Summary of the Workshop on Exotic Hadrons

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Syracuse University

6th International Conference on New Frontiers in Physics, Κολυμβάρι, Ελλάδα, 26 August 2017

Workshop program

Monday Aug 21: Light hadron exotics

15:00	[1130] Exotic Baryons at MAMI (30 minutes)	WERTHMÜLLER, Dominik (University of Glasgow)
16:30	[1326] light exotic hadrons at BESIII (40 minutes)	JIAO, Jianbin (Shandong University)
17:10	[1105] Structure of excited charmed baryons studied by pion emission decays (30 minutes)	Prof. NAGAHIRO, Hideko (Nara Women's University)
17:40	[1114] Heavy hadron production for the study of their structure (20 minutes)	HOSAKA, Atsushi (Osaka University)
18:00	[1142] Strange and Charm Baryon Spectroscopy at J-PARC (40 minutes)	Prof. NOUMI, H.
18:40	[1237] Excited vector mesons: phenomenology and predictions for a yet unknown vector $\bar{s}s$ state with a mass of about 1.93 GeV (20 minutes)	PIOTROWSKA, Milena (Jan Kochanowski University)

Tuesday Aug 22: Heavy-quarkonium-like exotics (experimental)

11:00	[1339] The X(3872) and other charmonium puzzles (40 minutes)	LARS OLSEN, Stephen
11:40	[1110] Z_c states observed in pipi transitions to charmonium states (40 minutes)	LYU, Xiao-Rui (University of Chinese Academy of Sciences)
12:20	[1239] Charged bottomonium-like states at Belle (40 minutes)	BONDAR, Alex (Budker Institute of Nuclear Physics (RU))
13:00	[1134] Vector states above open charm threshold (40 minutes)	Prof. WANG, Zhi-yong (IHEP,CAS)
15:00	[1238] Vector bottomonium-like states at Belle (40 minutes)	MIZUK, Roman (Lebedev Physical Institute)
15:40	[1127] BES III future prospects in exotic hadron spectroscopy (20 minutes)	Dr. ZHU, Kai (Institute of High Energy Physics, China)
16:30	[1209] Exotic meson candidates from amplitude analyses of B meson decays (40 minutes)	SKWARNICKI, Tomasz (Syracuse University (US))
17:10	[1148] Pentaquark candidates in LHCb (40 minutes)	ZHANG, Liming (Tsinghua University (CHINA))
17:50	[1396] Discussion (20 minutes)	

Wednesday Aug 23: Phenomenology of exotic hadrons

11:00	[1293] Hunting for exotic doubly hidden-charm/bottom $QQ\bar Q\bar Q$ tetraquark states (30 minutes)	Prof. CHEN, Wei (Sun Yat-sen University)
11:30	[1096] Charmed states on the lattice (30 minutes)	SOLOVJEVA, Olga (Alikhanov Institute of Theoretical and Experimental Physics)
12:00	[1176] Understanding X(3862), X(3872), and X(3930) in a Friedrichs-model-like scheme (30 minutes)	Dr. XIAO, Zhiguang (University of Science and Technology of China)
12:30	[1117] Quark-Gluon Mixing in Abelian Decomposition of QCD (30 minutes)	Prof. CHO, Yongmin (Konkuk University)
13:00	[1331] Amplitude analysis of the exotic states (30 minutes)	MIKHASENKO, Mikhail (University of Bonn (DE))
15:00	[1062] Threshold effects in hadron spectrum: a new spectroscopy? (30 minutes)	Dr. ORTEGA, Pablo G (IUFFyM Universidad de Salamanca)
15:30	[1179] Narrow-width tetraquarks in large-N_c QCD (30 minutes)	Prof. SAZDJIAN, Hagop (IPN, University Paris-Sud, Orsay)
16:30	[1244] Issues at forefront of heavy quark spectroscopy (45 minutes)	Prof. KARLINER, Marek (Tel Aviv U.)
17:15	[1444] Is there a common Ariadne thread for all Exotic Hadrons? (45 minutes)	MAIANI, Luciano
18:00	[1398] Round Table Discussion (30 minutes)	

Conveners:

Alex Bondar, Budker Institute of Nuclear Physics, Novosibirsk, Russia
Roman Mizuk, Lebedev Physical Institute, Moscow, Russia
Tomasz Skwarnicki, Syracuse University, Syracuse, NY, USA

This talk

- Use elements of various talks given at the workshop to illustrate status of exotic hadron spectroscopy
- Neither a complete review of the field nor of all the talks given at the workshop
- I apologize to the workshop speakers not mentioned in the summary
- All talks were interesting and we often had animated discussions

Indicates the speaker's name for material copied from a workshop talk

See this talk for more details

"Exotic" multiquark states conceived already at the birth of Quark Model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

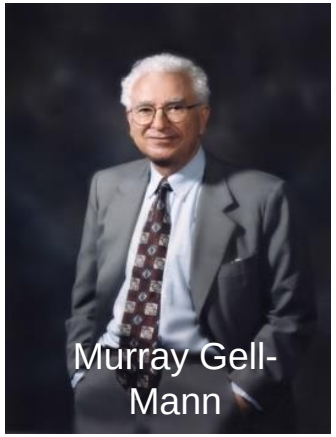
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

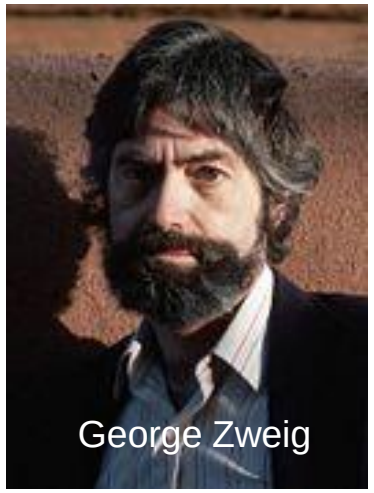
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

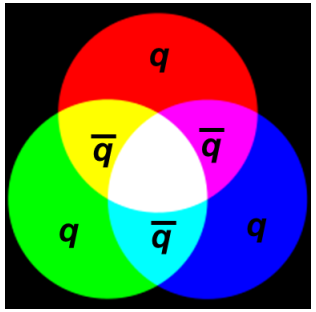
...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".



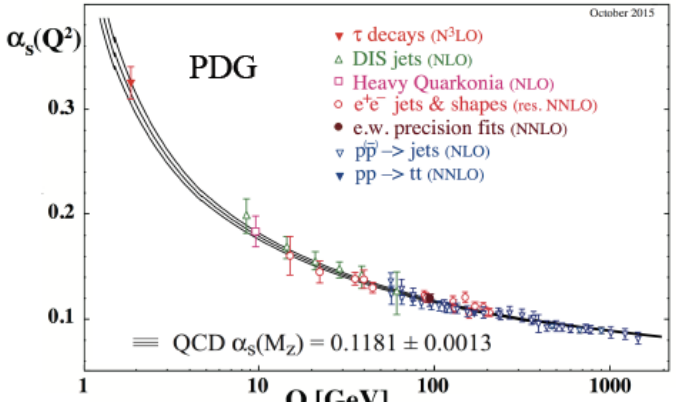
QCD

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



SU(3)$_{color}$
Gluons with
color-anticolor charge

1973



Confinement ⟺ Asymptotic freedom

Hadron sizes

Hadrons = Non-perturbative QCD

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

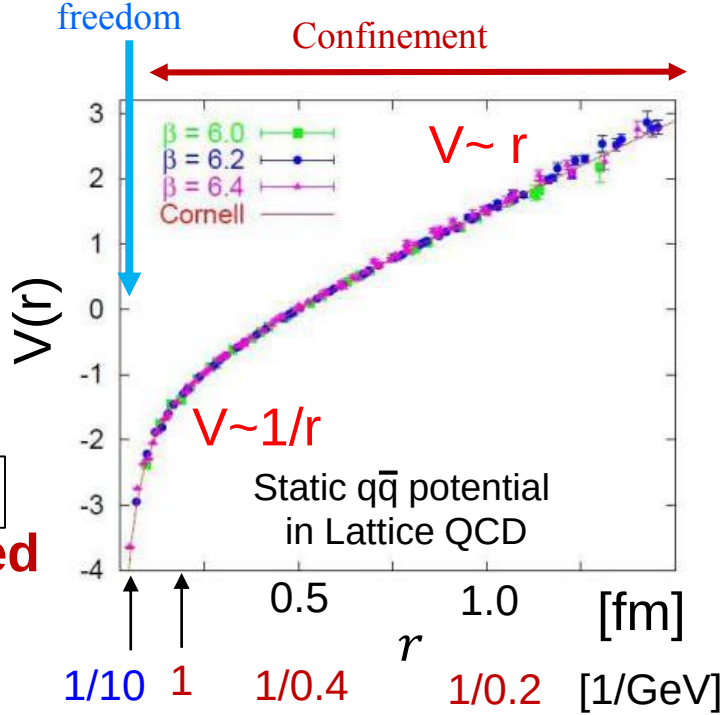
Only approximate lattice simulations for **unstable** higher excitations.

⟹ LQCD O.Solovjeva's talk

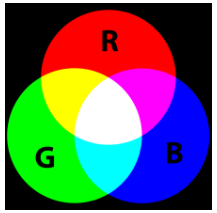
Expect hadrons with gluons as constituents:

- **Hybrids:** $(qq\boldsymbol{g}), (qqq\boldsymbol{g}), \ldots$
- **Glueballs:** $(\boldsymbol{gg}), \ldots$

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



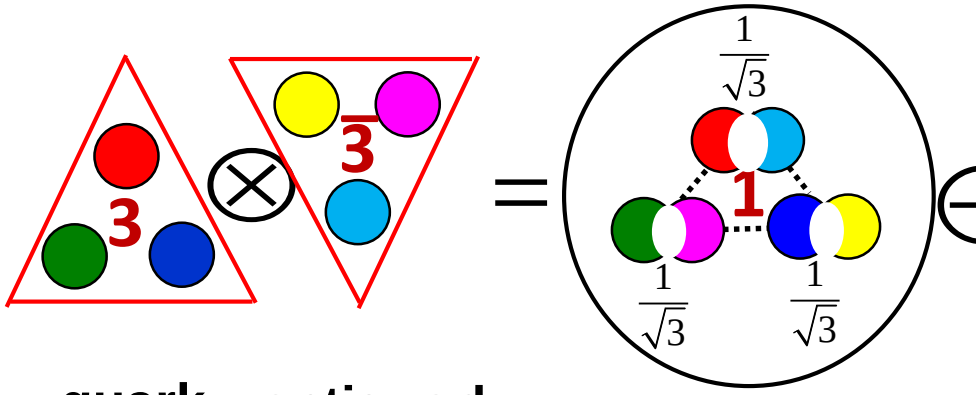
Mesons from quarks & antiquarks in QCD



color triplet

color antitriplet

color singlet

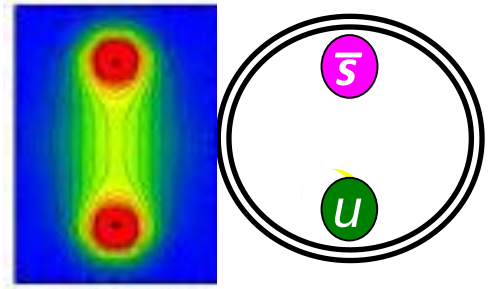


quark **antiquark**

q **q̄**

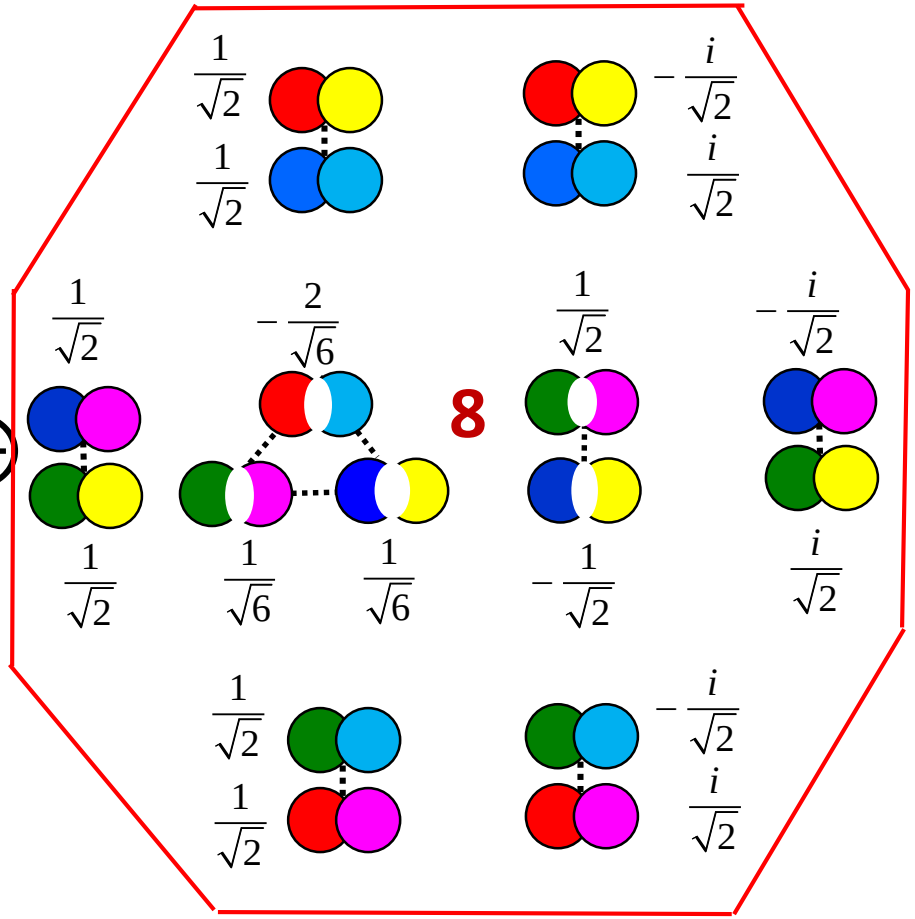
attractive color force

(qq̄) meson
e.g. K+



Color flux tube stretched between quark and antiquark with attractive potential

color octet

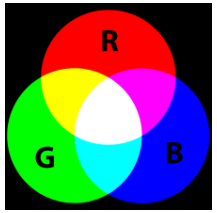


repulsive color force

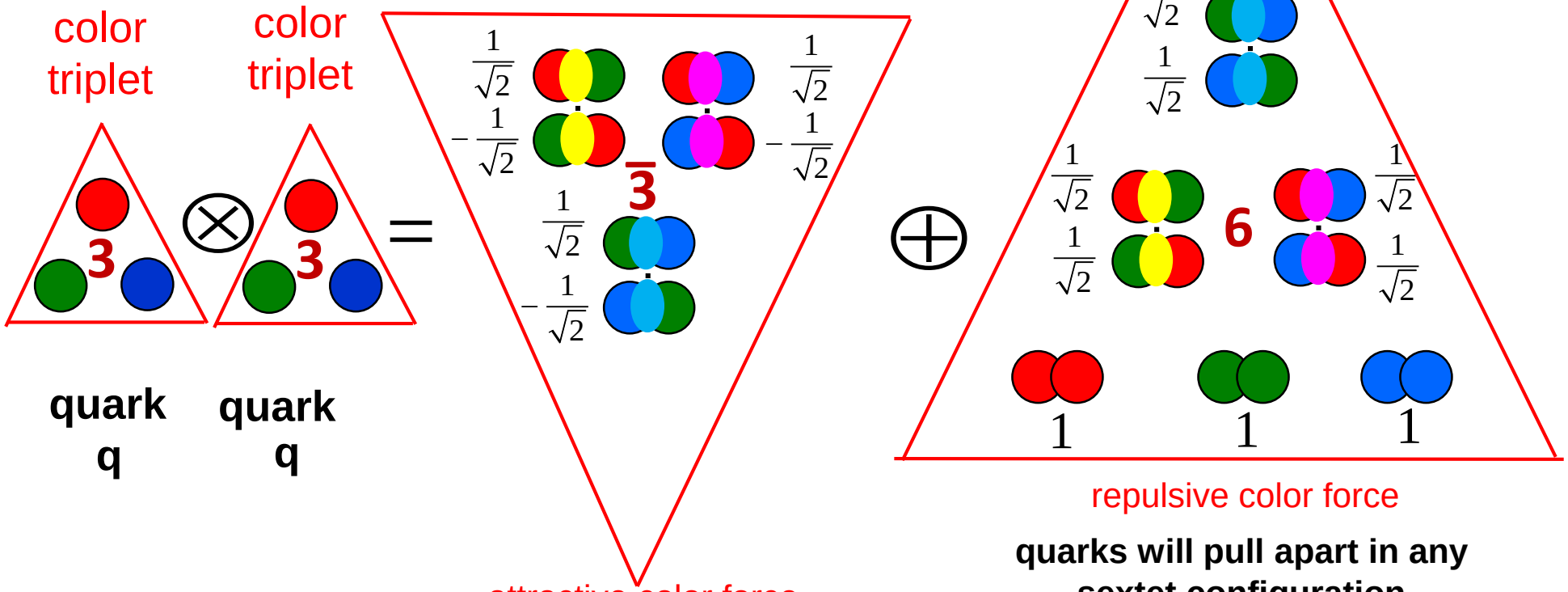
quarks will pull apart in any octet configuration

gluons happen to belong to the color octet

(Colored) diquarks in QCD



color triplet ⊗ color triplet = color antitriplet (antisymmetric) ⊕ color sextet (symmetric)



quark q **quark q**

attractive color force

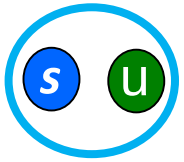
(half as strong as in the meson)

(qq) diquark

repulsive color force

quarks will pull apart in any sextet configuration

Color flux tube stretched between the quarks and extending to other color partners

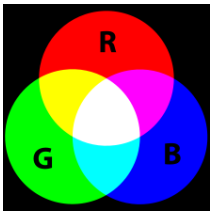


Not a particle, just a building block in QCD

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

⇨ *See Maiani's talk*

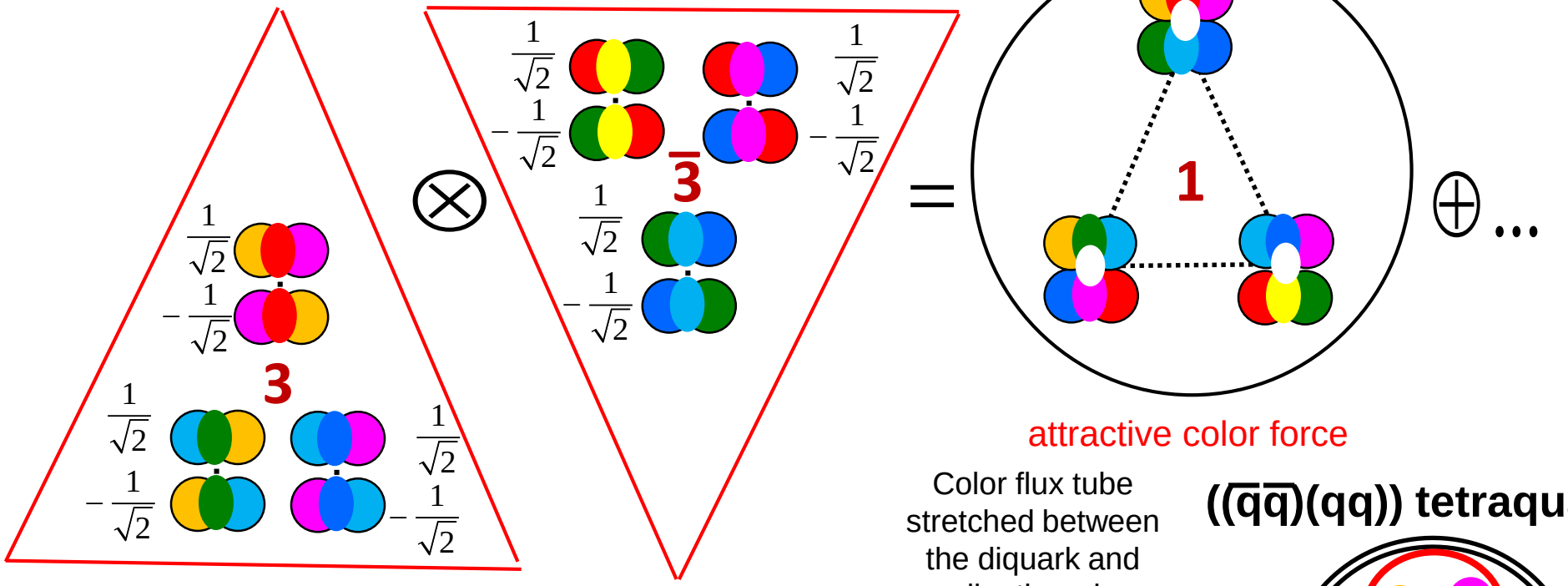
Diaquarks can make tetraquarks!



color triplet

color antitriplet

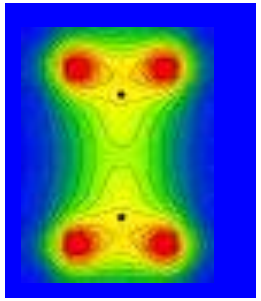
color singlet



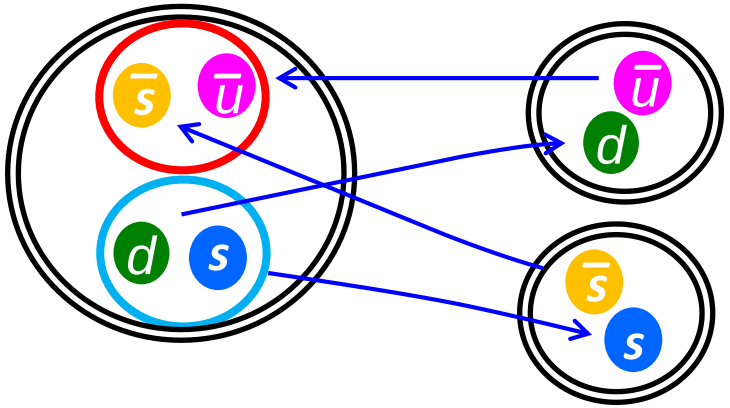
attractive color force

However, it is not clear if an efficient mechanisms to suppress the fall-apart mode to two mesons exists, especially when all quarks are light.

