HEAVY-QUARK EXOTICS

J. Rosner (University of Chicago) – Kyoto, June 15, 2018

New Frontiers in QCD 2018: Recent Developments in Quark-Hadron Sciences

1964: M. Gell-Mann and G. Zweig proposed that the known mesons were $q\bar{q}$ and baryons qqq, with quarks known at the time u ("up"), d ("down"), and s ("strange") having charges (2/3,–1/3,–1/3). Mesons and baryons would then have integral charges.

Mesons such as $qq\bar{q}\bar{q}$ and baryons such as $qqqq\bar{q}$ would also have integral charges. Why weren't they seen?

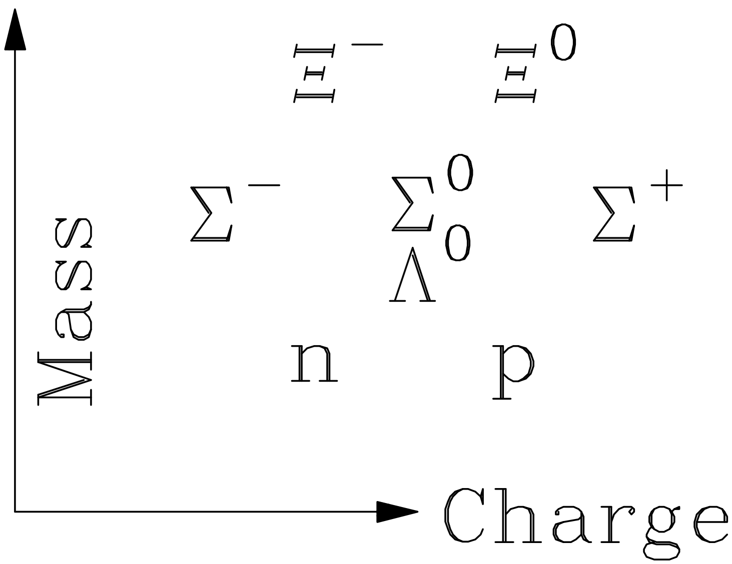
They *have* now been seen, as "molecules" of heavy-quark hadrons or as deeply bound states involving heavy quarks (charm and bottom).

Charm-anticharm and bottom-antibottom molecules; "pentaquark" as a charmed meson – baryon molecule; $\Xi_{cc}^{++} = ccu$ as the first doubly charmed baryon; ccs mass; stable $bb\bar{u}\bar{d}$ tetraquark; quark fusion

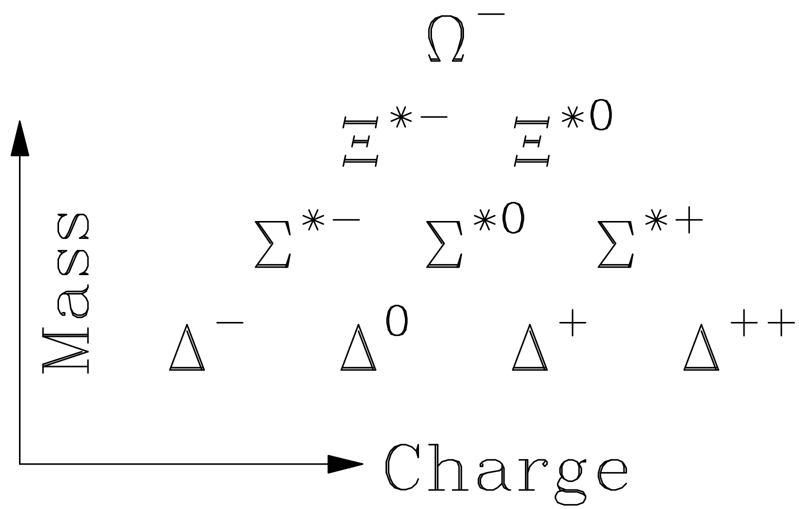
Thanks to Marek Karliner and Michael Gronau for many enjoyable collaborations on these and other topics. Bibliography at end has many references. Recent: M. Karliner, T. Skwarnicki, JLR, arXiv:1711.10626

THREE-QUARK BARYONS

Octet (spin 1/2)



Decuplet (spin 3/2)



