TETRAQUARKS AND PENTAQUARK(S)

J. Rosner - University of Chicago – November 16, 2015

Work with Marek Karliner, Tel Aviv University

LHCb: arXiv:1507.03414, PRL **115**, 072001 (2015): Discovery of two new states decaying to $J/\psi\ p$

M. Karliner and JLR, arXiv:1506.06386, PRL **115**, 122001 (2015): New exotic meson and baryon resonances from doubly heavy hadronic molecules

M. Karliner and JLR, arXiv:1508.01496, to be submitted to PLB: Photoproduction of exotic baryon resonances

LHCb announced (the day before Bastille Day) two new $J/\psi\ p$ resonances in the decay $\Lambda_b(5620) \to K^- J/\psi\ p$

$M = 4380 \pm 8 \pm 29$ MeV, $\Gamma = 205 \pm 18 \pm 86$ MeV (9σ)
$M = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma = 39 \pm 5 \pm 19$ MeV (12σ)

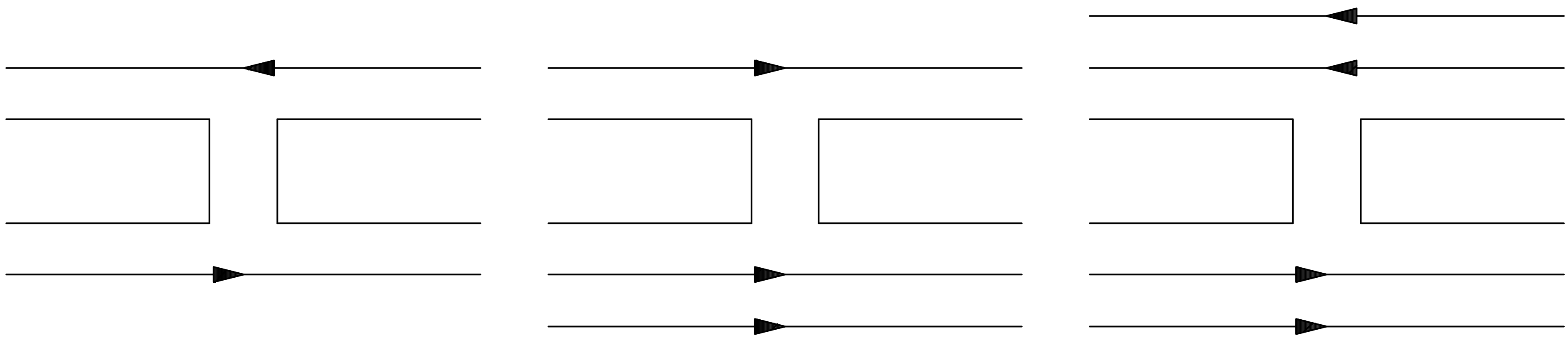
Preferred $J^P = 3/2^{\pm}$ for one, $5/2^{\mp}$ for other

SOME HISTORY

1964 (Gell-Mann and Zweig): $q\bar{q}$ mesons; qqq baryons

But also in principle could add $(q\bar{q})^n$ to any state

An argument for $qq\bar{q}\bar{q}$ in baryon-antibaryon channels based on duality between s, t channels (JLR, PRL **21**, 950 (1968)):



Meson-meson	Meson-baryon	Antibaryon-baryon
$q\bar{q}$ in t channel	$q\bar{q}$ in t channel	$q\bar{q}$ in t channel
$q\bar{q}$ in s channel	qqq in s channel	$\bar{q}\bar{q}qq$ in s channel

No light-quark $\bar{q}\bar{q}qq$ baryon-antibaryon resonances seen

HEAVY QUARKS MAKE A DIFFERENCE

Most light-quark $\bar{q}\bar{q}qq$ states fall apart easily into light meson-antimeson pairs; too broad to register as resonances

Inclusion of $c\bar{c}$ or $b\bar{b}$ pairs reduces internal kinetic energy and stabilizes molecular states of (e.g.) charmed or beauty meson-antimeson systems

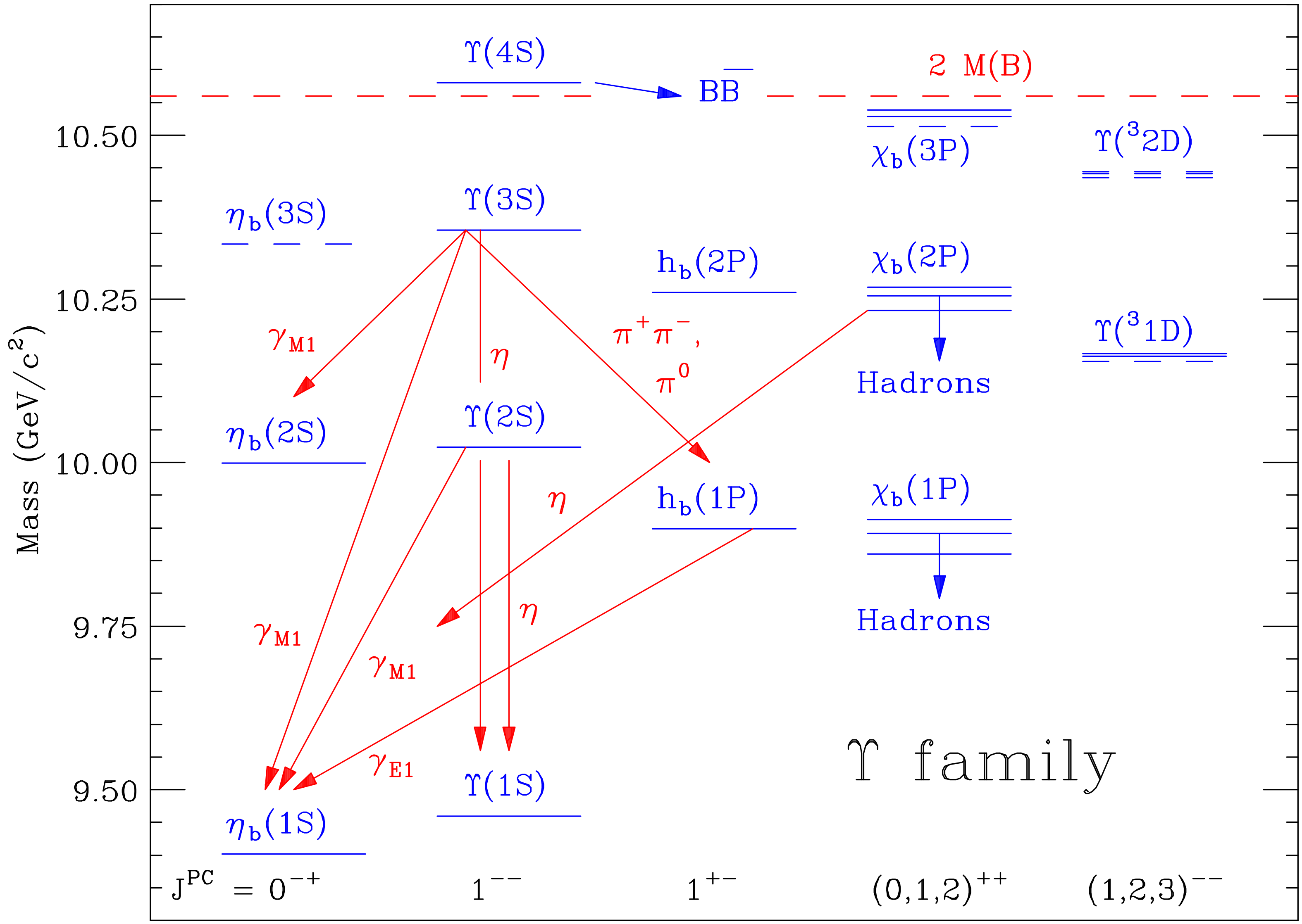
First such state was $X(3872)$, a $J/\psi\pi^+\pi^-$ resonance discovered by Belle Collaboration in $B \to KJ/\psi\pi^+\pi^-$

