Exotic Hadrons with Heavy Quarks: Experimental Perspective

Tomasz Skwarnicki

Syracuse University, NY, USA

XXIV International Baldin Seminar on High Energy Physics Problems

Relativistic Nuclear Physics & Quantum Chromodynamics

September 17 - 22, 2018, Dubna, Russia

My connection to Dubna

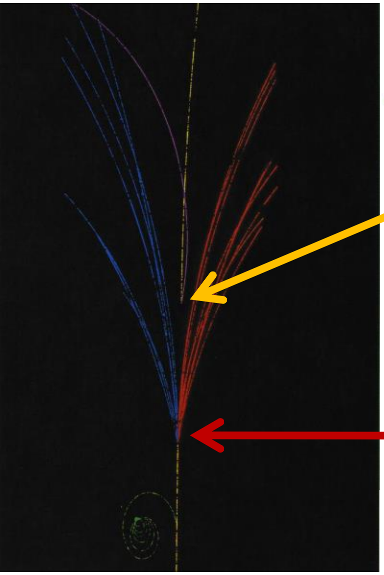
- My mentor during Ph.D. research (Crystal Ball experiment at DESY)

Bogdan Niczyporuk
1936-2017

M. Curie - Sklodowska University, Lublin, 1956-58;
M.S., Moscow University 1962;
Ph.D., Jagiellonian University, Krakow, 1973;
Dr.hab. Institute of Nuclear Physics, Krakow, 1983.

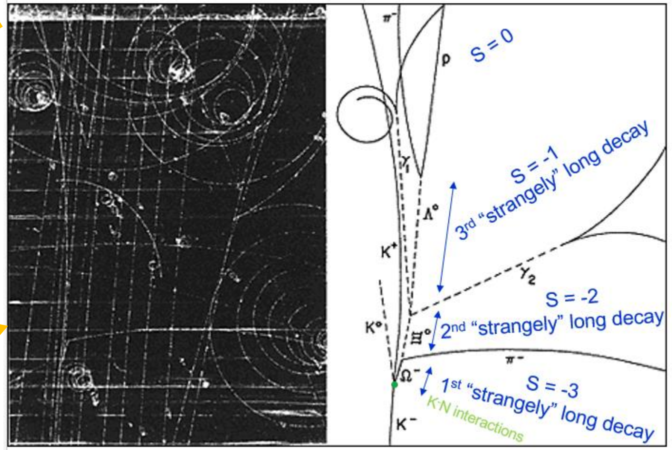
Research physicist, JINR, Dubna, 1963-73;
Adjunct, Institute of Nuclear Physics, Cracow, 1973-83;
Visiting Prof., Stanford University (CA), 1983-88;
Senior physicist, CEBAF (JLab) 1988-2003.

From particle zoo to Quark Model



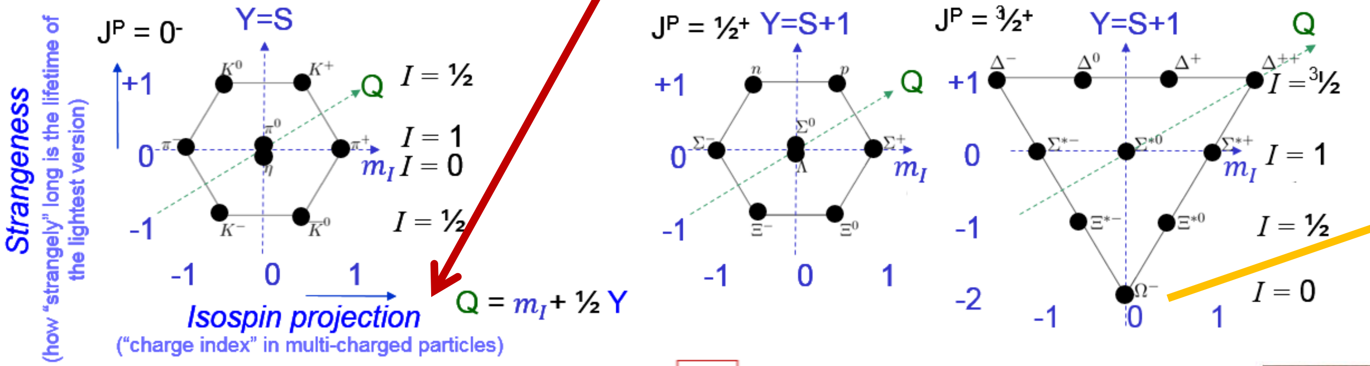
Strangely **long-lived states** gave us clues about the right **underlying symmetries**: Quarks and flavor independence of strong interactions

Ω⁻ 1964



"Eightfold Way" symmetry – Gell-Mann 1961

"hypercharge" Y=S+A (not really a "charge")

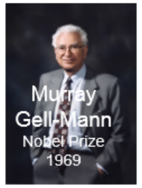


Meson octet

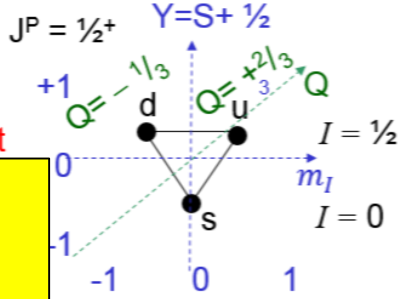
octet

Baryon decuplet

Quark Model

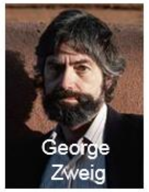


$(q\bar{q})$



Quark triplet

(qqq)



Nuclei are "molecules" of the lightest baryons (p,n)

$((qqq)(qqq) \ldots)$

Still investigating!

Why not:
$((q\bar{q})(q\bar{q}))$, $((q\bar{q})(qqq))$,… meson molecules
$(qq\bar{q}\bar{q})$, $(qqqq\bar{q})$,… tetra-, penta-quarks,…

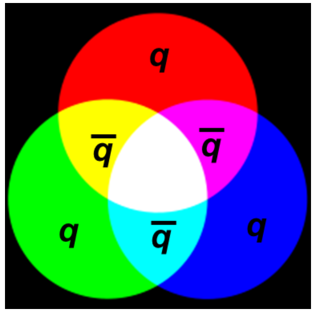
QM sounded crazy at that time:

- Particles with fractional Q and A not seen → confinement
- Ω : Can't have three identical fermions in the same quantum state → color

QCD
(came later)

QCD and QCD motivated states

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}\,(i\gamma_\mu D^\mu - m_q)\,q - \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$

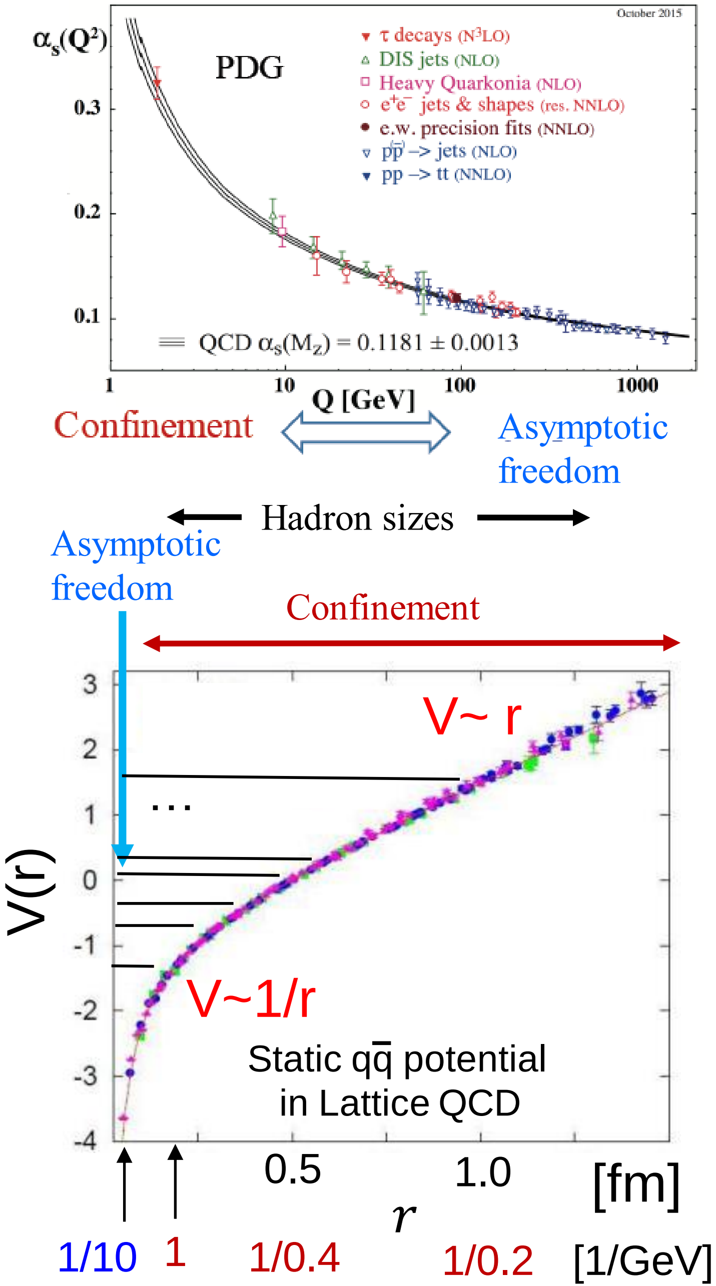


$SU(3)_{color}$

Gluons (g) with color-anticolor charge

We are still looking for these!

Expect:
$(q\bar{q}g)$, $(qqqg)$,… hybrid mesons and baryons
(gg),… glueballs



Hadrons = Non-perturbative QCD

Lattice QCD works well for lowest-excitations of (qq), (qqq).

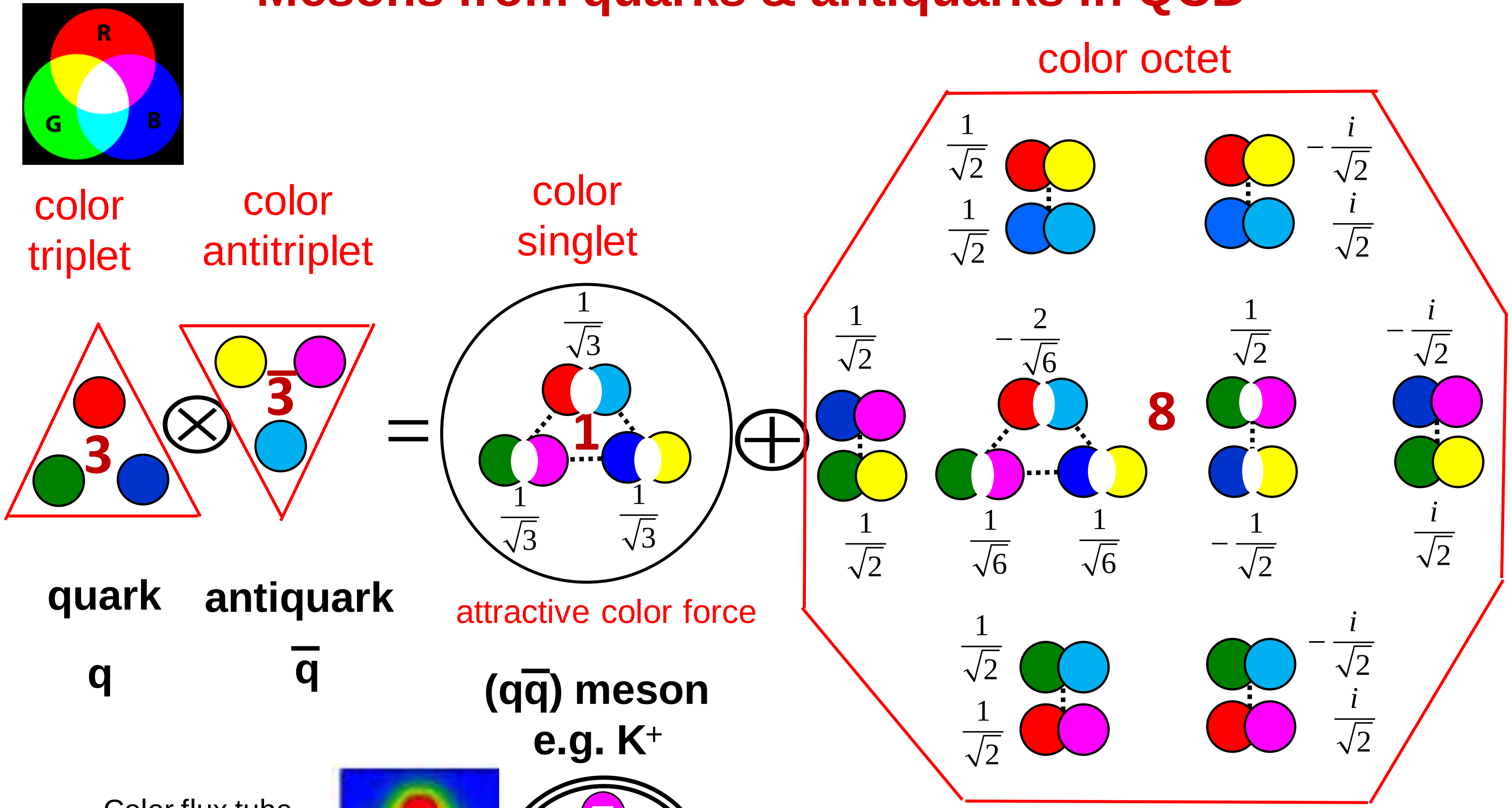
Only approximate lattice simulations for **unstable** higher excitations

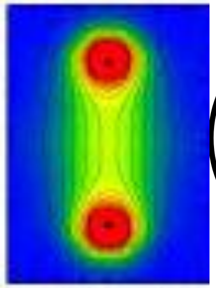
We have to **rely on data and QCD-motivated phenomenology** when trying to understand more complex hadronic structures.

A large number of hadronic states expected from radial and angular momentum excitations.

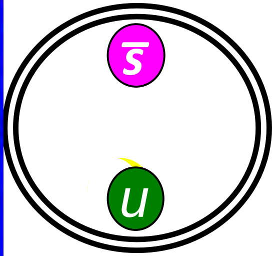
Unlike in QED, large fine and hyperfine structures for lower excitations.

Mesons from quarks & antiquarks in QCD





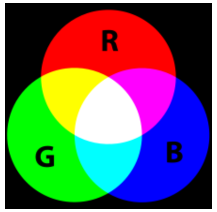
Color flux tube stretched between quark and antiquark with attractive potential

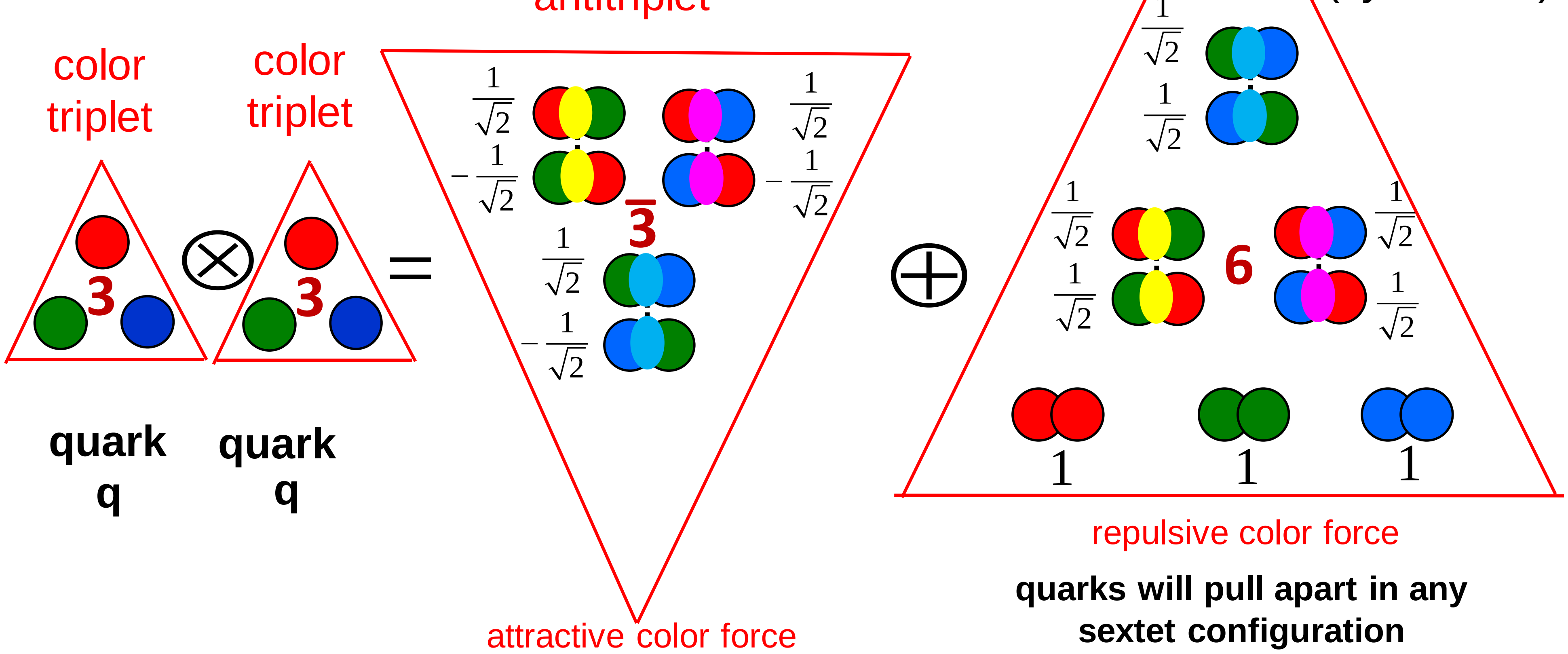


quarks will pull apart in any octet configuration

gluons happen to belong to the color octet

(Colored) diquarks in QCD

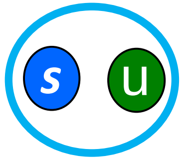




quarks will pull apart in any sextet configuration

(perturbatively: half as strong as in the meson)

(qq) diquark



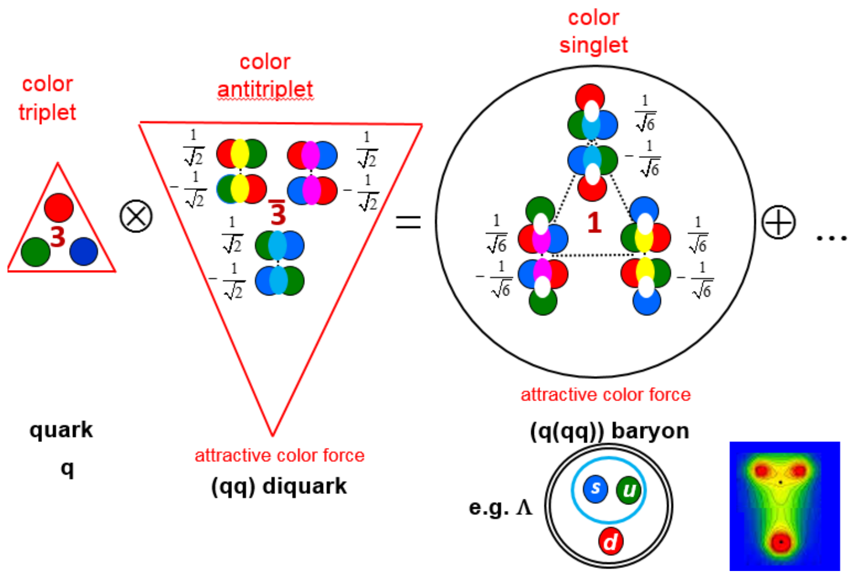
Not a particle, just a building block in QCD

Diquark can go in a place of antiquark in a hadron; antidiquark in place of quark.