Color flux tube stretched between the diquark and diantiquark



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



attractive color force

$(\bar{q}\bar{q})$ diantiquark

↑

q

attractive color force

(qq) diquark

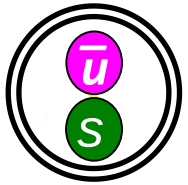
↑

$\bar{q}$

Conventional and "exotic" hadrons

Conventional

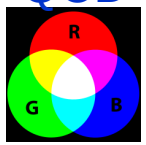
Strong binding.
Compact systems.



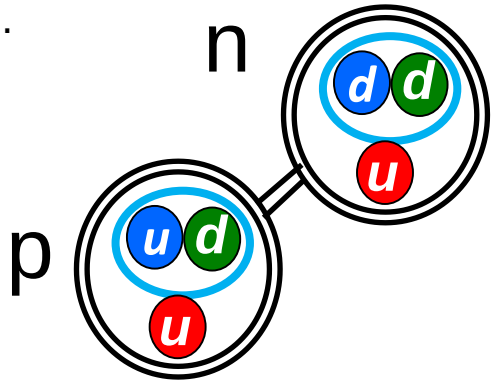
($s\bar{q}$)
K meson

((sd)u)
Λ baryon

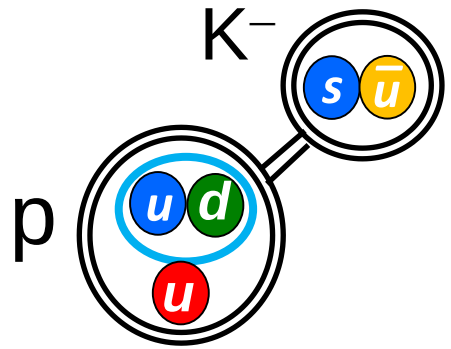
Meson and baryons motivated Quark Model and QCD



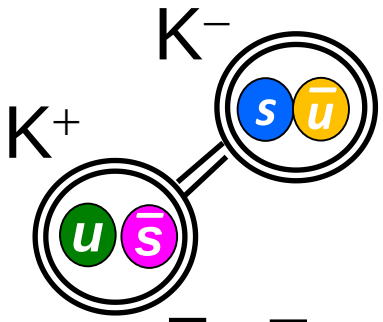
Weak binding. Large systems.



(u(ud)) (u(dd))
deutron



(u(ud)) ($s\bar{u}$))
KN **molecule**



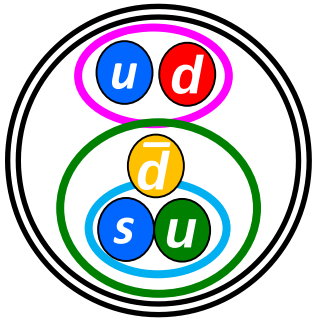
($s\bar{q}$) ($s\bar{q}$)
KK **molecule**

Baryonic molecules exists!

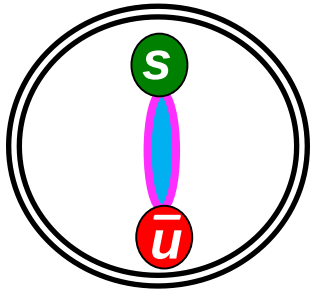
Are molecular forces in such systems strong enough to create bound states, or pronounced effects?

"Exotic"

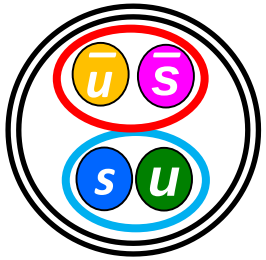
Strong binding. Compact systems.



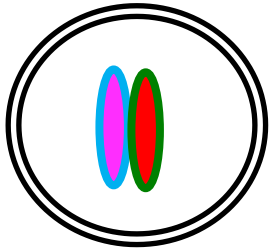
(($\bar{q}$(sq))(qq))
pentaquark



($s\bar{q}g$)
Hybrid meson



(($\bar{s}\bar{q}$)(sq))
tetraquark



(gg)
Glueball

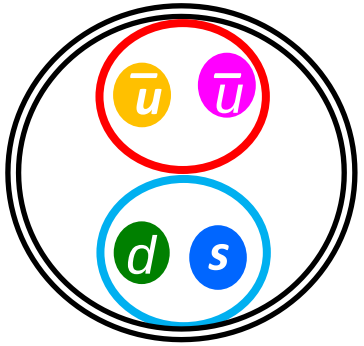
QCD predicts attractive forces in some of such configurations.
Do they live long enough to produce observable states/effects ?

Firmly expected in QCD

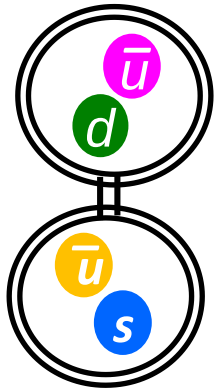
Tetraquarks vs meson-meson molecules

- 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

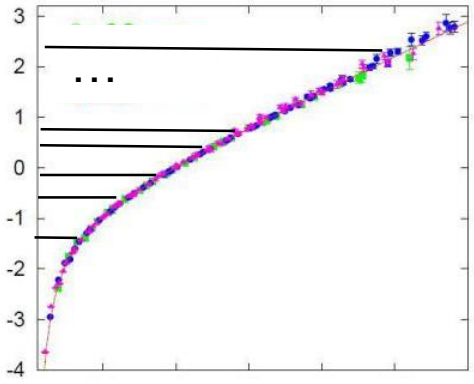


$(q\bar{q})$-$(q\bar{q})$
meson-meson molecule



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

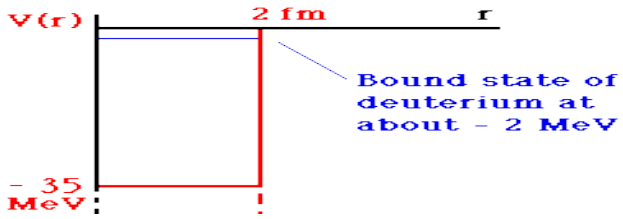
V(r)



r

Very rich mass spectrum expected!

However, states can be undetectable if extremely broad.



See Karliner's talk on Wed.

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

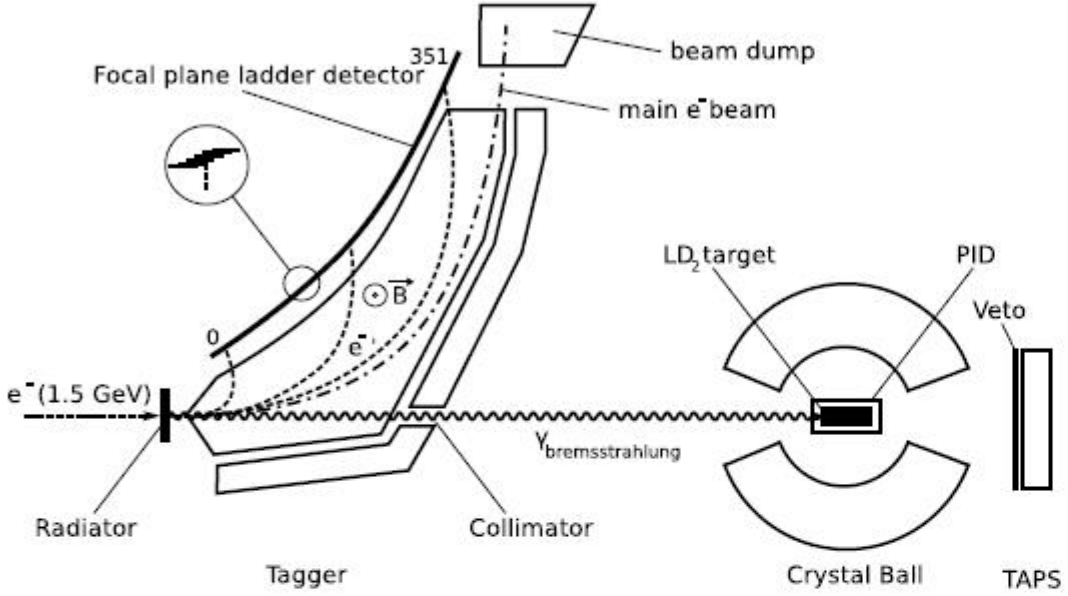
Fall apart prevented by spatial separation – long-lived states if below threshold.

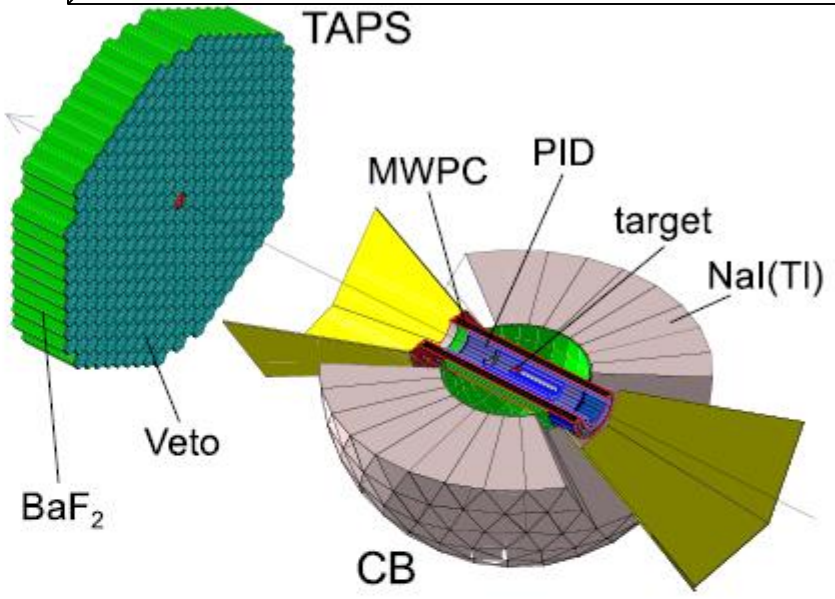
Mass and J^P fairly constrained from the constituents.

Exotic Baryons at MAMI

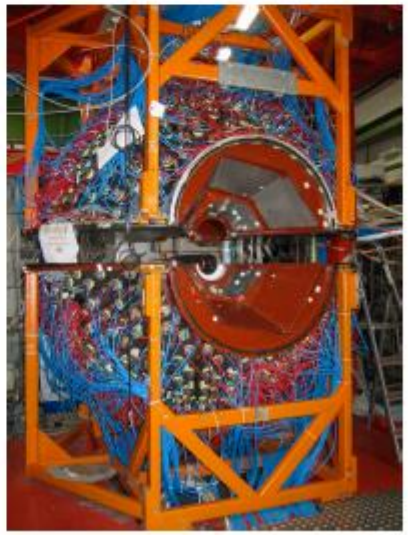
A2 Setup at MAMI

Dominik Werthmüller
on behalf of the A2 Collaboration at MAMI





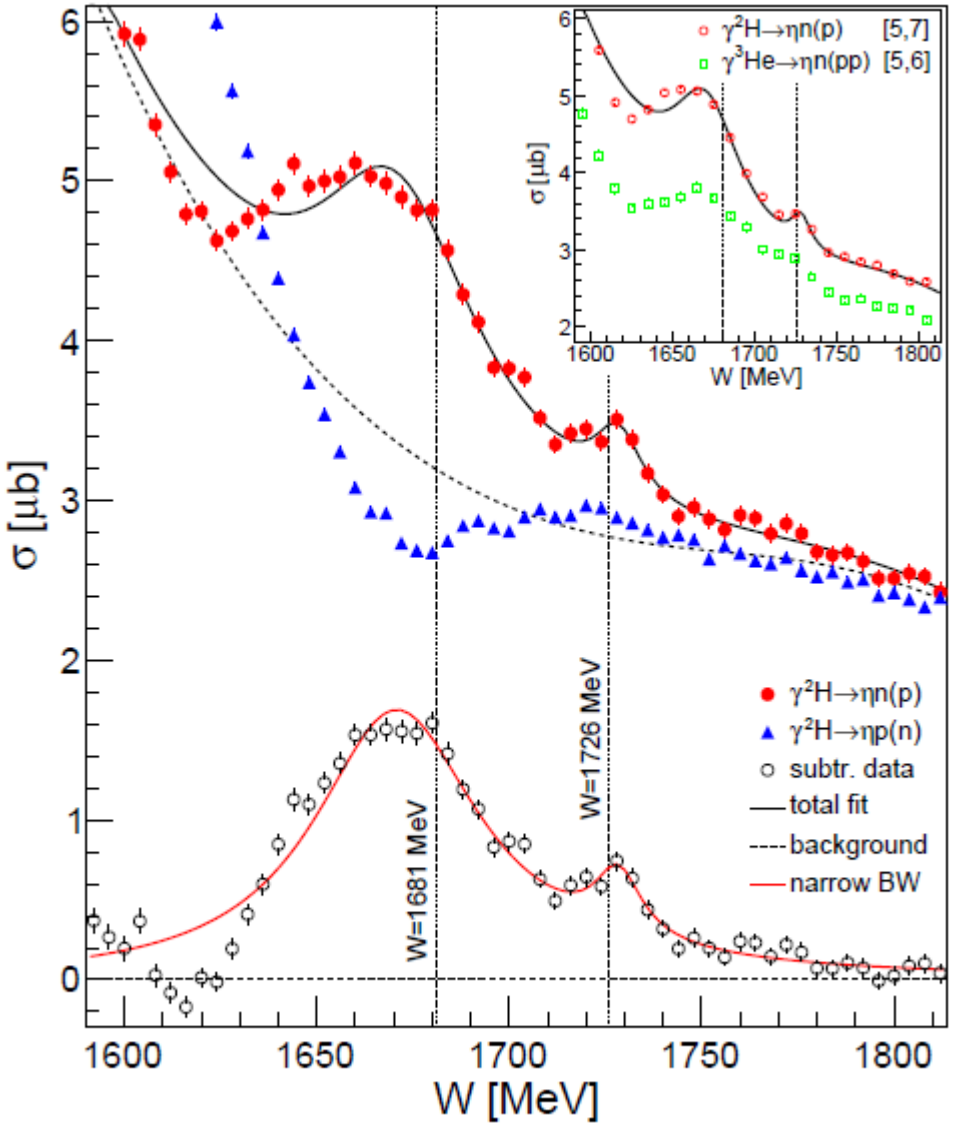
- energy-tagged bremsstrahlung photons from 1.6 GeV MAMI electron beam
- $\sim 4\pi$ calorimeter system (CB + TAPS)
- charged particle vetos / basic tracking
- available targets:
  - unpolarized: H, D, ^{3,4}He, solid targets
  - polarized: (D)-butanol, ^{3}He



N(1685)

Dominik Werthmüller

Unpolarized Cross Sections of $\gamma n \to \eta n$

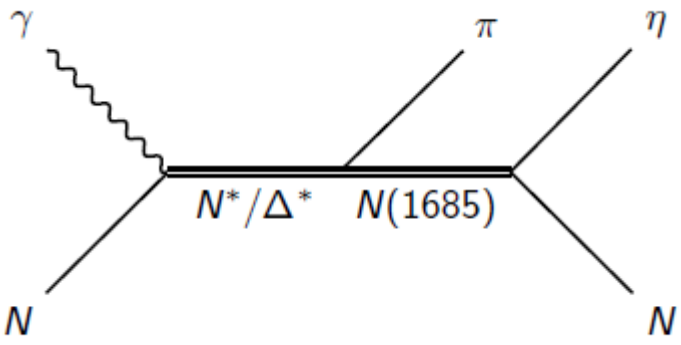


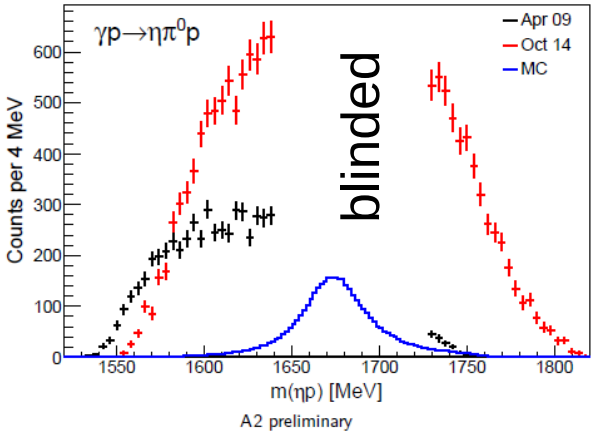
D. Werthmüller *et al.*, Phys. Rev. C 92, 069801 (2015)

N(1685) confirmed, N(1728)?

- Explanations:
  - interference of $N(1535)1/2^-$ and $N(1650)1/2^-$
  - strangeness threshold openings
  - exotic antidecuplet baryon i.e. pentaquark

Studies in progress:





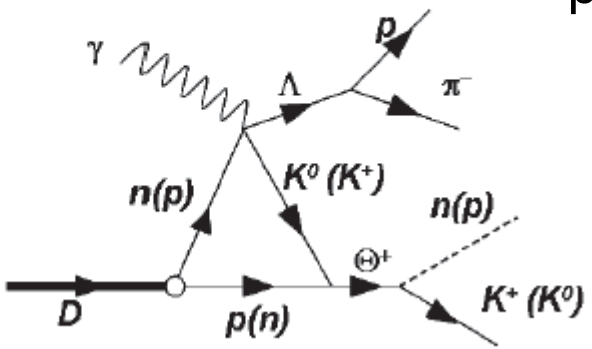
Proton target

Defamed Θ(1540)+

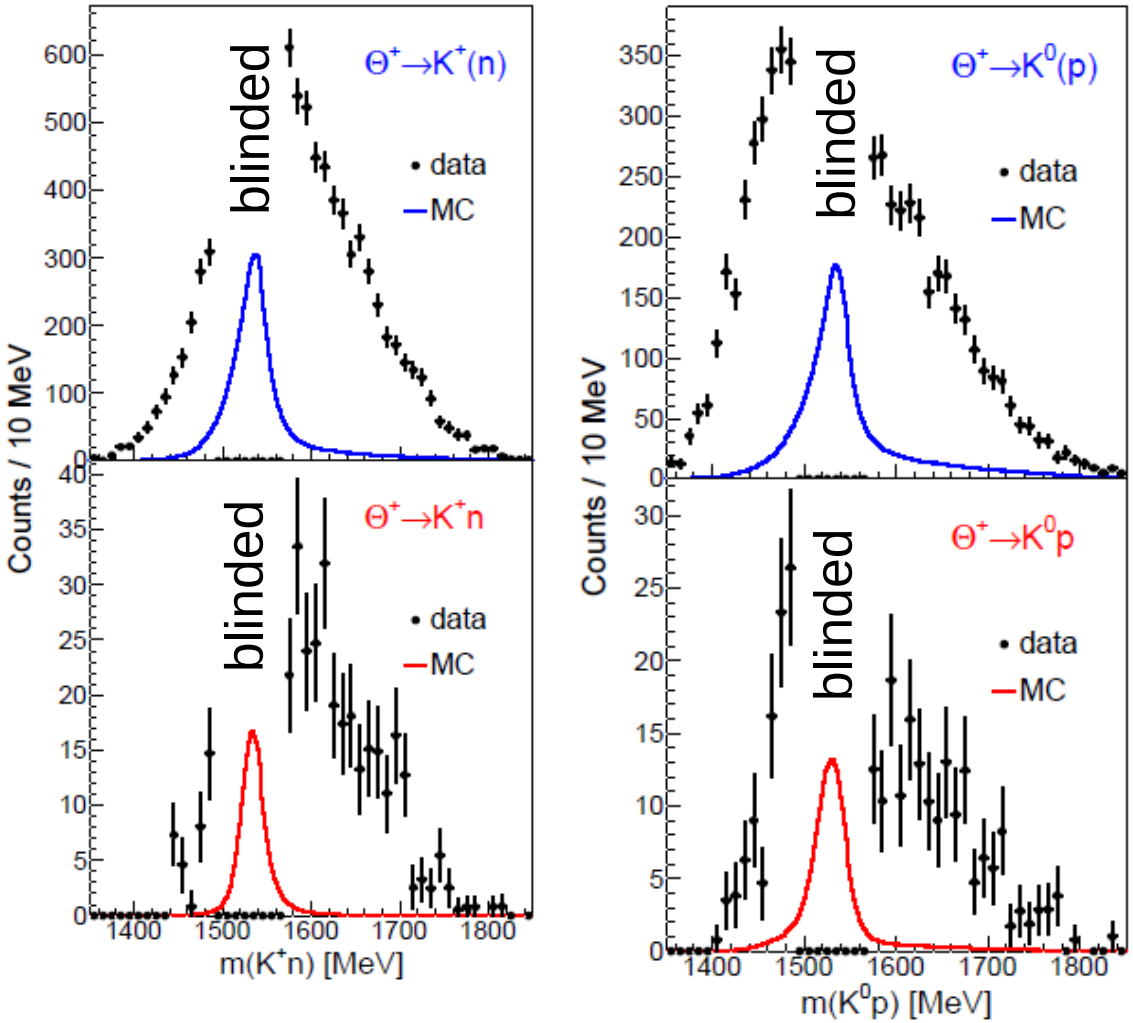
Dominik Werthmüller

$\Theta^+(1540)$ in $\gamma d \to \Lambda K N$

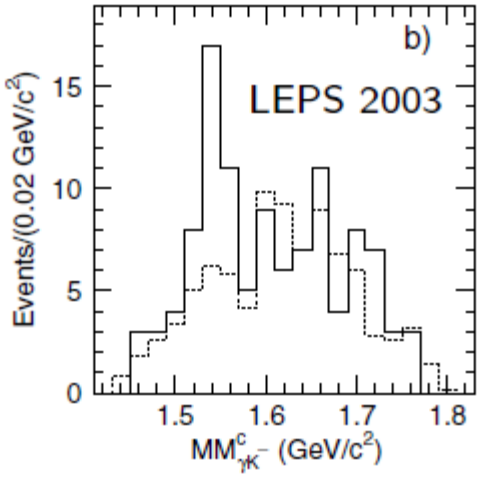
(uudd$\bar{s}$)
pentaquark candidate

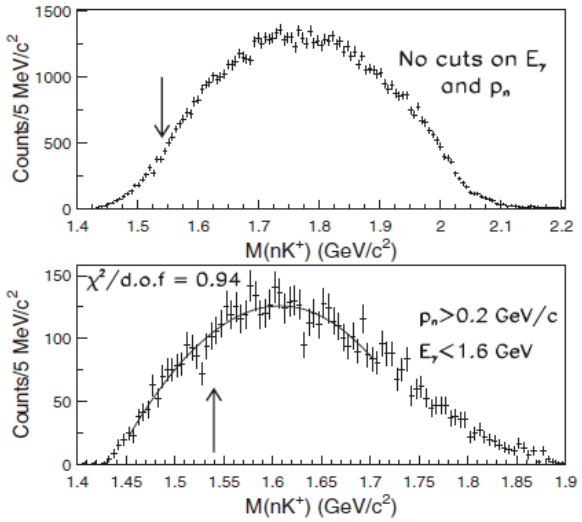


A2 experiment



negative result from CLAS





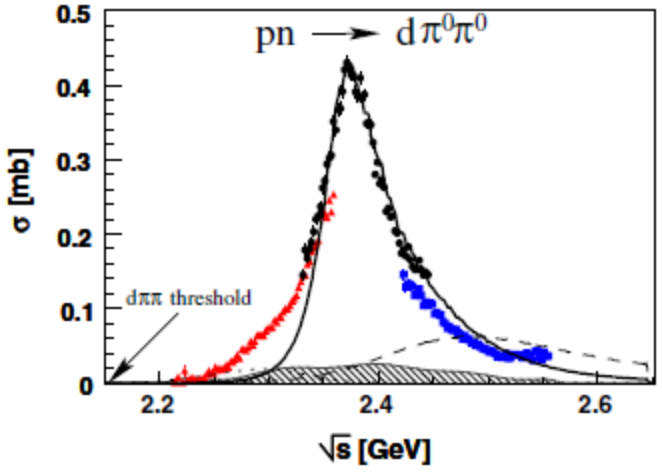
T. Nakano *et al.*, Phys. Rev. Lett. 91, 012002 (2003)
K. Hicks, Eur. Phys. J. H 37, 1 (2012)