$p = uud, \; n = udd$ $\qquad$ $\Delta^{++} = uuu, \; \Omega^- = sss$

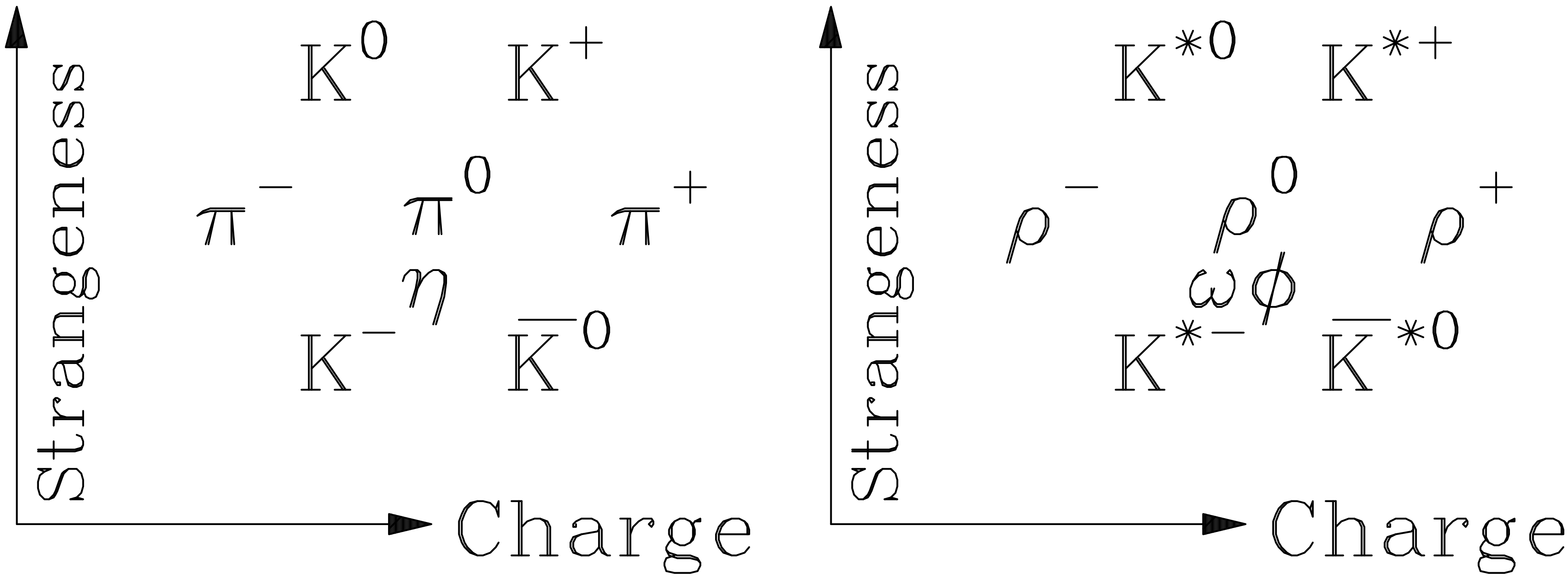
u, d, s have charges 2/3,–1/3,–1/3 and strangeness 0,0,–1

No $qqqq\bar{q}$ baryons seen made of just these three quarks

"Pentaquark" $uudd\bar{s}$ at 1540 MeV decaying to K^0p or K^+n claimed in early 2000's; not confirmed subsequently

QUARK-ANTIQUARK MESONS

Octet (spin 0) Nonet (spin 1)



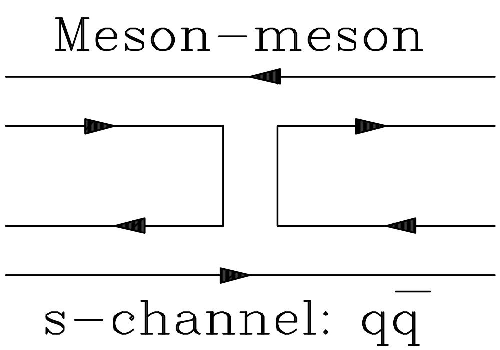
$\pi^+ = u\bar{d}$, $K^+ = u\bar{s}$ $\rho^+ = u\bar{d}$, $K^{*+} = u\bar{s}$

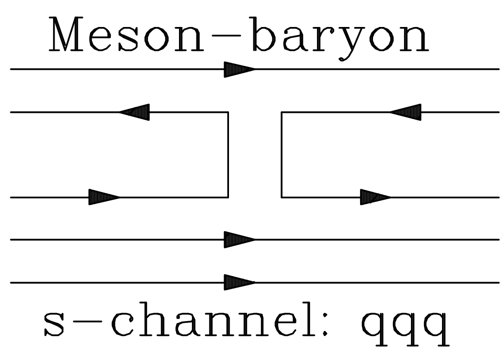
No resonances made of u, d, s seen which would correspond to $qq\bar{q}\bar{q}$ but not $q\bar{q}$ (e.g., $uu\bar{d}\bar{s}$ decaying to $K^+\pi^+$)

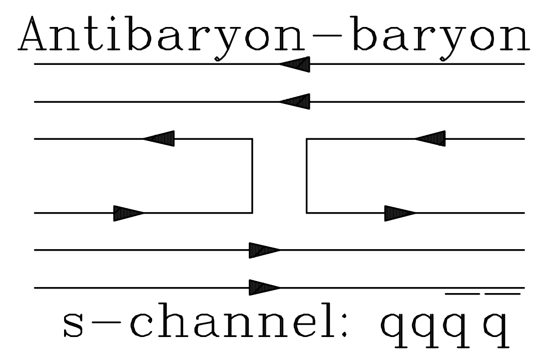
Situation changes with heavy quarks c (charm), b (bottom)

EARLY HINT OF EXOTICS

Processes "dual" (JLR, 1968) to t-channel $q\bar{q}$ exchange:





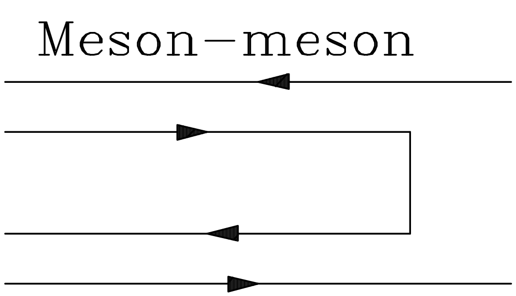


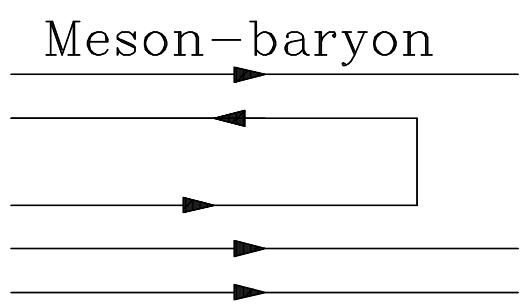
s-channel resonances $\Leftrightarrow$ t-channel Regge trajectories

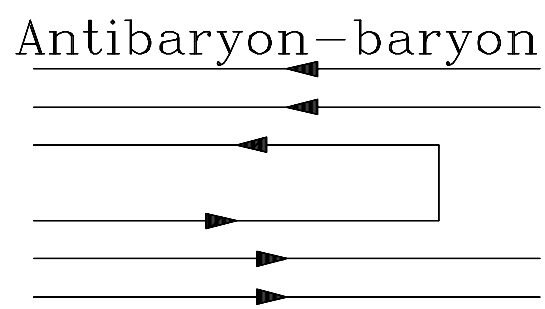
In antiproton-proton scattering, $q\bar{q}$ dual to $qq\bar{q}\bar{q}$

Predicts "exotic" $qq\bar{q}\bar{q}$ mesons, but where?

