Heavy quark exotics

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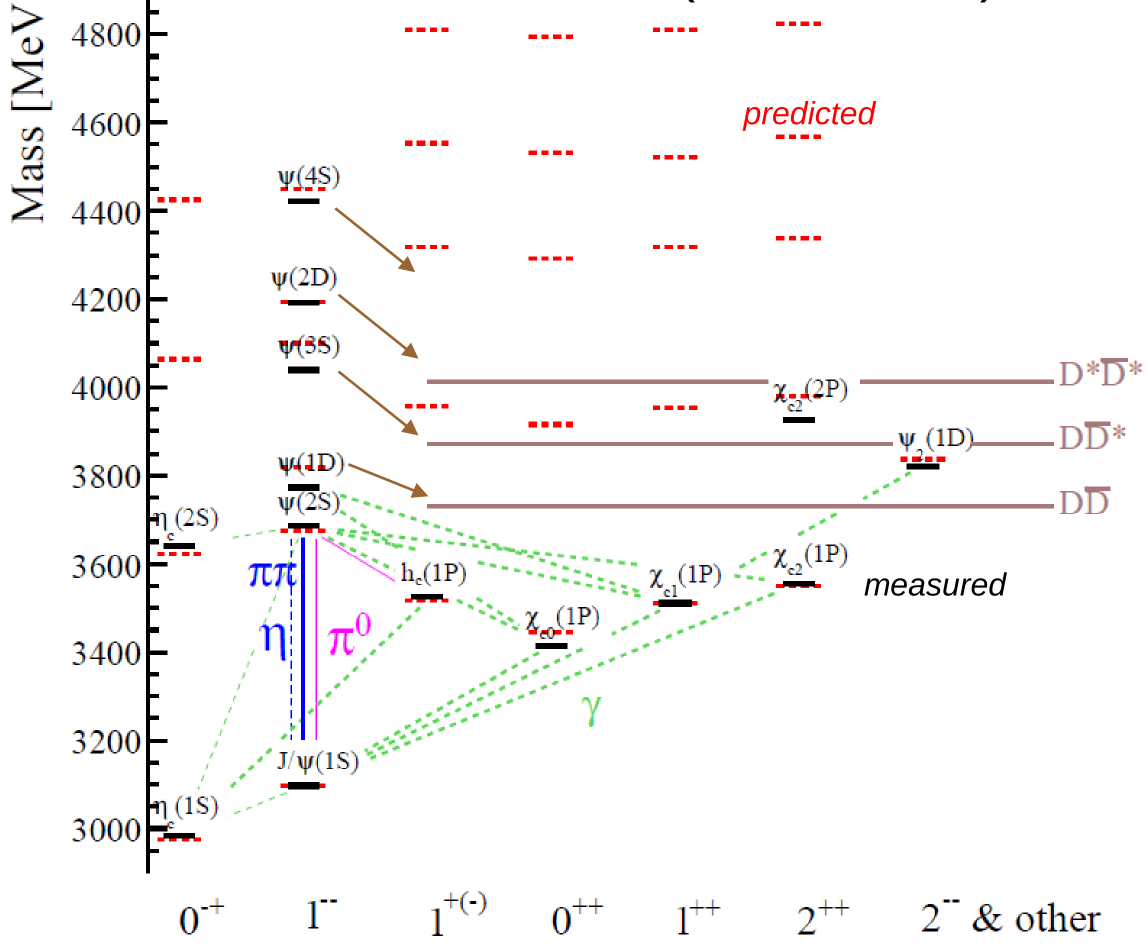
New particle Zoo: charmonium above flavor threshold

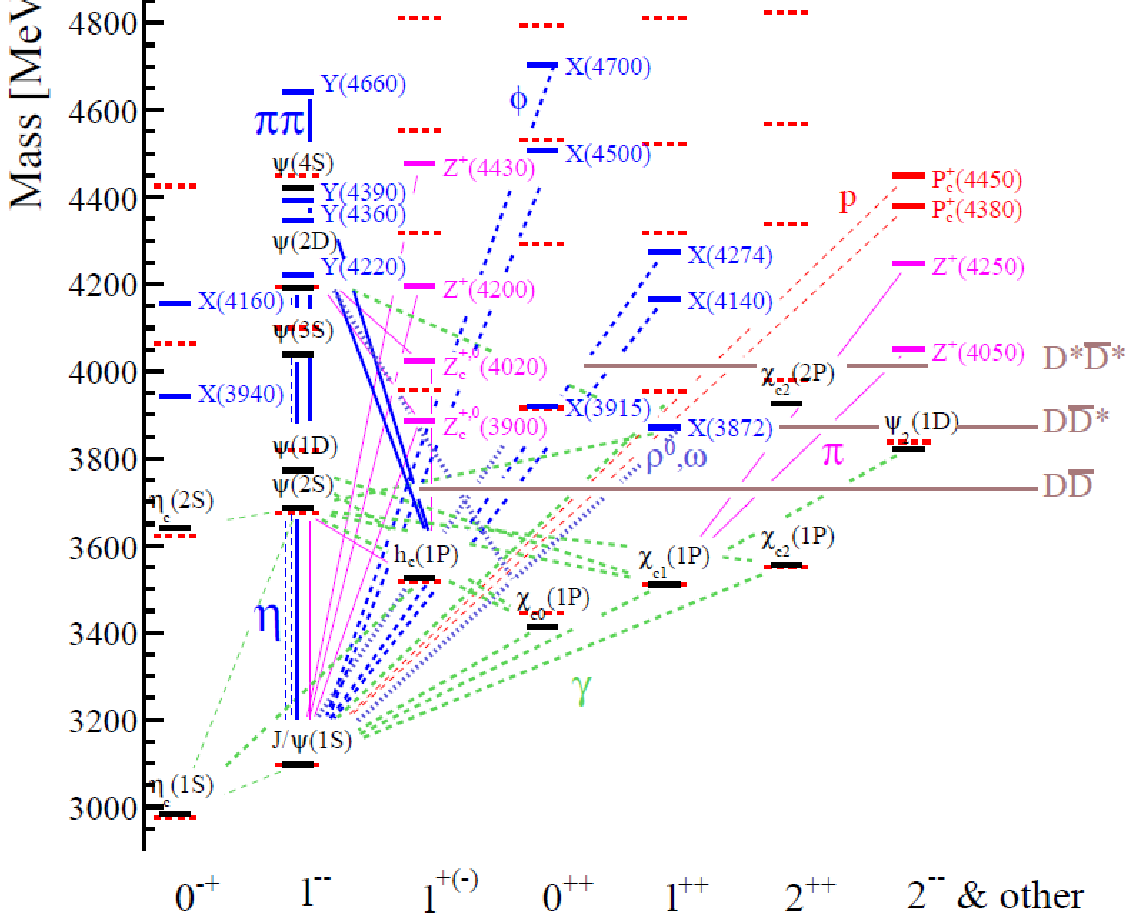
Above the flavor threshold: More exotic states than $c\bar{c}$ states!

Old narrative (before 2003)



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

New narrative



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

I will review most, but not all, quarkonium-like exotic hadron candidates.

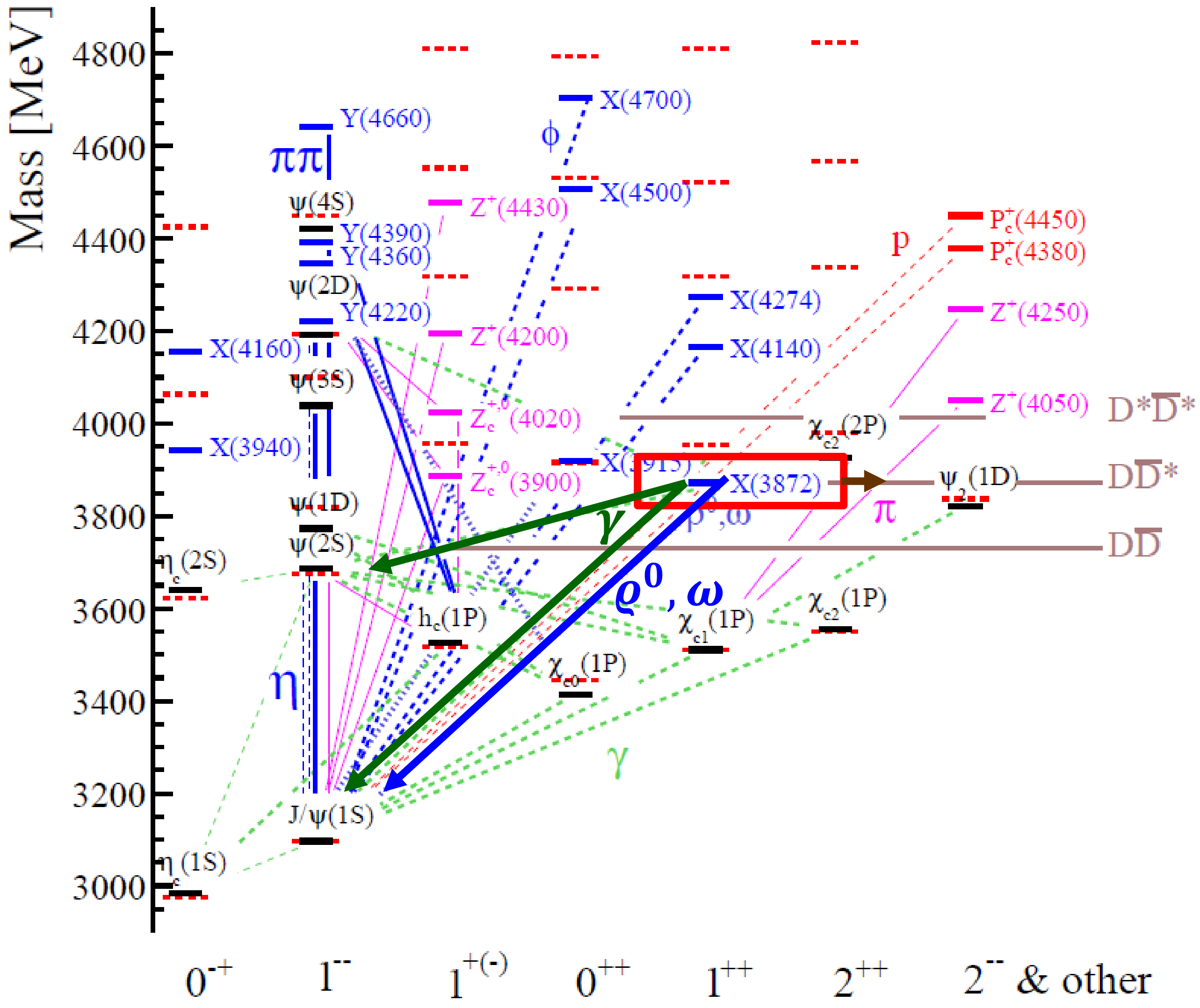
Mesons are **predominantly** $(q\bar{q})$ bound states below the open flavor threshold. **They are more complex structures above it,** and we have not yet understood them.

Status of X(3872)

2018 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$c\bar{c}$ MESONS
(including possibly non-$q\bar{q}$ states)

$\chi_{c1}(3872)$ $I^G(J^{PC}) = 0^+(1^{++})$
also known as $X(3872)$

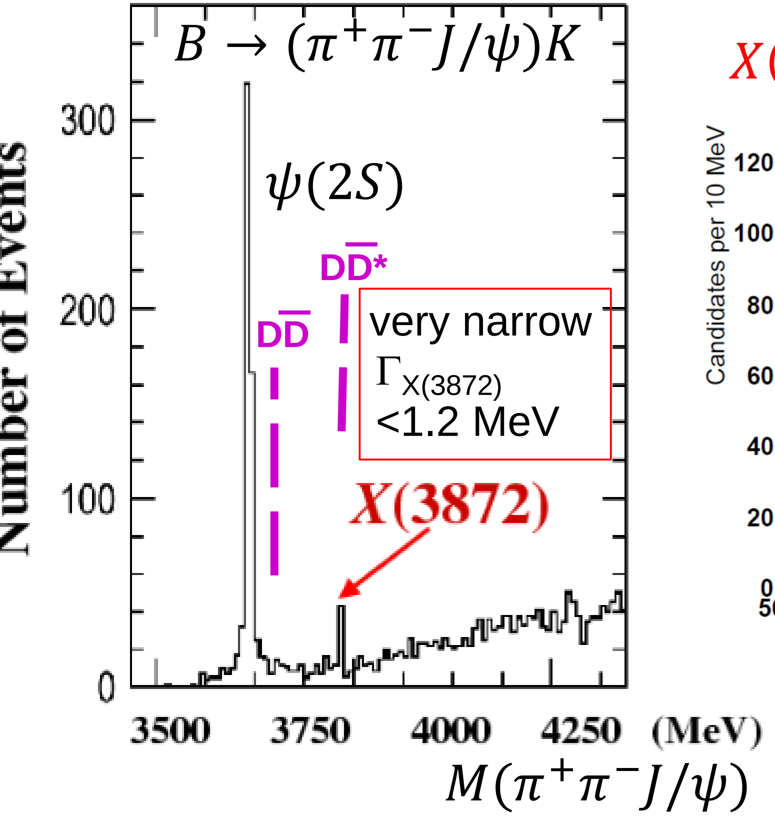


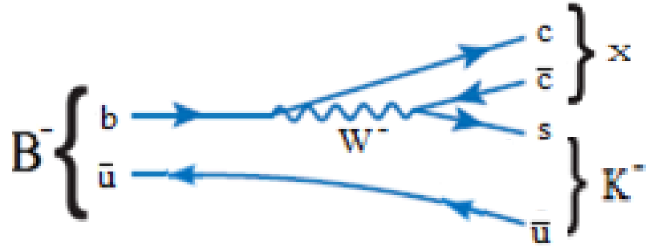
Charmonium near or above flavor threshold: back to complexity

Belle: Discovery of X(3872)

PRL 91, 262001 (2003)

The most cited Belle paper (1441 citations)

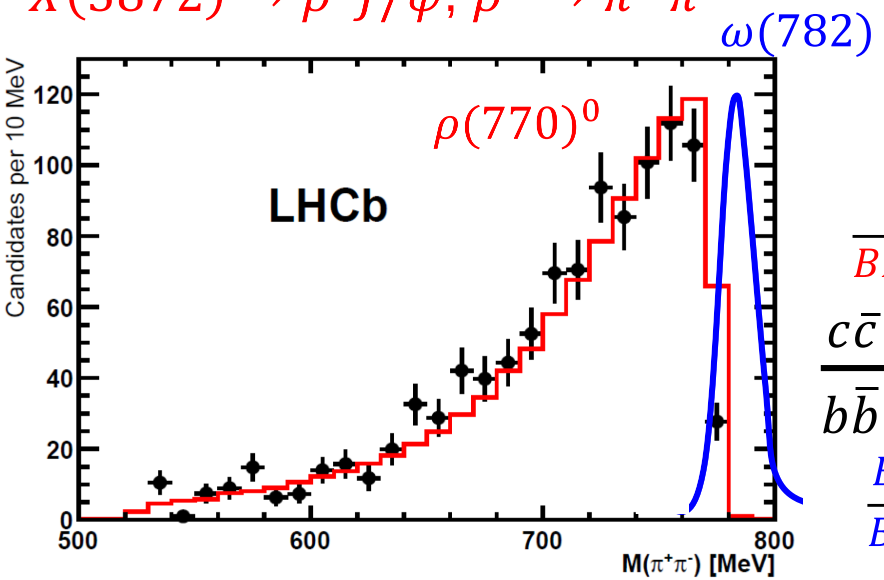




No charged partner found: $I=0$.

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)

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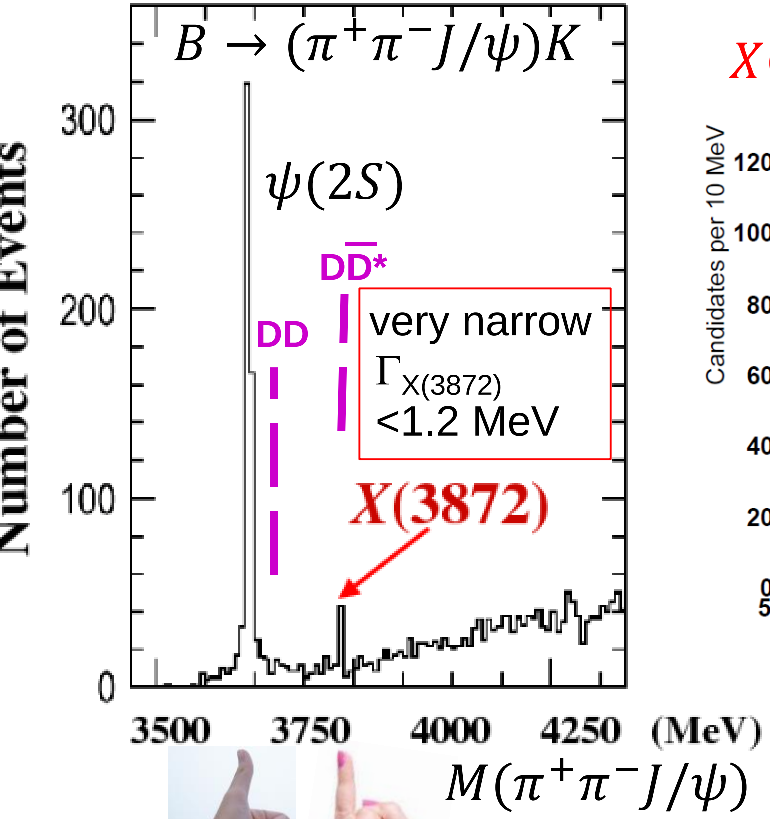


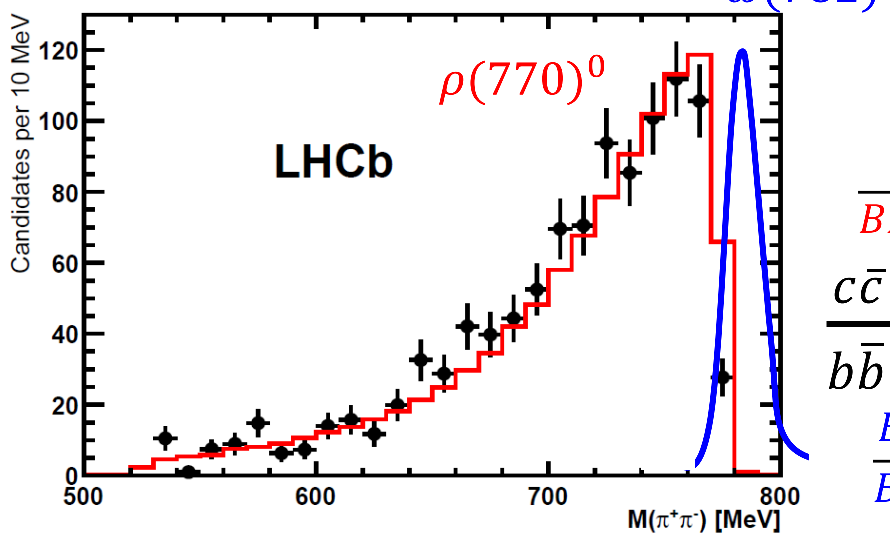
mesons are simple

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

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

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

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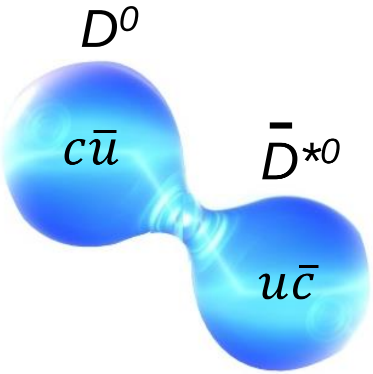
Enhancement of isospin violating $X(3872) \to \pi^+\pi^- J/\psi$ relative to radiative transitions rules out pure $\chi_{c1}(2^3P_1)$ interpretation

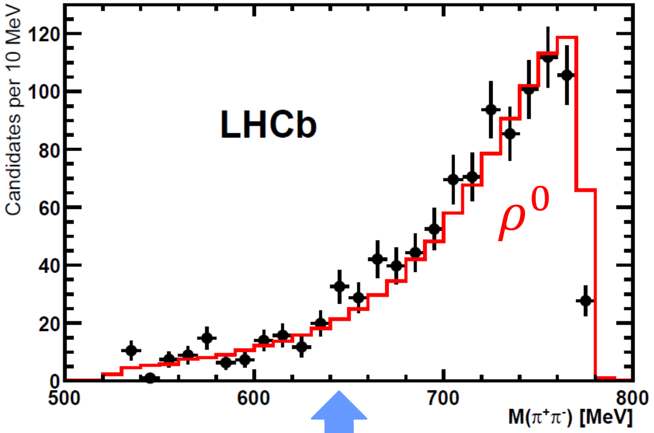
X(3872): molecular features

Mass near $D^0\overline{D}^{*0}$ threshold

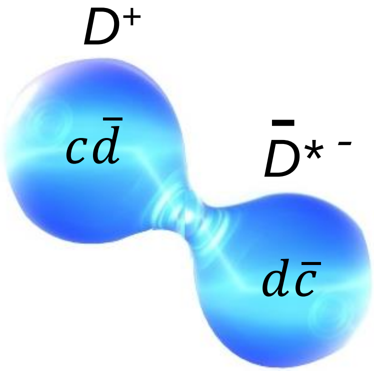


Enhanced isospin violating decays

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

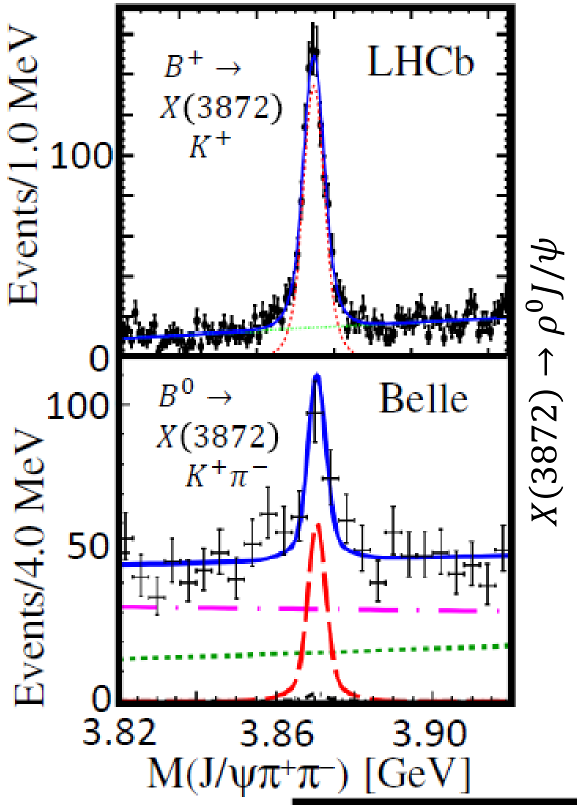


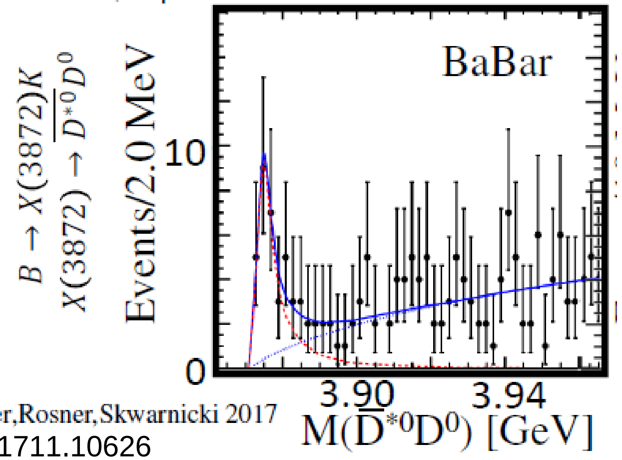
only small admixture of



8 MeV heavier constituents

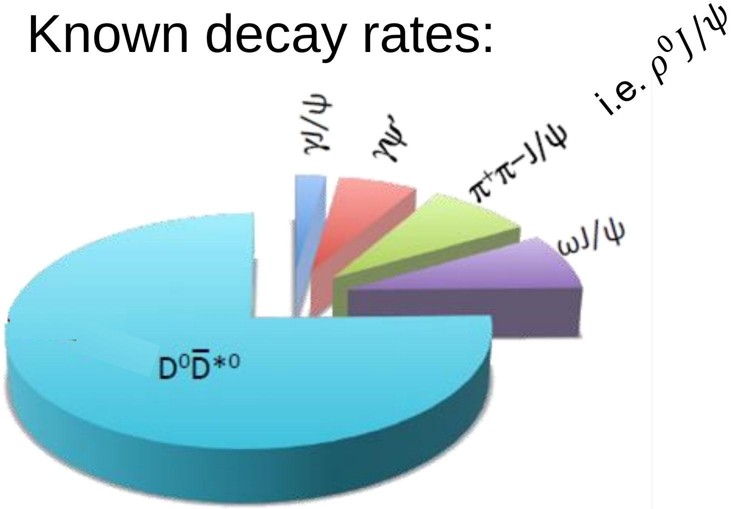
Narrow width in decays to $c\bar{c}$





Karliner, Rosner, Skwarnicki 2017
arXiv:1711.10626

Known decay rates:

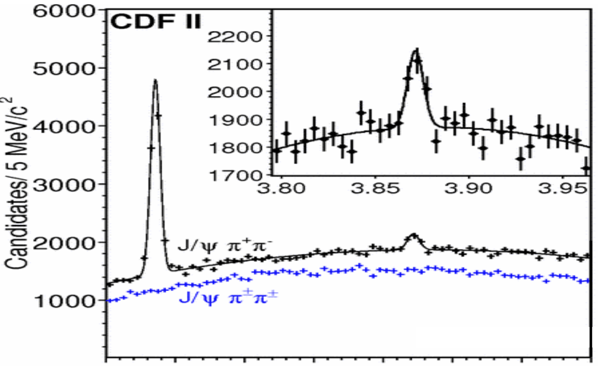


Huge fall-apart mode from the resonance tail above the $D^0\overline{D^{*0}}$ threshold