The state is so close to $D^0\bar{D}^{*0}$ threshold that one cannot tell whether it is a bound state or a virtual state

Appears to be a mixed configuration of 2^3P_1 $c\bar{c}$ (allowing it to decay to $\gamma J/\psi$) and $D^0\bar{D}^{*0}+$ c.c. in an S-wave, with spin-parity-charge parity $J^{PC} = 1^{++}$

Seen decaying to both $J/\psi\rho$ and $J/\psi\omega$, indicating an isospin $I = 0, 1$ admixture as expected from a $D^0\bar{D}^{*0}+$ c.c. molecule (D^+D^{*-} threshold is 8 MeV higher)

THE Υ FAMILY

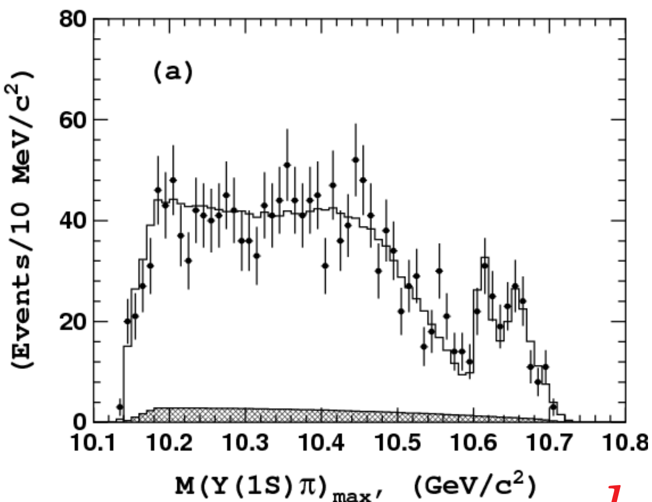


Belle: $\Upsilon(5S)$ [10.86 GeV] a potent source of bottomonium states below flavor threshold $[\Upsilon(1S, 2S, 3S)$, $h_b(1P, 2P)]$

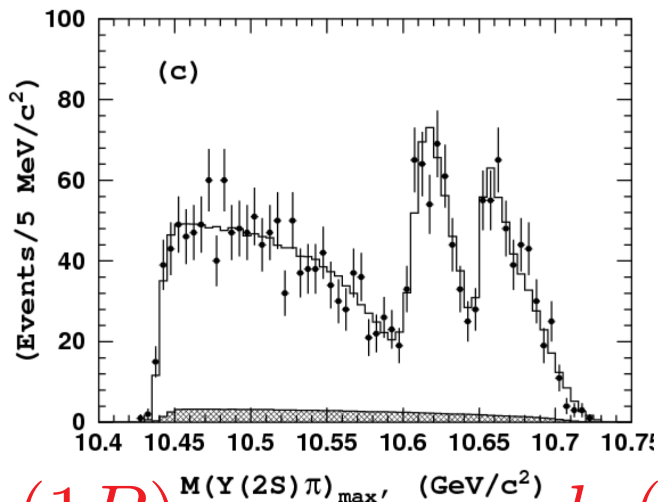
THE Z_b STATES

First seen by Belle in $\Upsilon(5S)$ decays to $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ and $h_b(1P, 2P)\pi^+\pi^-$: Bondar +, PRL **108**, 122001 (2012)