S. Niccolai *et al.*, Phys. Rev. Lett. 97, 032001 (2006)

d*(2380) dibaryon candidate

Dominik Werthmüller

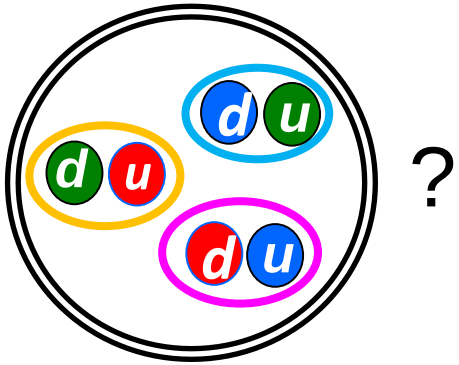
The $d^*(2380)$ Dibaryon Candidate



P. Adlarson *et al.*, Phys. Rev. Lett. 106, 242302 (2011)

- currently best dibaryon candidate
- complete measurement of decays
- most data exclusively from WASA-at-COSY

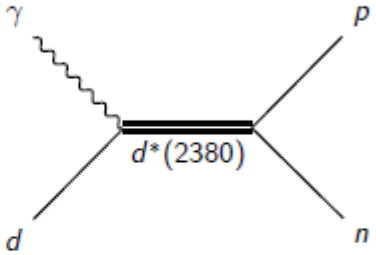
M. Bashkanov, H. Clement and T. Skorodko, Eur. Phys. J. A 51, 87 (2015)



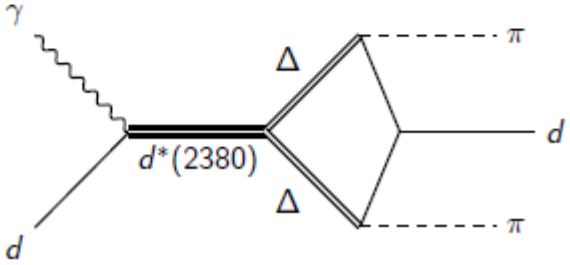
$$I(J^P) = 0(3^+)$$

Photonuclear reactions on deuteron:

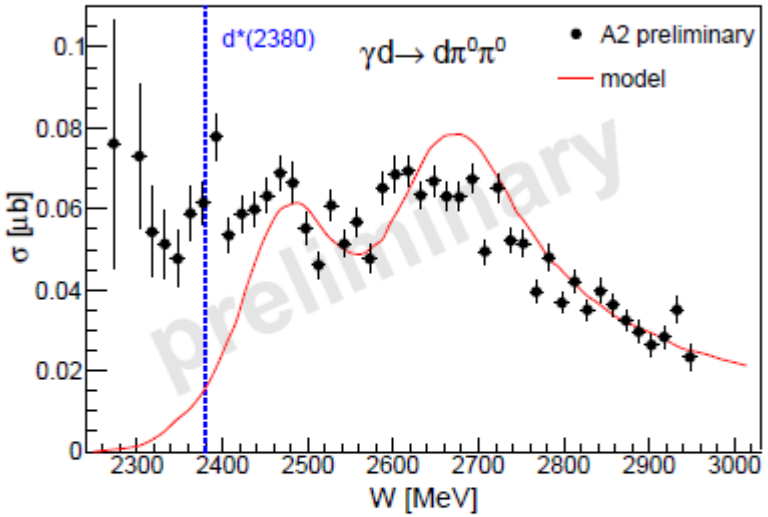
- photodesintegration



- coherent $\pi\pi$ production



$$\gamma d \to d\pi^0\pi^0$$



M. Günther (University of Basel)
Model: M. Egorov, A. Fix, Nucl. Phys. A 933, 104 (2015)

- small 'conventional' coherent background in neutral channel
- large quasifree background near threshold to be dealt with

Double-pole structure of Λ(1405)

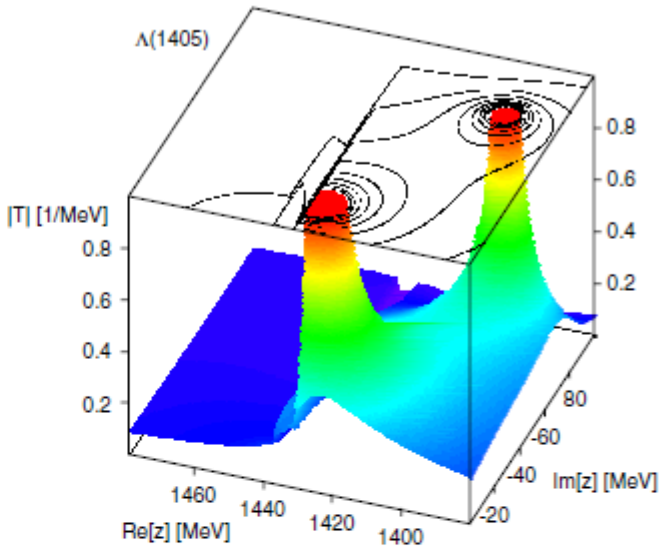
Dominik Werthmüller

The Puzzling Λ(1405)

Unitary Chiral Theories

- dynamical generation
- two poles near $\Sigma\pi$ (1327 MeV) and $\bar{K}N$ (1432 MeV) thresholds
- observables have contributions from both poles
- coupling to poles depends on reaction

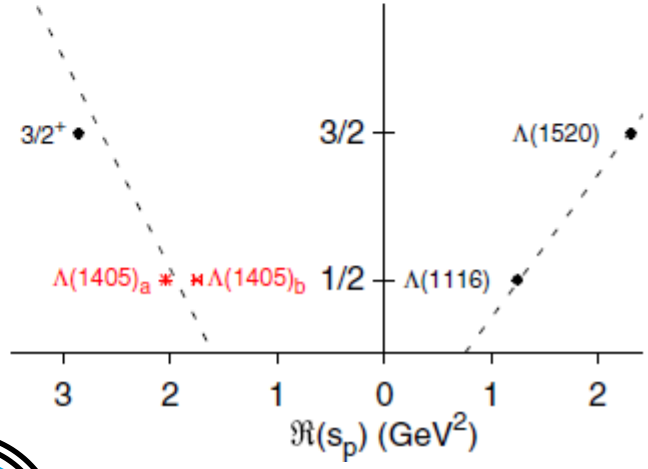
T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)
R. H. Dalitz, S. F. Tuan, Phys. Rev. Lett. 2, 425 (1959)
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A 594, 325 (1995)
E. Oset, A. Ramos, Nucl. Phys. A 635, 99 (1998)
J. A. Oller, U. G. Meissner, Phys. Lett. B 500, 263 (2001)

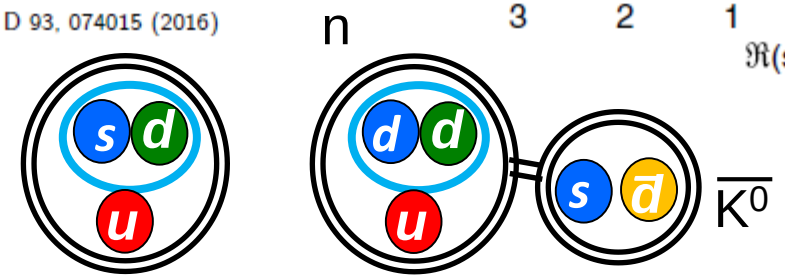


Regge-Analysis

- only higher-lying $\Lambda(1405)_a$ fits three-quark picture
- nonordinary nature of $\Lambda(1405)_b$

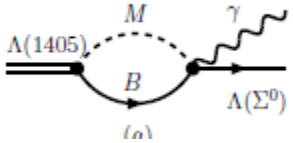
C. Fernandez-Ramirez *et al.* (JPAC), Phys. Rev. D 93, 074015 (2016)





Radiative Decays of the Λ(1405)

- relatively clean way of probing the internal structure of baryons
- radiative decay via meson-baryon loops ⇒ access to $\bar{K}N$



A2 expects to improve over earlier photo-production experiments

⇒ See also Noumi's talk (J-PARC)

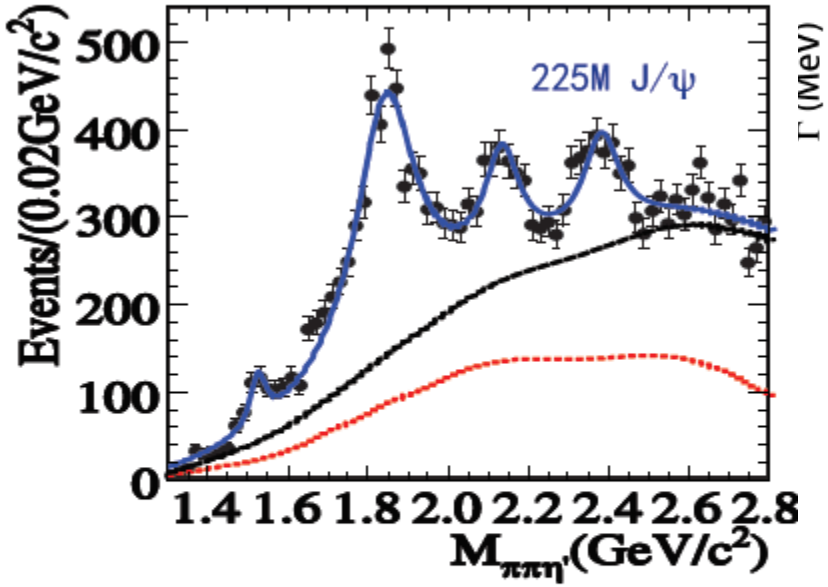
Jianbin Jiao

Light exotic hadrons at BESIII

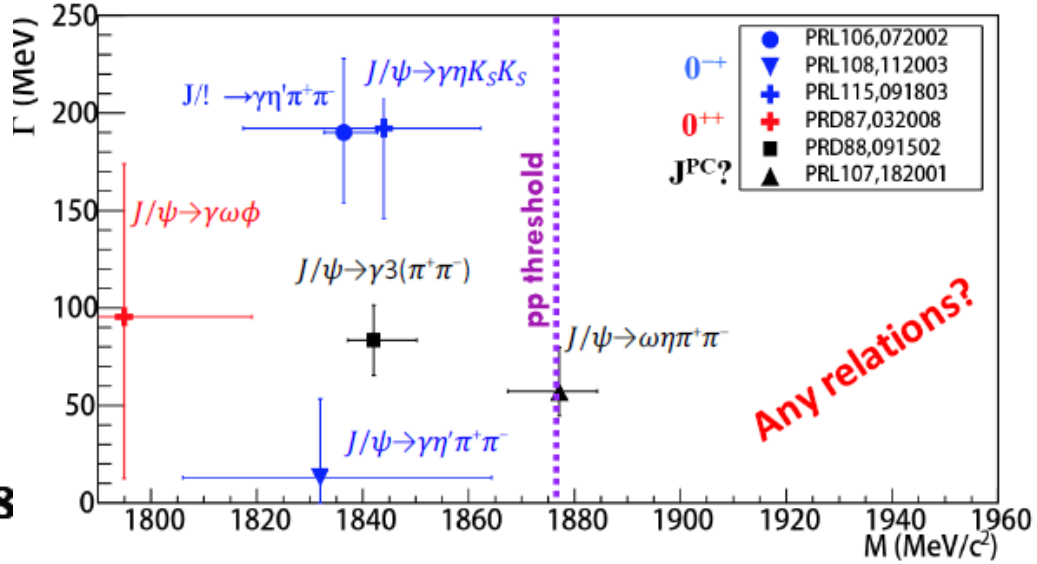
X(18??) State?

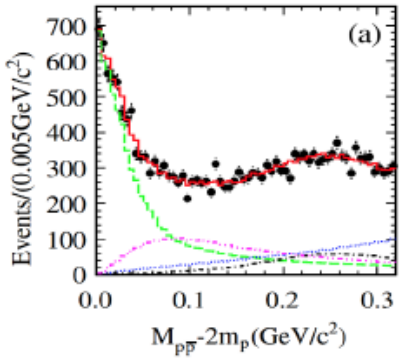
Phys. Rev. Lett. 106, 072002 (2011)

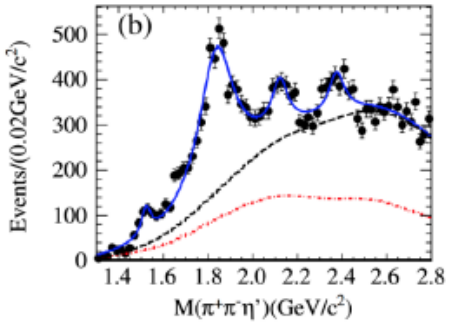
X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

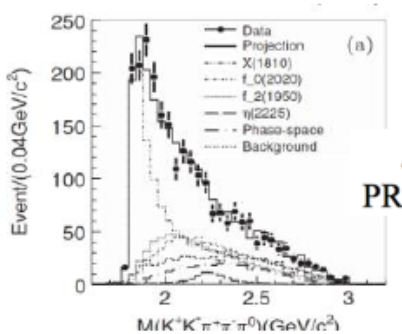


X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

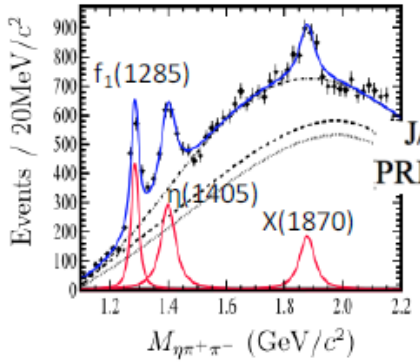




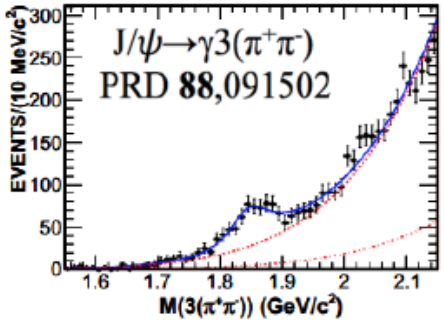




J/ψ→γωφ
PRD 87,032008



J/ψ→ωηπ⁺π⁻
PRL 107,182001

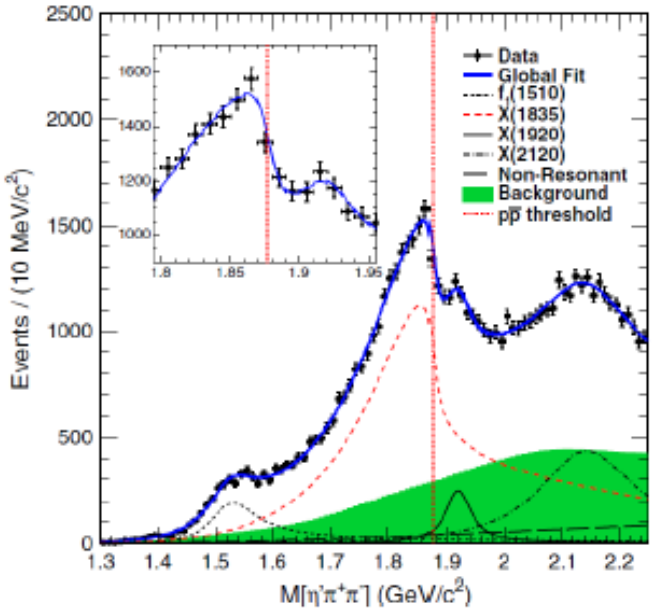


J/ψ→γ3(π⁺π⁻)
PRD 88,091502

- What is the role of the ppbar threshold (and other thresholds)?
- Patterns in the production and decay modes

Latest result on X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Phy. Rev. Lett. 117, 042002 (2016)



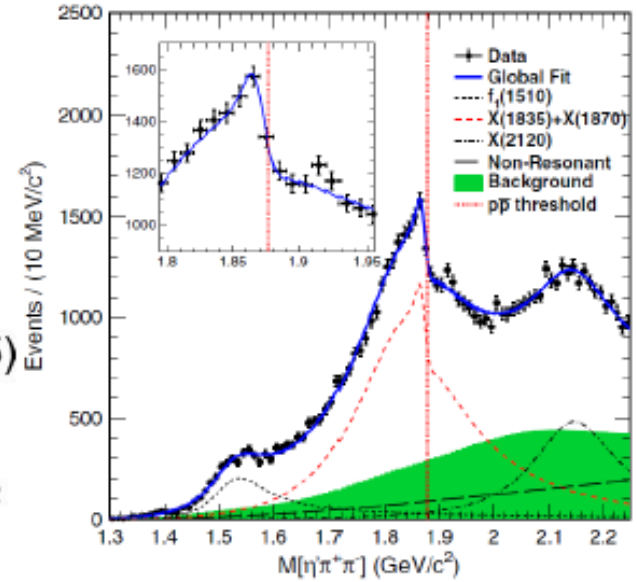
Model 1:
Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at ~1920 MeV/c²

X(1835)	
M (MeV/c^2)	$1825.3\,^{+2.4}_{-2.4}\,^{+17.3}_{-2.4}$
Γ (MeV/c^2)	$245.2\,^{+14.2}_{-12.6}\,^{+4.6}_{-9.6}$
B.R. (constructive interference)	$(3.01\,^{+0.17}_{-0.17}\,^{+0.26}_{-0.28}) \times 10^{-4}$
B.R. (destructive interference)	$(3.72\,^{+0.21}_{-0.21}\,^{+0.18}_{-0.35}) \times 10^{-4}$

X(1870)	
M (MeV/c^2)	$1870.2\,^{+2.2}_{-2.3}\,^{+2.3}_{-0.7}$
Γ (MeV/c^2)	$\mathbf{13.0\,^{+7.1}_{-5.5}\,^{+2.1}_{-3.8}}$
B.R. (constructive interference)	$(2.03\,^{+0.12}_{-0.12}\,^{+0.43}_{-0.70}) \times 10^{-7}$
B.R. (destructive interference)	$(1.57\,^{+0.09}_{-0.09}\,^{+0.49}_{-0.86}) \times 10^{-5}$

The state around 1.85 GeV/c²	
$\mathcal{M}$ (MeV/c^2)	$1638.0\,^{+121.9}_{-121.9}\,^{+127.8}_{-254.3}$
g_0^2 ((GeV/c^2)²)	$93.7\,^{+35.4}_{-35.4}\,^{+47.6}_{-43.9}$
$\mathbf{g_{p\bar{p}}^2/g_0^2}$	$\mathbf{2.31\,^{+0.37}_{-0.37}\,^{+0.83}_{-0.60}}$
M_{pole} (MeV/c^2) *	$1909.5\,^{+15.9}_{-15.9}\,^{+9.4}_{-27.5}$
Γ_{pole} (MeV/c^2) *	$273.5\,^{+21.4}_{-21.4}\,^{+6.1}_{-64.0}$
Branching Ratio	$(3.93\,^{+0.38}_{-0.38}\,^{+0.31}_{-0.84}) \times 10^{-4}$

Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c²



- Suggest the existence of a state, either a broad one with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold.
- Support the existence of a $p\bar{p}$ molecule-like state or bound state

Jianbin Jiao

Glueball studies in BES III

Jianbin Jiao

- **Pure scalar-glueball rate in J/ψ radiative decays**

LQCD
- BR(J/ψ→ γG(0^{++}))=3.8(9)×10^{-3}
- ✓ BR(J/ψ→ $\gamma f_0(1710)\to\gamma K\bar{K}$)= $(8.5^{+1.2}_{-0.9})\times10^{-4}$
- ✓ BR(J/ψ→ $\gamma f_0(1710)\to\gamma\pi\pi$)= $(4.0\pm1.0)\times10^{-4}$
- ✓ BR(J/ψ→ $\gamma f_0(1710)\to\gamma\omega\omega$)= $(3.0\pm1.0)\times10^{-4}$
- ✓ BR(J/ψ→ $\gamma f_0(1710)\to\gamma\eta\eta$)= $(2.35^{+1.3+1.24}_{-0.11-0.74})\times10^{-4}$

- **Pure Tensor-glueball rate in J/ψ radiative decays**

LQCD
- BR(J/ψ→ γG(2^{++}))=1.1(2)×10^{-2}
  Large decay rate is predicted
- ✓ BR(J/ψ→ $\gamma f_2(2340)\to\gamma\eta\eta$)= $(5.6^{+0.62+2.37}_{-0.65-2.07})\times10^{-4}$
- ✓ BR(J/ψ→ $\gamma f_2(2340)\to\gamma\phi\phi$)= $(1.91\pm0.07^{+0.72}_{-0..69})\times10^{-4}$
- ✓ $f_J(2220)$? Need to be confirmed!
- ✓ Need more experimental information!