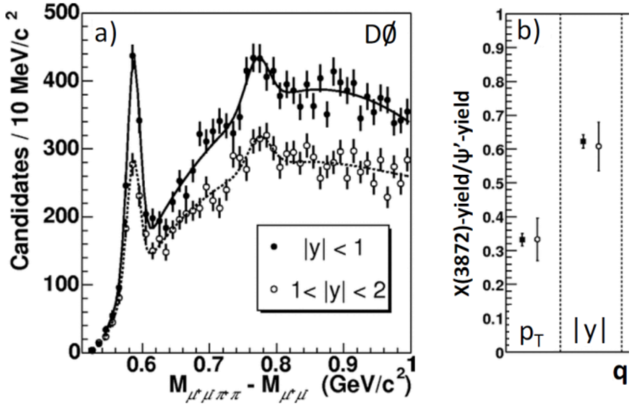
0^-1^- interacting in S-wave compatible with $J^{PC}=1^{++}$

Prompt production of X(3872)

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



PRL **93**, 072001 (2004)

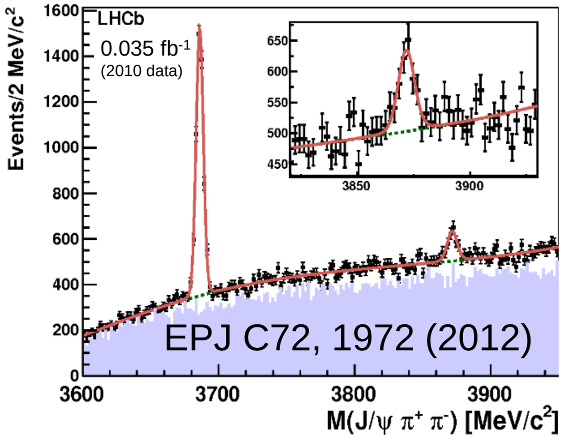


PRL **93**, 162002 (2004)

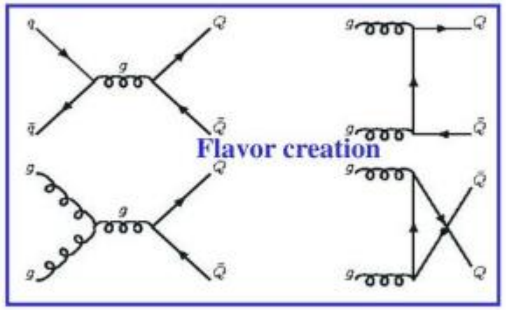
Dispute if large prompt production cross-section is compatible with molecular interpretation:

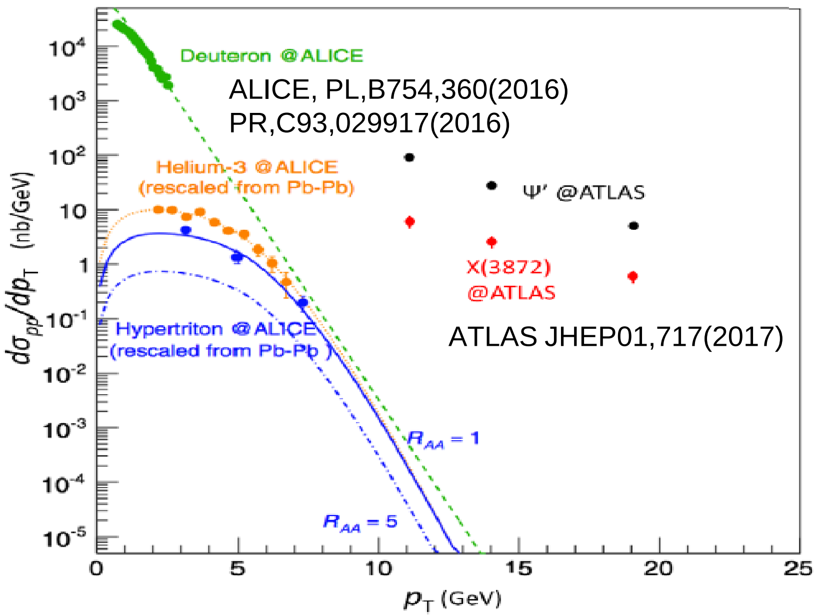
Bignamini, Grinstein, Piccinini, Polosa, Sabelli, PRL103, 162001 (**2009**); Artoisenet, Braaten, PRD81, 114018 (**2010**); PRD83, 014019 (**2011**); Bignamini et al, PLB684, 228 (**2010**); Guerrieri, Piccinini, Pilloni, Polosa, PRD90, 034003 (**2014**); Esposito, Guerrieri, Maiani, Piccinini, Pilloni, Polosa, Riquer PRD92, 034028 (**2015**); Albaladejo, Guo, Hanhart, Meißner, Nieves, Nogga, Z. Yang, Chin.Phys.C41, 121001 (**2017**), arXiv:1709.09101; Esposito et al. arXiv:1709.09631 (**2017**); Wang Chin.Phys.C Vol. 42, 043103 (**2018**), arXiv:1709.10382.

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



EPJ C72, 1972 (2012)





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

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

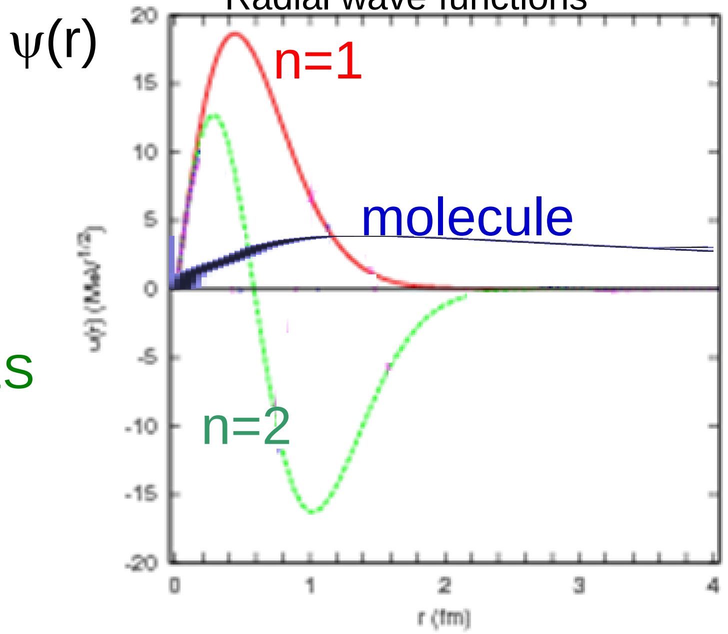
$$\frac{BR(X(3872)\to\psi(2S)\gamma)}{BR(X(3872)\to J/\psi(1S)\gamma)} = 2.48\pm0.64\pm0.29 \quad (>0 \text{ at } 4.4\sigma)$$

phase-space: suppressed ($\psi(2S)\gamma$), favored ($J/\psi(1S)\gamma$)

by a factor of ~100!

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

Radial wave functions



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

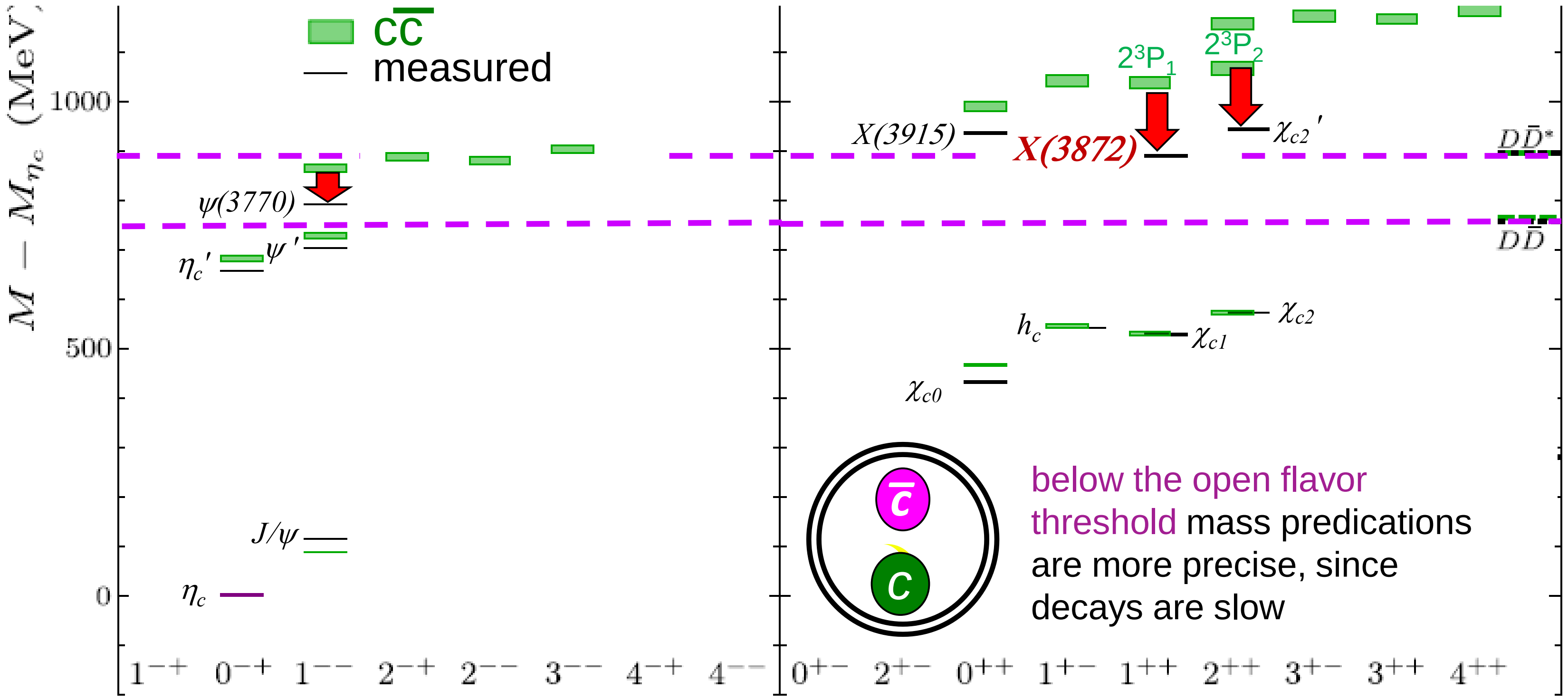
$|\langle 2S| r |2P\rangle|^2 \gg |\langle 1S| r |2P\rangle|^2$ — $\chi_{c1}(2^3P_{1++})$ ✓

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

- ➢ Points to $\chi_{c1}(2P)$ component in 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!

X(3872) story

Adopted from Steve Olsen
at SCGP Workshop on Exotic Hadrons and Flavor Physics, May 2018
http://media.scgp.stonybrook.edu/presentations/2017/20180529_Olsen.pdf

70 years ago

K-mesons discovered -- *associated production – strangeness – SU(3)* -- quark model

Dec. 1947 ← 16 years → Jan 1964

16 years ago

X(3872) discovered -- *molecule? charmonium? molecule? – charmonium? – diquark? – molecule? charmonium? molecule?* -- ????

Aug. 2003 ← 16 years → today

charmonium – molecule mix ?

Need high statistics coupled-channel analysis to clarify its nature

Experimental prospects for X(3872)

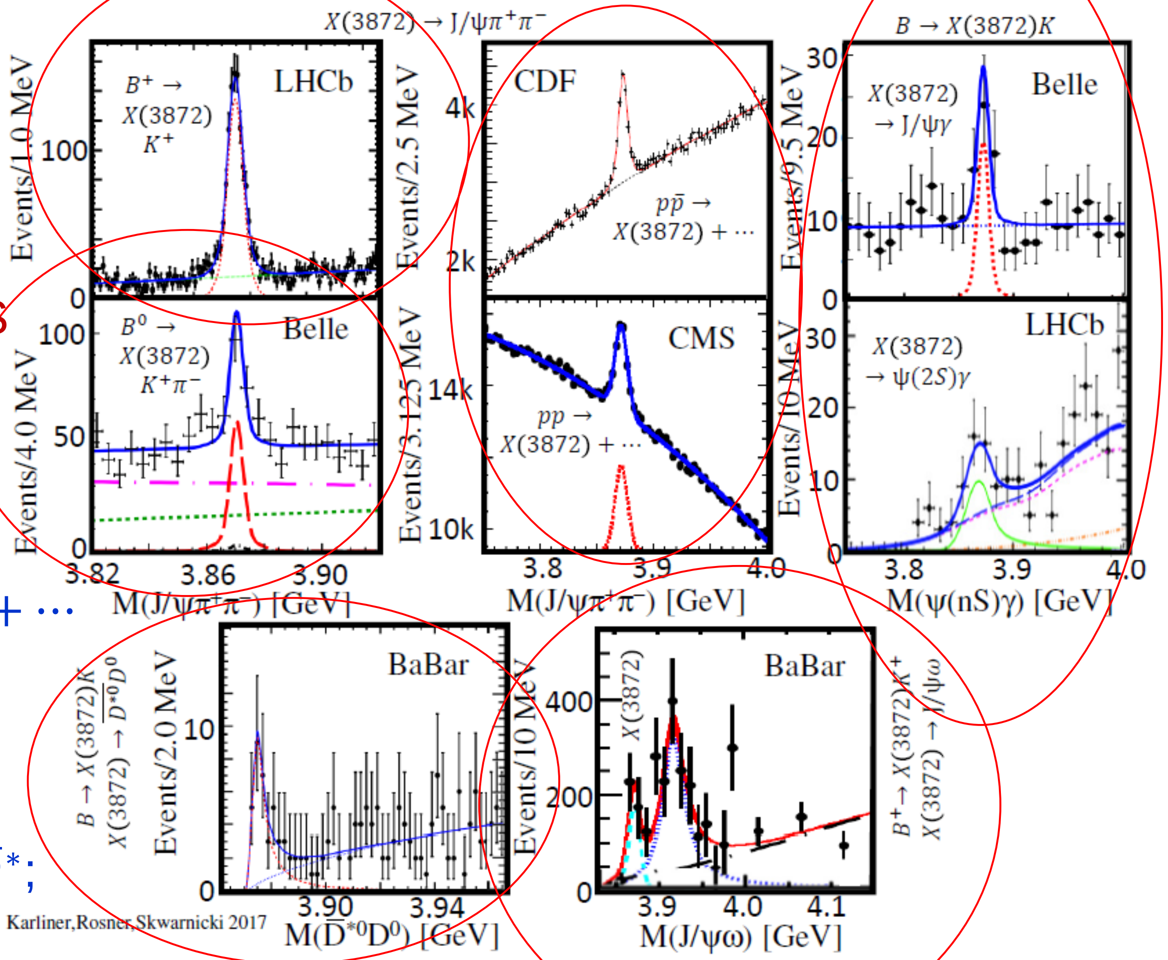
Mass and natural width of X(3872)
LHCb
PANDA

Details of prompt production in forward region at LHC
LHCb

Improve statistical errors on radiative decays of X(3872)
Belle II, LHCb

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

LHCb
CMS, ATLAS
More production modes
$B_s, B_c, \Lambda_b \to X(3872) + \cdots$



	LHCb 2010-18		U. Phase I 2020-30	Phase II 2030-35	Belle 2000-2009	II 2018-2025
	Run I	Run II				
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}	0.7 ab^{-1}	50 ab^{-1}
$B^+ \to K^+X(3872)$ $(\to J/\psi\pi^+\pi^-)$	1k	5k	33k	200k	0.17k	11k
$B^+ \to K^+X(3872)$ $(\to \psi(2S)\gamma)$	36	0.2k	*1k*	7k		2k
$B^+ \to K^+X(3872)$ $(\to J/\psi(1S)\gamma)$	0.6k	2.4k	*15k*	90k	36	2k

(crude projections)

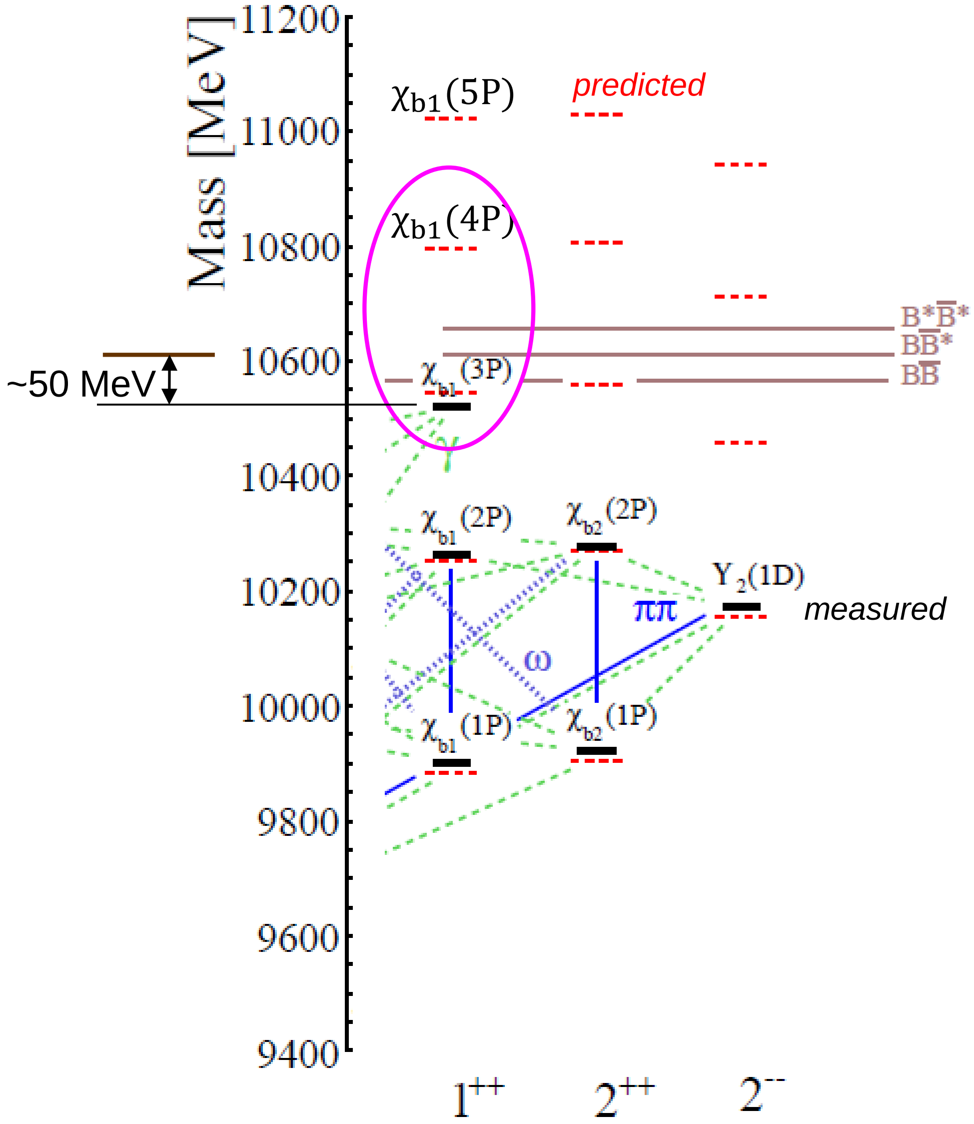
Study line shape in $D\bar{D}^*$; coupled-channel line-shape fit
Belle II, LHCb Phase II Upgrade

Improve statistical errors on X(3872)→ ωJ/ψ (clarify 2nd peak: X(3915)) LHCb, Belle II

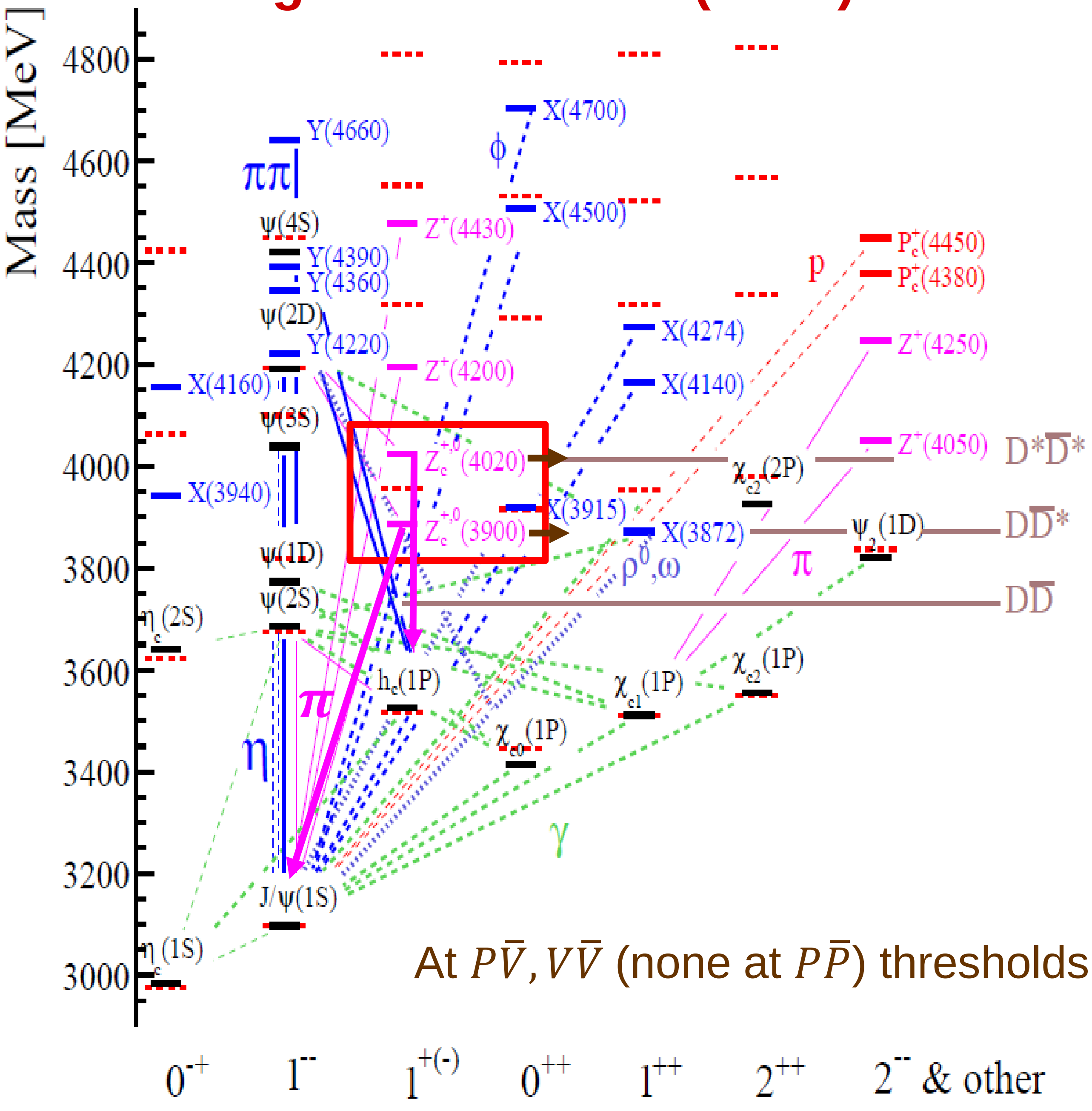
LHCb Upgrade
Look for: $X(3872) \to \pi^+\pi^-\chi_{c1}(1P)$
since
$BR(\chi_{b1}(2P) \to \pi^+\pi^-, \pi^0\pi^0\chi_{b1}(1P))$
$=(0.9 \pm 0.1)\%$

X(3872), so far, in unique!

