LHCb results on Tetra- and Penta-Quark candidates

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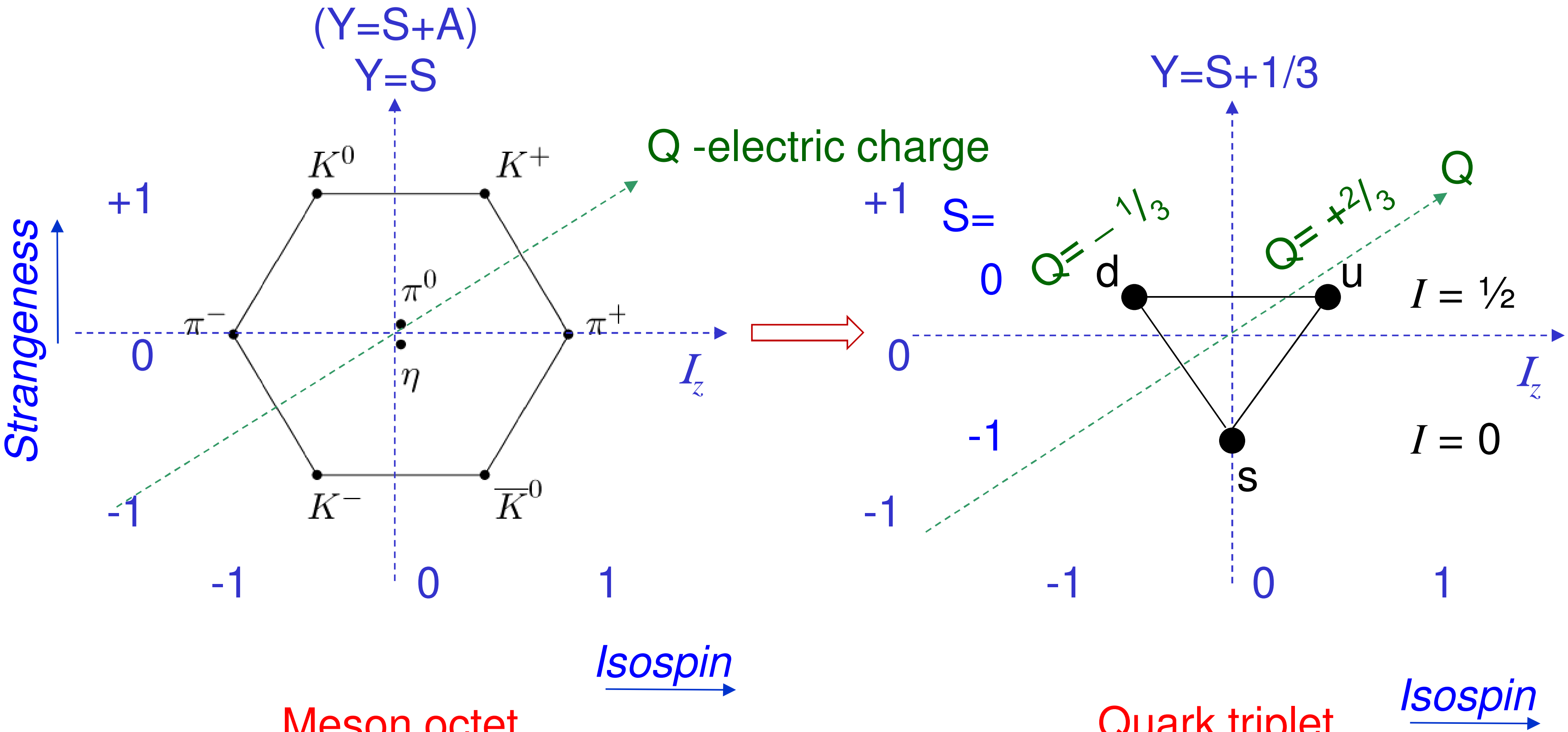
Syracuse University

Oct 26, 2015
at

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Quark hypothesis – SU(3) flavor symmetry

"Eightfold Way" symmetry – Gell-Mann 1961



Meson octet

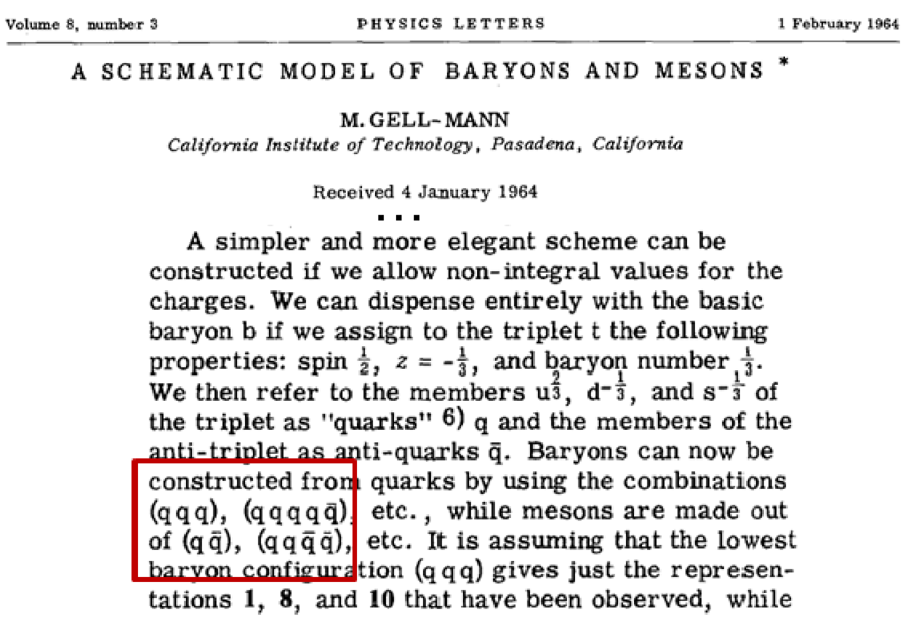
J = 0

Quark triplet

(also J=1/2 baryon octent and J=3/2 decuplet)

- Quarks initially treated as mathematical abstractions

“Exotic” mutiquark 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 *

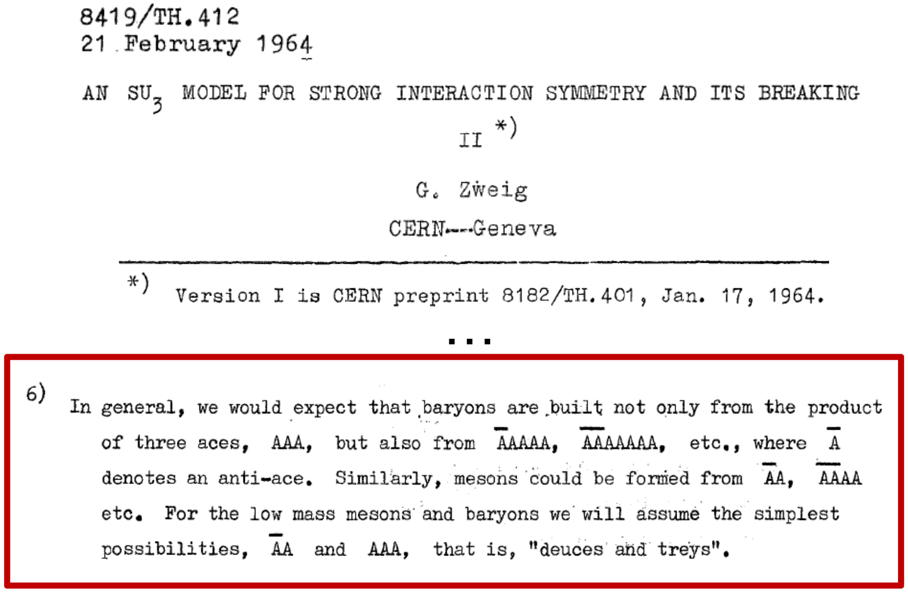
M. GELL-MANN

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

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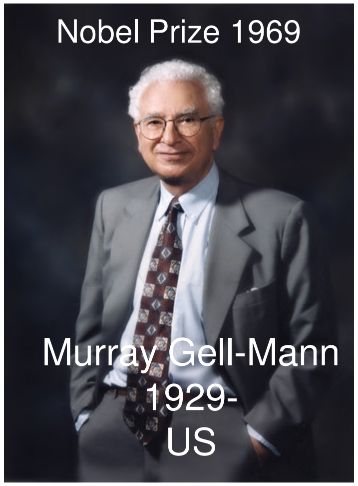
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

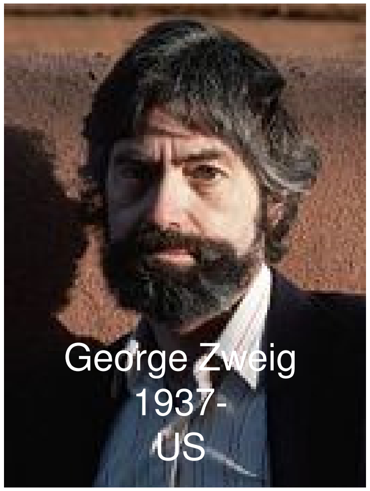
. . .

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



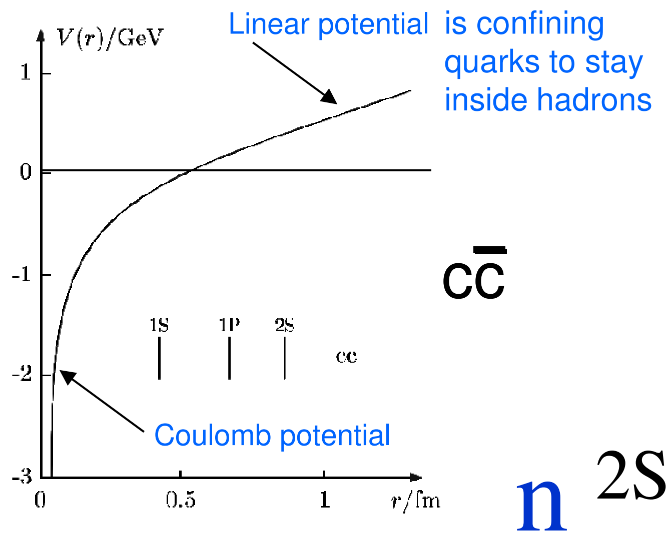
Nobel Prize 1969

Murray Gell-Mann
1929-
US

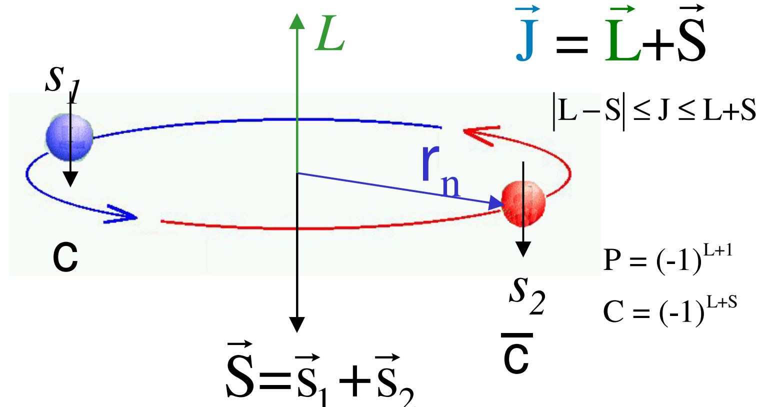


George Zweig
1937-
US

Charmonium – narrow (i.e. long-lived) states



Non-relativistic quantum mechanics!



$\vec{J} = \vec{L} + \vec{S}$

$|L - S| \le J \le L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

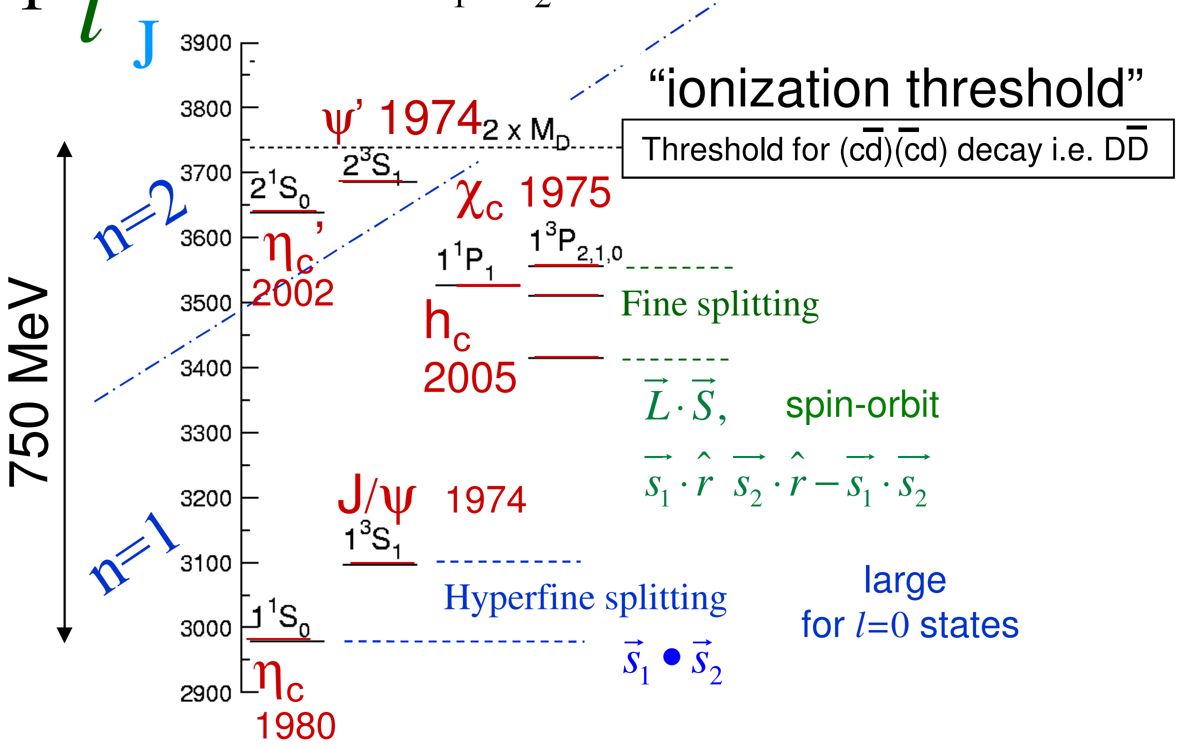
$\vec{S} = \vec{s}_1 + \vec{s}_2$

$n\ {}^{2S+1}l_J$

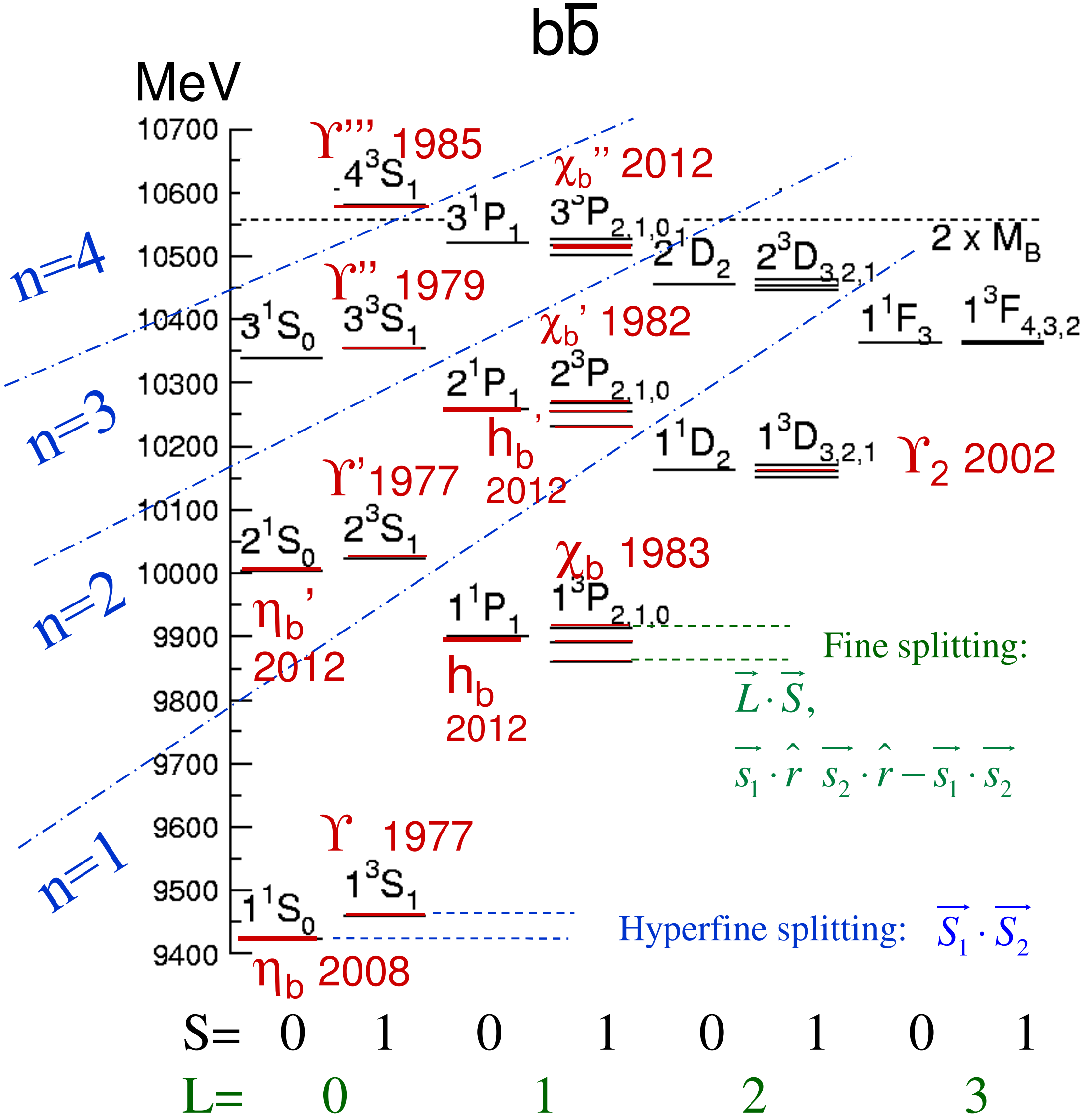
Forces between quarks
are 10-100 times **stronger**
than between nucleons!

1974 November revolution:

- Quark Model and $q\bar{q}$ hypothesis for mesons firmly established!
- However, near mass equality of light quarks was coincidental



Bottomonium – narrow states



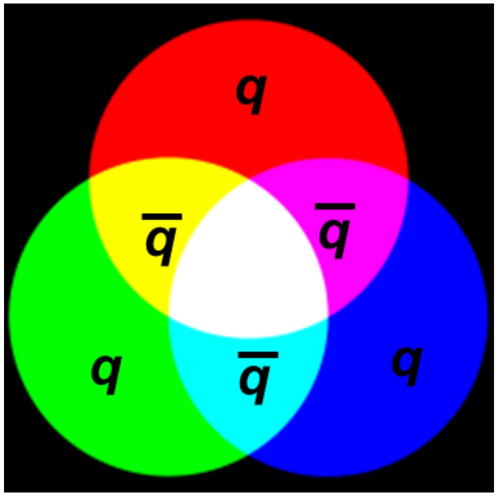
“ionization threshold” ($B\bar{B}$)

- Even more long-lived states

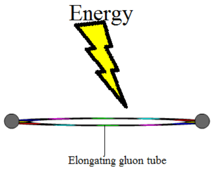
Impressive agreement between the observed states and $b\bar{b}$ non-relativistic potential model

SU(3) color symmetry

- Fundamental parts of SU(3)$_{\text{flavor}}$ symmetry discovered by Gell-Mann & Zweig:
  - Quark flavor independence of strong interactions
  - Rules for making hadrons out of quarks – led to development of exact theory of strong interactions, QCD based on SU(3)$_{\text{color}}$ symmetry

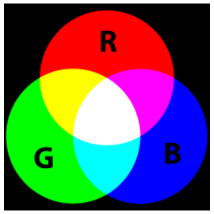


Breaking of color field flux tube by popping of $q\bar{q}$ pair:



Strength of color interactions raises with separation of color charges → confinement of color charge → hadrons must be color neutral i.e. “white” ($q\bar{q}$, qqq, ….)

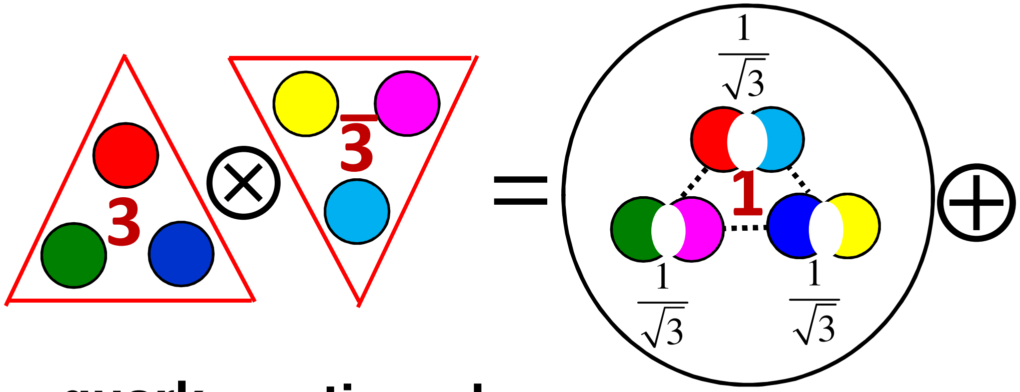
Mesons from quarks & antiquarks in QCD



color triplet

color antitriplet

color singlet



quark

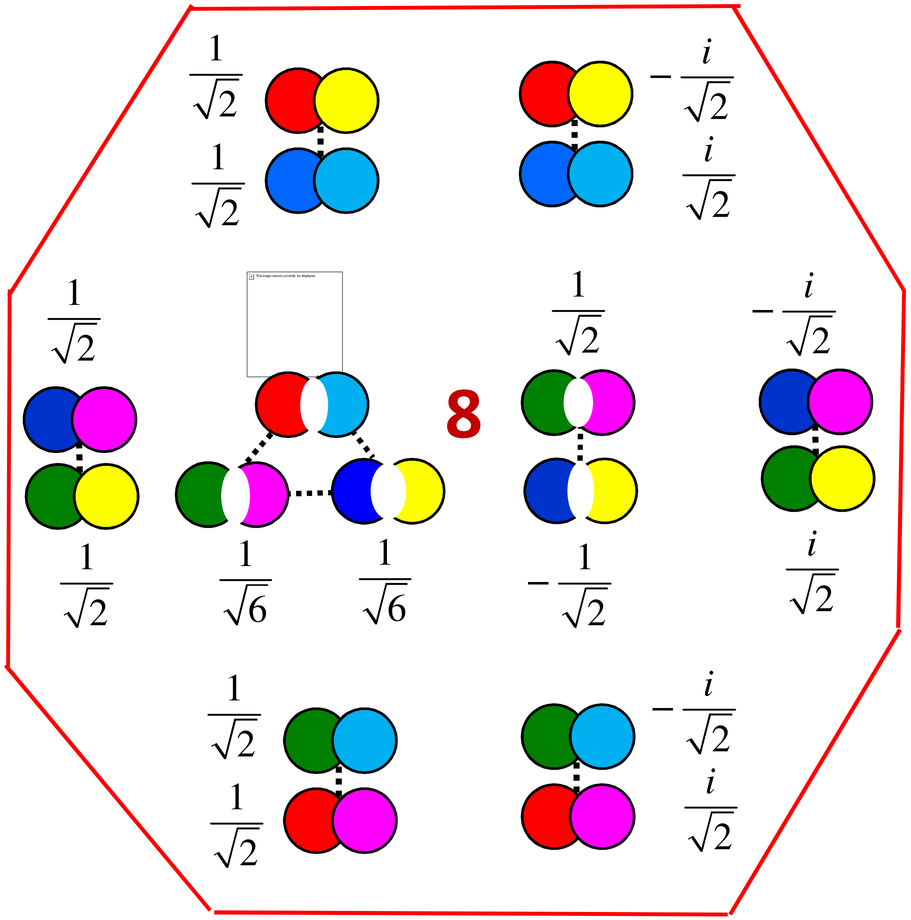
antiquark

q

$\bar{q}$

attractive color force

color octet



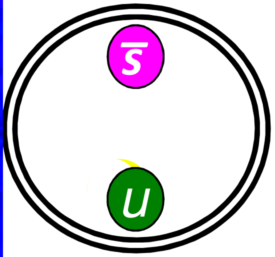
repulsive color force

quarks will pull apart in any octet configuration

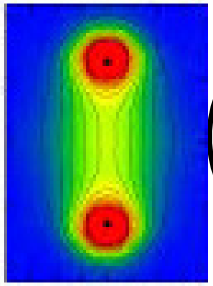
gluons happen to belong to the color octet

$(q\bar{q})$ meson

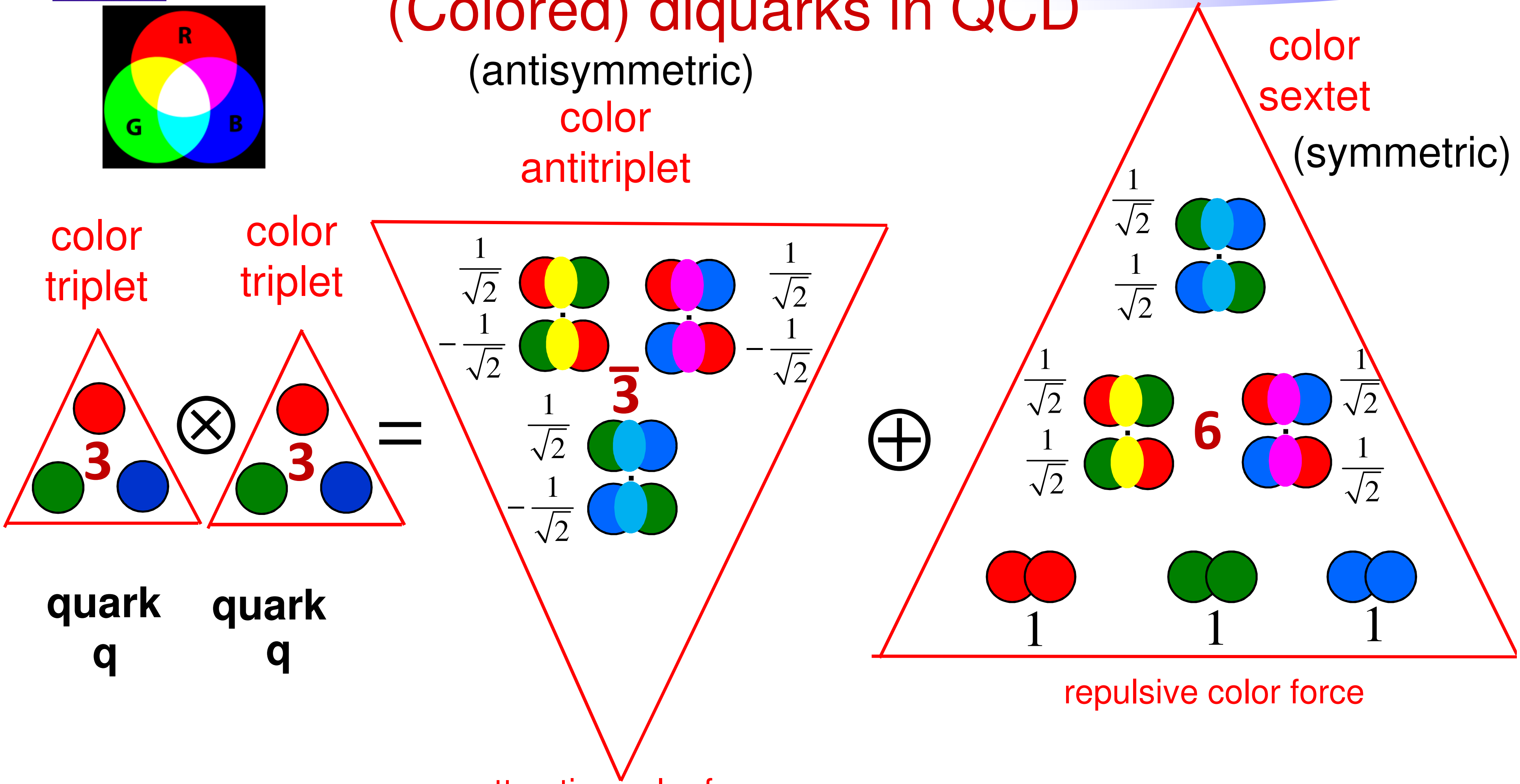
e.g. K^+



Color flux tube stretched between quark and antiquark with attractive potential



(Colored) diquarks in QCD

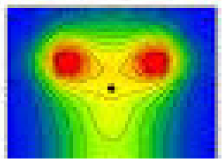


repulsive color force

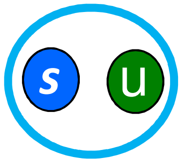
attractive color force
(half as strong as in the meson)