PRL 110 (2013) 021601
PRL 111 (2015) 091601
PDG 2010
PRD 87 (2013) 092009
PRD 93 (2016) 112011

At BESIII

- $f_0(1710)$ and $f_0(2100)$ are observed in $J/\psi\to\gamma\eta\eta,\gamma\pi^0\pi^0$
- $f_2(2340)$ is observed in $J/\psi\to\gamma\eta\eta/\phi\phi/\pi^0\pi^0$
- X(2120) and X(2370) in of $J/\psi\to\gamma\pi^+\pi^-\eta'$
- Systematic studies needed
  - $J/\psi\to\gamma\eta\eta'$
  - $J/\psi\to\gamma\eta'\eta'$
  - $J/\psi\to\gamma K_sK_s$
  - $J/\psi\to\phi X,\omega X$

Low lying glueballs have ordinary quantum number→mixing with $q\bar{q}$ mesons

⇒ See also Y.M.Cho's talk

Beginning of XYZ saga

Stephen Lars Olsen

The X(3872) & other charmonium puzzles

Stephen Lars Olsen ibs Institute for Basic Science Daejeon, KOREA

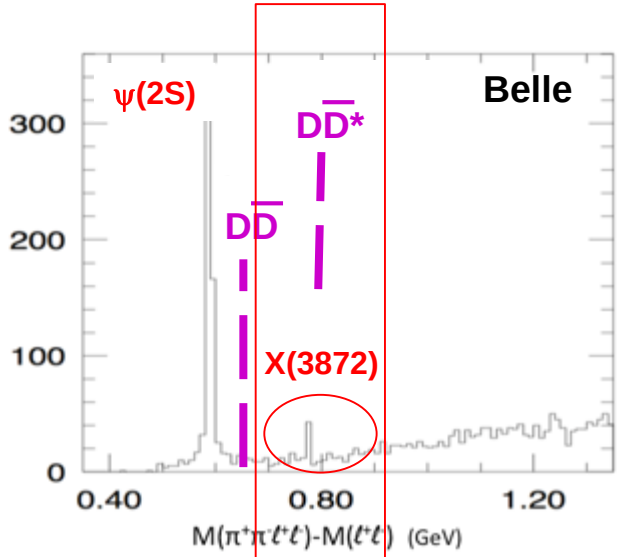
Workshop on Exotic Hadrons at 6th International Conference on New Frontiers in Physics, Kolymbari, Greece, Aug. 21-23, 2017

Phys.Rev.Lett. 91 (2003) 262001

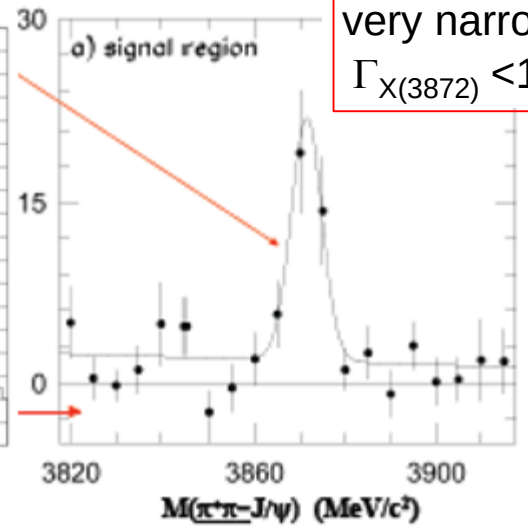
The most cited Belle paper (1369 citations)

Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] ...



Molecule?



very narrow

$\Gamma_{X(3872)}$ <1.2 MeV

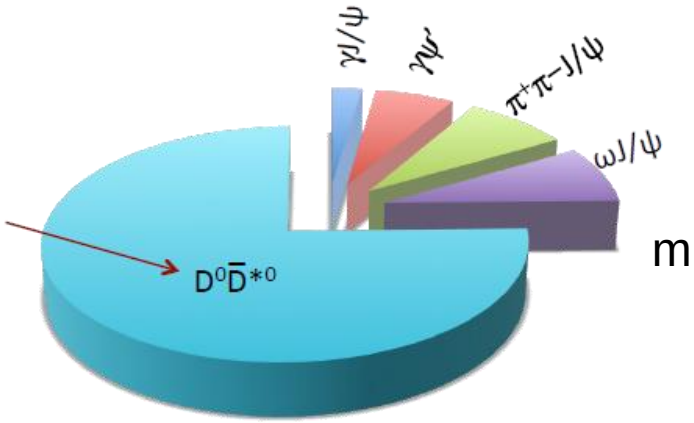
Molecule?

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

Preference for $\gamma\psi'$ over $\gamma J/\psi$ points to 2^3P_1 component

χ_{c1}' ?

Large isospin violation in these decays,



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

due to $m(D^0)-m(D^-)$?

Molecule?

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

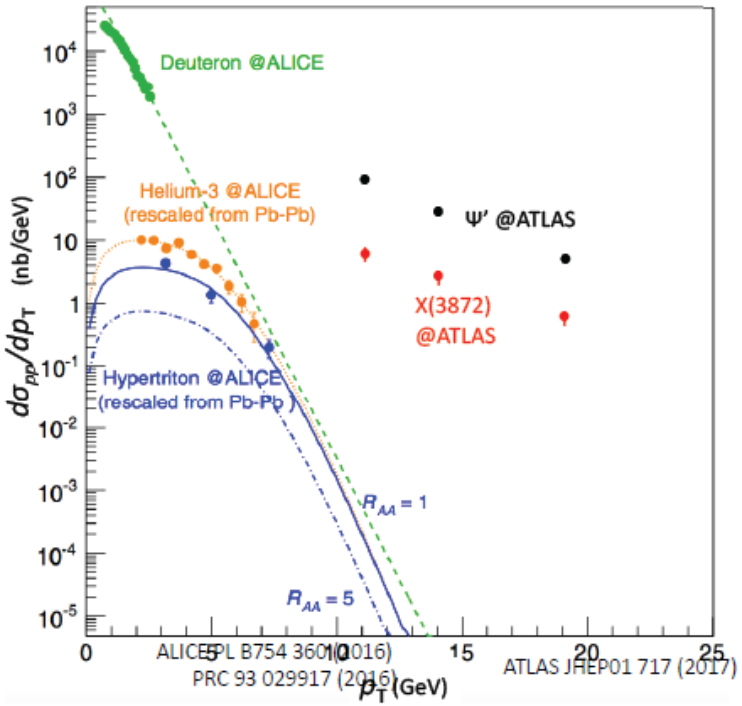
Molecule?

Prompt production of X(3872)

Stephen Lars Olsen

X_{3872} produced like ψ'; very unlike ^{3}He, etc.

See Esposito et al., PRD 92 034028 (2015(



Wednesday talks/discussion:

Luciano Maiani

Can't be a molecule!
It is a tightly bound-tetraquark.

Marek Karliner

Agree, can't be a pure molecule!
It is a mixture of a molecule and 2^3P_1 charmomium.

and many others including:

Talk by

Threshold effects in hadron spectrum: a new spectroscopy?

Pablo G. Ortega, J. Segovia, D.R. Entem, F. Fernández

Constituent QM supplemented with couplings to meson-meson states

Pablo Ortega

E_{bind}	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^\pm D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
−0.25 MeV	8.00 %	86.61 %	4.58 %	0.53 %	0.29 %

See also Xiao's talk

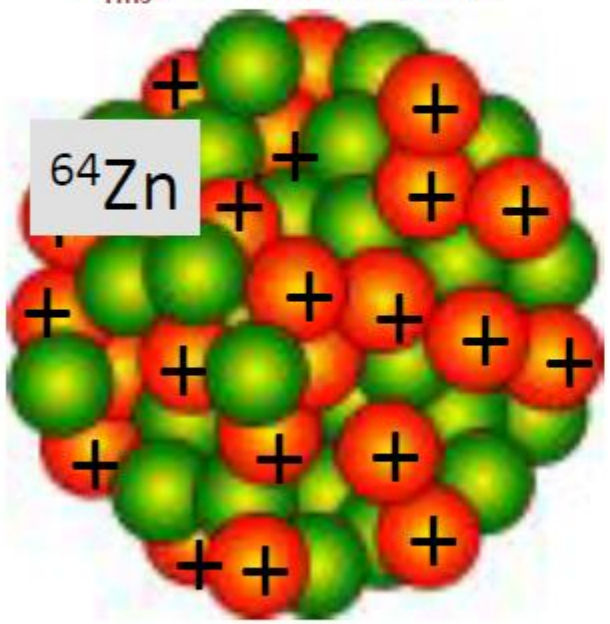
Can a large molecule mix with a compact charmonium?

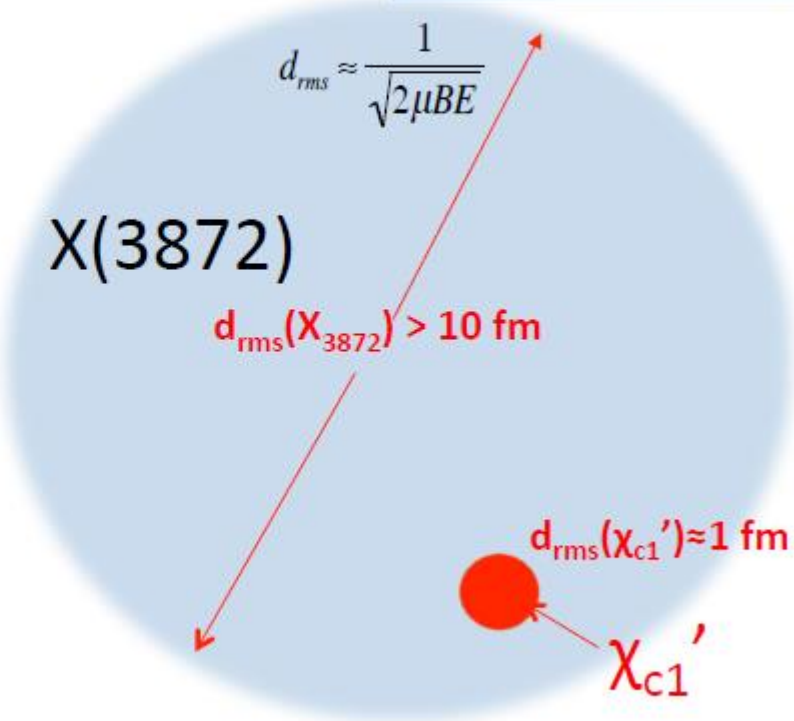
Stephen Lars Olsen

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

E. Braaten, J. Stapleton PRD81, 014019

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





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

Wednesday discussion session:

It is not plausible for such a large molecular state to mix with such a compact charmonium state

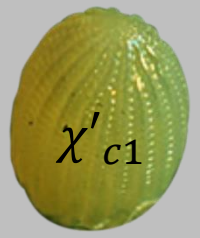
Luciano Maiani

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

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

Resonance decay

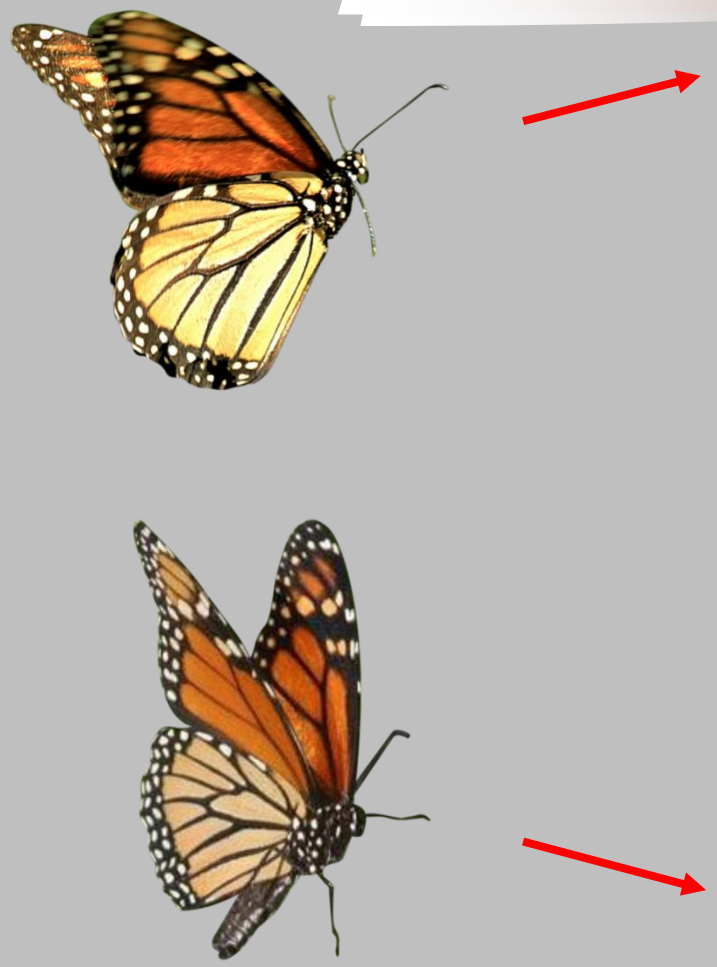
Resonance decay

Resonance decay

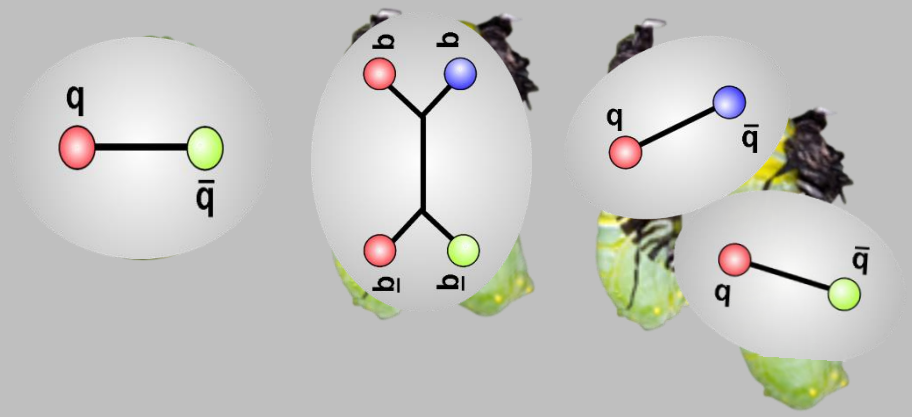
Resonance decay

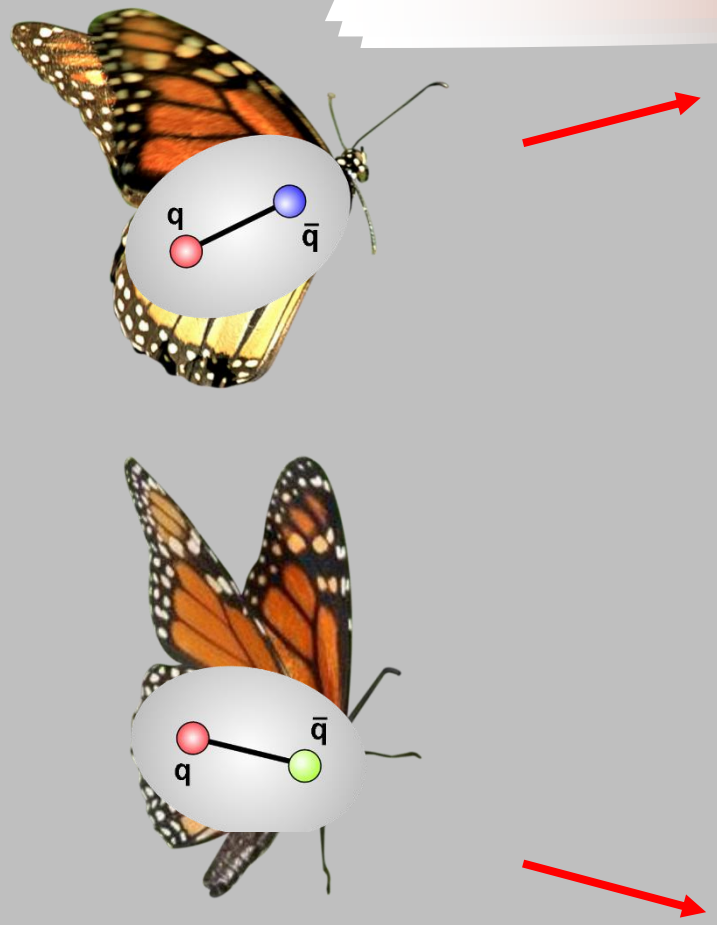
Resonance decay

Resonance decay



Resonance decay

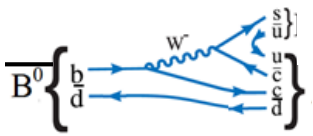




Decaying $q\bar{q}$ meson resonance can go through tetraquark and/or molecular configurations.

This can sometimes lead to

Dynamically generated state;
an extra pole in the scattering matrix

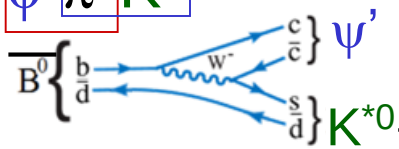


Discovery of Z(4430)+

T. Skwarnicki (Tue.)

Zc+ K*

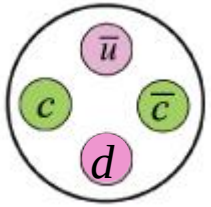
B→ψ'π+K



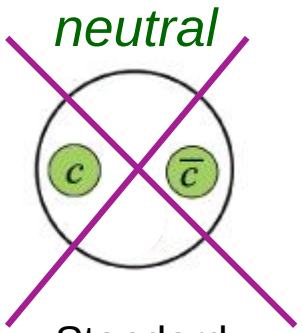
Belle 2008

PRL 100, 142001 (2008)

First charged charmonium-like state discovered!



not

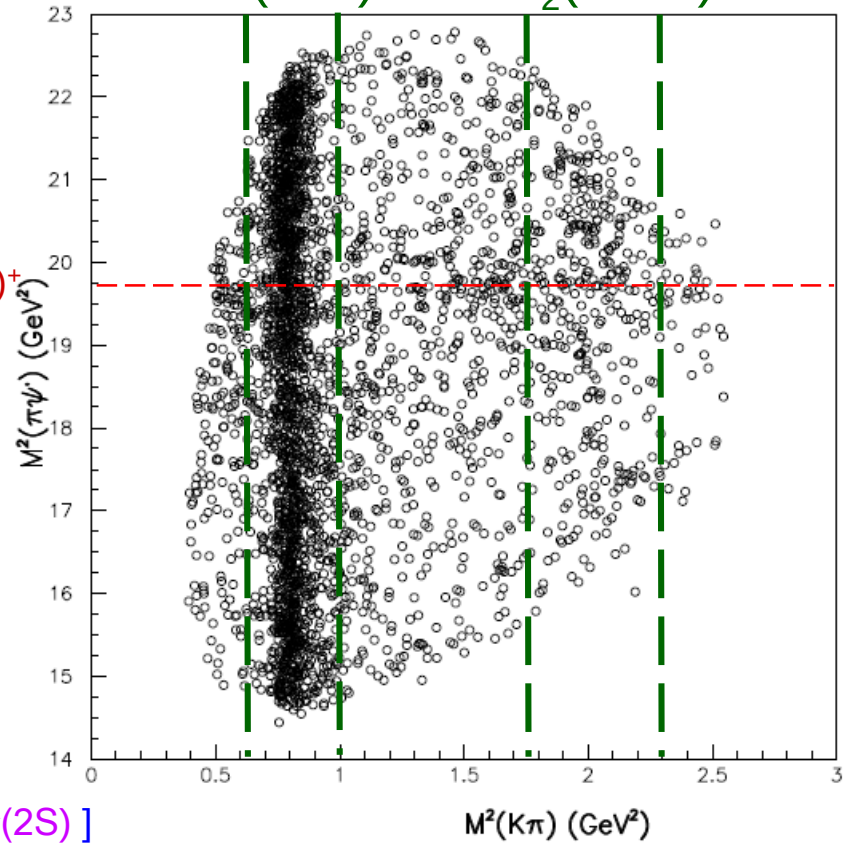


Exotic tetraquark, molecule, …

Standard charmonium

K*(892) K*2(1430)

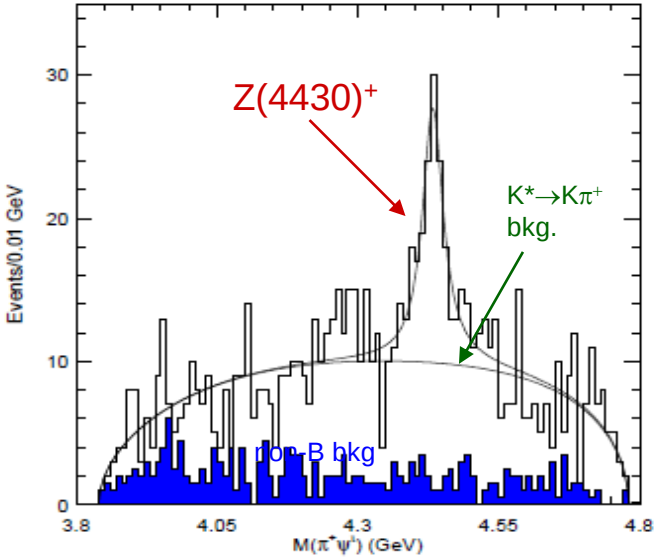
Z(4430)+



[ψ' ≡ ψ(2S)]

1D M(ψ'π−) mass fit

"K* veto region": suppress K*(892) and K*2(1430)



$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

significance 6.5σ

LHCb confirmed $Z_c(4430)^+$ in 2014

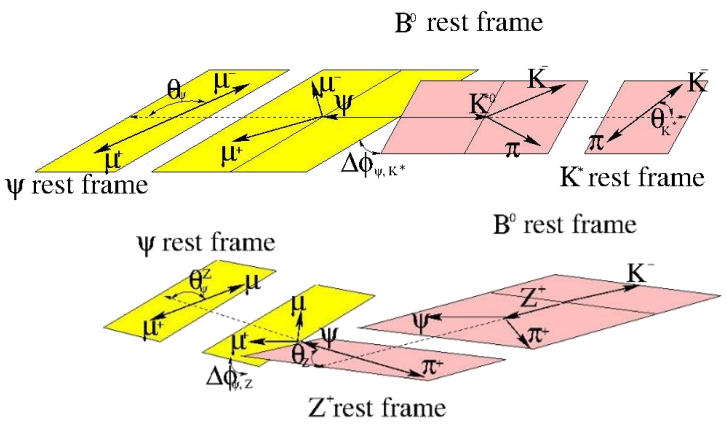
4D fits to masses and decay angles of six $K^{*0} \to K^- \pi^+$ and 1-2 $Z_c^+ \to \psi' \pi^+$

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

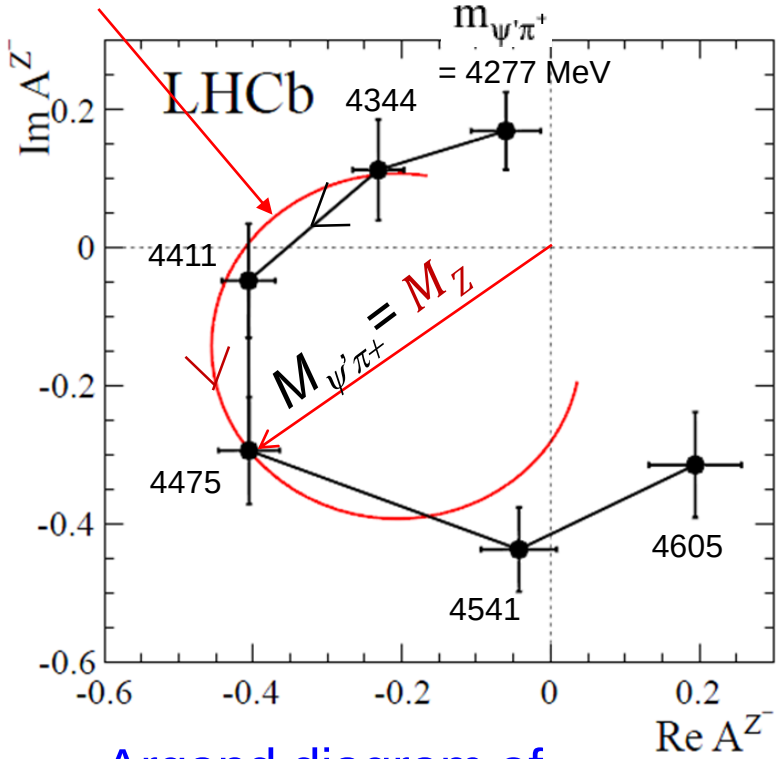
Breit-Wigner amplitude

$Z(4430)^-$	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_{1-Z} [%]	$16.7 \pm 1.6^{+2.6}_{-5.2}$	
Significance	$> 13.9\sigma$	$> 5.2\sigma$
$J^P=1^+$	9.7σ	3.4σ

Much wider, bigger errors, than in the naïve mass fit!