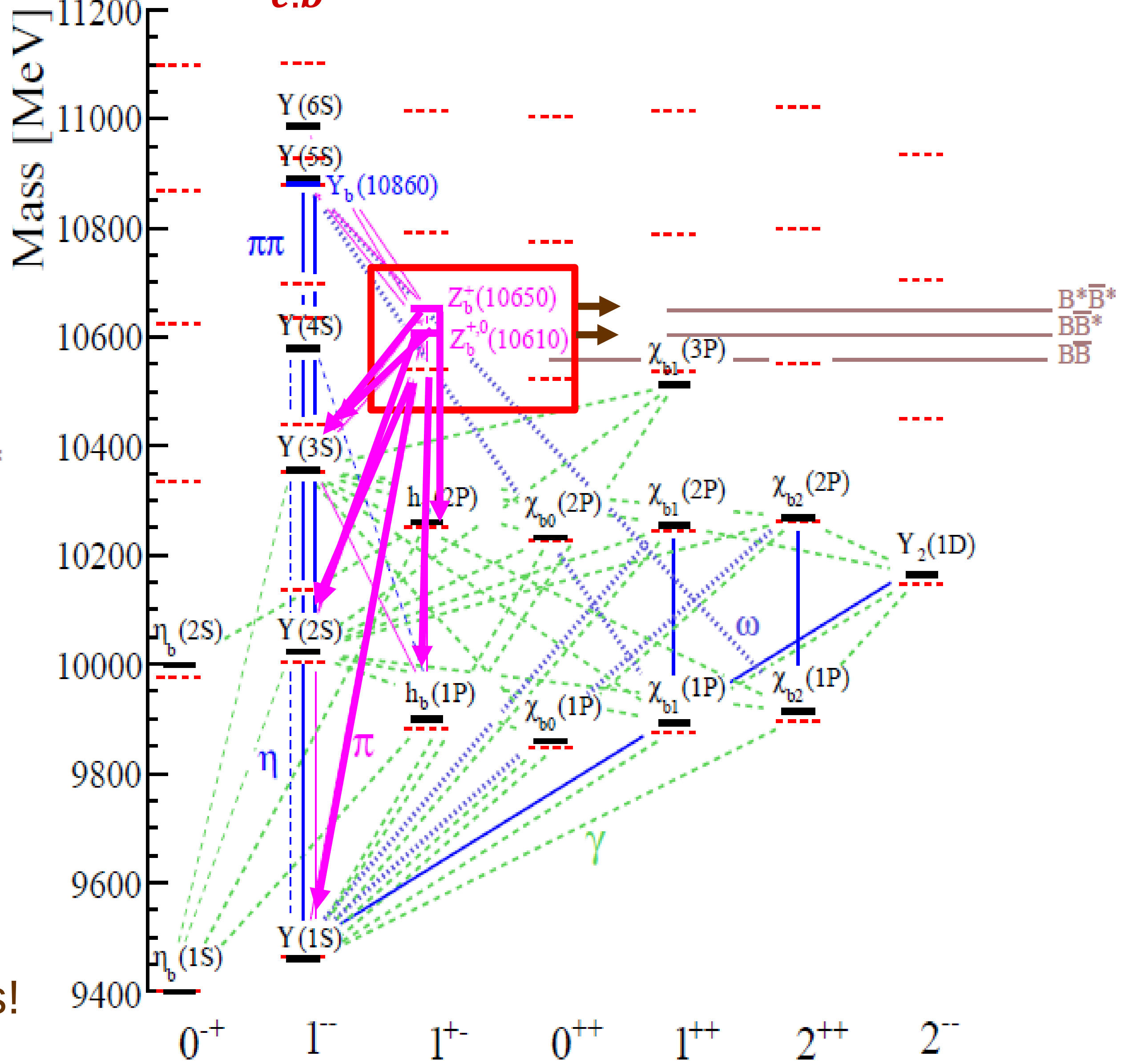
- The only exotic charmonium-like candidate which shows up consistently in many different productions mechanism, accompanying well-behaved $c\bar{c}$ state $-\ \psi(2S)$, and detected in many different decays modes
- If coincidence of $\chi_{c1}(2^3P_1)$ with the $D^0\overline{D}^{0*}$ threshold is responsible 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 and neutral ($I = 1$) threshold states $Z_{c.b}^{\pm,0}$



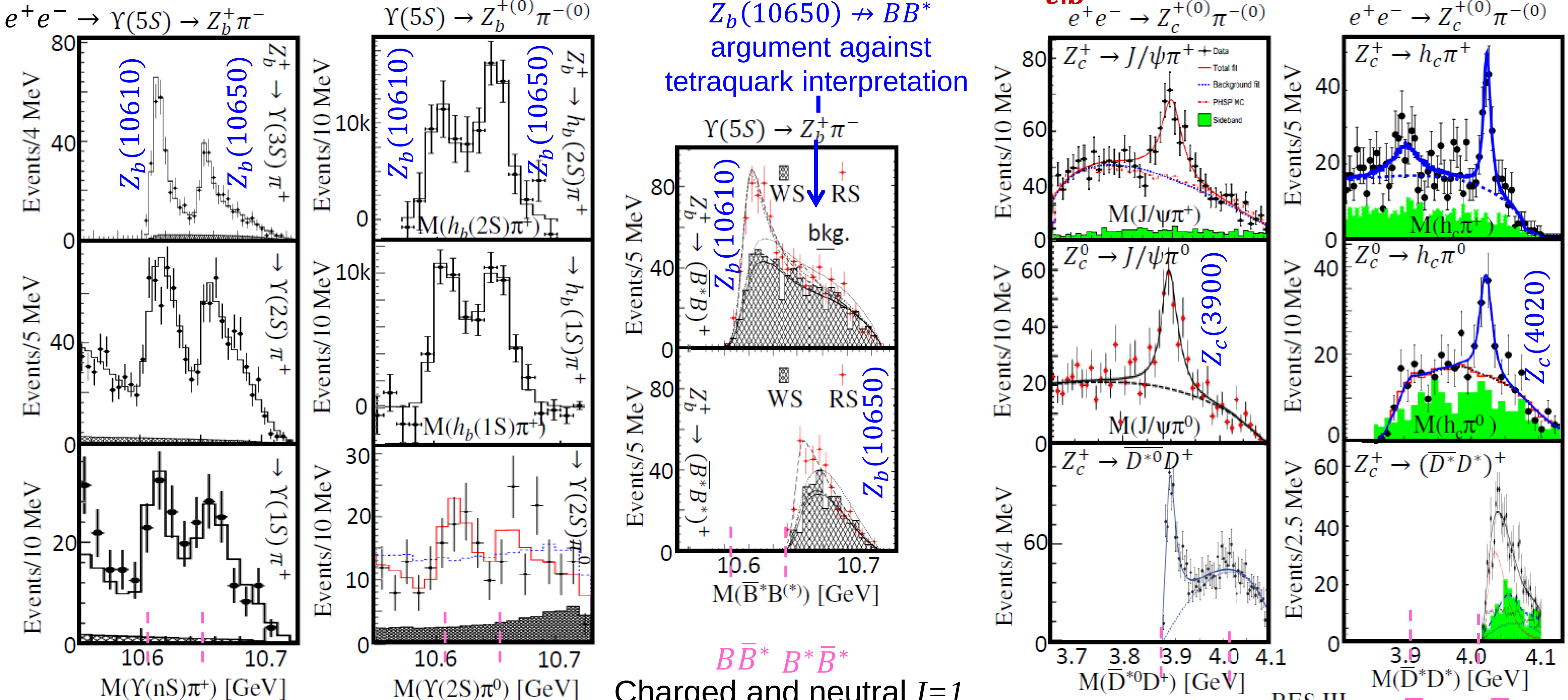
At $P\bar{V}, V\bar{V}$ (none at $P\bar{P}$) thresholds!



Their masses follow the thresholds not the heavy quarkonium excitation spectrum

Charged and neutral ($I = 1$) threshold states $Z_{c,b}^{\pm,0}$

$Z_b(10650) \nrightarrow B\bar{B}^*$
argument against
tetraquark interpretation



Karliner,Rosner,Skwarnicki 2017

Belle

$B\bar{B}^*$ $B^*\bar{B}^*$

$B\bar{B}^*$ $B^*\bar{B}^*$

$B\bar{B}^*$ $B^*\bar{B}^*$

Charged and neutral $I=1$

$J^{P(C)}=1^{+(-)}$

Karliner,Rosner,Skwarnicki 2017

BES III

$D\bar{D}^*$ $D^*\bar{D}^*$

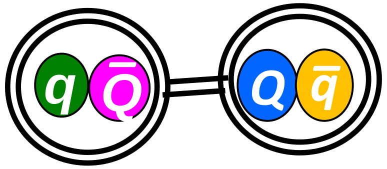
$D\bar{D}^*$ $D^*\bar{D}^*$

No confusion with quarkonia states (charge!).

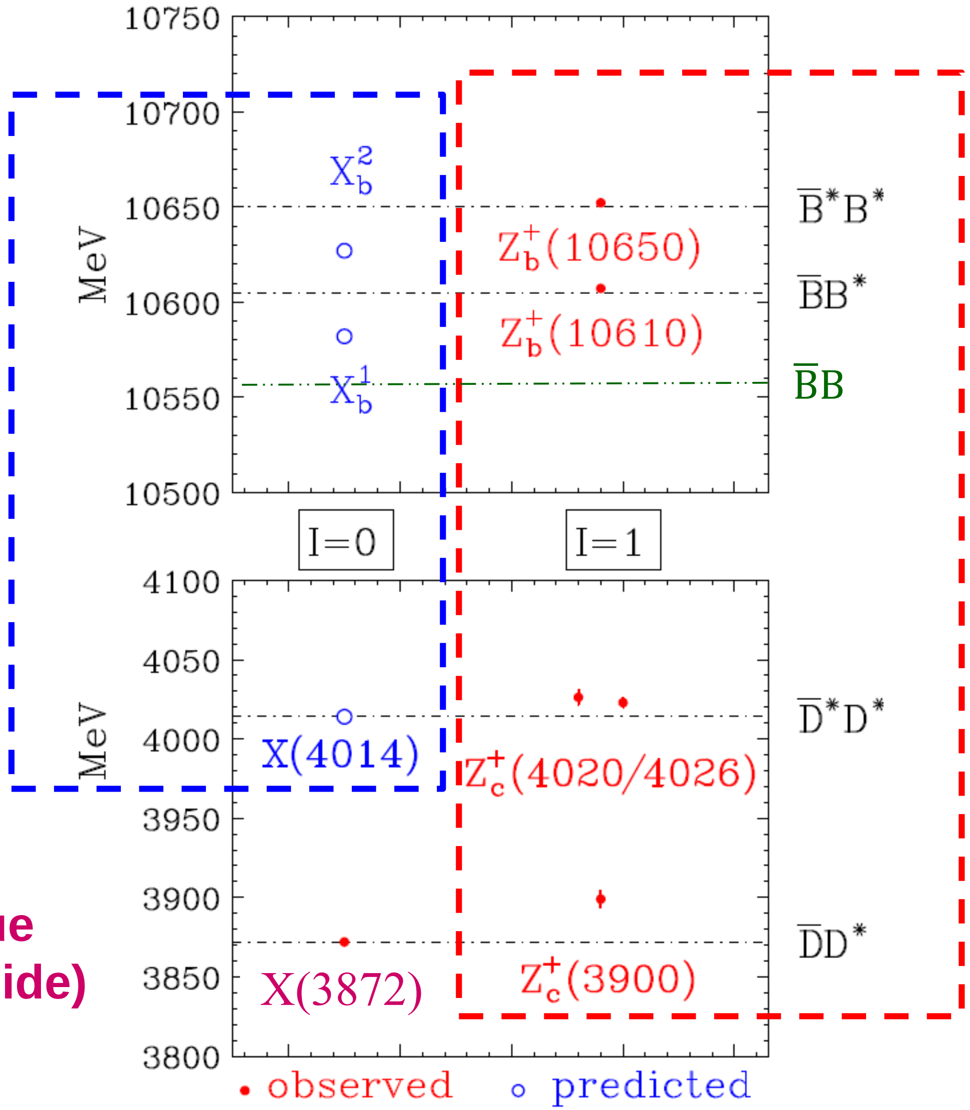
Near thresholds. Relatively narrow. Large fall-apart rates. Observable rates to quarkonia.

⇨ 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

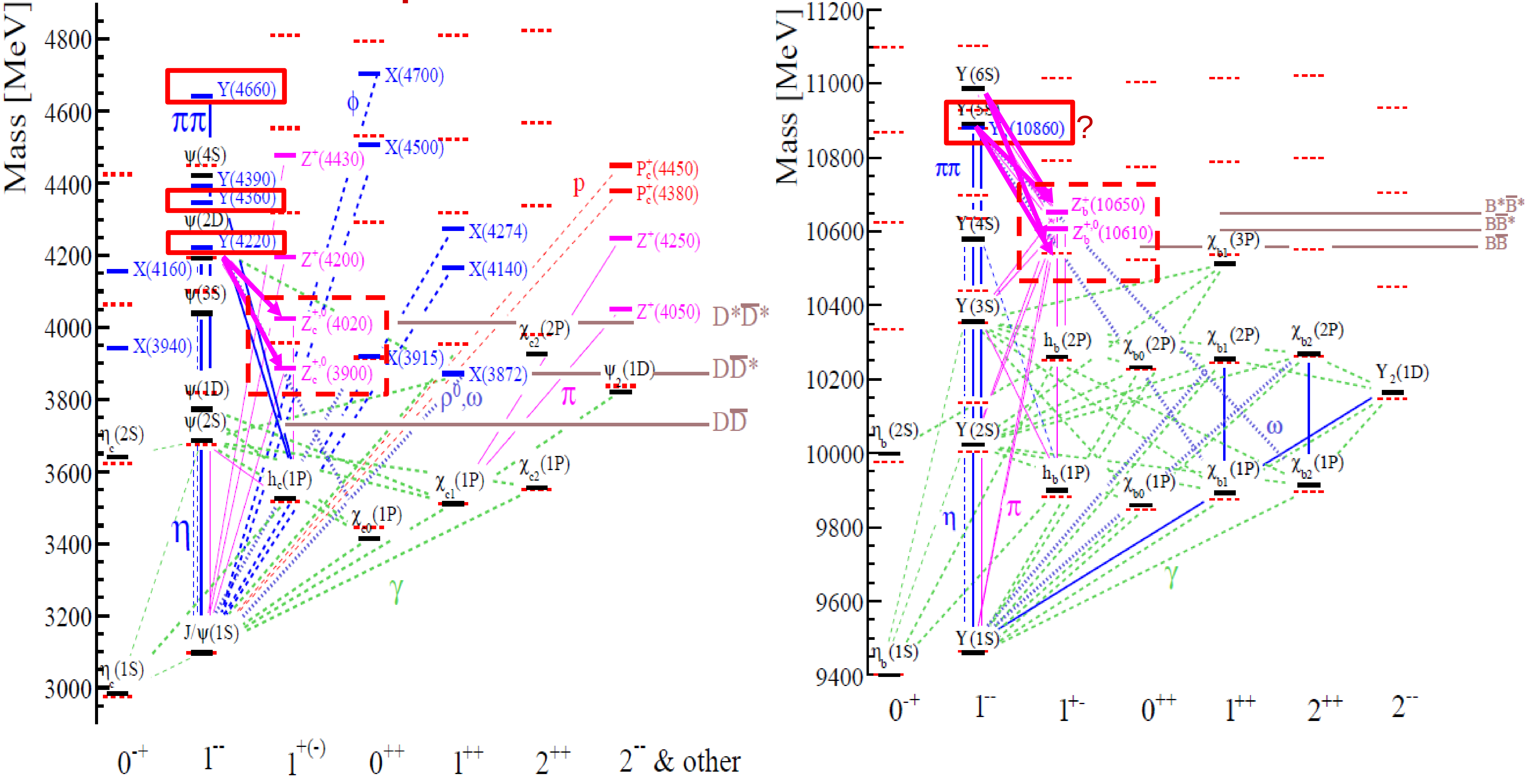
No sign of such states at $D\bar{D}$ and $B\bar{B}$, hints at forces dominated by π exchange

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

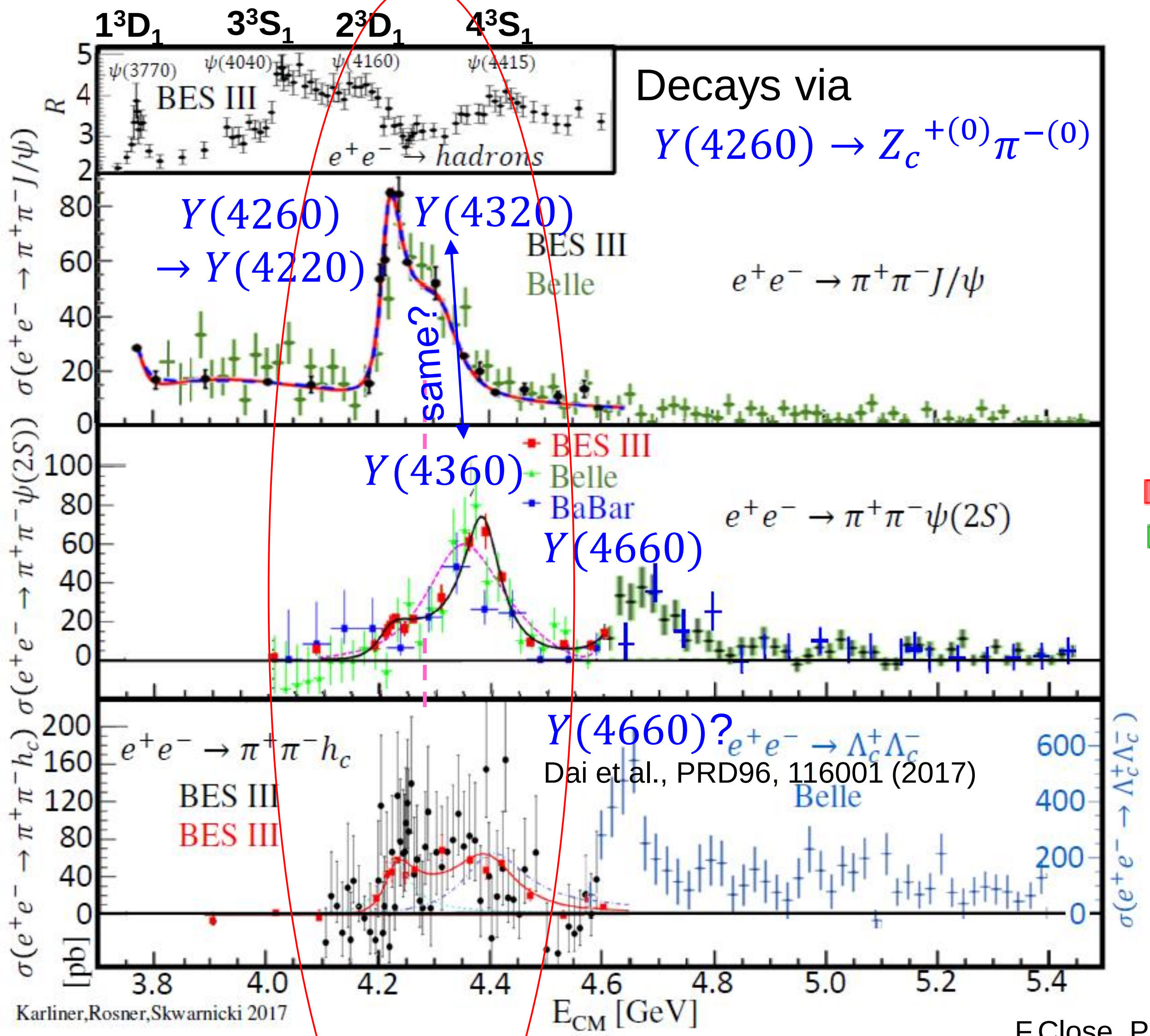
Alternative viewpoint: tightly bound tetraquarks
A. Ali, L. Maiani, A. Polosa, V. Riquer, PRD91, 017502 (2015)

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 quarkonium-like vector states

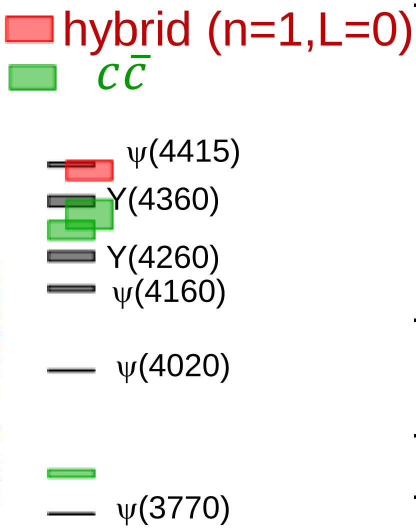


Anomalous charmonium-like vector states

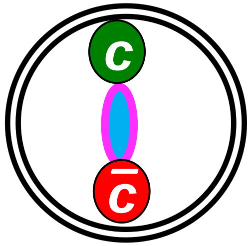


- $Y(4220)$ and $Y(4320/4360)$ do not align with $c\bar{c}$ states
- Γ_{ee} widths suppressed by $10^{2\text{-}3}$
- $\Gamma_{\pi\pi\psi}$ widths huge

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

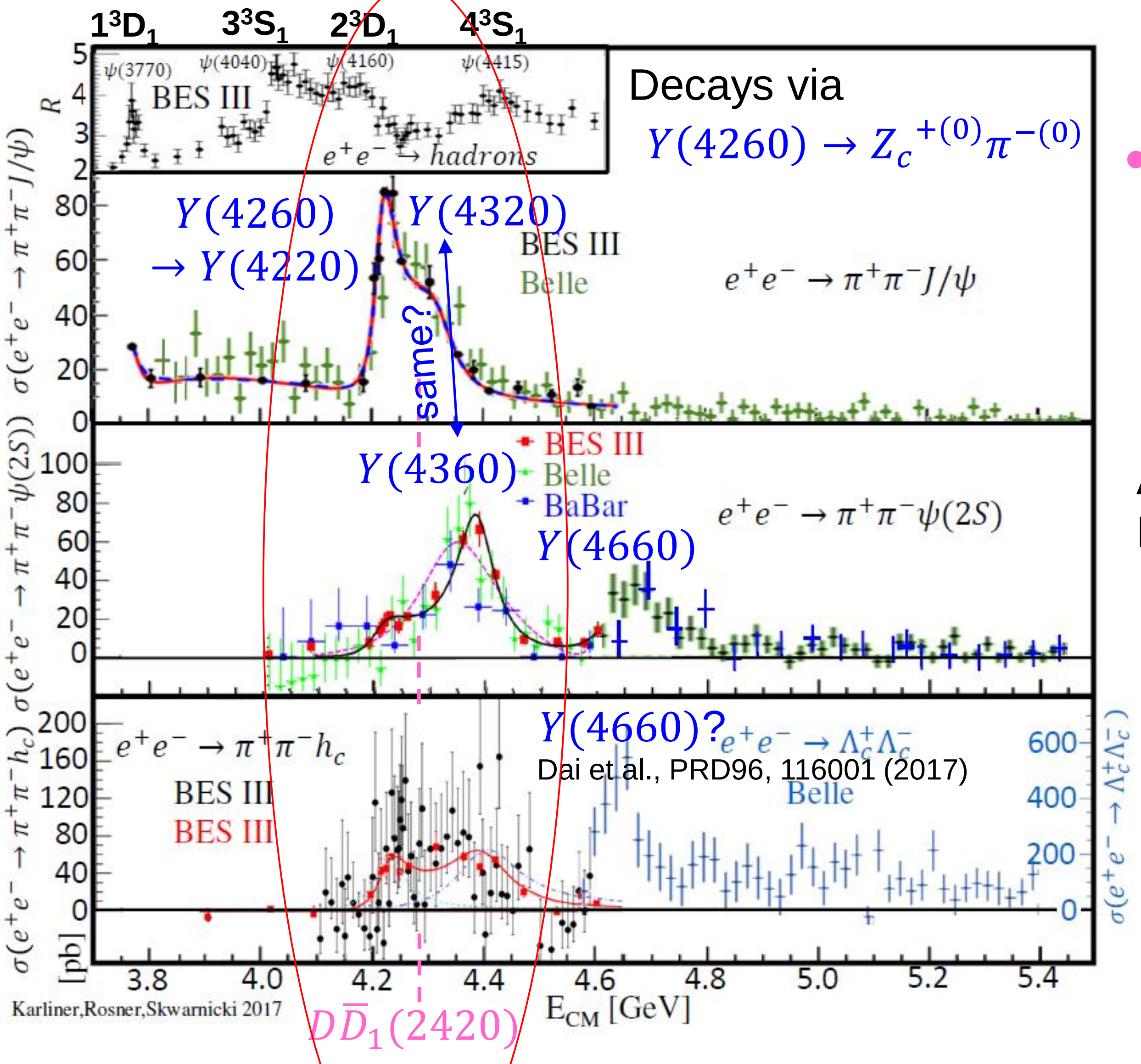
– Γ_{ee} suppressed by a spin-flip needed to produce cc in S=0 configuration

– ππψ can proceed via DD** rescattering

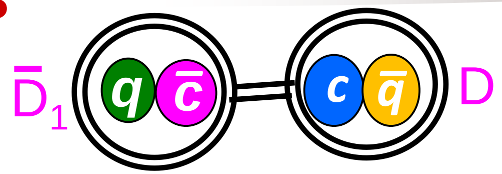
– However, expected to decay to $DD^{(*)}\pi$, but not observed [CLEO-c PR D80, 072001(2009)]

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) …

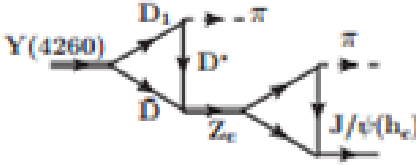
Anomalous charmonium-like vector states



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



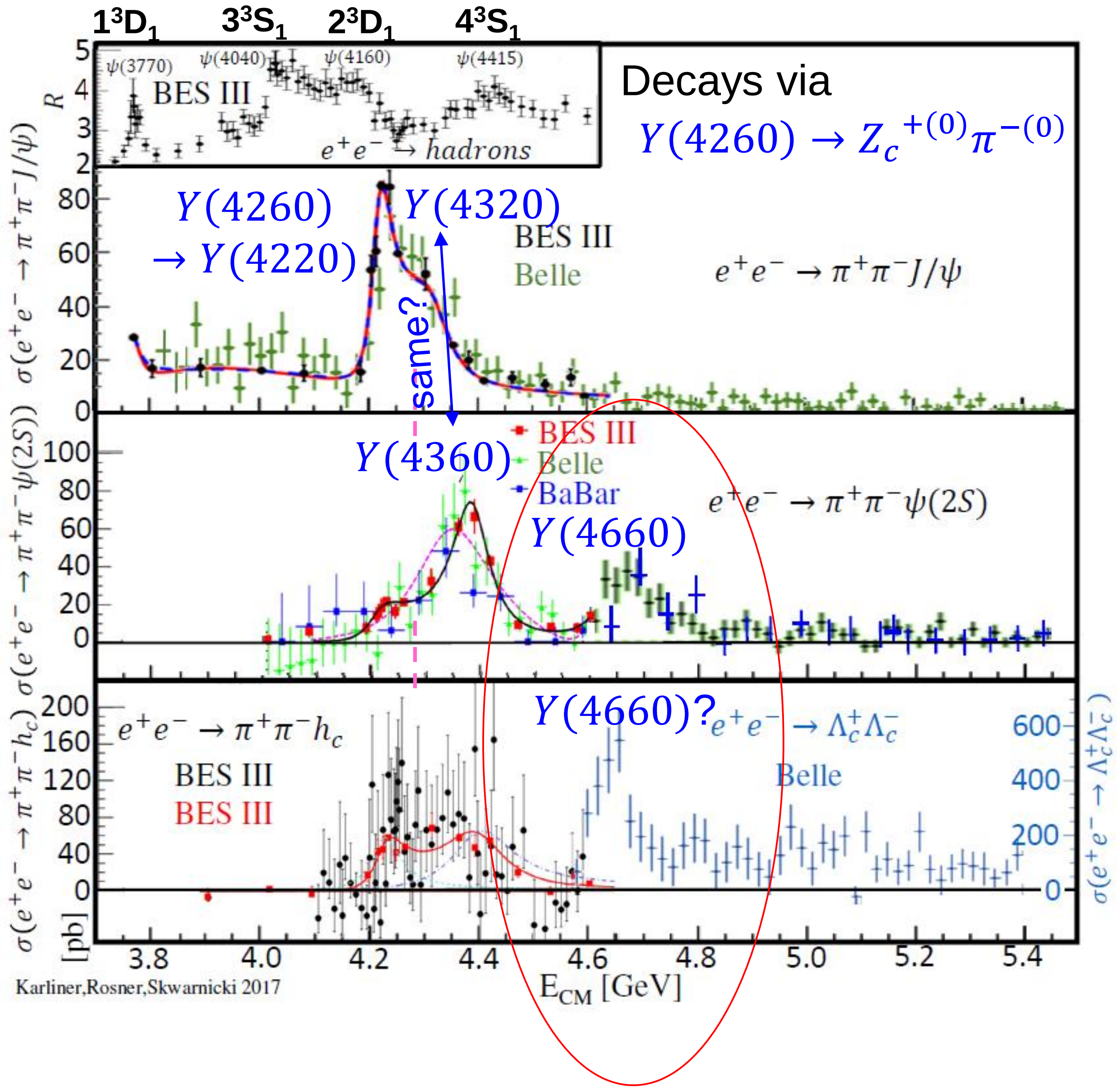
- $D\bar{D}_1(2420)$ **molecule** Q.Wang, C.Hanhart, Q.Zhao, **PRL 111 (2013) 132003**