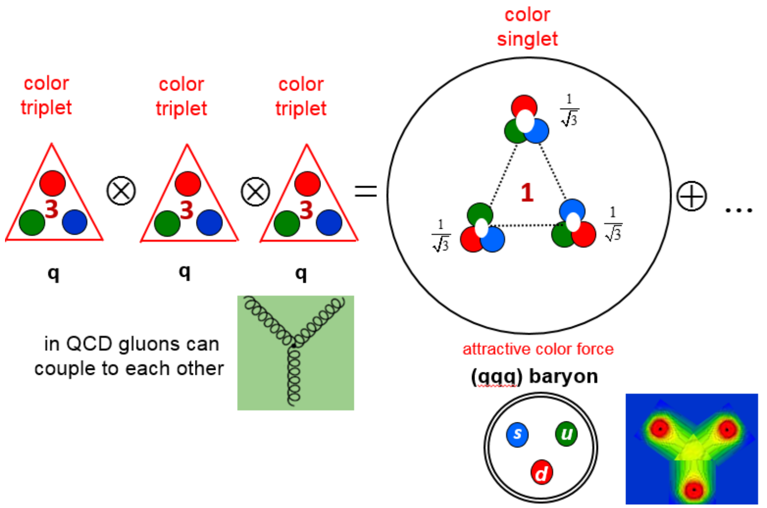
Hadrons from diquarks?

Still an open question!

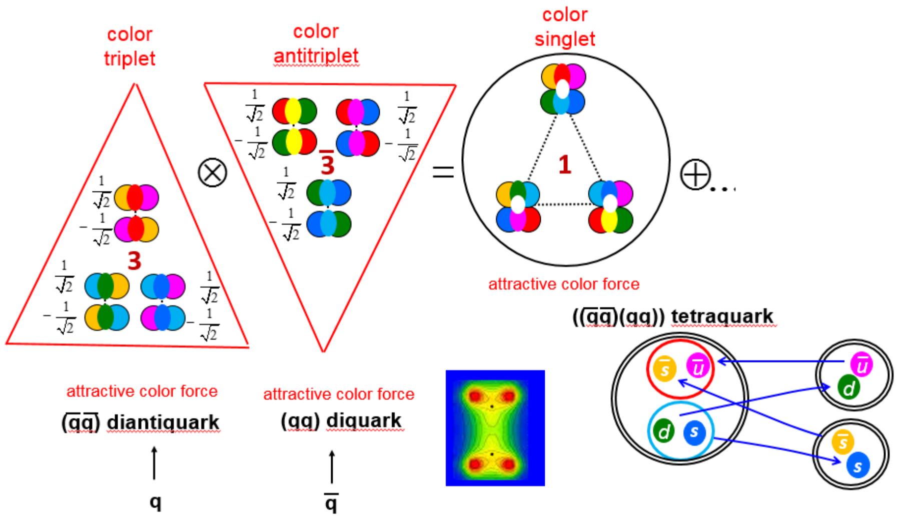
Role of diquarks in building hadrons?

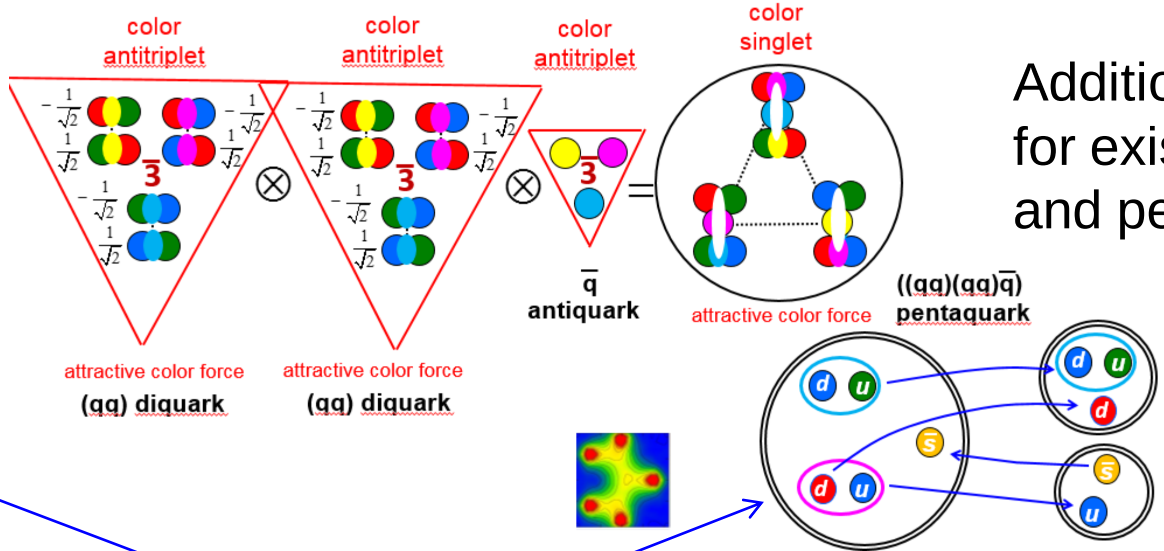


vs.



Light and heavy baryon spectroscopy is sensitive to this question





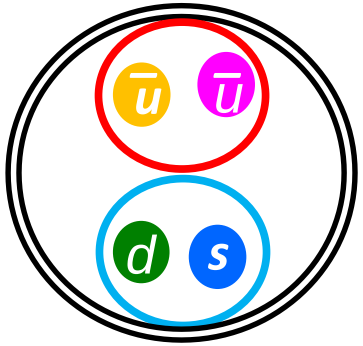
Additional motivation for existence of tetra- and penta-quarks.

Does effective mechanism to suppress rapid fall-apart exist?

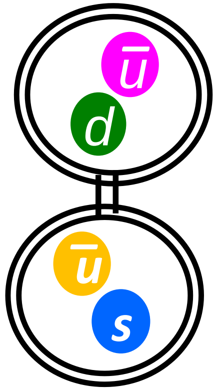
Tetraquarks (pentaquarks) vs meson-meson (meson-baryon) molecules

- The same quark content can, in principle, create a meson-meson molecule or a tetraquark
- However, mass spectrum from these two types of bindings are very different

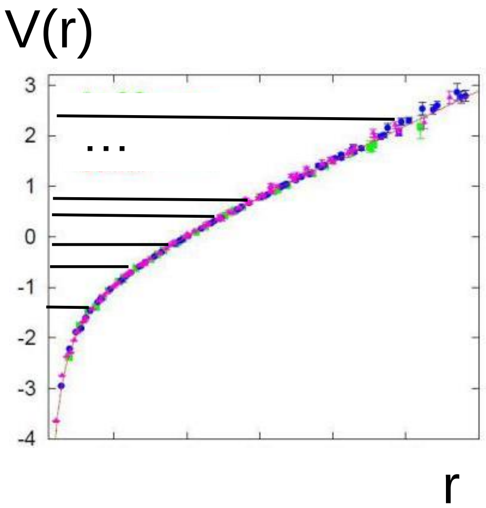
$((\bar{q}\bar{q})(qq))$
tetraquark



$(q\bar{q})$-$(q\bar{q})$
meson-meson molecule

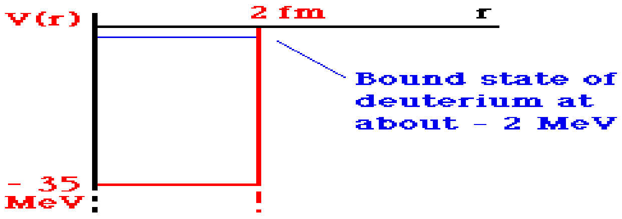


We don't know if either one exist ("exotic hadron")



Very rich mass and J^P spectrum expected!

However, states can be undetectable if extremely broad.



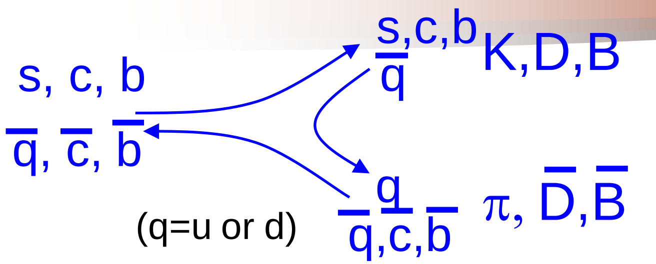
Typically expect only **one state**
n=1, L=0.

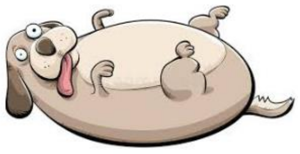
Fall apart prevented by spatial separation – long-lived states if below threshold.

Mass and J^P fairly constrained from the constituents.

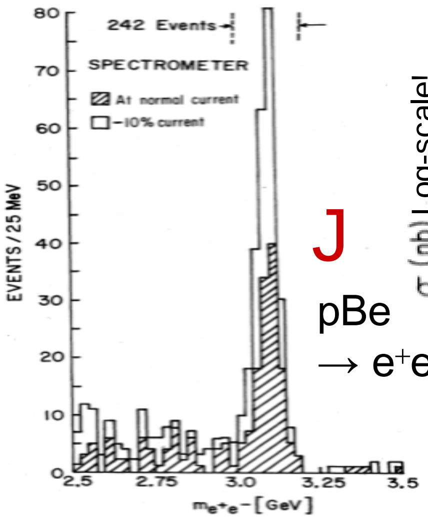
Hadron spectroscopy and heavy flavors

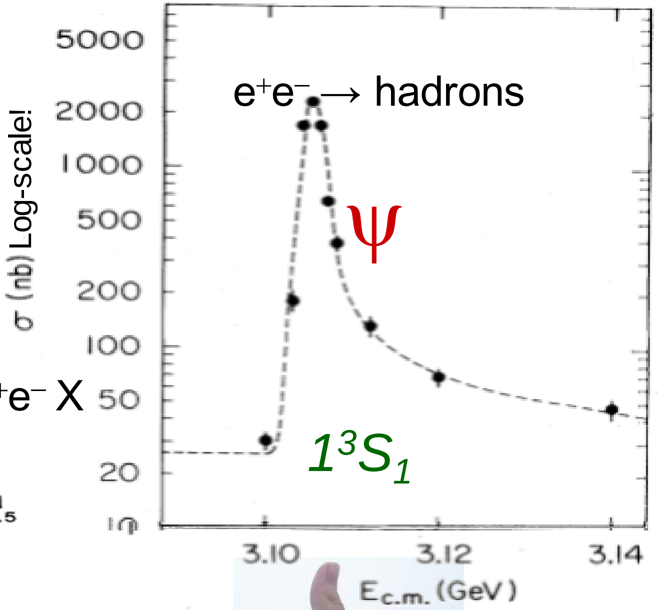
K*, ψ'', ϒ'''

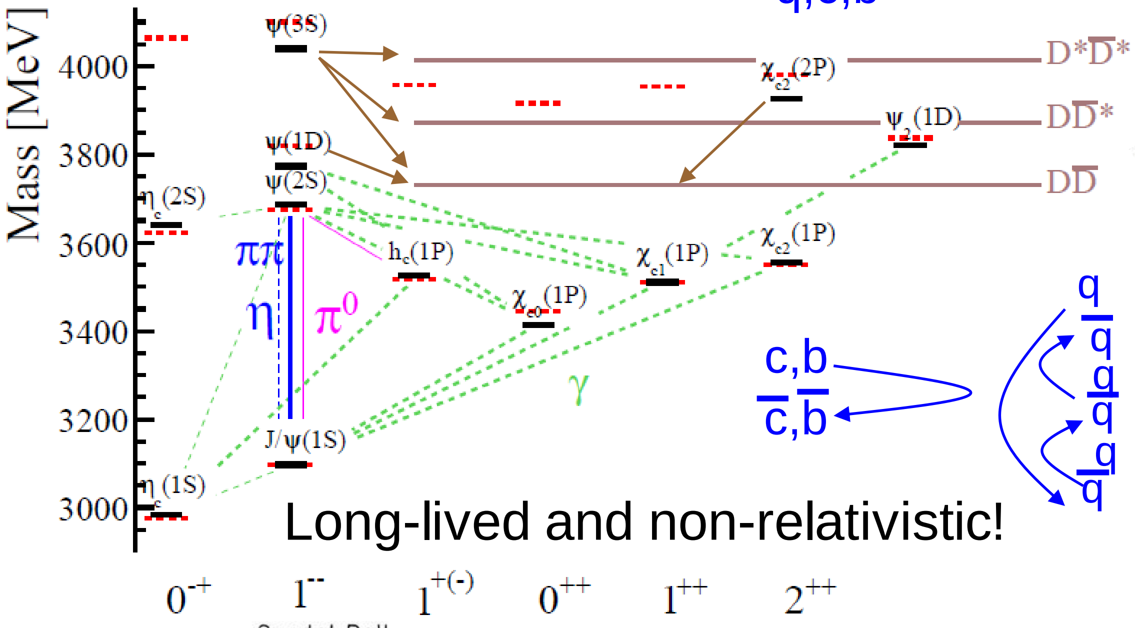




November revolution
of 1974







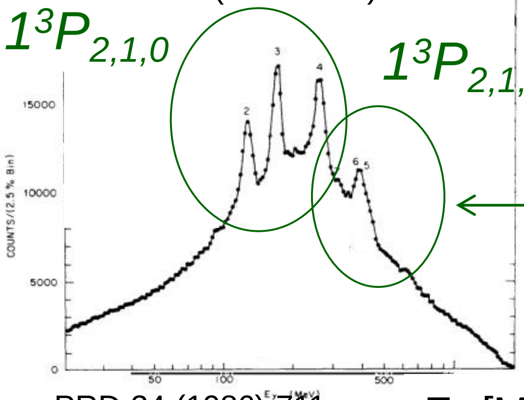
Long-lived and non-relativistic!

Quarks are real
and
mesons are simple $q\bar{q}$ systems!

Crystal Ball
(at SPEAR)

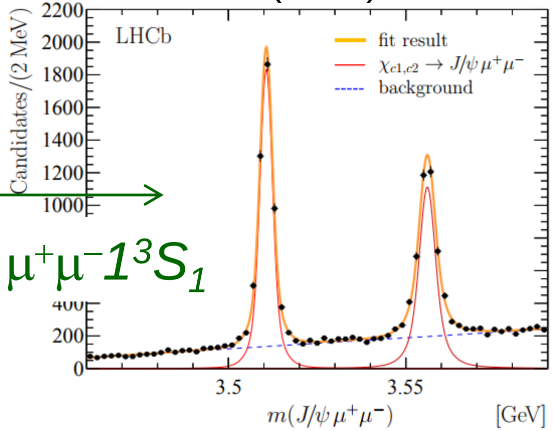
$2^3S_1 \to \gamma\ 1^3P_{2,1,0}$

$1^3P_{2,1,0} \to \gamma 1^3S_1$



PRD 34 (1986) 711

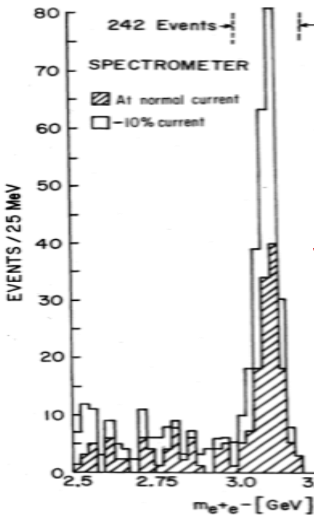
PRL 119 (2017) 221801



$1^3P_{1,2} \to \mu^+\mu^- 1^3S_1$

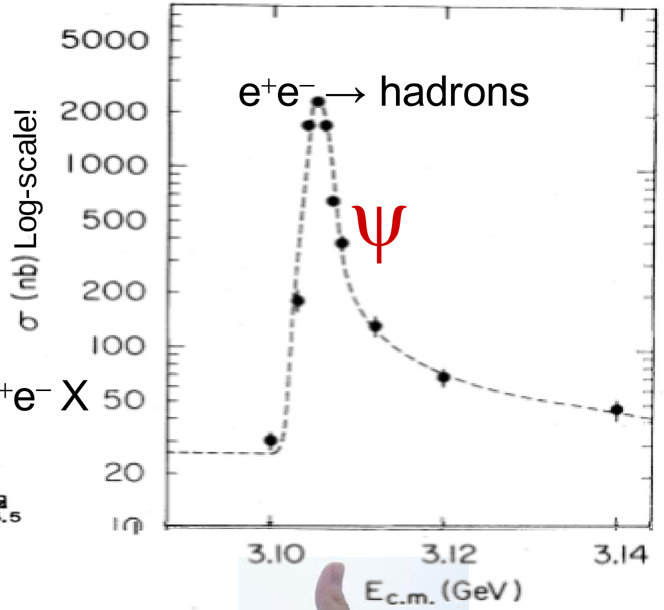
Hadron spectroscopy and heavy flavors

November revolution of 1974



J

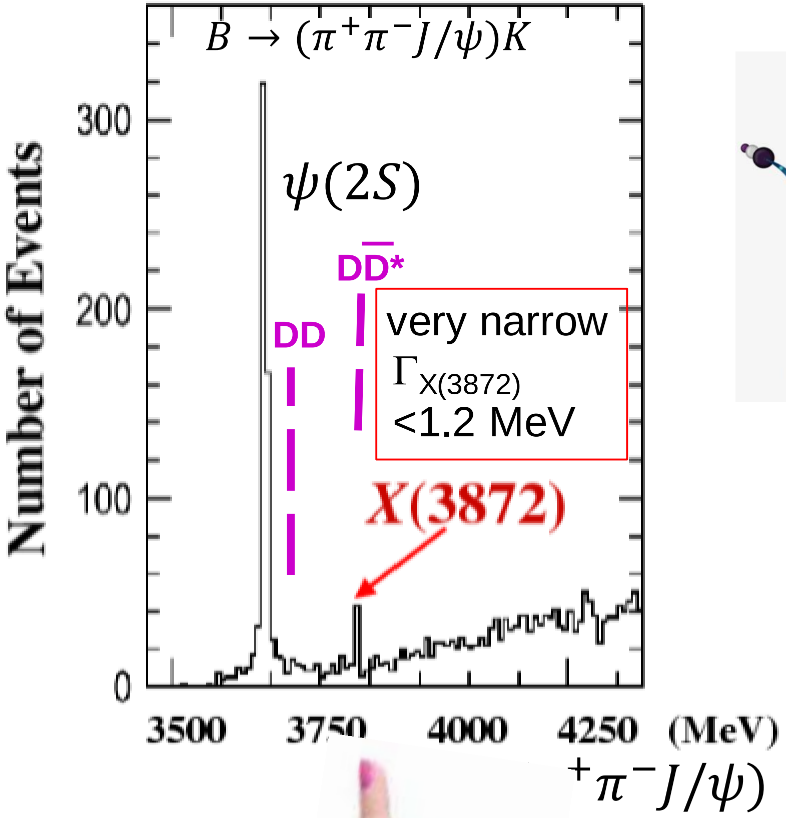
pBe $\rightarrow e^+e^- X$



Quarks are real
and
mesons are simple $q\bar{q}$ systems!