quarks will pull apart in any sextet configuration

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

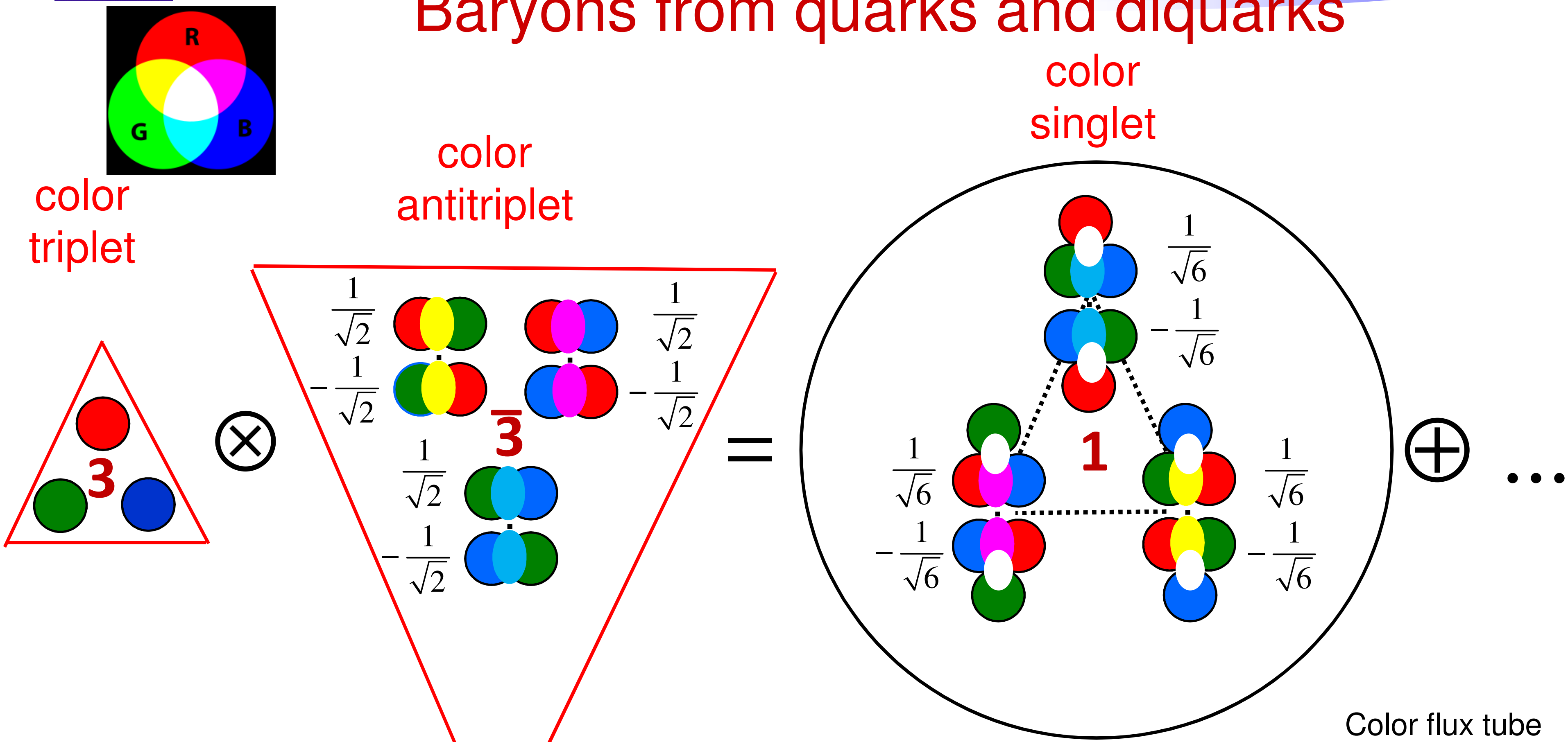


(qq) diquark



Not a particle, just a building block in QCD

Baryons from quarks and diquarks



color
triplet

color
antitriplet

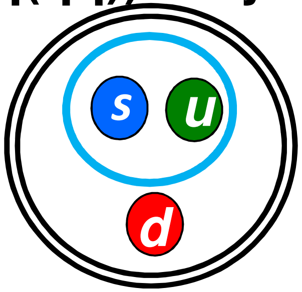
color
singlet

quark
q

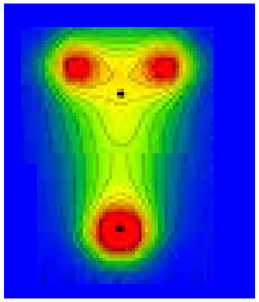
attractive color force
(qq) diquark

attractive color force
(q(qq)) baryon

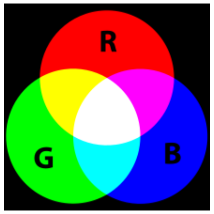
e.g. Λ



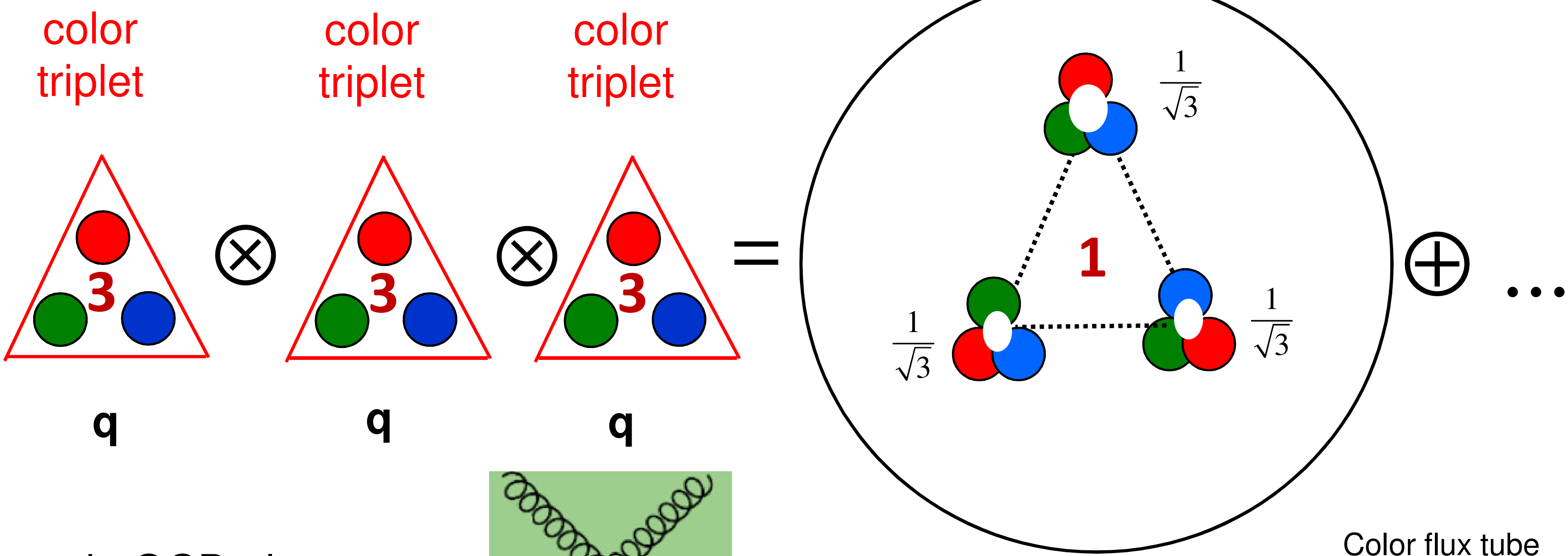
Color flux tube
stretched between
the diquark and the
third quark



Baryons directly from 3 quarks



color singlet

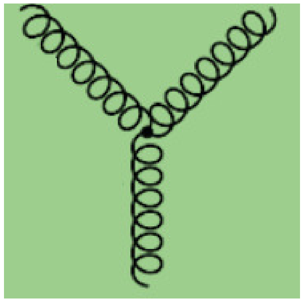


color triplet

color triplet

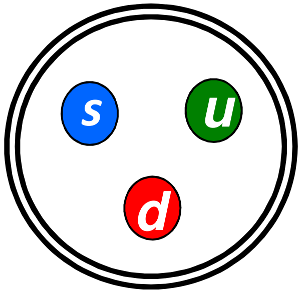
color triplet

in QCD gluons can couple to each other

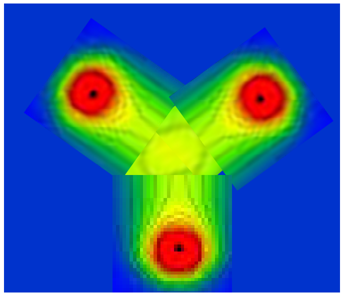


attractive color force

(qqq) baryon

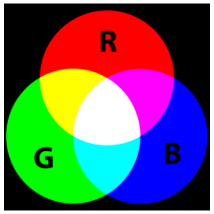


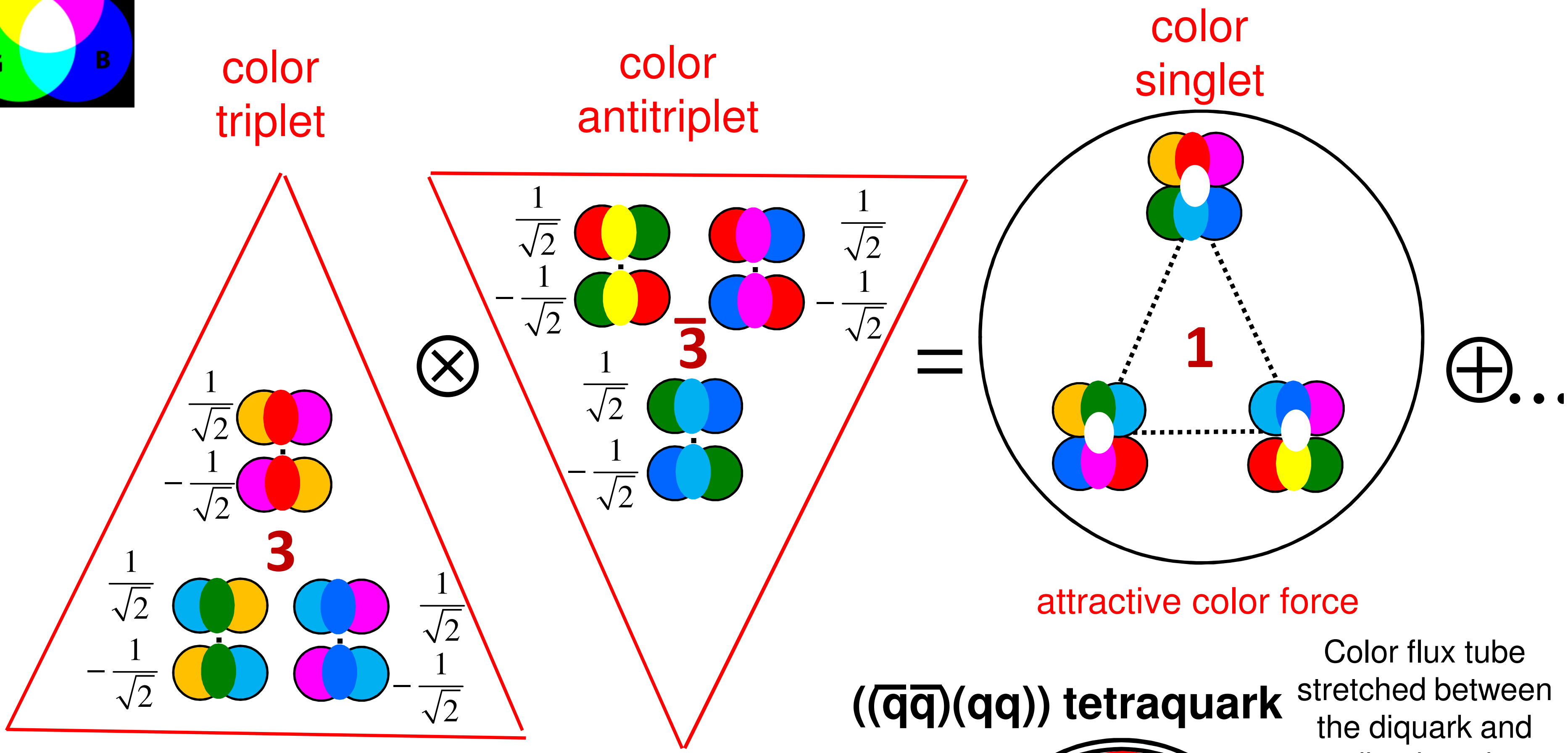
Color flux tube stretched between three quarks



Different forms of quark configurations in a baryon can coexist. Relative importance of diaquarks can depend on quark flavors.

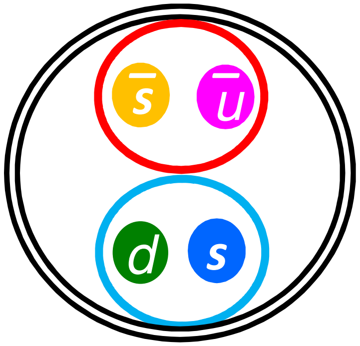
Tetraquarks from diquarks and diantiquarks



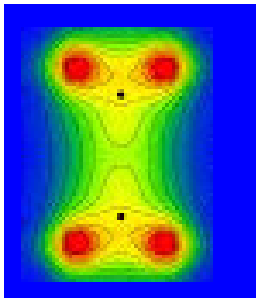


attractive color force

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



Color flux tube stretched between the diquark and diantiquark

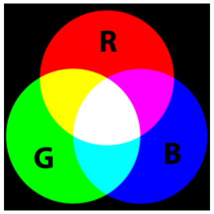


attractive color force

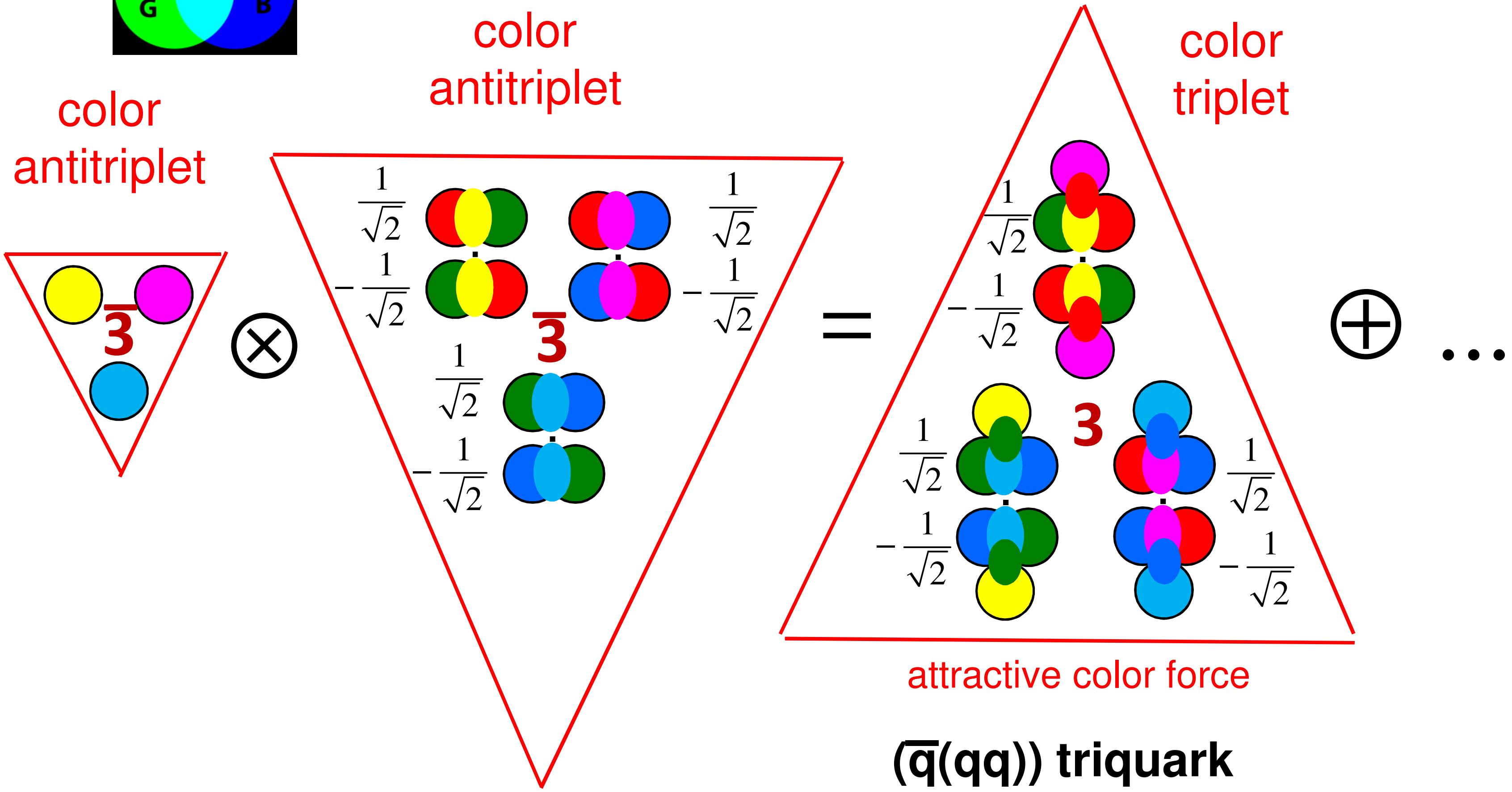
$(\bar{q}\bar{q})$ diantiquark

attractive color force

(qq) diquark



(Colored) triquarks from antiquarks and diquarks



color antitriplet

color antitriplet

color triplet

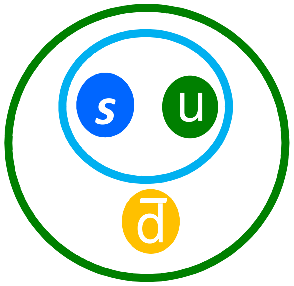
attractive color force

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

attractive color force

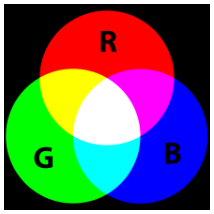
(qq) diquark

$\bar{q}$
antiquark



Not a particle, just a building block in QCD

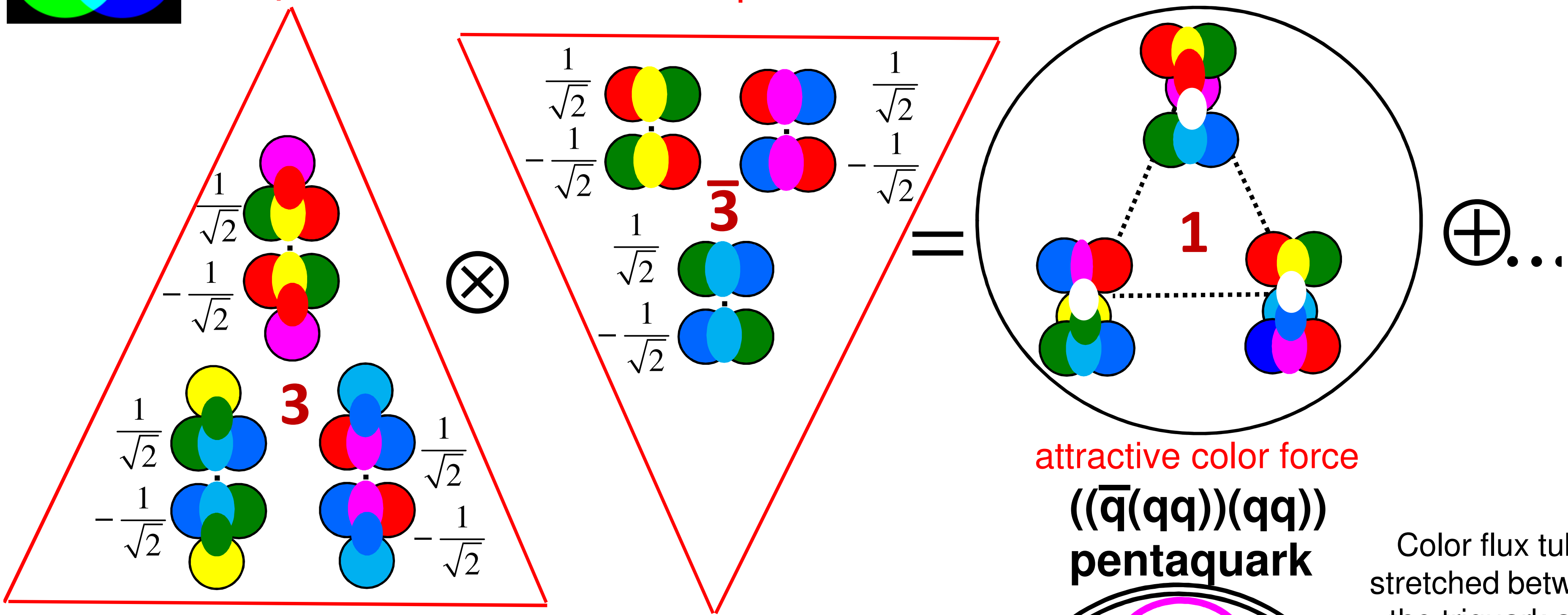
Pentaquark from triquarks and diquarks



color triplet

color antitriplet

color singlet



attractive color force

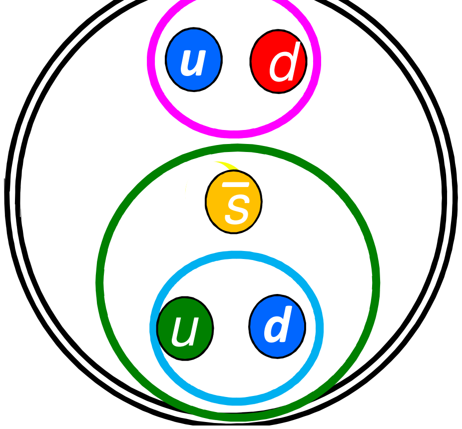
$((\bar{q}(qq))(qq))$ pentaquark

attractive color force

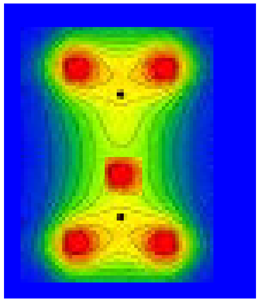
$(\bar{q}(qq))$ triquark

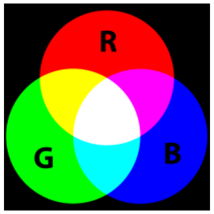
attractive color force

(qq) diquark

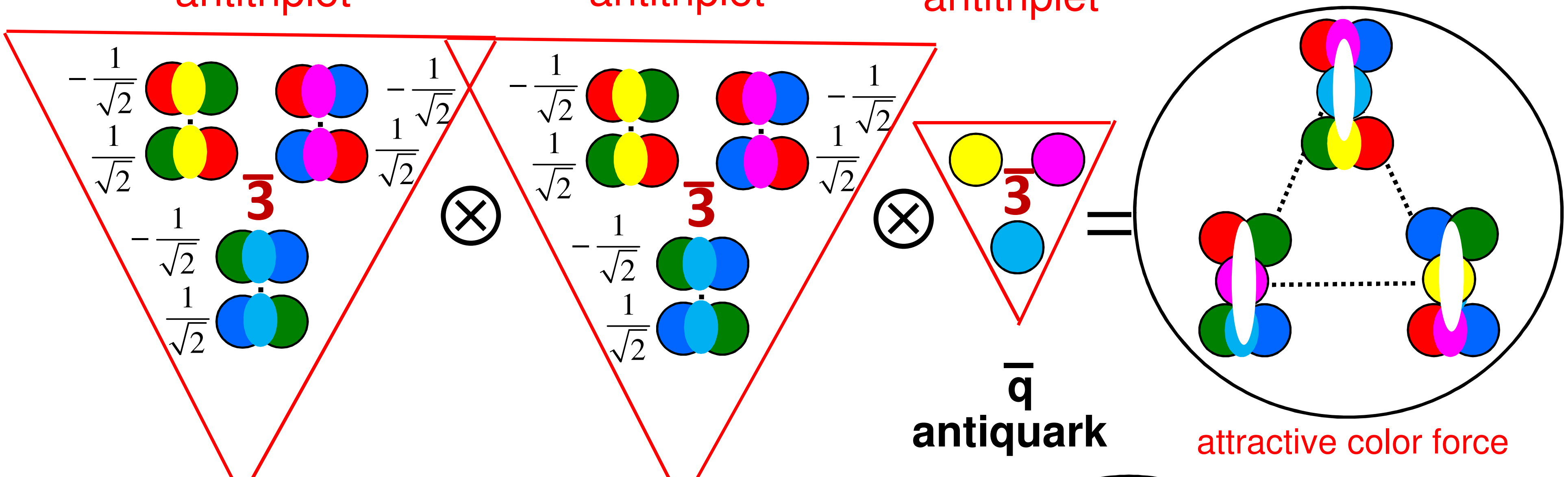


Color flux tube stretched between the triquark and diquark





Pentaquark directly from two diquarks and antiquark



color antitriplet

color antitriplet

color antitriplet

color singlet

$\bar{q}$ **antiquark**

attractive color force

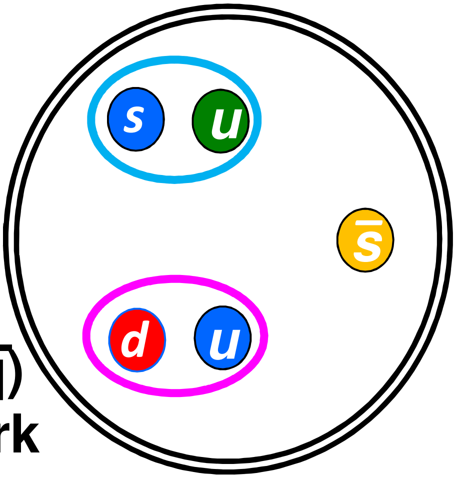
attractive color force

attractive color force

(qq) diquark

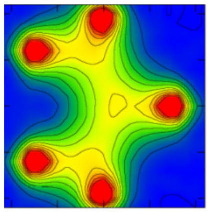
(qq) diquark

Different forms of quark configurations in a pentaquark can coexist. Modeling of pentaquarks is complicated.

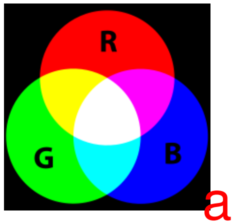


((qq)(qq)$\bar{q}$) pentaquark

Color flux tube stretched between the diquarks and antiquark



Hexaquark directly from three diquarks

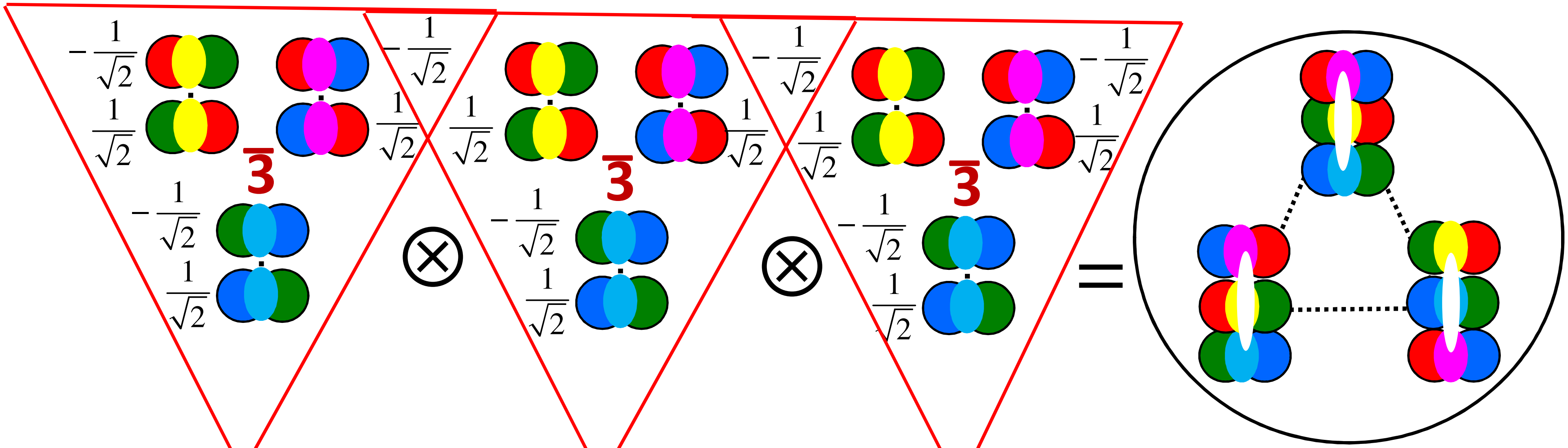


color antitriplet

color antitriplet

color antitriplet

color singlet



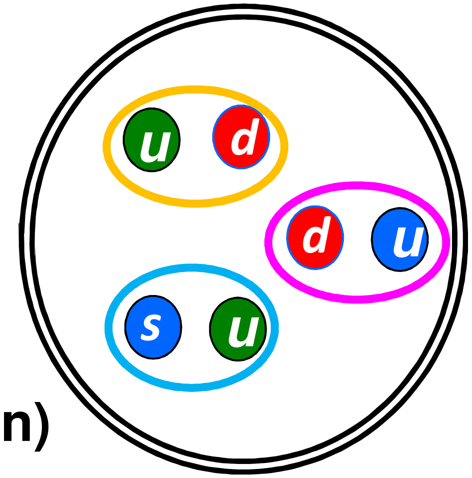
attractive color force

attractive color force

attractive color force

attractive color force

(qq) diquark **(qq) diquark** **(qq) diquark**



((qq)(qq)(qq))
hexaquark (dibaryon)

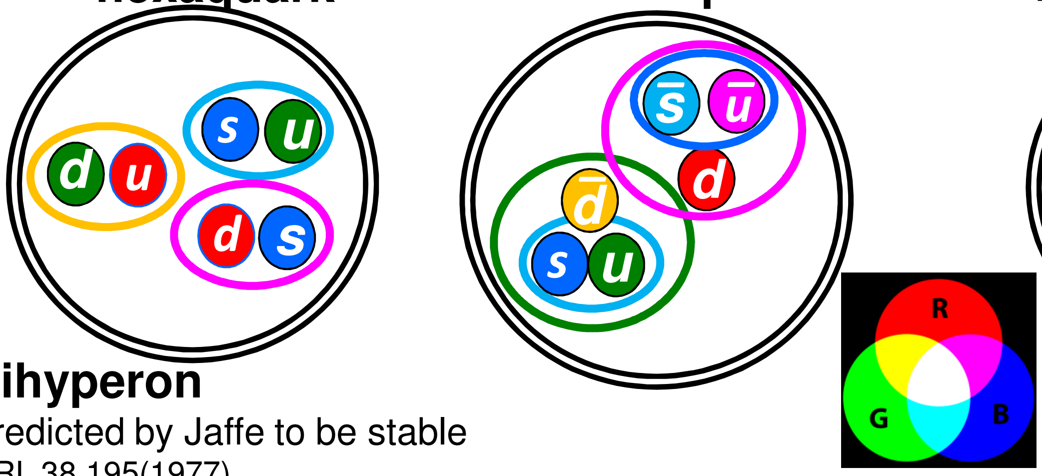
Tightly and loosely bound multiquark states

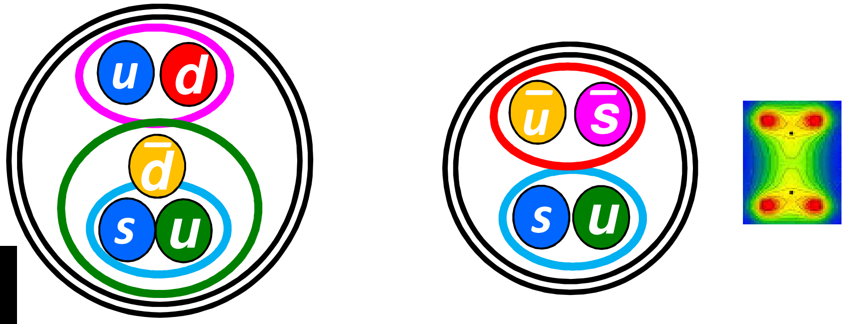
$(((sq)(sq))(qq))$ hexaquark

$((\bar{q}(sq))(q(\overline{sq})))$ hexaquark

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

$((\overline{sq})(sq))$ tetraquark



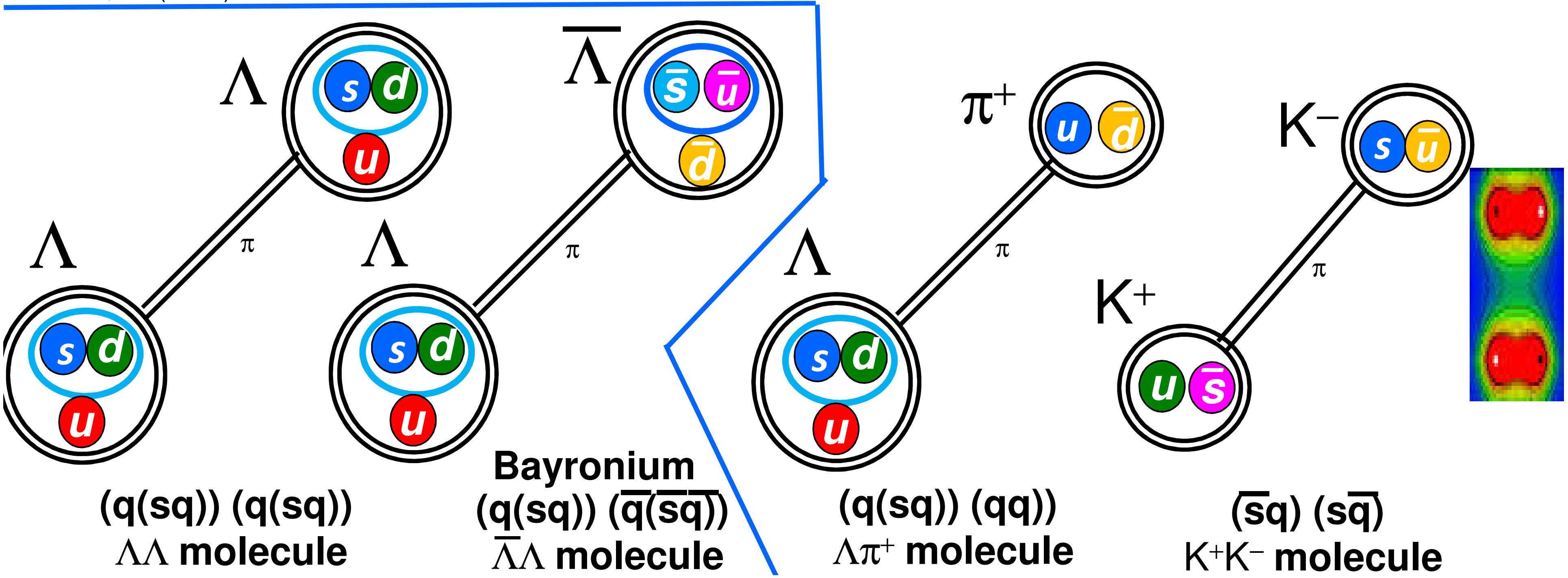


dihyperon

predicted by Jaffe to be stable

PRL 38,195(1977)

Any of these states would be considered an “exotic” hadron.