Do resonances form via $q\bar{q}$ annihilation? (JLR, 1972):

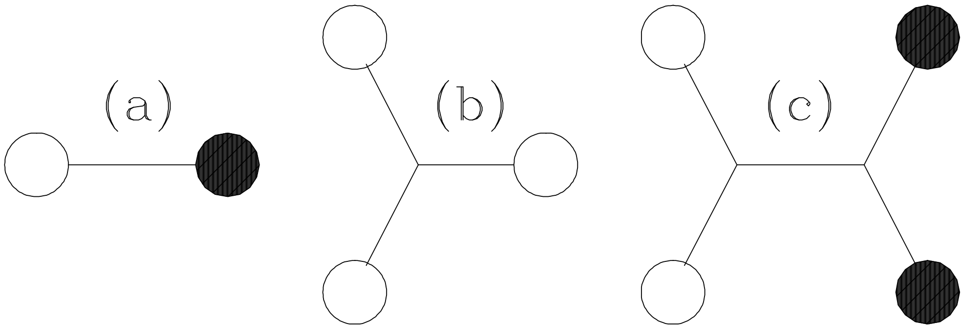






$p^* \leq 350$ MeV$/c$ $\quad$ $p *^{\leq} 250$ MeV$/c$ $\quad$ $p^* \leq 200$ MeV$/c$?

BARYON-ANTIBARYON EXOTICS



(a) $q\bar{q}$: Standard meson

(b) qqq: Standard baryon

(c) $qq\bar{q}\bar{q}$: Exotic meson

Freund-Waltz-JLR 1969, Imachi + 1974-7, Rossi-Veneziano 1977: decays occur via quark pair production (breaking of QCD string) $\Rightarrow qq\bar{q}\bar{q} \rightarrow$ baryon-antibaryon

Don't see meson + baryon $\rightarrow$ baryon + (exotic meson)

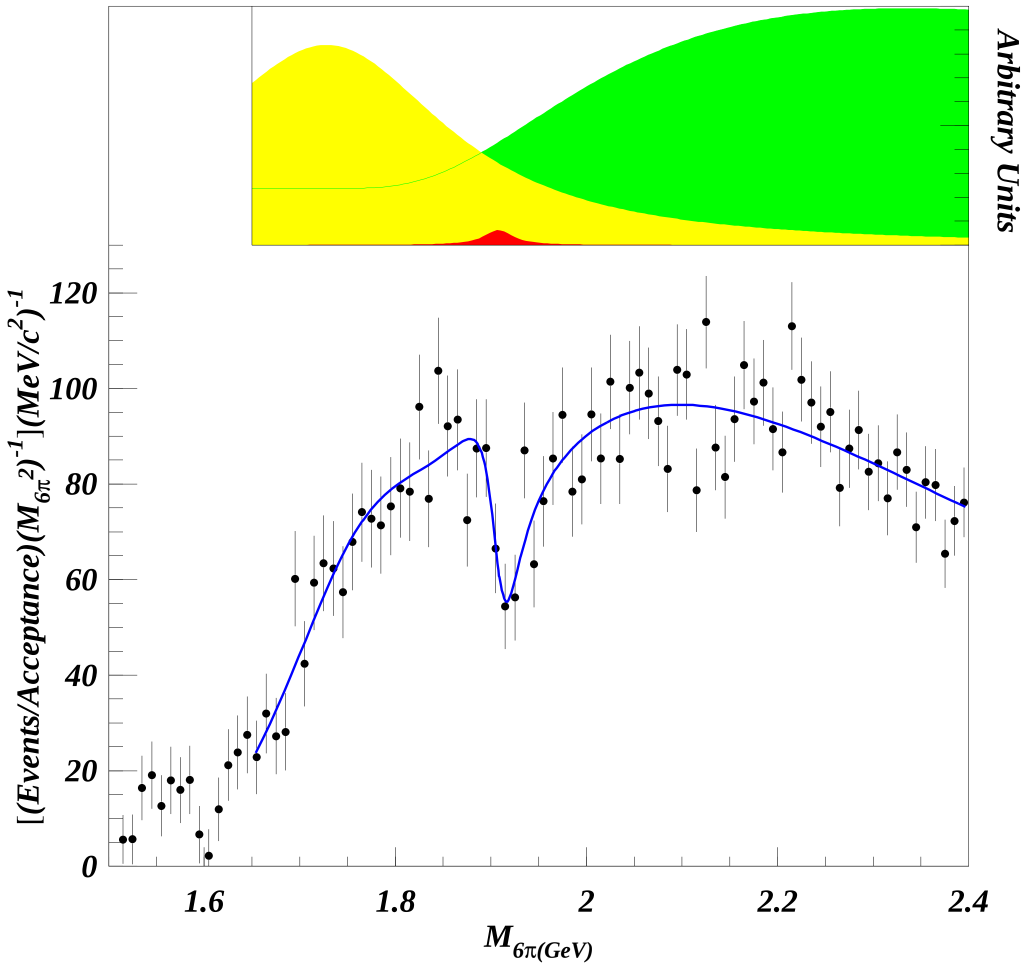
Such exotics may fall apart into meson pairs and may be too broad to show up as distinct resonant peaks