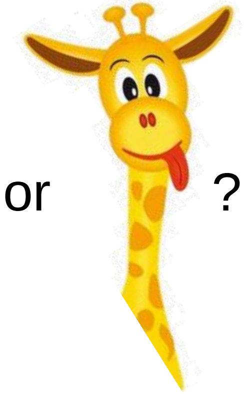
Belle 2003

$e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$



not all mesons are simple!

or



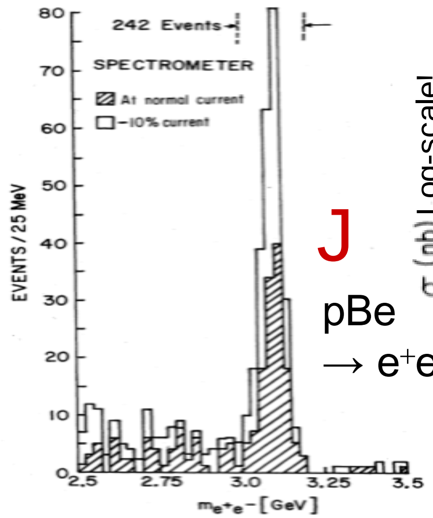
?

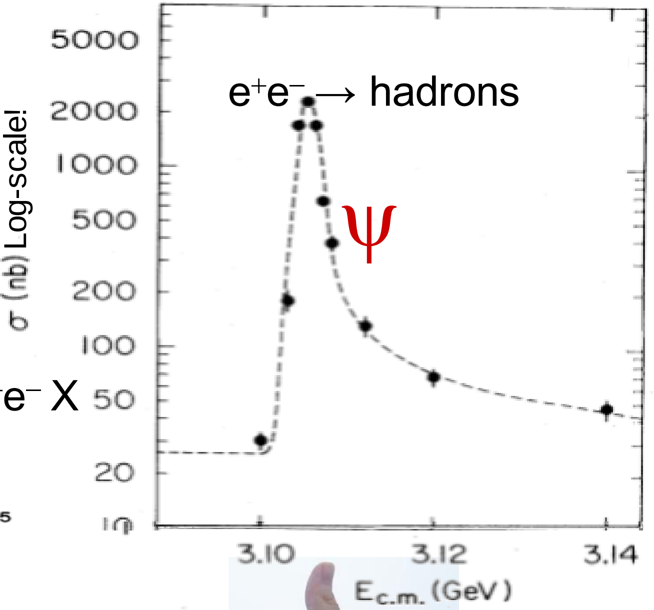
X(3872) $J^{PC}=1^{++}$

Could be $\chi_{c1}(2^3P_1)$ but its isospin violating decay $X(3872) \rightarrow \varrho^0 J/\psi,\ \varrho^0 \rightarrow \pi^+\pi^-$ an order of magnitude too large for a (pure) $c\bar{c}$ state

Hadron spectroscopy and heavy flavors

November revolution of 1974

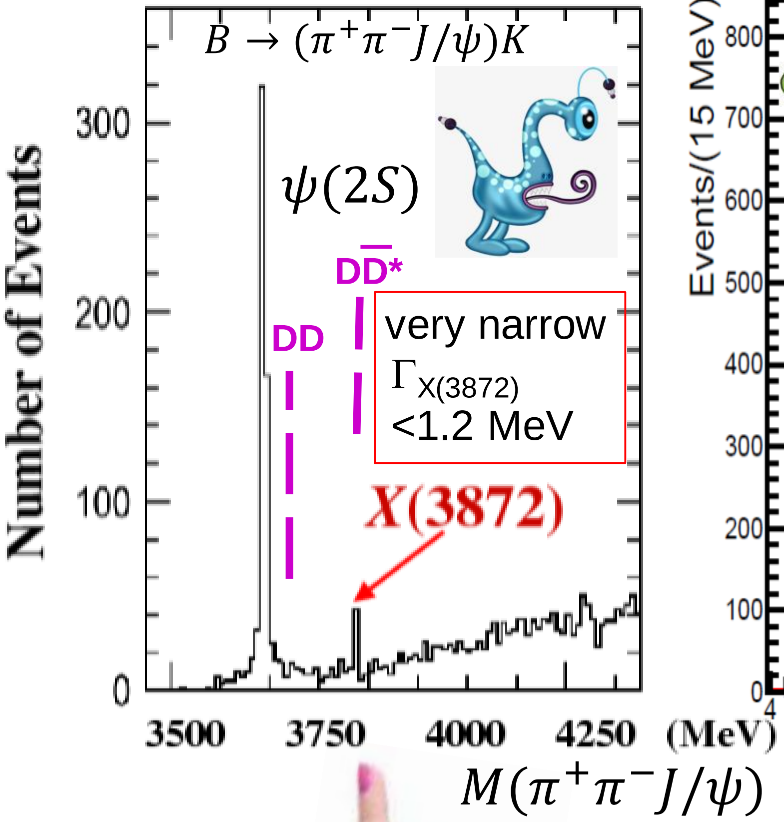




Quarks are real
and
mesons are simple $q\bar{q}$ systems!

Belle 2003

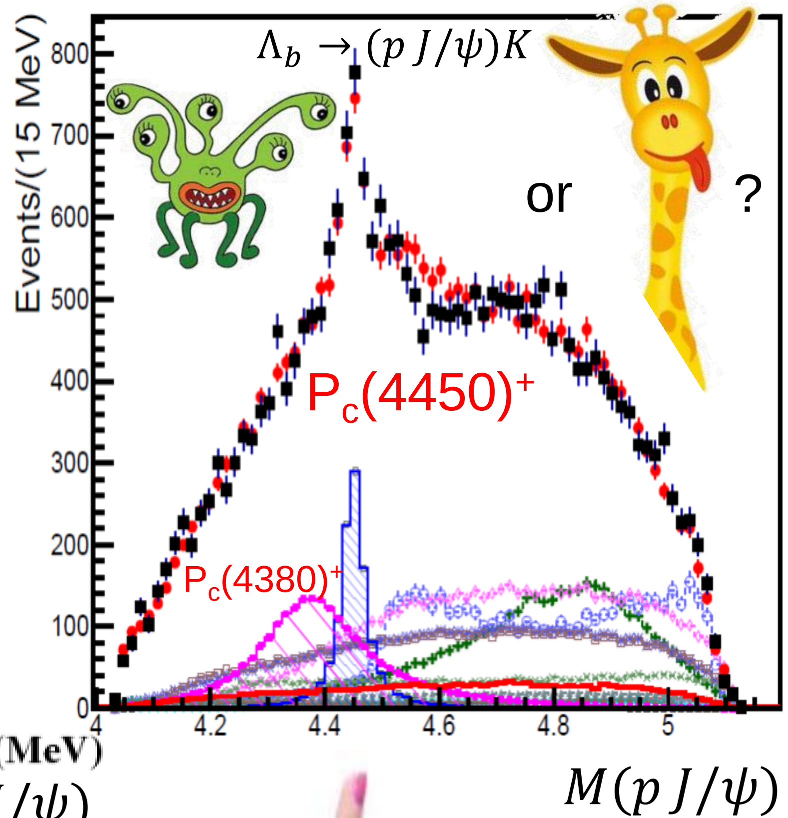
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$



not all mesons are simple!

LHCb 2015

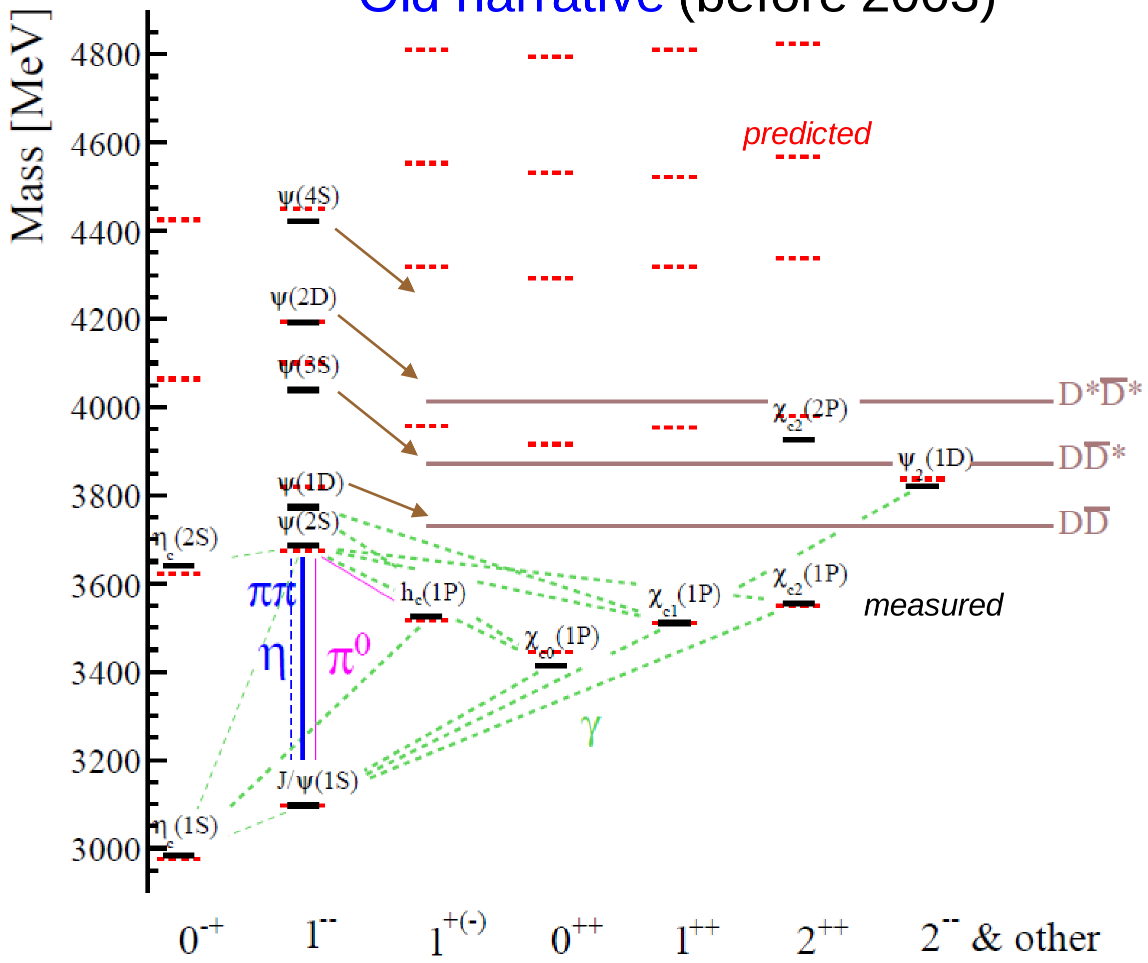
$pp \to \Lambda_b + \cdots$



neither are all baryons

New particle zoo: charmonium above flavor threshold

Old narrative (before 2003)



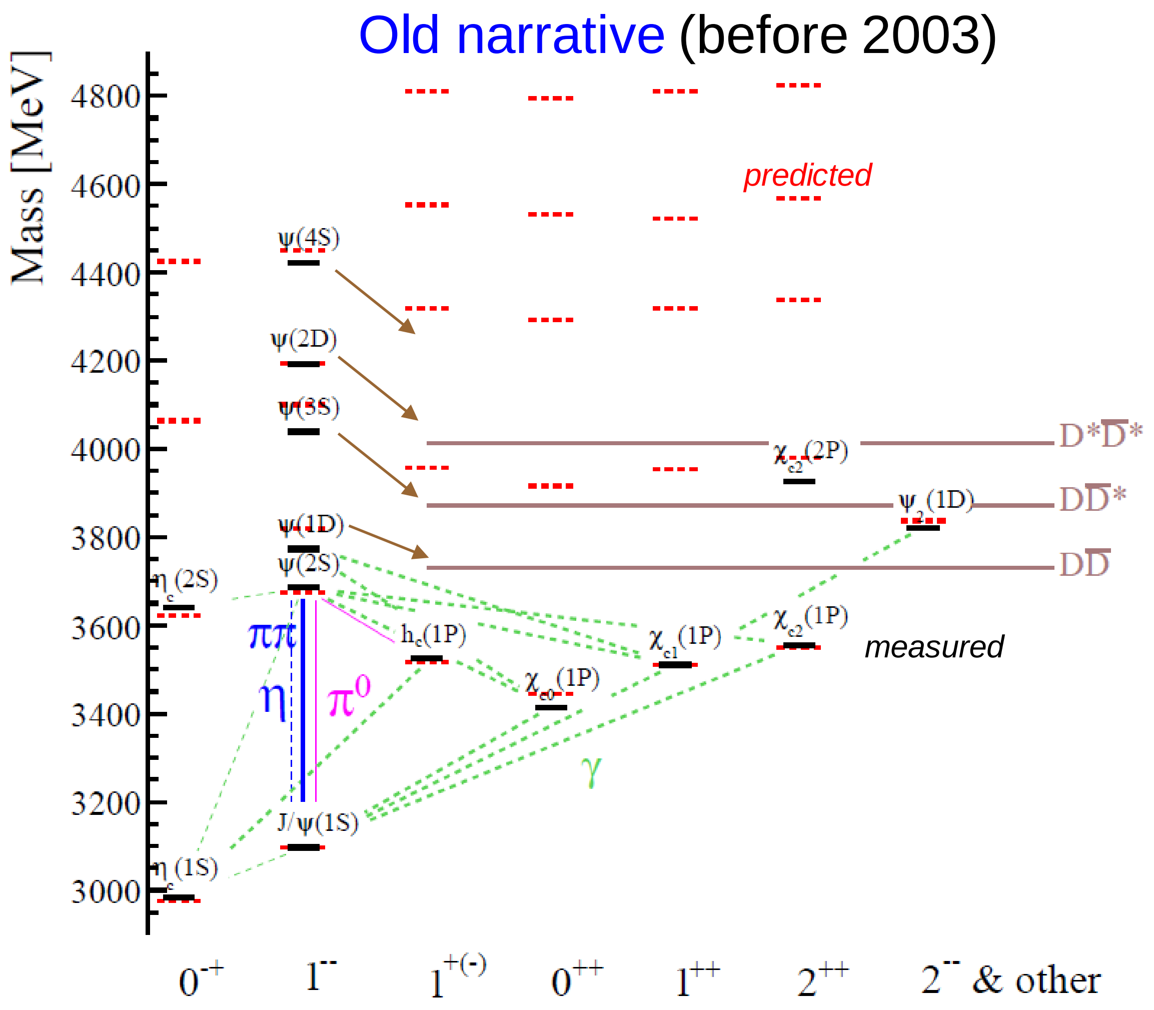
Figures from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

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

New particle zoo: charmonium above flavor threshold (mostly a freak show)

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

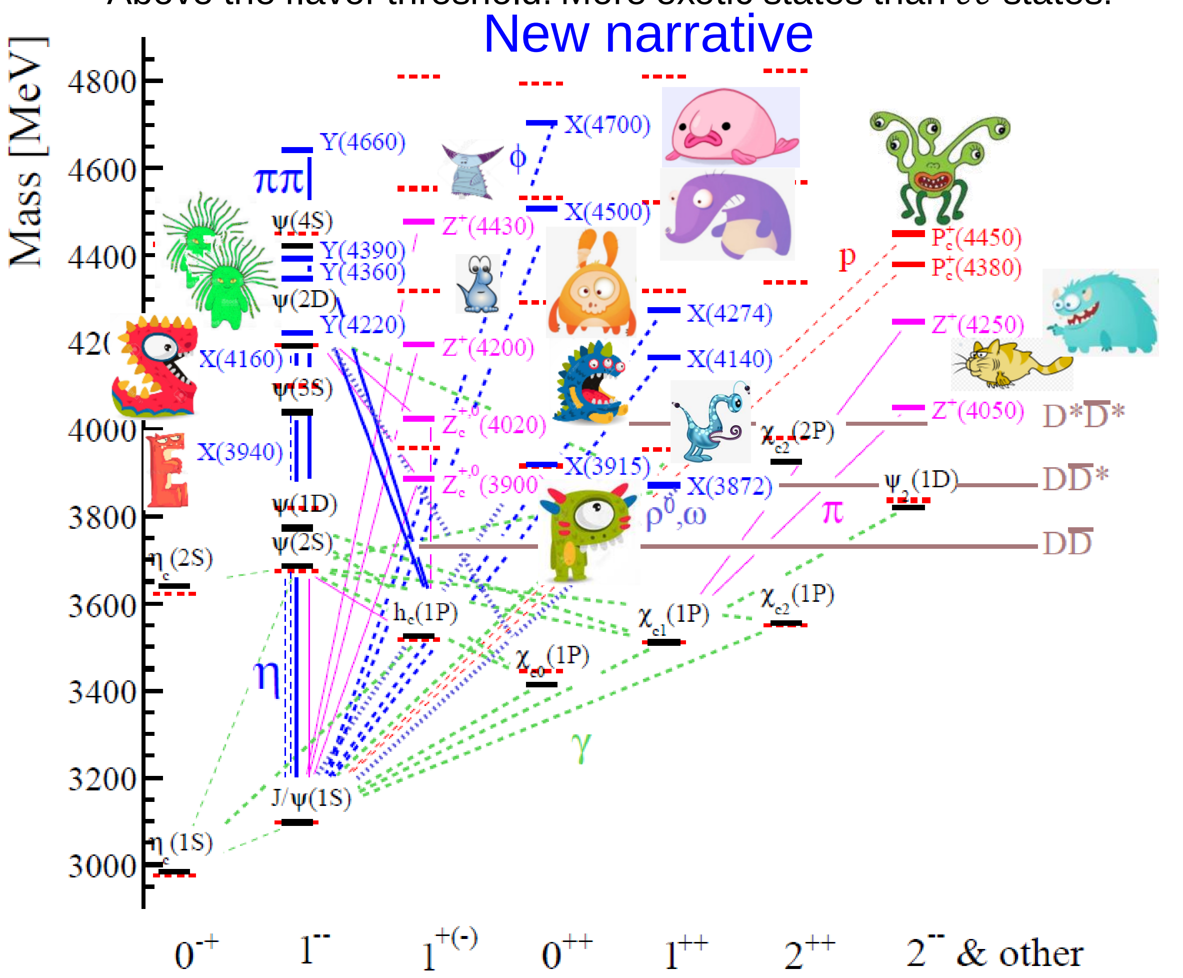
Old narrative (before 2003)



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

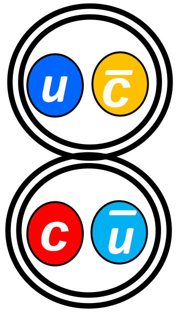
Mesons are $(q\bar{q})$ bound states.