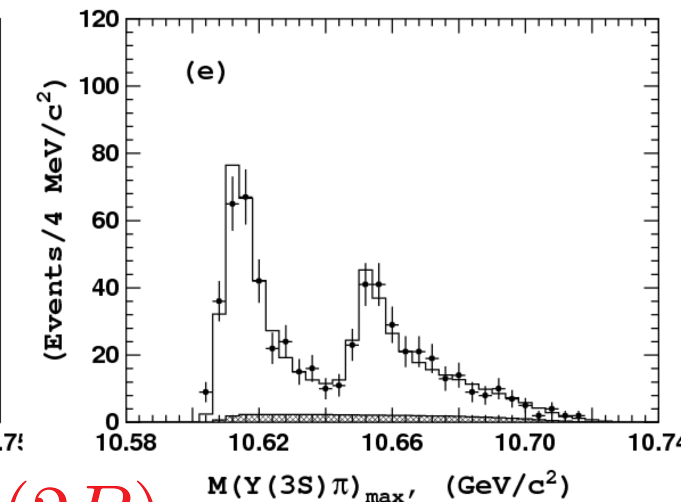
$\Upsilon(1S)\pi$



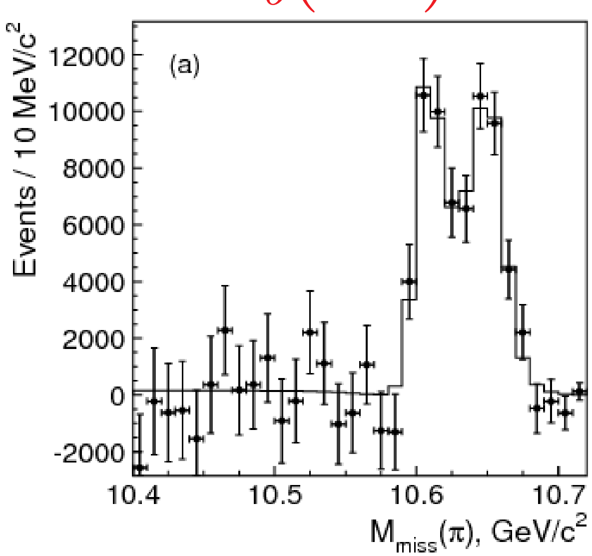
$\Upsilon(2S)\pi$



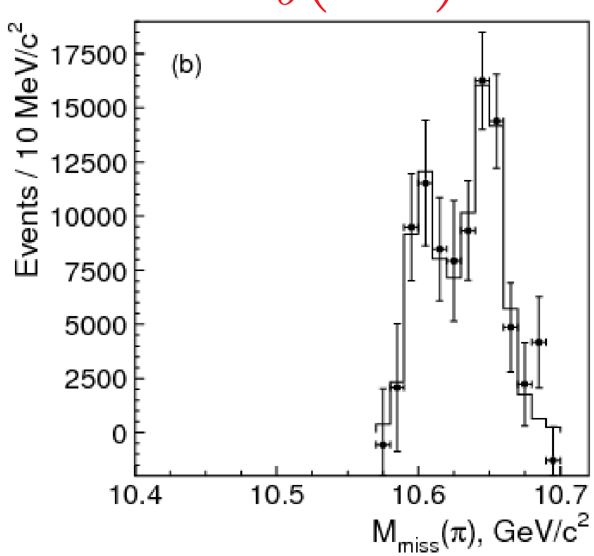
$\Upsilon(3S)\pi$



$h_b(1P)\pi$



$h_b(2P)\pi$

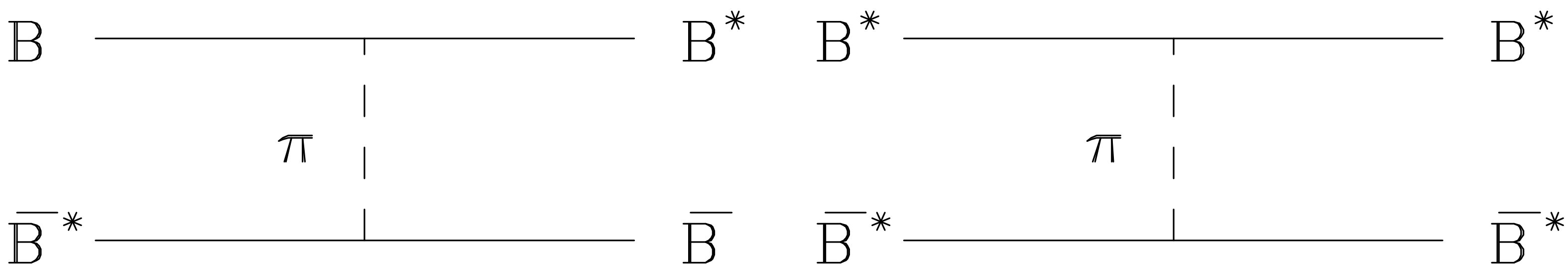


Z_b INTERPRETATION

States at 10.61 and 10.65 GeV, widths 10–20 MeV

$Z_b(10610)$ very near $B\bar{B}^*$ threshold (10605 MeV);
$Z_b(10650)$ very near $B^*\bar{B}^*$ threshold (10650 MeV)

Suggests molecular interpretation; pion exchange can bind



Parity: No πBB coupling; no pion exchange for $B\bar{B}$

Attraction or repulsion depends on $\langle S_1 \cdot S_2\ I_1 \cdot I_2 \rangle$, where S is spin and I is isospin

Attractive (e.g.) for $D^0\bar{D}^{*0}$ + c.c. and $B\bar{B}^*$ + c.c. in S wave; favors $J = 2$ for $Z_b(10650)$

THE X, Y, Z STATES

X. Liu, arXiv:1312.7408v2, Chin. Sci. Bull. 59, 3825 (2014)

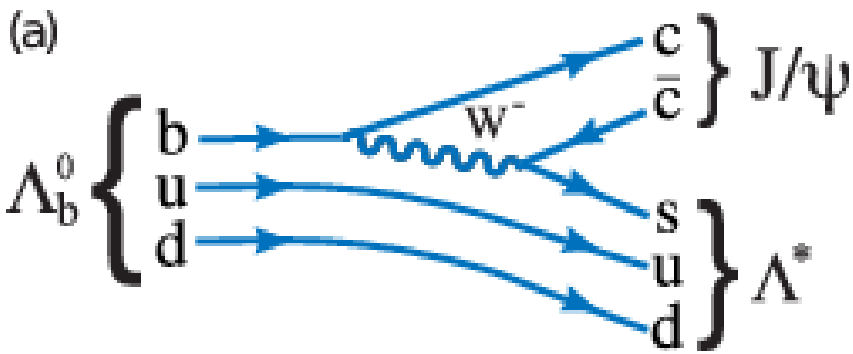
States & production mechanisms (*Caveat Emptor!*):

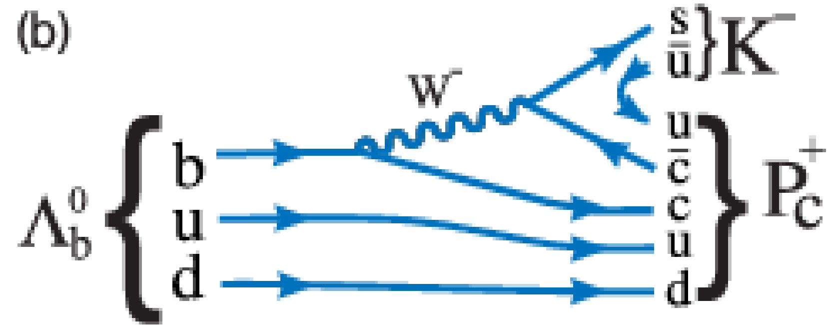
B decay	e^+e^- annihilation	Double charm	$\gamma\gamma$ fusion	Hidden/open charm + pion
$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_b(10510)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_b(10650)$
$Z^+(4430)$	$Y(4360)$	–	$Z(3930)$	$Z_c(3900)$
$Z^+(4051)$	$Y(4660)$	–	–	$Z_c(4025)$
$Z^+(4248)$	$Y(4630)$	–	–	$Z_c(4020)$
$Y(4140)$	–	–	–	$Z_c(3885)$
$Y(4274)$	–	–	–	–