Bayronium

$(q(sq))\ (q(sq))$
$\Lambda\Lambda$ molecule

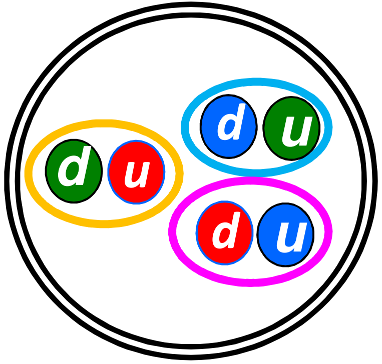
$(q(sq))\ (\bar{q}(\overline{sq}))$
$\bar{\Lambda}\Lambda$ molecule

$(q(sq))\ (qq)$
$\Lambda\pi^{+}$ molecule

$(\bar{s}q)\ (s\bar{q})$
$K^{+}K^{-}$ molecule

Tightly versus loosely bound multiquark systems

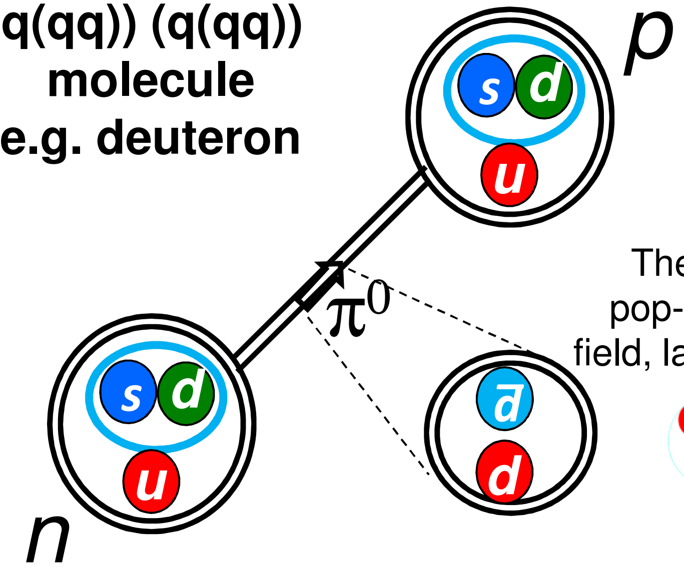
(((qq)(qq))(qq))
hexaquark (dibaryon)



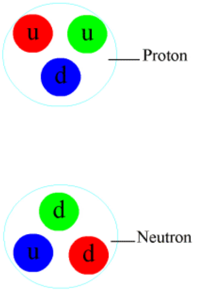
The same
quark content

Quite different
spectroscopy

(q(qq)) (q(qq))
molecule
e.g. deuteron



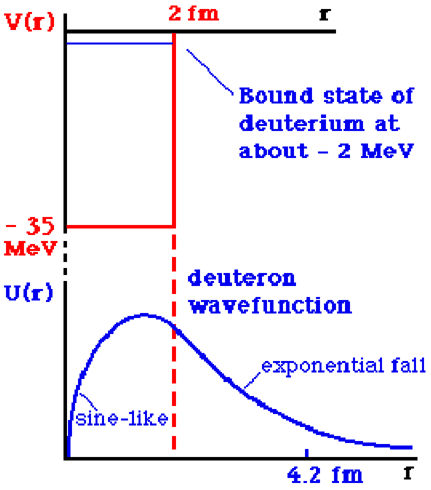
These quarks
pop-out of gluon
field, later annihilat



Molecular forces can be described
as exchange of a pion

- Rich excitation spectrum, in principle, possible:
  - n, l, S
  - hundreds of MeV in energy between different excitations
  - high $\vec{J} = \vec{L} + \vec{S}$ values possible

Such structures may be extremely unstable (wide).
No firm input from lattice QCD (yet) which, if any, multiquark structures form well defined bound states.



Difficult to get more than one state (n=1,l=0).

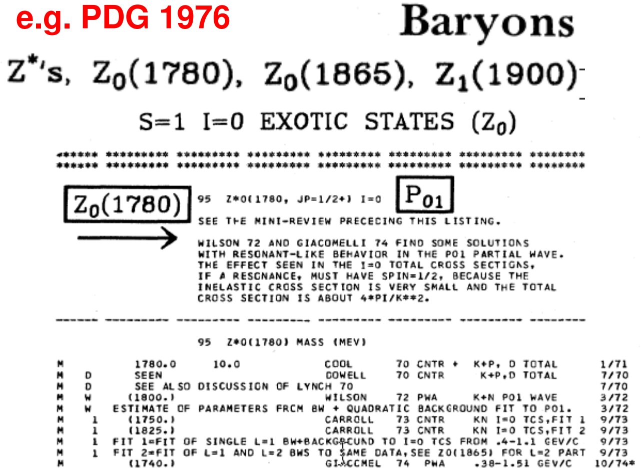
$M = M_1+M_2$ – (a few MeV)

$J^P = (J_1 \otimes J_2)^{P1*P2}$

$\Gamma \sim \max(\Gamma_1,\Gamma_2)$

Two waves of past pentaquark claims (with $\bar{s}$)

e.g. PDG 1976



Baryons

Z^{*}'s, $Z_0(1780)$, $Z_0(1865)$, $Z_1(1900)$

S=1 I=0 EXOTIC STATES (Z_0)

$Z_0(1780)$ → P_{01}

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****** ********* ********* ********* ********* ********* ********* ********
****** ********* ********* ********* ********* ********* ********* ********

            95  Z*0(1780, JP=1/2+) I=0
            SEE THE MINI-REVIEW PRECEDING THIS LISTING.

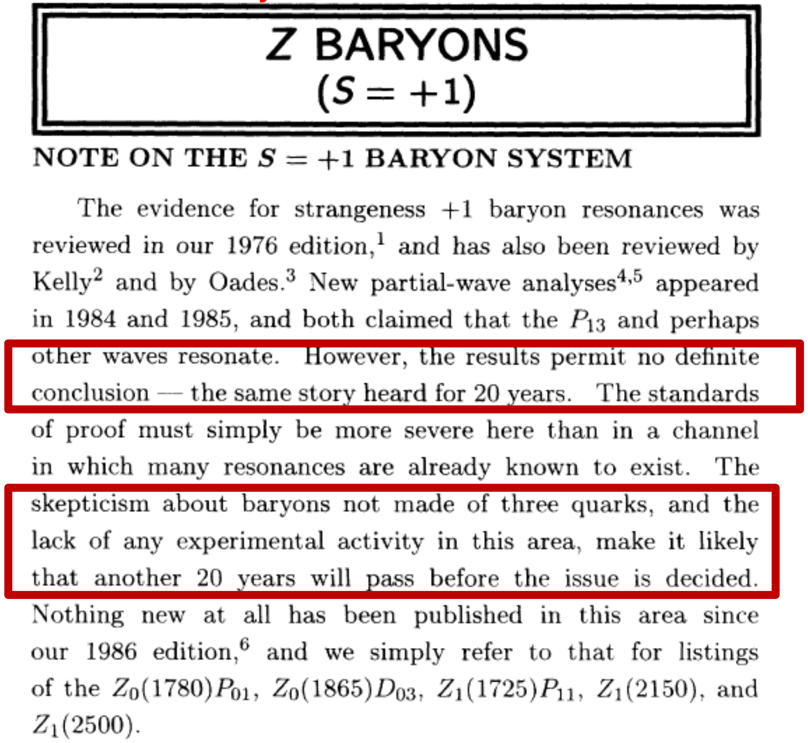
            WILSON 72 AND GIACOMELLI 74 FIND SOME SOLUTIONS
            WITH RESONANT-LIKE BEHAVIOR IN THE P01 PARTIAL WAVE.
            THE EFFECT SEEN IN THE I=0 TOTAL CROSS SECTIONS,
            IF A RESONANCE, MUST HAVE SPIN=1/2, BECAUSE THE
            INELASTIC CROSS SECTION IS VERY SMALL AND THE TOTAL
            CROSS SECTION IS ABOUT 4*PI/K**2.