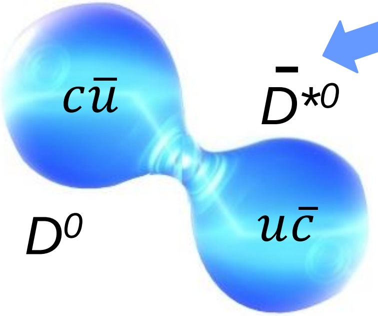
New narrative



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.

Dual nature of X(3872)



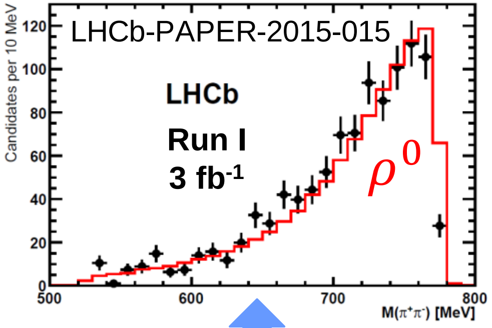


Mass near $D^0\overline{D}^{*0}$ threshold

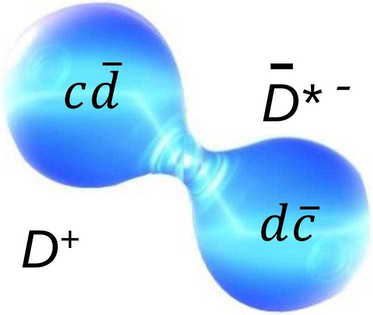
Narrow width in decays to $c\bar{c}$

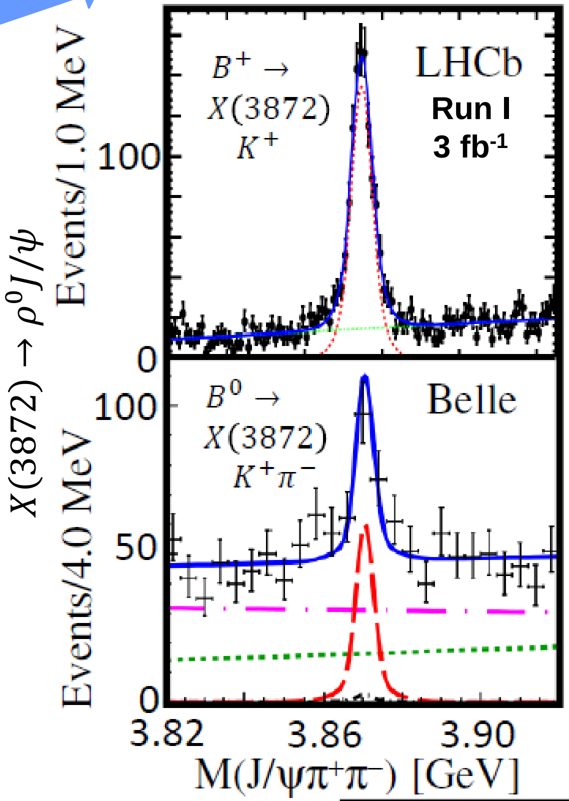
Enhanced isospin violating decays

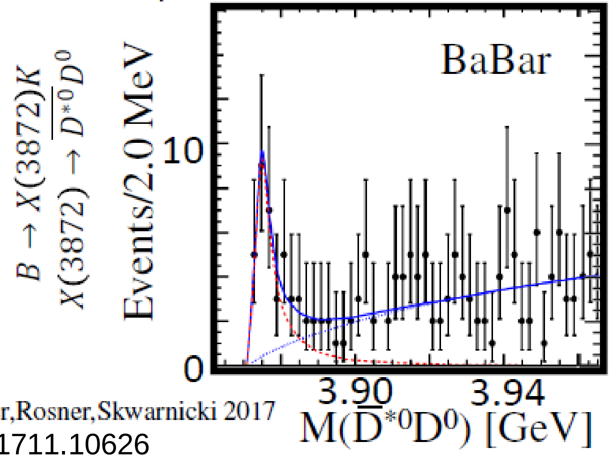
$X(3872) \to \rho^0 J/\psi$



only small admixture of

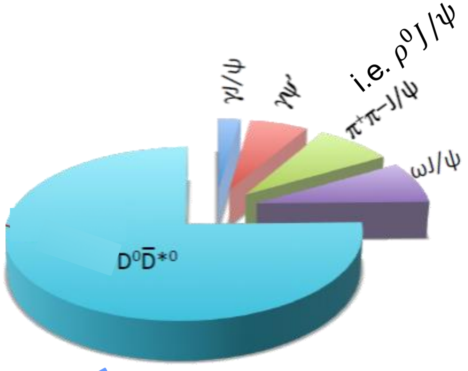






Karliner,Rosner,Skwarnicki 2017
arXiv:1711.10626

Known decay rates:

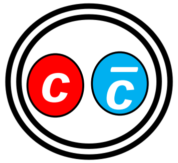


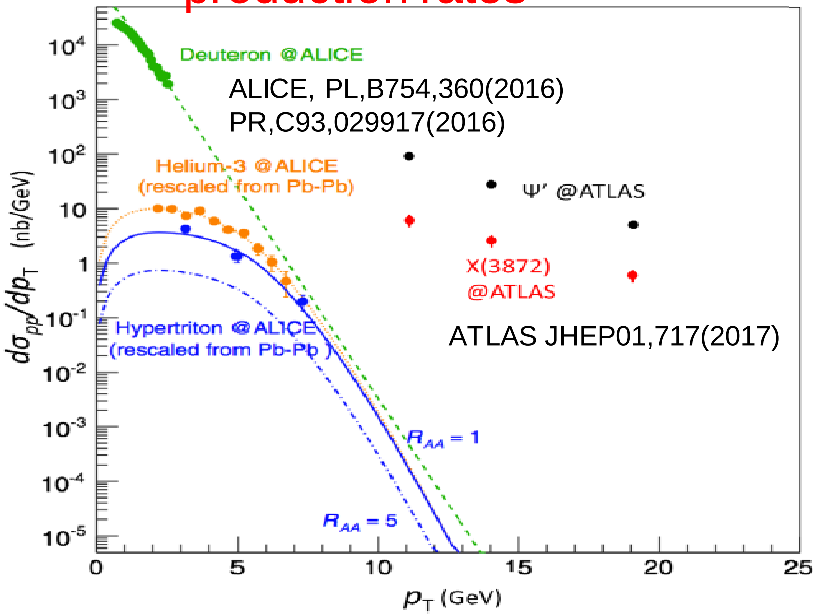
Huge fall-apart mode from the resonance tail above the $D^0\overline{D^{*0}}$ threshold

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

molecular features

Charmonium-like prompt production rates





A.Esposito et al. PRD92, 034028 (2015)
(ATLAS data inserted by S.Olsen)

Charmonium-like pattern of radiative decays

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

$= 2.48\pm0.64\pm0.29$ (>0 at 4.4σ)

LHCb-PAPER-2014-008

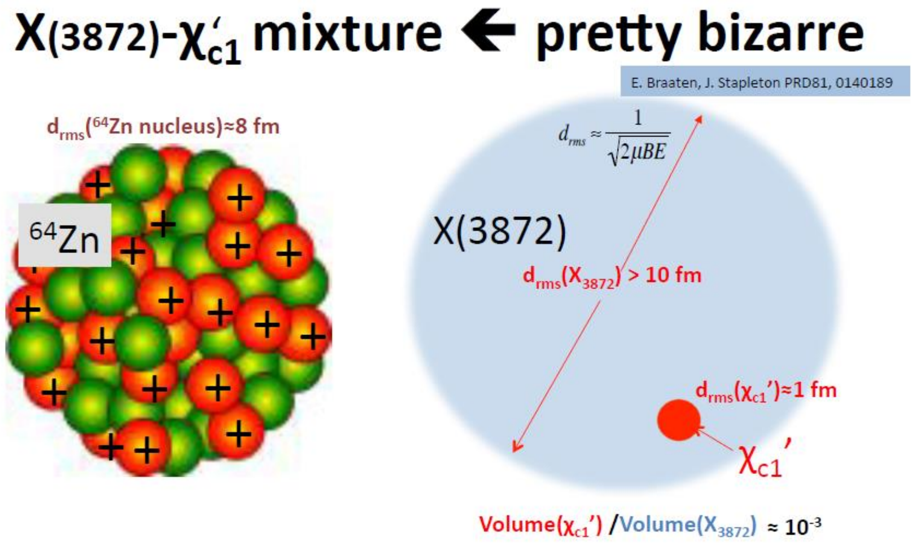
unlike a molecule

Lessons from X(3872)

- Answers to the nature of some of unusual hadrons don't need to be simple; more than one binding mechanisms can be at play (X(3872): $(c\bar{c})$ + $(D\bar{D}^*)$)
- Coincidence of conventional hadron with an S-wave hadron-hadron threshold can have a profound impact on properties of the state
- We have seen examples of the latter from lighter hadrons, too:
  - $a_0(980), f_0(980)$ and $K\bar{K}$ threshold (?); $f_1(1420)$ and $K\overline{K^*}$
  - $\Lambda(1405)$ and $K\bar{N}$ threshold
  - $D_{s0}(2317)$ and $D\bar{K}$, $D_{s1}(2460)$ and $D^*\bar{K}$
  - …

Be aware that the $(c\bar{c})$ + $(D\bar{D}^*)$ interpration of X(3872) remains controversial:

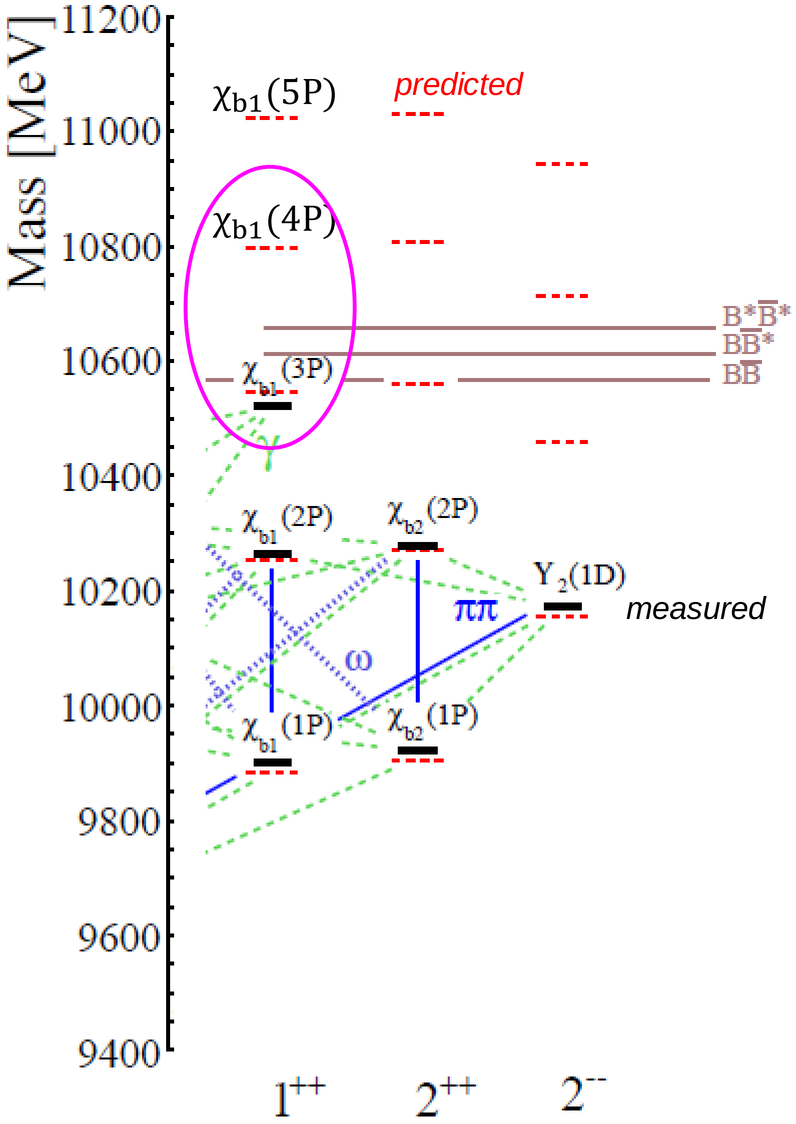
More data will be useful to clarify its nature!



Very weak $D\bar{D}^*$ binding $\longrightarrow$ very large state

X(3872), so far, is unique!

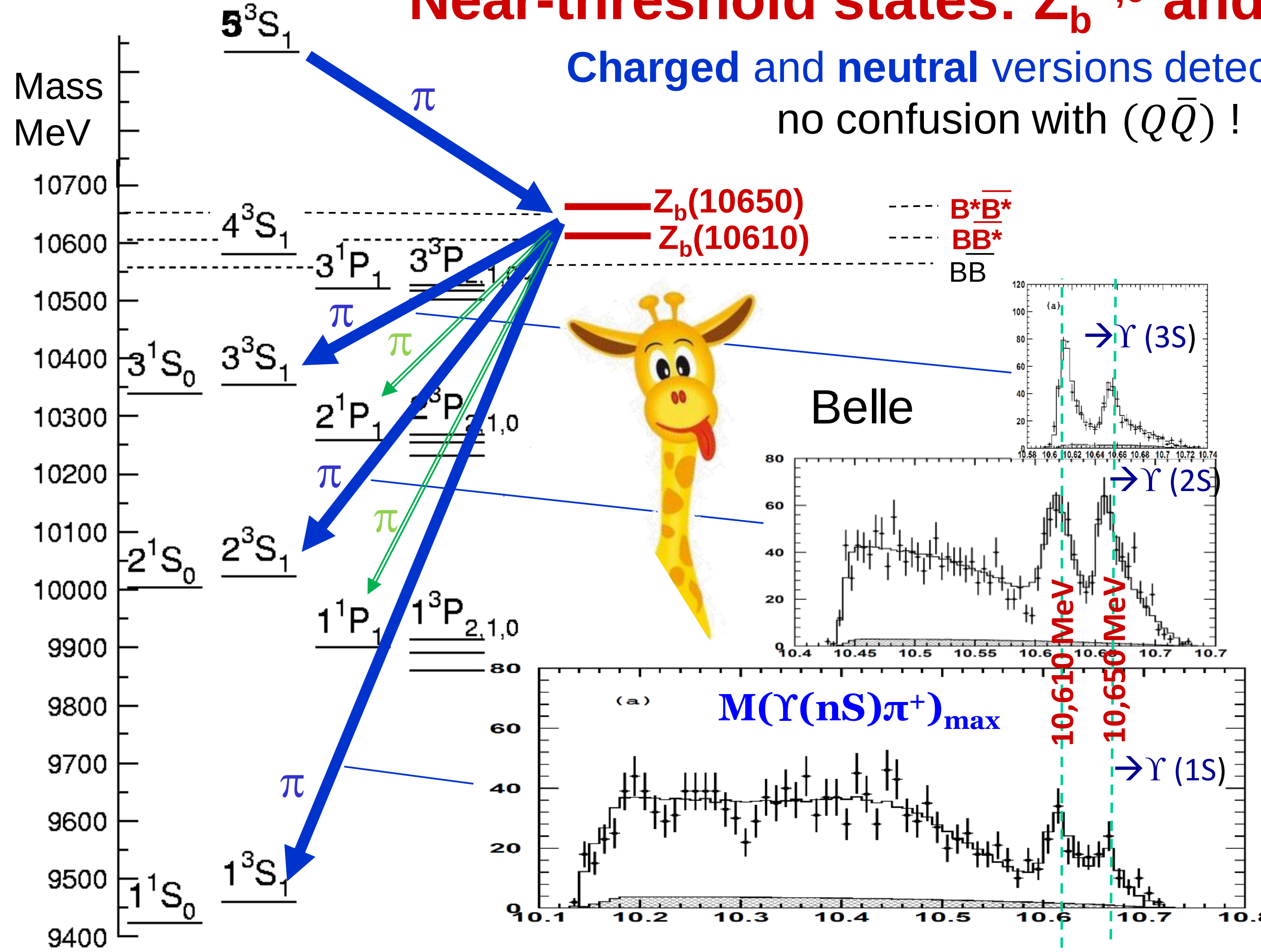
- The only exotic charmonium-like candidate which shows up consistently in many different productions mechanism, accompanying well-behaved $c\bar{c}$ state $-\ \psi(2S)$, and detected in many different decays modes
- If coincidence of $\chi_{c1}(2^3P_1)$ with the $D^0\overline{D}^{0*}$ threshold is responsible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

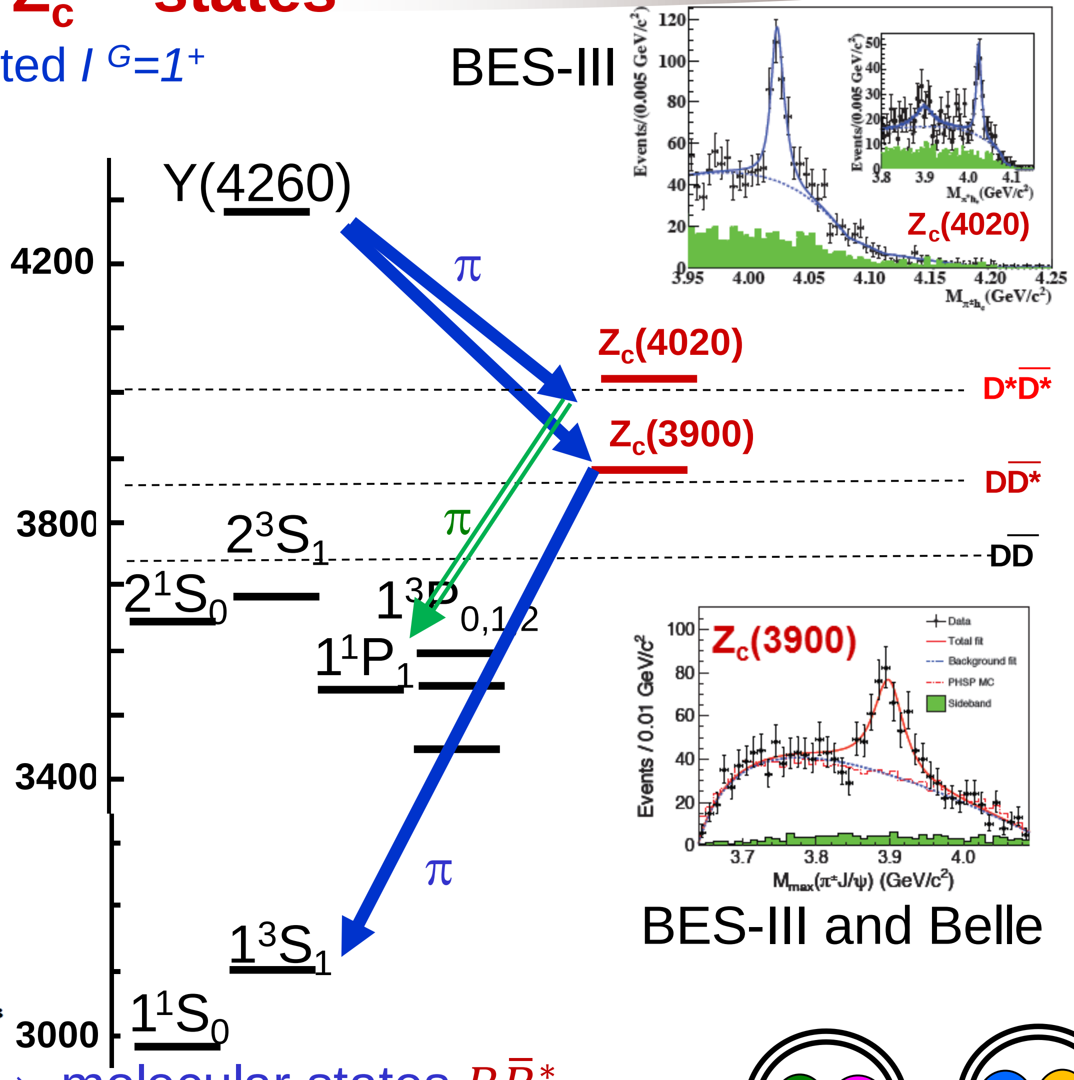


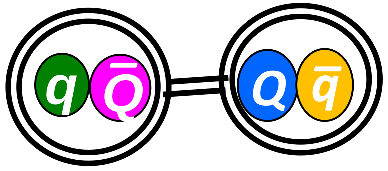
Near-threshold states: $Z_b^{+,0}$ and $Z_c^{+,0}$ states

Charged and **neutral** versions detected / ^{G}=1$^+$

no confusion with $(Q\bar{Q})$!

