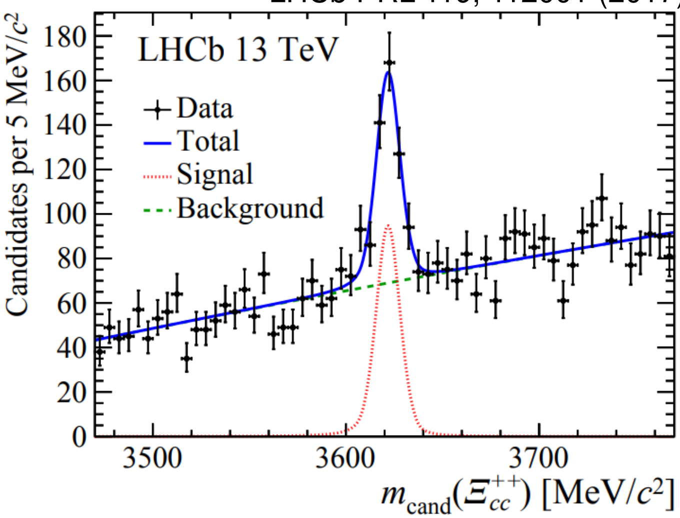
Doubly heavy systems

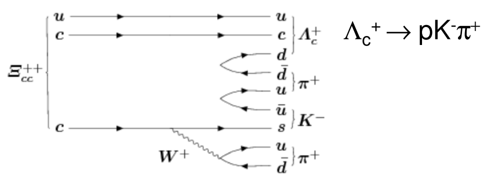






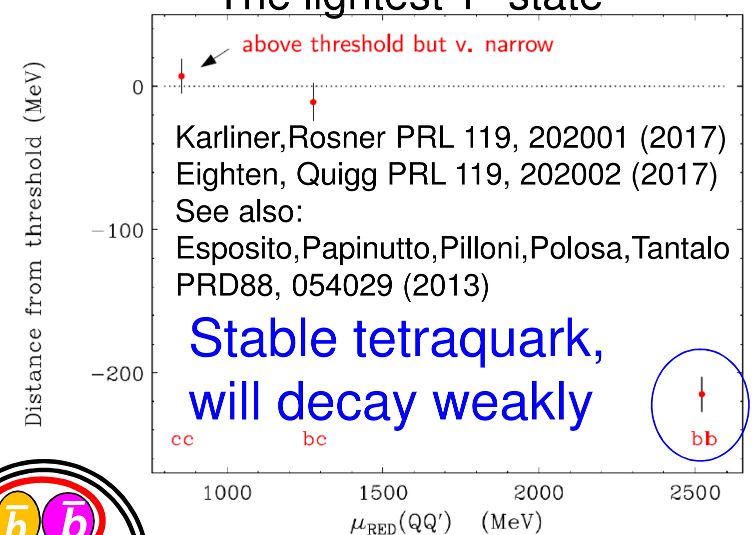
LHCb PRL 119, 112001 (2017)





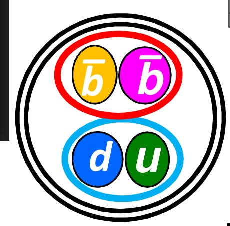
the same toolkit

The lightest 1^+ state



Karliner,Rosner PRL 119, 202001 (2017)
Eighten, Quigg PRL 119, 202002 (2017)
See also:
Esposito,Papinutto,Pilloni,Polosa,Tantalo PRD88, 054029 (2013)

Stable tetraquark, will decay weakly



Karliner,Rosner PRD90,094007 (2014)

State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

55

Consistent results predicted by LQCD:
Francis,Hudspith,Lewis,Maltman PRL 1118,142001 (2017)

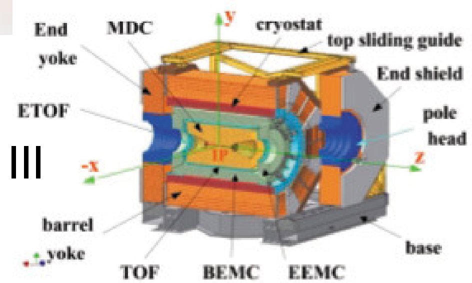
Summary

- New particle zoo for heavy quarkonia families above flavor threshold signals the crisis of the "textbook" quark model ($q\bar{q}$, qqq).
- It sheds doubts at our view of light hadron spectroscopy as well (all excitations are above "flavor threshold" for light hadrons). Perhaps experimental efforts to fill in all excited $SU(3)_f$ multiplets and find "missing" baryon states in misguided.
- Experimentally, exotic candidates do not follow the same pattern:
  - X(3872), so far, is one of the kind, in its $c\bar{c}$ production and radiative decays pattern and exhibiting stunning non-$c\bar{c}$ feature at the same time (huge rate to isospin violating decay mode)
  - Family of PV, VV relatively-narrow threshold states, with $I = 1$ (manifestly exotic!) seen only in $e^+e^- \to \pi^{\pm,0}Z^{\mp,0}$ decaying to both $\pi^{\pm,0}(c\bar{c})$ and related meson-antimeson pairs
  - Collection of $Z_c^{\pm}$ produced only in $B \to Z_c^- K$ decays, decaying only to $\pi^{\pm}(c\bar{c})$. Possibly $\phi J/\psi$ states produced in B decays belong to the same category.
  - Family of oddly behaving vector quarkonia states above the open flavor threshold. So far seen only in e^+e^- production.
  - A few other states I did not have time to talk about e.g. $X(3915) \to \omega J/\psi$
- It is possible that more than one dynamical effect is responsible for their existence.
- Need better experimental investigation of properties of all of these candidates to shed more light into their dynamics. Awaiting new exotic states as well!