R. Jaffe (1976-8): extensive study of $qq\bar{q}\bar{q}$ states within bag model of QCD; light diquark-antidiquark states could be familiar ones with masses of a GeV or less

First "baryonium" candidate: the pion (Fermi-Yang 1949)

$p\bar{p}$ THRESHOLD EFFECT

Fermilab E687: Dip in diffractive 6π photoproduction near $p\bar{p}$ threshold (shading: amplitudes w/o interference)

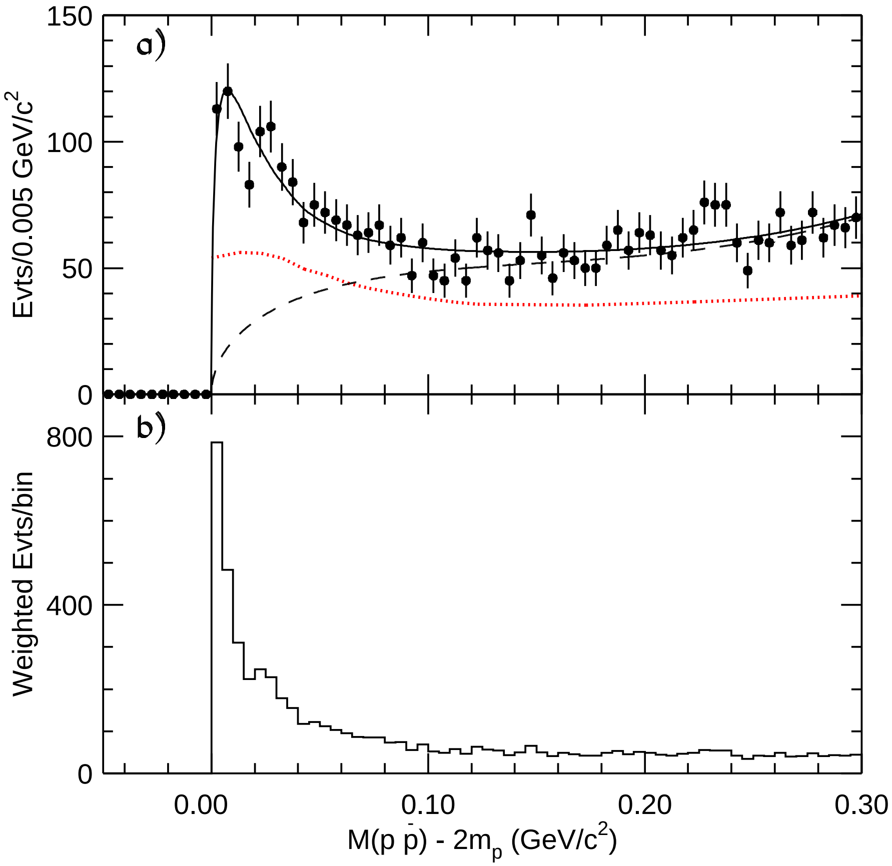


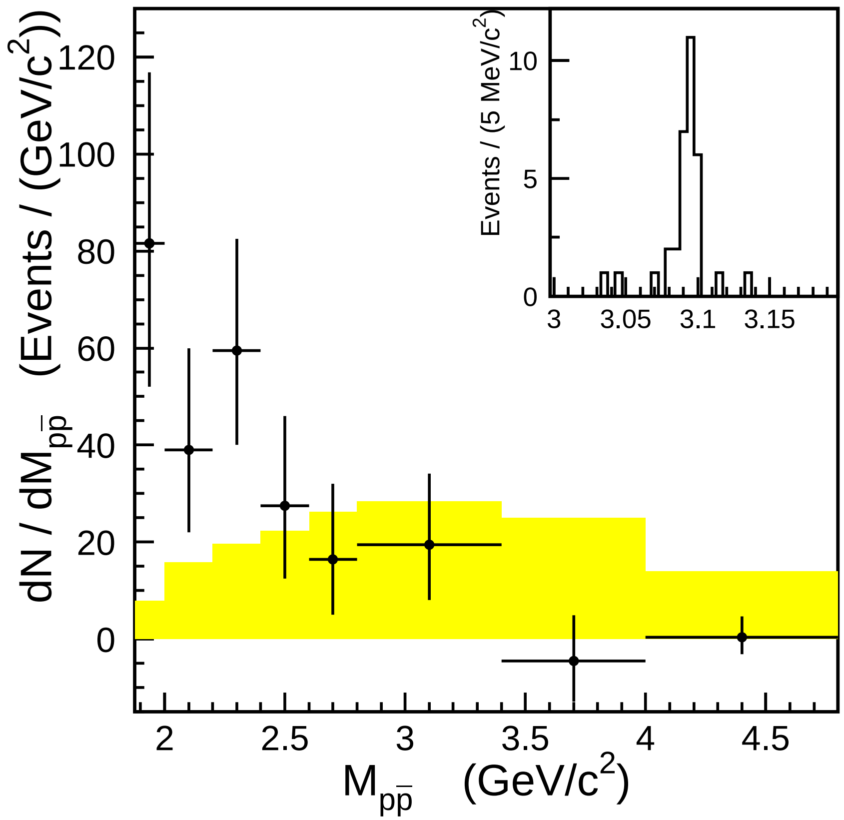
The $p\bar{p}$ channel is "robbing" the 6π channel; rapid variation suggests production in an S-wave, and coupling to a photon suggests a ${}^3S_1$ state: $J^{PC} = 1^{--}$