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: $Y(4260)\to Z_c(3900)\pi$, $Y(4260)\to X(3872)\gamma$ (possibly observed by BESIII)

Anomalous charmonium-like vector states



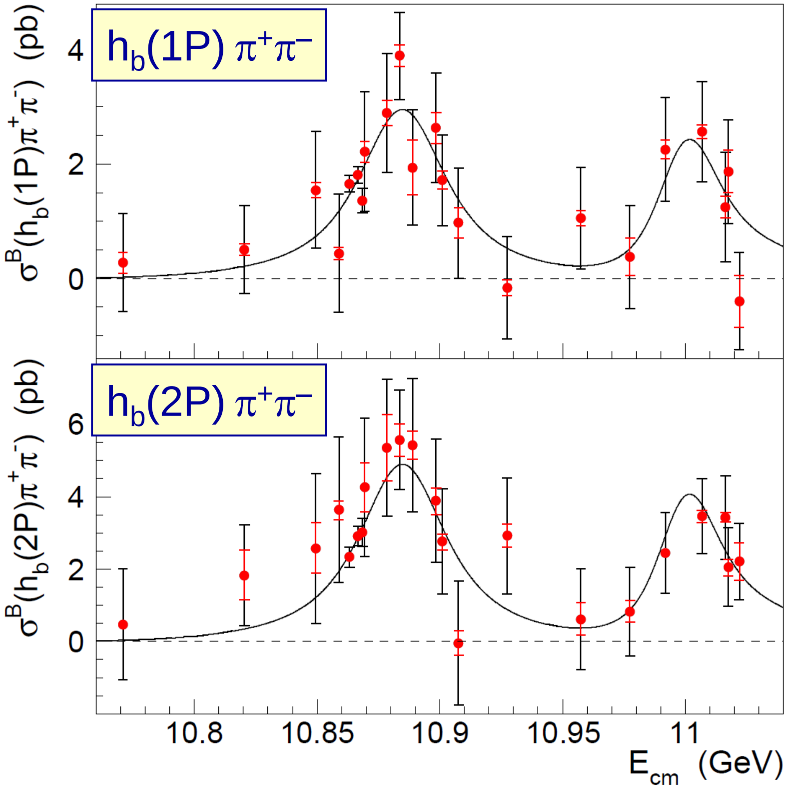
Y(4660): the same or different state in $e^+e^- \to \pi^+\pi^-\psi(2S)$ and $e^+e^- \to(\gamma)\ \Lambda_c^+\Lambda_c^-$

Dai et al., PRD96, 116001 (2017)

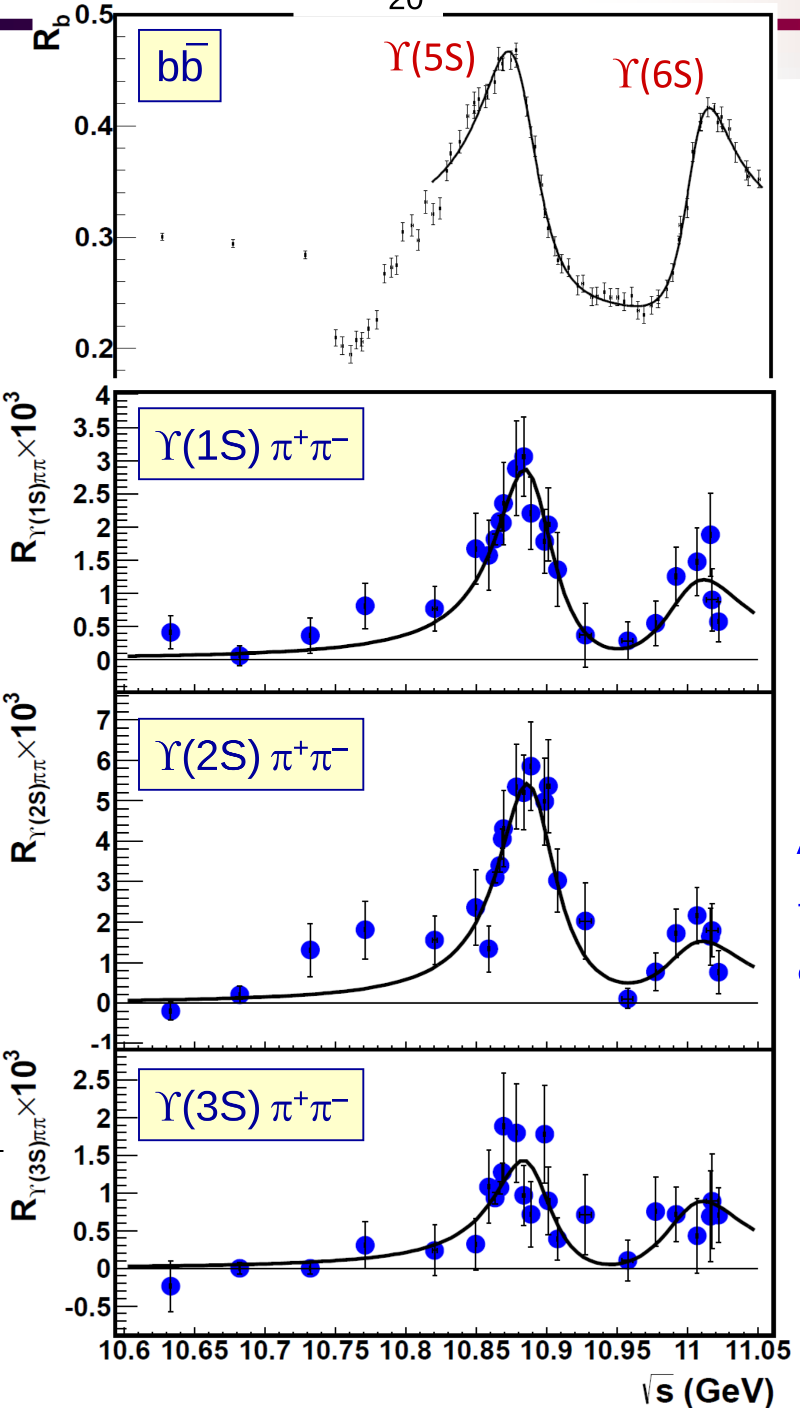
- $\psi(5^3S_1)$ or $\psi(6^3S_1)$?
- tetraquark?
- baryonium?

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 $\Upsilon(3S)$, $\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-$

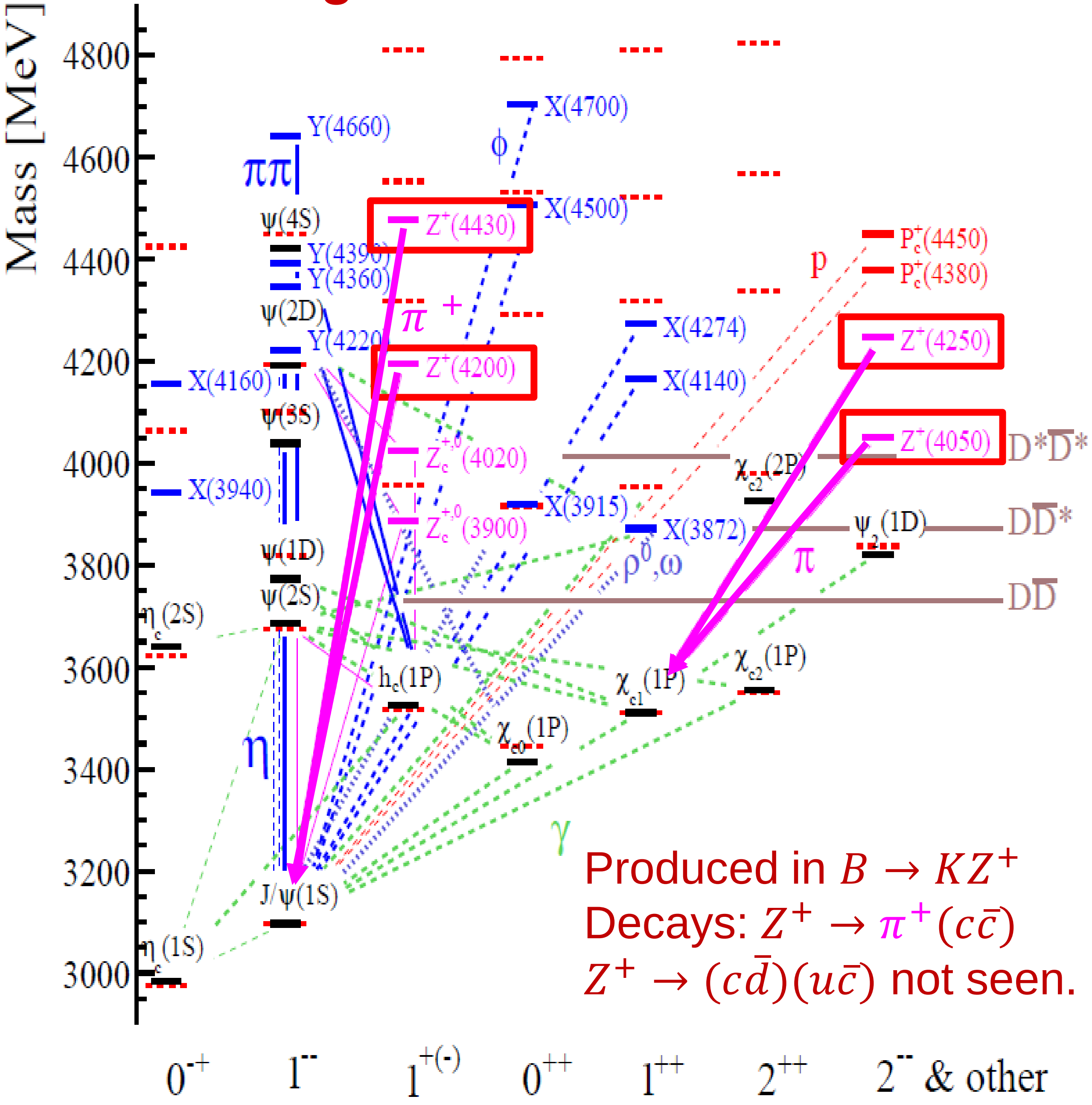
OZI-rule violation

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

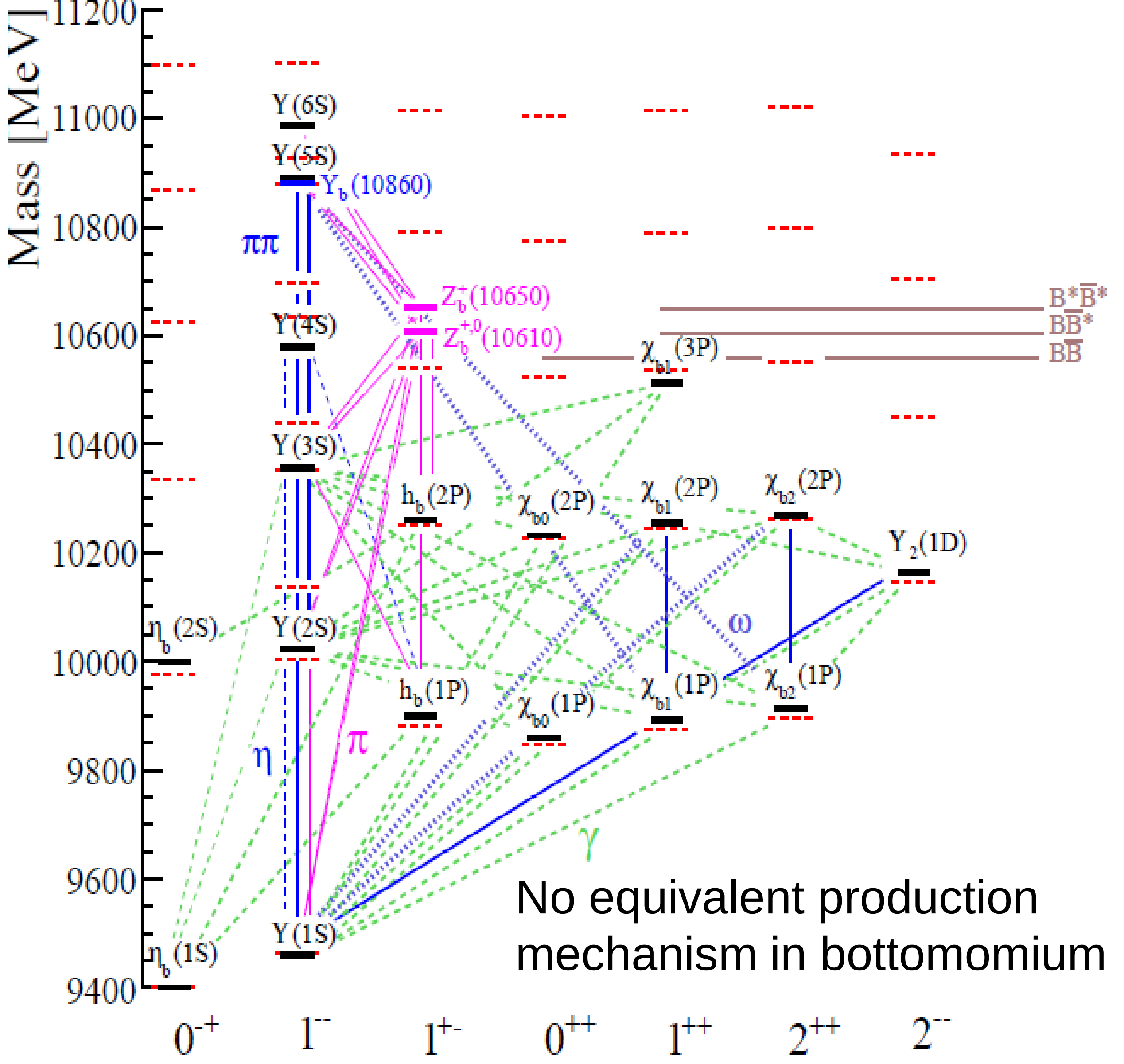
HQSS violation

Like in charmonium!

Charged charmonium-like states in B decays



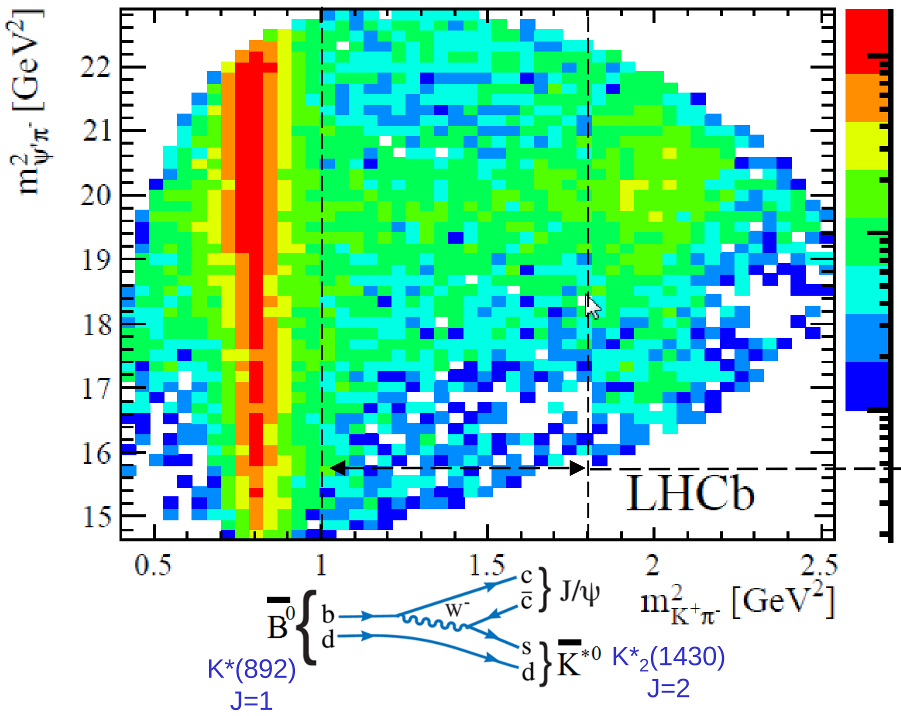
Produced in $B \to K Z^+$
Decays: $Z^+ \to \pi^+ (c\bar{c})$
$Z^+ \to (c\bar{d})(u\bar{c})$ not seen.

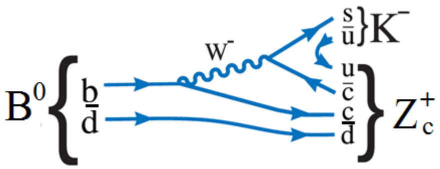


No equivalent production mechanism in bottomomium

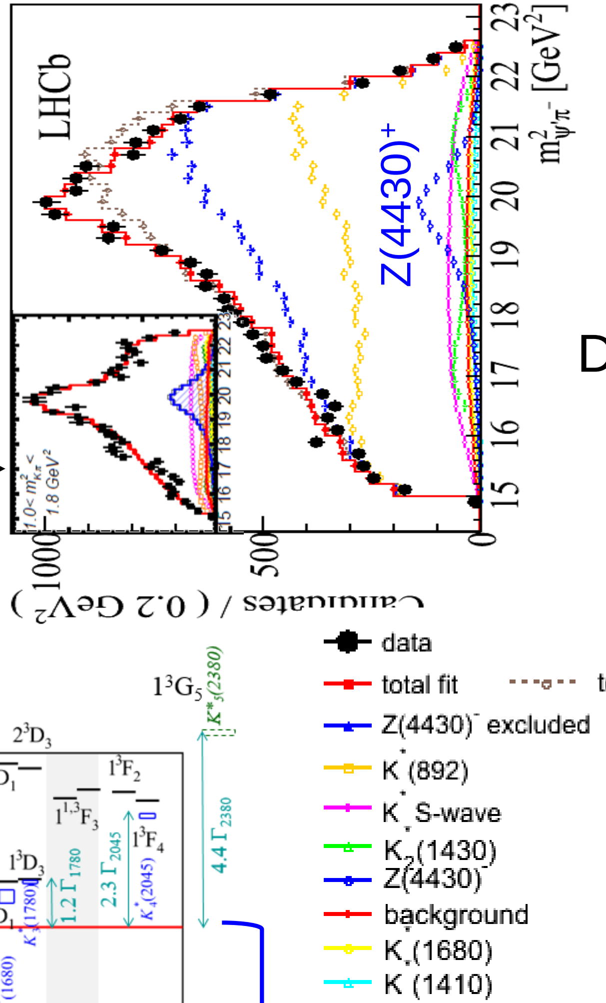
$\overline{B^0} \to \psi(2S)\pi^+K^-$

PRL 112, 222002 (2014)



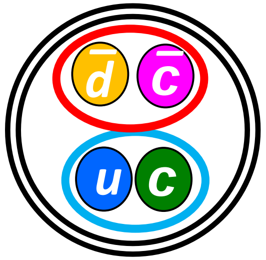


$Z_c(4430)^+ \to \psi(2S)\pi^+$

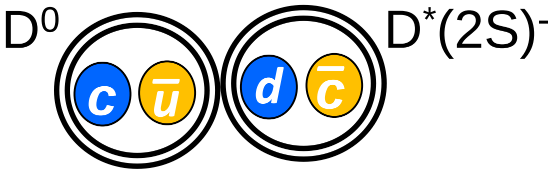


Broad structure:

$\Gamma_{Z(4430)}$=181±31 MeV

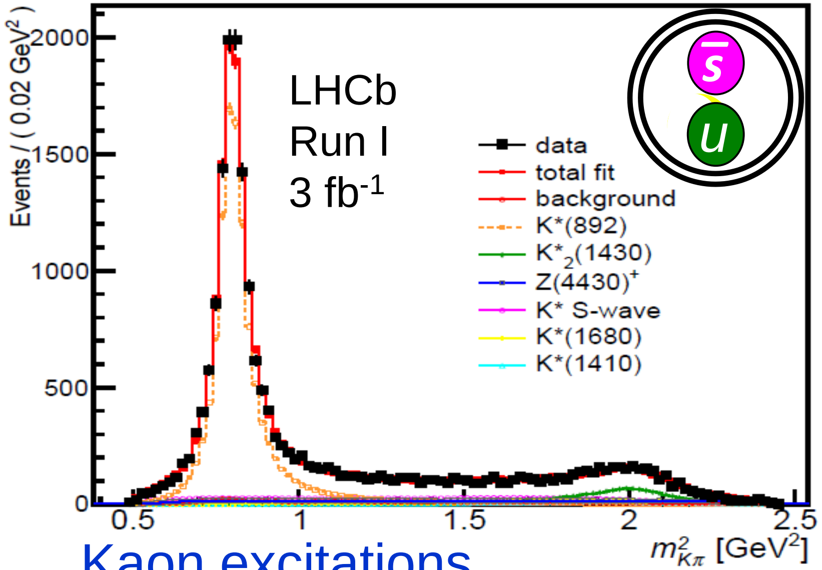


Tetraquark ?

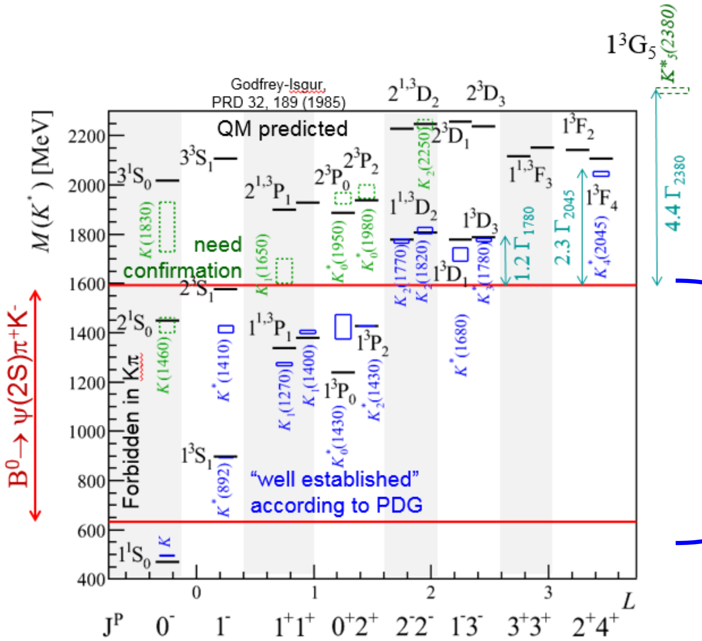


Molecule or cusp?

The results improved on the earlier characterization of $Z(4430)^-$ by Belle.



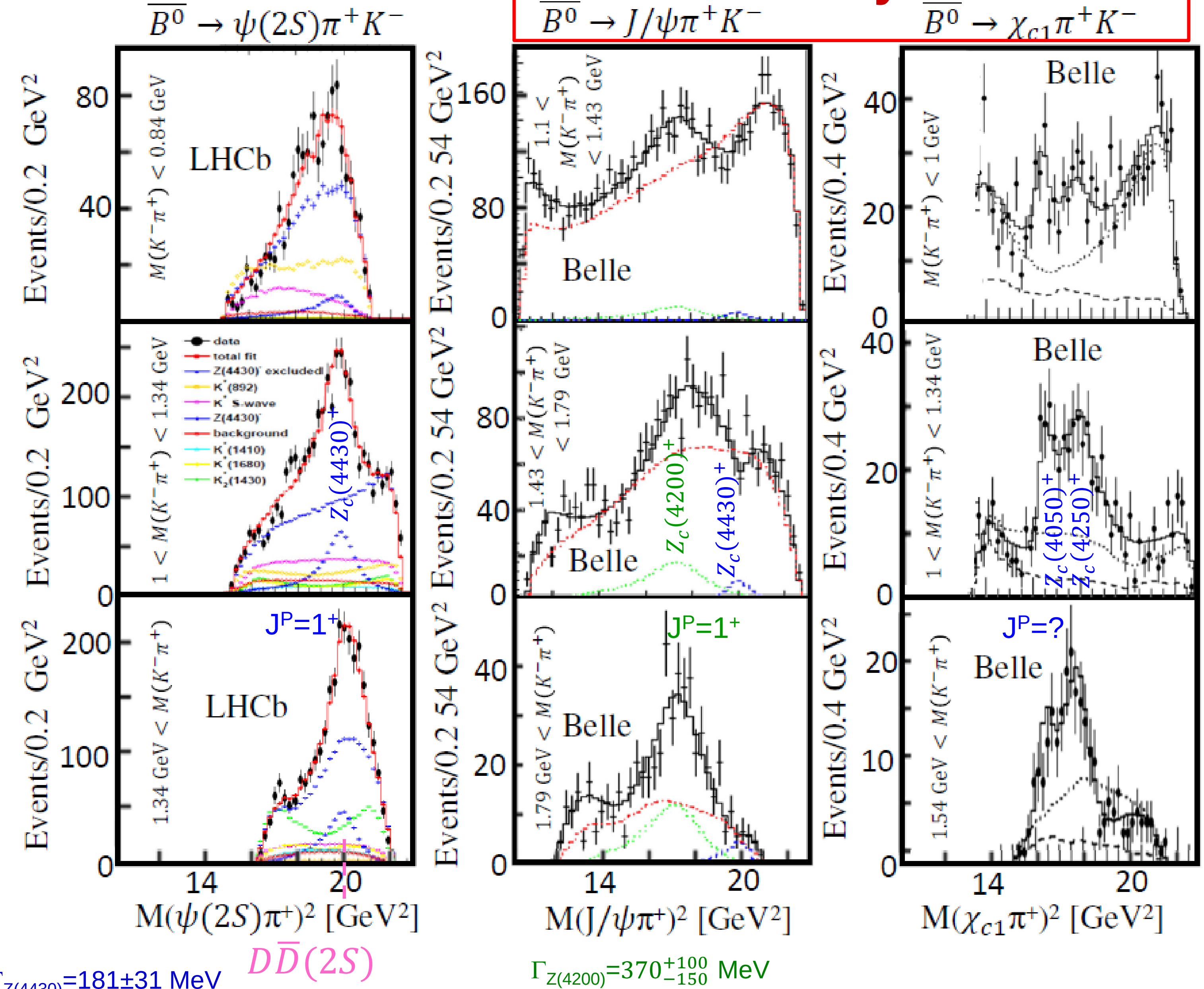
Kaon excitations



4 expected and well experimentally established kaon resonances in the 4D amplitude fit

Charged charmonium-like states in B decays

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



$\Gamma_{Z(4430)}$=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.