------ --------- --------- --------- --------- --------- --------- --------

            95  Z*0(1780) MASS (MEV)

M        1780.0     10.0             COOL      70 CNTR +  K+P, D TOTAL      1/71
M   D     SEEN                       DOWELL    70 CNTR     K+P,D TOTAL      7/70
M   D     SEE ALSO DISCUSSION OF LYNCH 70                                   7/70
M   W    (1800.)                     WILSON    72 PWA     K+N P01 WAVE      3/72
M   W  ESTIMATE OF PARAMETERS FRCM BW + QUADRATIC BACKGROUND FIT TO P01.    3/72
M   1    (1750.)                     CARROLL   73 CNTR    KN I=0 TCS,FIT 1  9/73
M   1    (1825.)                     CARROLL   73 CNTR    KN I=0 TCS,FIT 2  9/73
M   1  FIT 1=FIT OF SINGLE L=1 BW+BACKGROUND TO I=0 TCS FROM .4-1.1 GEV/C    9/73
M   1  FIT 2=FIT OF L=1 AND L=2 BWS TO SAME DATA,SEE Z0(1865) FOR L=2 PART  9/73
M        (1740.)                     GIACCMEL  74  PWA     .38-1.51 GEV/C   10/74*
```

Last mention of baryonic Z*'s PDG 1992



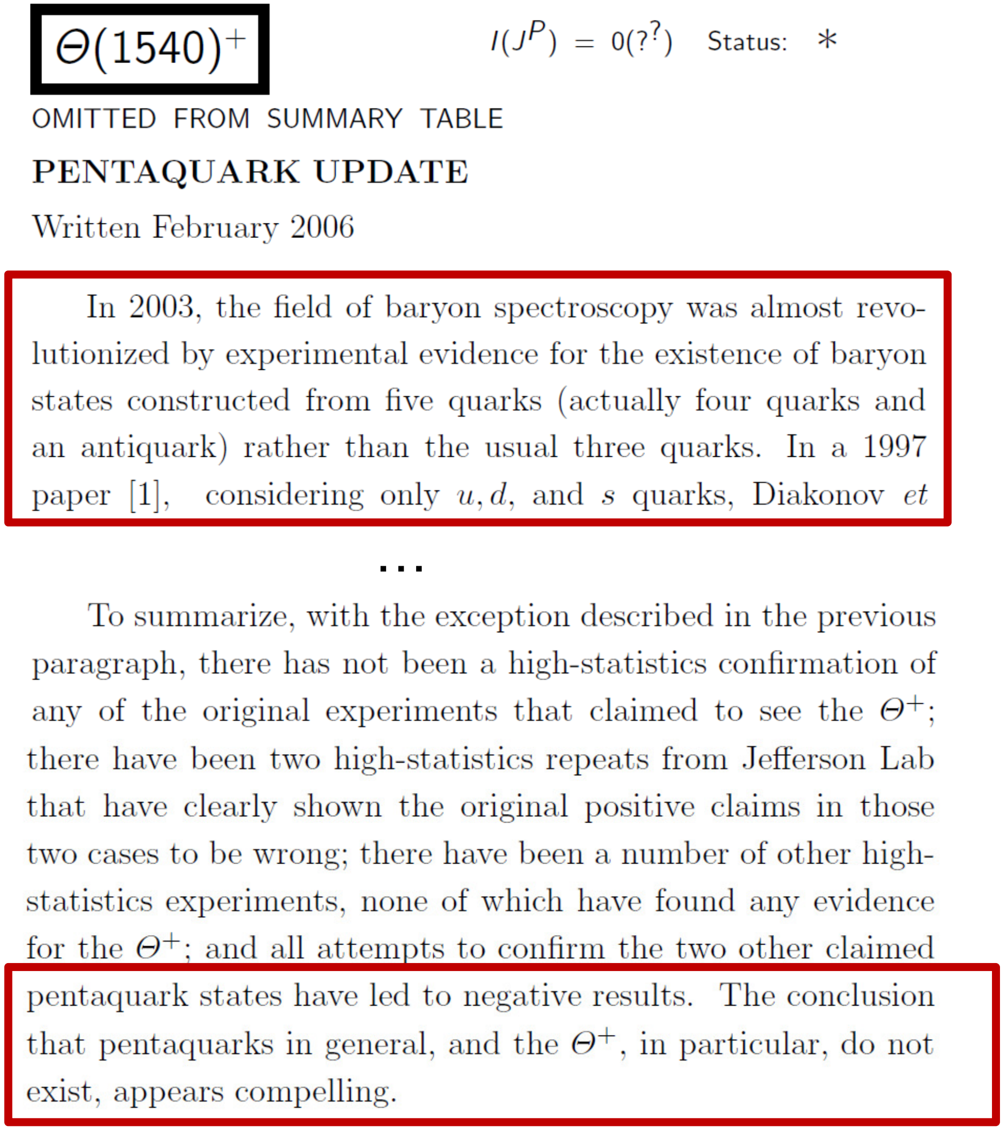
Z BARYONS ($S = +1$)

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The skepticism about baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

Last mention of 2nd pentaquark wave: PDG 2006

Found/debunked by looking for "bumps" in mass spectra



$\Theta(1540)^{+}$

$I(J^P) = 0(?^?)$ Status: $*$

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006

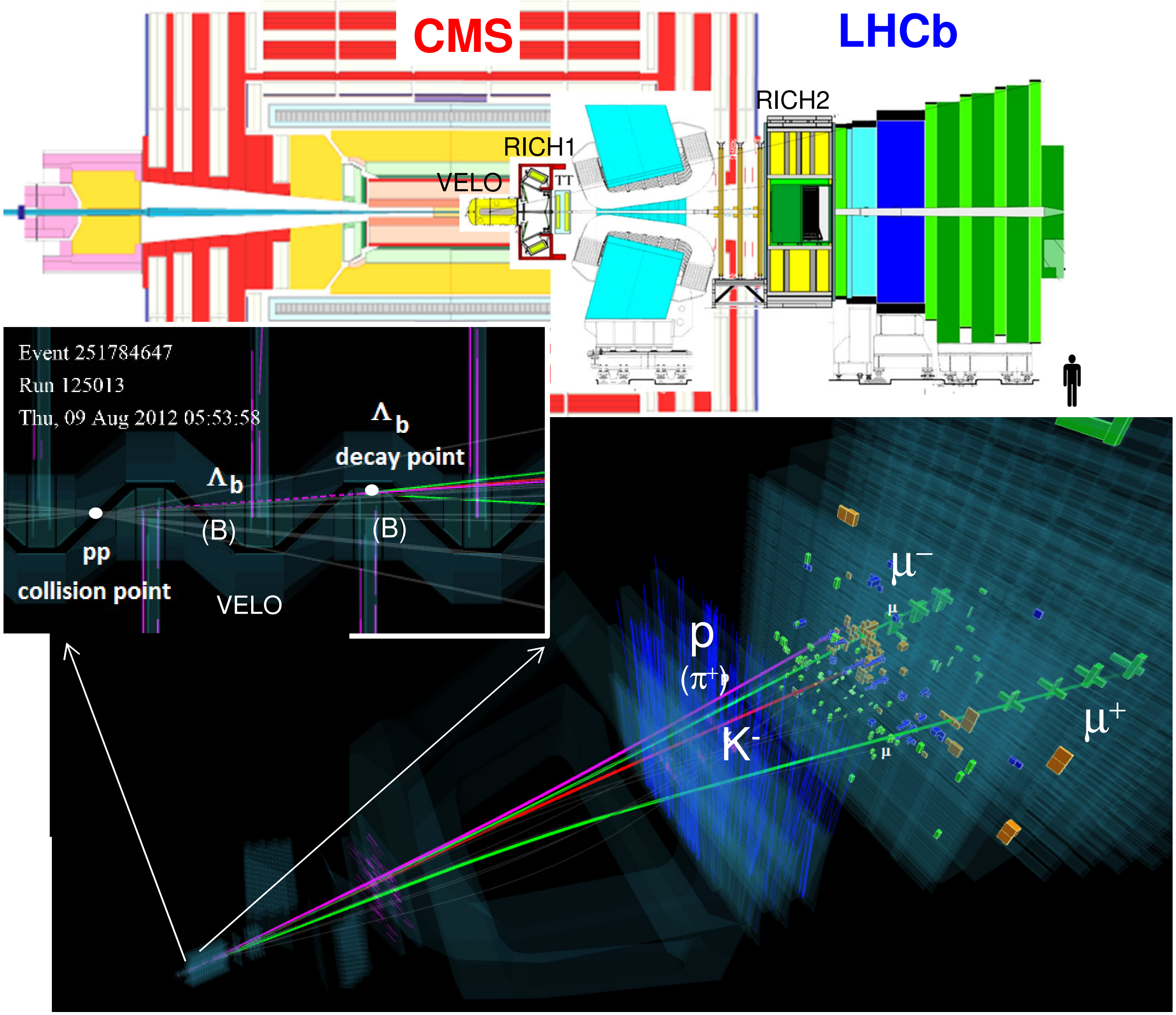
In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov *et*

…

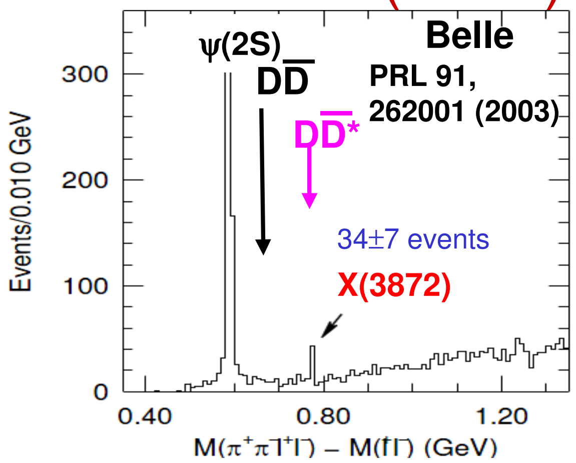
To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^{+}; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^{+}; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^{+}, in particular, do not exist, appears compelling.

LHCb: first dedicated b,c detector at hadronic collider

- Advantages over e^+e^- B-factories (Belle, BaBar):
  - ~1000x larger b production rate
  - **produce b-baryons at the same time as B-mesons**
  - long visible lifetime of b-hadrons (no backgrounds from the other b-hadron)
- Advantages over ATLAS, CMS, CDF, D0:
  - RICH detectors for π/K/p discrimination (smaller backgrounds)
  - Small event size allows large trigger bandwidth (up to 5 kHz in Run I); all devoted to flavor physics



X(3872) – discovered in 2003



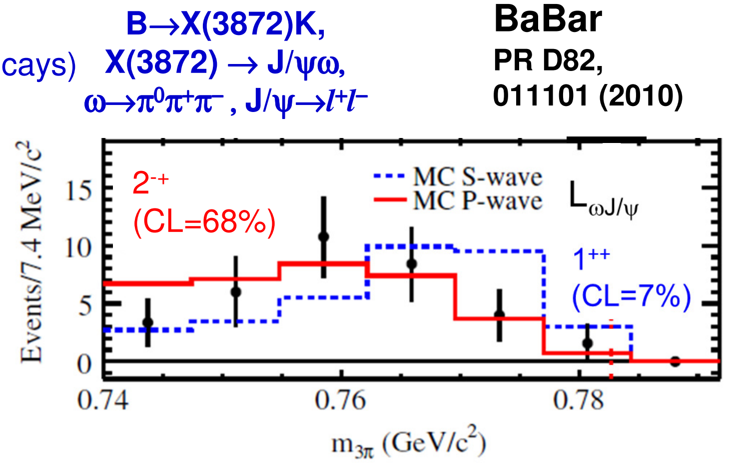
B→X(3872)K, X(3872) → J/ψρ^0, ρ^0→ π⁺π⁻, J/ψ→l^+l^-

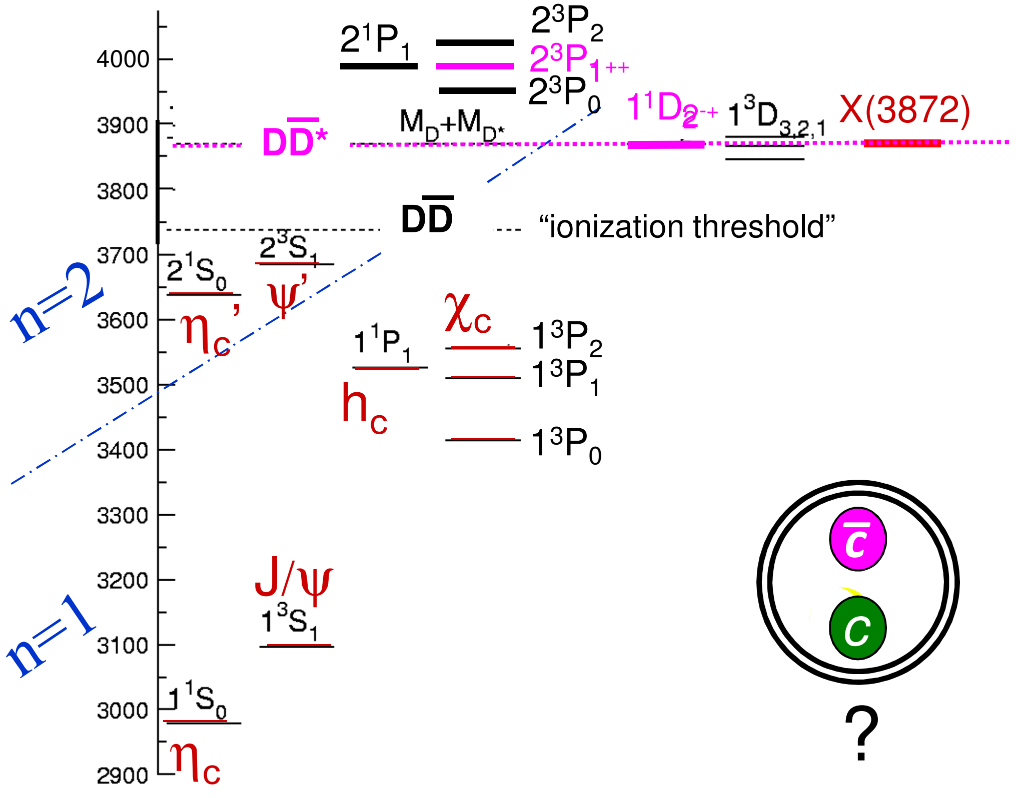
(isospin violating decays)

B→X(3872)K, X(3872) → J/ψω, ω→π^{0}π⁺π⁻, J/ψ→l^+l^-

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

very narrow





"ionization threshold" for states which cannot decay to DD̄: 1⁺⁺,2⁻⁺

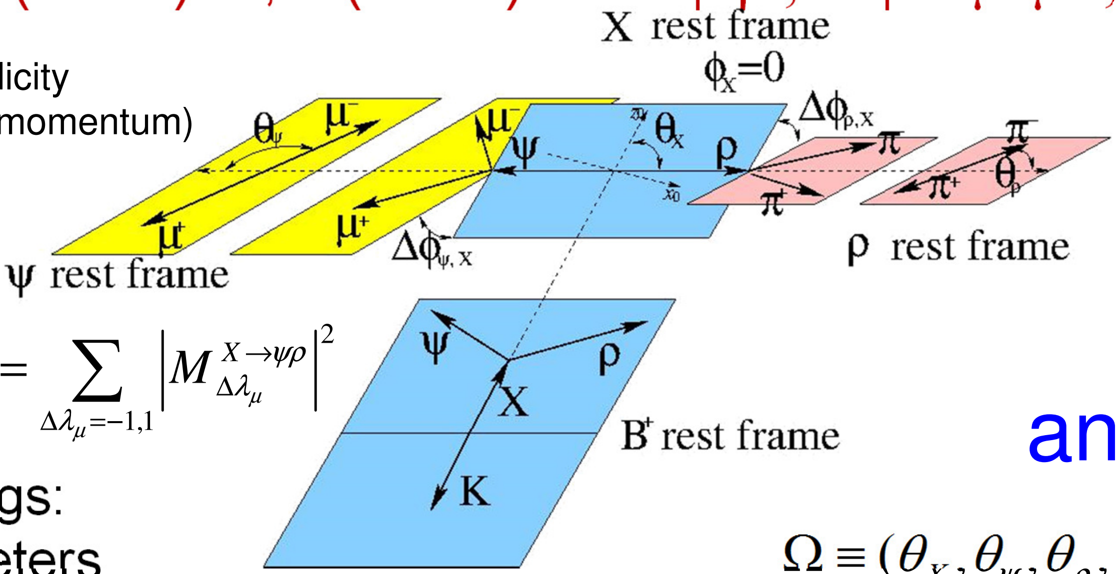
$M_{X(3872)} - [M_{D^0}+M_{D^{*0}}]$
$= -0.11\pm0.19$ MeV

Mass indistinguishable from D^{0}D̄^{*0} thresholds

BaBar data preferred J^P=2⁻⁺ (without ruling out 1⁺⁺) from the shape of $m_{3\pi}$ distribution → η(1^{1}D$_2$) cc̄ state?

Helicity amplitudes for $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\,\rho$, $J/\psi \to \mu^+\mu^-$, $\rho \to \pi^+\pi^-$

λ – particle helicity
(spin projection onto its momentum)



$$\left|M(\Omega\,|\,J_X, A^{J_X}_{\lambda_\psi,\lambda_\rho})\right|^2 = \sum_{\Delta\lambda_\mu=-1,1}\left|M^{X\to\psi\rho}_{\Delta\lambda_\mu}\right|^2$$

↑

Helicity couplings:
nuisance parameters

5D analysis

$$\Omega \equiv (\theta_X, \theta_\psi, \theta_\rho, \Delta\phi_{\psi,X}, \Delta\phi_{\rho,X})$$

$$M^{X\to\psi\rho}_{\Delta\lambda_\mu} = \sum_{\lambda_\psi=-1,0,1}\ \sum_{\lambda_\rho=-1,0,1} A^{J_X}_{\lambda_\psi,\lambda_\rho}\, D^{J_X}_{0,\lambda_\psi-\lambda_\rho}(0,\theta_X,0)^*\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,X},\theta_\psi,0)^*\, D^1_{\lambda_\rho,0}(\Delta\phi_{\rho,X},\theta_\rho,0)^*$$

$$A^{J_X}_{\lambda_\psi,\lambda_\rho} = \sum_L\sum_S B^{J_X}_{L,S}\left(\begin{array}{cc|c} J_\psi & J_\rho & S \\ \lambda_\psi & -\lambda_\rho & \lambda_\psi-\lambda_\rho \end{array}\right)\left(\begin{array}{cc|c} L & S & J_X \\ 0 & \lambda_\psi-\lambda_\rho & \lambda_\psi-\lambda_\rho \end{array}\right)$$

Clebsch-Gordan coefficients

$|J_\psi - J_\rho| \le S \le J_\psi + J_\rho$

$S = 0,1,2$

$|J_X - S| \le L \le J_X + S$

$P_X = P_\psi P_\rho (-1)^L = (-1)^L$

(P-conservation
since strong decay)

Number of B_{LS} coupling equals number of independent $A_{\lambda\psi,\lambda\rho}$ couplings (1-5 depending on J_X) – no gain, unless high L values neglected

Determination of J^{PC} for X(3872)

Belle 711 fb^{-1}
173±16 events
PRD84(2011)052004

3 x 1D χ^2 analysis

$$(L=L_{min})$$

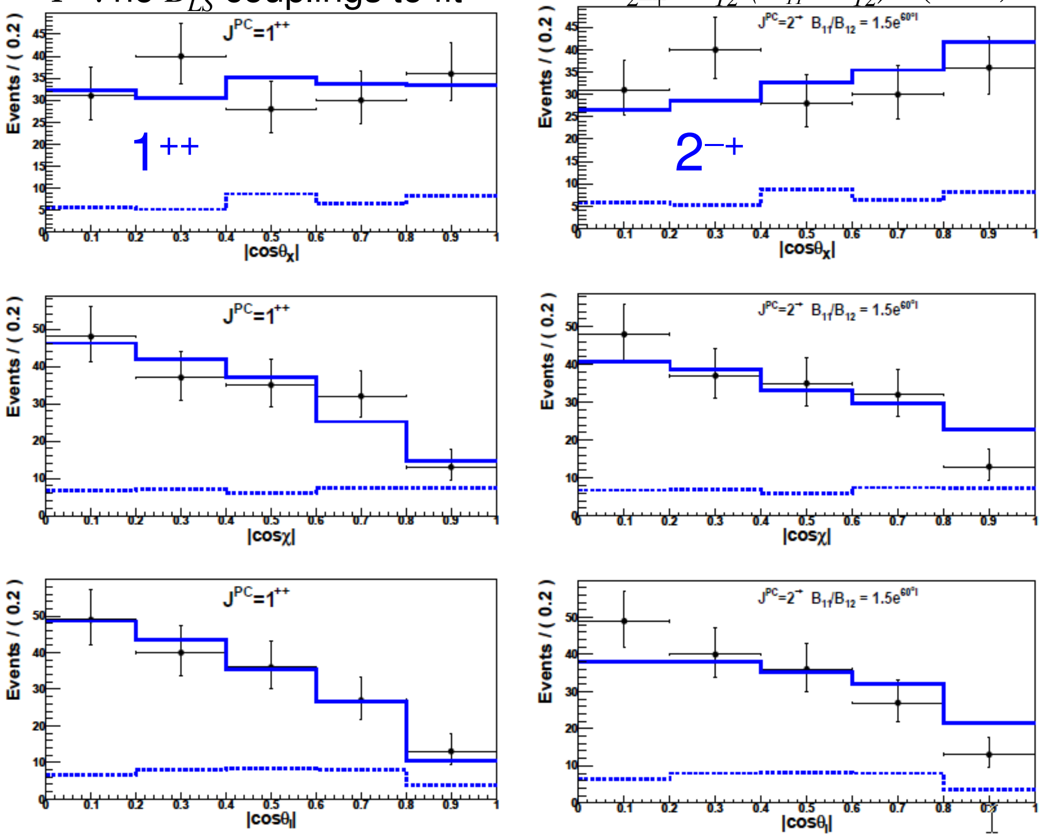
LHCb 1 fb^{-1} (2011 data)
313±26 events

$\sqrt{313/173} = 1.3$ small gain is statistical errors

5D unbinned likelihood ratio analysis

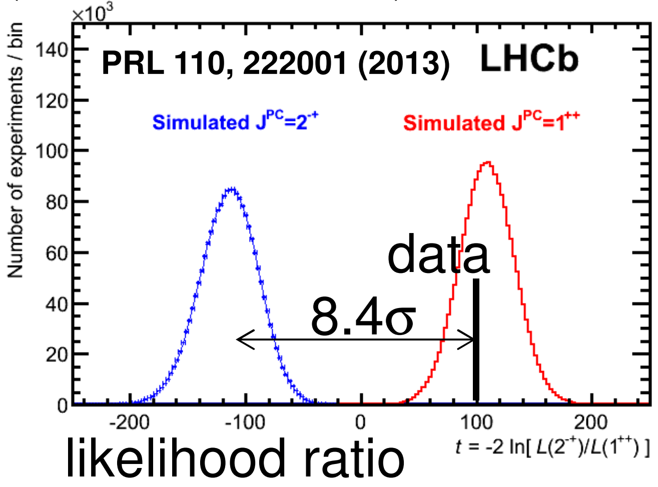
1^{++}: no B_{LS} couplings to fit

2^{-+}: $\alpha_{2-+}=B_{12}/(B_{11}+B_{12})=(0.64,0.27)$



Could not distinguish between 1^{++} and 2^{-+}

$\alpha_{2-+}=(0.671\pm0.046, 0.280\pm0.046)$



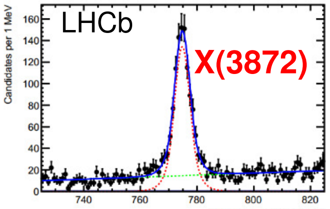
Very clear separation between 1^{++} and 2^{-+}

The data choose 1^{++}

- **It is important to analyze data in all sensitive dimensions simultaneously.** Angular correlations by far more powerful than 1D projections.

2015 update to X(3872) J^{PC} determination

(all L values allowed)



LHCb 3 fb^{-1} (2011+2012 data)

1011±38 events

PRD92, 011102 (2015)

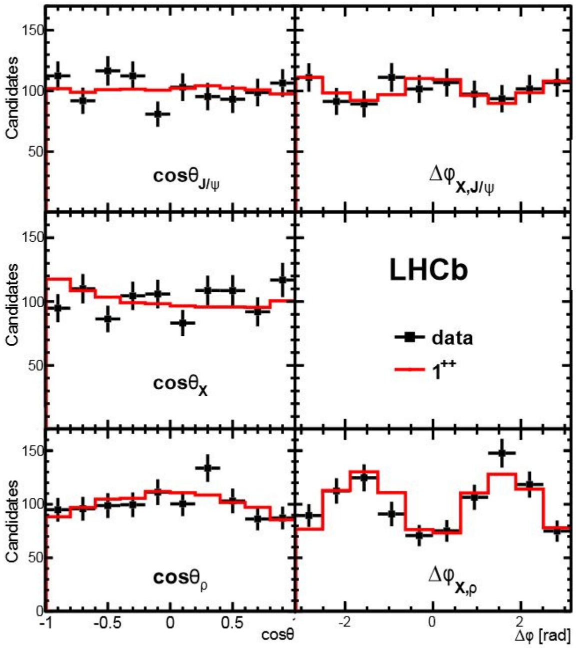
J^{PC}	B_{LS} all L	minimal L
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

LHCb 2015

Many more amplitudes to fit

CDF 2007

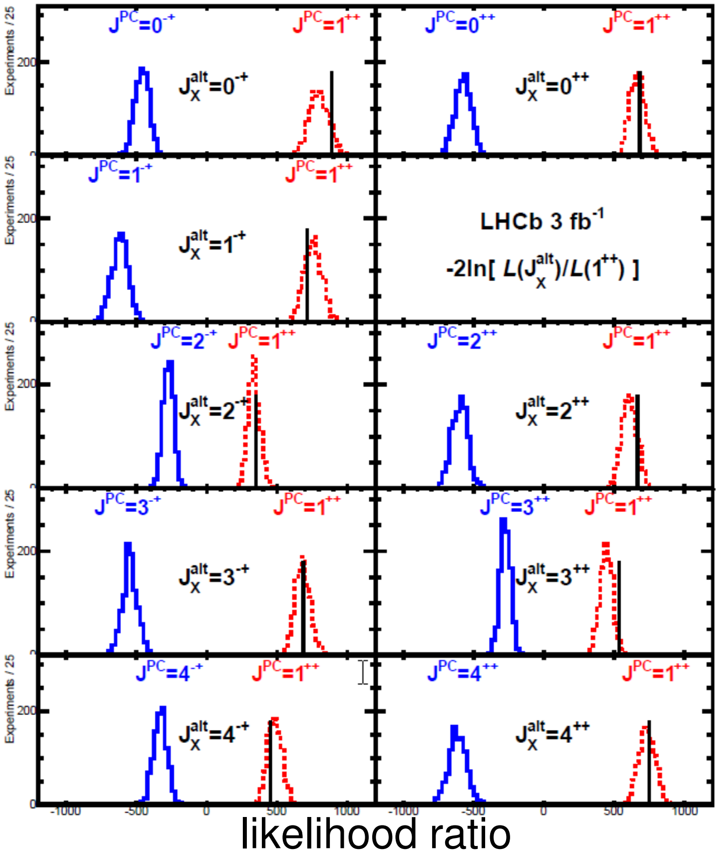
LHCb 2013



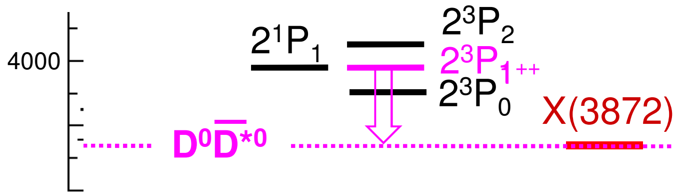
J^{PC} = **1⁺⁺** at 16σ

$$f_D = \frac{\int |\mathcal{M}(\Omega)_D|^2 \, d\Omega}{\int |\mathcal{M}(\Omega)_{S+D}|^2 \, d\Omega}$$

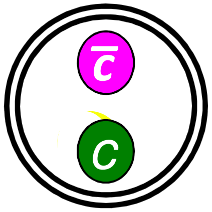
<4% at 95% CL



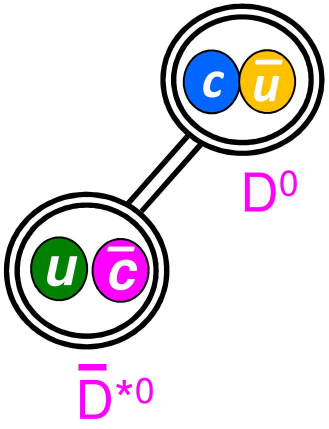
X(3872) interpretation



$M_{X(3872)} - [M_{D^0}+M_{D^{*0}}]$
$= -0.11\pm0.19$ MeV

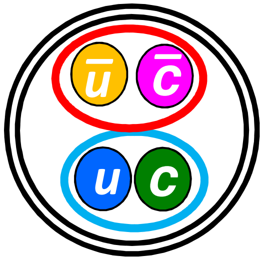