Similar behavior in $I = 0$ $\pi\pi$ S wave near 1 GeV when $K\bar{K}$ threshold opens up near $f_0(980)$

Solodov, Baldini (Bad Honnef, 4/18): Behavior in $e^+e^- \to$ (hadrons) near $p\bar{p}$, $\Lambda_c\bar{\Lambda}_c$ thresholds

BEHAVIOR NEAR $p\bar{p}$ THRESHOLD





BES: $M(p\bar{p})$ in $J/\psi \to \gamma p\bar{p}$ Belle: $M(p\bar{p})$ in $B^+ \to K^+ p\bar{p}$

Peak now seen also in $J/\psi \to \gamma\pi^+\pi^-\eta'$:
$M(\pi^+\pi^-\eta') = 1834 \pm 7$ MeV, $\Gamma = 68 \pm 21$ MeV

Solodov (CMD-3): Dip at $p\bar{p}$ threshold now also seen in $e^+e^- \to K^+K^-\pi^+\pi^-$

THE CHARMED QUARK

Leptons: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$ (no strong interactions)

1964: Bjorken–Glashow, ...: quark–lepton analogy;

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \Leftrightarrow \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}$$

Glashow–Iliopoulos–Maiani (1970): $m_c \simeq 2$ GeV$/c^2$;
Gaillard-Lee (1973): electroweak role of charmed quark

1974: Charmed quark c in $J/\psi = c\bar{c}$. $J =$ "Ting" (co-discoverer). *Charmonium* ($c\bar{c}$) spectrum is still evolving

Particles with one charmed quark: rich spectrum today

Large m_c: nonrelativistic QM provides some insights

3RD QUARK-LEPTON FAMILY

At the same time as charm: the τ lepton (M. Perl, 1974)

Quark-lepton analogy:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \Leftrightarrow \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Third lepton pair $(\nu_\tau, \tau^-) \Rightarrow$ third quark pair (t [top], b [bottom]), predicted by Kobayashi and Maskawa.

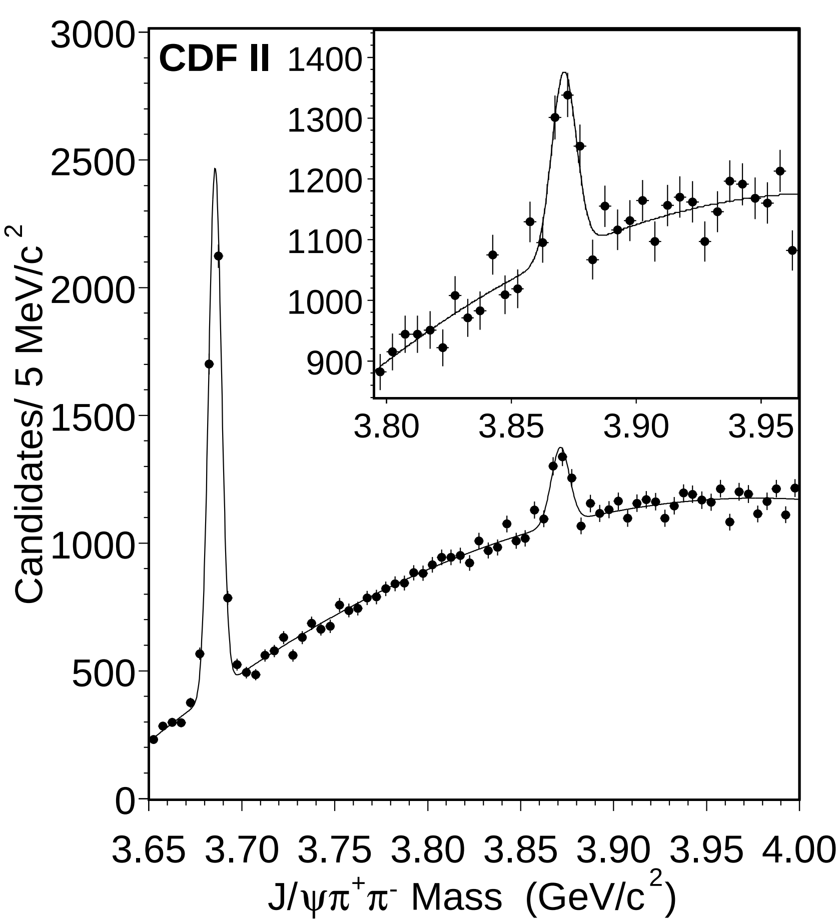
1977 (Fermilab): Υ family of spin–1 $b\bar{b}$ particles produced in proton-proton interactions, decaying to e^+e^-, $\mu^+\mu^-$