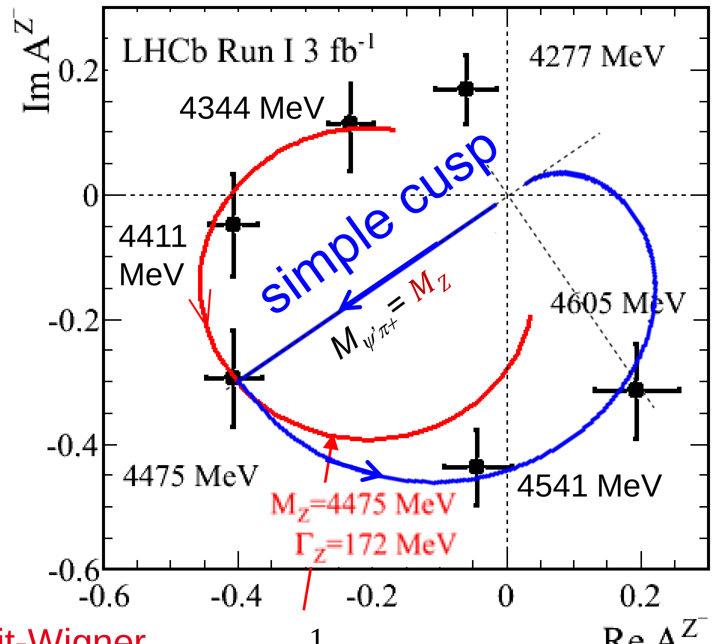
No clear explanations.

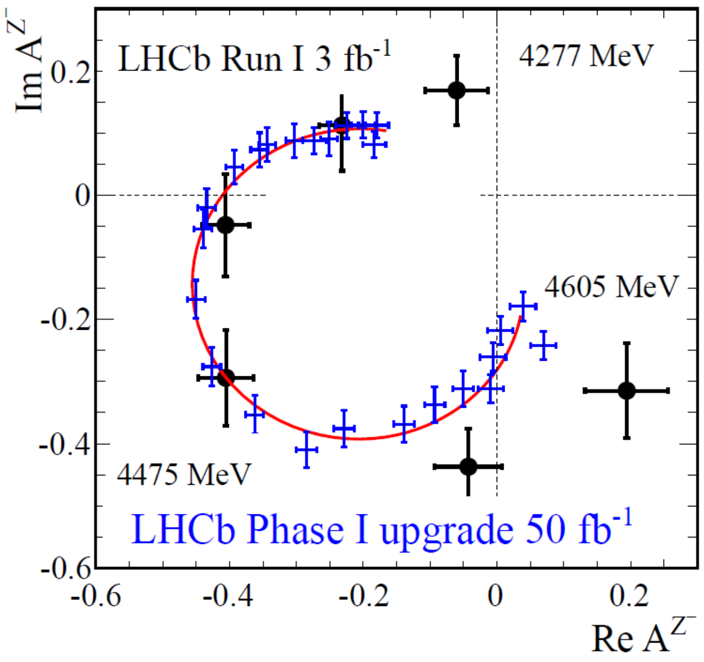
- Too broad to be molecular bound states?
- No tetraquark model can accommodate all of them.
- Rescattering effects?
- Artifacts of complicated amplitude analyses?

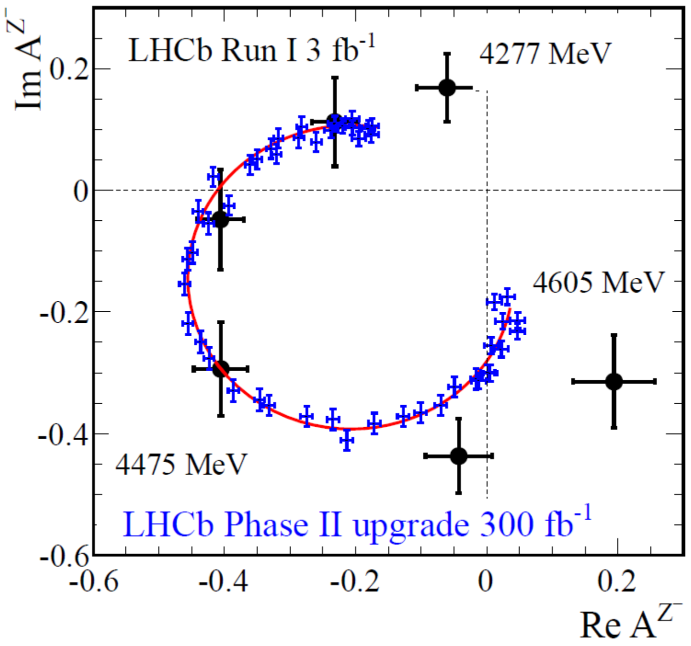
Resonant structure of Z(4430)⁻ ?

- Detailed studies of “exotic” amplitudes desired to shed light onto their nature: example Argand diagram of $Z(4430)^- \to \psi(2S)\pi^-$.

LHCb-PAPER-2014-014







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

$D^0\bar{D}^*(2S)^-$ cusp would be smeared by $\Gamma_{D^*(2600)} = 139$ MeV, and more round if produced via a triangle diagram

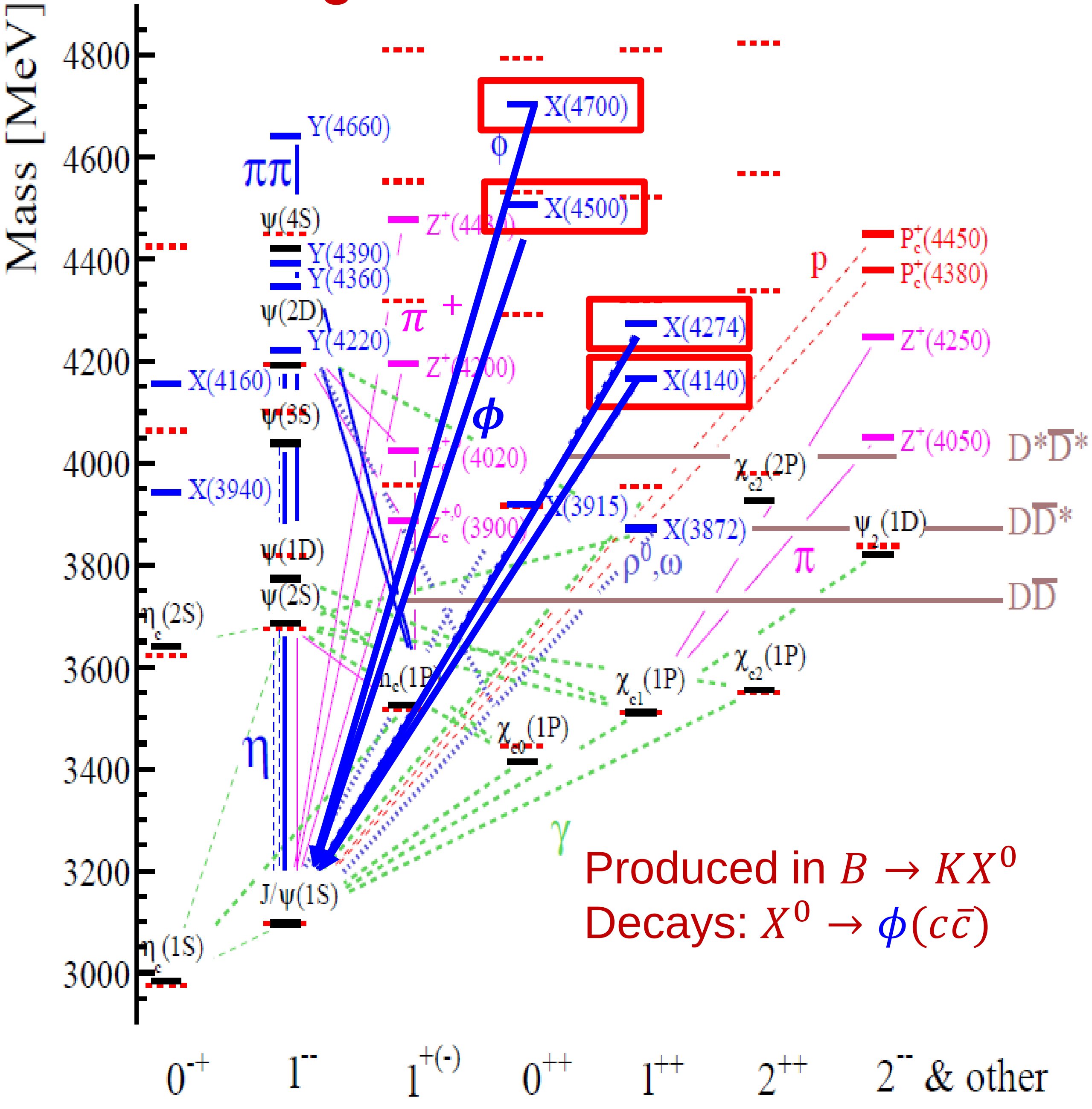
	LHCb	U.Phase I		II	Belle	II
Decay mode	3 fb⁻¹	8 fb⁻¹	50 fb⁻¹	300 fb⁻¹	0.7 ab⁻¹	50 ab⁻¹
$B^0 \to \psi(2S)\pi^-K^+$	25k	0.13M	0.8M	5M	2k	0.14M
$B^0 \to J/\psi(1S)\pi^-K^+$	0.4M	1.3M	10M	62M	30k	2M
$B^0 \to \chi_{c1}\pi^-K^+$	19k	0.1M	0.5M	3M	2.7k	0.19M

Statistical accuracy will be sufficient to distinguish between resonant poles and cusps/triangles.
Systematic errors hard to predict.
Need to scrutinize dependence on:

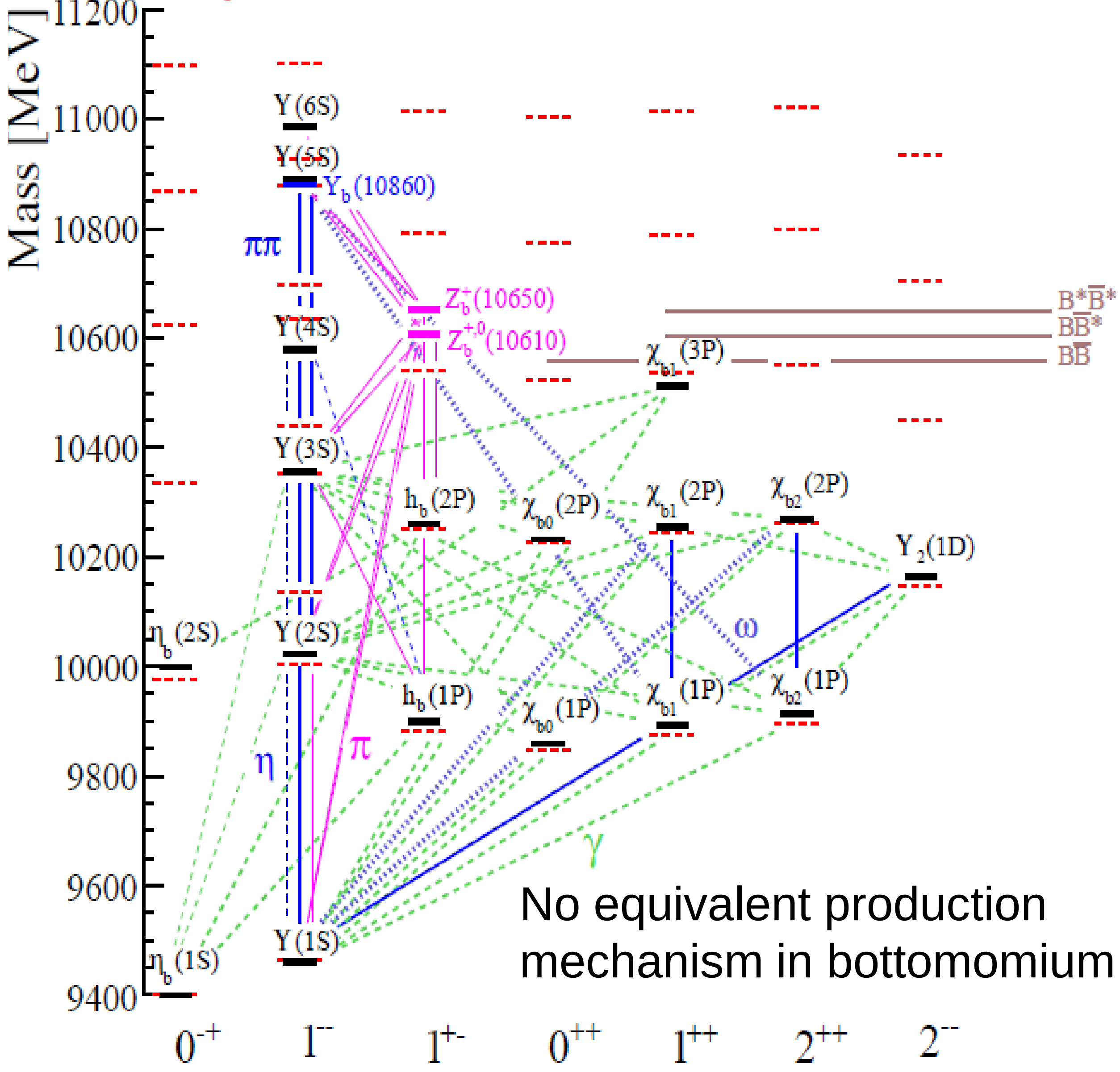
- formalism (work with JPAC; see Mikhasenko et al EPJ, C78, 229 (2018), arXiv:1712.02815)
- K* model

Huge statistics already for detailed studies of $J/\psi(1S)\pi^-$ exotics. Phase-space in $K\pi$ reaches to $K_4^*(2045)$ pole.

Charged charmonium-like states in B decays



Produced in $B \rightarrow K X^0$
Decays: $X^0 \rightarrow \phi(c\bar{c})$

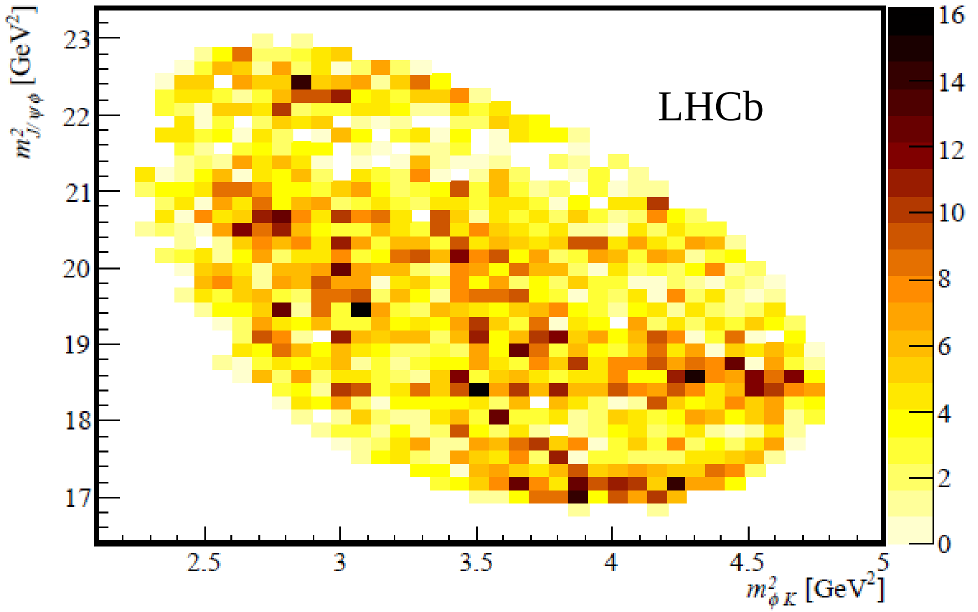


No equivalent production mechanism in bottomonium

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

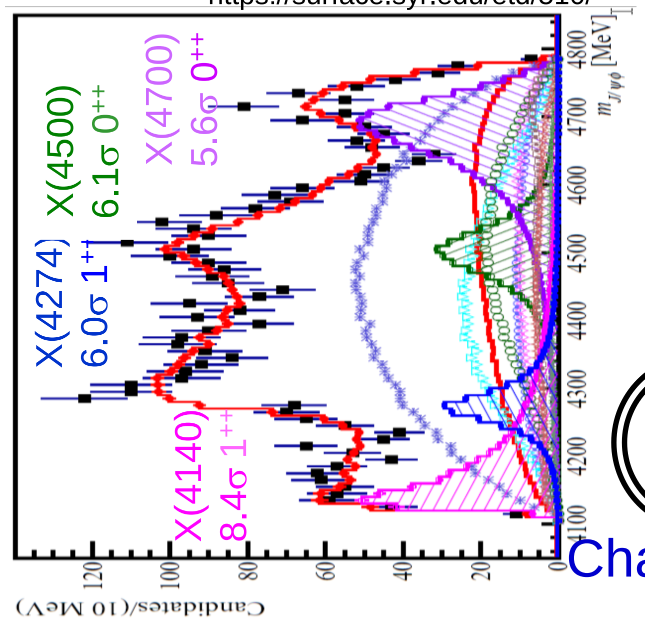
PRL118, 022003 (2017)
PR, D95, 012002 (2017)

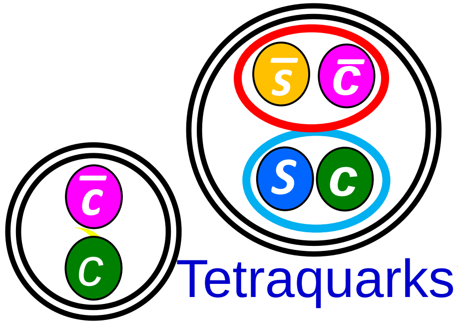
Thomas Britton, PhD, Syracuse. 2016
https://surface.syr.edu/etd/510/



X(4700)
X(4500)

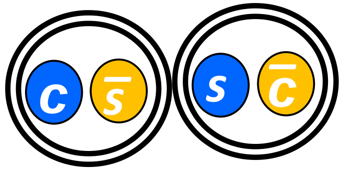
X(4274)
X(4140)
$\to J/\psi\phi$



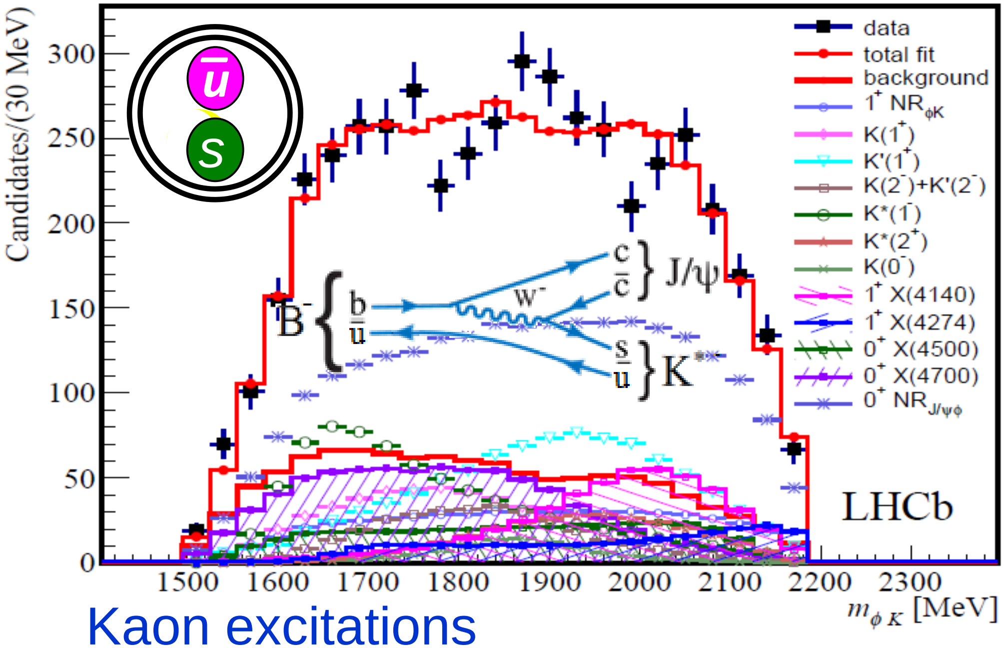


Tetraquarks?

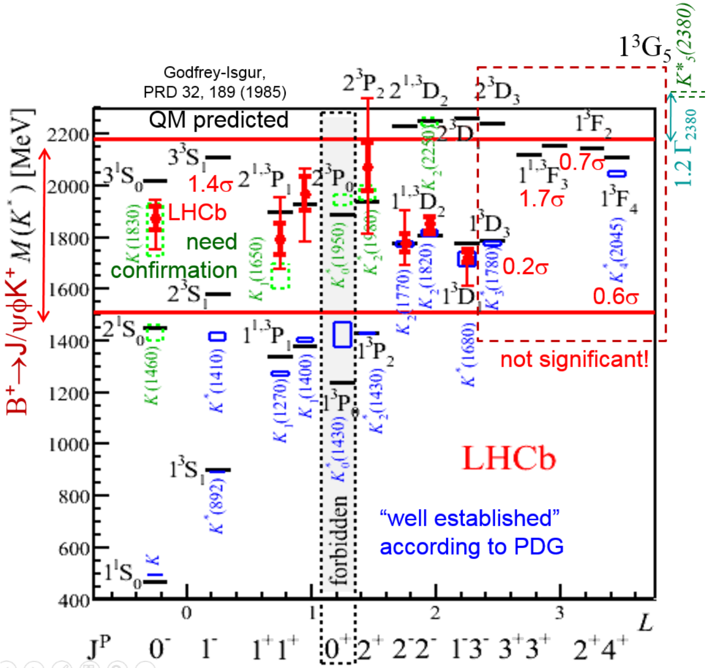
Charmonium?



Molecules or cusps?



Kaon excitations



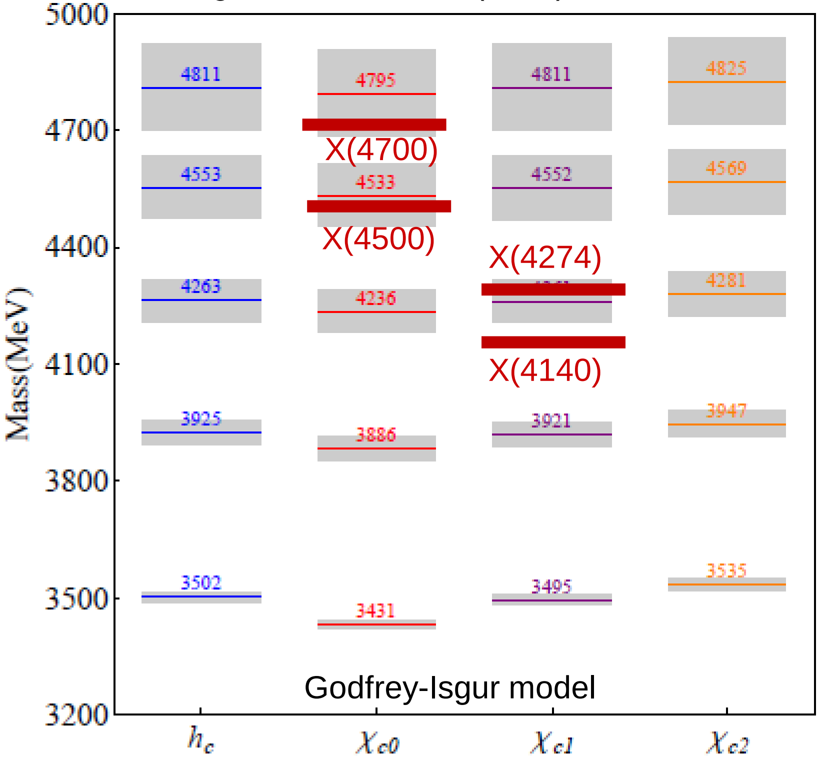
6D amplitude analysis:
since mostly not established states,
LHCb determined $K^{*+} \to \phi K^+$ content entirely from their data (red points): 6 K* resonances (of 4 different J^P) + 1 NR ϕK

Previously X(4140), X(4274) were observed by CDF,CMS and D0

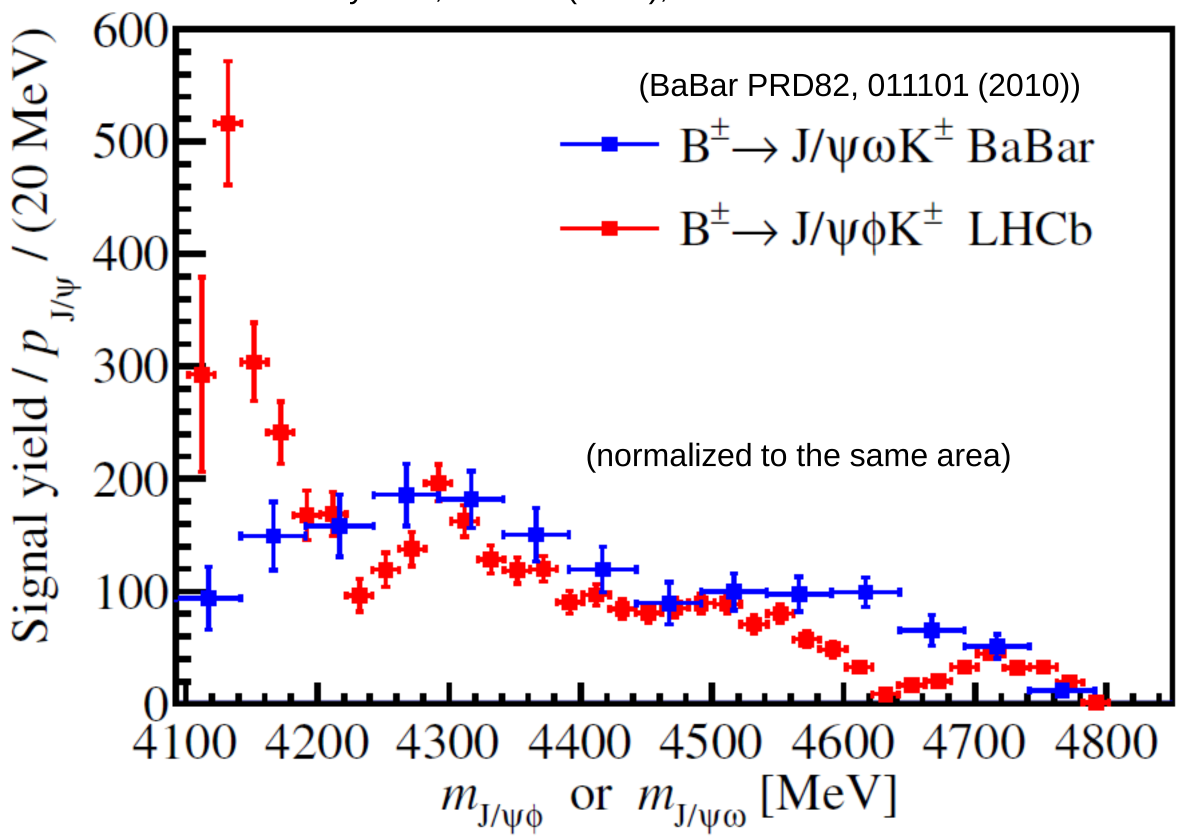
Interpretation of J/ψϕ structures?