$\chi_c(2^3P_1)$ "attracted" by $D^0\bar{D}^{*0}$ threshold?



L=0
Meson-meson molecule?
essentially no binding energy?

mixture?



tightly bound tetraquark "attracted" by $D\bar{D}^*$ threshold ?

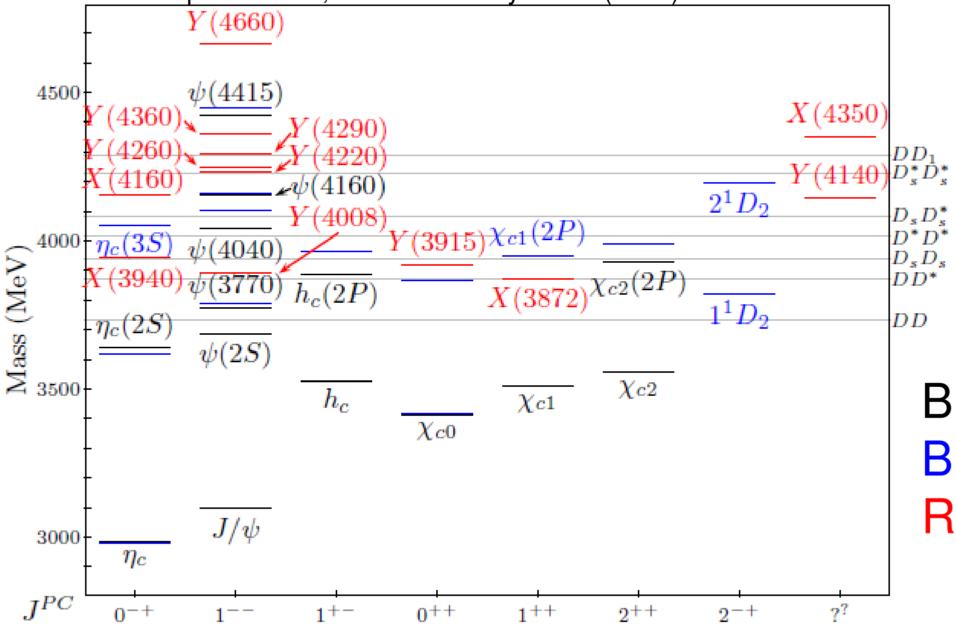
e.g. L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRD **89** (2014) 114010

$$[cu]_{S=1}\,[\bar{c}\bar{u}]_{S=0} + [cu]_{S=0}\,[\bar{c}\bar{u}]_{S=1}$$

Growing XY zoo

- Many more neutral states at higher masses of the charmonium system have been discovered since then, which are candidates for exotic hadrons (none as narrow as X(3872))

Esposito *et al.*, Int. J. Mod. Phys. A**30** (2014)1530002



Black: Observed conventional $c\bar{c}$ states

Blue: Predicted conventional $c\bar{c}$ states

Red: Exotic state candidates with $c\bar{c}$ inside

- Many of them await experimental confirmation.
- Many of them discovered near $D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$ thresholds.
- No single model can explain all of them.

$Z(4430)^+$ discovery and its importance

Phys.Rev.Lett. 100, 142001 (2008)

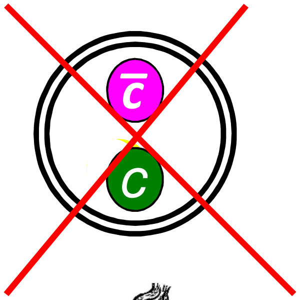
Observation of a resonance-like structure in the $\pi^\pm\psi'$ mass distribution in exclusive $B \to K\pi^\pm\psi'$ decays

Press Release

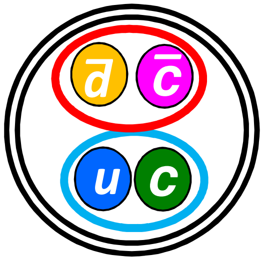
Belle Discovers a New Type of Meson

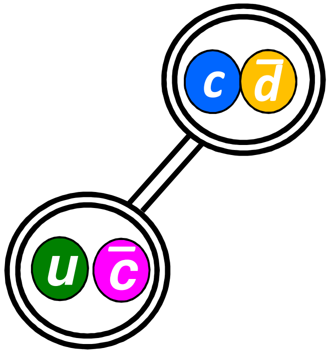
November 13, 2007
High Energy Accelerator Research Organization (KEK)

neutral



charged





$Z(4430)^-$ previous measurements

$[\ \psi' \equiv \psi(2S)\ ]$

$B \to \underbrace{\psi'\overbrace{\pi^-}^{}}_{Z^-}\!\!\underbrace{\pi^- K}_{K^*}$

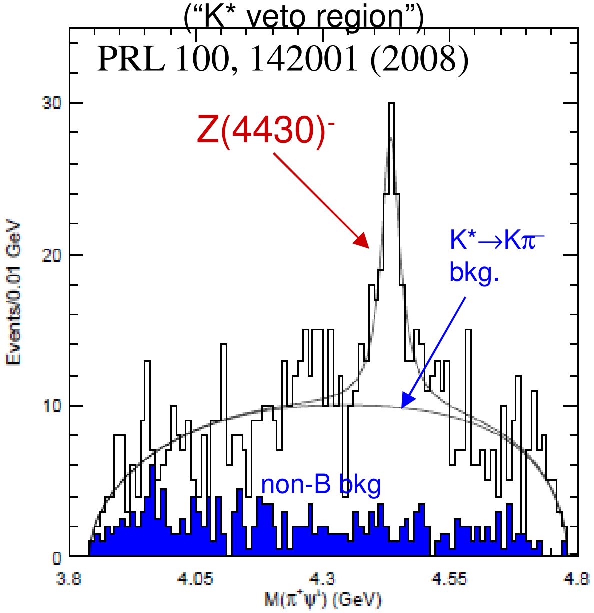
Z⁻ K*

$B \to \psi' \pi^- K$

Belle 2008

1D M(ψ'π⁻) mass fit

("K* veto region")



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

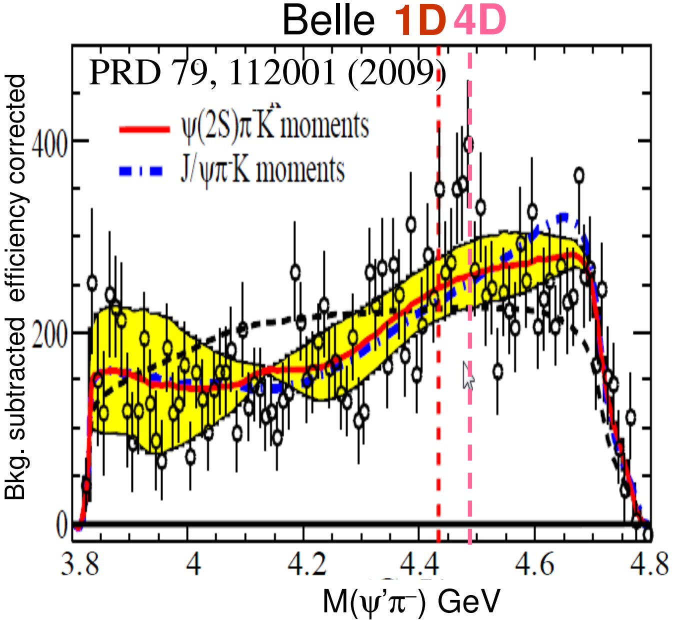
$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}\ \text{MeV}$

significance 6.5σ

Ad hoc assumption about the K*→Kπ⁻ background shape.

BaBar 2009

Harmonic moments of K*s (2D) reflected to M(ψ'π⁻)



BaBar did not confirm Z(4430)⁻ in B sample comparable to Belle.

Did not numerically contradict the Belle results.

Almost **model independent** approach to K*→Kπ⁻ backgrounds.

Belle 2013

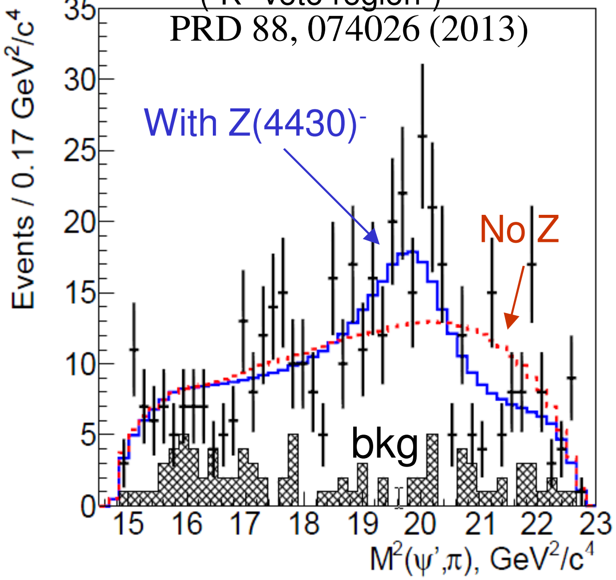
(2D amplitude fit in 2009)

4D amplitude fit

(subsample with $\psi' \to l^+ l^-$)

$0.996\ \text{GeV}/c^2 < M(K,\pi) < 1.332\ \text{GeV}/c^2$

("K* veto region")



$M(Z) = 4485^{+22}_{-22}{}^{+28}_{-11}\ \text{MeV}$

$\Gamma(Z) = 200^{+41}_{-46}{}^{+26}_{-35}\ \text{MeV}$

6.4σ (5.6σ with sys.)

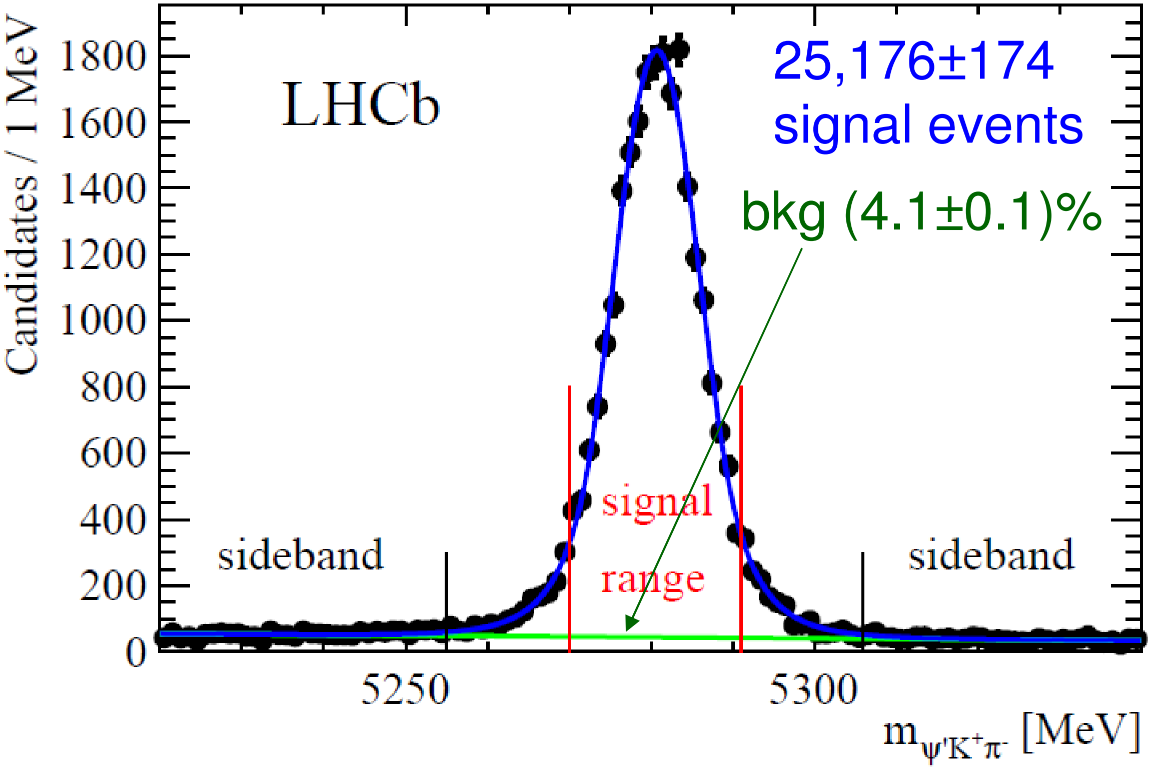
$J^P = 1^+$ preferred by >3.4σ

Model dependent approach to K*→Kπ⁻ backgrounds.
Higher statistical sensitivity.

$Z(4430)^+$ in LHCb

LHCb-PAPER-2014-014 **PRL 112, 222002 (2014)**

- $B^0 \to \psi' K^+ \pi^-$, $\psi' \to \mu^+ \mu^-$ (3 fb^{-1})



25,176±174 signal events

bkg (4.1±0.1)%

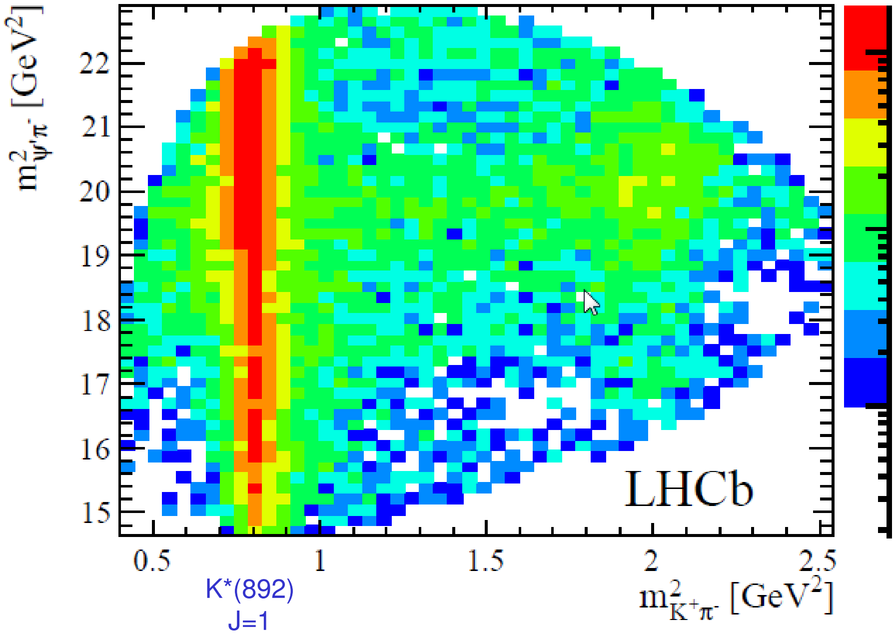
vs
Belle: 2,010±50
BaBar: 2,021±53

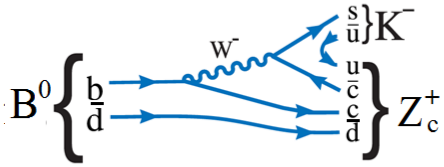
vs. bkg in Belle: 7.8%

An order of magnitude larger signal statistics than in Belle or BaBar thanks to hadronic production of b-quarks at LHC.

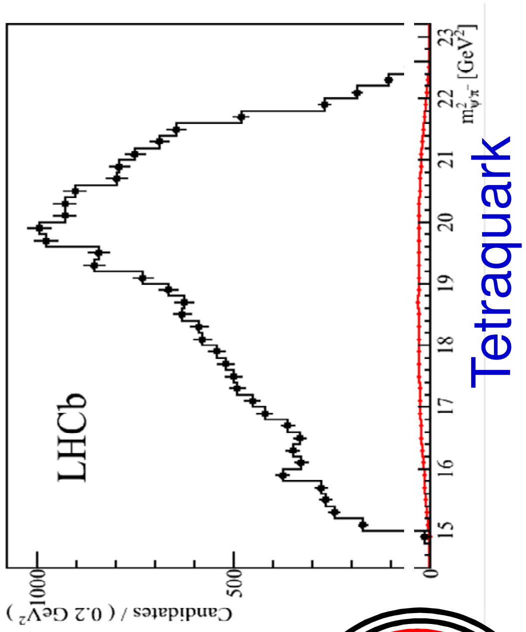
Even smaller non-B background than at the e^+e^- experiments thanks to excellent performance of the LHCb detector (vertexing, PID)

$B^0 \rightarrow \psi'\pi^+K^-$

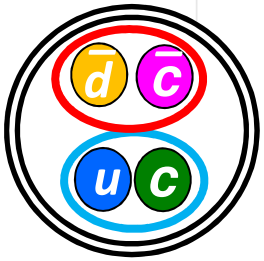


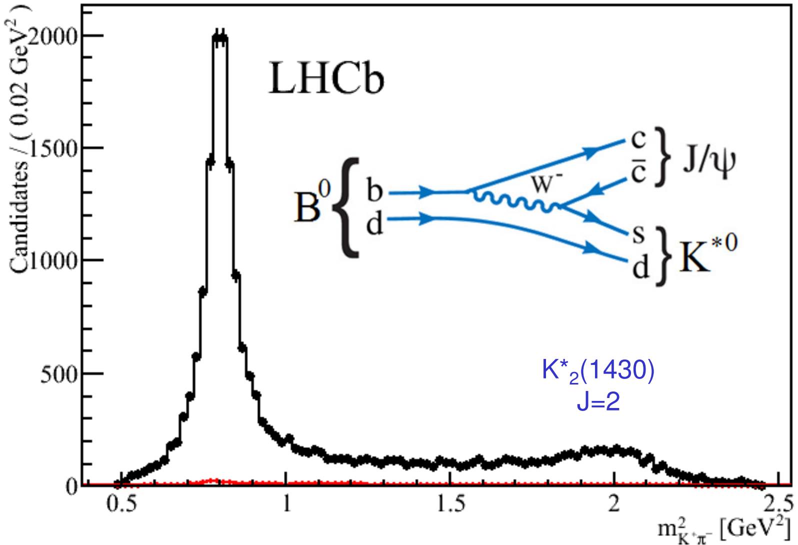


← $Z_c\,(4430)^+$
$\rightarrow J/\psi\pi^+$
? →

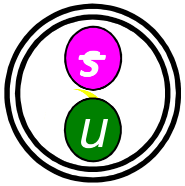


Tetraquark





Kaon excitations



Is it a reflection of interfering K^*'s $\rightarrow \pi^+K^-$?

Proper amplitude analysis necessary to check

Amplitude Analysis of $B^0 \to \psi'\pi^+K^-$, $\psi' \to \mu^+\mu^-$

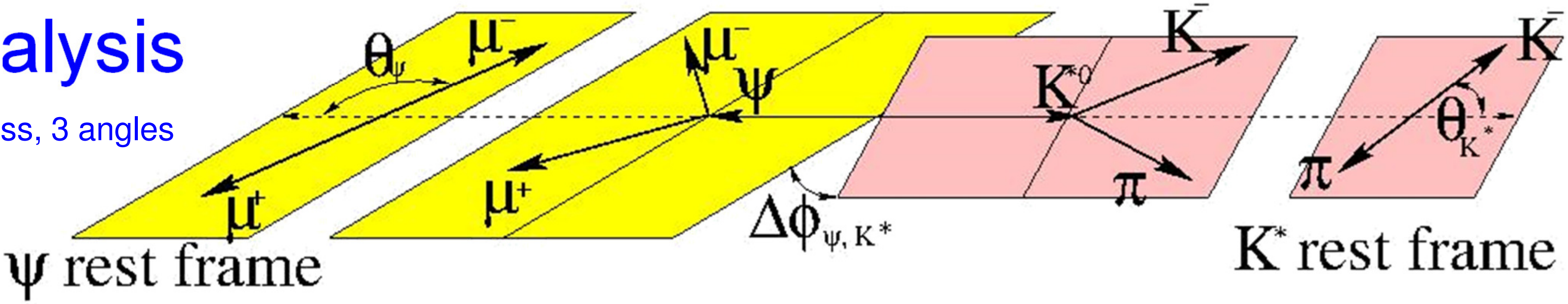
$$\left| M(\mathrm{m}_{K\pi}, \Omega \mid A_{\lambda_\psi}^{B\to\psi K_n^*}) \right|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| M_{\Delta\lambda_\mu}^{K^*} \right|^2$$

$$\Omega \equiv (\theta_{K^*}, \theta_\psi, \Delta\phi_{\psi,K^*})$$

B^0 rest frame

4D analysis

1 mass, 3 angles



$$M_{\Delta\lambda_\mu}^{K^*} = \sum_n \sum_{\lambda_\psi=-1,0,1} A_{\lambda_\psi}^{B\to\psi K_n^*} D_{\lambda_\psi,0}^{J_{K^*}}(0, \theta_{K^*}, 0)^* R(m_{K\pi} \mid M_{K_n^*}, \Gamma_{K_n^*}) D_{\lambda_\psi,\Delta\lambda_\mu}^{1}(\Delta\phi_{\psi,K^*}, \theta_\psi, 0)^*$$

1-3 independent **complex** helicity couplings per K_n^* resonance

Breit-Wigner amplitude:

$$R(m \mid M_X, \Gamma_X) = \frac{B'_{L_B}(p, p_0, d)\left(\frac{p}{M_B}\right)^{L_B} B'_{L_X}(q, q_0, d)\left(\frac{q}{m}\right)^{L_X}}{M_X{}^2 - m^2 - iM_X\Gamma(m)} \qquad \Gamma(m) = \Gamma_X \left(\frac{q}{q_0}\right)^{2L_X+1} \frac{M_X}{m} B'_{L_X}(q, q_0, d)^2$$

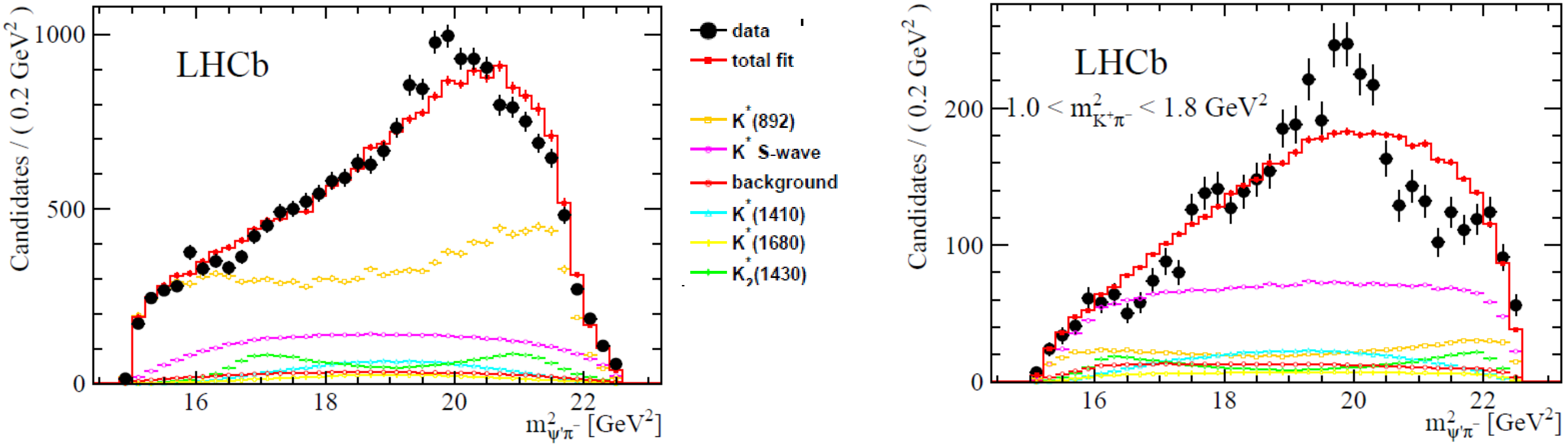
Blatt-Weisskopf functions

$$n = 0^+ : K_0^*(800), K_0^*(1430), NR; \quad 1^- : K^*(892), K^*(1410), K^*(1680) \quad 2^+ : K_2^*(1430) \quad (3^- : K_3^*(1780))$$

# of fit parameters: 32

Amplitude fits without Z(4430)$^-$

\# of fit parameters: 32



(“all data”)

(“K* veto region”)

- The χ^2 p-value < 2×10^{-6}

⇩

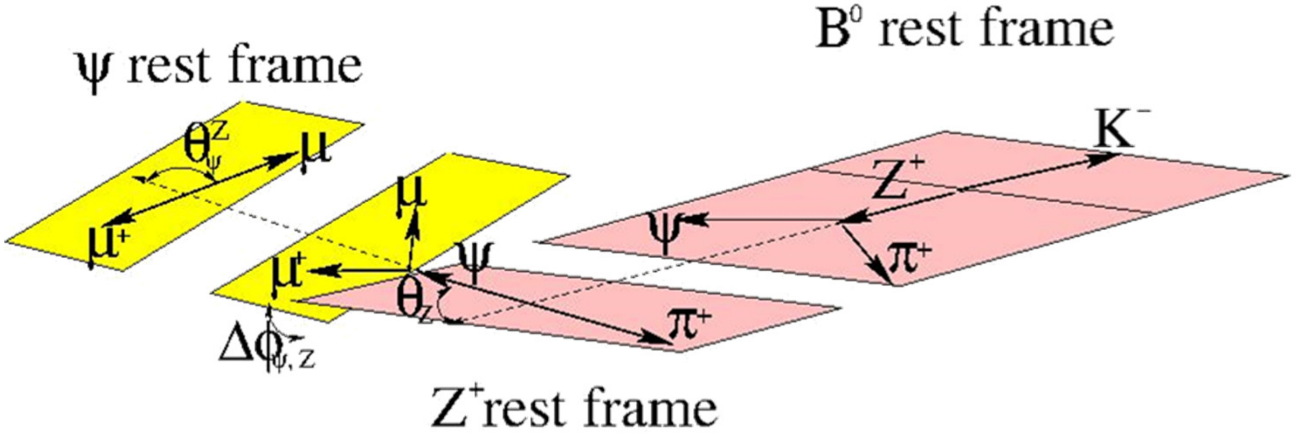
- The data cannot be adequately described with the J ≤ 3 K* contributions alone

Amplitude Analysis of $B^0 \to \psi'\pi^+K^-$, $\psi' \to \mu^+\mu^-$

$$\left|M(m_{K\pi},\Omega\,|\,M_Z,\Gamma_Z,J_Z,A^{Z\to\psi\pi}_{\lambda_\psi},A^{B\to\psi K^*_n}_{\lambda_\psi})\right|^2=\sum_{\Delta\lambda_\mu=-1,1}\left|M^{K^*}_{\Delta\lambda_\mu}+e^{i\Delta\lambda_\mu\alpha_\mu}M^{Z}_{\Delta\lambda_\mu}\right|^2$$

4D analysis

1 mass, 3 angles
all derivable from the K^* variables



$$M^{Z}_{\Delta\lambda_\mu}=\sum_{\lambda_\psi=-1,0,1}A^{Z\to\psi\pi}_{\lambda_\psi}D^{J_Z}_{\lambda_\psi,\lambda_\psi}(0,\theta_Z,0)^*R(m_{\psi\pi}\,|\,M_Z,\Gamma_Z)D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,Z},\theta_\psi^{Z},0)^*$$

1 independent **complex** helicity coupling after $L=L_{min}$

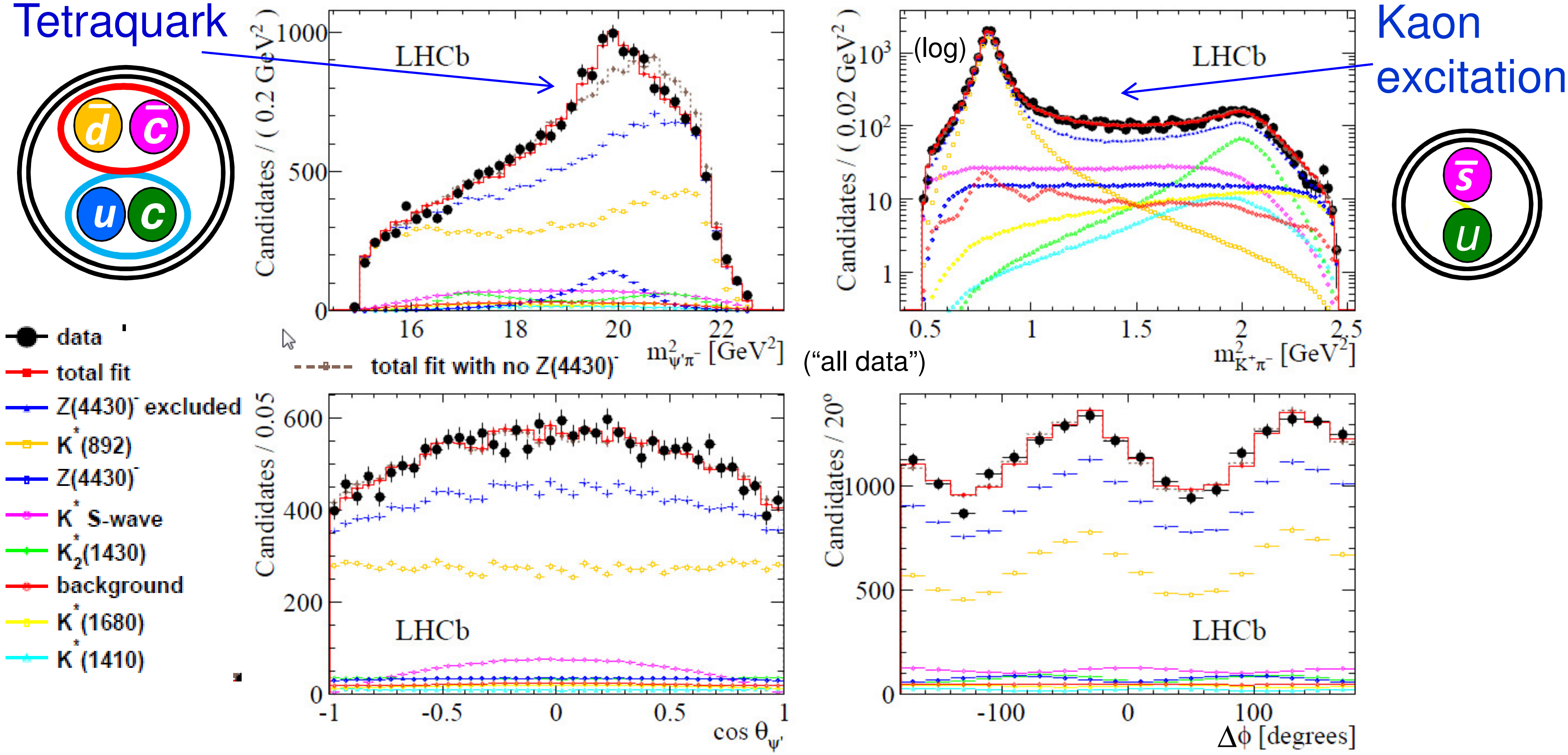
\# of fit parameters: 32 + 4 = 36

Amplitude fits with $J^P=1^+$ Z(4430)$^+$