Double charm: $e^+e^- \rightarrow J/\psi + X$; favors $J^{PC} = 0^{\pm+}$ states

$\gamma\gamma$ fusion: $J^{PC} = (0,2)^{\pm+}$ states

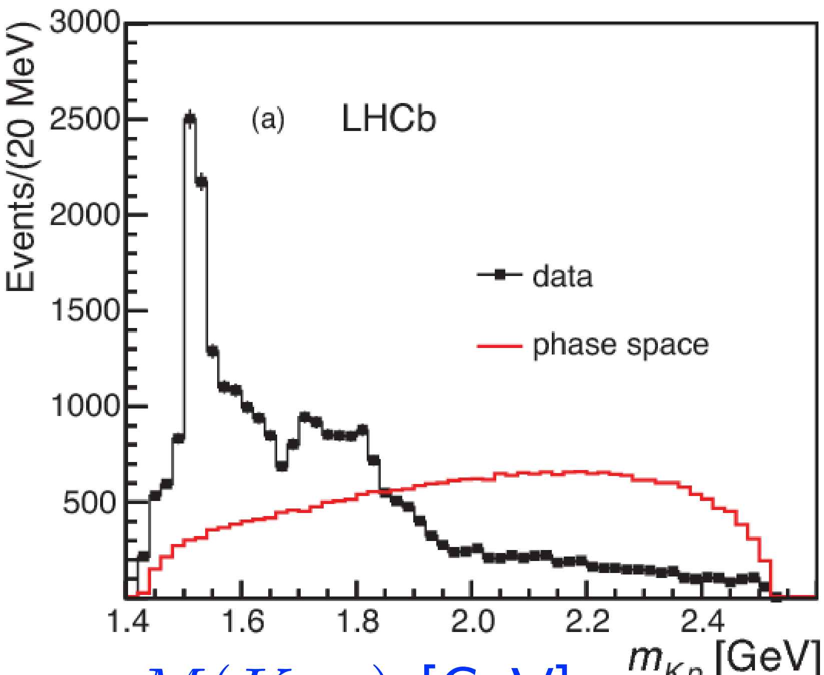
DECAYS OF Λ_b

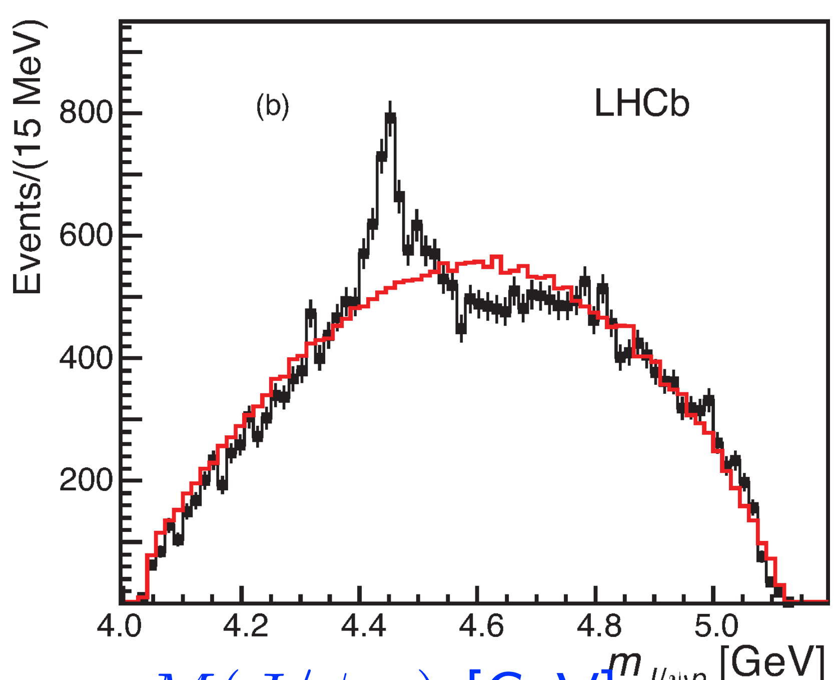




(a): $K^- p$ ("Λ^*") resonances; (b) "Pentaquark" P_c formation

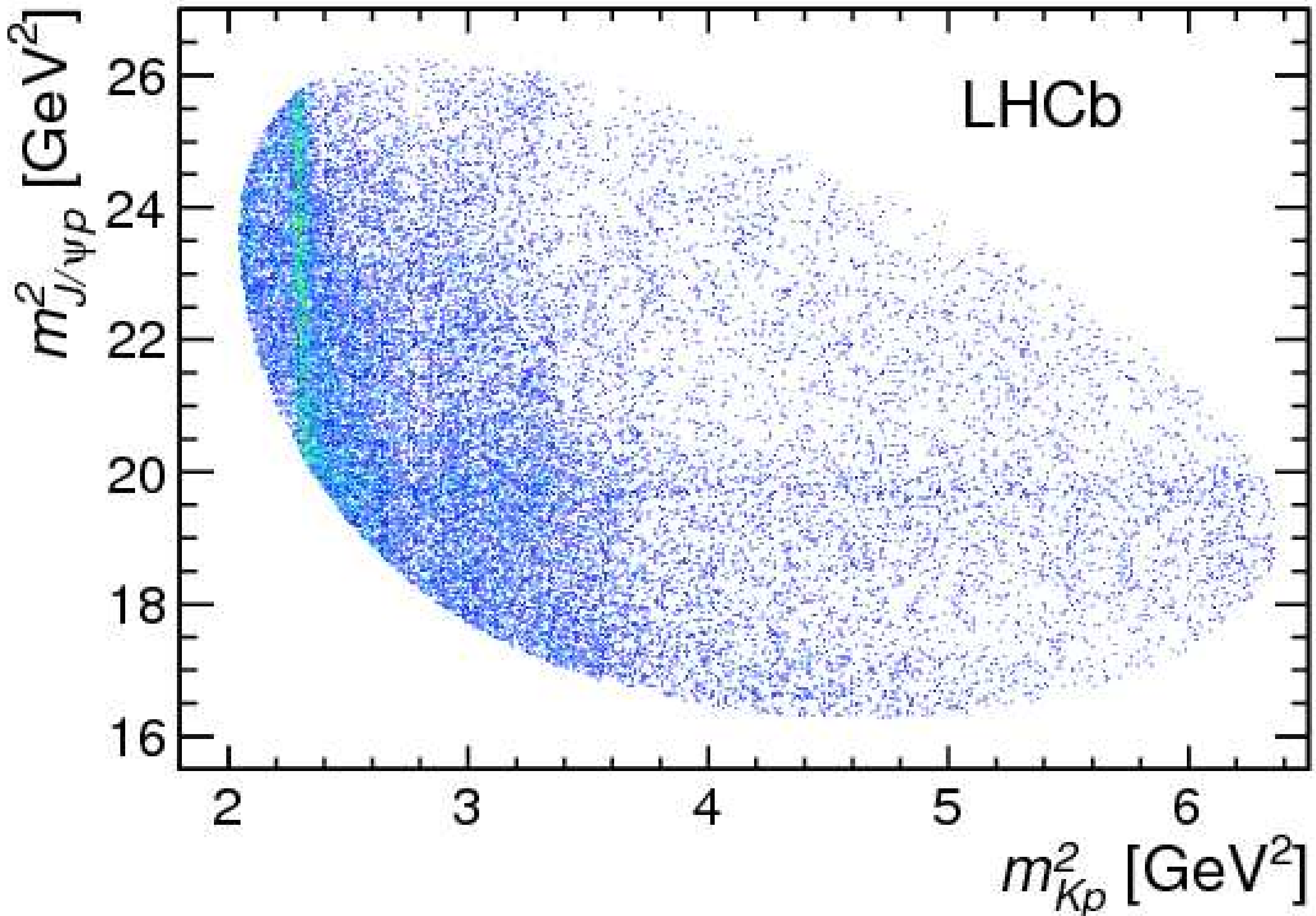
Dalitz plot projections:





$M(K^- p)$ [GeV] $M(J/\psi\ p)$ [GeV]

$\Lambda_b \to K^- J/\psi\ p$ DALITZ PLOT



Horizontal band at $M^2(J/\psi\ p) \simeq 19.8\ \mathrm{GeV}^2$

Strongest vertical band at $M^2(K^- p) \simeq 2.3\ \mathrm{GeV}^2$

Modeling all Λ^* resonances is a challenge.

EXPERIMENTAL DETAILS

Full LHCb sample: 7 TeV (1 fb^{-1}); 8 TeV (2 fb^{-1})

Trigger: opposite-charge dimuons, $p_T > 500$ MeV each

RICH particle ID; veto events consistent with B^0 or B_s

26,007 $\pm$ 166 signal candidates (5.4% background) within ± 15 MeV ($\pm 2\sigma$) of $J/\psi\ K^- p$ mass peak

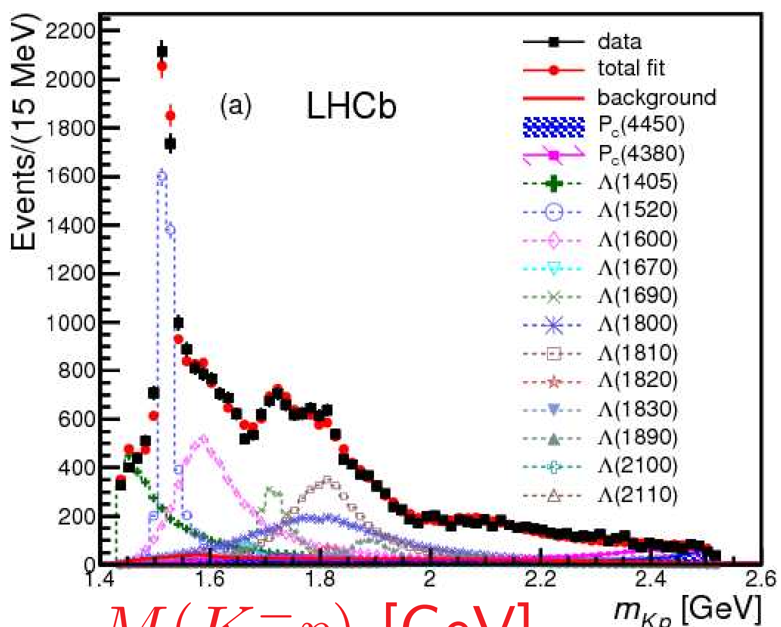
Fits using Breit-Wigner resonances in $K^- p$ and $J/\psi\ p$ channels; no structure seen in $J/\psi\ K^-$

Up to 14 Λ^* resonances used in fit (parameters from PDG)

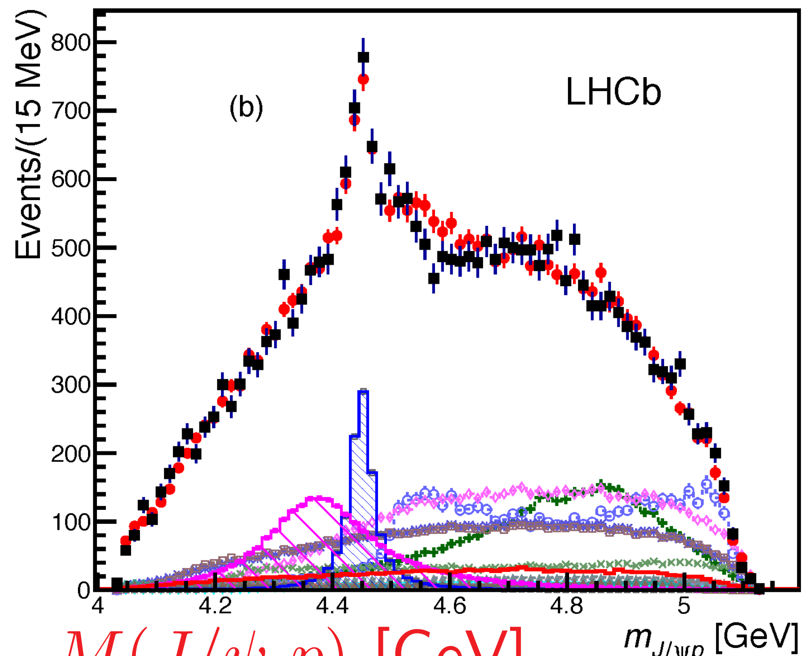
Helicity formalism for sequential decays

Although $P_c(4450)$ is the only obvious $J/\psi\ p$ resonance in Dalitz plot, poor fit with it alone in $J/\psi\ p$ channel

DEFAULT FIT COMPONENTS



$M(K^{-}p)$ [GeV]



$M(J/\psi\ p)$ [GeV]