Future prospects

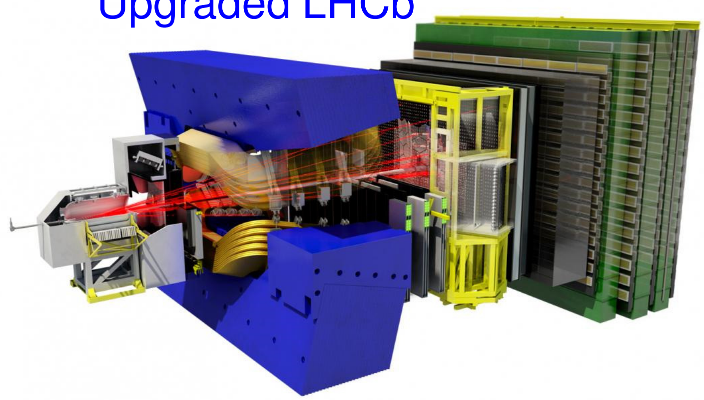
- Need more data to make progress
- More data are forthcoming!

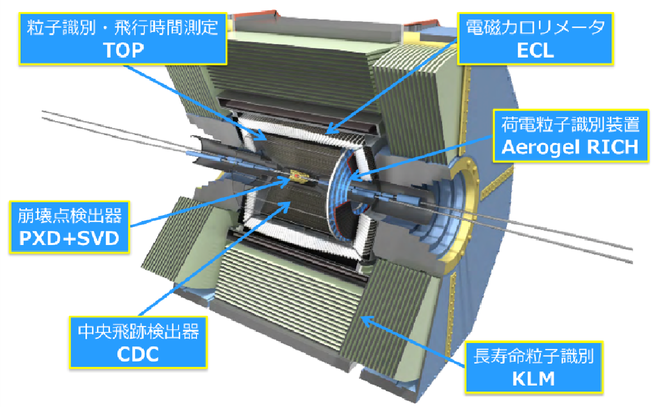
BES III

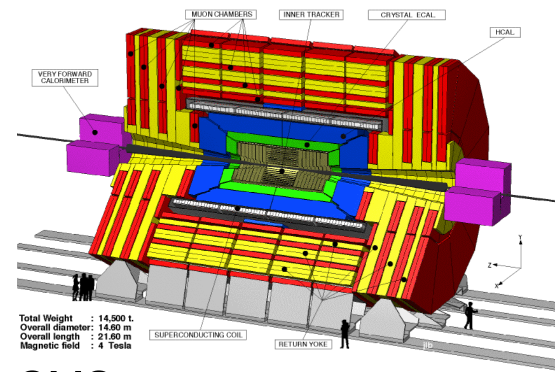


Belle II 測定器

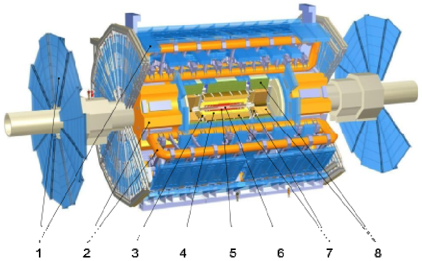
Upgraded LHCb

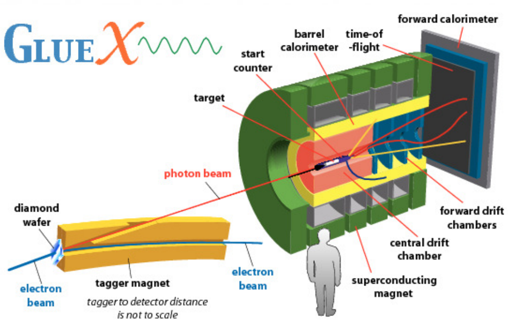


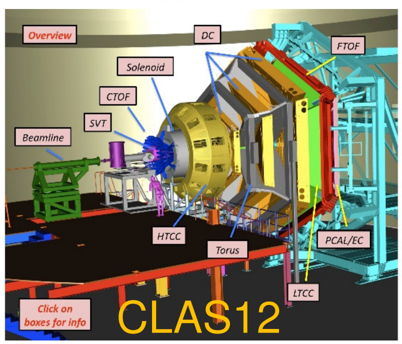


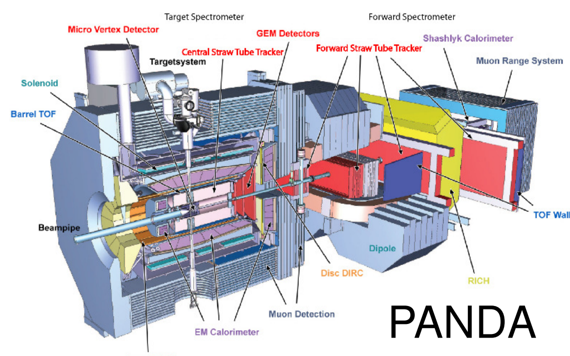


CMS









PANDA

ATLAS

and other…