\# of fit parameters: 32 + 4 = 36

Tetraquark

Kaon excitations

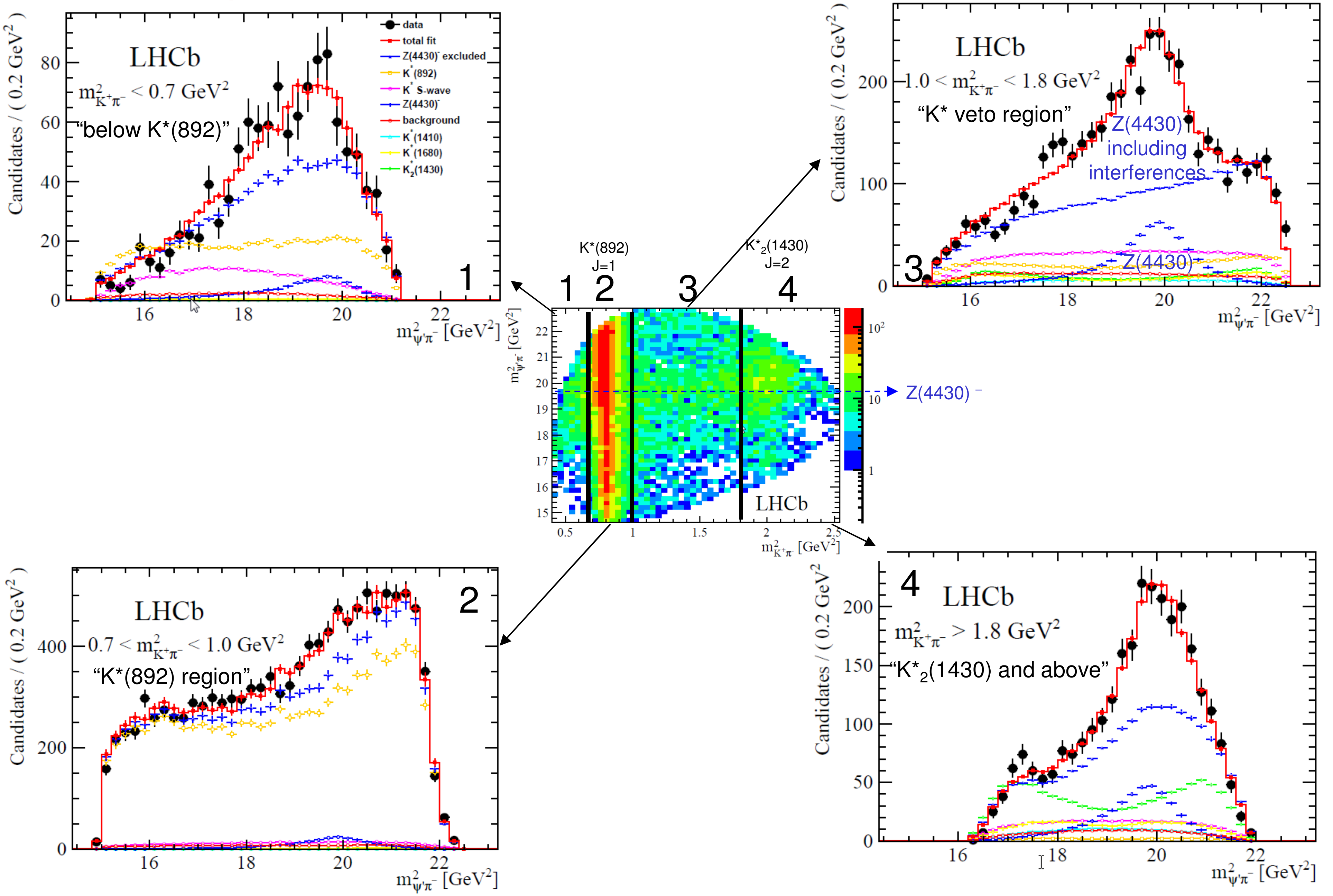


- The χ^2 p-value = 12%

⇩

- The data are well described when $J^P=1^+$ Z(4430)$^+$ is included in the fit
- Z(4430)$^+$ significances from $\Delta(-2\ln L)$ is 18.7σ (13.9σ with systematic variations)

Amplitude fits with $J^P=1^+$ $Z(4430)^-$



Z(4430)$^-$ parameters: LHCb vs Belle

	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_Z^I [%] (with interferences)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	
Significance	$> 13.9\sigma$	$> 5.2\sigma$

(new large systematic effect included by LHCb)

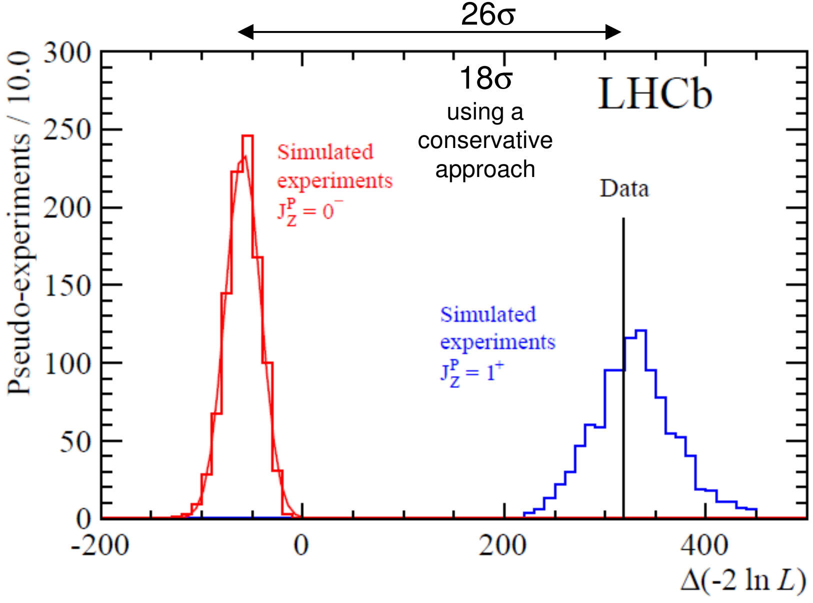
Amplitude fractions [%]
(statistical errors only)

Contribution	LHCb	Belle
S-wave total	10.8 ± 1.3	
NR	0.3 ± 0.8	
$K_0^*(800)$	3.2 ± 2.2	5.8 ± 2.1
$K_0^*(1430)$	3.6 ± 1.1	1.1 ± 1.4
$K^*(892)$	59.1 ± 0.9	63.8 ± 2.6
$K_2^*(1430)$	7.0 ± 0.4	4.5 ± 1.0
$K_1^*(1410)$	1.7 ± 0.8	4.3 ± 2.3
$K_1^*(1680)$	4.0 ± 1.5	4.4 ± 1.9
$Z(4430)^-$	5.9 ± 0.9	$10.3^{+3.0}_{-3.5}$

(not in the default fit $K^*_3(1780)$ 0.5 ± 0.2)

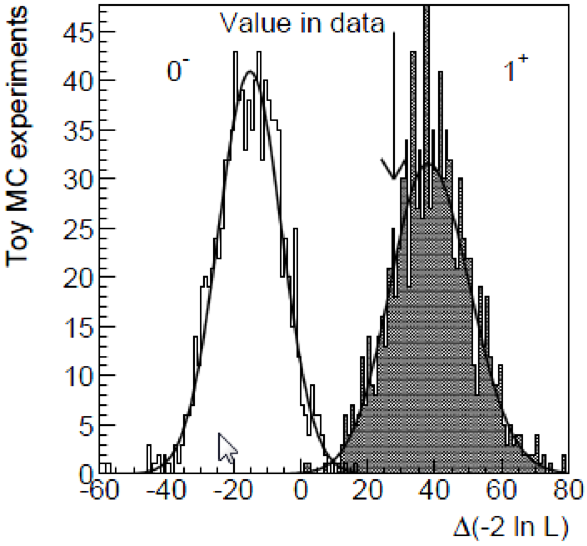
- Overall excellent consistency between LHCb and Belle
- Errors substantially improved

Z(4430)$^+$ spin-parity analysis



Belle

PRD 88, 074026 (2013)

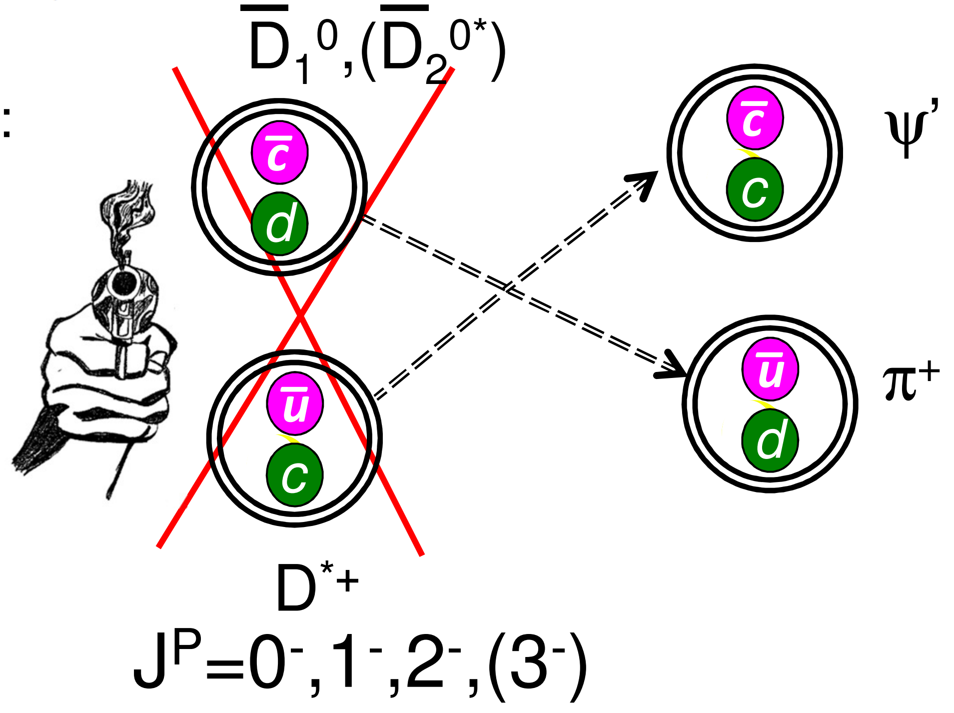


Including systematic variations:

	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

- $J^P=1^+$ now established beyond any doubt

threshold cusp



Hadronic resonances – Argand diagram

Forced harmonic oscillator:

Restoring force

Damping force:

Driving force

$$m\frac{d}{dt}\left(\frac{dx}{dt}\right) = -\,k\,x \qquad -\,b\,\frac{dx}{dt} \qquad -\,F_0\cos(\omega_{ext}t)$$

resonant frequency: $\omega_0 = \sqrt{\frac{k}{m}}$

dumping factor: $\gamma = \frac{b}{2m}$

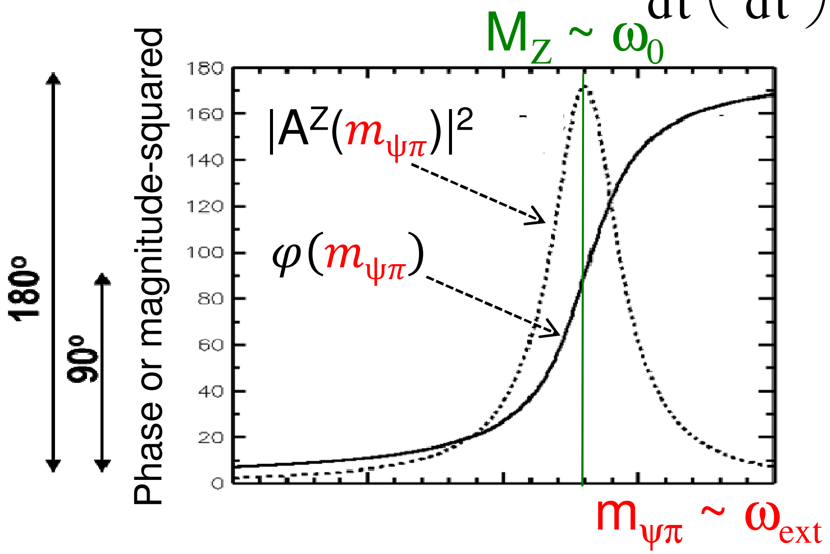
driving frequency

phase lag

$$x(t) \xrightarrow{t\to\infty} \frac{F_0/m}{\sqrt{(\omega_0^{\,2}-\omega_{ext}^{\,2})^2+(2\gamma\omega_{ext})^2}}\cos(\omega_{ext}t+\varphi)$$

$$\varphi = \mathrm{atan}\left(\frac{2\gamma\omega_{ext}}{\omega_0^{\,2}-\omega_{ext}^{\,2}}\right)$$

DEMO



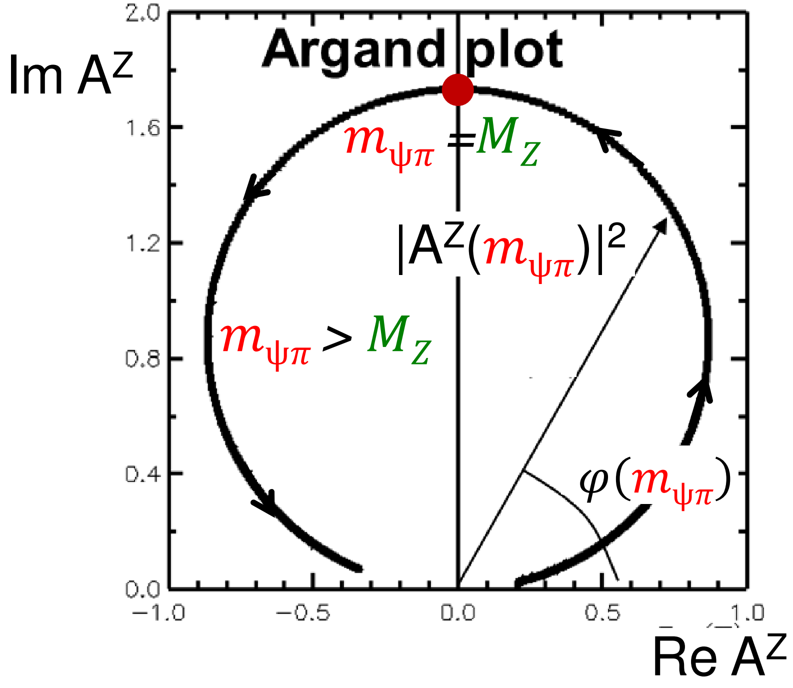
$$A^Z(m_{\psi\pi}) \sim \frac{1}{M_Z^{\,2}-m_{\psi\pi}^{\,2}-i\,M_Z\Gamma_Z} = |A^Z(m_{\psi\pi})|\,e^{i\varphi(m_{\psi\pi})}$$

$$|A^Z(m_{\psi\pi})|^2 \sim \frac{1}{(M_Z^{\,2}-m_{\psi\pi}^{\,2})^2+(M_Z\Gamma_Z)^2}$$

$$\varphi(m_{\psi\pi}) = \mathrm{atan}\left(\frac{M_Z\Gamma_Z}{M_Z^{\,2}-m_{\psi\pi}^{\,2}}\right)$$

Breit-Wigner amplitude

- $m_{\psi\pi} \sim \omega_{ext}$ driving frequency
- $M_Z \sim \omega_0$ resonance frequency
- $\Gamma_Z = \hbar / \tau_Z \sim \gamma/2$ dumping factor (mass indeterminacy)

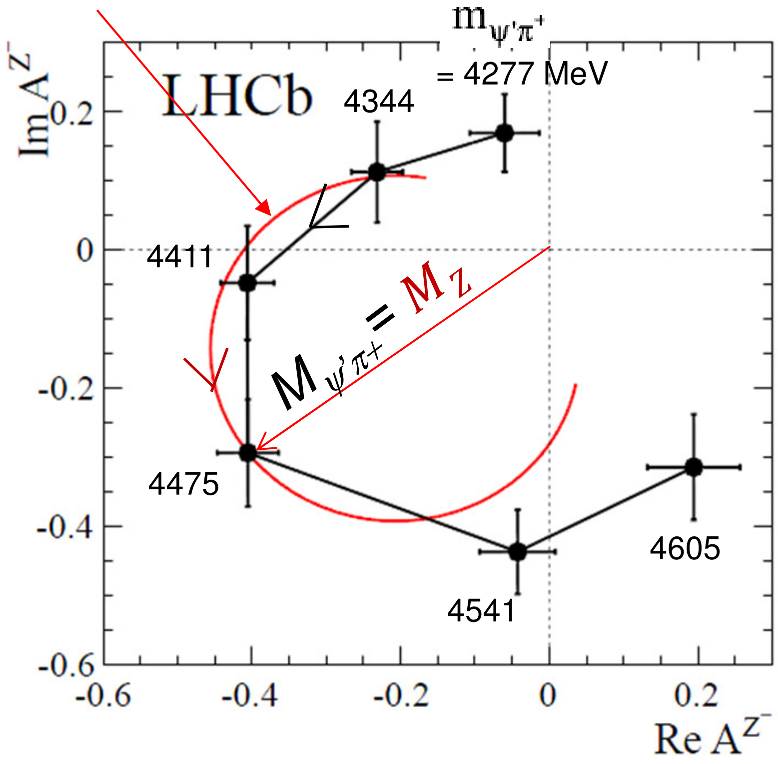


Argand diagram of Z(4430)$^+$

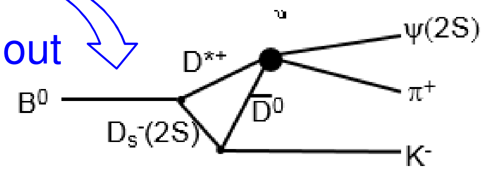
- Thanks to the large data statistics LHCb has been able to extract Argand diagram of Z(4430)$^+$ amplitude from its interference with the K* amplitudes:

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

Breit-Wigner amplitude

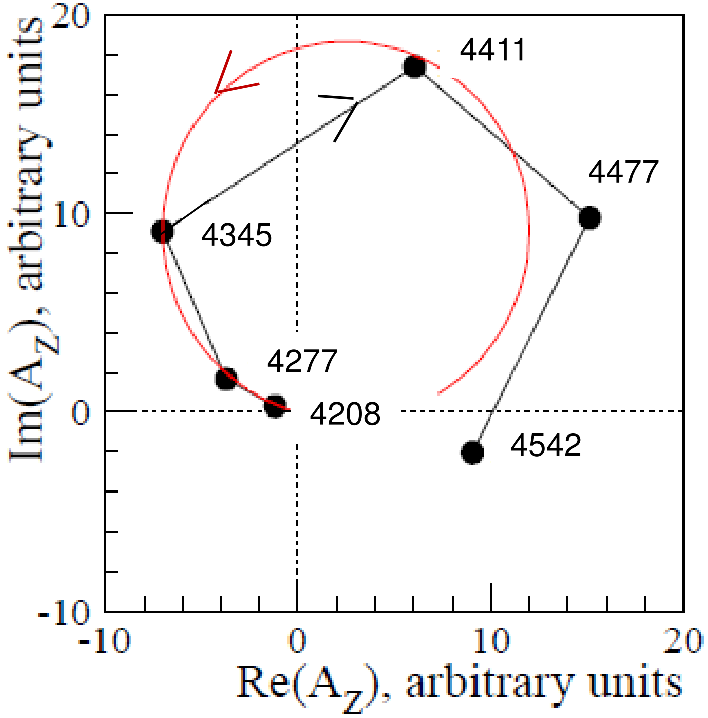


rules out



rescattering model

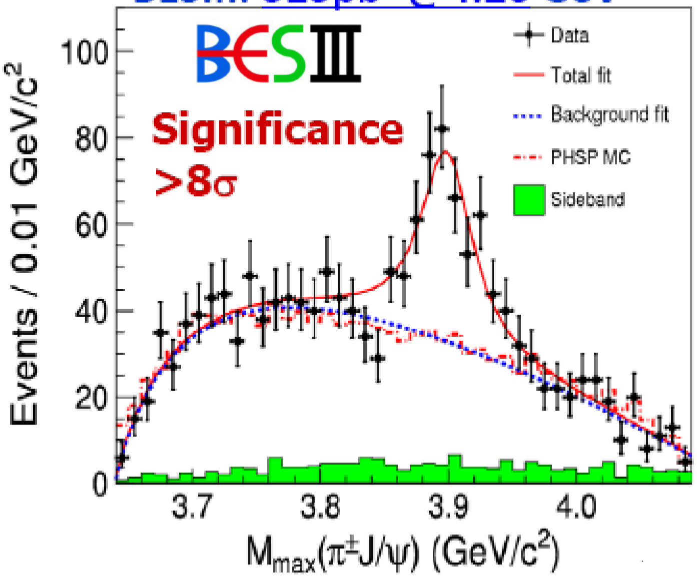
P. Pakhlov, T. Uglov
PL B748, 183 (2015)

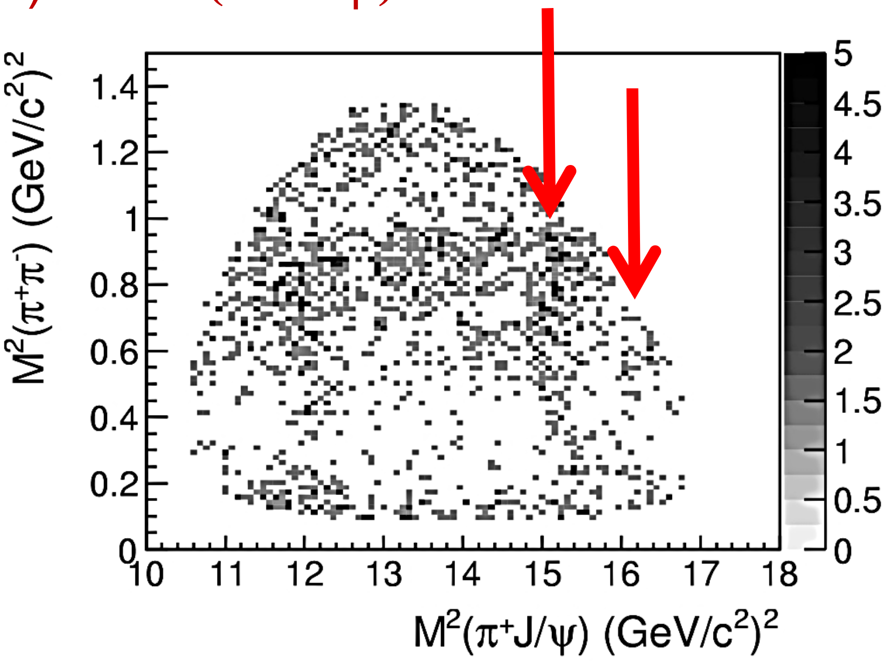


Previously confirmed Z_c^+ state: $Z_c(3900)^+$

$e^+e^- \to Y(4260) \to \pi^-(\pi^+ J/\psi)$

BESIII: 525pb^{-1}@4.26 GeV

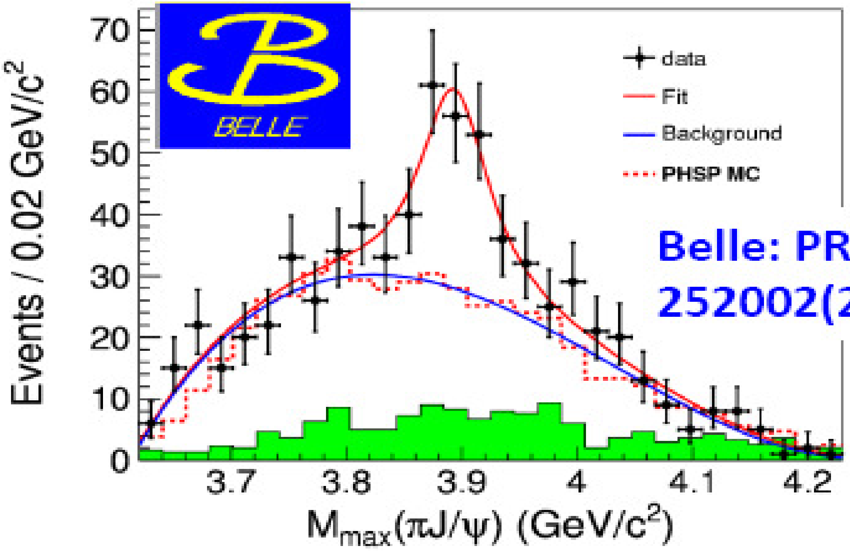




BESIII: PRL110, 252001 (2013)

- **$M = 3899.0 \pm 3.6 \pm 4.9$ MeV**
- **$\Gamma = 46 \pm 10 \pm 20$ MeV**
- **307 ± 48 events**

(no Argand diagram analysis)



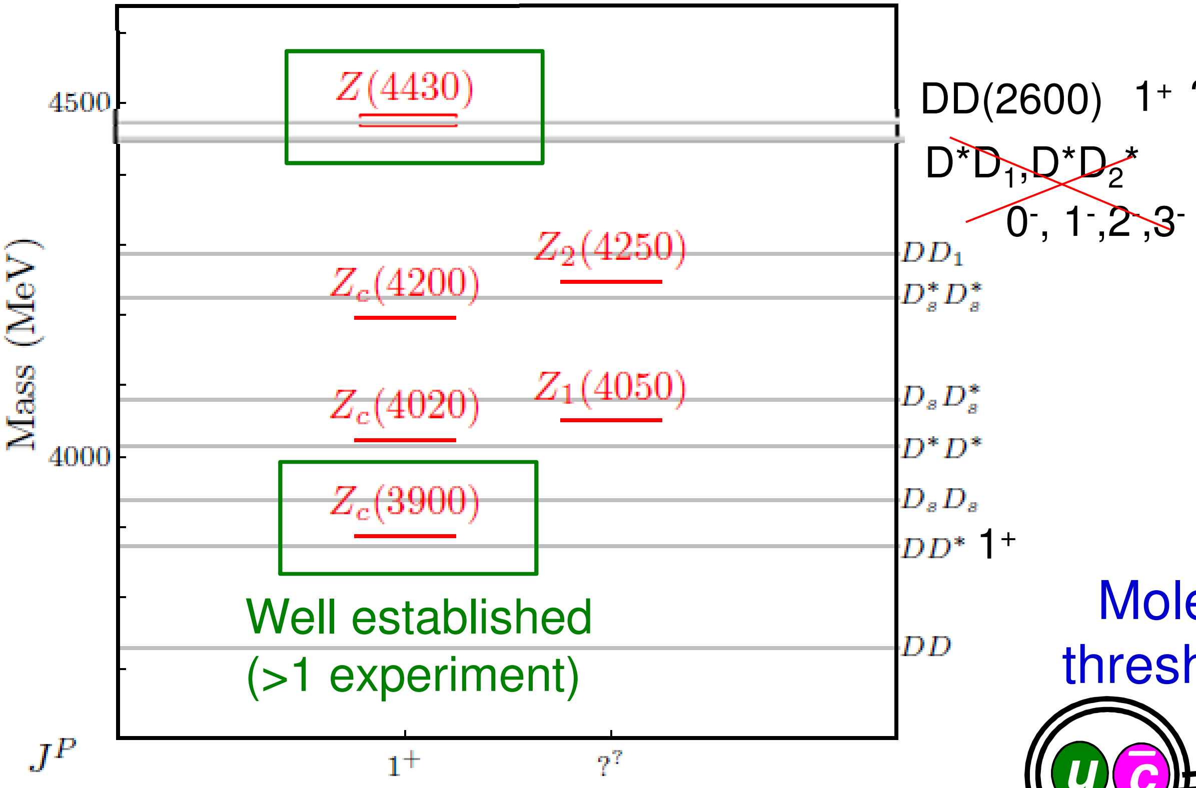
Belle: PRL 11
252002(2013)

24±6 MeV above the $D\overline{D}^*$ threshold

$Z(4430)^+$ and other Z_c^+ states

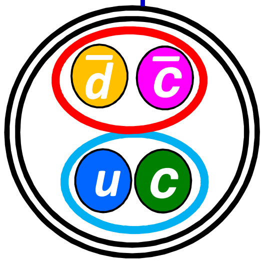
- The only threshold still at play for $Z(4430)^+$: DD(2600) if D(2600) exists (needs confirmation!) and if it is 1^- states (2^3S_1)
- Other charged Z_c^+,Z_b^+ states are near $D^{(*)}\bar{D}^{(*)}$, $B^{(*)}\bar{B}^{(*)}$ thresholds

Radial excitation of tightly bound tetraquark

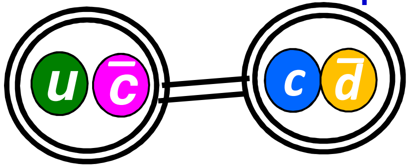


Radial excitation of the $^3S_1$ meson inside meson molecule

Tetraquark



Molecule or threshold cusp



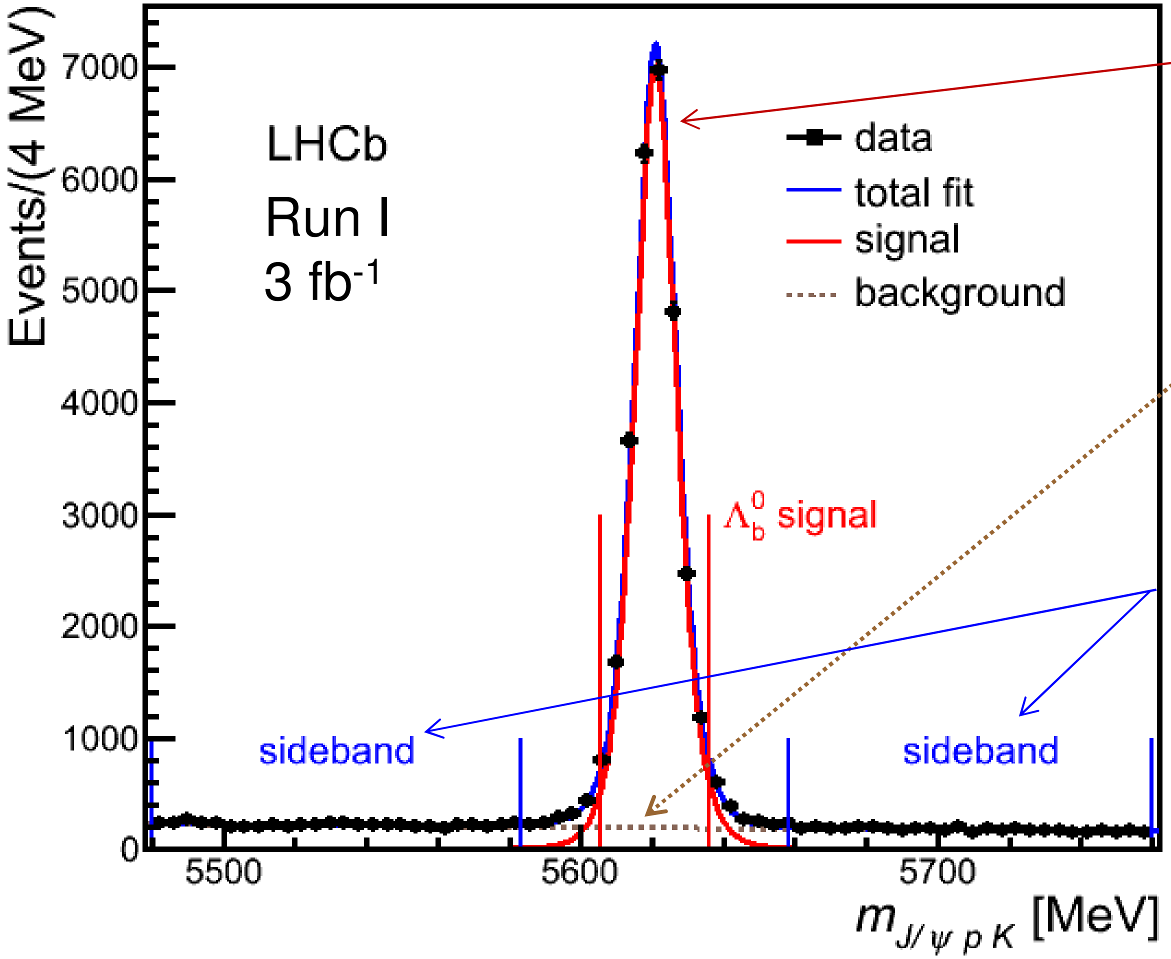
Diquark states can be “attracted” towards the mesonic-pair threshold masses

Meson molecules should be a few MeV below the threshold,
Meson-meson cusps alone should be exactly at the thresholds.

$Z_c(3900)^+$ is 24±6 MeV above the $D\bar{D}^*$ threshold (favors tetraquark picture)

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

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201



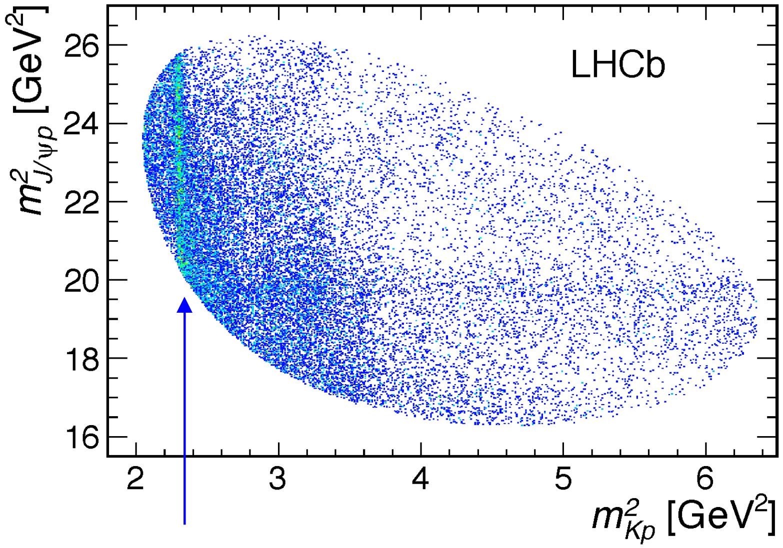
26,007±166 Λ_b^0 candidates

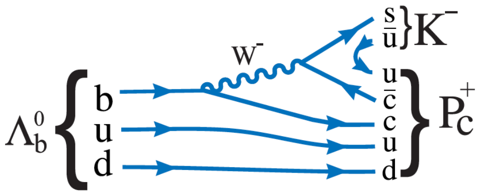
The background is only 5.4% in the signal region!

The sideband distributions are flat → no major reflections from the other b-hadrons after the selection

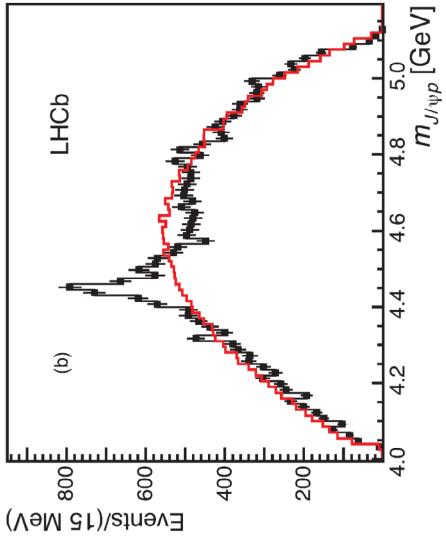
- The decay first observed by LHCb and used to measure Λ_b^0 lifetime (LHCb-PAPER-2013-032, PRL 111, 102003)

$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected structure in $m_{J/\psi\, p}$



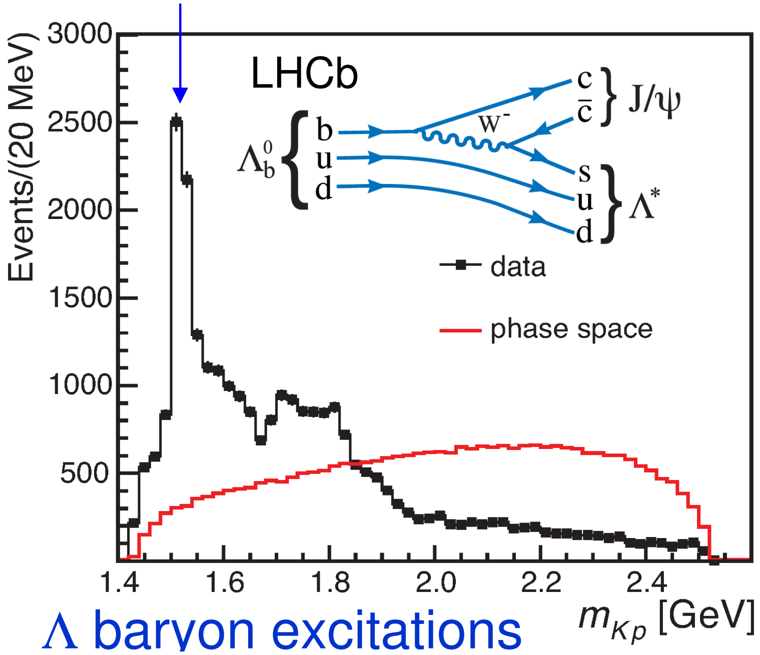


$P_c^+ \rightarrow J/\psi\ p$
?



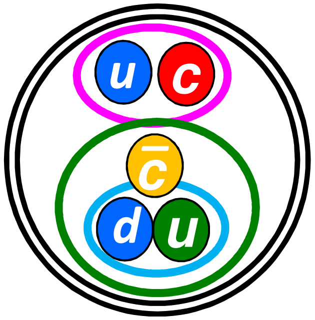
Exotic pentaquark

$\Lambda(1520)$ and other Λ^*'s $\rightarrow$ p K^-

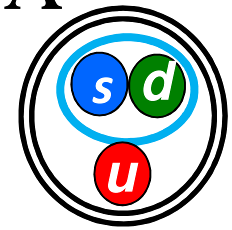


Λ baryon excitations

- Unexpected, narrow peak in $m_{J/\psi\, p}$
- Ignored in LHCb for more than 2 years. We, like almost everybody else, did not believe in pentaquarks:



Λ^*



assumed to be a reflection of interfering Λ^*'s $\rightarrow$ p K^- ?

Proper amplitude analysis absolutely necessary to check

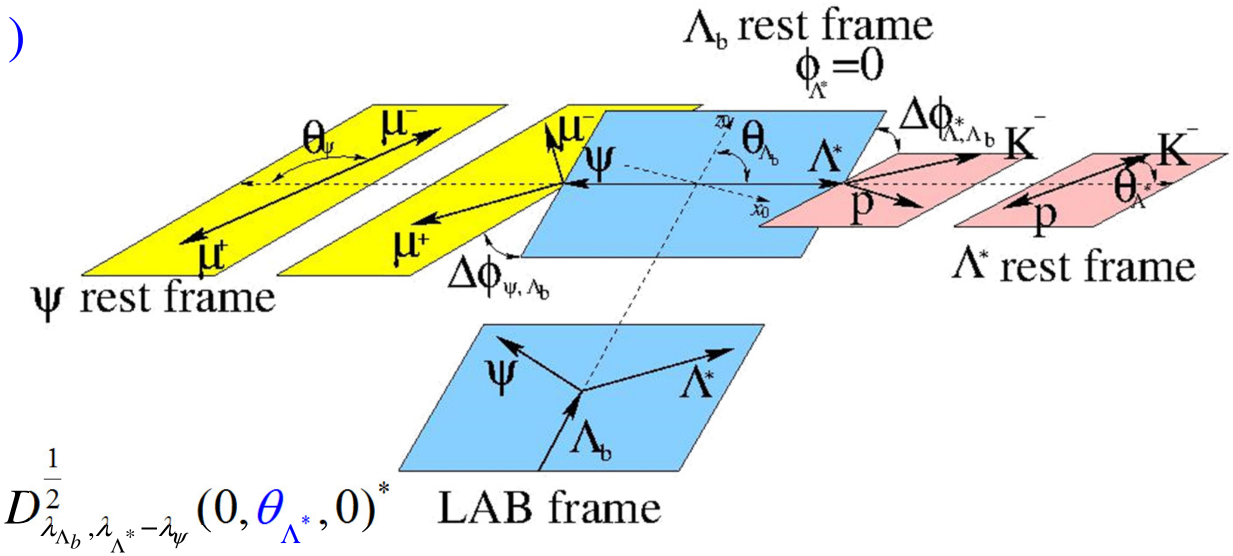
Amplitude Analysis of $\Lambda_b \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$

$$\left|M(m_{Kp},\Omega\,|\,A^{\Lambda_b\to\psi\Lambda_n^*}_{\lambda_\psi,\lambda_{\Lambda^*}},\ A^{\Lambda_n^*\to pK}_{\lambda_p})\right|^2 = \sum_{\lambda_{\Lambda_b}=-1/2,+1/2}\ \sum_{\lambda_p=-1/2,+1/2}\ \sum_{\Delta\lambda_\mu=-1,1}\left|M^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu}\right|^2$$