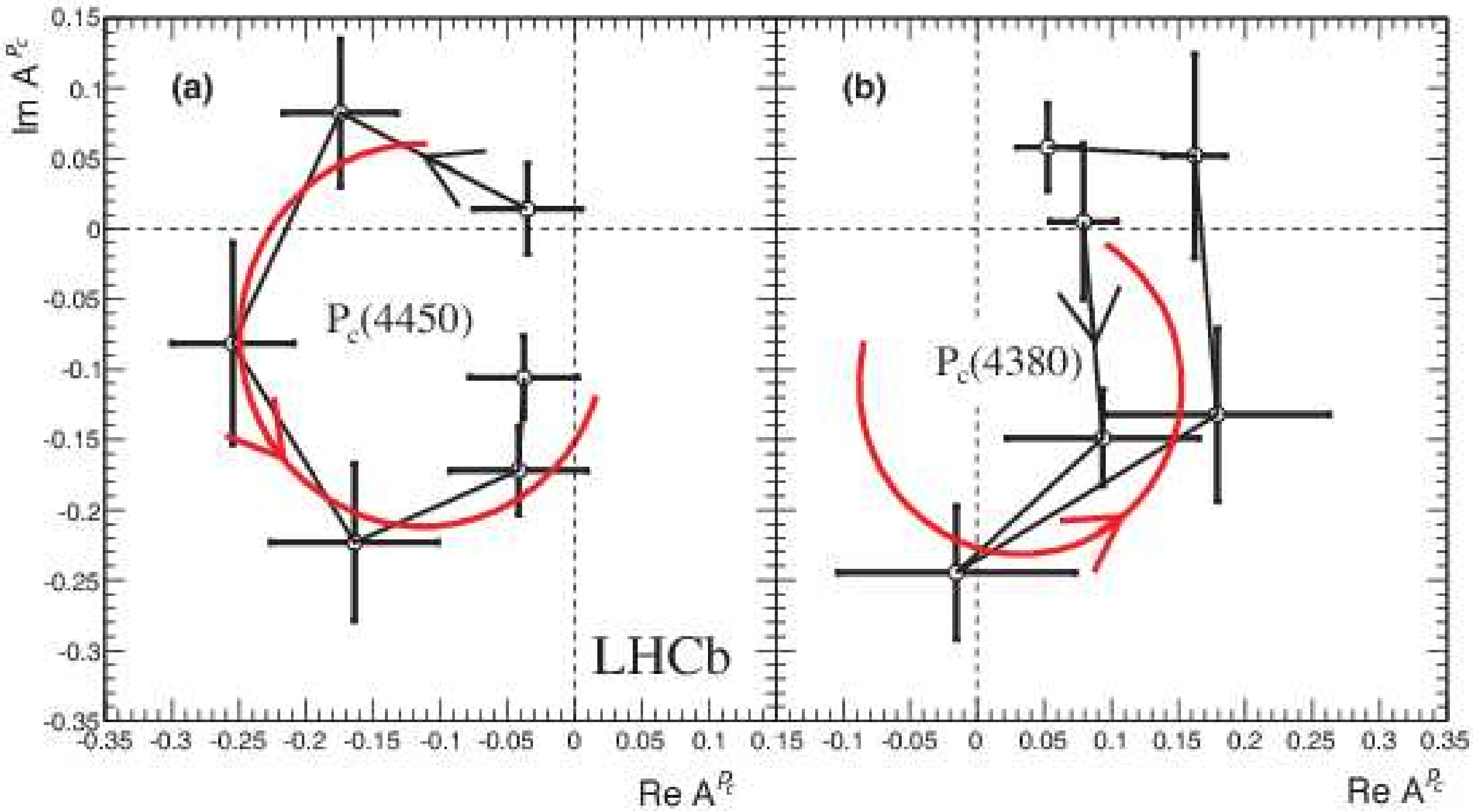
Major contributors with mass, J^P, and fit fraction:

$P_c(4380, 3/2^-)$ 8%	$P_c(4450, 5/2^+)$ 4%	$\Lambda(1405, 1/2^-)$ 14.5%
$\Lambda(1520, 3/2^-)$ 19%	$\Lambda(1600, 1/2^+)$ 24%	$\Lambda(1690, 3/2^-)$ 8.6%
$\Lambda(1800, 1/2^-)$ 17.5%	$\Lambda(1810, 1/2^+)$ 17.6%	

Six other Λ^* under 4%

ARGAND PLOTS

Error bars are statistical only; larger for $P_c(4380)$



Fitted values of the real and imaginary parts of the amplitudes for the default $(3/2^-, 5/2^+)$ fit for (a) $P_c(4450)$ and (b) $P_c(4380)$, each divided into six $m(J/\psi\ p)$ bins between $-\Gamma_0$ and $+\Gamma_0$ [$m(J/\psi\ p)$ increases counterclockwise]. The solid (red) curves are the prediction of the Breit-Wigner formula for the same mass ranges with M_0 (Γ_0) of 4450 (39) MeV and 4380 (205) MeV, respectively.

EDITORIAL COMMENTS

The state at 4450 MeV looks like a genuine narrow resonance

Its profile on the Dalitz plot is affected by interference with some amplitude of opposite parity, leading to asymmetry along its band [equivalently, in $m(K^- p)$].

In my opinion, based on the large number of variables in the collection of Λ^* resonances and the anemic behavior of the Argand diagram, it is too early to say whether the $P_c(4380)$ is a genuine resonance or a proxy for interference of the $P_c(4450)$ with unspecified amplitudes.

What follows will be a theoretical discussion which can account for the $P_c(4450)$ as a bound state of a charmed baryon $\Sigma_c(2453)$ and anticharmed meson $\bar{D}^*(2007)$ but is at a loss to explain the $P_c(4380)$.

DOUBLY-HEAVY MOLECULES

In the past 12 years, evidence has accumulated for molecular states of heavy mesons with a charmed or bottom quark shallowly bound to mesons with an anticharm or antibottom quark:

State (mass)	Constituents
$X(3872)$	$D^0\bar{D}^{*0}$+ c.c.
$Z_c(3900)$	$D\bar{D}^*$+ c.c.
$Z_c(4020/4025)$	$D^*\bar{D}^*$
$Z_b(10610)$	$B\bar{B}^*$+ c.c.
$Z_b(10650)$	$B^*\bar{B}^*$

With M. Karliner, generalized this behavior to any hadron pair each containing a heavy quark which can attract one another via pion exchange.

The absence of $D\bar{D}$ and $B\bar{B}$ bound states is due to the absence of $DD\pi$ or $BB\pi$ couplings. Molecular picture of $P_c(4450)$ is supported by this as well as by its narrow width despite very large phase space for decay to quarkonium + pion(s) with BR($J/\psi\ p$) $\ll$ BR for “fall apart decay”

CONDITIONS FOR RESONANCE

The state contains two heavy hadrons. They have to be heavy, as the repulsive kinetic energy is inversely proportional to the reduced mass.

The two hadrons carry isospin, so that they can couple to pions. Channels like $\Sigma_c \bar{\Lambda}_c$, in which one of the particles has zero isospin, can exchange a pion to become the equal-mass channel $\Lambda_c \bar{\Sigma}_c$.

The spin and parity of the two hadrons have to be such that they can bind through single pion exchange.