Excellent agreement !



Argand diagram of $Z_c(4430)^+$ is consistent with this structure being a resonance

2nd Z^- at lower mass?

$J^P=0^-$

$M(Z_0) = 4239 \pm 18^{+45}_{-10}$ MeV

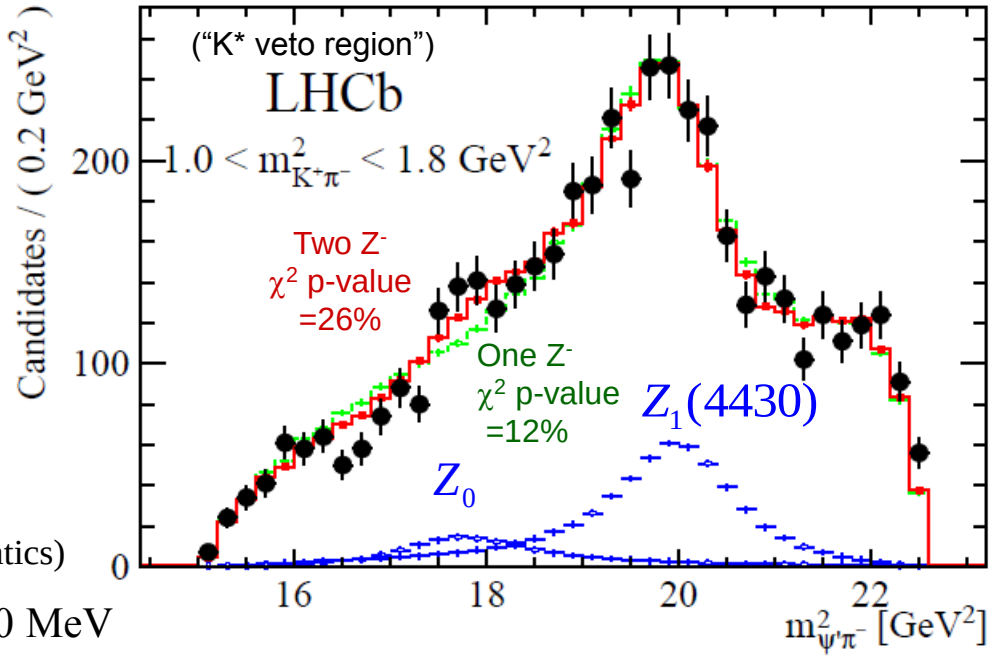
$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74}$ MeV

$f_{Z_0} = 1.6 \pm 0.5^{+1.9}_{-0.4}$ %

$f^I_{Z_0} = 2.4 \pm 1.1^{+1.7}_{-0.2}$ %

6σ significane (with systematics)

$J^P=1^+$ also possible Γ=660±150 MeV

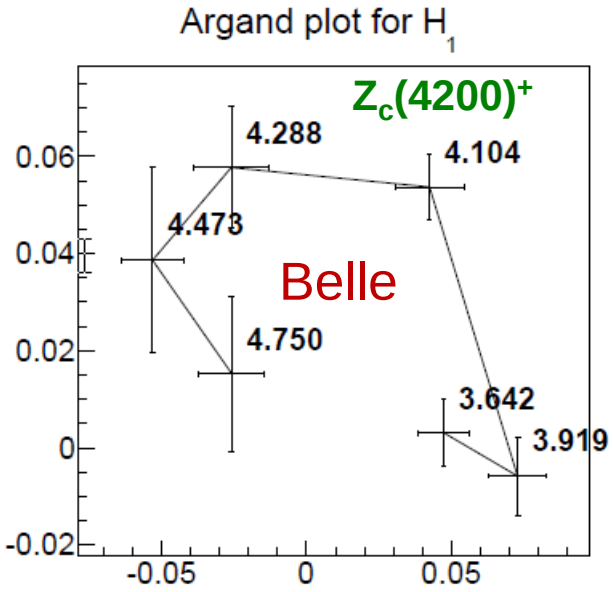


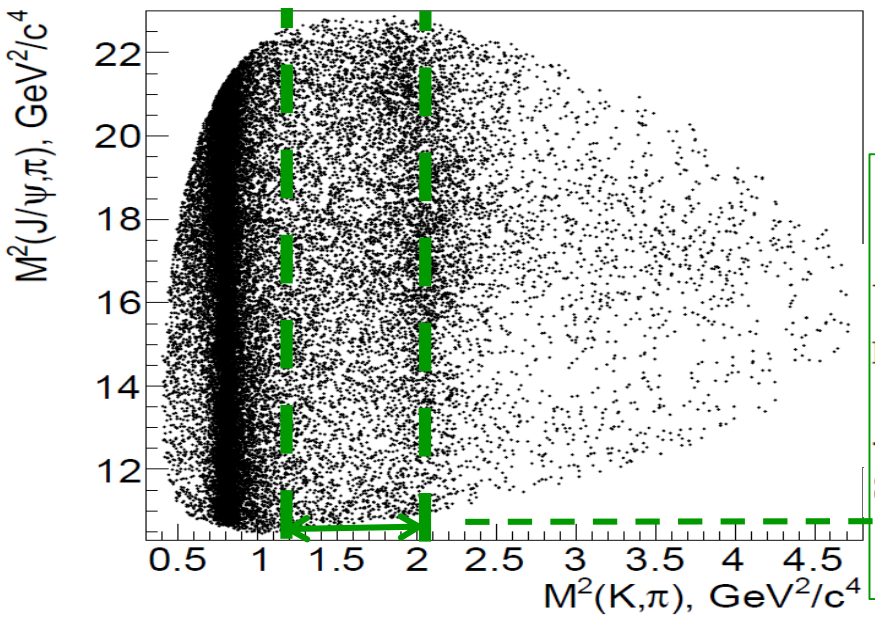
T. Skwarnicki (Tue.)

$\overline{B^0} \to J/\psi\, \pi^+ K^-$ in Belle

Belle PR D90, 112009 (2014)

4D amplitude analysis





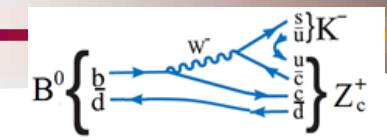
Significance	5.1σ
f_Z [%]	$(0.5^{+0.4}_{-0.1})\%$

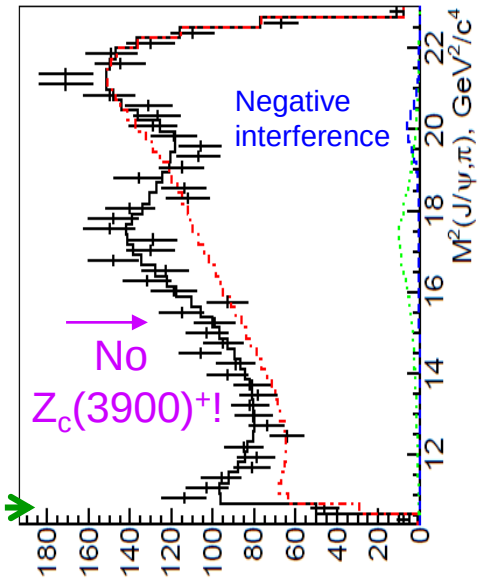
$Z_c(4430)^+ \to J/\psi\pi^+$

$Z_c(4200)^+ \to J/\psi\pi^+$

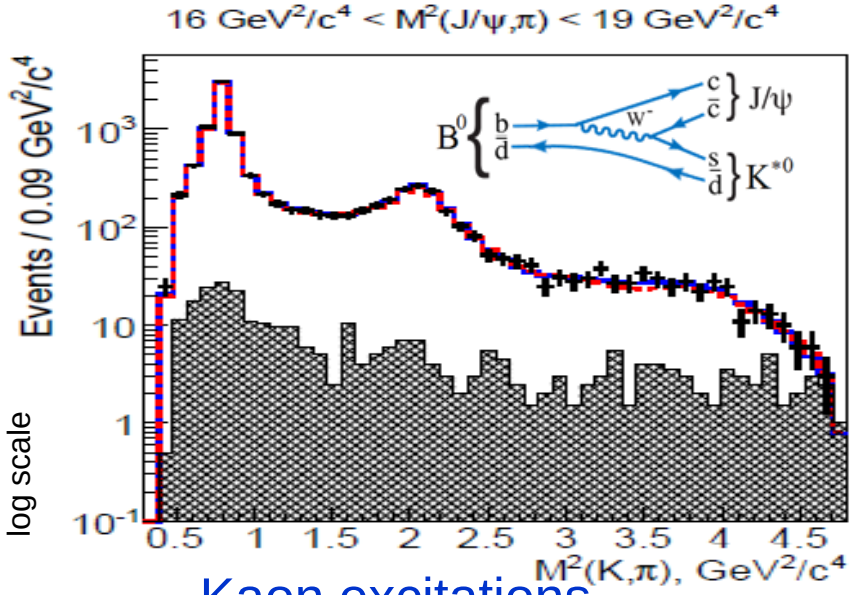
$M(Z)$ [MeV]	4196^{+31+17}_{-29-13}
$\Gamma(Z)$ [MeV]	$370^{+70+70}_{-70-132}$
f_Z [%]	$(1.9^{+0.7}_{-0.5})\%$
Significance	6.2σ
$J^P=1^+$	4.4σ

Small fit fractions!





Tetraquark or meson-meson molecule

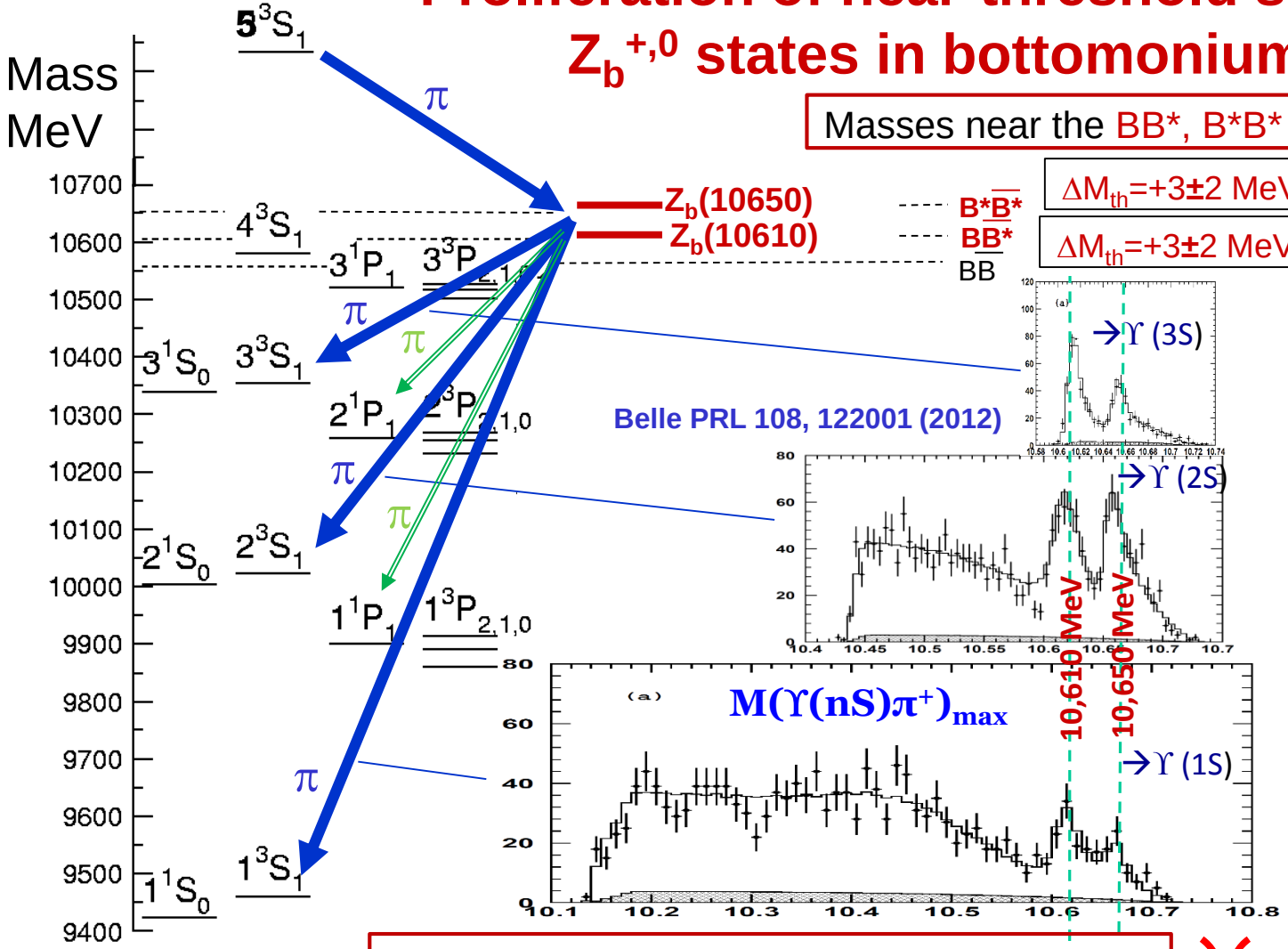


Kaon excitations

- The $Z_c(4430)^+$ observed in the 2nd decay mode!
- A broad but significant 2nd 1^+ resonances at the lower mass, $Z_c(4200)^+$
  - Possibly the same structure as observed by the LHCb in $\overline{B^0} \to \psi'\pi^+K^-$ (1^+ was not ruled out by LHCb)

T. Skwarnicki (Tue.)

Proliferation of near-threshold states: $Z_b^{+,0}$ states in bottomonium

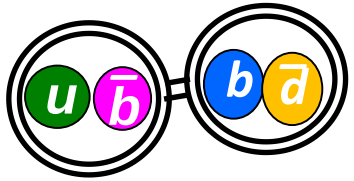


Masses near the $B\bar{B}^*$, $B^*\bar{B}^*$ thresholds ϒ

Γ 11.5 ± 2.2, 18.4 ± 2.4 MeV ϒ

Both $J^{P(C)}=1^{+(-)}$ ϒ

Charged and **neutral** versions detected $I^G=1^+$



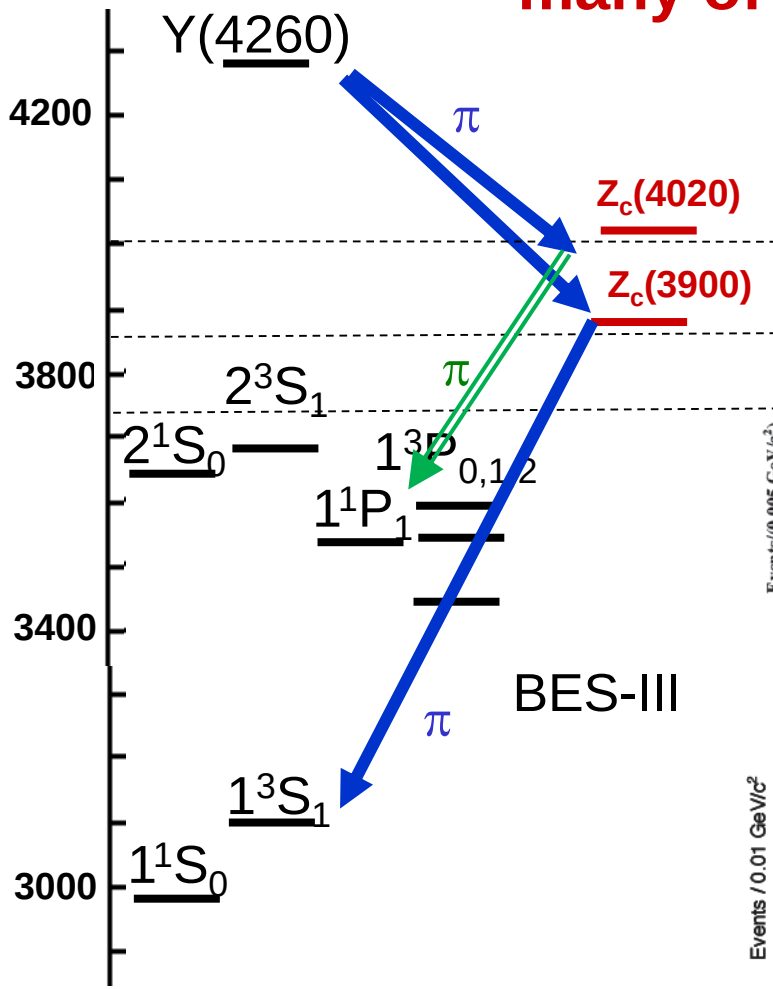
⇒ *See Bondar's talk*

Large rate to fall-apart modes observed ϒ

- Likely molecular states of $B\bar{B}^*$, $B^*\bar{B}^*$ (very weakly bound or slightly virtual) ⇒ *Karliner's talk*
- Tightly bound diquark tetraquarks advocated by Maiani and collaborators ⇒ *Maiani's talk*

More near-threshold states: many of $Z_c^{+,0}$ charmonium states

- Expected from Z_b states and Heavy Quark Symmetry



Masses a few MeV above the $D\bar{D}^*$, $D^*\bar{D}^*$ thresholds ✓

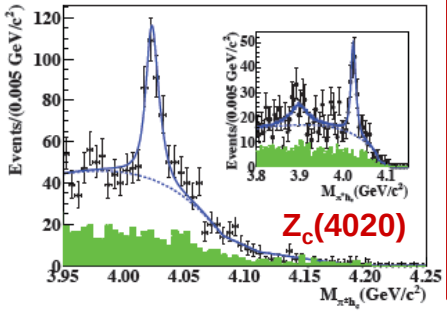
$D^*\bar{D}^*$ ΔM_{th}=+7±2 MeV

$D\bar{D}^*$ ΔM_{th}=+11±3 MeV

Γ 13 ±5 MeV
28.1± 2.6 ✓

$J^{P(C)}=1^{+(-)}$
(established only for $Z_c(3900)$) ✓

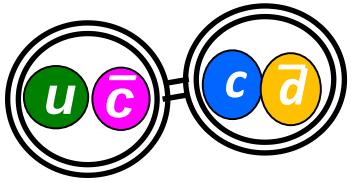
$D\bar{D}$

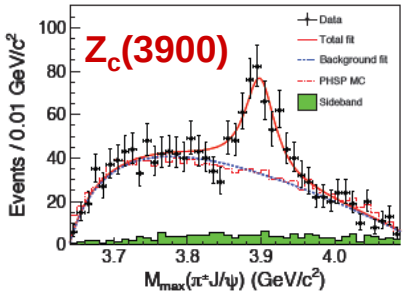


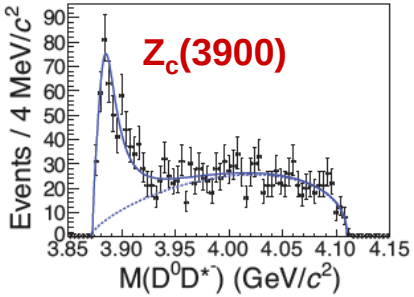
Large rate to fall-apart modes

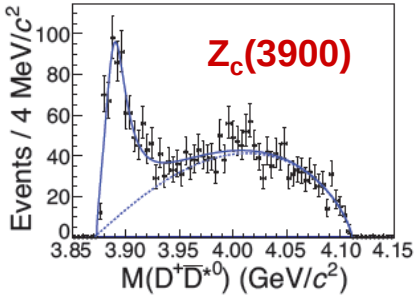
$$\frac{\Gamma[Z_c(4025)\to D^*D^*]}{\Gamma[Z_c(4020)\to\pi h_c]} \sim 9.$$

$$\frac{\Gamma[Z_c(3900)\to DD^*]}{\Gamma[Z_c(3900)\to\pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}$$ ✓









Charged and **neutral** versions detected $I^G=1^+$

(also seen be Belle)