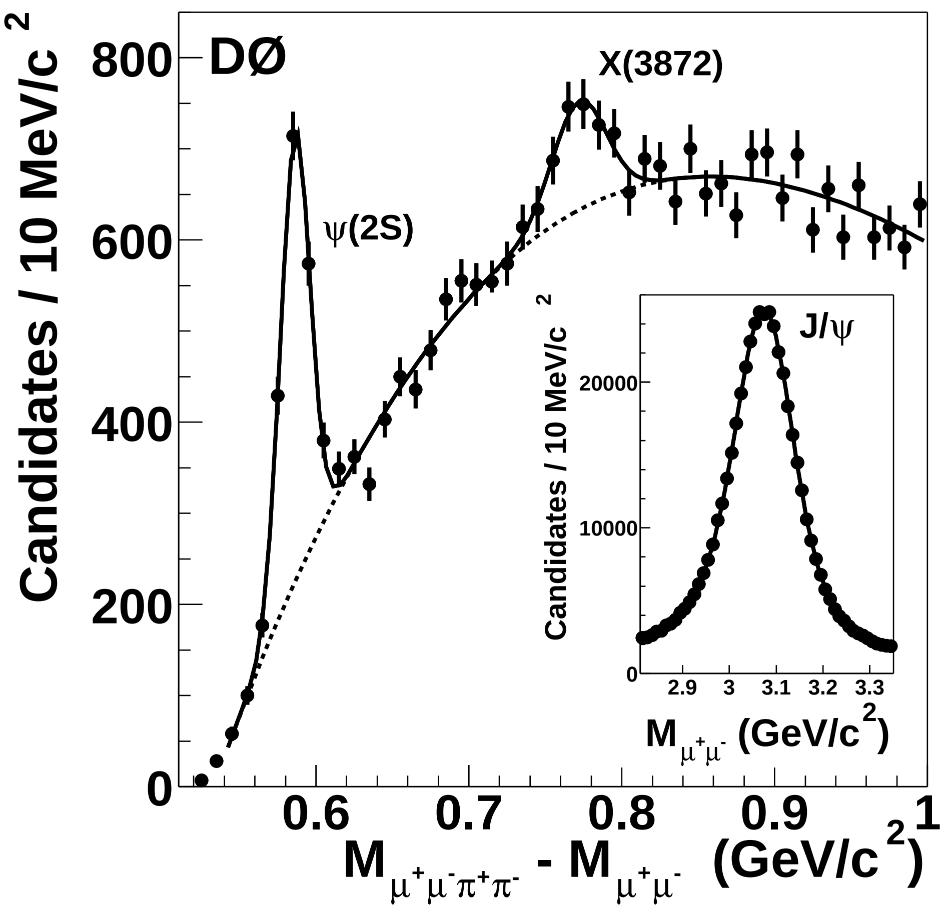
Rich $b\bar{b}$ spectroscopy; "B" mesons containing a single b quark. Decays of particles with b quarks: an active field.

Top (1994 at Fermilab Tevatron): mass $M_t \simeq 173$ GeV$/c^2$ large so decays too rapidly to have interesting spectroscopy

$X(3872)$: GENUINE EXOTIC

State decaying to $J/\psi\pi^+\pi^-$ discovered by Belle (2003) at 3872 MeV (shown with $\psi'(3686\ \mathrm{MeV})$); also seen by CDF (2004, left), D0 (2004, right), and BaBar (2008)





Within ~ 0.2 MeV of $D^0\bar{D}^{*0}$ threshold

$X(3872)$ PROPERTIES

$M(X) = (3871.69 \pm 0.17)$ MeV $\simeq M(D^0) + M(\bar{D}^{*0}) = (3871.68 \pm 0.07)$ MeV $\Rightarrow$ key role for that channel

Decay $X \to \gamma J/\psi$ seen; implies $C(X) = +$ and some admixture of $c\bar{c}$ in its wave function

Angular distribution of decay products implies $J^{PC} = 1^{++}$ as expected for S-wave state of $D^0 \bar{D}^{*0} + \mathrm{c.c.}$

C invariance $\Rightarrow C(\pi^+\pi^-) = - \Rightarrow \pi^+\pi^-$ in a ρ meson

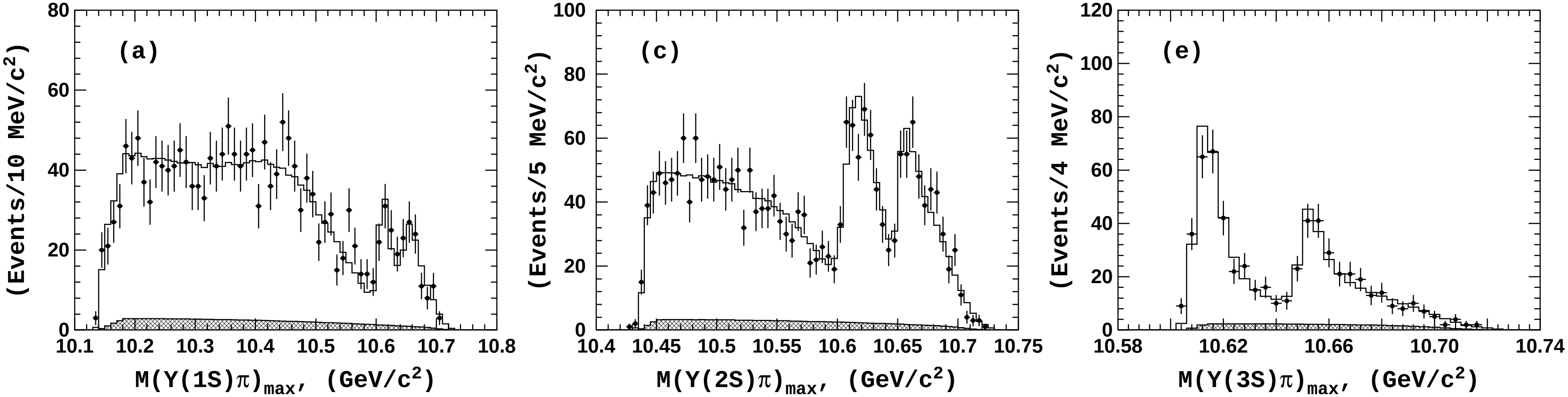
Large $M(D^{(*)+} - D^{(*)0}) \Rightarrow$ little $D^{(*)\pm}$ in wave function

$\Gamma(X \to \omega J/\psi)$ comparable to $\gamma(X \to J/\psi \rho)$, as one would expect for a state with $c\bar{c}u\bar{u}$ admixture