- P-wave charmonia?

(Q-F.Lu,Y-B.,Dong PRD94, 074007 (2016) arXiv:1607.05570)



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



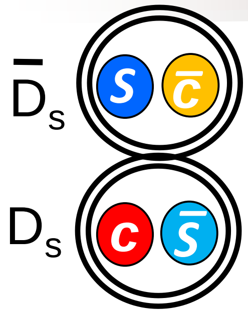
It is possible to find matching χ_{cJ}(nP) states but the J^P-mass patterns are different

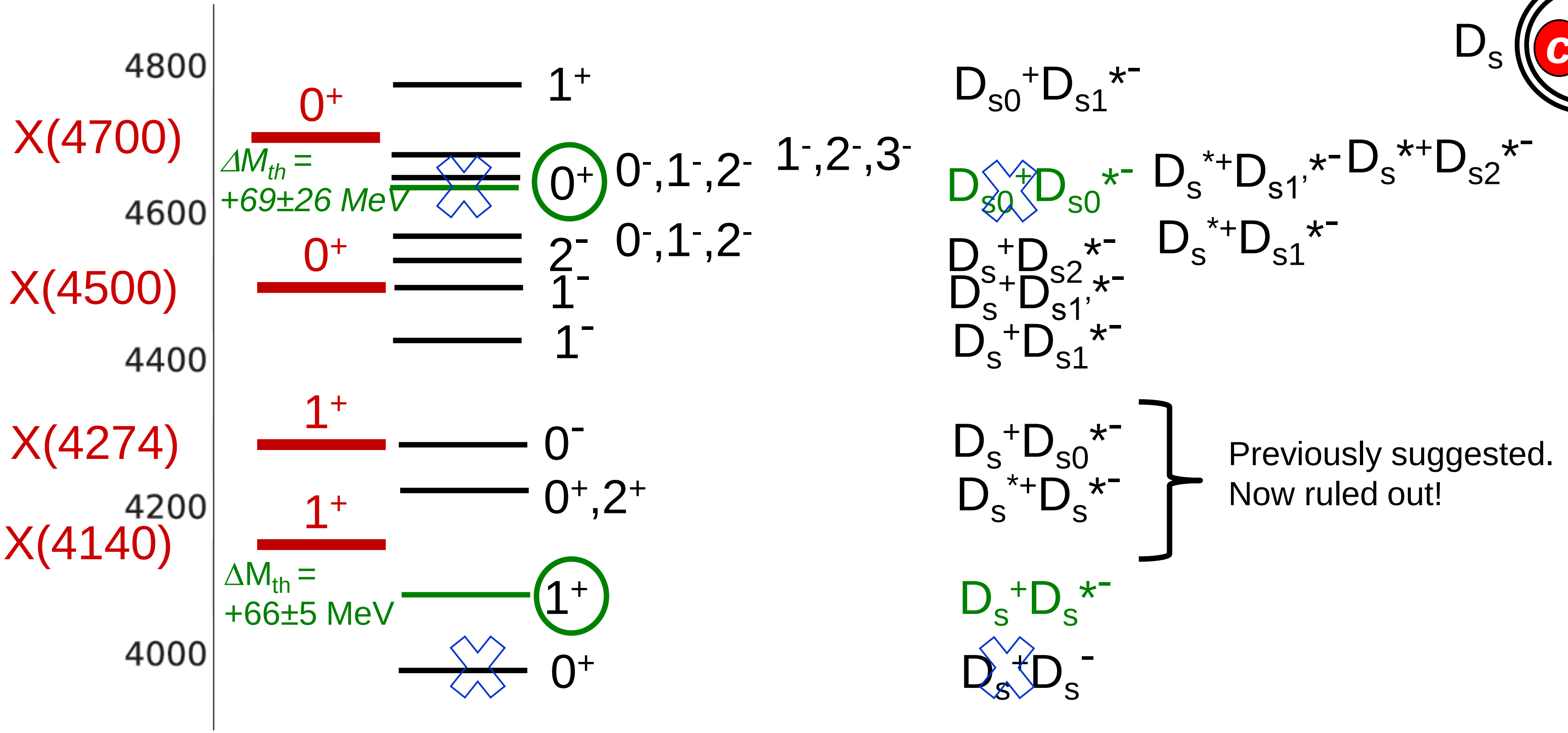
χ_{cJ}(nP) states would couple to J/ψϕ and J/ψω the same way. The J/ψϕ structures do not show up in J/ψω spectrum.

- It appears unlikely that the J/ψϕ states are pure $c\bar{c}$ states.
- Interplay of χ_{cJ}(nP) states with $(c\bar{s})(\bar{c}s)$ or $((cs)(\bar{c}\bar{s}))$?

Interpretation of J/ψϕ structures?

- A molecule/threshold effect?





No π-exchange forces (*I=0*)!

η-exchange possible, unless crossed-over (M.Karliner,J.L.Rosner **Nucl.Phys. A954 (2016) 365,** arXiv:1601.00565)

- Except for X(4140) being possibly affected by a $D_s^+D_s^{*-}$ threshold, the observed J/ψϕ structures don't fit the D_{sJ}(*)-pair mass thresholds or their quantum numbers

Interpretation of J/ψϕ structures?

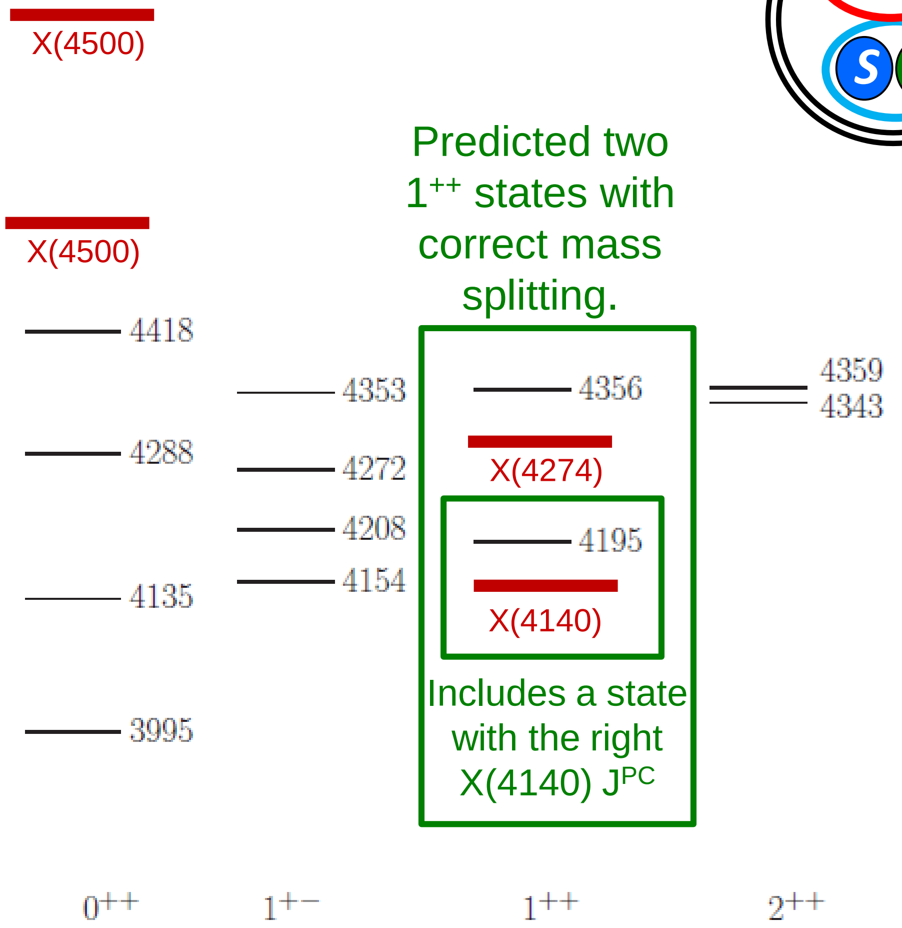
- Tetraquarks?

PREDICTION

F. Stancu,
J. Phys. G37 (2010) 075017,
arXiv:0906.2485

Allow S=0 and S=1 diquarks.
Allow diquarks in color triplet and sextet configurations.

Calculated n=0,L=0 states.



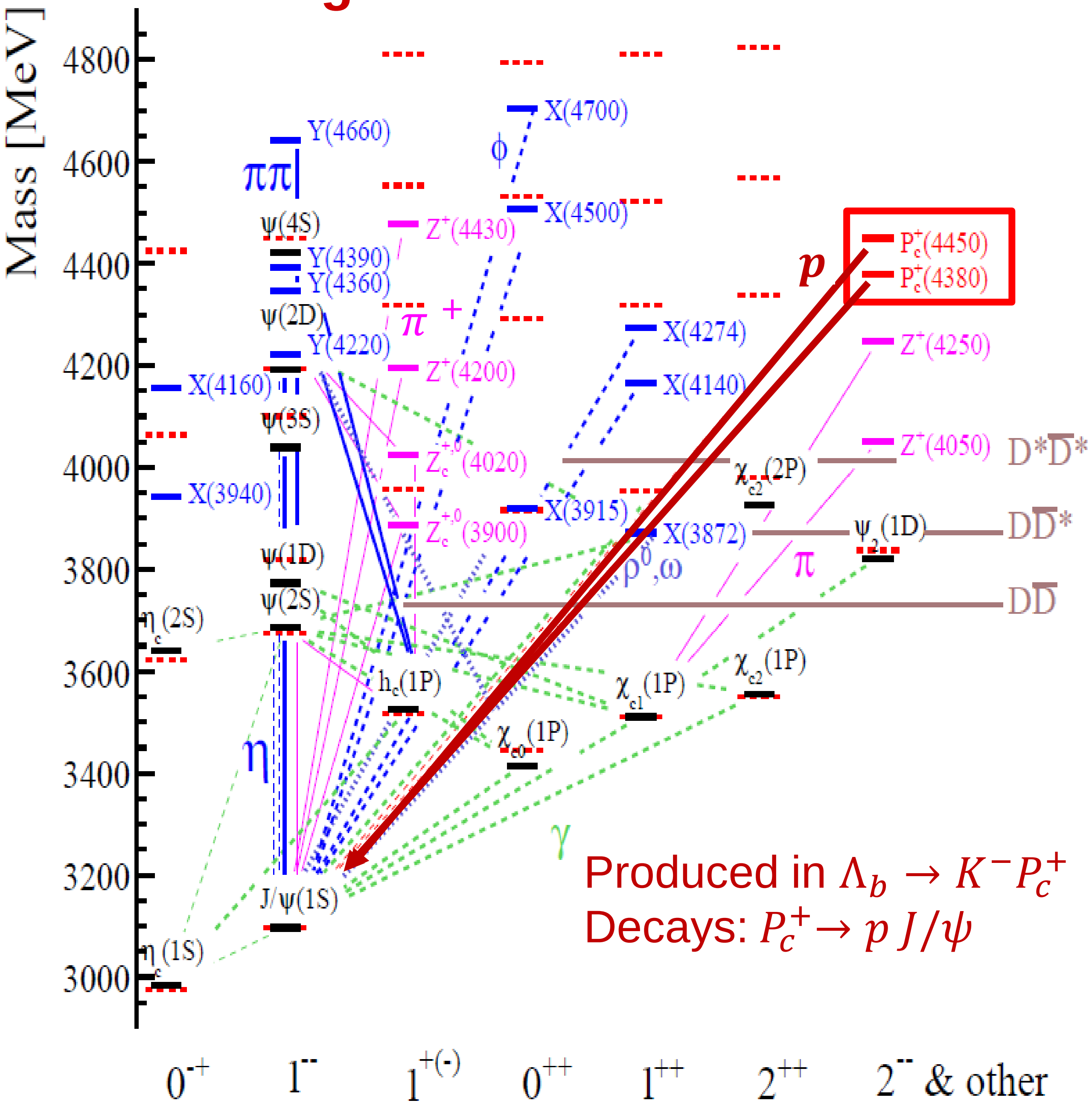
MANY MORE RECENT PAPERS

e.g. L. Maiani, A.D. Polosa, V. Riquer
PRD94, 054026 (2016) **arXiv:1607.02405**

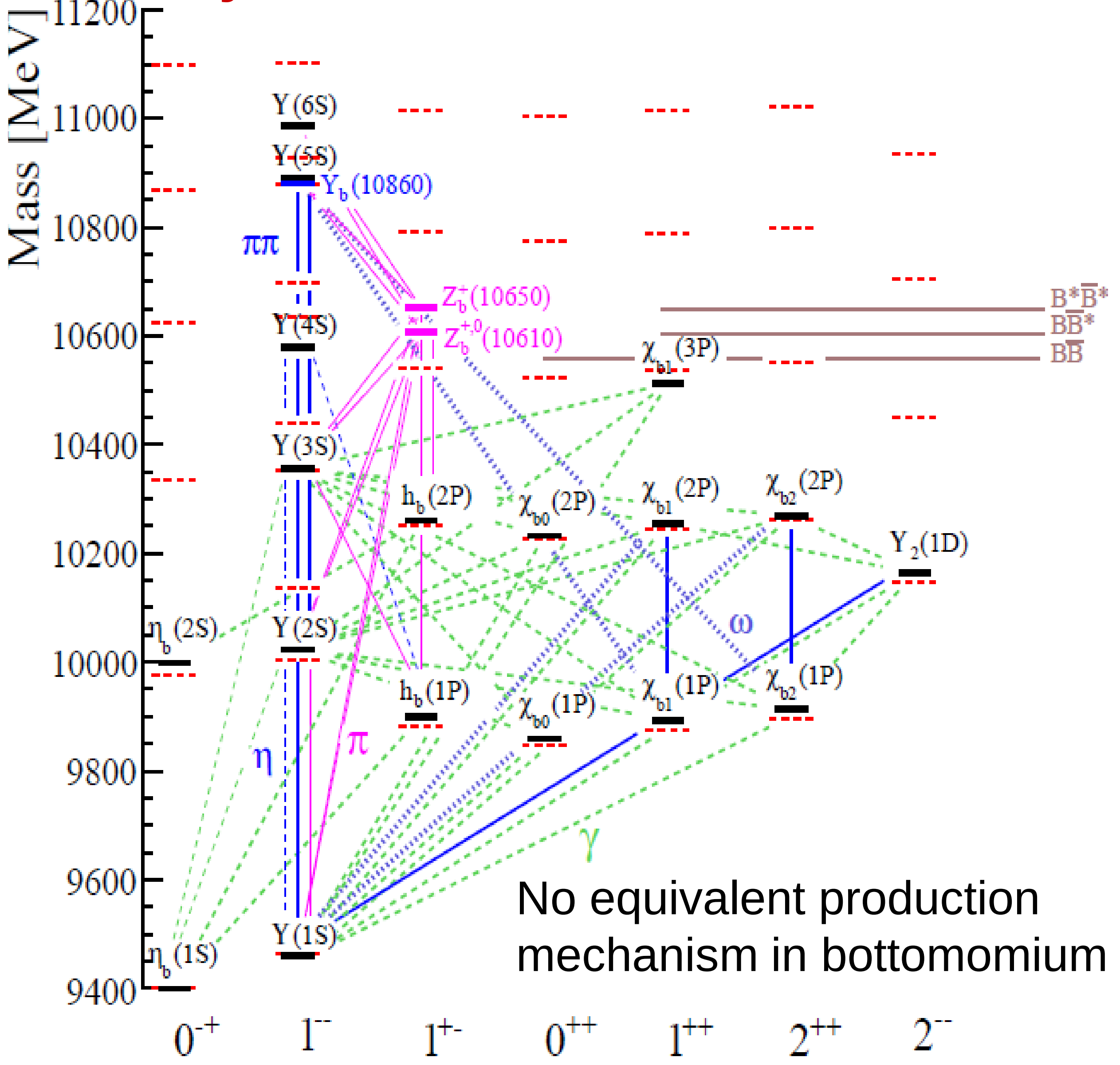
Allow diquarks only in color triplet configuration; cuts # of states in half: only one 1^{++} state.
Describe X(4500),X(4700) 0^{++} states as the radial excitations (n=1).

	LHCb		U. Phase I	II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to J/\psi\varphi K^+$	4.3k	15k	0.1M	0.6M

Charged charmonium-like states in B decays



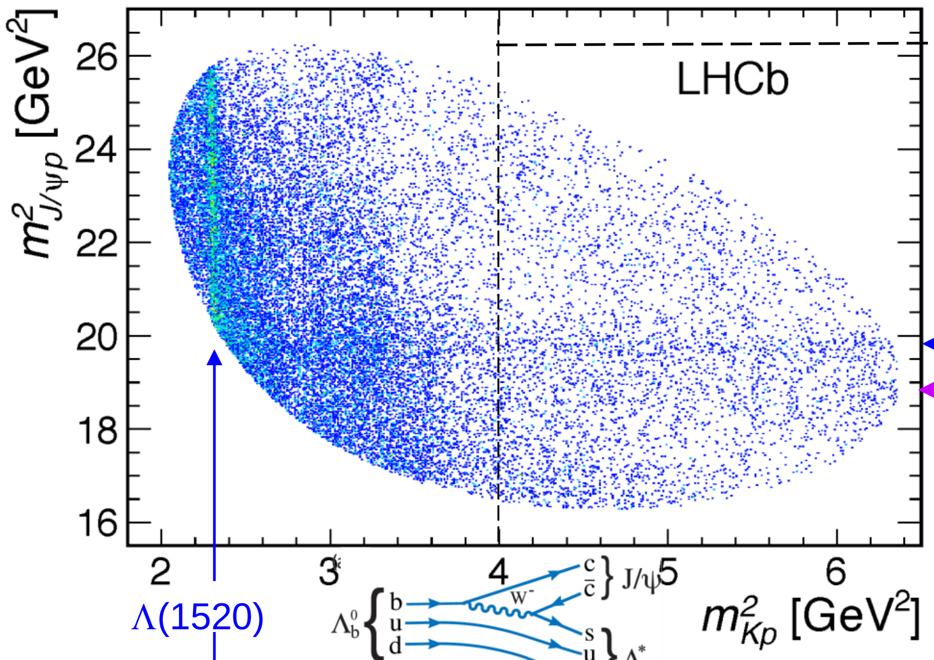
Produced in $\Lambda_b \to K^- P_c^+$
Decays: $P_c^+ \to p\, J/\psi$

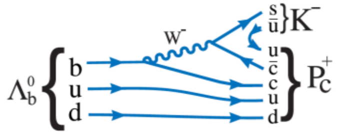


No equivalent production mechanism in bottomomium

$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected $J/\psi p$ structures

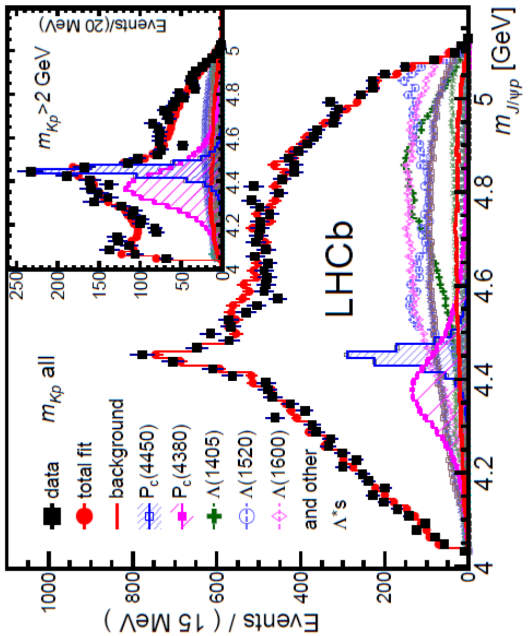
Nathan Jurik, Ph.D., Syracuse 2016
https://surface.syr.edu/etd/640/



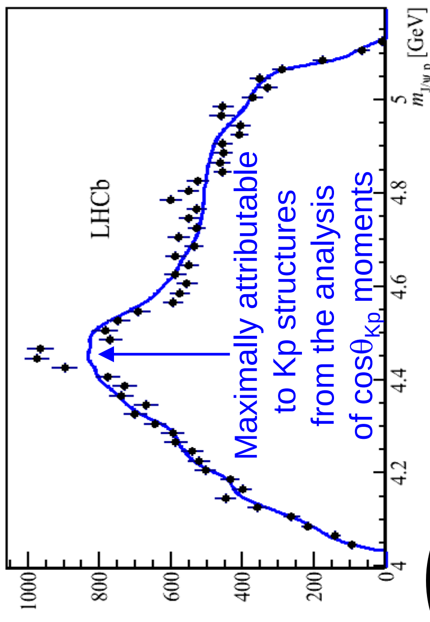


P_c^+ (4450)
P_c^+ (4380)
$\rightarrow J/\psi$ p

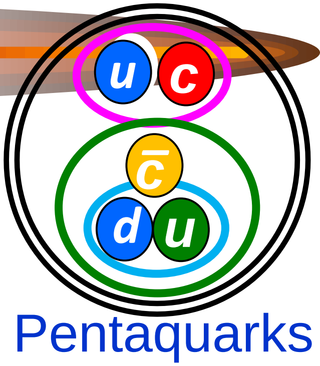
PRL 115, 072001 (2015)

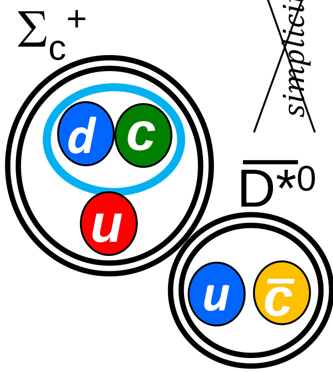


PRL 117, 082002 (2016)