⇨ *See Lyu's talk*

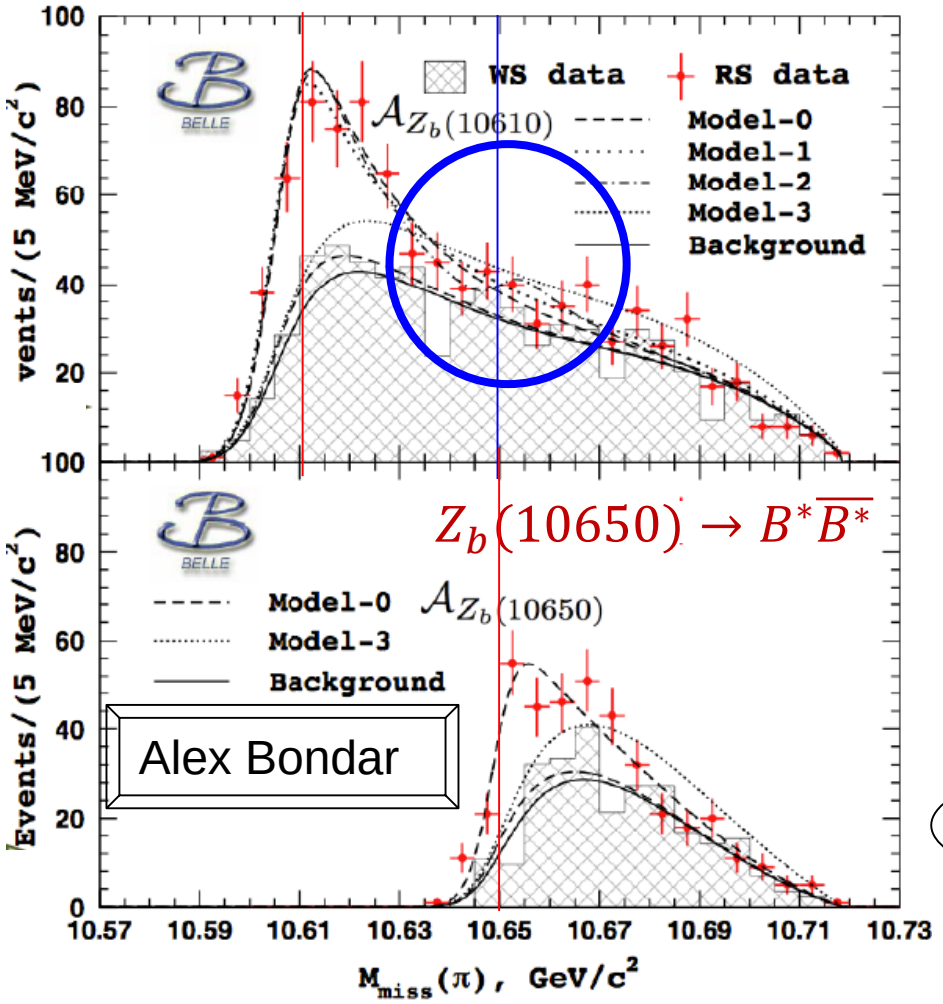
Molecular states of $D\bar{D}^*$, $D^*\bar{D}^*$? ⇨ *Karliner's talk*

Diquark tetraquarks ? ⇨ *Maiani's talk*

Good discussion about Z_b and corresponding Z_c states

Easy to understand if $Z_b(10650)$ is a $B^*\overline{B^*}$ molecule,
but not in a tetraquark model

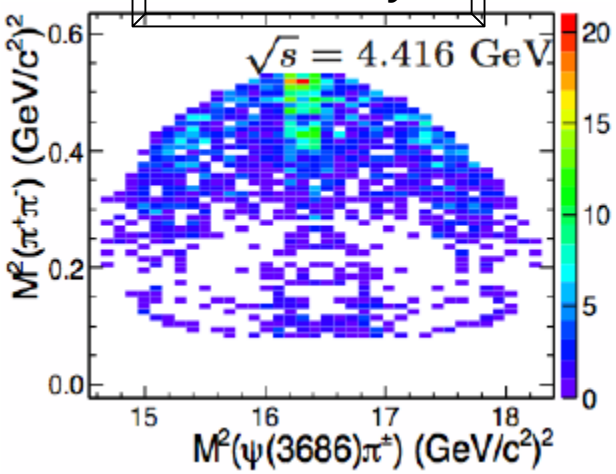
$Z_b(10610) \to B\overline{B^*}$ $\quad Z_b(10650) \not\to B\overline{B^*}$



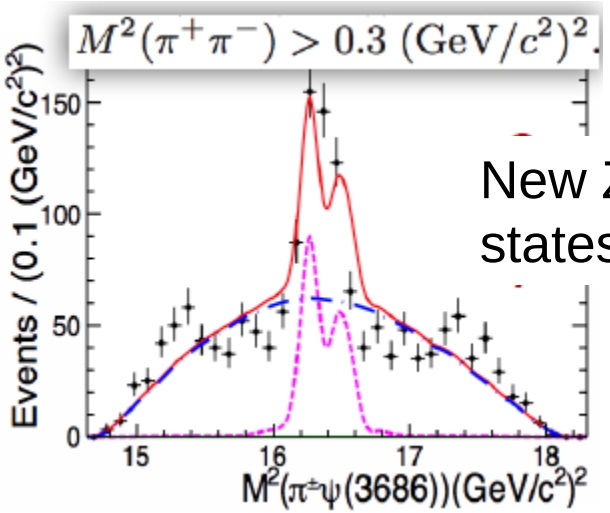
Alex Bondar

- Why the differences in decay pattern of Z_b and Z_c states?
  - Some of it can be misinterpretations of the data e.g.

Xiao-Rui Lyu



$\psi(2S)\pi^+$



New Z_c states?

M=4030.3±0.1 MeV,
Γ=5.1±0.2 MeV

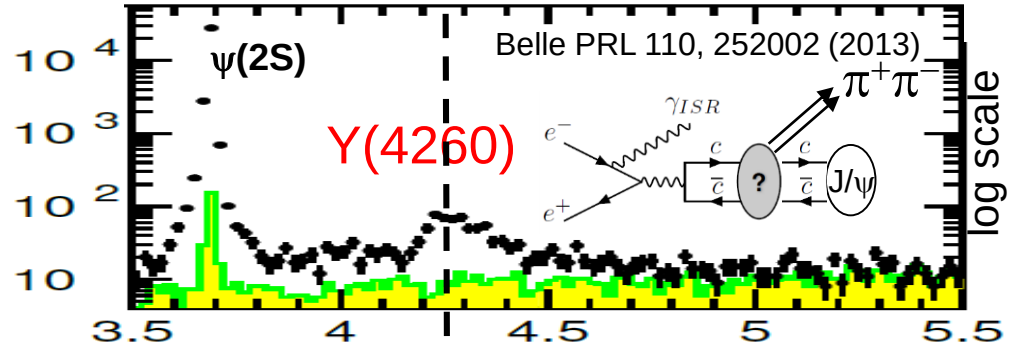
Different behavior between high and low $M^2(\pi^+\pi^-)$!

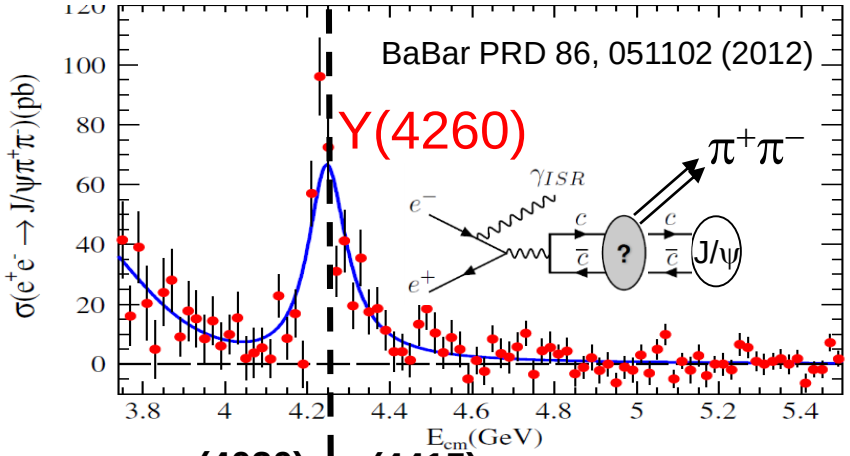
Mass, width not determined properly since did not allow for Z_c – NR bkg interference hinted by the Dalitz plot. This is likely $Z_c(4020) \to \psi(2S)\pi^+$ expected from $Z_b(10650) \to \Upsilon(2S)\pi^+$

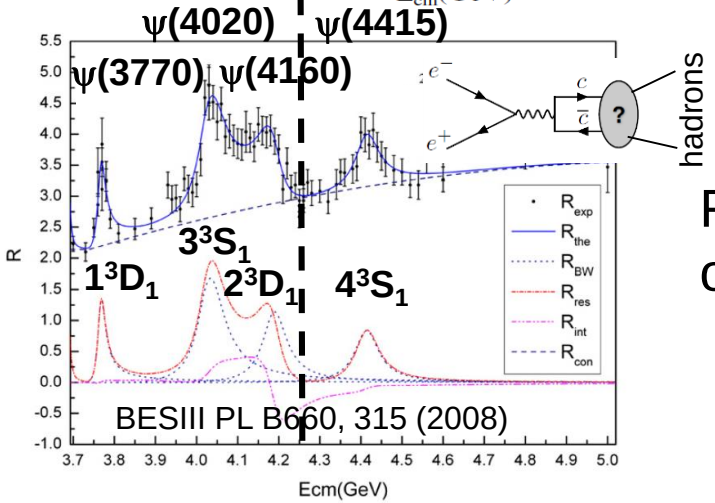
Alex Bondar

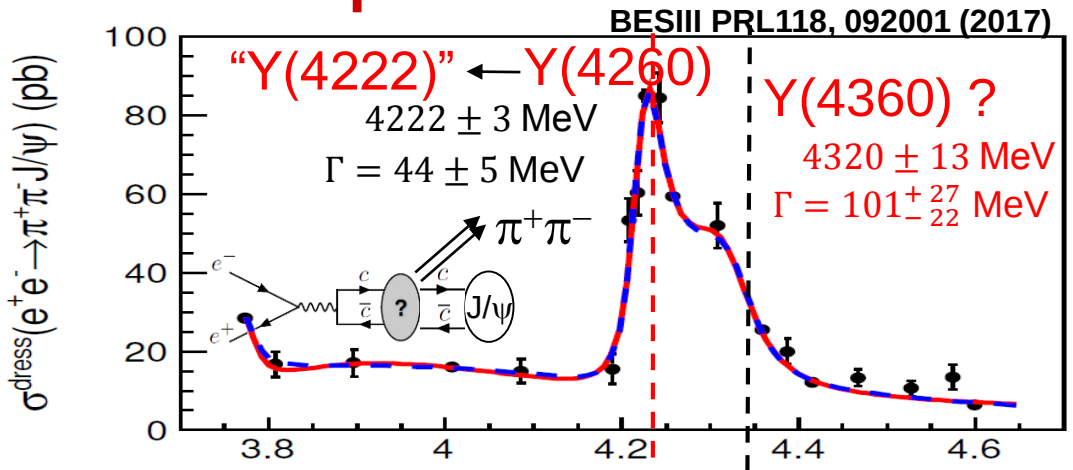
Anomalous 1^{--} states above open charm threshold

First observed by BaBar in 2005

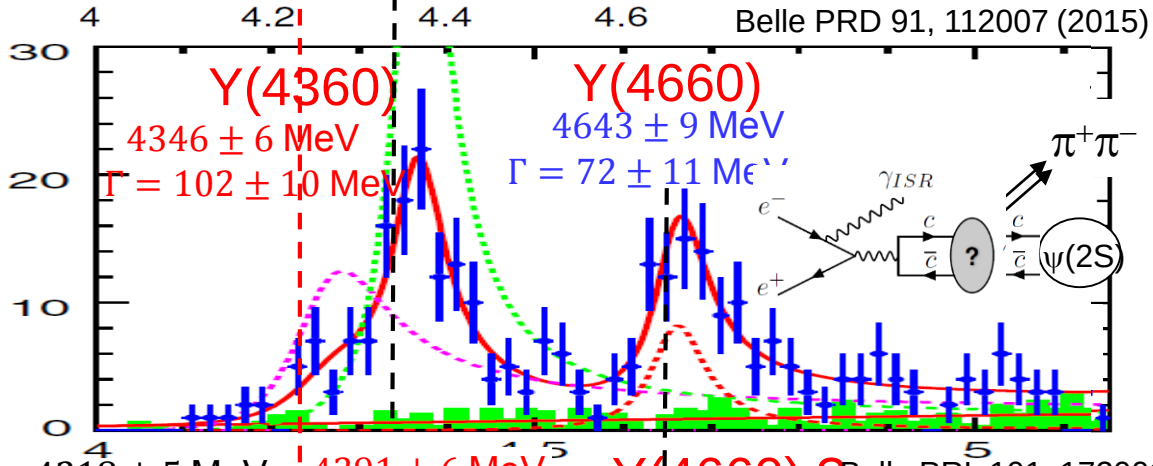


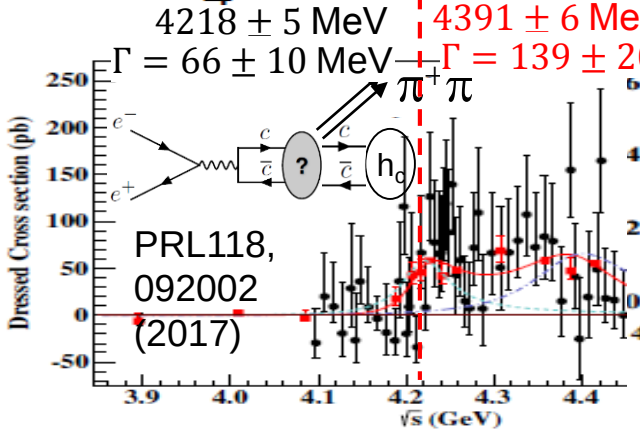


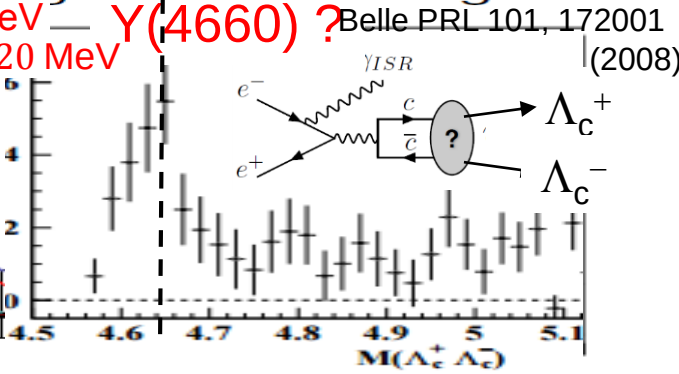




Famous Y(4260) is now Y(4220)+Y(4320)







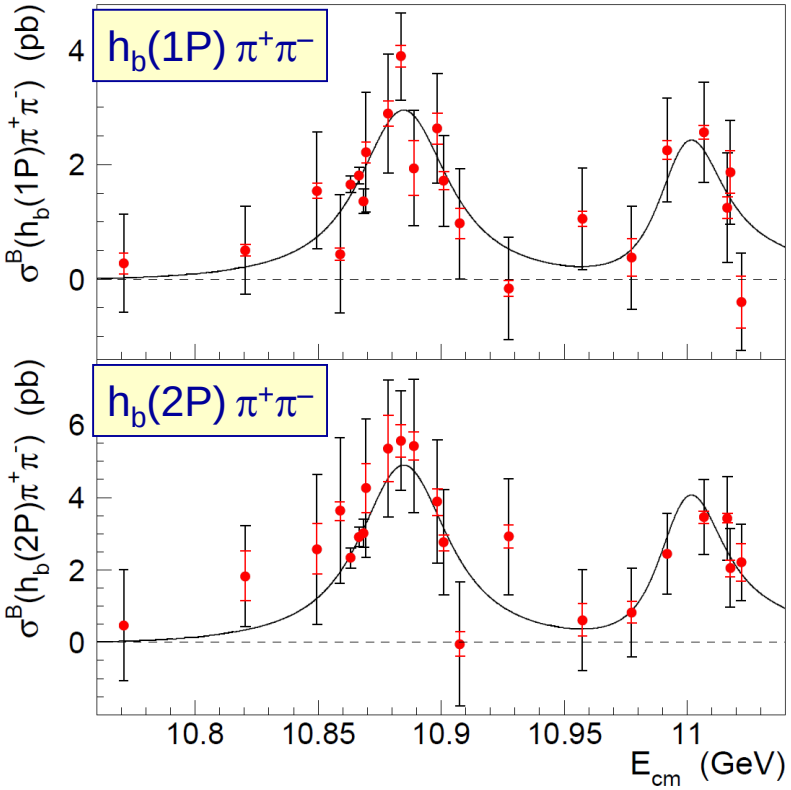
4634^{+9}_{-11} MeV $\Gamma = 92^{+41}_{-32}$ MeV

For much more on this see ⇩

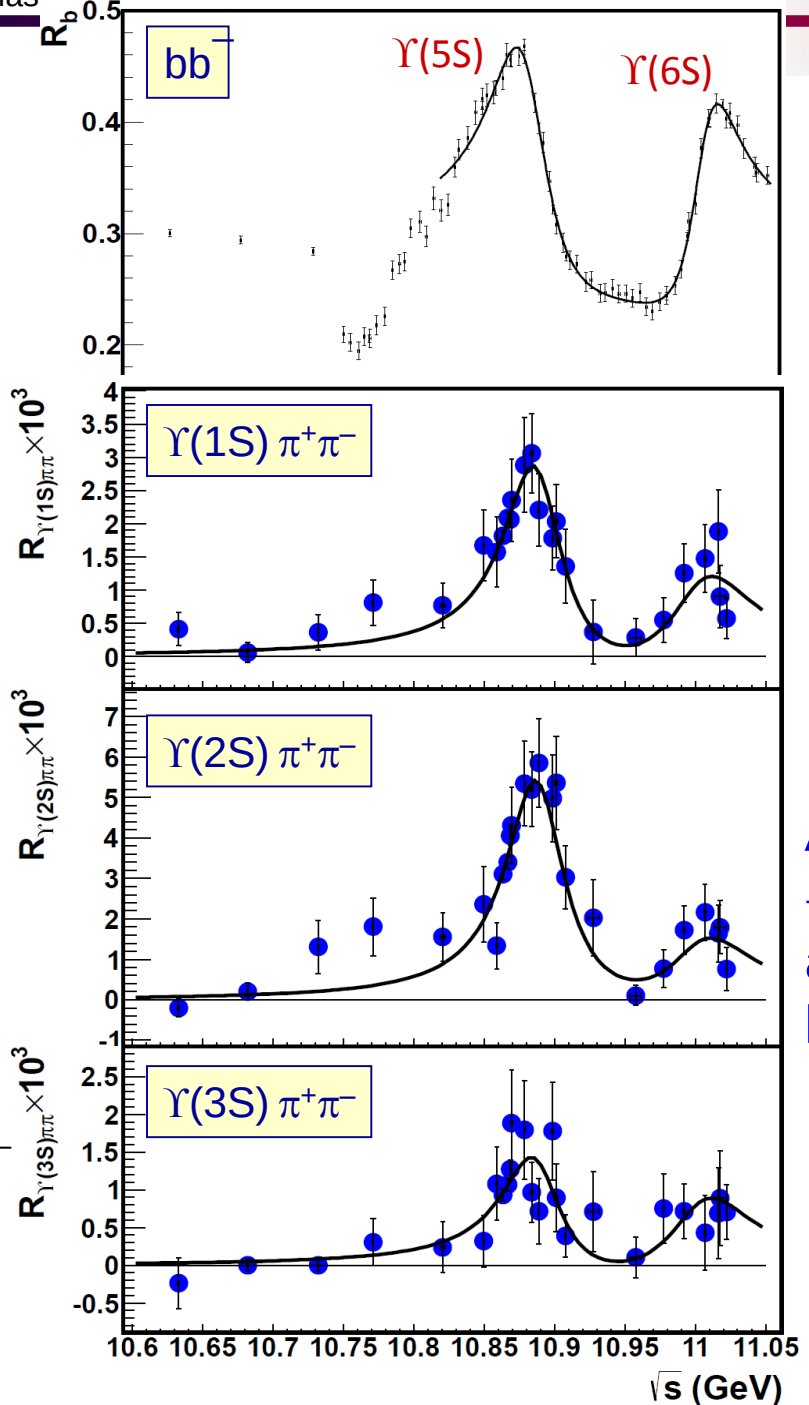
Z.Wang's talk

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

Roman Mizuk



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



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

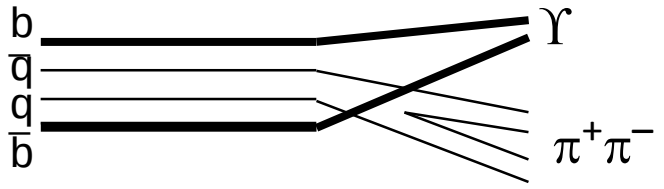
Like in charmonium!

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

Unlike in charmonium!

Interpretation?

~~OZI~~ ⇒ light d.o.f.