$$\Omega \equiv (\theta_{\Lambda_b},\theta_{\Lambda^*},\Delta\phi_{\Lambda^*,\Lambda_b},\theta_\psi,\Delta\phi_{\psi,\Lambda_b})$$

6D analysis

1 mass, 5 angles



$$M^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n\sum_{\lambda_\Lambda}\sum_{\lambda_\psi=-1,0,1} A^{\Lambda_b\to\psi\Lambda_n^*}_{\lambda_\psi,\lambda_{\Lambda^*}} D^{\frac{1}{2}}_{\lambda_{\Lambda_b},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda^*},0)^*$$

$$A^{\Lambda_n^*\to pK}_{\lambda_p} D^{J_{\Lambda^*}}_{\lambda_{\Lambda^*},\lambda_p}(\Delta\phi_{\Lambda^*,\Lambda_b},\theta_{K^*},0)^* R(m_{Kp}\,|\,M_{\Lambda_n^*},\Gamma_{\Lambda_n^*}) D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,\Lambda_b},\theta_\psi,0)^*$$

↑

4-6 independent **complex** helicity couplings per Λ_n^* resonance

Λ^* resonance model

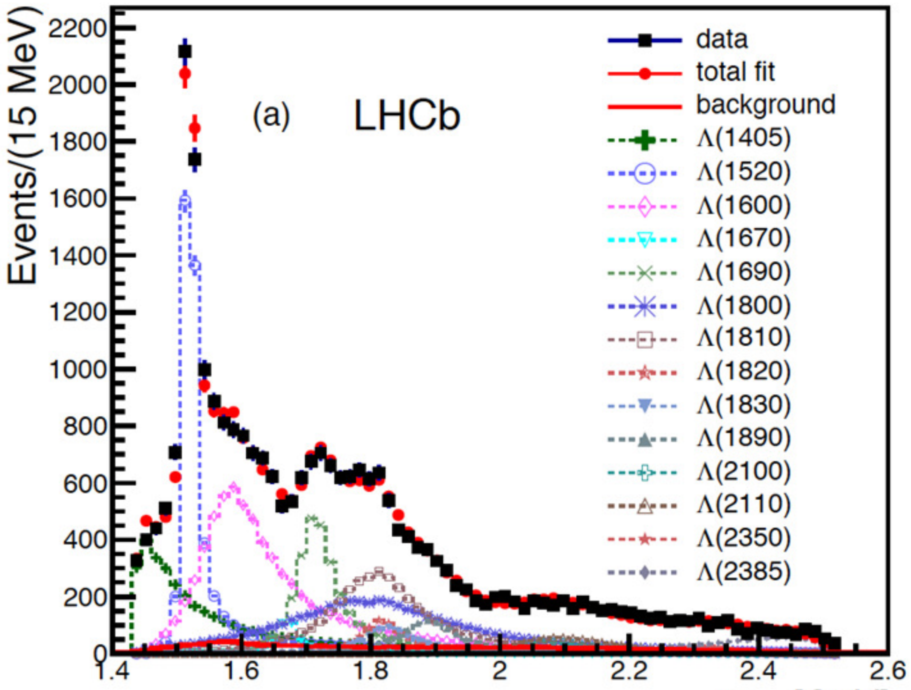
All known Λ^* states
from KN scattering
experiments

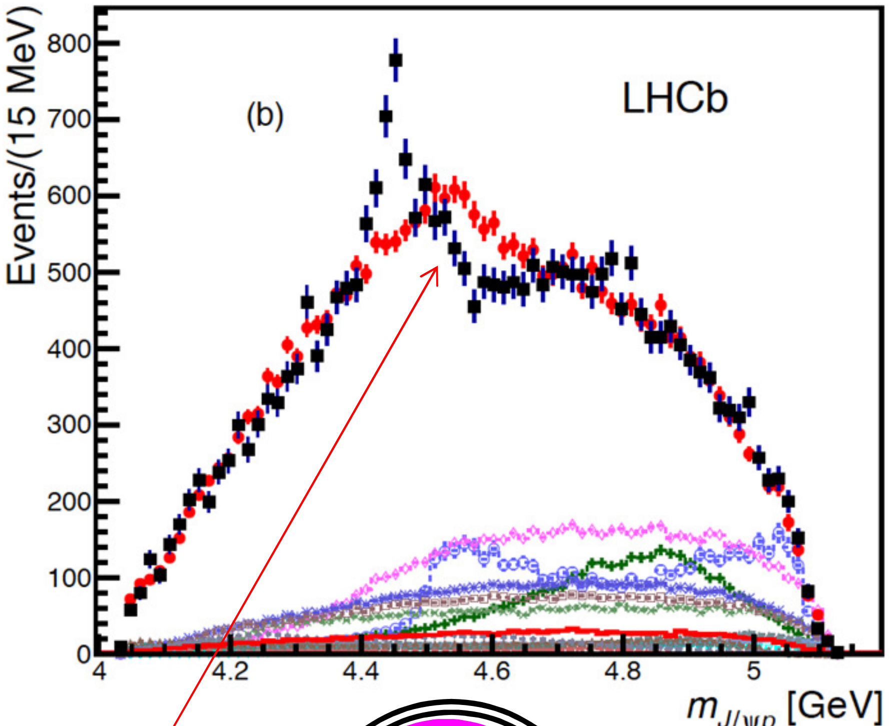
No high-J^P high-mass states

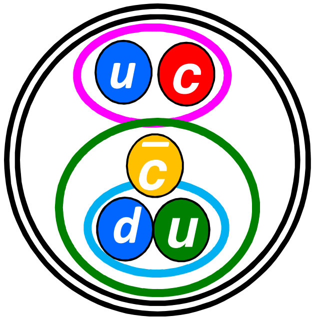
State	J^P	M_0 (MeV)	Γ_0 (MeV)	limit L # Reduced	All states, all L # Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	$5/2^-$?	≈2585	200	0	6
		# of fit parameters:		64	146

Fit with $\Lambda^* \to pK^-$ contributions only

\# of fit parameters: 146







- Include all known Λ excitations:
- m_{Kp} looks fine, but not $m_{J/\psi p}$

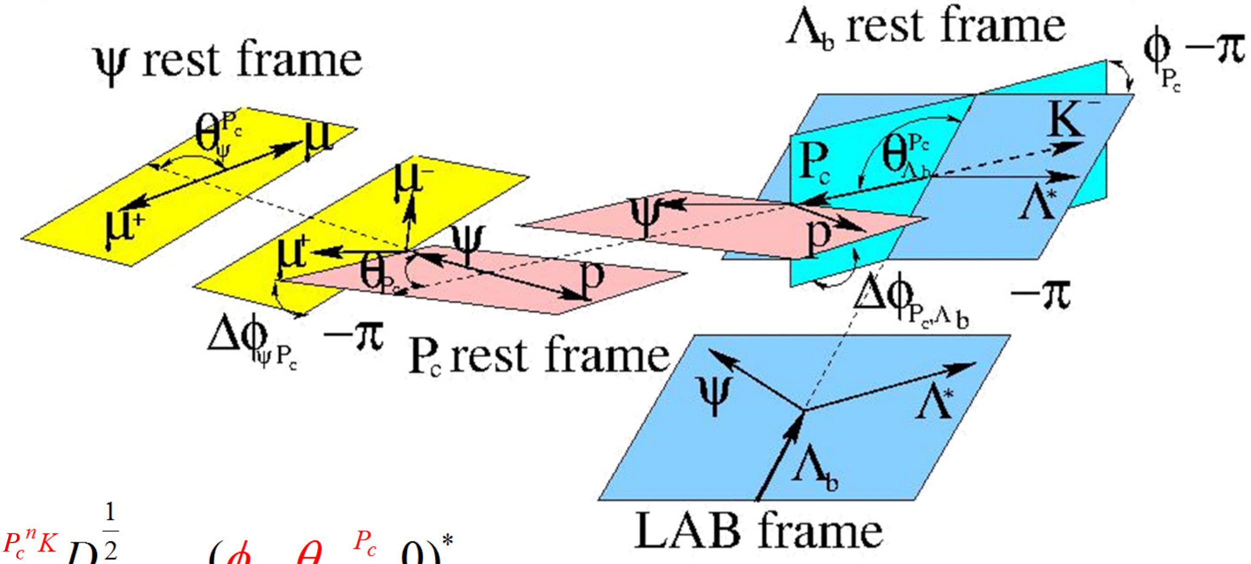
Amplitude Analysis of $\Lambda_b \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$

$$\left| M\left(\mathrm{m}_{Kp}, \Omega \mid M_{P_c^n}, \Gamma_{P_c^n}, J_{P_c^n}, A_{\lambda_{P_c^n}}^{\Lambda_b \to P_c^n K}, A_{\lambda_\psi, \lambda_p}^{P_c^n \to \psi p}, A_{\lambda_\psi, \lambda_{\Lambda^*}}^{\Lambda_b \to \psi \Lambda_n^*}, A_{\lambda_p}^{\Lambda_n^* \to pK}\right)\right|^2 =$$

$$\sum_{\lambda_{\Lambda_b}=-1/2,+1/2} \sum_{\lambda_p=-1/2,+1/2} \sum_{\Delta\lambda_\mu=-1,1} \left| M_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu}^{\Lambda^*} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p{}^{P_c}=-1/2,+1/2} d_{\lambda_p{}^{P_c}, \lambda_p}^{\frac{1}{2}}(\theta_p) M_{\lambda_{\Lambda_b}, \lambda_p{}^{P_c}, \Delta\lambda_\mu}^{P_c} \right|^2$$

6D analysis

1 mass, 6+2 angles
all derivable from the Λ^* variables



$$M_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu}^{P_c} = \sum_n \sum_{\lambda_{P_c}} \sum_{\lambda_\psi=-1,0,1} A_{\lambda_{P_c}}^{\Lambda_b \to P_c^n K} D_{\lambda_{\Lambda_b}, \lambda_{P_c^n}}^{\frac{1}{2}}(\phi_{P_c}, \theta_{\Lambda^*}{}^{P_c}, 0)^*$$

$$A_{\lambda_\psi, \lambda_p}^{P_c^n \to \psi p} D_{\lambda_{P_c^n}, \lambda_\psi - \lambda_p}^{J_{P_c^n}}(\Delta\phi_{P_c, \Lambda_b}, \theta_{P_c}, 0)^* R(m_{\psi p} \mid M_{P_c^n}, \Gamma_{P_c^n}) D_{\lambda_\psi, \Delta\lambda_\mu}^{1}(\Delta\phi_{\psi, P_c}, \theta_\psi{}^{P_c}, 0)^*$$

↑

3-4 independent **complex** helicity
couplings per P_c^n resonance

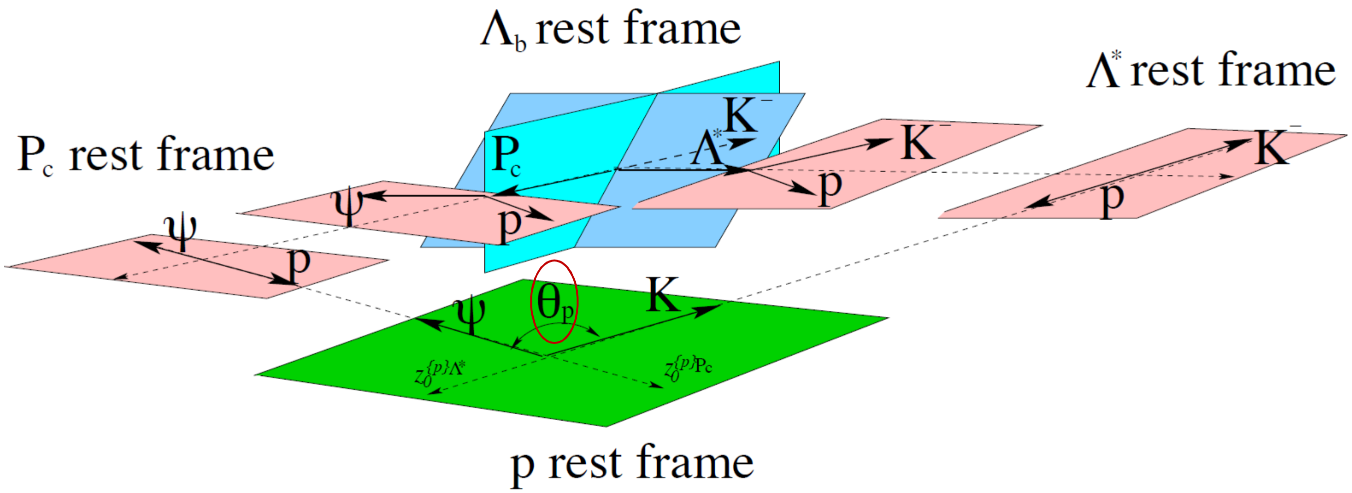
Λ^* Plus P_c^+ Matrix Element

2 additional angles to align the muon and proton helicity frames between the Λ^* and P_c^+ decay chains

also derivable from the Λ^* decay variables

$$\left| M\left(m_{Kp}, \Omega \,|\, M_{P_c^{\,n}}, \Gamma_{P_c^{\,n}}, J_{P_c^{\,n}}, A_{\lambda_{P_c^{\,n}}}^{\Lambda_b \to P_c^{\,n} K}, A_{\lambda_\psi, \lambda_p}^{P_c^{\,n} \to \psi p}, A_{\lambda_\psi, \lambda_{\Lambda^*}}^{\Lambda_b \to \psi \Lambda_n^*}, A_{\lambda_p}^{\Lambda_n^* \to pK}\right) \right|^2 =$$

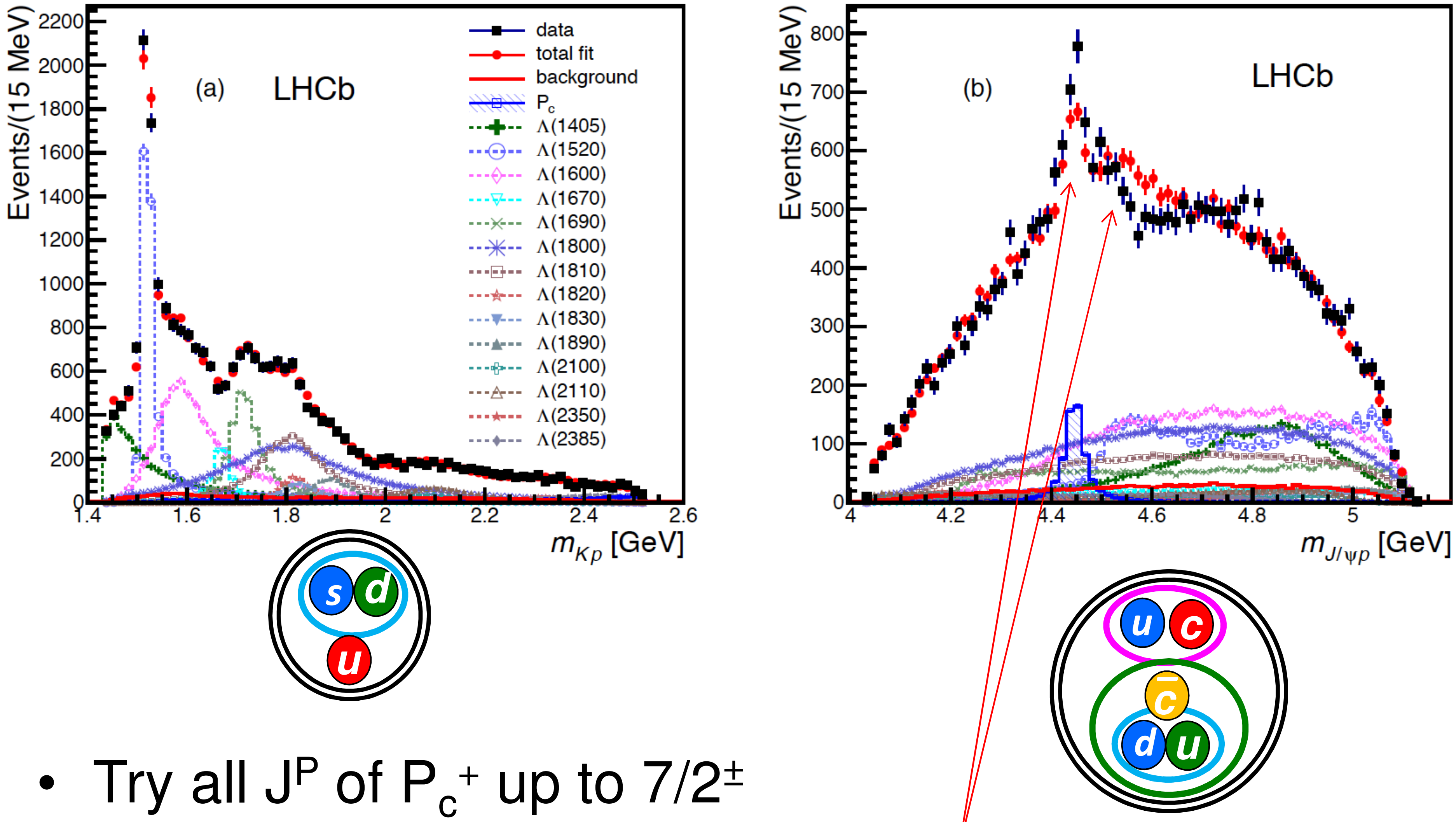
$$\sum_{\lambda_{\Lambda_b}=-1/2,+1/2} \; \sum_{\lambda_p=-1/2,+1/2} \; \sum_{\Delta\lambda_\mu=-1,1} \left| M_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu}^{\Lambda^*} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}=-1/2,+1/2} d_{\lambda_p^{P_c}, \lambda_p}^{\frac{1}{2}}(\theta_p)\, M_{\lambda_{\Lambda_b}, \lambda_p^{P_c}, \Delta\lambda_\mu}^{P_c} \right|^2$$



- Without this realignment can't describe Λ^* plus P_c^+ interferences properly
- They integrate out to zero in full phase-space but present in the differential 6D fit-PDF

Fit with Λ*'s and one $P_c^+ \to J/\psi p$ state

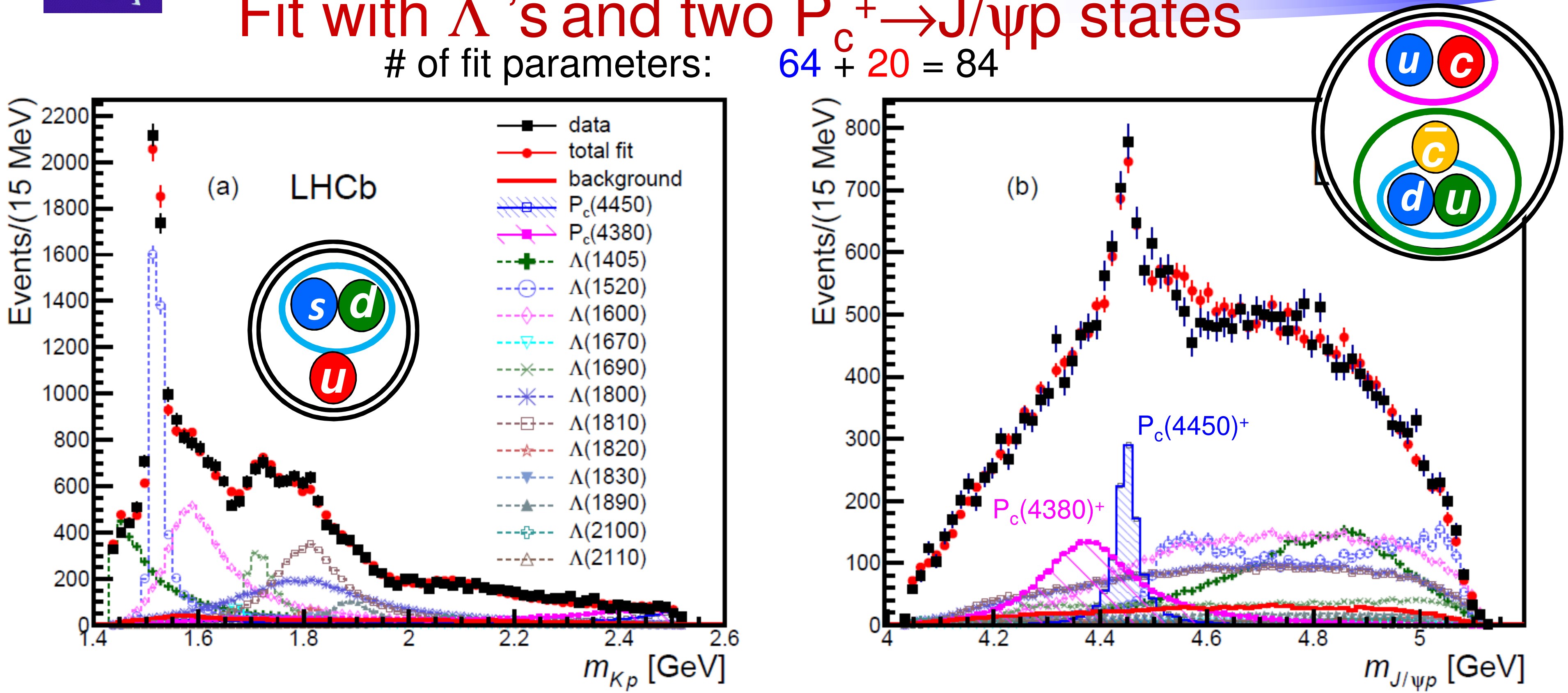
of fit parameters: 146 + 10 = 156



- Try all J^P of P_c^+ up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

Fit with Λ*'s and two $P_c^+ \to J/\psi p$ states

\# of fit parameters: 64 + 20 = 84



- Obtain good fits even with the reduced Λ* model

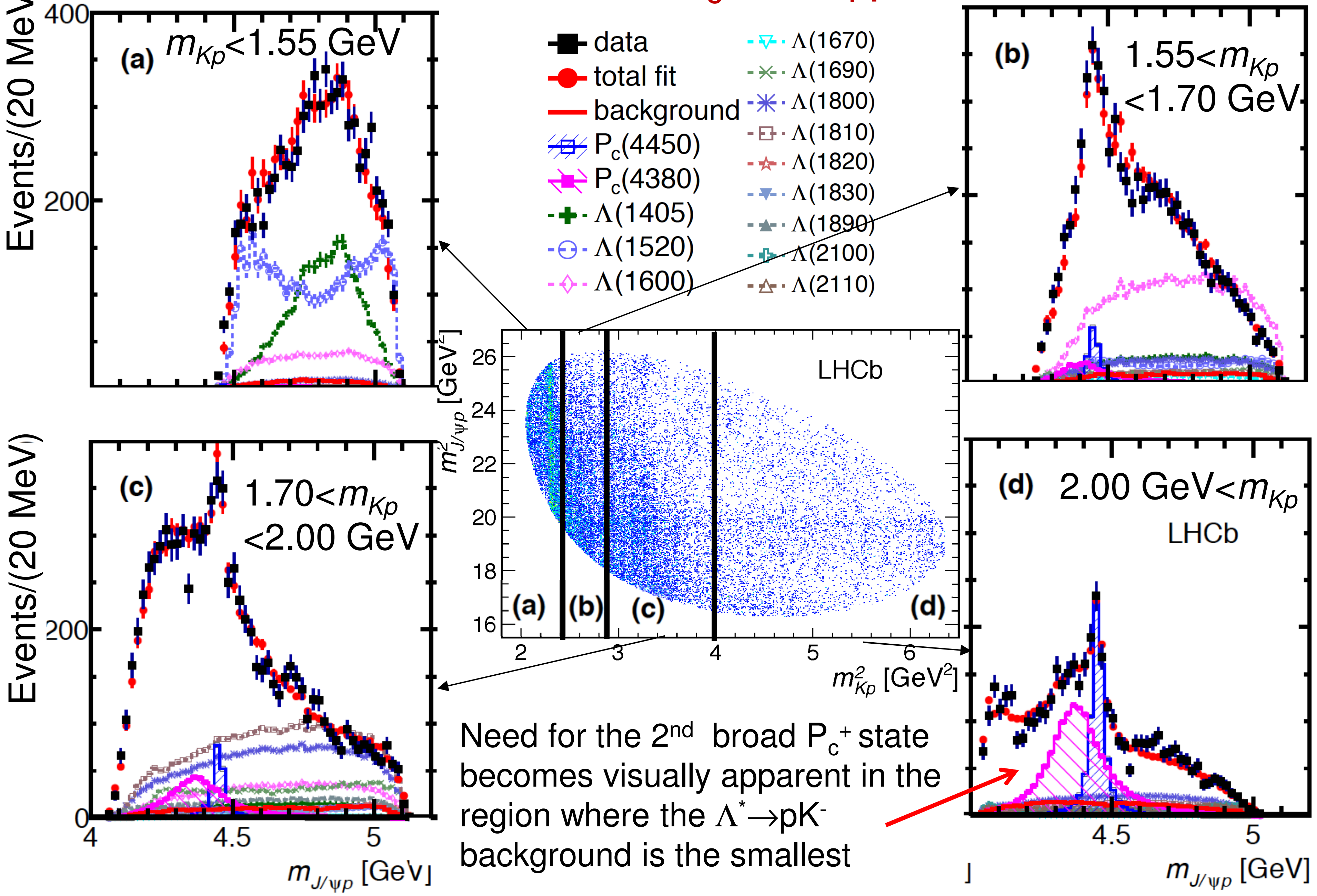
State	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2	9σ
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ

- Best fit has J^P=(3/2⁻, 5/2⁺), also (3/2⁺, 5/2⁻) & (5/2⁺, 3/2⁻) are preferred

Statistical significances

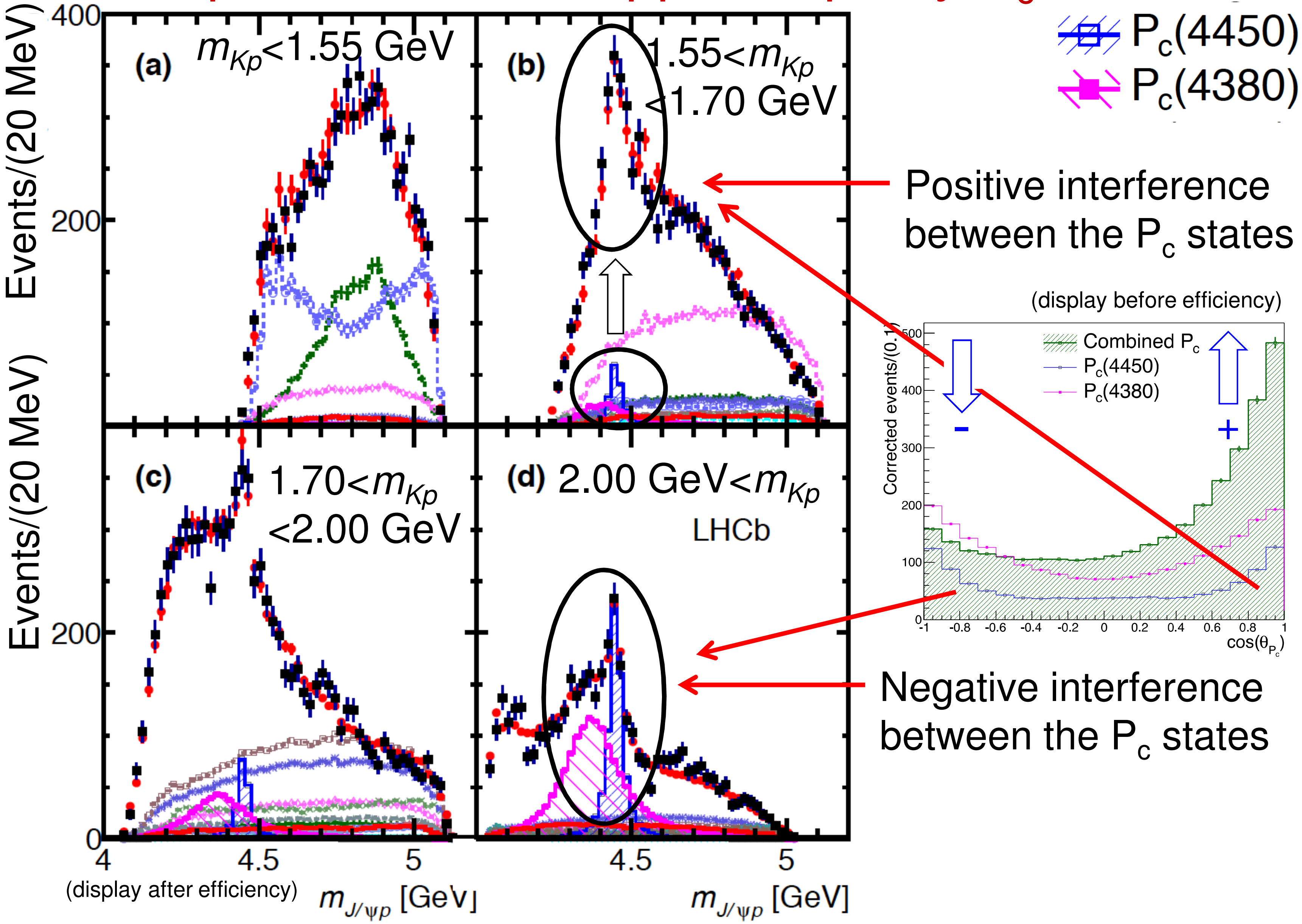
- Fit improves greatly, for 1 P_c $\Delta(-2\ln\mathcal{L})=14.7^2$, adding the 2nd P_c improves by 11.6^2, for adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Simulations of pseudoexperiments are used to turn the $\Delta(-2\ln\mathcal{L})$ values to significances:
  - significance of $P_c(4450)^+$ state is 12σ
  - significance of $P_c(4380)^+$ state is 9σ
  - combined significance of the two P_c^+ states is 15σ
- This includes the dominant systematic uncertainties, coming from difference between extended and reduced Λ^* model results.

Fit with Λ^{*}'s and two $P_c^+ \to J/\psi p$ states



Need for the 2nd broad P_c^+ state becomes visually apparent in the region where the $\Lambda^* \to pK^-$ background is the smallest

Data preferrence for opposite parity P_c^+ states



Positive interference between the P_c states

(display before efficiency)

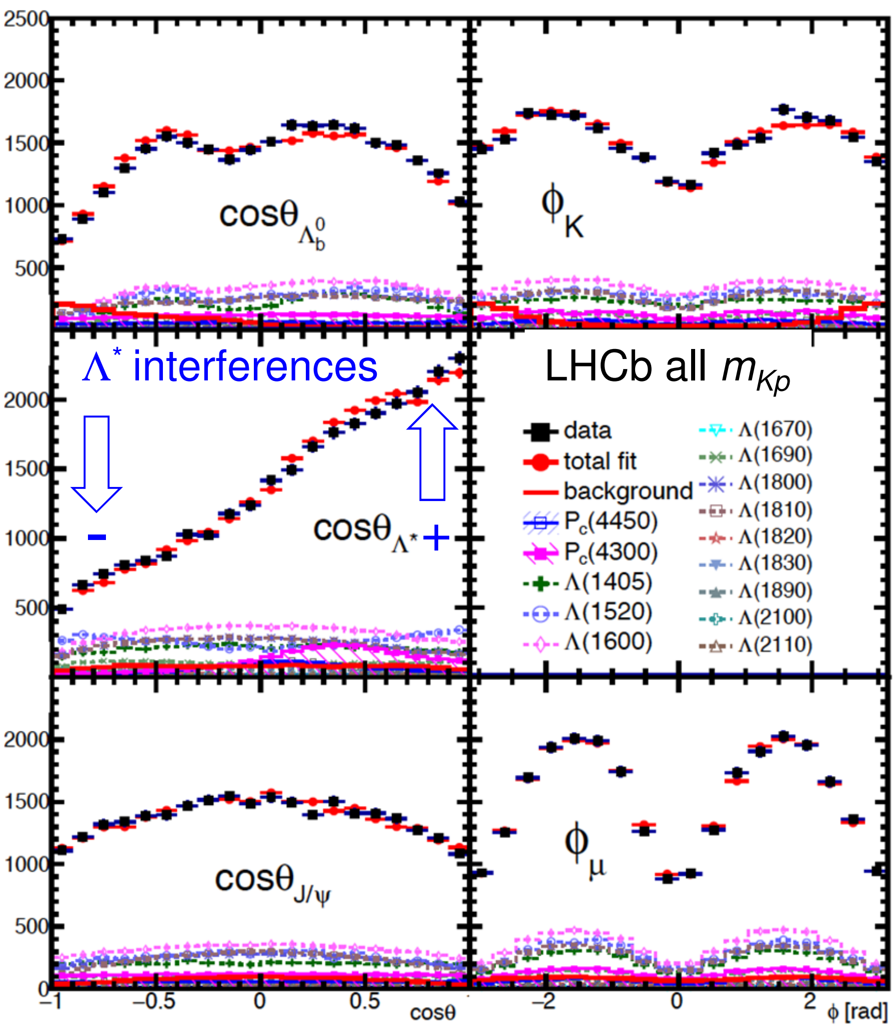
Negative interference between the P_c states

(display after efficiency)

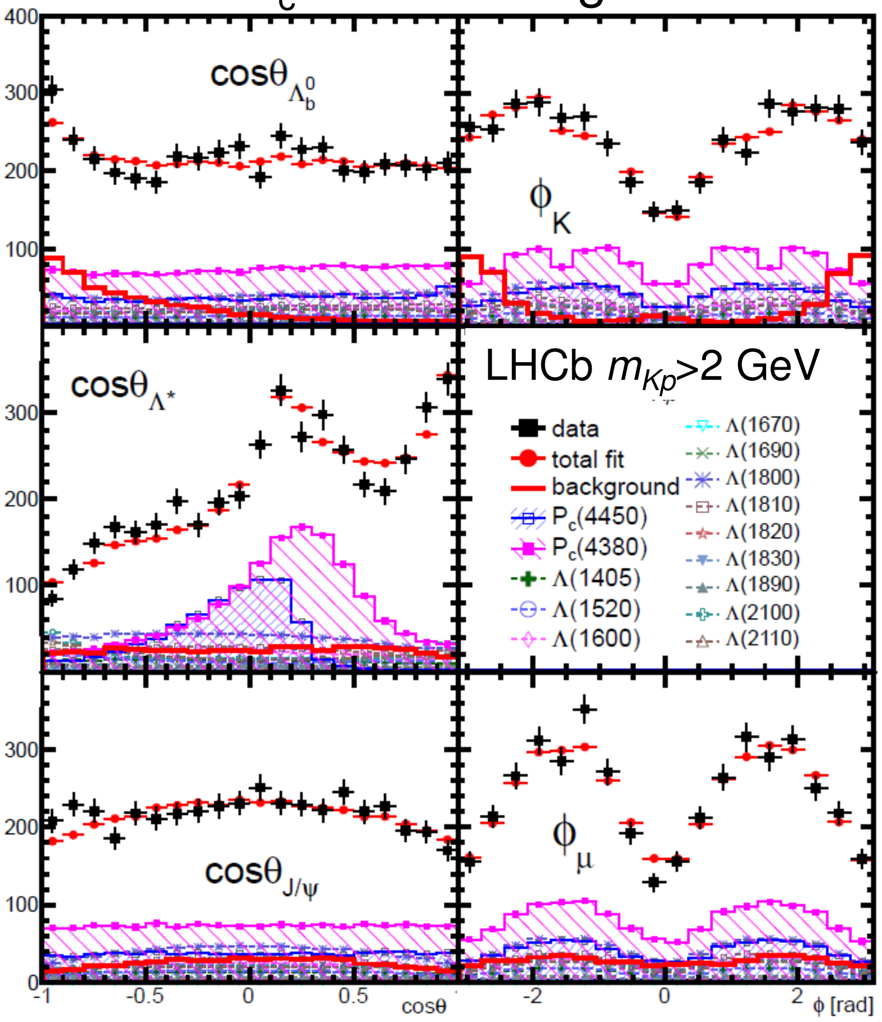
- This interference pattern only for states with opposite parity

Angular distributions

All data



P_c enriched region



- Good description of the data in all 6 dimensions!