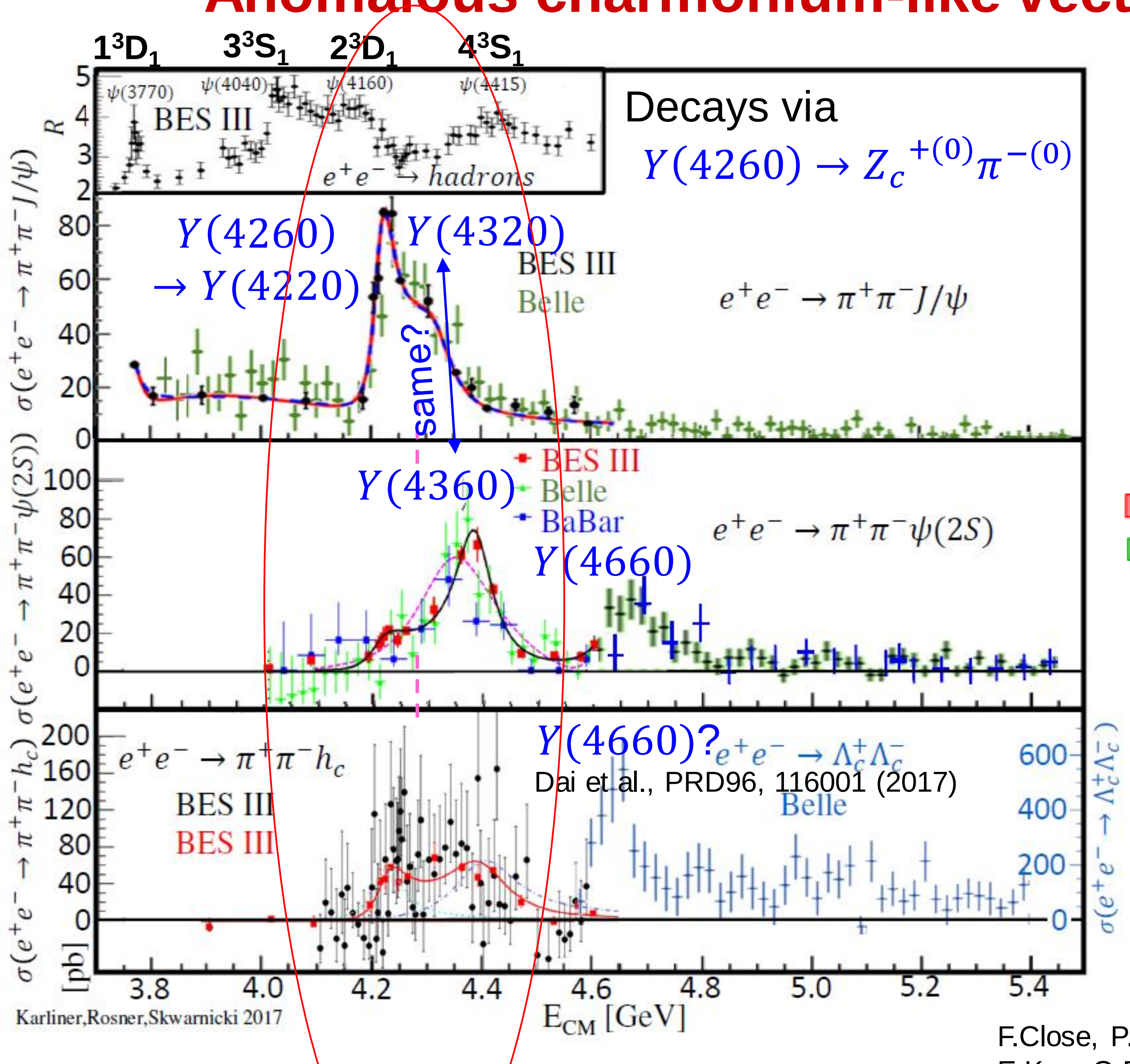




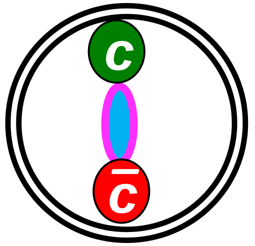


- Near thresholds, narrow, large fall-apart modes, J^P=1$^+$ ⟶ molecular states $B\bar{B}^*$, $B^*\bar{B}^*$(very weakly bound or slightly virtual). No sign of such states at $D\bar{D}$ and $B\bar{B}$, hints at forces dominated by π exchange.
- This is the only clear spectroscopy emerging from new particle zoo. (Not everybody agrees: see e.g. A. Ali, L. Maiani, A. Polosa, V. Riquer, PRD91, 017502 (2015) ⟶ tetraquarks.)

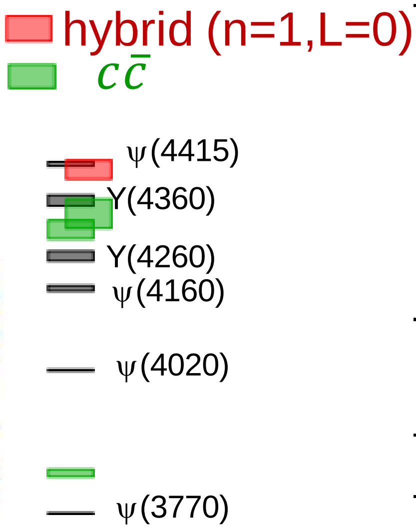
Anomalous charmonium-like vector states




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



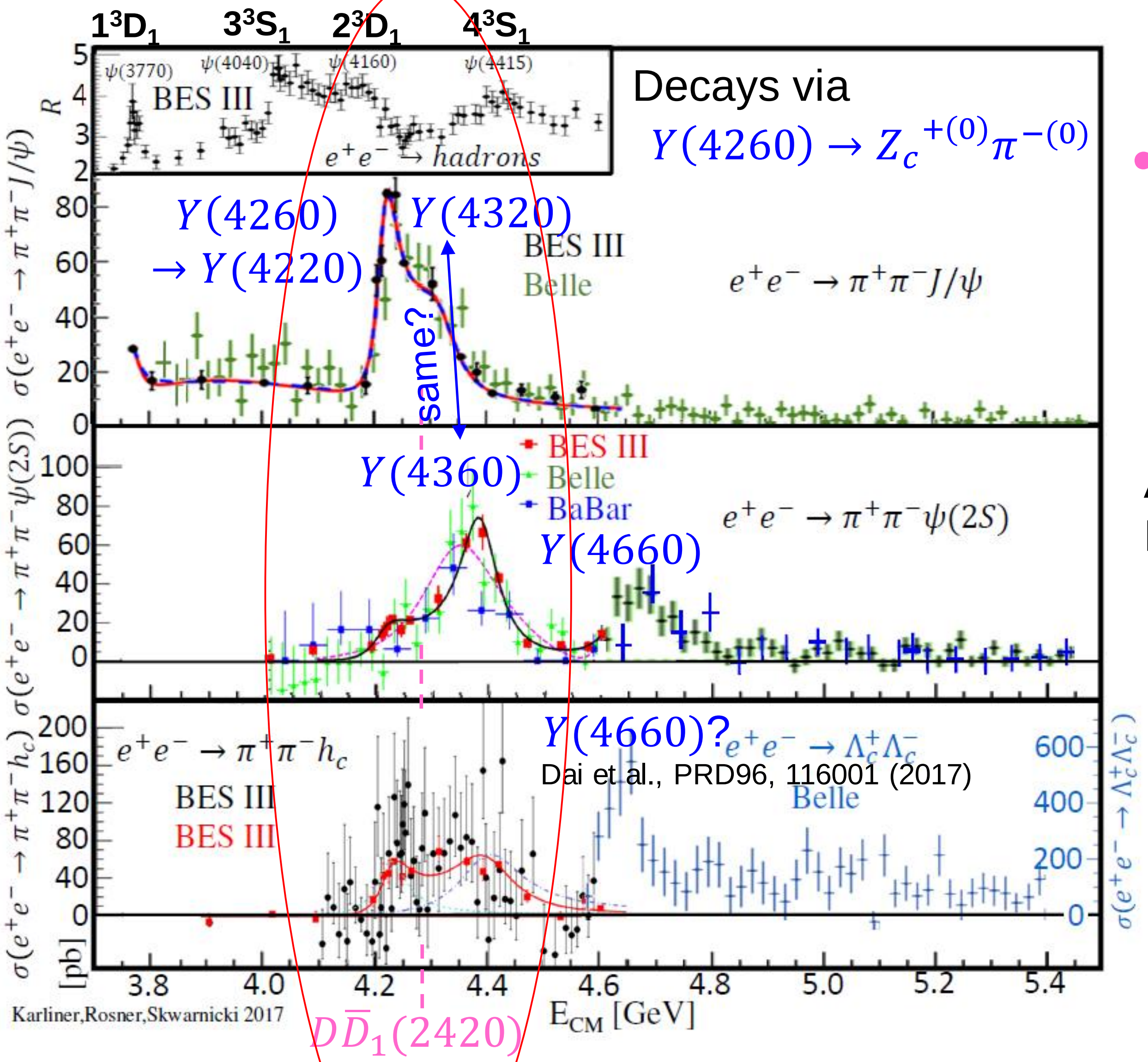
Hadron Spectrum Collaboration (LQCD m_π=240 MeV)
JHEP 1612, 089 (2016)



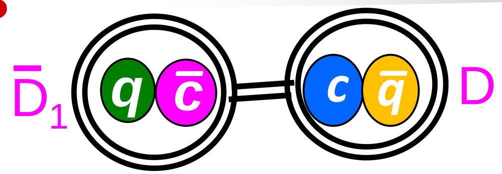
- **Hybrid-charmonium ?**
  - Masses not too far from the predicted 1^{--} hybrid by the lattice QCD:
    - Only one 1^{--} hybrid expected in this mass range
    - ψ(4020),ψ(4160),ψ(4415) not well reproduced by lattice
  - Γ_{ee} suppressed by a spin-flip needed to produce cc in S=0 configuration
  - 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) …

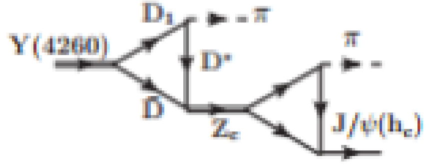
Anomalous charmonium-like vector states



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



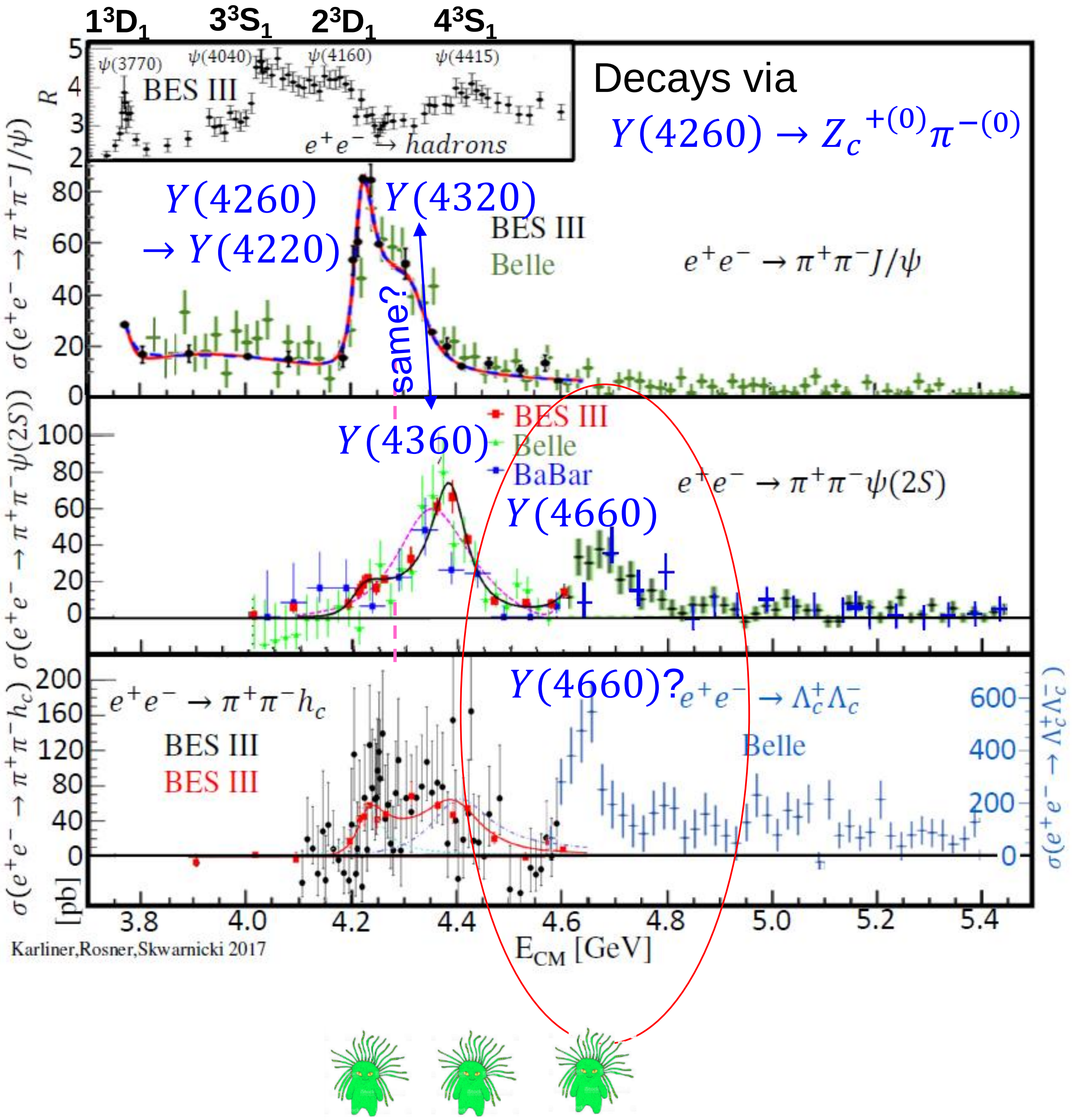
- $D\bar{D}_1(2420)$ **molecule** Q.Wang, C.Hanhart, Q.Zhao, **PRL 111 (2013) 132003**



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



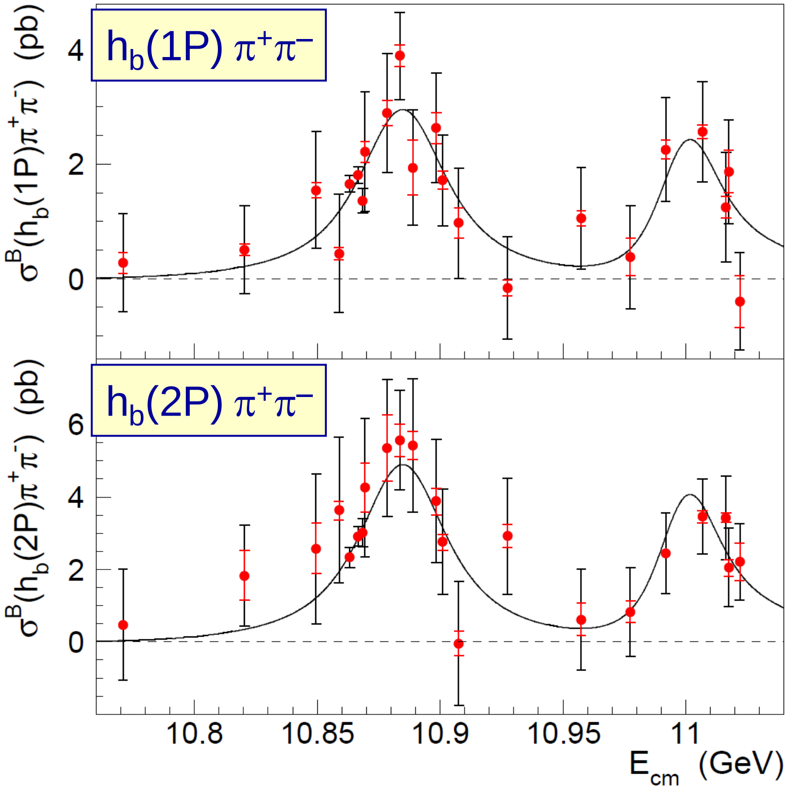
Y(4660): the same or different state in $e^+e^- \to \pi^+\pi^-\psi(2S)$ and $e^+e^- \to(\gamma)\, \Lambda_c^+\Lambda_c^-$?