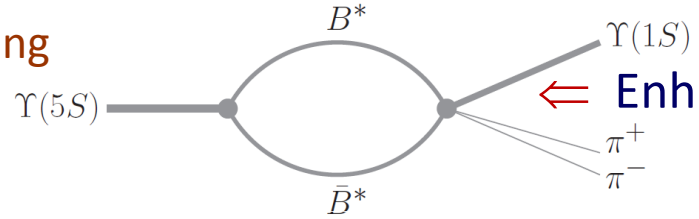


Roman Mizuk

compact tetraquark $(bq)(\bar{b}\bar{q})$	hadronic admixture $(b\bar{q})(\bar{b}q)$	hadro-quarkonium $(b\bar{b})(q\bar{q})$
–	V	–
V	V	–

Bottomonium-like states
open flavor decays dominate
transition to various bottomonia

admixture + rescattering



⇐ Enhanced if $B^{(*)}\bar{B}^{(*)}$ are on-shell

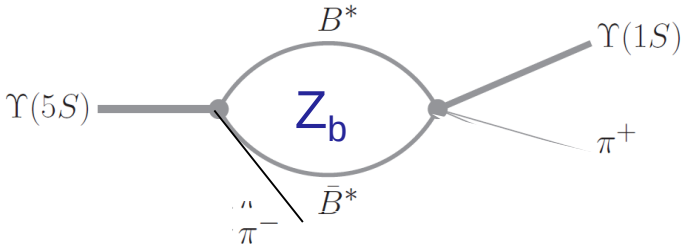
Simonov JETP Lett 87,147(2008)
Meng Chao PRD77,074003(2008)

Molecules are ***not*** eigenstates of the total bb spin

$Z_b = B\bar{B}^*$
$Z_b' = B^*\bar{B}^*$

$I^G(J^P) = 1^+(1^+)$

Bondar, Garmash, Milstein, RM, Voloshin, PRD84,054010(2011)



Decomposition ⇒

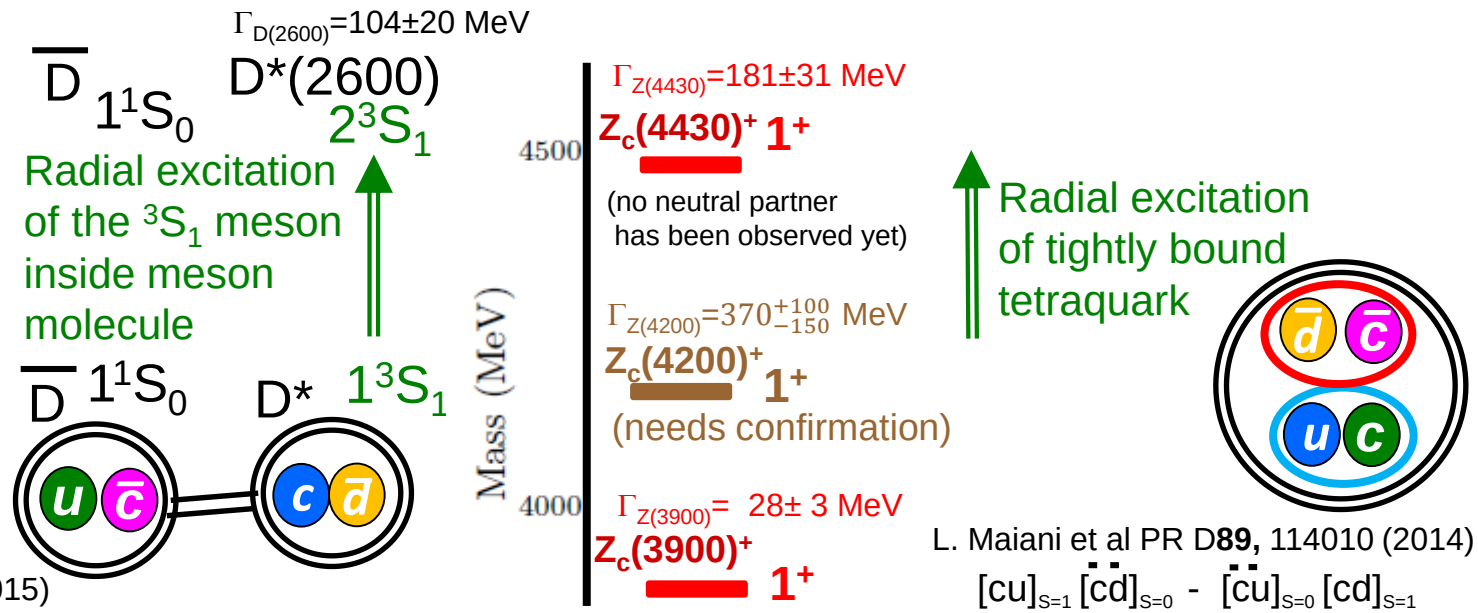
$$|Z_b'\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} - 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

$$|Z_b\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} + 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

$h_b(mP)\pi$ $\Upsilon(nS)\pi$

Decays via Z_b states explain HQSS violation

Interpretations of Z_c^+ states observed in B decays



L. Ma et al PRD 90, 037502 (2014)
T. Barnes et al, PRD 91, 014004 (2015)

L. Maiani et al PR D**89,** 114010 (2014)
$[cu]_{S=1}[\bar{c}\bar{d}]_{S=0}$ - $[\bar{c}\bar{u}]_{S=0}[cd]_{S=1}$

Absence of $Z_c(3900)^+$ in B decays makes it questionable to pair it up with $Z_c(4430)^+$

No molecular thresholds can explain $Z_c(4200)^+$

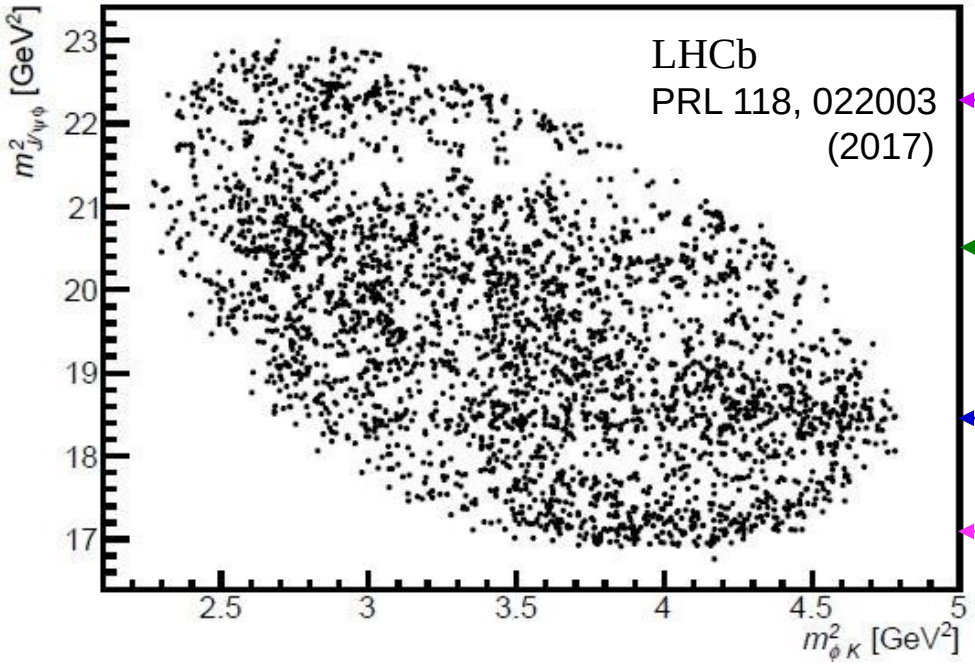
While it has been suggested $Z_c(4200)^+$ is a tetraquark, no tetraquark model can accommodate it together with $Z_c(4430)^+$
C.Deng et al PR D92, 034027 (2015)

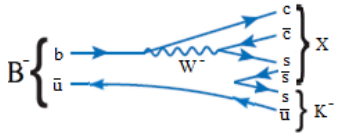
$Z_c(4200)^+$ needs confirmation!

T. Skwarnicki (Tue.)

X(4140) first observed by CDF
PRL 102, 242002 (2009)

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





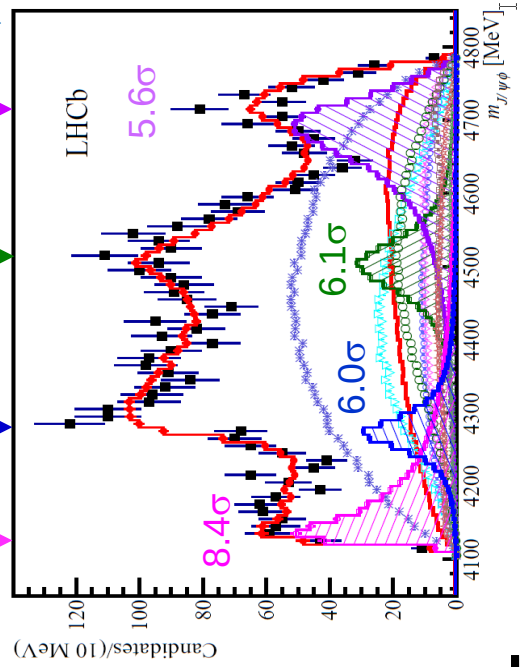
6D amplitude analysis

X(4700)→ J/ψϕ

X(4500)→ J/ψϕ

X(4274)→ J/ψϕ

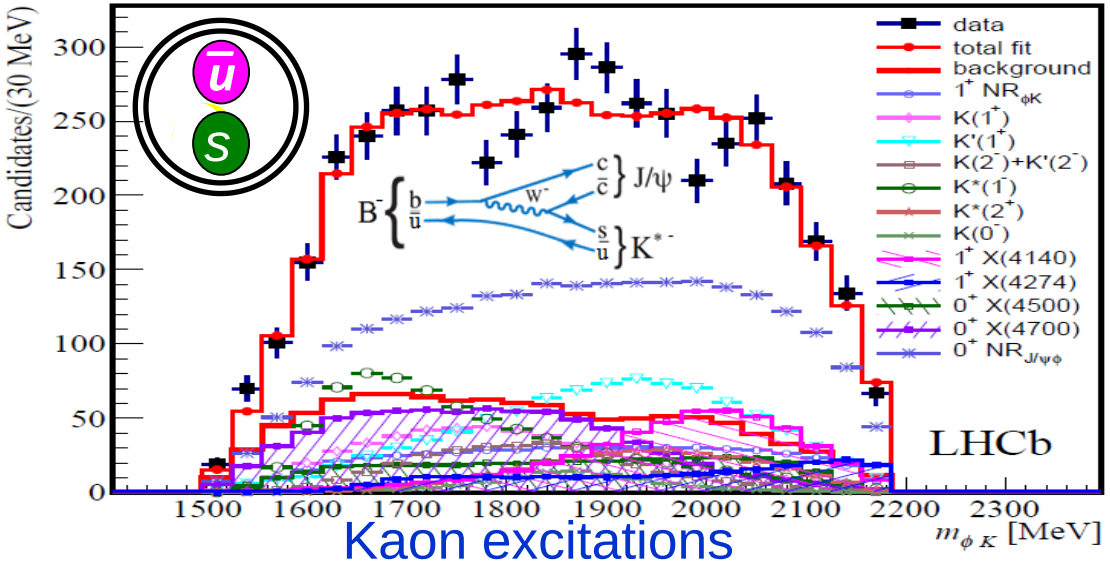
X(4140)→ J/ψϕ



Not enough data to test resonant amplitudes on Argand diagrams.

See T.S. (Tue.)

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

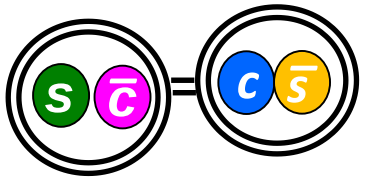


Kaon excitations

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

No η-exchange

$D_{s0}^+ D_{s0}^{*-}$ +69±26 MeV



No π-exchange forces!

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

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

4800

X(4700) 0^{++}

4600

X(4500) 0^{++}

4400

X(4274) 1^{++}

4200

X(4140) 1^{++}

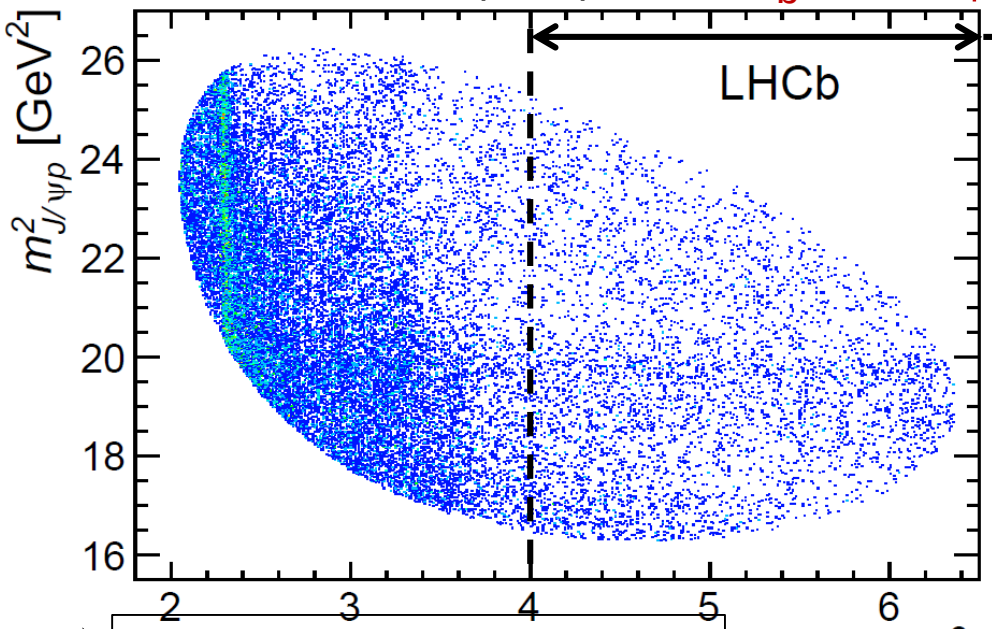
Postdiction by L.Maiani, A.D.Polosa, V. Riquer PRD94, 054026 (2016)
Possibly radially excited 0^{++} tetraquarks. However, only one 1^{++} state with color triplet diquarks.

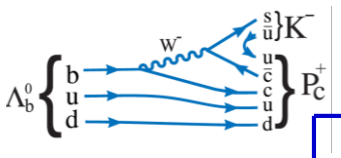
F. Stancu, J.Phys. G37, 075017 (2010)
Predicted two 1^{++} tetraquarks in this mass range (S=0,1 diquarks in color triplet and sextet)

PRL 115, 07201 (2015)

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

5D amplitude analysis





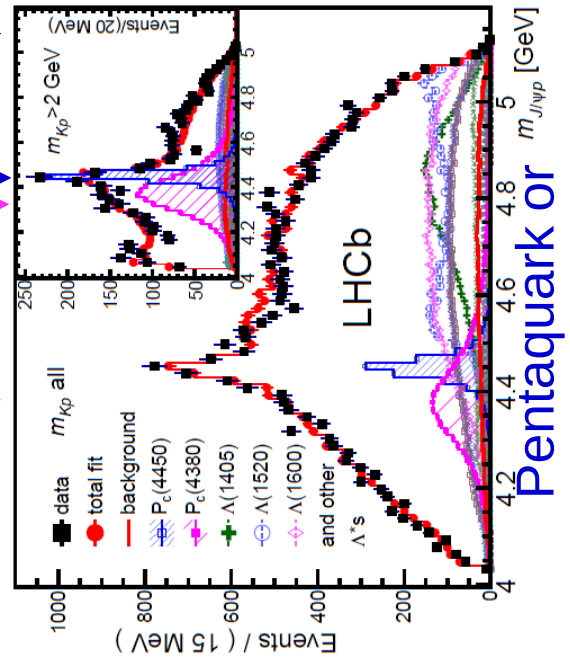
$\Gamma = 39 \pm 20$ MeV

$P_c(4450)^+ \to J/\psi\, p$

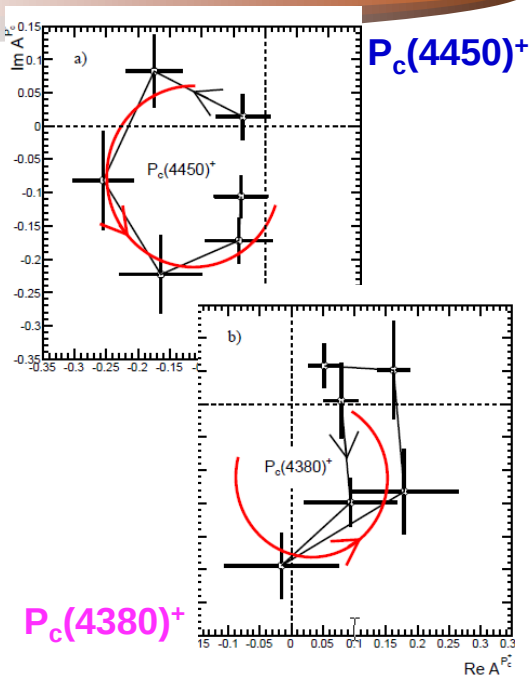
$P_c(4380)^+ \to J/\psi\, p$

$\Gamma = 205 \pm 88$ MeV

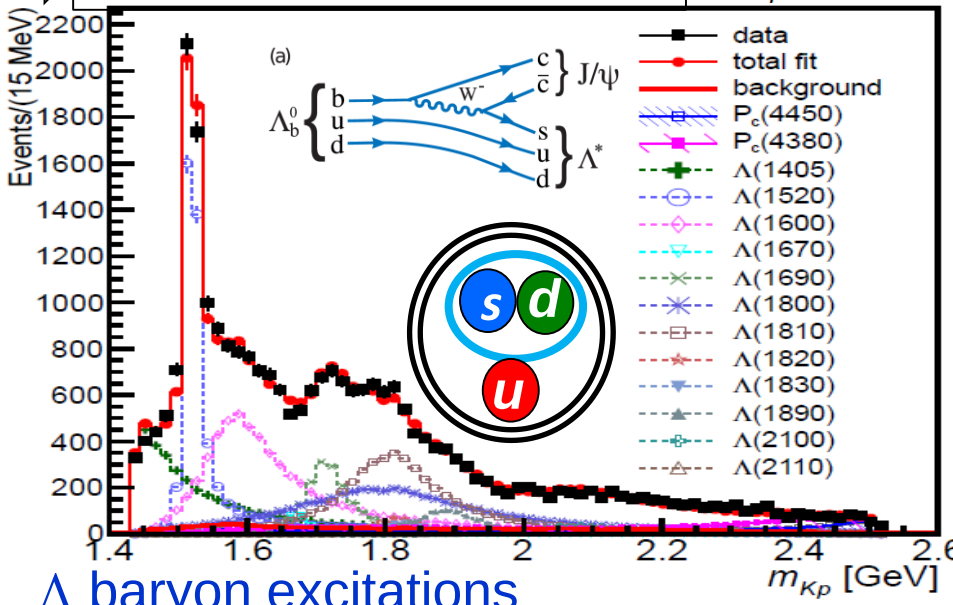
No $\frac{5}{2}^{\pm}$ molecules in this mass range



Pentaquark or baryon-meson molecule



See Liming Zhang's talk



Λ baryon excitations

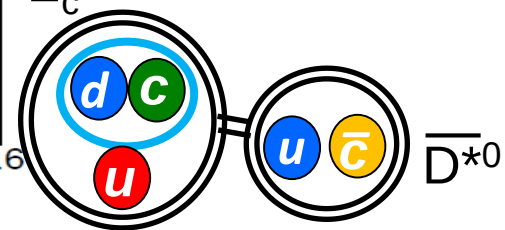
Karliner,Rosner PRL115, 122001(2015) and others

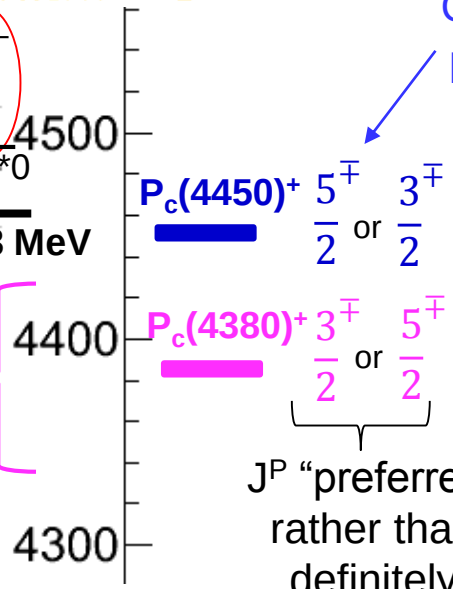
No π-exchange

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

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

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



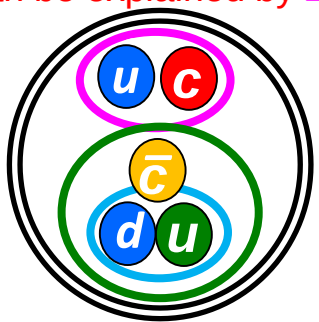


J^P "preferred" rather than definitely determined

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

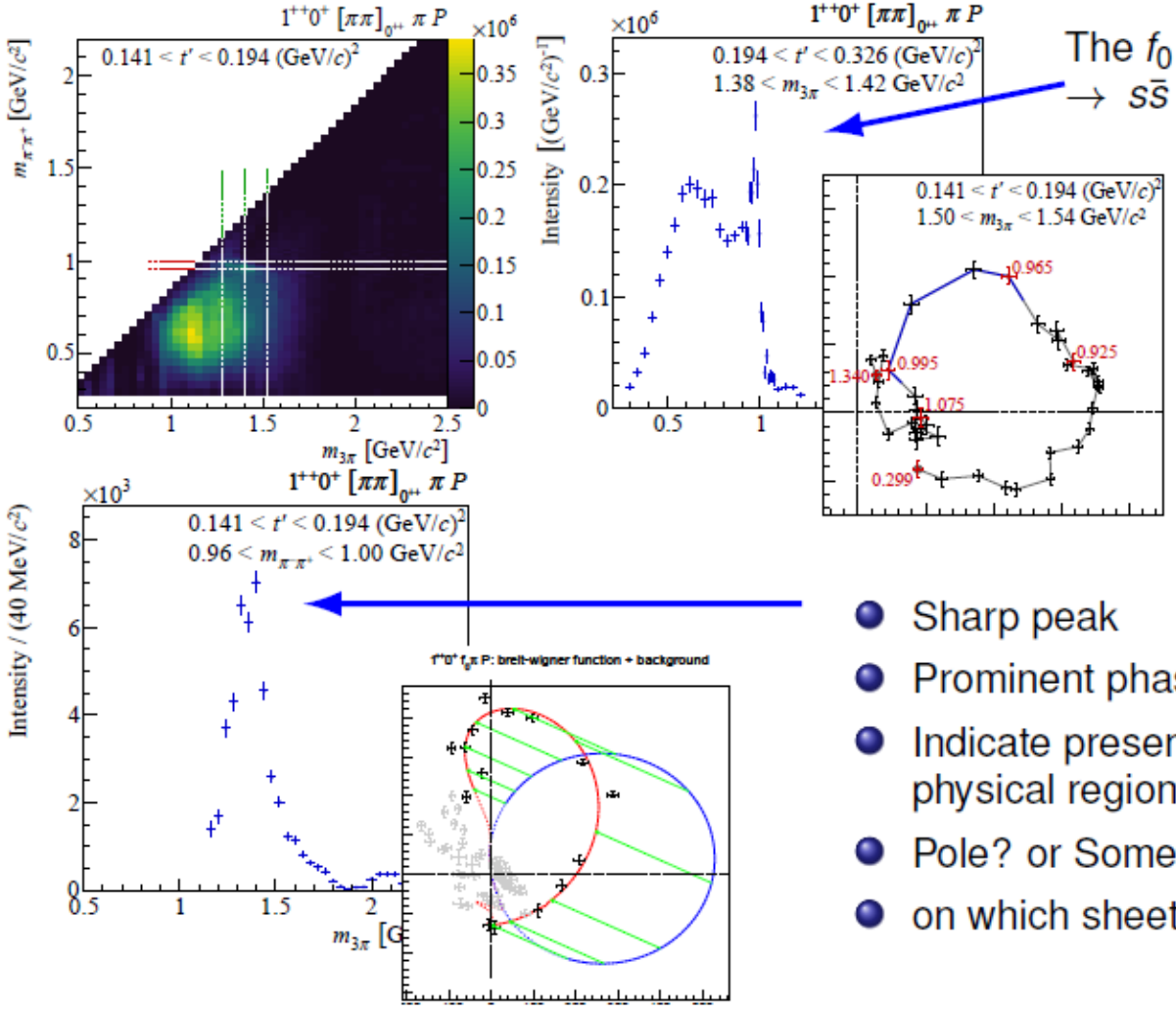
Maiani et al PLB749, 289 (2015) and many others

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

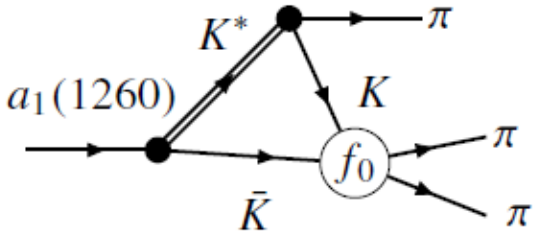


Tomography of $J^{PC}M^{\epsilon} = 1^{++}0^{+}\,(\pi\pi)_S\,P$-wave

[Phys. Rev. D95 (2017) 032004]



The $f_0(980)$ shows up as a peak
$\rightarrow$ $s\bar{s}$ source



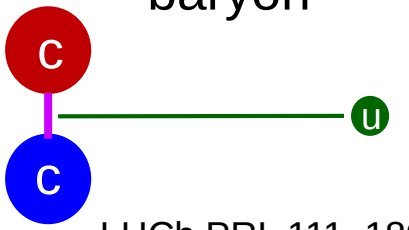
Misha Mikhasenko

- Sharp peak
- Prominent phase motion
- Indicate presence of singularity near the physical region
- Pole? or Something else?
- on which sheet?