In addition to $X(3872)$ (mixture of 2^3P_1 $c\bar{c}$ state and $J^{PC} = 1^{++}$ $c\bar{c}u\bar{u}$ state) one expects an orthogonal mixture (potential models: probably > 3900 MeV)

THE BELLE $\Upsilon(nS)\pi$ PEAKS

Belle: $\Upsilon(10865) \rightarrow \Upsilon(1S, 2S, 3S)\pi^+\pi^-$ $\Rightarrow$ unexpected structures "$Z_b(10610, 10650)$" in $M[\pi^{\pm}\Upsilon(1S, 2S, 3S)]$



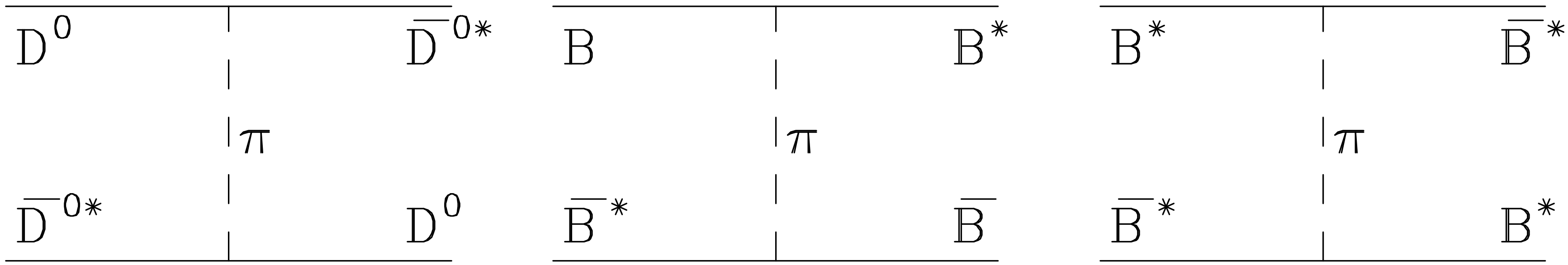
$M(\Upsilon(1S)\pi)$ $M(\Upsilon(2S)\pi)$ $M(\Upsilon(3S)\pi)$

All spectra: peaks at $M(\Upsilon(nS)\pi = 10.61$ and 10.65 GeV

Within a few MeV of $M(B)+M(\bar{B}^*)$ and $M(B^*)+M(\bar{B}^*)$

Looks like S-wave molecules of $B\bar{B}^*(+\mathrm{c.c.})$ and $B^*\bar{B}^*$

PION EXCHANGE AND $X_{c,b}$



$D^0\bar{D}^{*0}+\mathrm{c.c.}$ molecule $B\bar{B}^*+\mathrm{c.c.}$ molecule $B^*\bar{B}^*$ molecule

Pion doesn't couple to a pair of pseudoscalar mesons (P)

Implies no $D\bar{D}$ or $B\bar{B}$ molecules; doesn't preclude genuine $c\bar{c}$ or $b\bar{b}$ resonances slightly above threshold (e.g., $\Upsilon(4S)$)

Potential: $V \sim \pm(I_1 \cdot I_2)(S_1 \cdot S_2)$ for $(qq, q\bar{q})$ interactions

Expect $J^{PC} = 1^{++}$ X_b (analogue of $X(3872)$) to have $I = 0$ because $M(B^{(*)-}) \simeq M(B^{(*)0})$

Distinct from the Z_bs which have $I = 1$; expect $M(X_b) \sim$ 10562–10585 MeV ($\chi_b(3^3P_1)$?)(Karliner + JLR, PR D **91**)

V EXPECTATION VALUES

Most deeply bound $D\bar{D}^*$, $D^*\bar{D}^*$, $B\bar{B}^*$, $B^*\bar{B}^*$ states:

$D^*\bar{D}^*$ or $B^*\bar{B}^*$: $\langle I_1 \cdot I_2 \rangle = (-\frac{3}{4}, \frac{1}{2})$ for $I = 0, 1$;
$\langle S_1 \cdot S_2 \rangle = (-2, -1, 1)$ for $S = (0, 1, 2)$

Hence $\langle V \rangle = -(I_1 \cdot I_2)(S_1 \cdot S_2)$ for $D^*\bar{D}^*$ or $B^*\bar{B}^*$ is most attractive in the $I = S = 0$ channel

$Z_c(4020)$, $Z_b(10650)$ have $I = 1$; $\langle V \rangle < 0$ for $S = 2$; expect lower-mass $I = S = 0$ states

$D\bar{D}^*$, $B\bar{B}^*$: use basis (e.g.) $[D^0\bar{D}^{*0}, D^{*0}\bar{D}^0, D^+D^{*-}, D^{*+}D^-]$

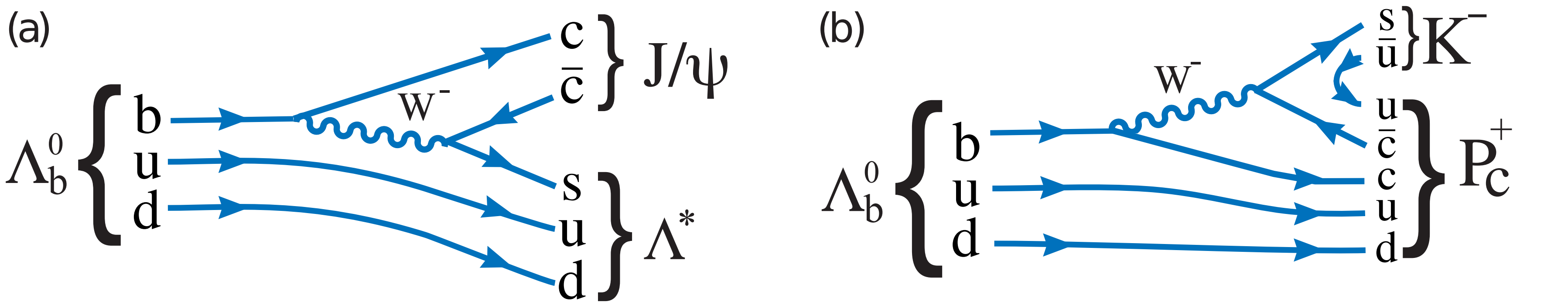
Eigenstates of potential have definite C, I