The hadrons making up the molecule have to be sufficiently narrow, as the molecule's width cannot be smaller than the sum of its constituents' widths.

For pion exchange between states 1 and 2 with isospins $I_{1,2}$ and spins $S_{1,2}$, the effective potential is
$V \sim \pm(I_1 \cdot I_2)(S_1 \cdot S_2)$ for $(qq, q\bar{q})$ interactions

MOLECULAR THRESHOLDS

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	S-wave J^P	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	1^+	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$0^+, 1^+, 2^+$	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$0^+, 1^+, 2^+$	$B_c^+\omega$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	1^+	$\Upsilon(nS)\omega$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$0^+, 1^+, 2^+$	$\Upsilon(nS)\omega$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$1/2^-, 3/2^-$	$J/\psi\,p$ $\Leftarrow$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	$1/2^-, 3/2^-$	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	$1/2^-, 3/2^-$	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$1/2^-, 3/2^-$	$\Upsilon(nS)p$ $\Leftarrow$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$0^-, 1^-$	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$0^-, 1^-$	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$0^-, 1^-$	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$0^-, 1^-$	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$0^-, 1^-$	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$0^-, 1^-$	$\Upsilon(nS)\pi\pi$

States $\rightarrow$ $J/\psi\ p$ and $\Upsilon(nS)p$ can be photoproduced

$\gamma p \to X \to J/\psi\ p$

Assume photoproduction of a $J/\psi\ p$ resonance X is dominated by the elastic process $J/\psi\ p \to X \to J/\psi\ p$

Estimate photon-J/ψ coupling from the J/ψ leptonic width: $\Gamma(J/\psi \to \ell^+\ell^-) = 5.55 \pm 0.14 \pm 0.02$ keV

Breit-Wigner cross section for production of a resonance with spin J by particles of spins S_1 and S_2 is

$$\sigma_{BW}(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k_{\rm in}^2} \frac{B_{\rm in}B_{\rm out}(\Gamma_{\rm tot}^2/4)}{(E-E_R)^2+(\Gamma_{\rm tot}^2/4)}$$

k = CM 3-momentum, E = total CM energy, E_R = resonance energy, $B_{\rm in}$ and $B_{\rm out}$ = resonance branching fractions into the incoming and outgoing channels; $\Gamma_{\rm tot}$ = resonance total width. For $E_R = (4380, 4450)$ MeV, $k_{\rm in}^{A,B} = (2090, 2126)$ MeV; $k_{\rm out}^{A,B} = (741, 820)$ MeV.

$B_{\rm in}/B_{\rm out} = 1.24 \times 10^{-3}$ for 4450 (take S-wave $J/\psi\ p$)

CROSS SECTION

$\sigma_{BW}(E) = \frac{C_R(B_{\rm out})^2(k_{\rm in}^R/k_{\rm in})^2(\Gamma_{\rm tot}^2/4)}{(E-E_R)^2+(\Gamma_{\rm tot}^2/4)}$; $C_R \equiv \frac{2J_R+1}{4}\frac{4\pi}{(k_{\rm in}^R)^2}\frac{B_{\rm in}}{B_{\rm out}}$

In our model, $P_c(4450) \equiv X_B$ has $J^P = 3/2^-$ while $P_c(4380) \equiv X_A$ has $J^P = 5/2^+$. Consider X_B for now.

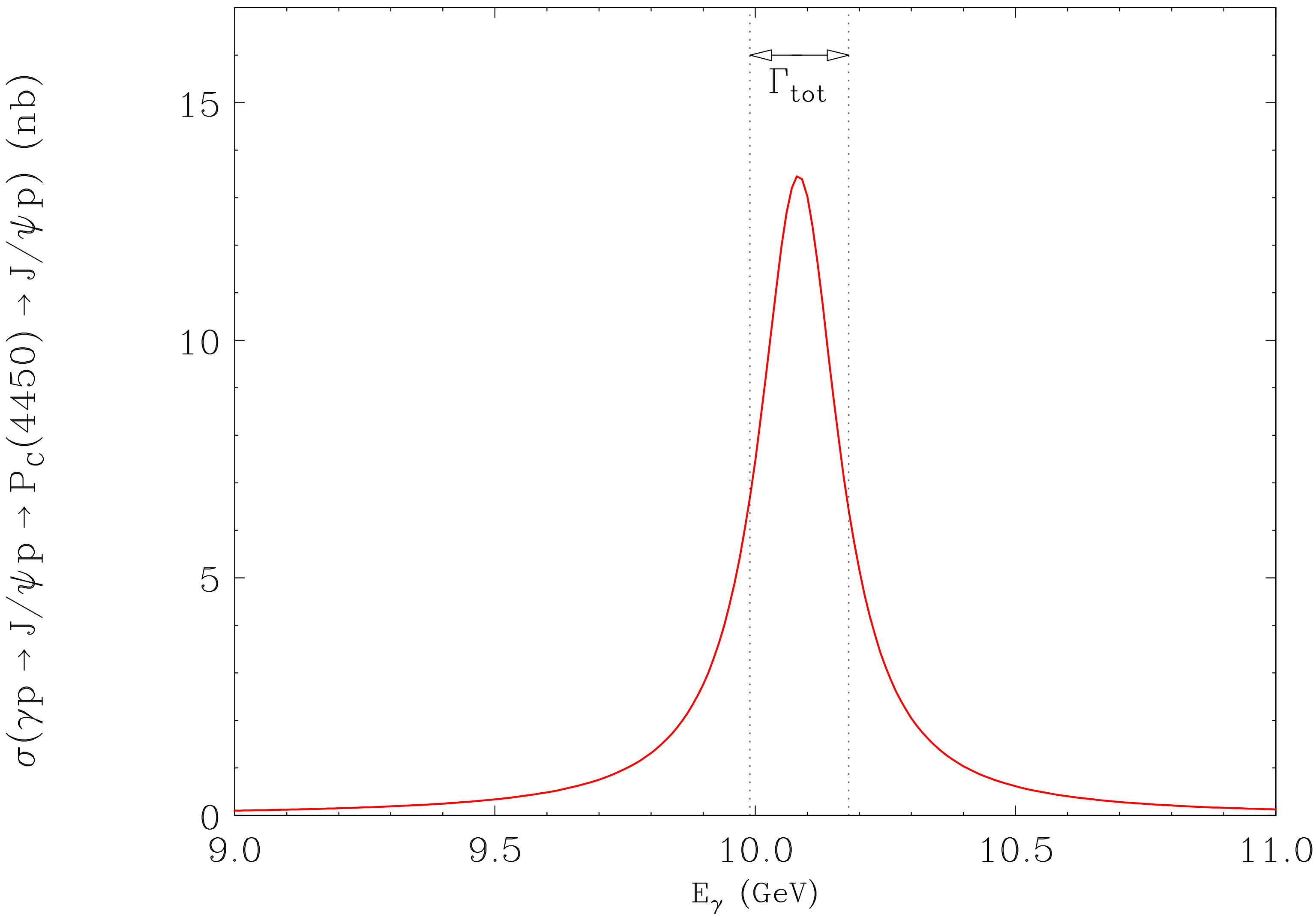
Then $C_B = 1.35\mu$b: substantial compared with diffractive $\sigma(\gamma p \to J/\psi p) < 1$ nb at $E = 4.4$ GeV

Branching ratios of Z_b states to $\Upsilon(nS) + \text{pion(s)}$ are less than a percent despite much larger phase space than for pair of $B^{(*)}$ mesons, suggesting $B_{\rm out} \ll 1$.