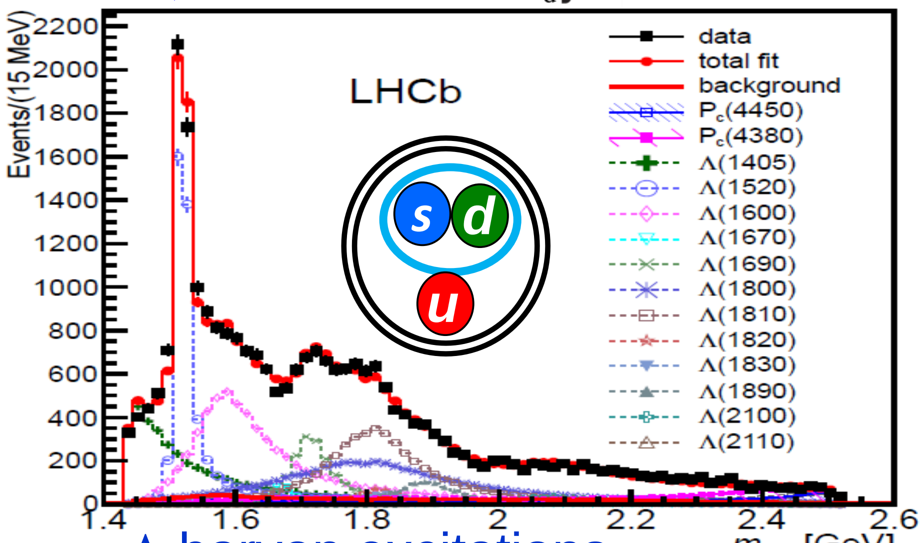


bkg-subtracted eff.-corrected yield/20 MeV

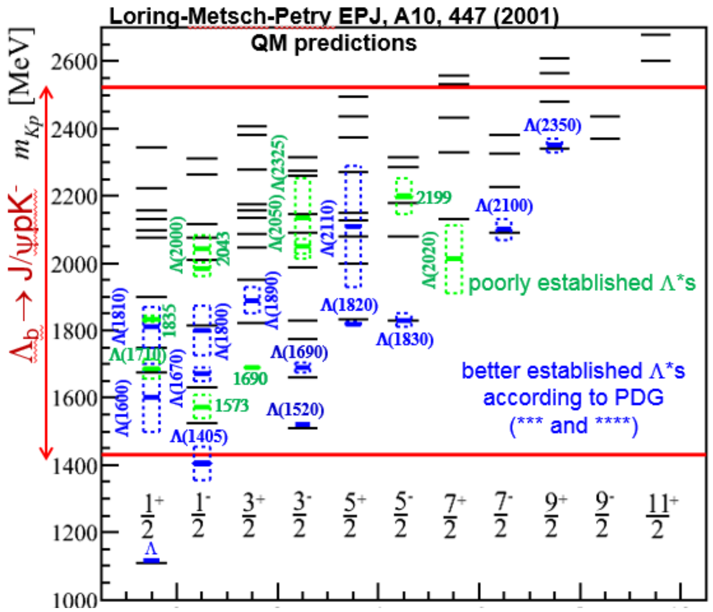




Molecules or cusps



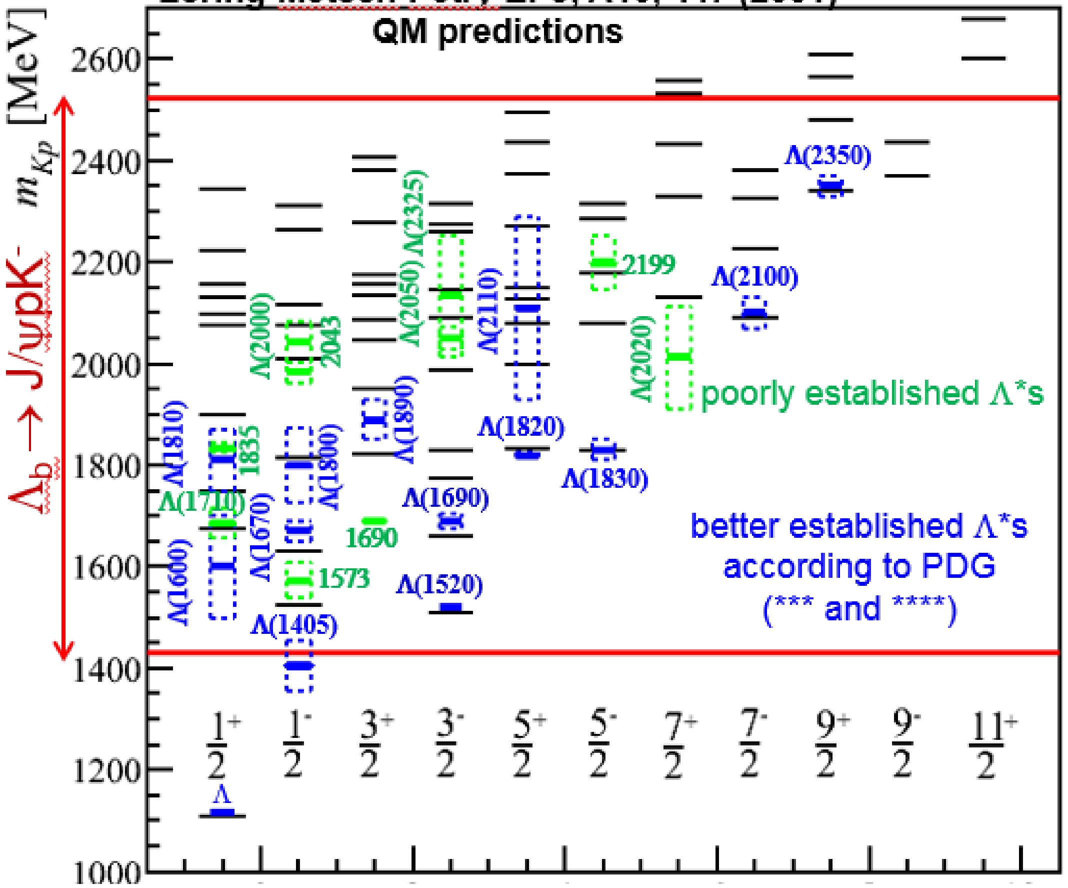
Λ baryon excitations



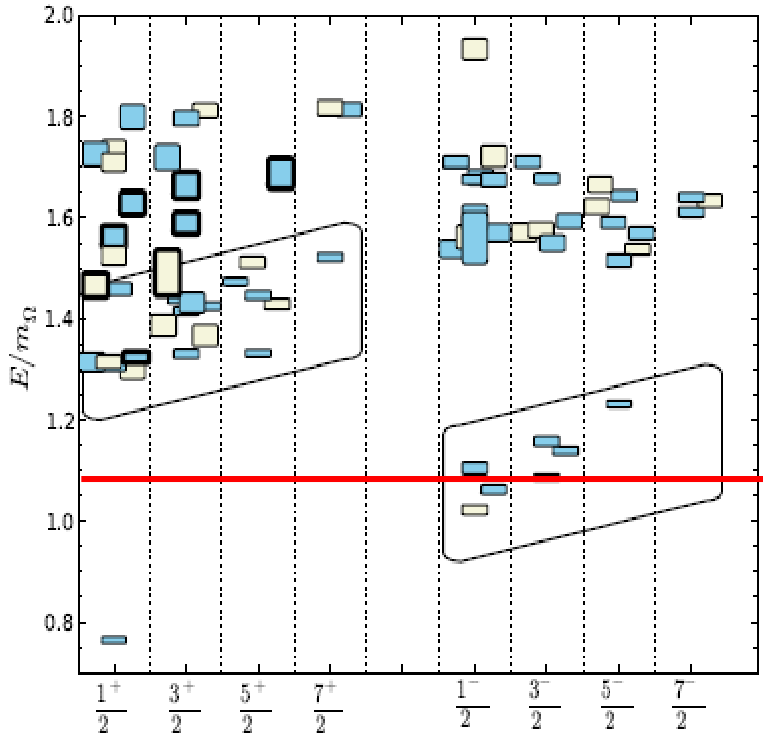
6D amplitude analysis:
13 better established Λ* states (*** and ****).
in the amplitude fit.
Over 60 expected from the quark model.

Expected complexity of Λ excitation spectrum within the mass range relevant to $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

Loring-Metsch-Petry EPJ, A10, 447 (2001)



R.G.Edwards et al (Hadron Spectrum Collab.)
PRD87 (2013) 054506
LQCD predictions

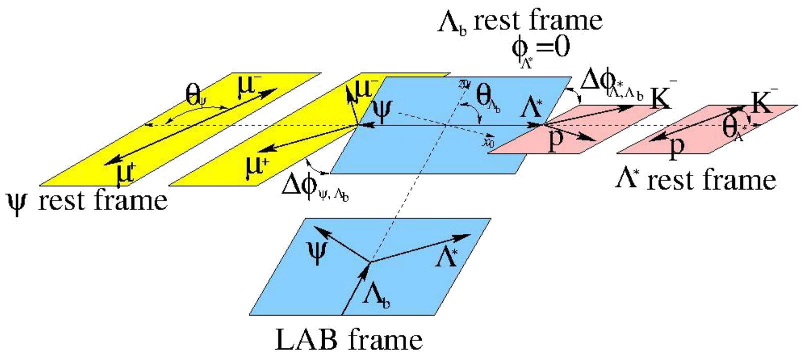


m_π=391 MeV

~57 sdu states
~7 $sdug$-rich states (hybrids)

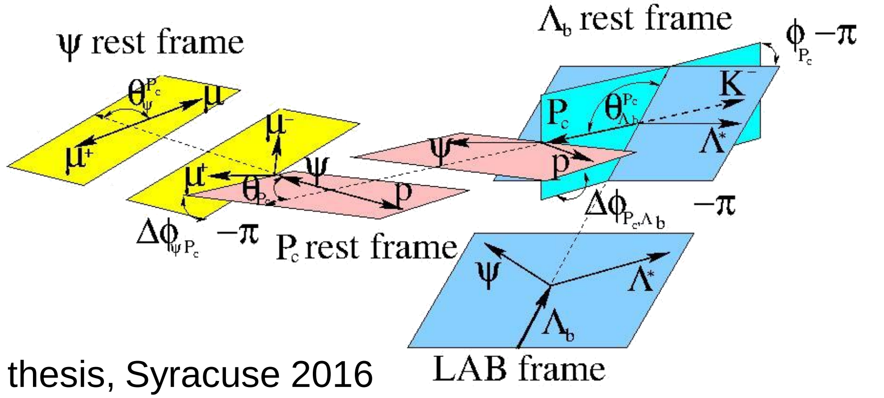
- Many overlapping states at high mass. Widths and couplings to pK not well predicted.

Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$



6D maximum likelihood fit

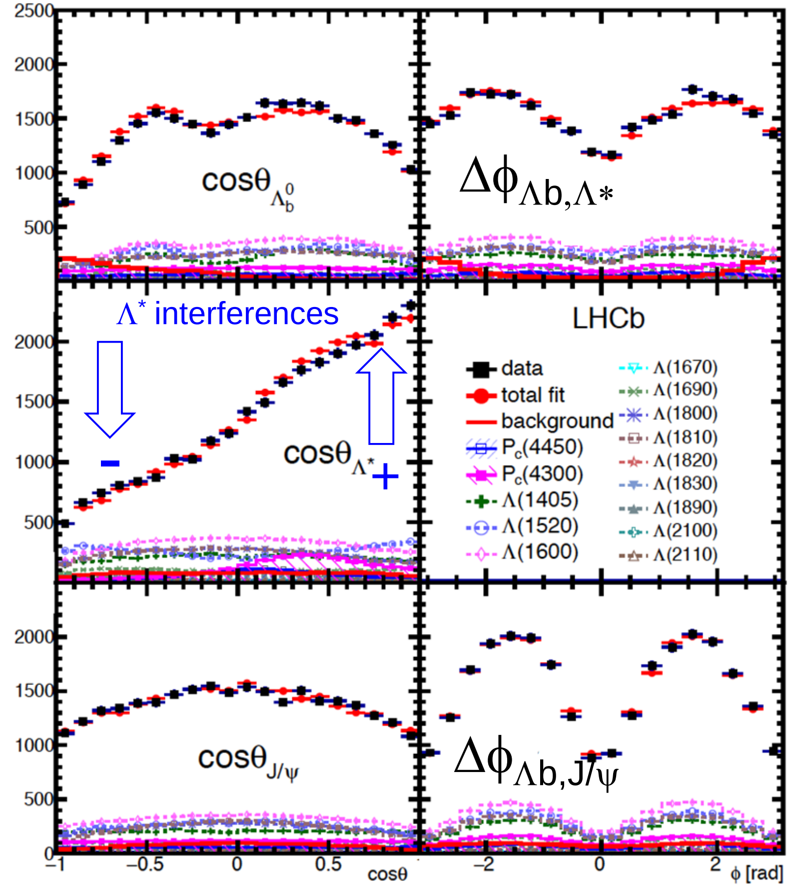
$$(m_{pK}^2, m_{\psi p}^2, \theta_\psi, \varphi_\psi, \theta_\Lambda, \varphi_\Lambda)$$



All fit displays with

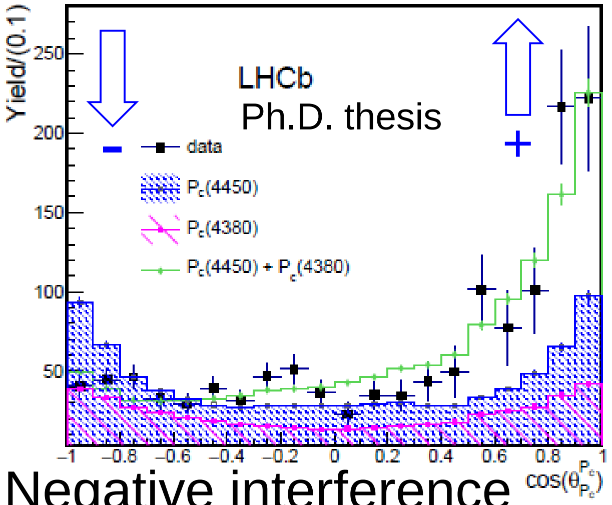
$J^P = \frac{3}{2}^-$ for $P_c(4380)^+$

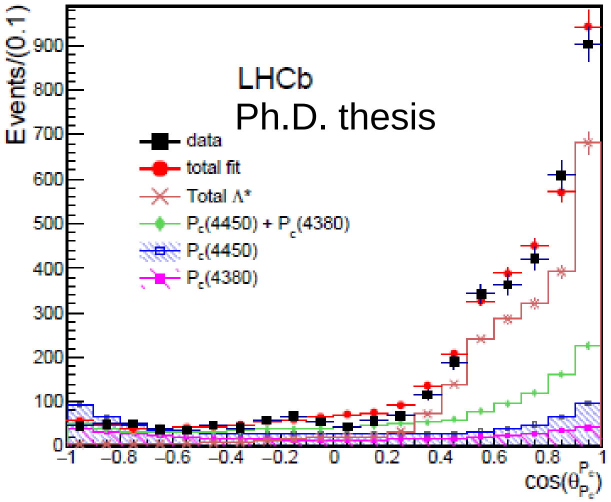
$J^P = \frac{5}{2}^+$ for $P_c(4450)^+$



Nathan Jurik, Ph.D. thesis, Syracuse 2016

$$|m_{J/\psi p} - m_{Pc(4450)}| < \Gamma_{Pc(4450)}$$





Negative interference between the P_c states

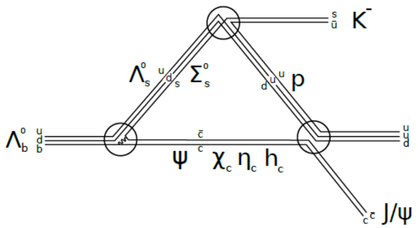
Requires two P_c states of opposite parity

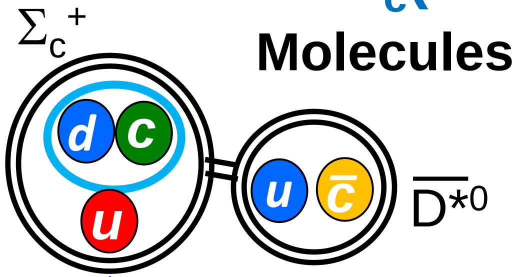
Subtraction of Λ^* contributions peaking at large $\cos\theta_{Pc}$

Source of ambiguities in J^P determination of P_cs.

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

Molecules

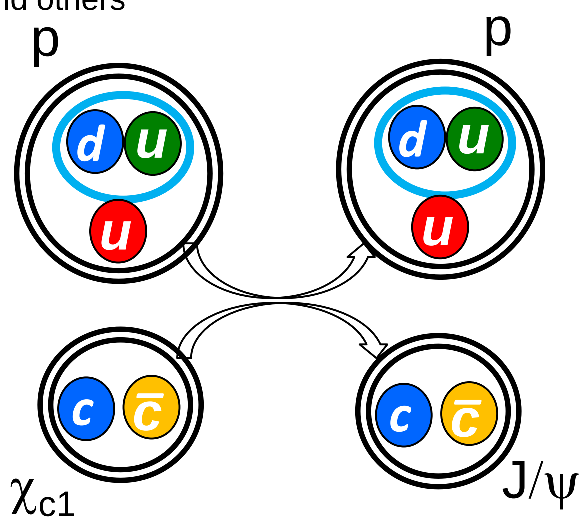




No $\frac{5}{2}^{\pm}$ molecules in this mass range with reasonable values of binding energies

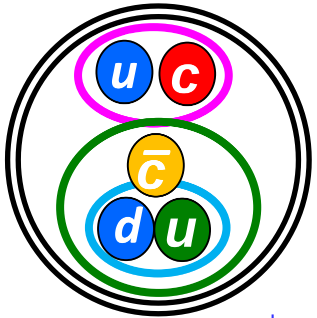
Szczepaniak PL,B747, 410 (2015)
Guo,Meissner et al PRD92, 071502 (2015)
Mikhasenko arXiv:1507.06552
and others

Karliner,Rosner PRL115,122001(2015) and others



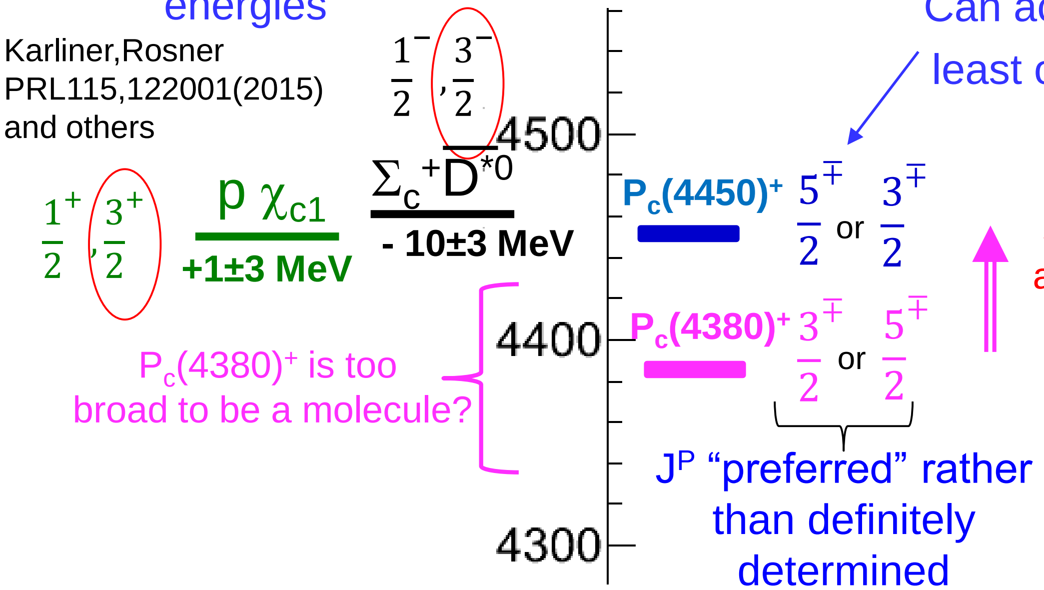
Realistic **rescattering mechanisms (cusps, triangle anomalies)** have the same J^P selection rules as realistic molecular models (must happen in S-wave)

Tightly-bound penatquark



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

Maiani et al PLB749, 289 (2015);
Ali et al PRD94, 054001 (2016);
and others



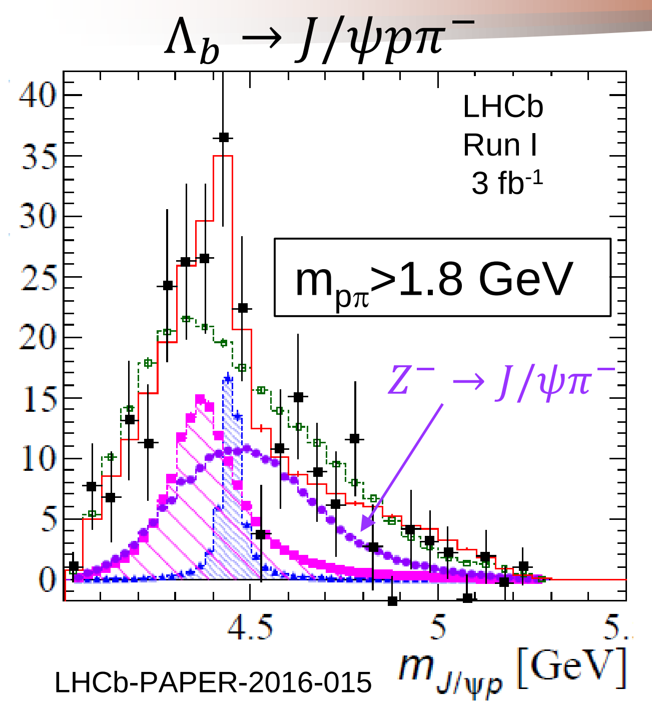
It is crucial to determine J^Ps!

Need more robust verifications of resonant hypothesis.

Both require better understanding of $\Lambda \to pK$ contributions (work in progress in collaboration with JPAC)

	LHCb		U. Phase I	II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \to J/\psi p K^-$	25k	0.13M	0.8M	5M

Other channels related to $P_c(4450)^+$,$P_c(4380)^+$



LHCb-PAPER-2016-015

	LHCb		U. Phase I	II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \to J/\psi pK^-$	26k	0.13M	0.8M	5M
$\Lambda_b \to J/\psi p\pi^-$	1.9k	10k	63k	0.4M
$\Lambda_b \to \chi_{c1} pK^-$	0.45k	2.2k	15k	0.1M

$\Lambda_b \to J/\psi pK_s^0\pi^-$

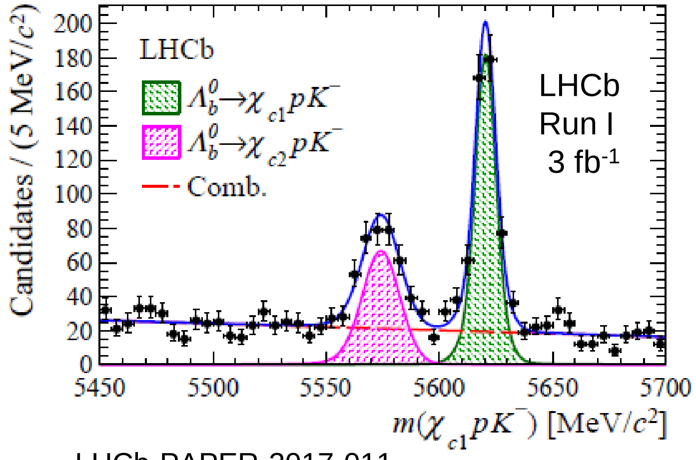
$\Lambda_b \to J/\psi p\bar{p}$

…

Hints of $J/\psi p$ structure; complicated by ambiguities with $Z^- \to J/\psi\pi^-$

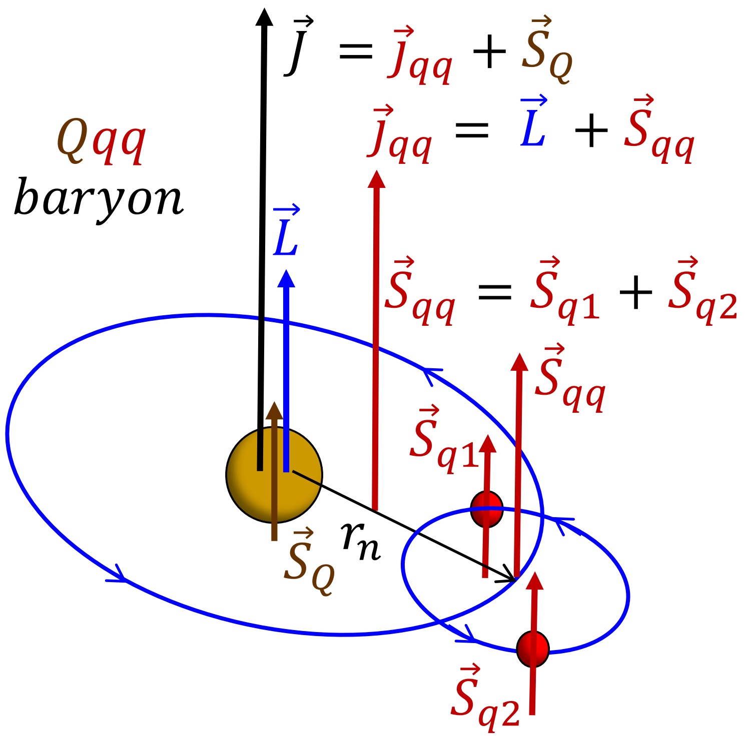
A coupled-channel to $J/\psi p$. The $\chi_{c1}p$ mass threshold near $P_c(4450)^+$.

Upgrade statistics will allow for amplitude analyses of sensitivity comparable (much better) than in the discovery paper



LHCb-PAPER-2017-011

Heavy-light-light baryons



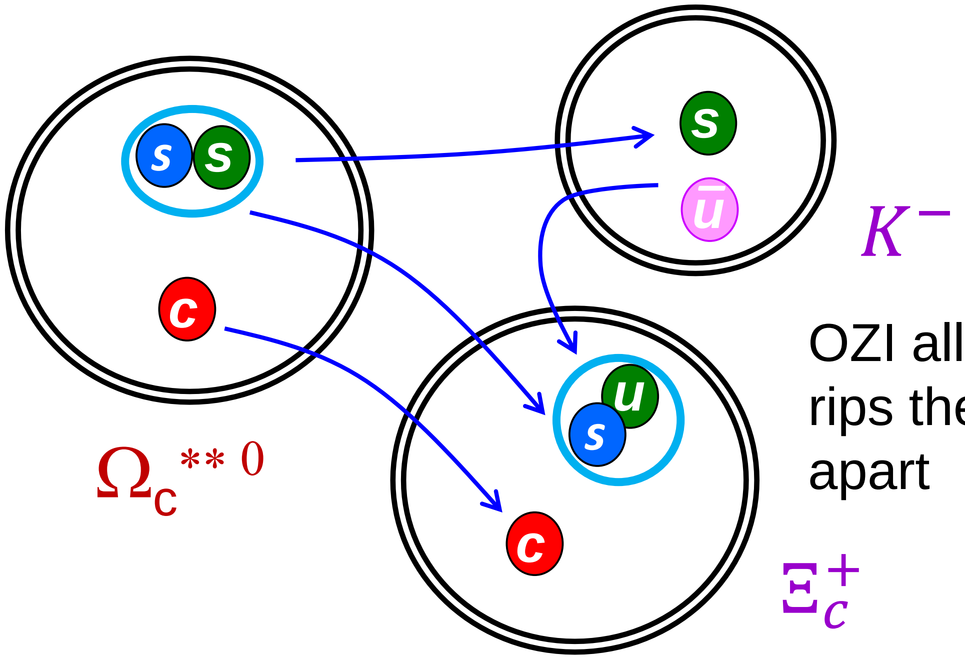
In usual diaquark model: n_{qq} =1 $\vec{L}_{qq}=0$

$S_{qq}=0,1$

Scalar and axial-vector diquarks

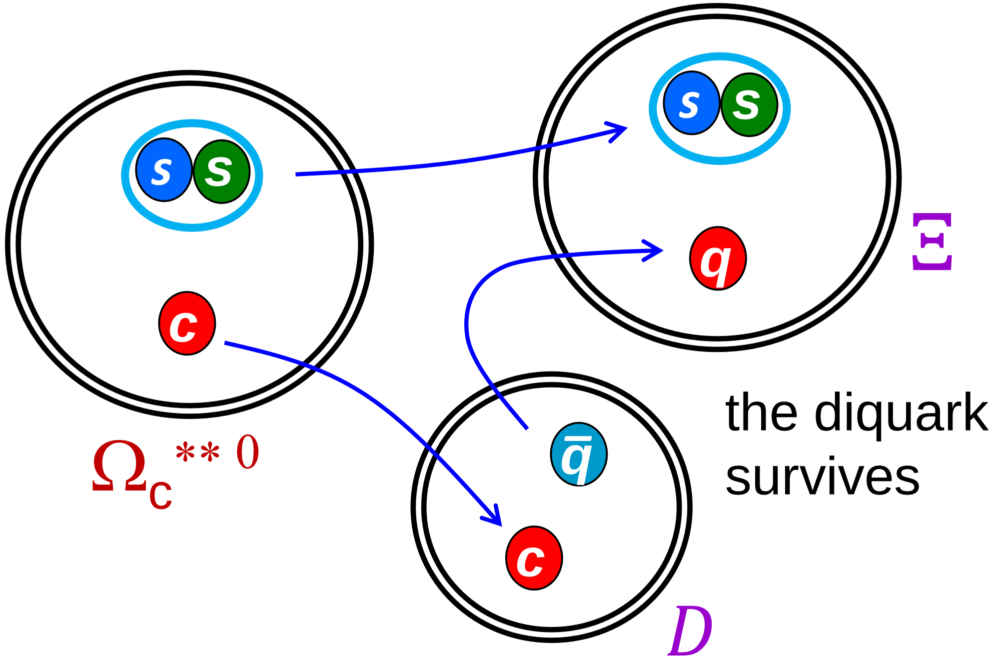
- Qqq baryons are a perfect place to study diquark structures as the heavy quark spin decouples from light quark spins
- QCD motivated diquarks need to be in the ground state, $n_{qq}=1$, $L_{qq}=0$,which eliminates a large number of possible excitations:
  - States can be labeled with ***n,L*** of the 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 Ω_c^{**0} states observed by LHCb are narrow?