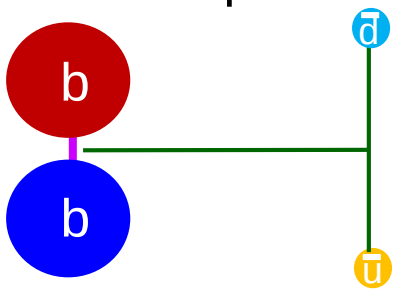
Possibility of triangle anomalies should be explored via amplitude fits to the data which yielded XYZ,Pc states.

Doubly heavy systems

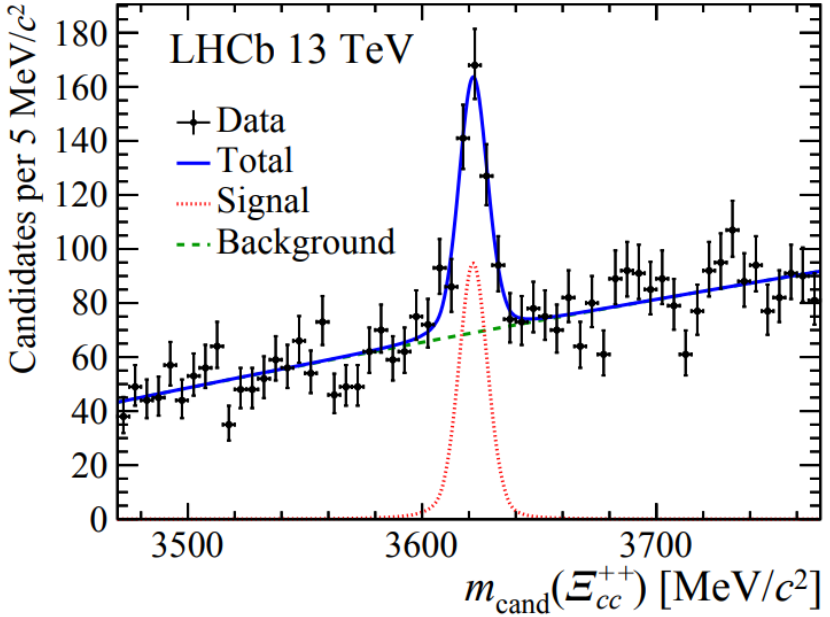
baryon



tetraquark



LHCb PRL 111, 180001 (2017)



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

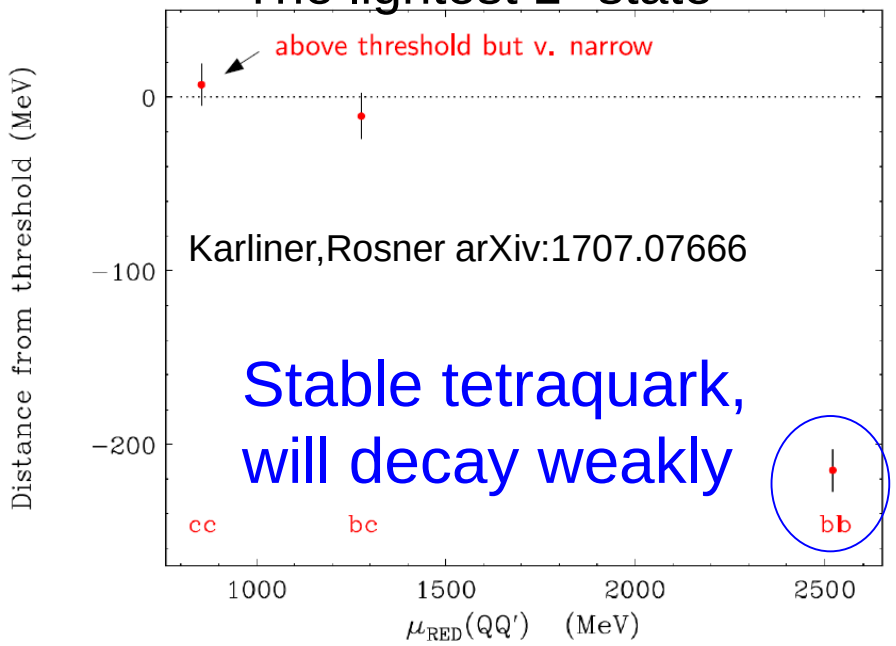
55

Marek Karliner

the same toolkit

See also Chen's talk on quadruple-heavy tetraquarks

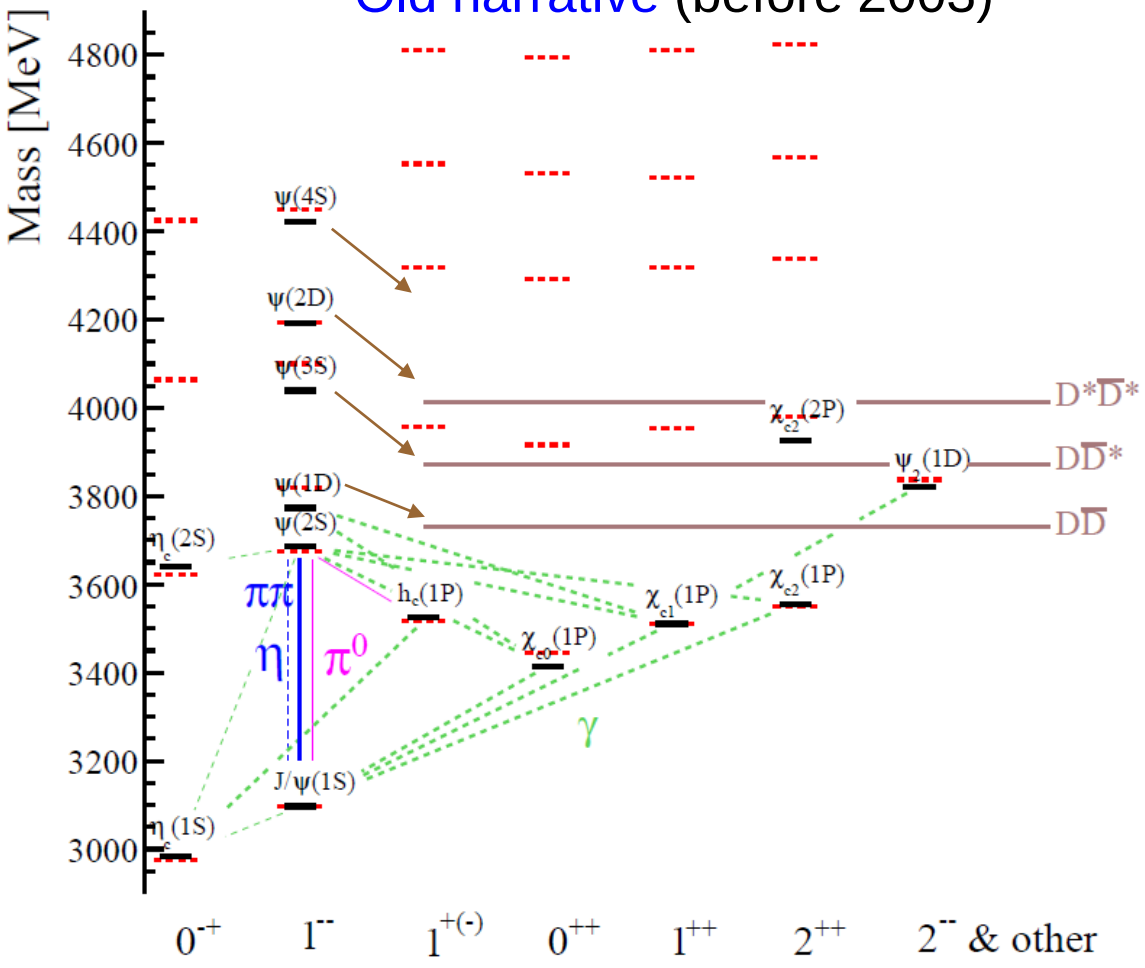
The lightest 1^+ state



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

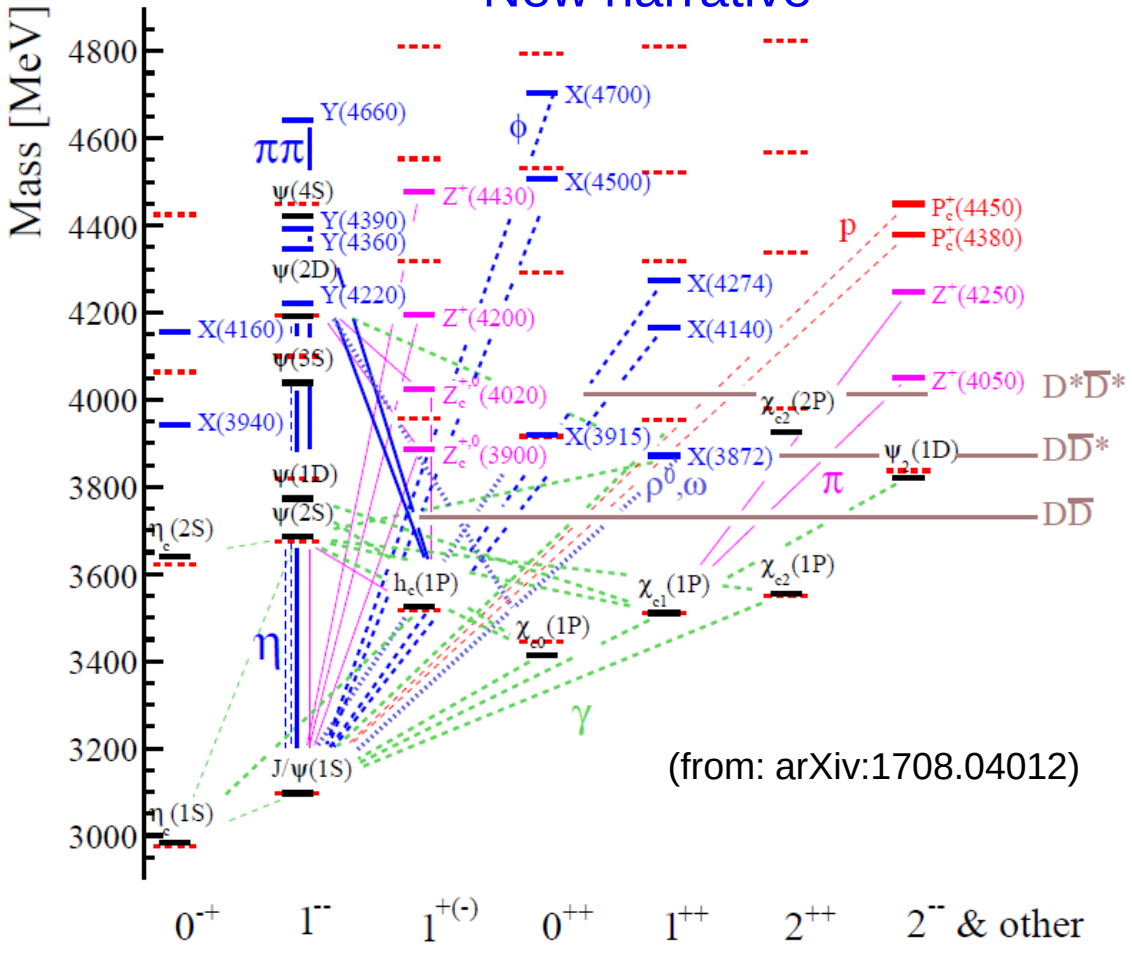
Summary I

Old narrative (before 2003)



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

New narrative

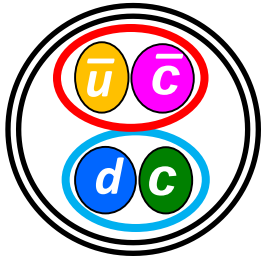


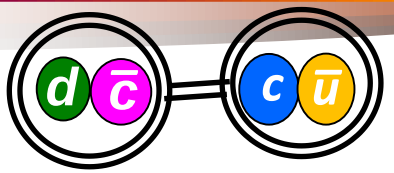
(from: arXiv:1708.04012)

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.

Summary II

(Aug 23, Wednesday session)





Claim most (all?) of XYZ states are tetraquarks or pentaquarks

Necessarily claim there are many more to be discovered

Proliferation of threshold states requires mixing with virtual hadron pairs

Predict prompt production of all XYZ states at hadron colliders

No width predictions so far

Everybody agrees, the lightest 1^+ is stable

Crucial difference.
Lack of experimental reports on prompt production of most of XYZ,P_c states anecdotally favors molecular forces (**need experiments to publish limits**!)

Proliferation of threshold states is the main feature of this model (supported also by lighter meson spectroscopy).

Narrow widths expected!

Cannot account for some observed XYZ,P_c states. Leave room for other dynamics to play a role.

More threshold states expected, but predictive power somewhat limited. No agreement on exact dynamical model (only π-exchange?).

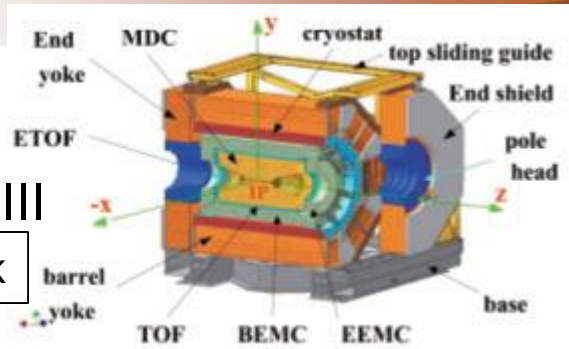
No prompt production, unless mix with compact hadron.

Summary III

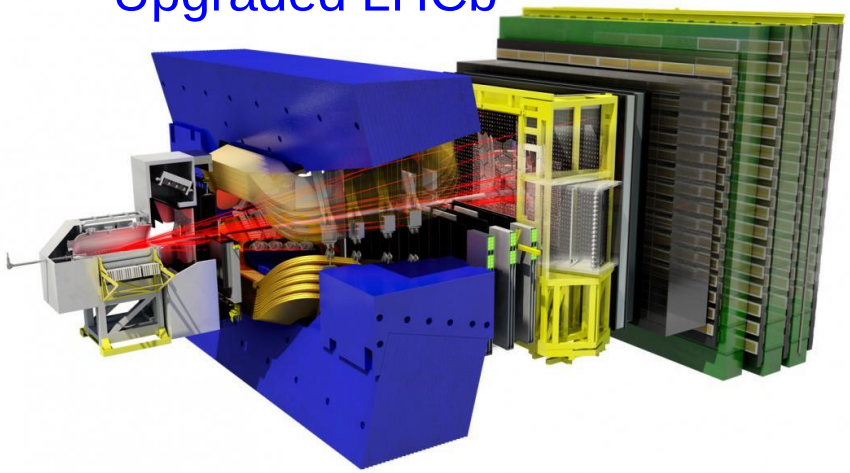
- Need more data to settle the phenomenological disputes
- More data are forthcoming!

⇨ BES III

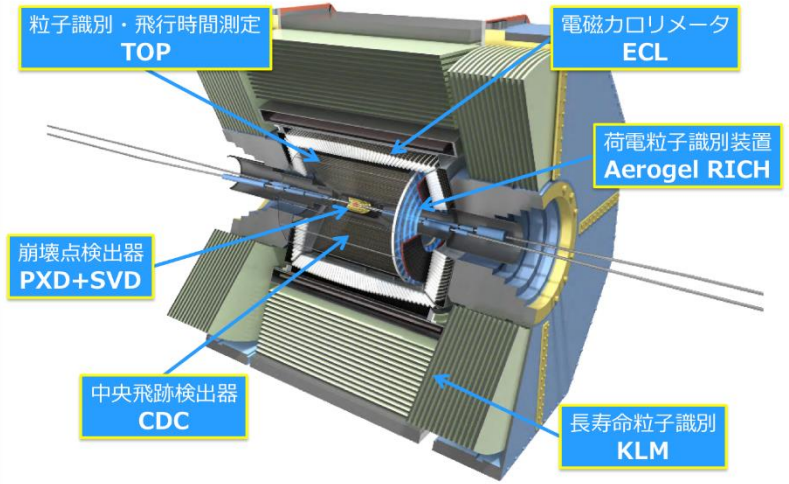
See K.Zhu's talk

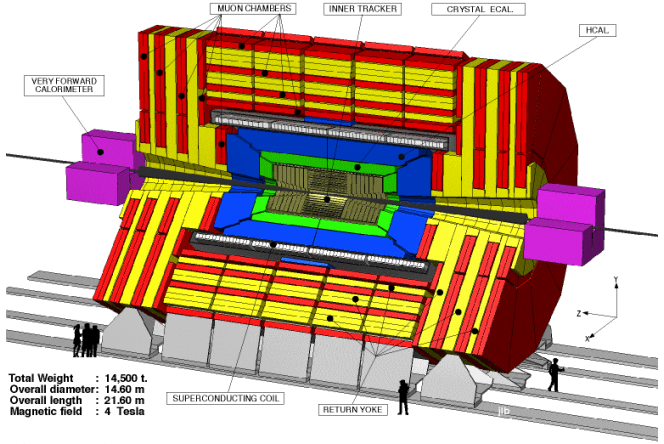


Upgraded LHCb

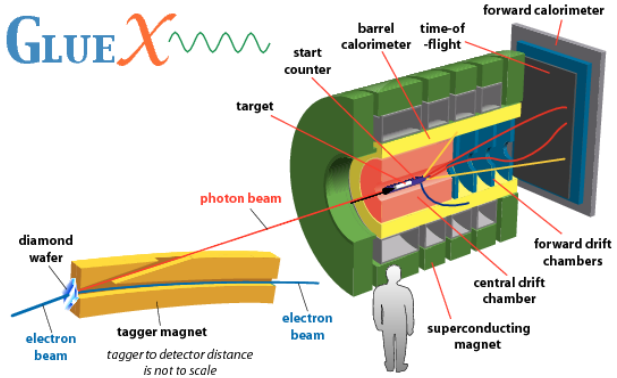


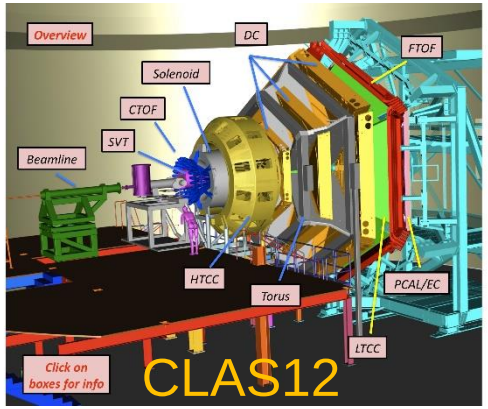
Belle II 測定器

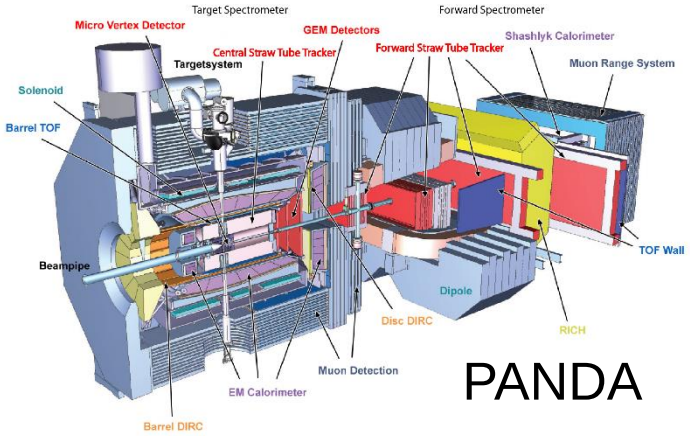




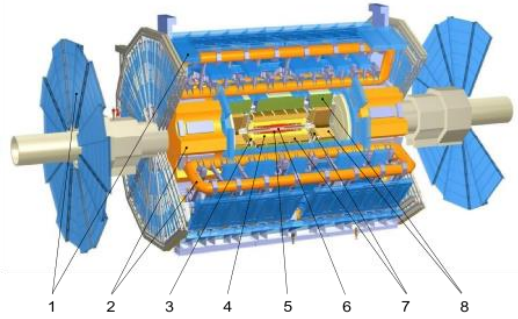
CMS







PANDA



ATLAS

and other…