Dai et al., PRD96, 116001 (2017)

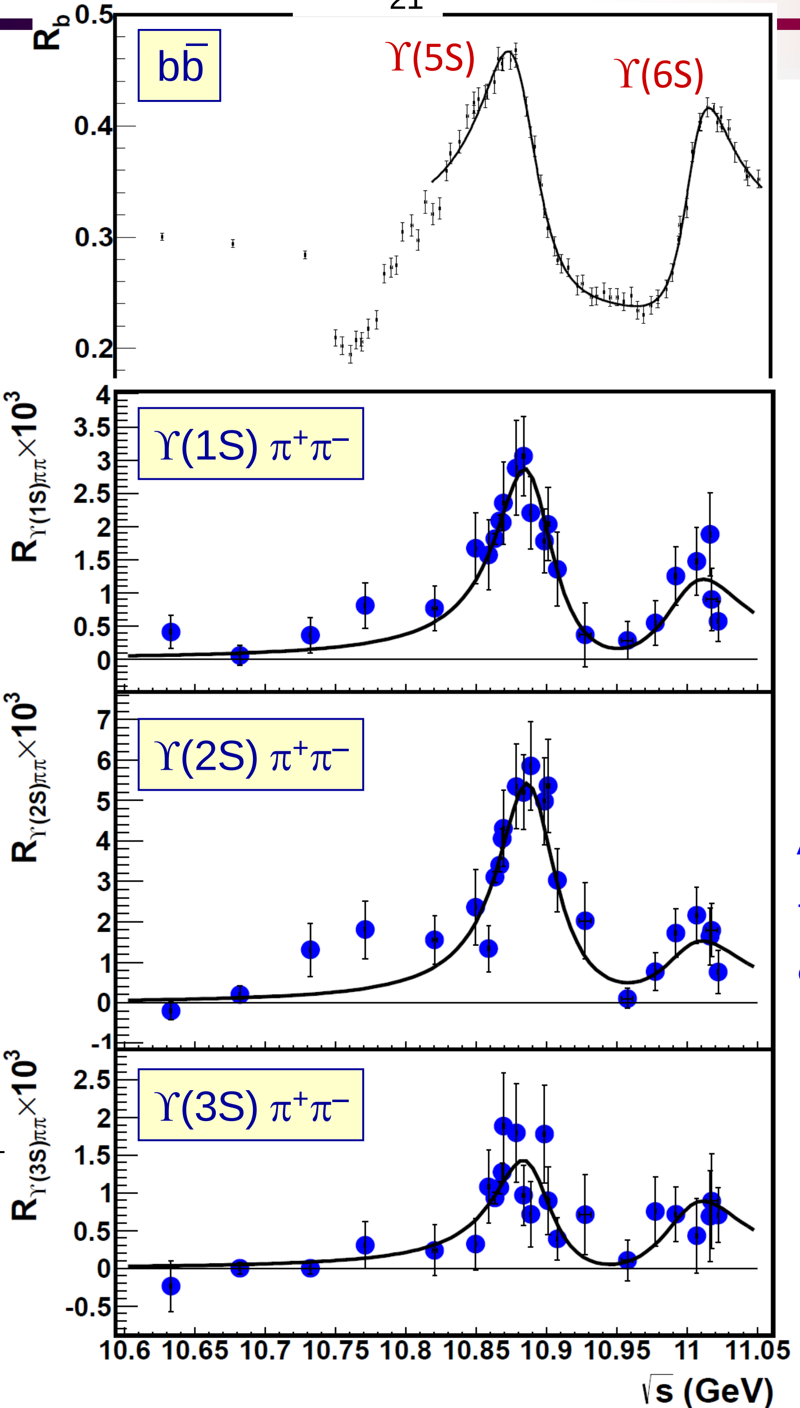
- $\psi(5^3S_1)$ or $\psi(6^3S_1)$ affected by $(\Lambda_c\bar{\Lambda}_c)$?
- tetraquark?
- Baryonium ?

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

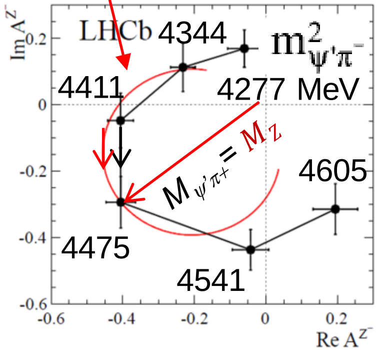
Like in charmonium!

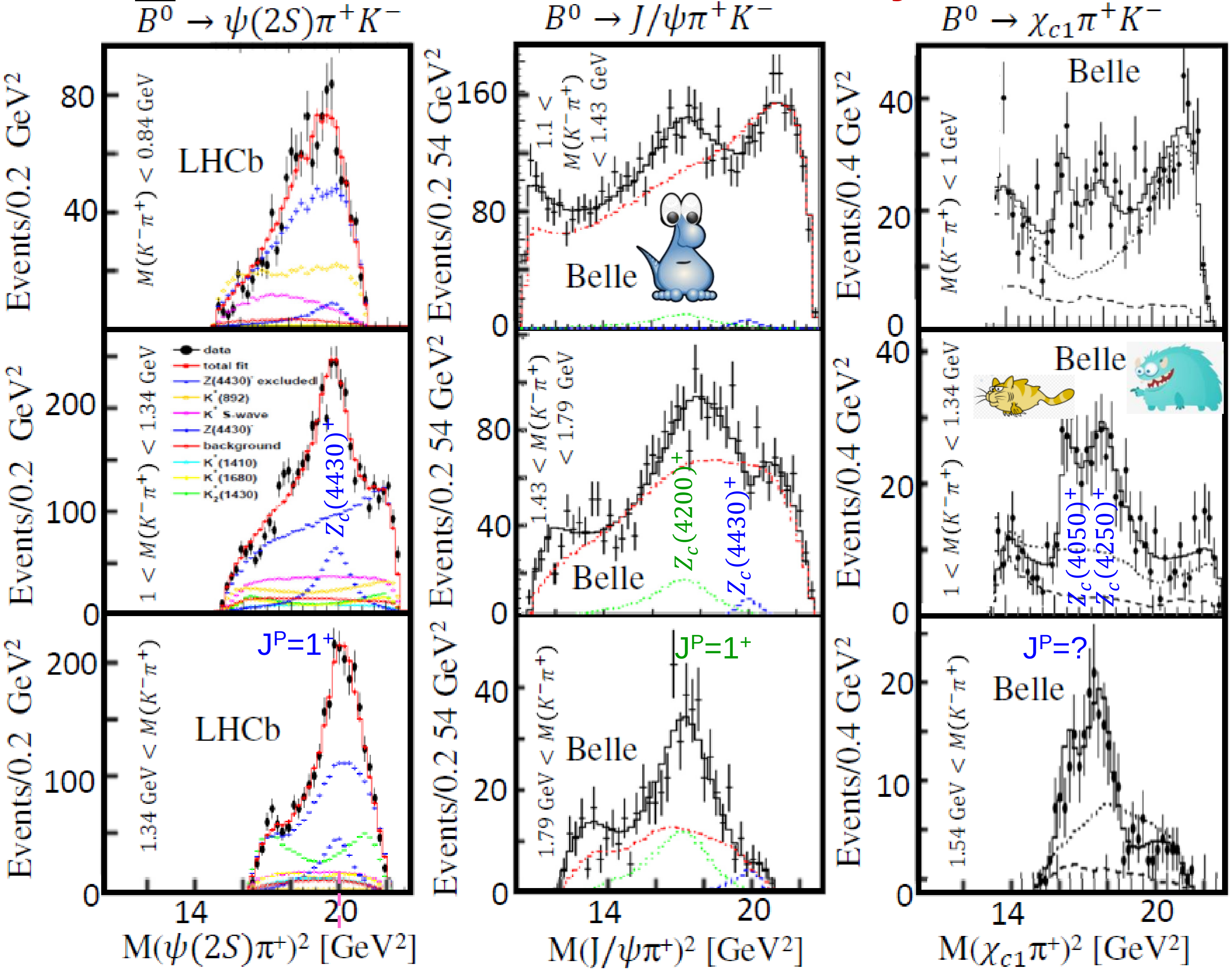
Charged charmonium-like states in B decays

(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?

Many other strange animals with no clear interpretation

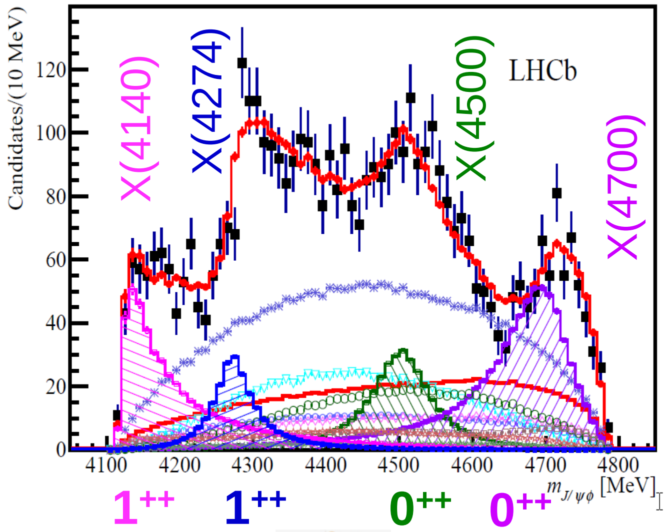
LHCb PRL118, 022003 (2017)
PRD95, 012002 (2017)

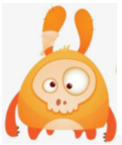
Thomas Britton, PhD, Syracuse. 2016
https://surface.syr.edu/etd/510/

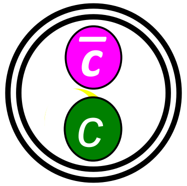
$B \to XK, X \to J/\psi\phi$

molecules, tetraquarks, $3,4^3P_{1,0}\ (c\bar{c})$ in the mix?

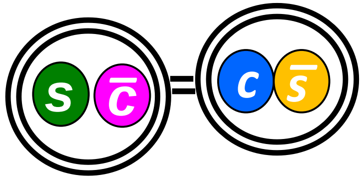
(some seen also by CDF,D0,CMS)





Comparison with $B \to XK, X \to J/\psi\omega$ and the strange J^P pattern speak against $c\bar{c}$ interpretation

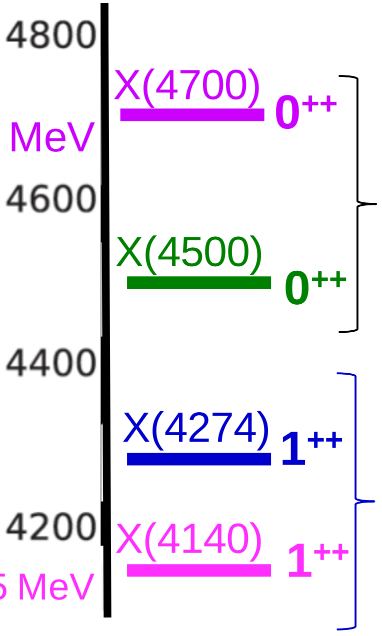


Plenty of other thresholds, but no matching J^{PC} numbers

No η-exchange

No π-exchange forces!

η-exchange OK



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)

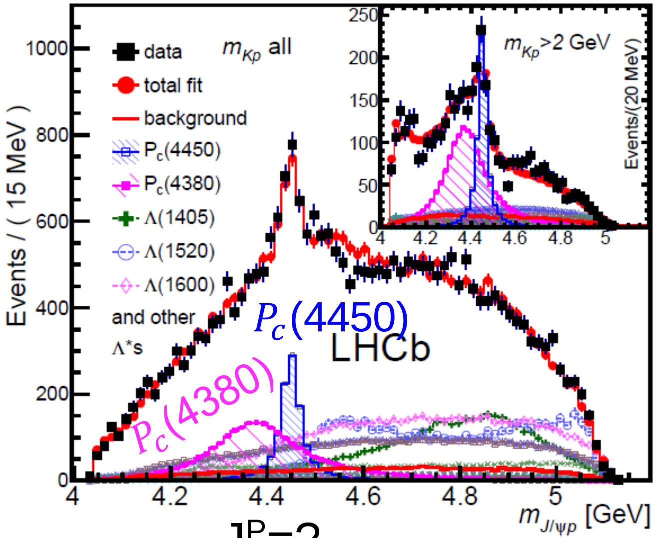
Many other strange animals with no clear interpretation

LHCb PRL 115, 072001 (2015)

Nathan Jurik. PhD Syracuse 2016
https://surface.syr.edu/etd/640/

$\Lambda_b^+ \to P_c^+ K, P_c^+ \to J/\psi p$

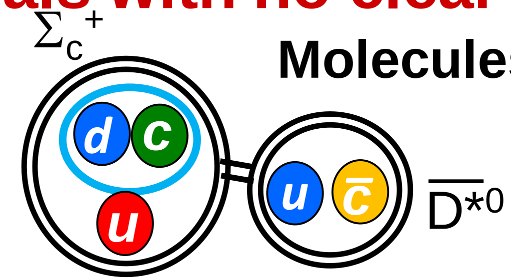
molecules,tetraquarks,
triangle anomalies?



J^P=?

LHCb will have almost 10x more $\Lambda_b^+ \to J/\psi p K$ by Dec.

Molecules



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

Karliner,Rosner PRL115, 122001(2015) and others

$\frac{1}{2}^+, \frac{3}{2}^+$ — $p\,\chi_{c1}$ +1±3 MeV

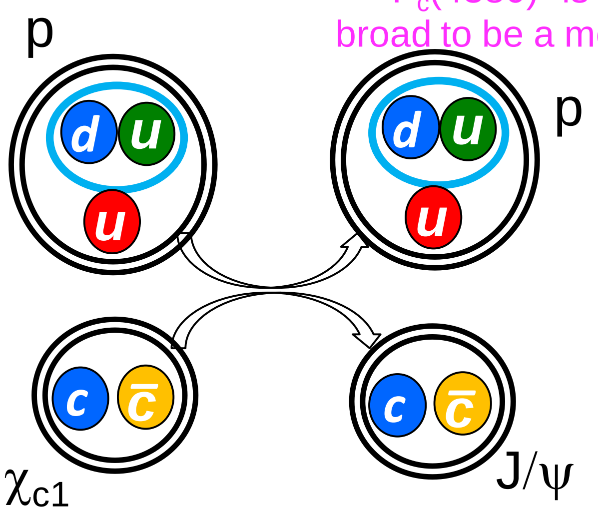
$\frac{1}{2}^-, \frac{3}{2}^-$ — $\Sigma_c^+ \bar{D}^{*0}$ - 10±3 MeV

$P_c(4450)^+$ $\frac{5}{2}^{\mp}$ or $\frac{3}{2}^{\mp}$

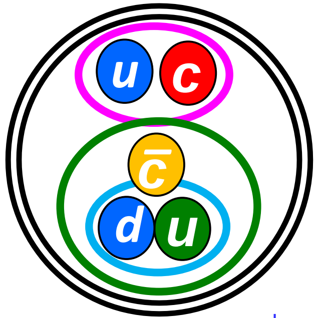
$P_c(4380)^+$ $\frac{3}{2}^{\mp}$ or $\frac{5}{2}^{\mp}$

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

J^P "preferred" rather than definitely determined



Tightly-bound penatquark



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

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

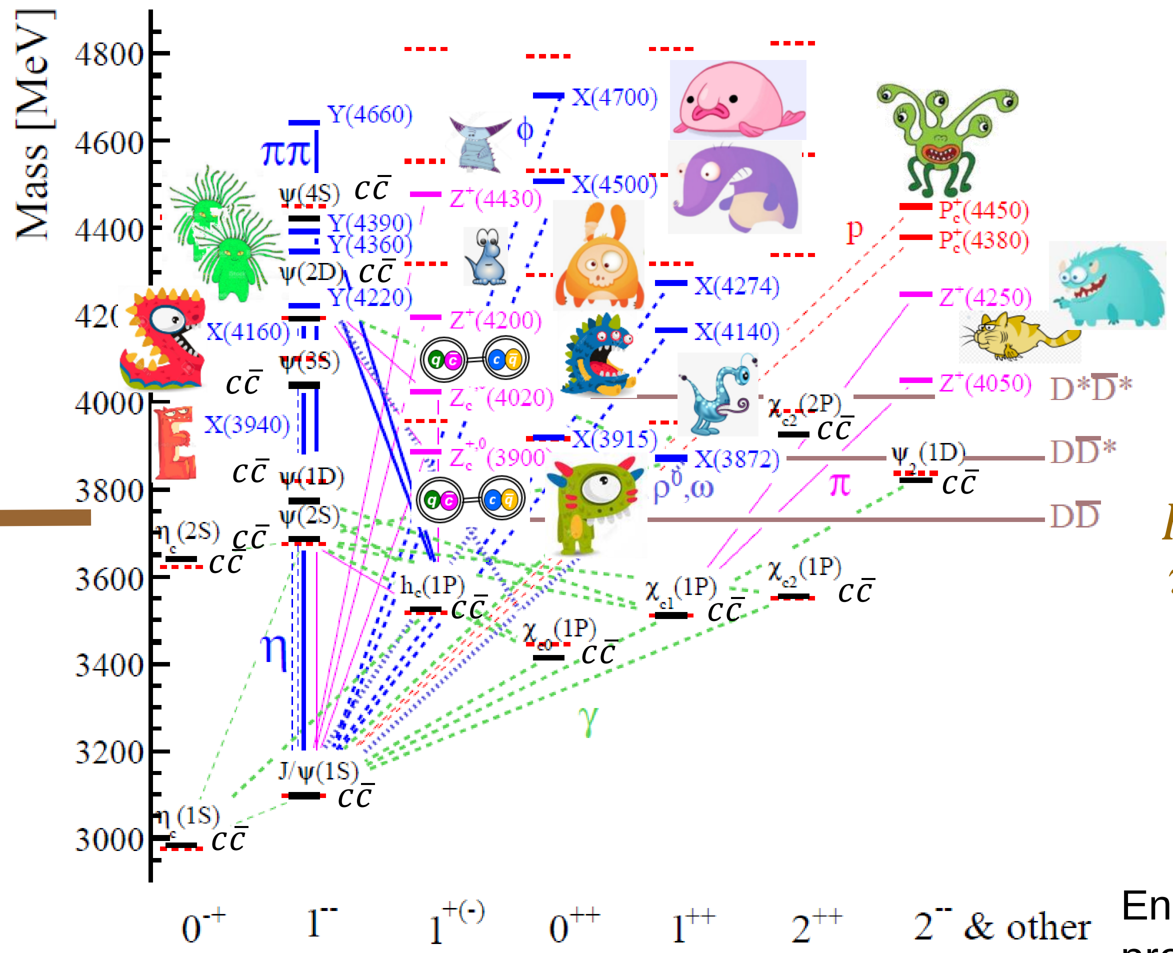
Such mass difference and the opposite parity can be explained by $\Delta L=1$ and $\Delta S=1$