OZI allowed but rips the diquark apart

ΞD threshold



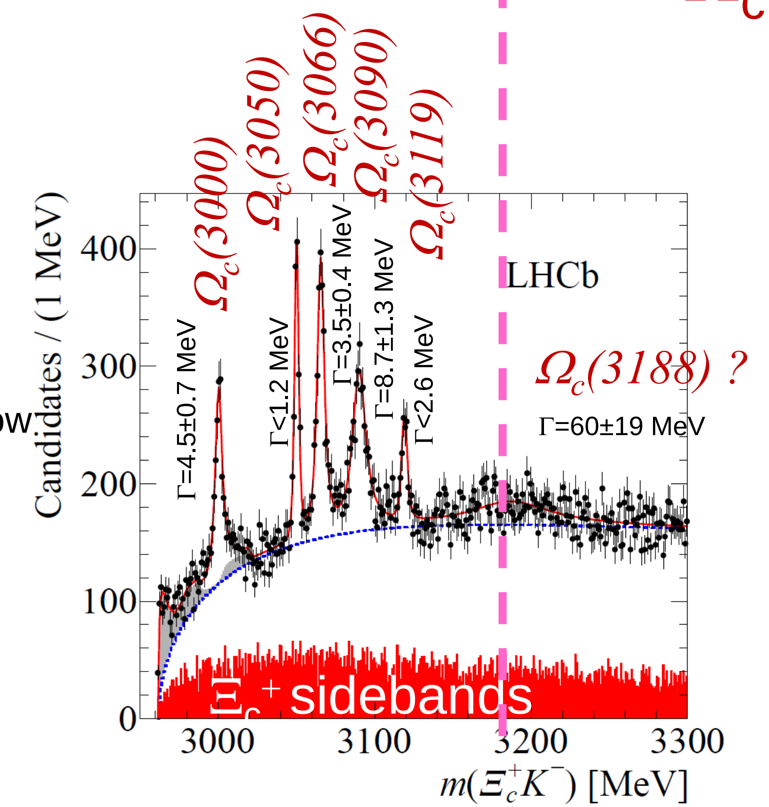
the diquark survives

LHCb PRL 118, 182001 (2017).

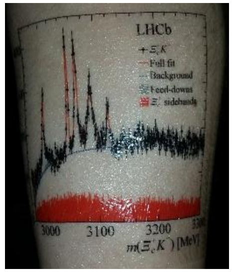
$\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$

(Strong decay)

Significance of each of the narrow resonances > 10σ



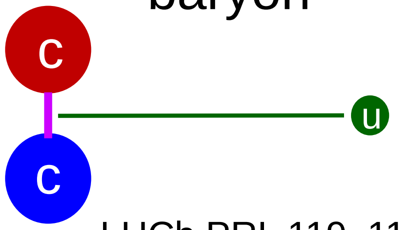
The narrow states observed by LHCb are likely 1P and 2S of c-(ss diaquark)



Tattooed on a forearm of LHCb grad student

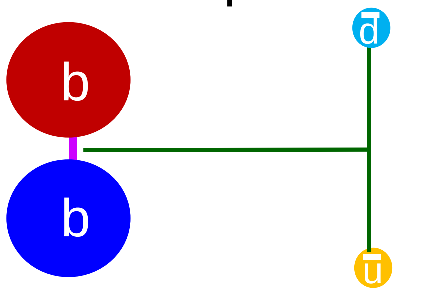
Doubly-flavored tetraquarks

baryon

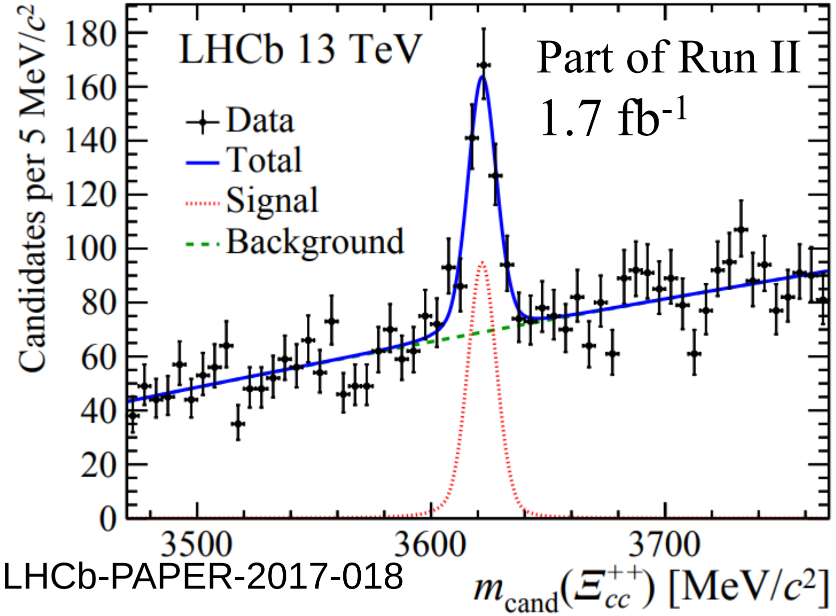


Replace the light quark with light anti-diquark in color triplet configuration

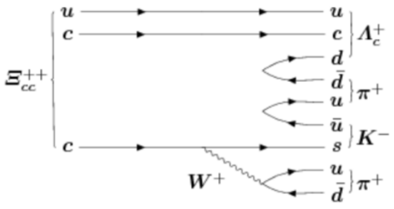
tetraquark



LHCb PRL 119, 112001 (2017)

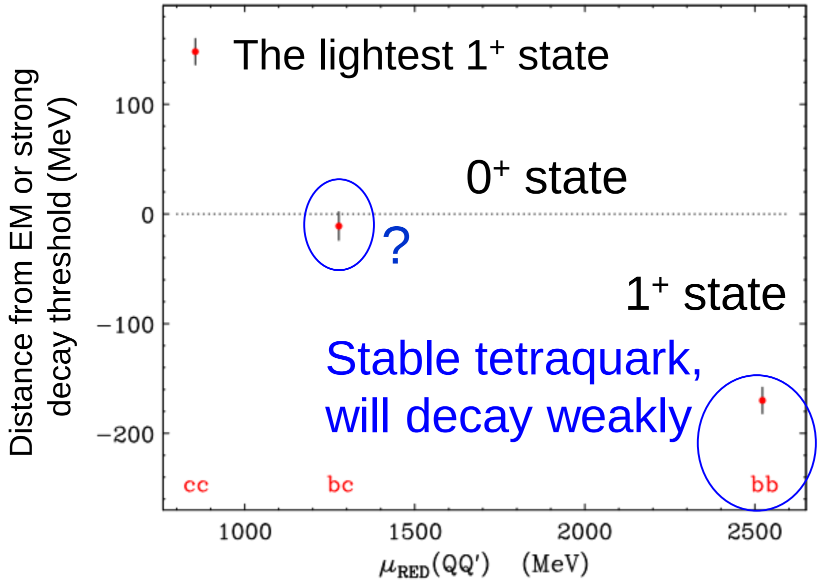


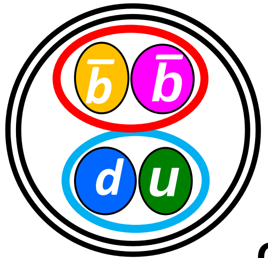
LHCb-PAPER-2017-018



$\Lambda_c^+ \to pK^-\pi^+$

the same toolkit





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

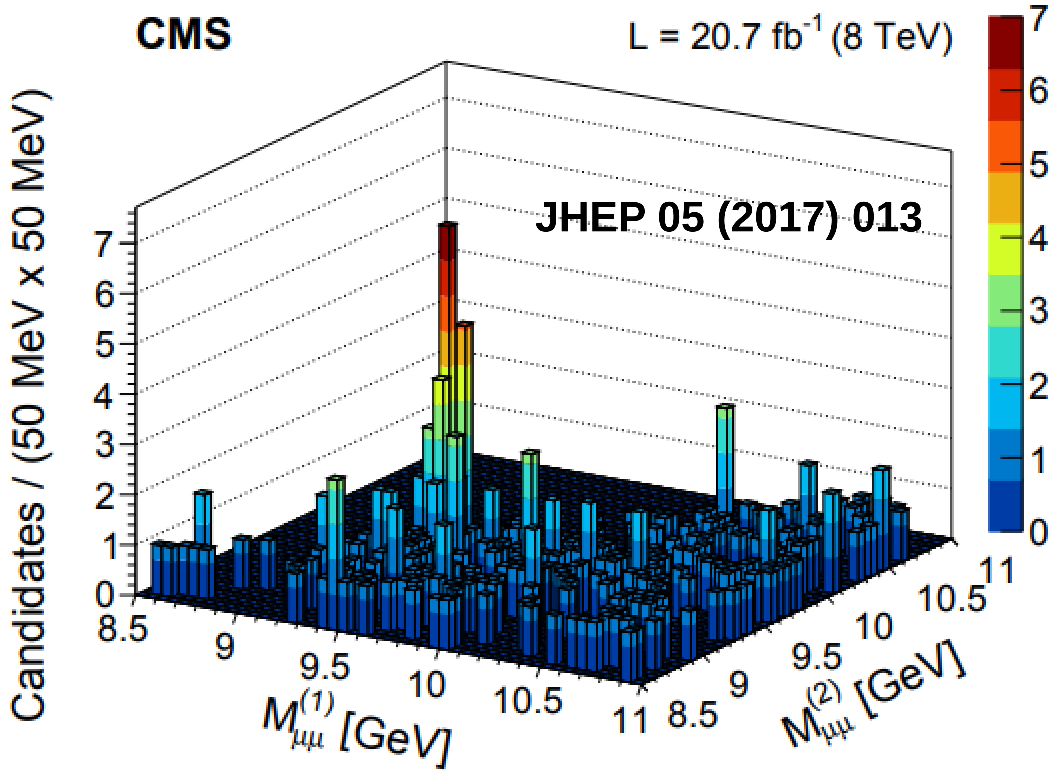
Karliner,Rosner PRL 119, 202001 (2017)

See also:

Eighten, Quigg PRL 119, 202002 (2017);
Esposito,Papinutto,Pilloni,Polosa,Tantalo PRD88, 054029 (2013); and others

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

Observation of double Y production at LHC



- First observation of $b\bar{b}+b\bar{b}$ production at LHC. An example, where high luminosity of CMS, and central region coverage, won over lower muon momentum thresholds in forward region at LHCb.
- bb not in the same hadron yet.
- Can look for $(bb)(\bar{b}\bar{b})$ tetraquark in decays to Υ(1S)Υ(1S) – some predicted it to be narrow.
- In stable teraquark need to look for $b \to cW$ decay. Look out for observations of bbq baryons, as signs of reaching sensitivity to detect $(bb)(\overline{ud})$. It will be hard to detect it even at LHCb Phase II upgrade. A better chance to detect $(bc)(\overline{ud})$ if stable or narrow (thousands of $(b\bar{c})$ mesons have been already detected at LHC).

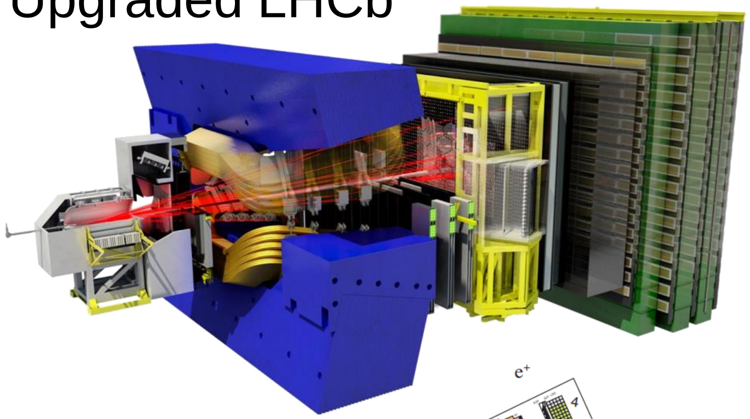
Summary

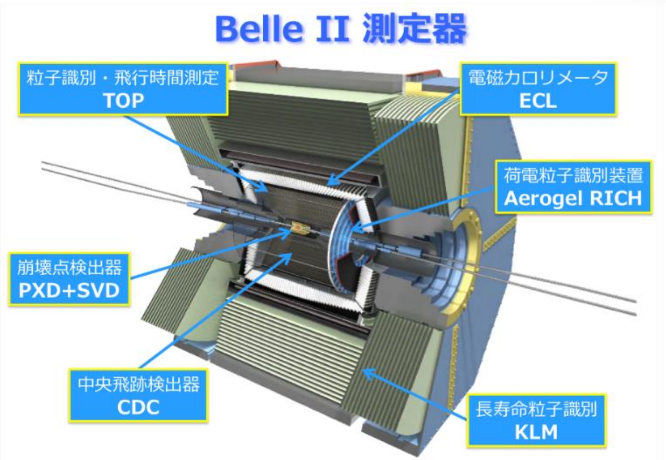
- New particle zoo for heavy quarkonia families above flavor threshold signals the crisis of the "textbook" quark model ($q\bar{q}$, qqq).
- It sheds doubts at our view of light hadron spectroscopy as well (all excitations are above "flavor threshold" for light hadrons). Perhaps experimental efforts 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 $e^+e^- \rightarrow \pi^{\pm,0}Z^{\mp,0}$ decaying to both $\pi^{\pm,0}(c\bar{c})$ and related meson-antimeson pairs
  - Collection of $Z_c^{\pm}$ produced only in $B \rightarrow Z_c^- K$ 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. $X(3915) \rightarrow \omega J/\psi$
- It is possible that more than one dynamical effect is responsible for their existence/properties.
- 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

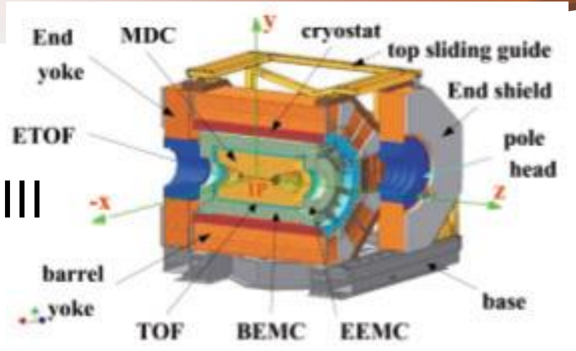
- Need more data to make further progress
- More data are forthcoming!

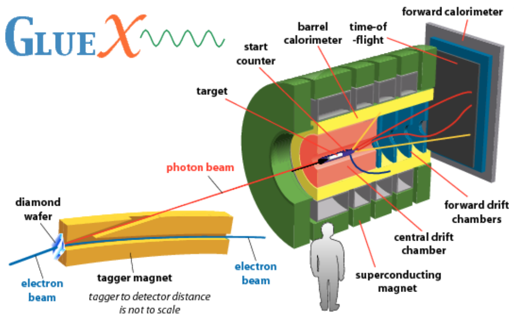
Upgraded LHCb

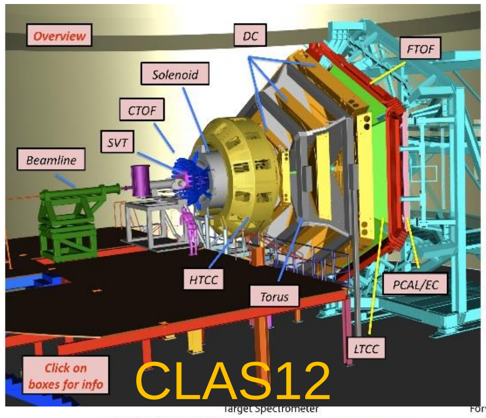




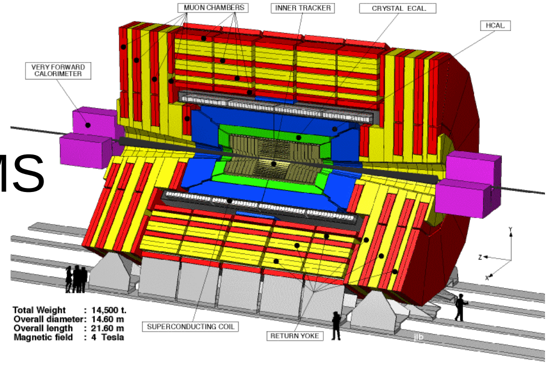
BES III

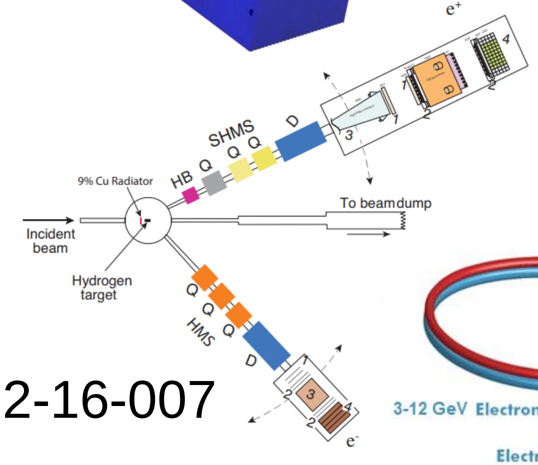






CMS





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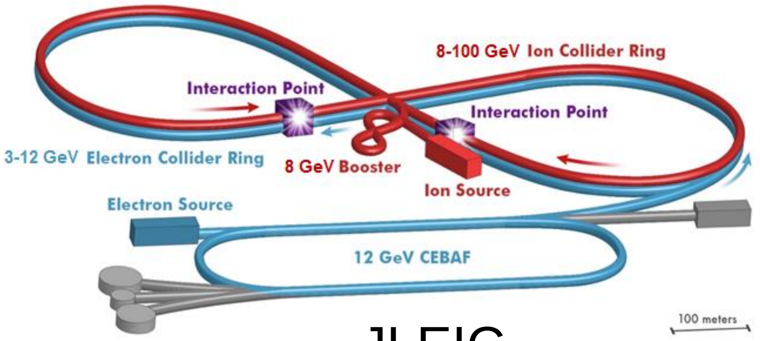
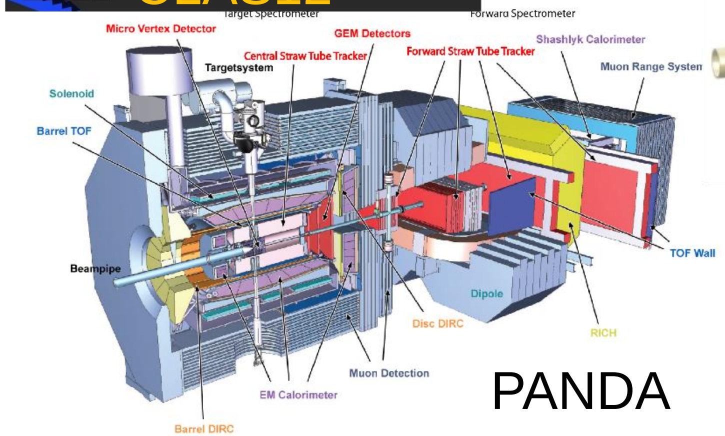
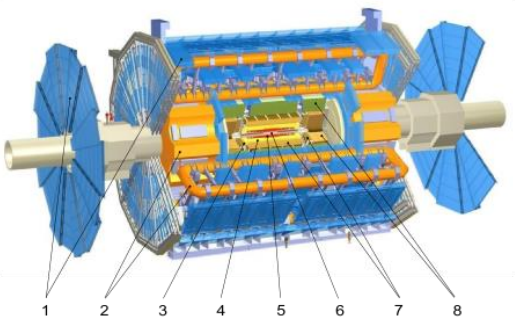


JLEIC



PANDA



ATLAS

and other…

END

LHCb data samples: present & future

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
LHCb Int. Lumi.	3 fb^{-1}	8 fb^{-1}	⟶	50 fb^{-1}	*300 fb^{-1}
Inst. Lumi.	4×10^{32} $cm^{-2}s^{-1}$		2×10^{33} $cm^{-2}s^{-1}$		2×10^{34} $cm^{-2}s^{-1}$

upgrade in preparation

anticipated upgrade

present results

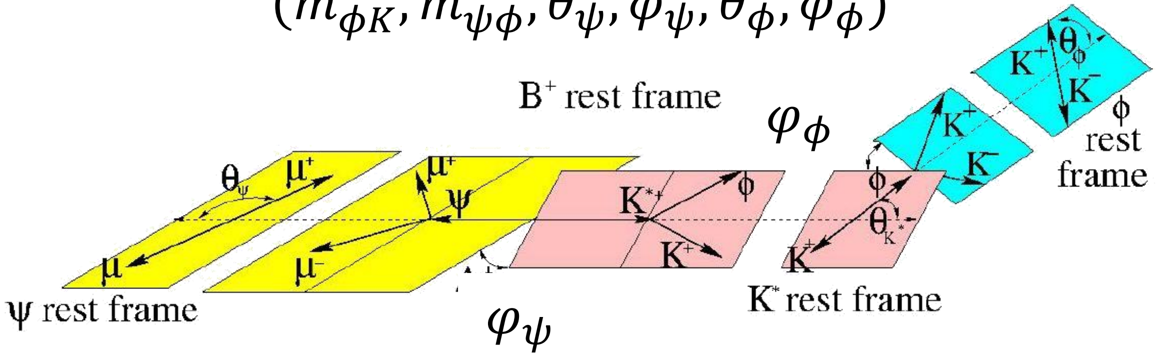
The main mission of the experiment is to look for New Physics indirectly (in quantum loops affecting rare decays and CP asymmetries). As prospects for NP in direct searches at LHC diminish, the importance of indirect probes grows.

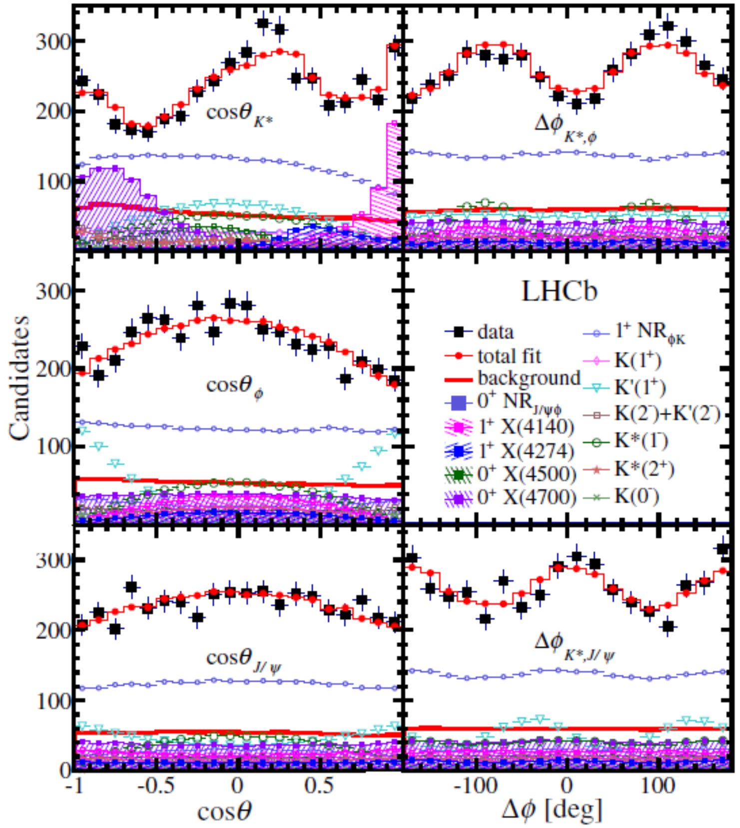
Broad supplementary program in LHCb, including hadron spectroscopy.

Amplitude analysis of $B^+ \to J/\psi\phi K^+$, $\phi \to K^+K^-$

6D maximum likelihood fit

$$(m^2_{\phi K}, m^2_{\psi\phi}, \theta_\psi, \varphi_\psi, \theta_\phi, \varphi_\phi)$$





The inclusion of all decay angles in the amplitude fit, allowed resolution of various $K\phi$ partial waves, and led to a firm determination of J^{PC} of $J/\psi\phi$ resonances:

X(4140): 1^{++} determined at 5.7σ

X(4274): 1^{++} determined at 5.8σ

X(4500): 0^{++} determined at 4.0σ,

X(4700): 0^{++} determined at 4.5σ