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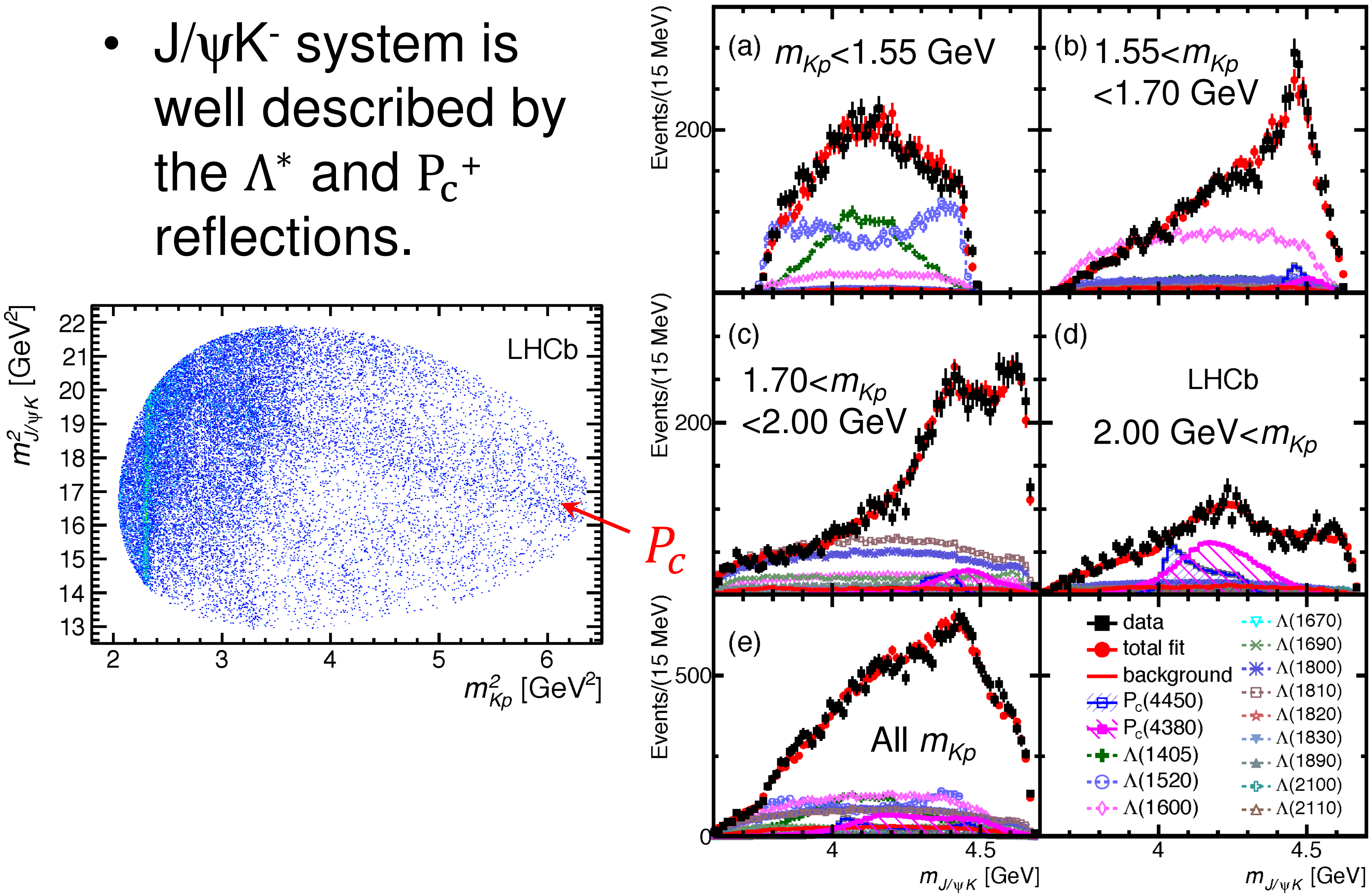
No need for exotic J/ψK$^-$ contributions

- J/ψK$^-$ system is well described by the Λ* and P$_c$$^+$ reflections.



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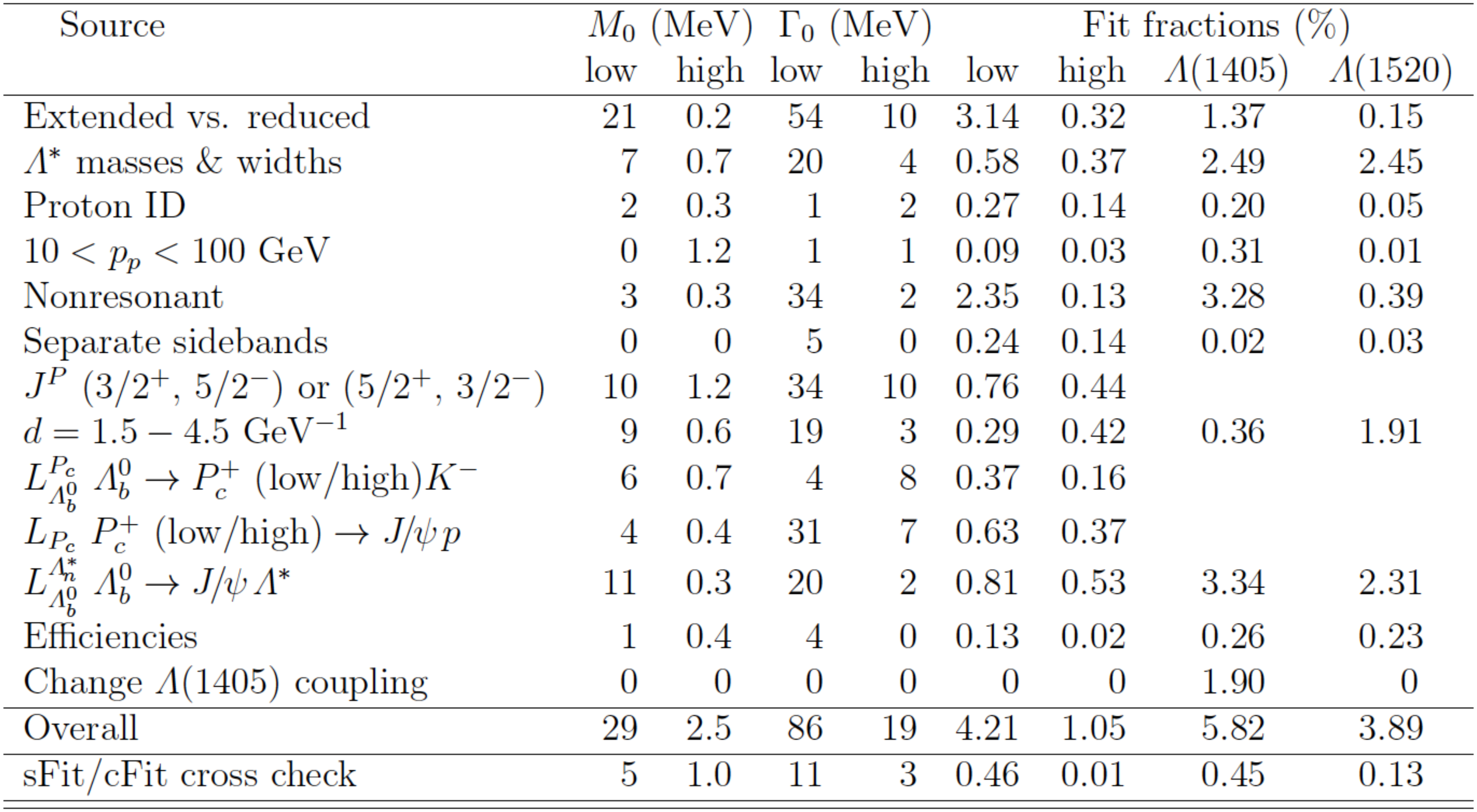
Systematic uncertainties



Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda^0_b}$ $\Lambda^0_b \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda^*_n}_{\Lambda^0_b}$ $\Lambda^0_b \to J/\psi \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

- Uncertainties in the Λ^* model dominate

Additional cross-checks

- Many additional cross-checks have been done. Some are listed here:
  - The same P_c^+ structure found using very different selections by different LHCb teams
  - Two independently coded fitters using different background subtractions (cFit & sFit)
  - Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T$ low$)/\Lambda_b(p_T$ high)
  - Extended model fits tried without P_c states, but with two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

Argand diagrams

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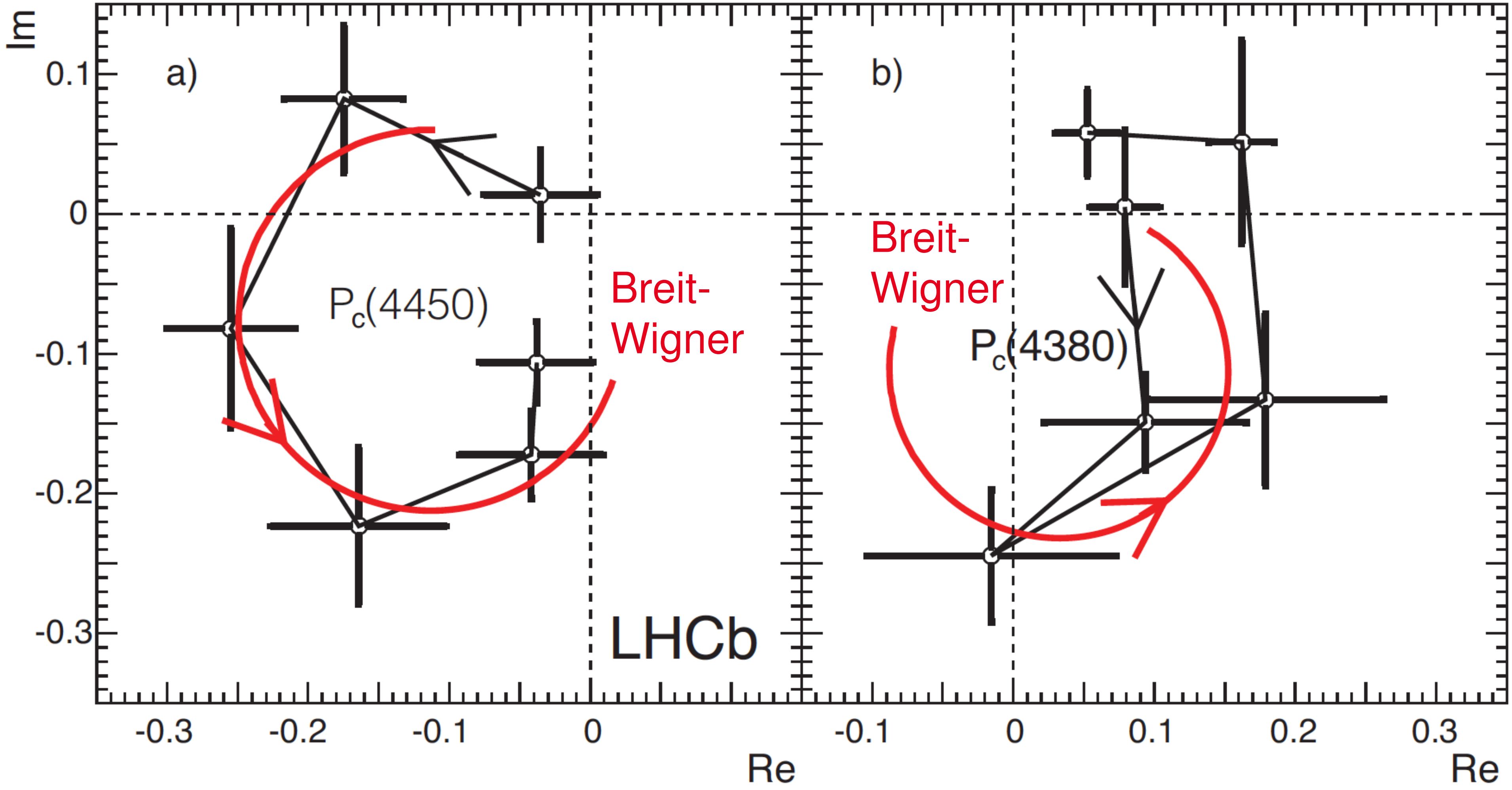
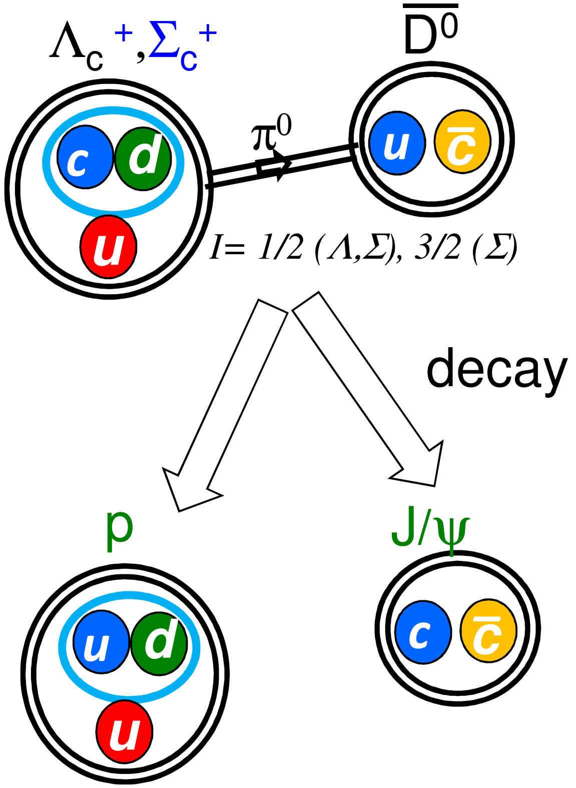
P_c^+ amplitudes for 6 $m_{J/\psi p}$ bins between $+\Gamma$ & $-\Gamma$ around the resonance mass

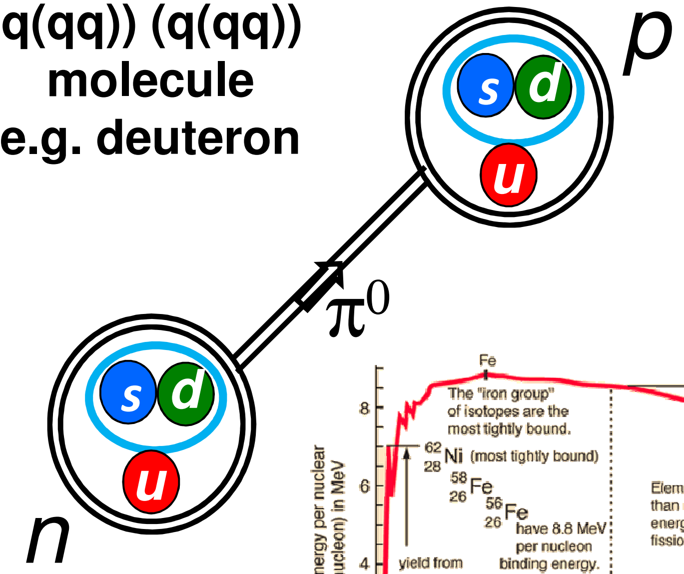


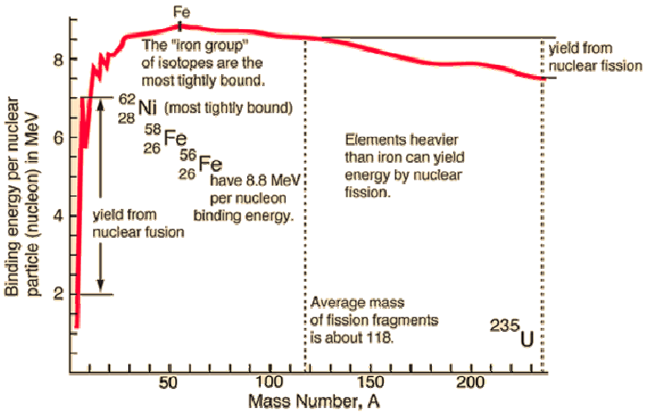
- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

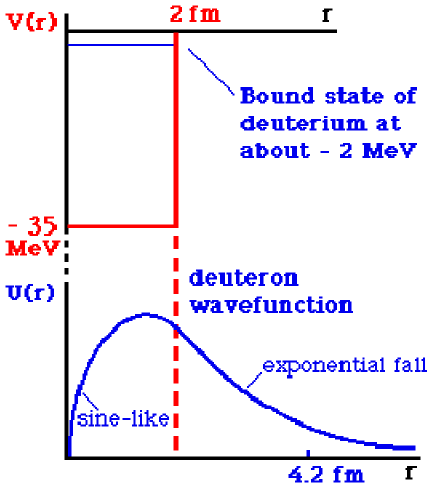
Molecular states?



(q(qq)) (q(qq))
molecule
e.g. deuteron







Difficult to get more than one state ($n=1, l=0$).

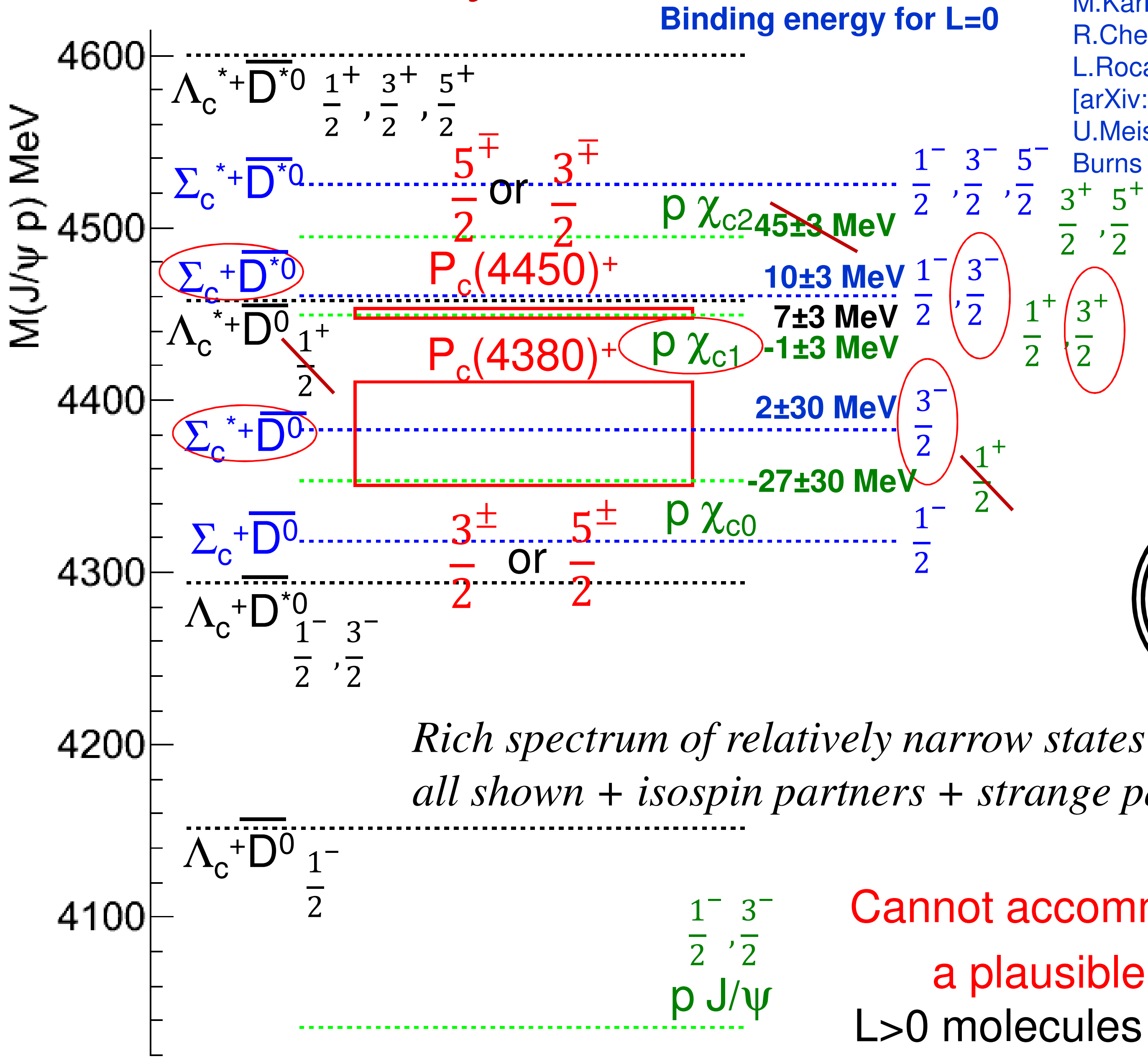
$M = M_1+M_2 - $ (a few MeV)

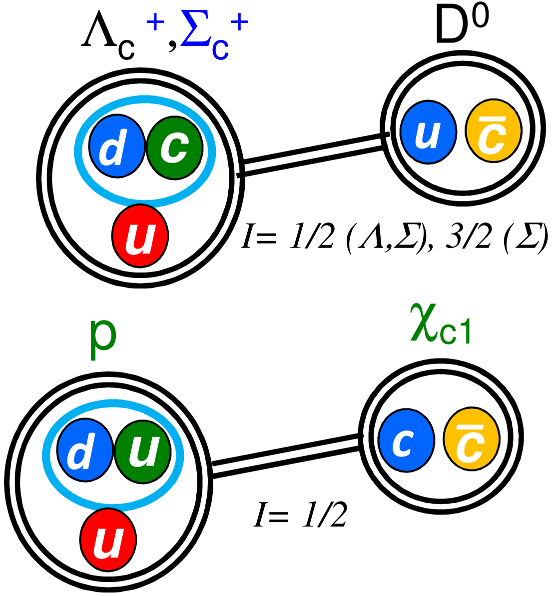
$J^P = (J_1 \otimes J_2)^{P1*P2}$

$\Gamma \sim \max(\Gamma_1,\Gamma_2)$

Baryon-meson molecules?

M.Karliner, J.Rosner [arXiv:1506.06386], R.Chen et al [arXiv:1507.03704 L.Roca,J.Nieves,E.Oset [arXiv:1507.04249].J.He [arXiv:1507.05200] U.Meissner,A.Oller [arXiv:1507.07478],T.J. Burns [arXiv:1509.02460]



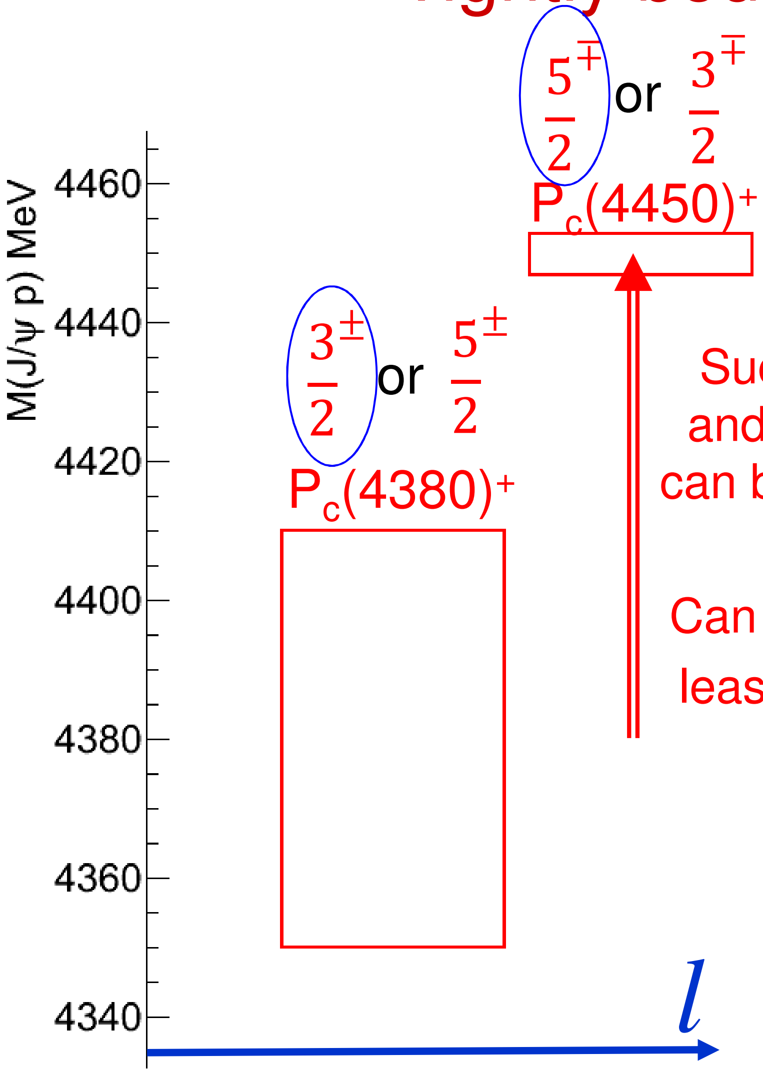


Rich spectrum of relatively narrow states expected:
all shown + isospin partners + strange partners + b quark + …

Cannot accommodate a $\frac{5}{2}^{\pm}$ state with a plausible S-wave molecule

L>0 molecules not likely to be bound

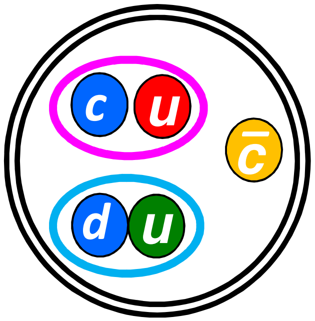
Tightly bound pentaquarks?



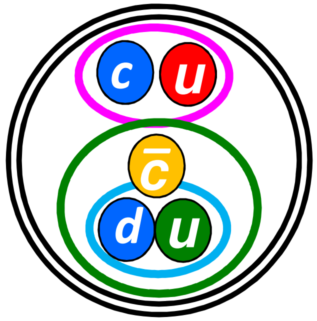
Such mass difference and the opposite parity can be explained by *Δl=1*

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

Maiani, Polosa,Riquer [arXiv:1507.04980],
Anisovich et al [arXiv:1507.07652,1509.04898],
Li,He,He [arXiv:1507.08252],
Ghosh et al [arXiv:1508.00356]



R. Lebed [arXiv:1507.05867]



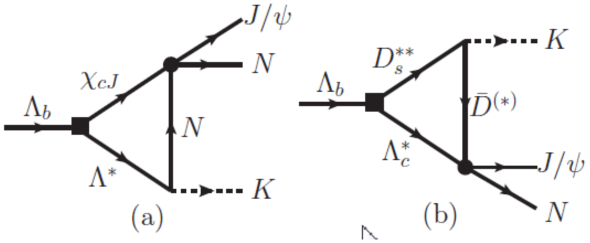
Rich spectrum of states expected:
S=0 (lower J)+ l + n + isospin partners
+ strange partners + b quark + …

e.g.

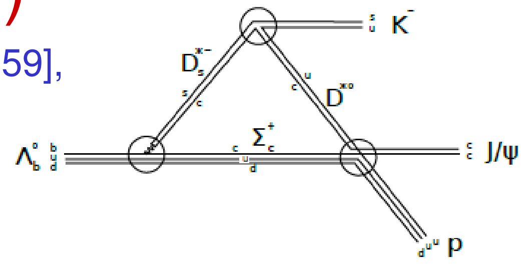
$\bar{c}[cu]_{S=1}\,[ud]_{S=0}$ ***(l=1)***

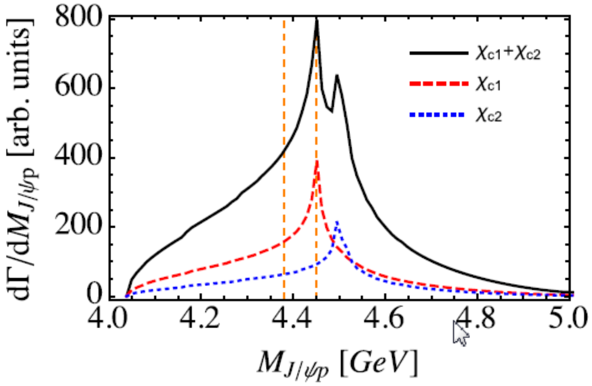
$\bar{c}[cu]_{S=1}\,[ud]_{S=1}$ ***(l=0)***

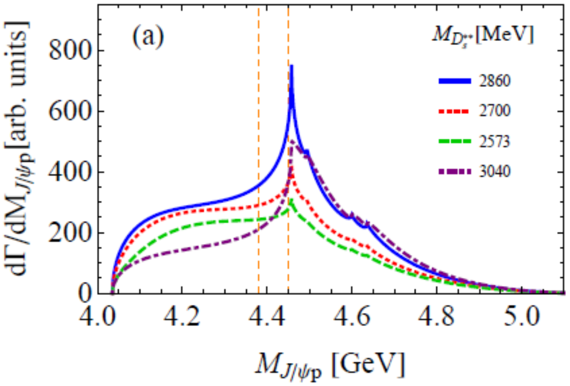
Rescattering (triangular singularity)

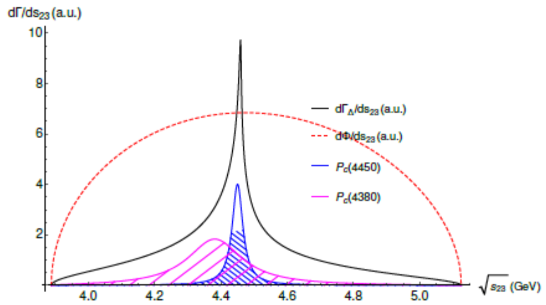


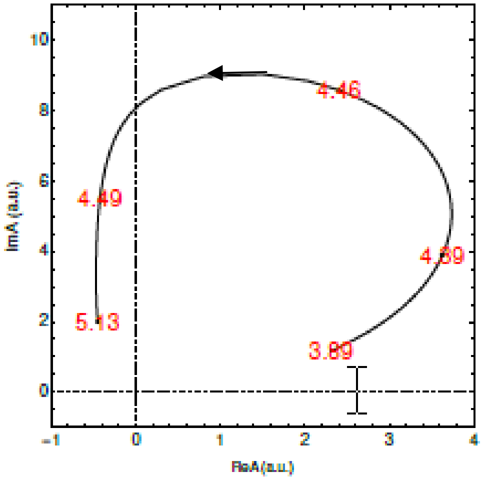
Z.-H.Liu,Q.Wang,Q.Zhao [arXiv:1507.05359],
M. Mikhashenko [arXiv:1507.06552],
A. Szczepaniak [arXiv:1510.01789]











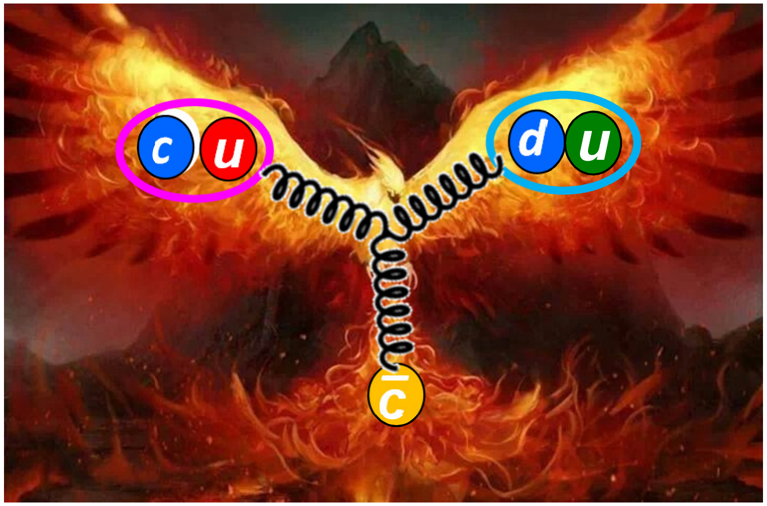
- Conventional hadrons produced and then rescatter (rearrange quarks) to produce a peak in the exotic channel. Peaking structures related to mass thresholds.
- Ad hoc parameter values to generate desired structures.
- Can sometimes arrange for the resonant-like phase running.
- Given proliferation of thresholds, why aren't they everywhere?
- Not clear these models can describe decay angles distributions – predictions and tests on the data are needed.
- In the past, many resonances which are well established by now, were proposed to be rescattering effects (e.g. $a_1(1260)$).

Outlook to the future

- At present there are many plausible explanations for the observed P_c^+ states.
- The main competition is between tightly bound models based on diquark substructure, loosely bound molecules and rescattering effects.
- Clarifying J^P values and resonant nature of the discovered P_c^+ states with more statistics will be very important.
- All models predict many other related states to exist. Different models predict different mass spectra. We badly need to discover more elements of future periodic table of such states!
- Interactions forming pentaquark states must also play a role in tetraquark states. It is important to pursue both spectroscopies together!
- Searches for states with even more quarks e.g. sextquarks (i.e. dibaryons) interesting.
- We can do more to test the diquark idea in ordinary baryons! Need experimentalists to do better on identifying all excited baryons.
- So far the most compelling tetraquark and pentaquark candidates have been discovered with hidden charm inside ($c\bar{c}$). The other heavy quark systems should also be creating bound structures ($b\bar{b}$, $b\bar{c}$, $cc\bar{c}$, …)
- We are only at the beginning of hopefully very interesting road ahead…

Conclusion

- Two pentaquark candidates decaying to J/ψp observed by LHCb with overwhelming significance in a state of the art amplitude analysis: they will not go away!



Frank Wilczek's twit on 7/14/15: "Pentaquarks rise from the ashes: a phoenix pair"

Pentaquark candidates rise from the ashes for the 2nd time.

- LHC resurrects them: should not be a surprise given baryon cross-sections.

$c\bar{c}$ pair inside:

- Given the history of Quark Model should not be a surprise either.

Hopefully true July 2015 revolution!

- The simplicity of lower mass excitations of mesons and baryons, which led us to the discovery of quarks via $q\bar{q}$, qqq structures, also misled us to believe that we had already understood hadronic structures. Much experimental and theoretical work remains to be done to achieve this goal.