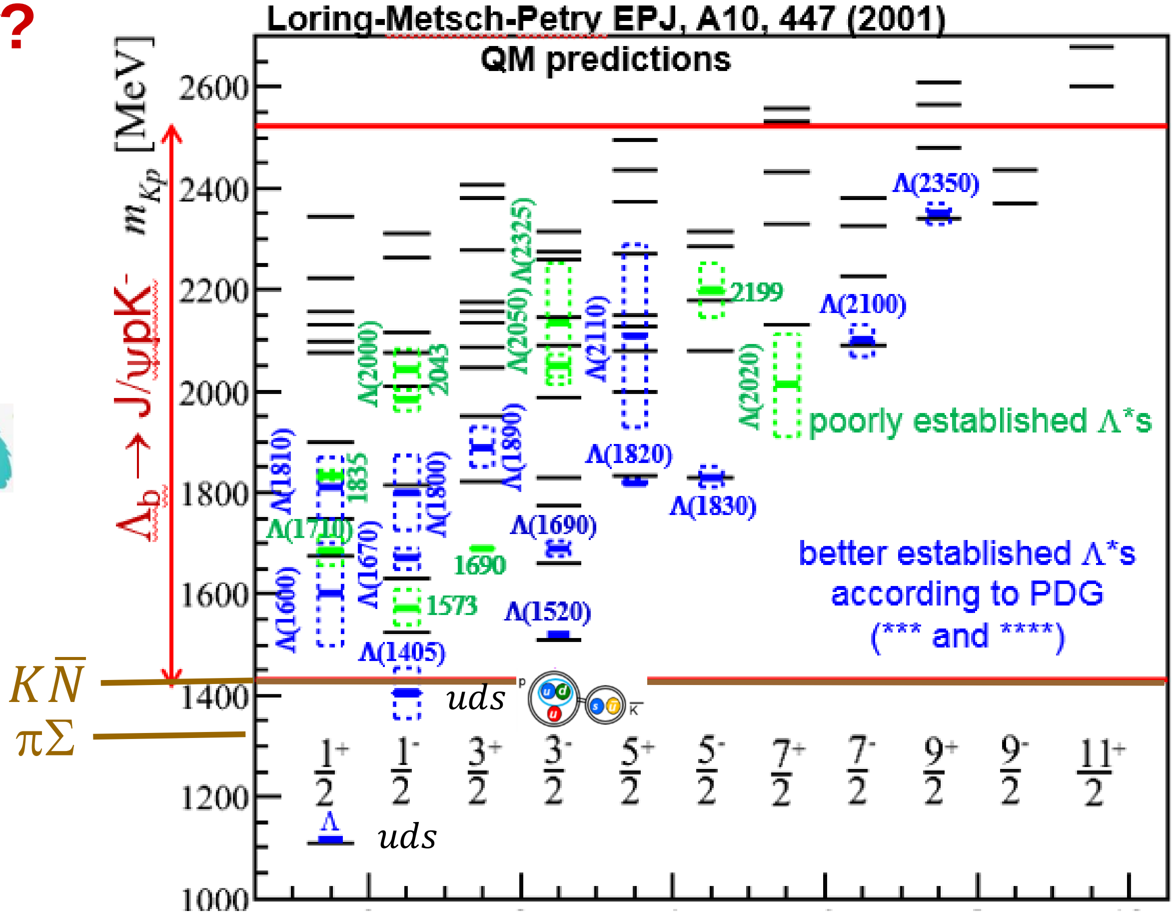
However, where are all the expected other excitations ?

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

Rethinking of light hadron spectroscopy?

Above multiquark-threshold

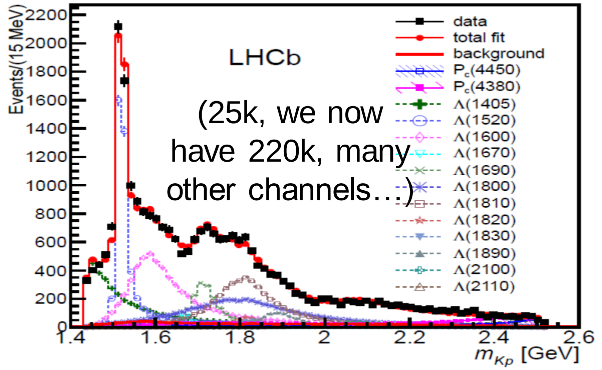




States may be “missing” for a good reason

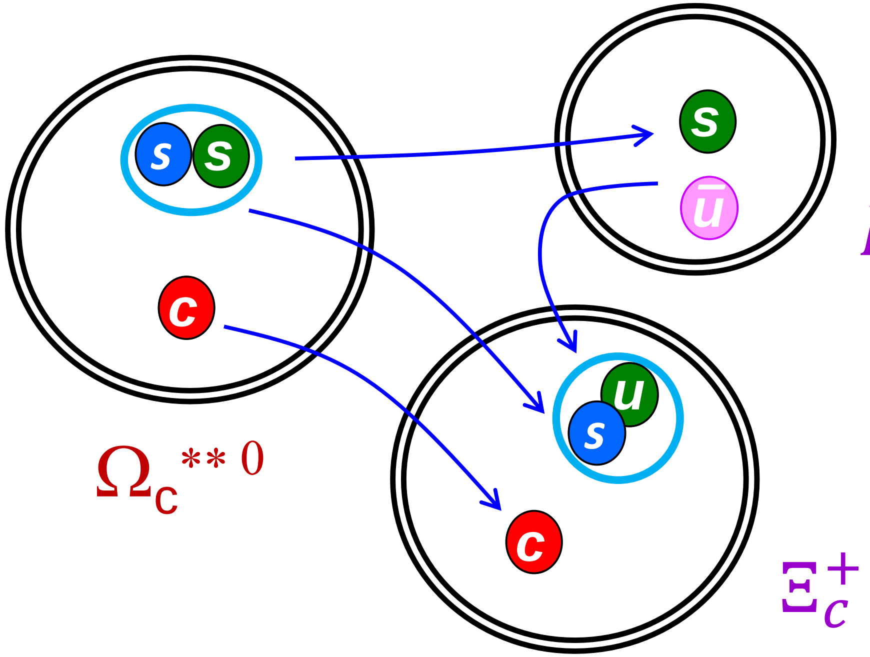
If charmonium is such a freak-show zoo above the open flavor threshold, we need to keep an open mind about multiquark or hybrid states altering expectations based on naïve $(q\bar{q}),(qqq)$ models. Analyzes of coupled channels, and of many observables are important for probing natures of the observed states.

Enormous samples of light hadrons produced in decays of b-hadrons are largely unutilized → opportunity for nuclear and high-energy communities to team up



Plenty of evidence for diquarks in heavy baryons (example)

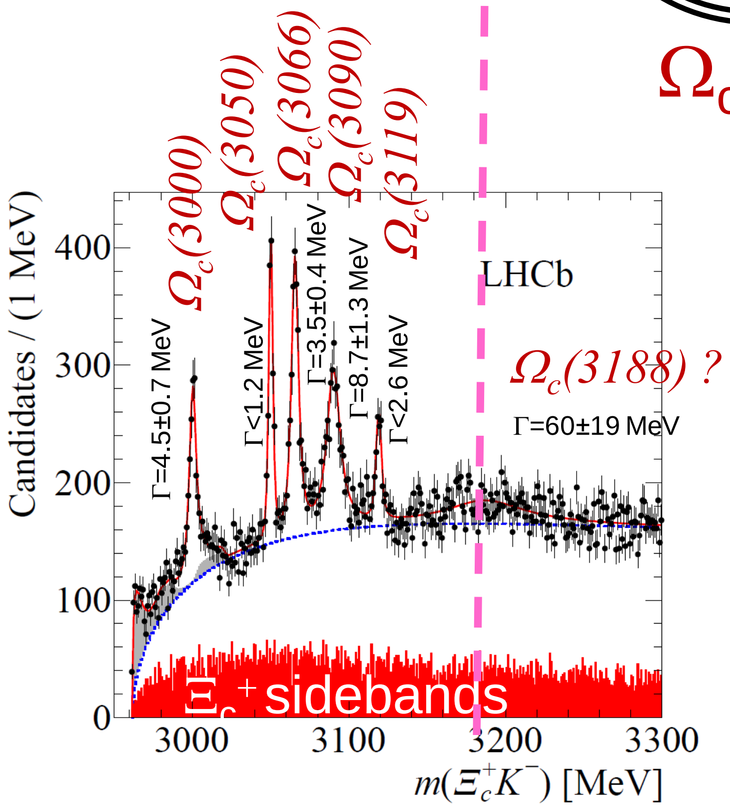
Spin of charm quark decouples because of its heavy mass: good place to study ss quark pairs:

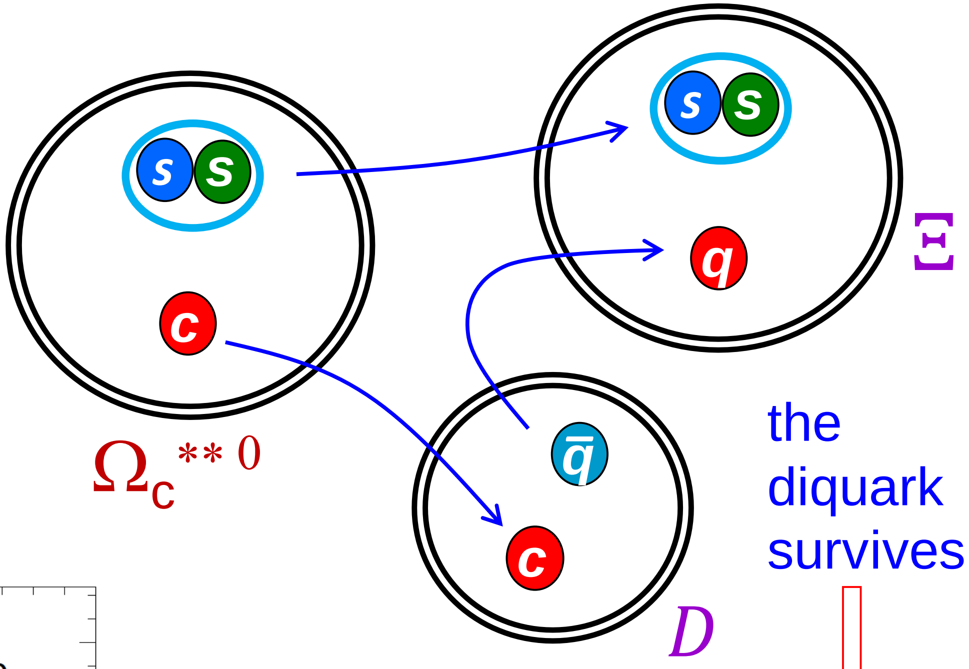


OZI allowed but rips the diquark apart

narrow

ΞD threshold





the diquark survives

wide

LHCb PRL 118, 182001 (2017).

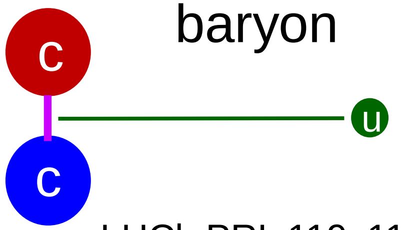
$\Omega_c^{**\,0} \to \Xi_c^+ K^-$

(Strong decay)

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

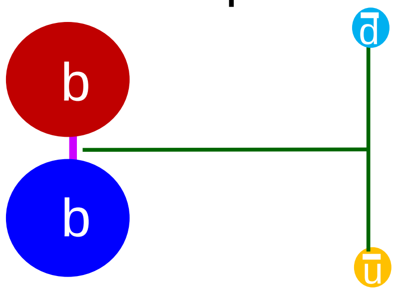
Doubly-flavored tetraquarks

baryon

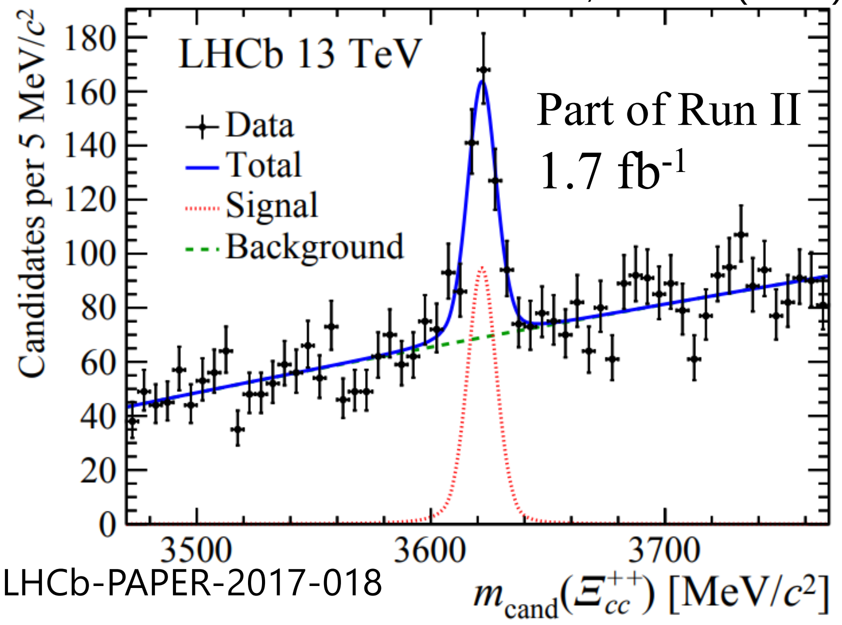


Replace the light quark with light anti-diquark in color triplet configuration

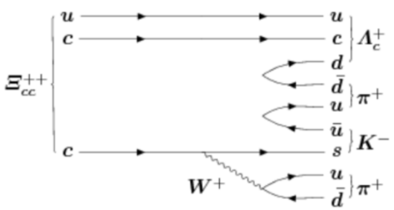
tetraquark



LHCb PRL 119, 112001 (2017)

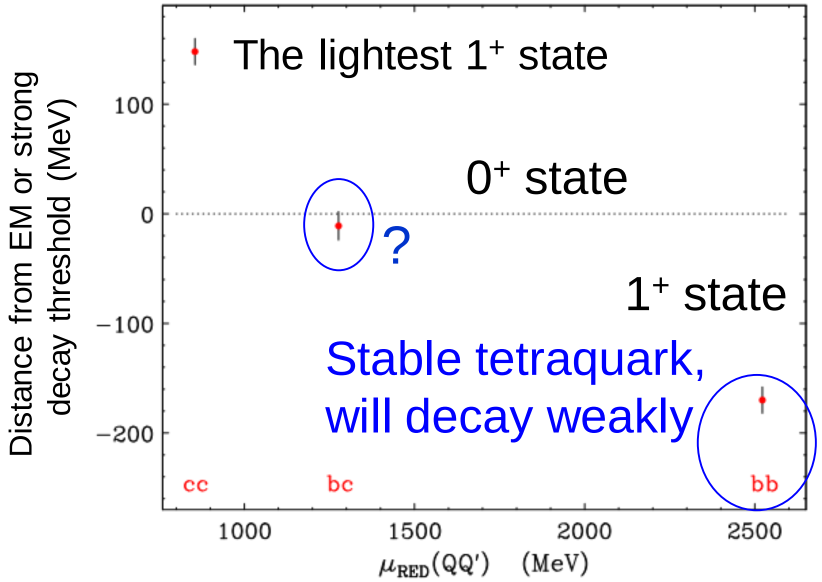


LHCb-PAPER-2017-018



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

the same toolkit



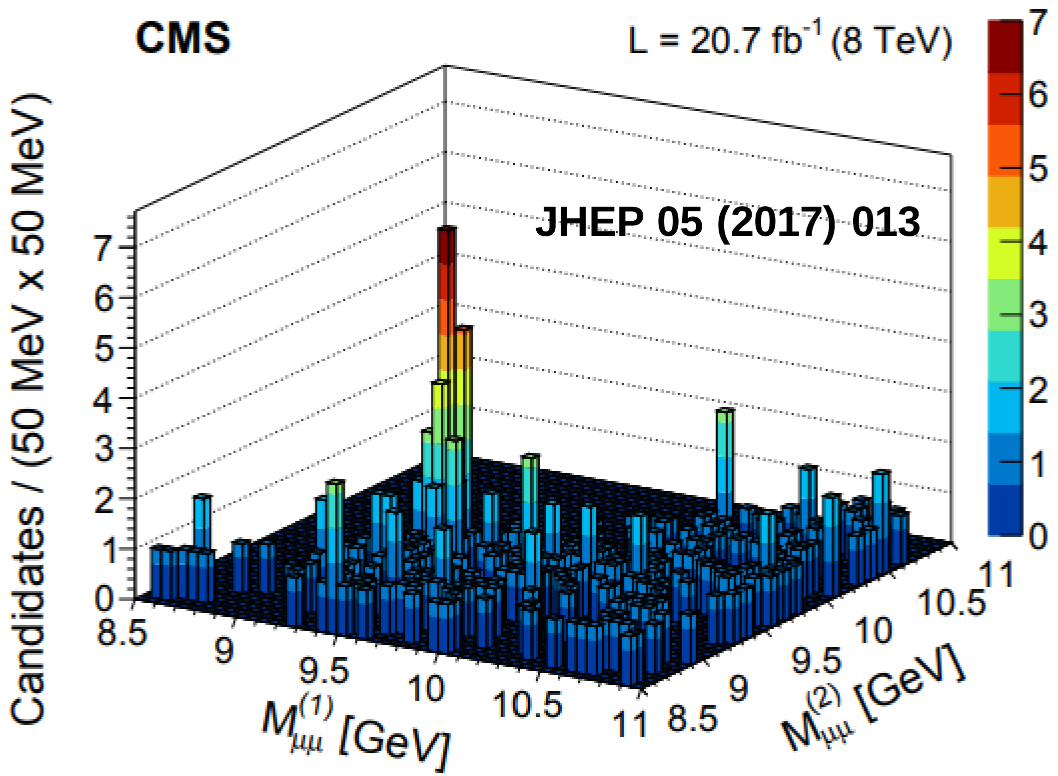
Karliner,Rosner PRD90,094007 (2014)

State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
		LHCb 3621 ± 1	
Ebert,Faustov,Galkin,Martynenko PRD66, 014008 (**2002**)		3620	3627