We shall take $B_{\rm out} = 0.1$ as a nominal value and rescale predicted cross sections accordingly.

Peak cross section for $\gamma p \to P_c(4450) \to J/\psi\ p$ is then (13.5 nb)$(B_{\rm out}/0.1)^2$

P_c CROSS SECTION IN LAB



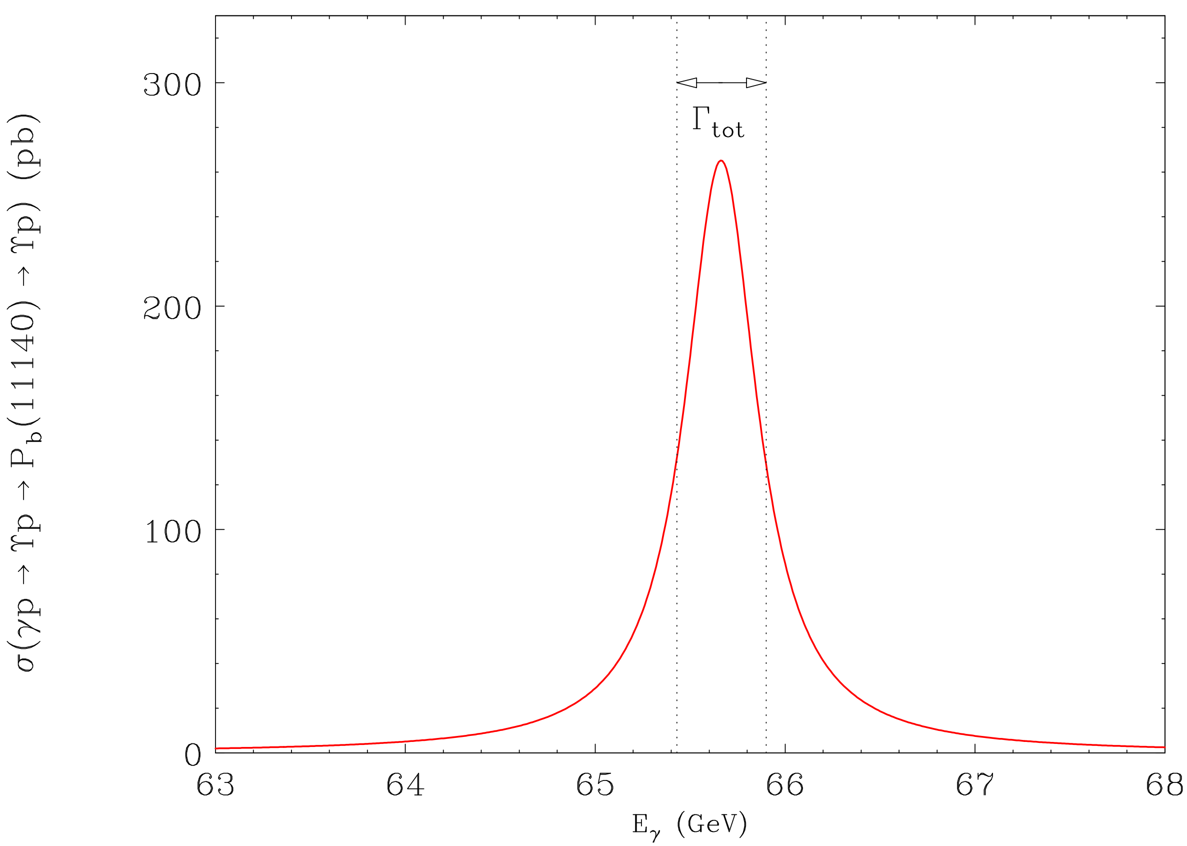
JLAB can achieve photon energy resolution sufficient to trace out resonance peak or set useful upper limits on $B_{\rm out}$

$\gamma p \to X \to \Upsilon p$

Similar calculation implies $B_{\rm in}/B_{\rm out} = 1.66 \times 10^{-4}$.

Photoproduction of $J{=}3/2$ resonance at $\Sigma_b B^*$ threshold:

$$\sigma_{BW}(E) = \frac{C_R (B_{\rm out})^2 (k_{\rm in}^R/k_{\rm in})^2 (\Gamma_{\rm tot}^2/4)}{(E-E_R)^2 + (\Gamma_{\rm tot}^2/4)}\ , \quad C_R \equiv \frac{2J+1}{4}\,\frac{4\pi}{(k_{\rm in}^R)^2}\,\frac{B_{\rm in}}{B_{\rm out}} = 26.6\ {\rm nb}$$



$\sigma(\gamma p \to X(11.14) \to \Upsilon p)$ assuming $B_{\rm out} = 0.1$

Scales as $(B_{\rm out})^2$

Could be sought in HERA electroproduction

Any LHC experiment could look for Υp resonances

SUMMARY

LHCb has announced two new resonances: $P_c(4380)$ (broad) and $P_c(4450)$ (narrow), decaying to $J/\psi\ p$

Favored spins and parities: $3/2^{\pm}$ for one; $5/2^{\mp}$ for other

Seen in 26K $\Lambda_b \to K^- p J/\psi$ events with low background

Dalitz plot is largely populated by $\Lambda^* = K^- p$ resonances, making me suspicious of the claim for the broad state

Argand plot healthy for $P_c(4450)$, less so for $P_c(4380)$

Marek Karliner and I have interpreted $P_c(4450)$ as a $\Sigma_c \bar{D}^*$ molecule, predicting a similar state near 11140 MeV (the $\Sigma_b B^*$ threshold) and an experimental bonanza of additional states (see Table). $P_c(4380)$ may be a more tightly bound pentaquark with more favored decay to $J/\psi p$.