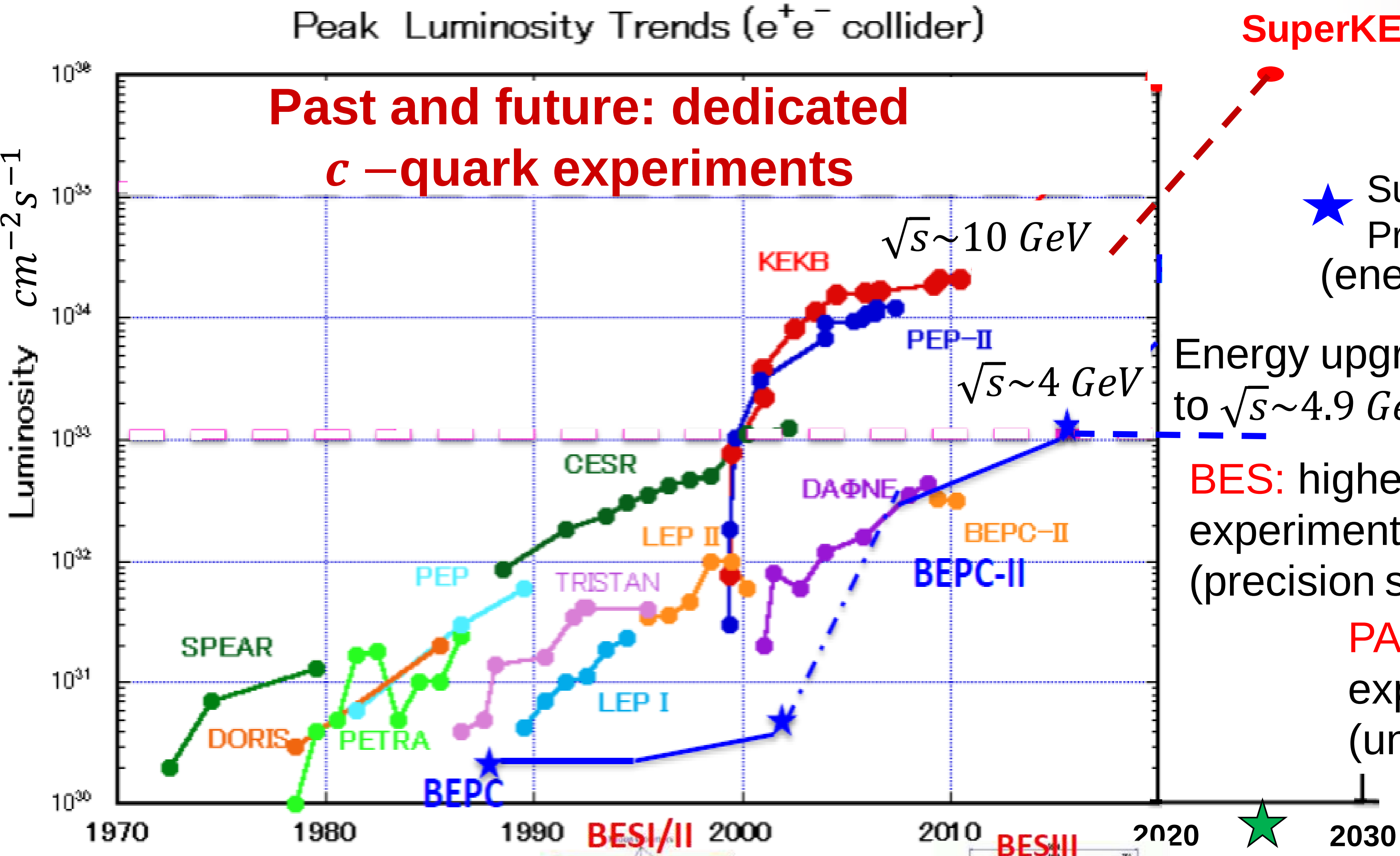
Karliner,Rosner PRL 119, 202001 (2017)
See also:
Eighten,Quigg PRL 119, 202002 (2017);
Czarnecki,Leng,Voloshin PL B778, 233 (2018)
Esposito,Papinutto,Pilloni,Polosa, et al PRD88, 054029 (2013); and others

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 Y(1S)Y(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).



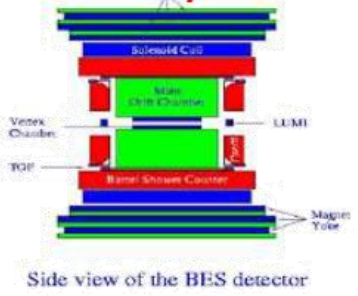
★ Super Tau-Charm Factory (STCF)
Proposed at Beijing and Novosibirsk
(energy up to $\sqrt{s}$~7 GeV)

Energy upgrade to $\sqrt{s}$~4.9 GeV

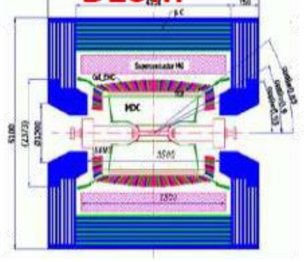
BES: highest luminosity $e^+e^- \to c\bar{c}$ experiment near the charm threshold (precision scanning)

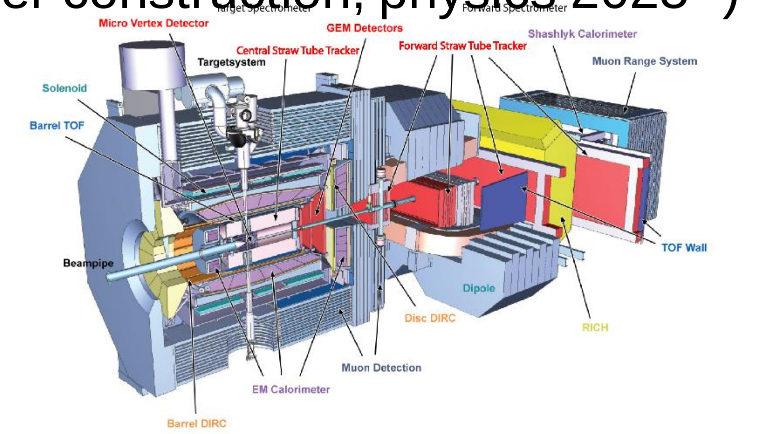
PANDA: highest luminosity $p\bar{p} \to c\bar{c}$ experiment near the charm threshold (under construction; physics 2025-)

BESI/II

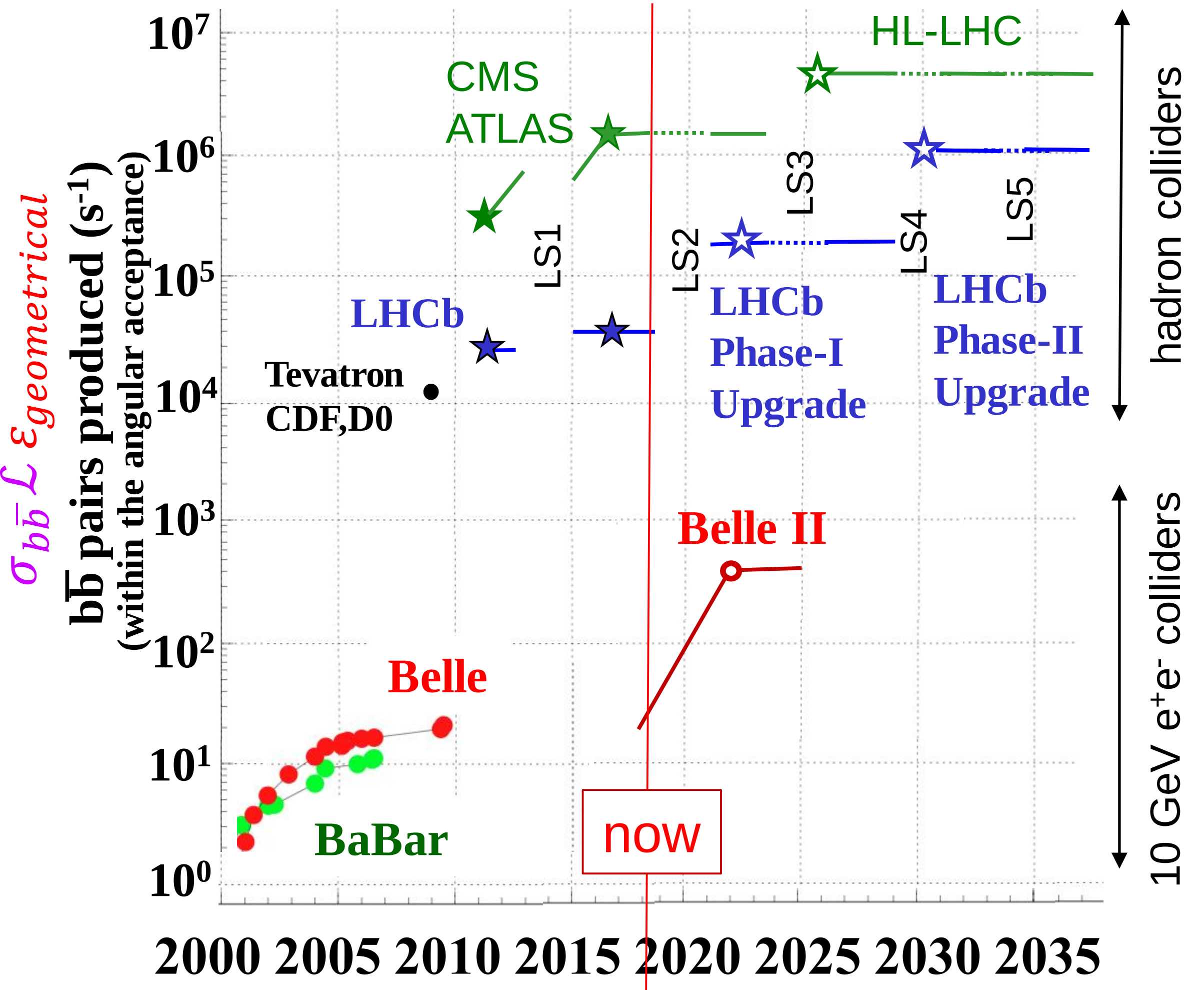


BESIII





Colliders and $b\bar{b}$ rates Past and future: experiments producing b-hadrons

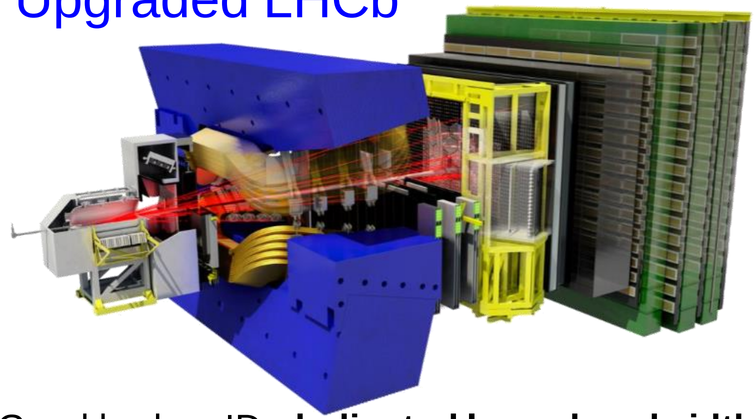


CDF 10 fb^{-1} , D0 8 fb^{-1}

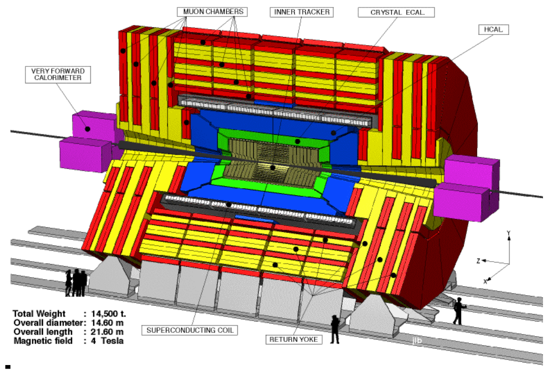
$\int \mathcal{L}\, dt$	Run I	Run II	Run III	Run IV	Run V+VI
LHCb	3 fb^{-1}	5 fb^{-1}		50 fb^{-1}	300 fb^{-1}
ATLAS,CMS	25 fb^{-1}	450 fb^{-1}		3000 fb^{-1}	
$\sqrt{s_{pp}}$	7-8 TeV	13 TeV	14 TeV	14 TeV	(27 TeV HE-LHC?)

- Decays of b-quark proved to be an excellent source of hadrons containing $c, c\bar{c}$
- These experiment see directly produced charm as well

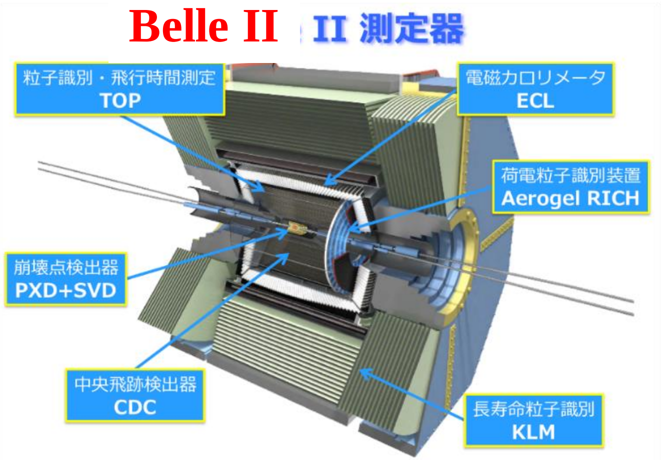
Upgraded LHCb



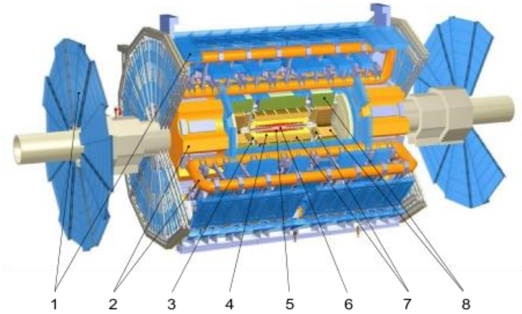
CMS



Good hadron ID, **dedicated large-bandwidth triggers.**
Enormous rates of b-mesons and **b-baryons**



Good hadron ID, **good detection of neutrals**.
Good absolute reconstruction efficiencies.



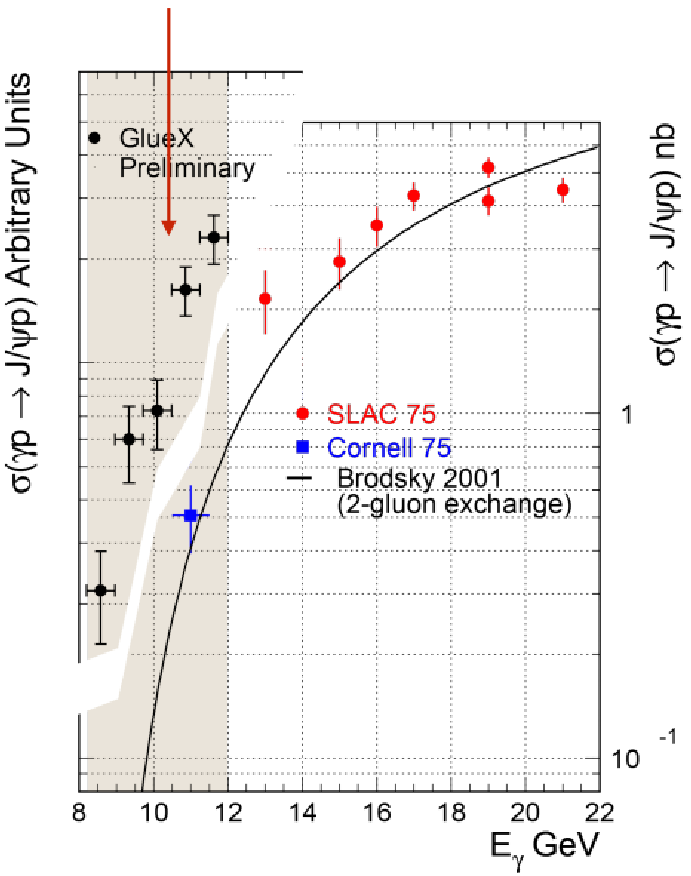
ATLAS

Higher luminosities than LHCb.
No hadron ID. Limited triggers.

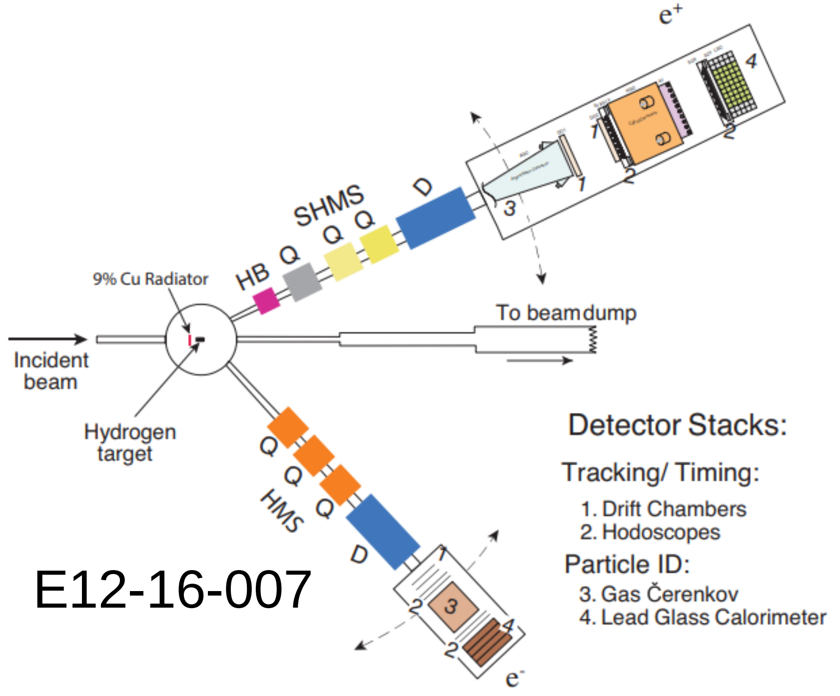
Future: photo-production of P_c states at JLab

$$\gamma p \rightarrow J/\psi p$$

GlueX preliminary

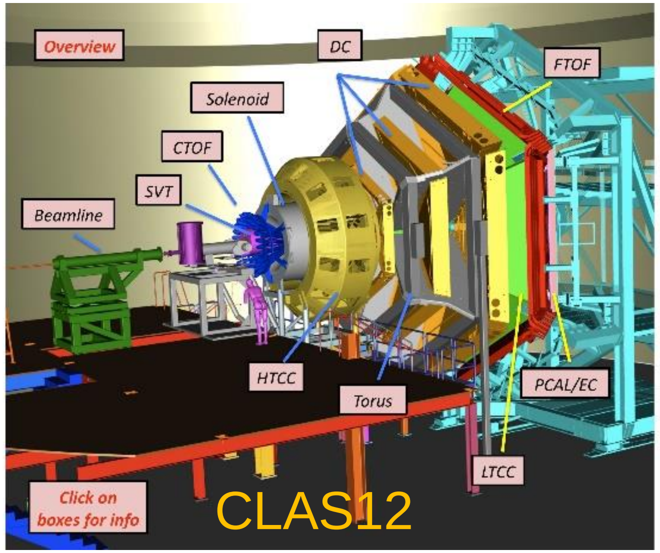


M. R. Shepherd
Bound States in Strongly Coupled Systems
March 15, 2018



E12-16-007

will run in Spring 2019



Conclusion

- New particle zoo for charmonium above open flavor threshold: more “exotic” than conventional states
  - Interplay of conventional states and meson-meson thresholds (molecules?) in X(3872) and in a few lighter hadrons
  - Good evidence for meson-meson molecules from the threshold $Z_b^{\pm,0}$, $Z_c^{\pm,0}$
  - Many more weird states (including pentaquark candidates) without well-established explanation
- Possible implications for light-quark hadron spectroscopy?
- No well established states with gluon as a constituent, but experimental efforts continue.
- Great prospects for orders of magnitude larger samples from on-going and future projects – expect resolution of existing questions but hopefully also new surprises