Most attractive channel with $\langle V \rangle = -3$ in some units has $C = +$, $I = 0$.

$Z_c(3900)$, $Z_b(10610)$ have $I = 1$; if their $\langle V \rangle < 0$ then it is 1/3 that for $C = +$, $I = 0$ state, and their $C = -$

PENTAQUARK P_c

LHCb (PRL **115**, 072001) sees bumps in $J/\psi\ p$ invariant mass in the decay $\Lambda_b \to K^- J/\psi\ p$ at 4380 and 4450 MeV



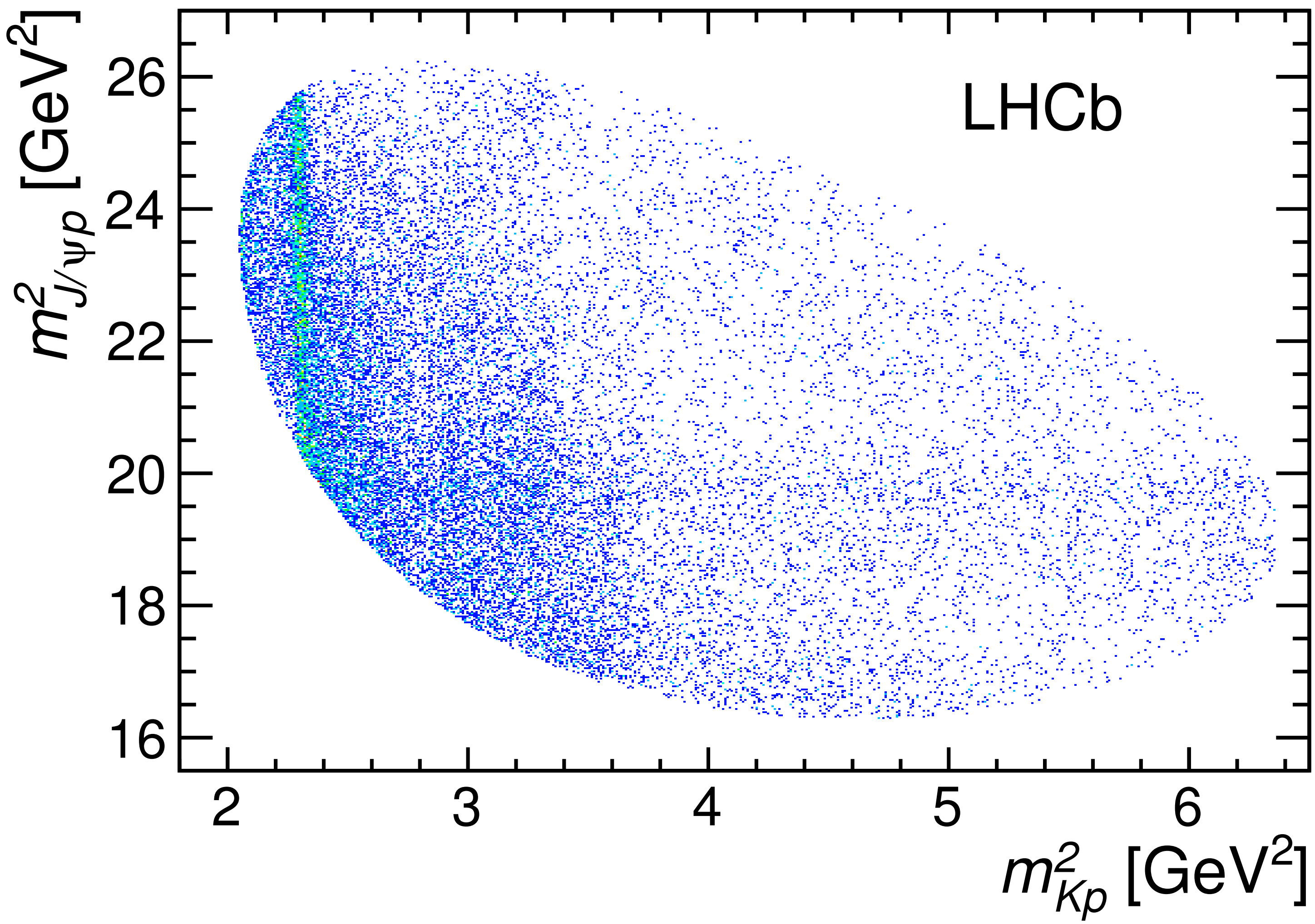
Λ^* excitation $\qquad$ P_c excitation

Dalitz plot: many $K^- p$ resonances (all $I = 0$: $b \to c\bar{c}s$ is $\Delta I = 0$). May be missing high-$M(K^- p)$ states.

Prominent narrow band at $M(J/\psi\ p) = 4449.8 \pm 1.7 \pm 2.5$ MeV with fitted width $\Gamma = 39 \pm 5 \pm 8$ MeV

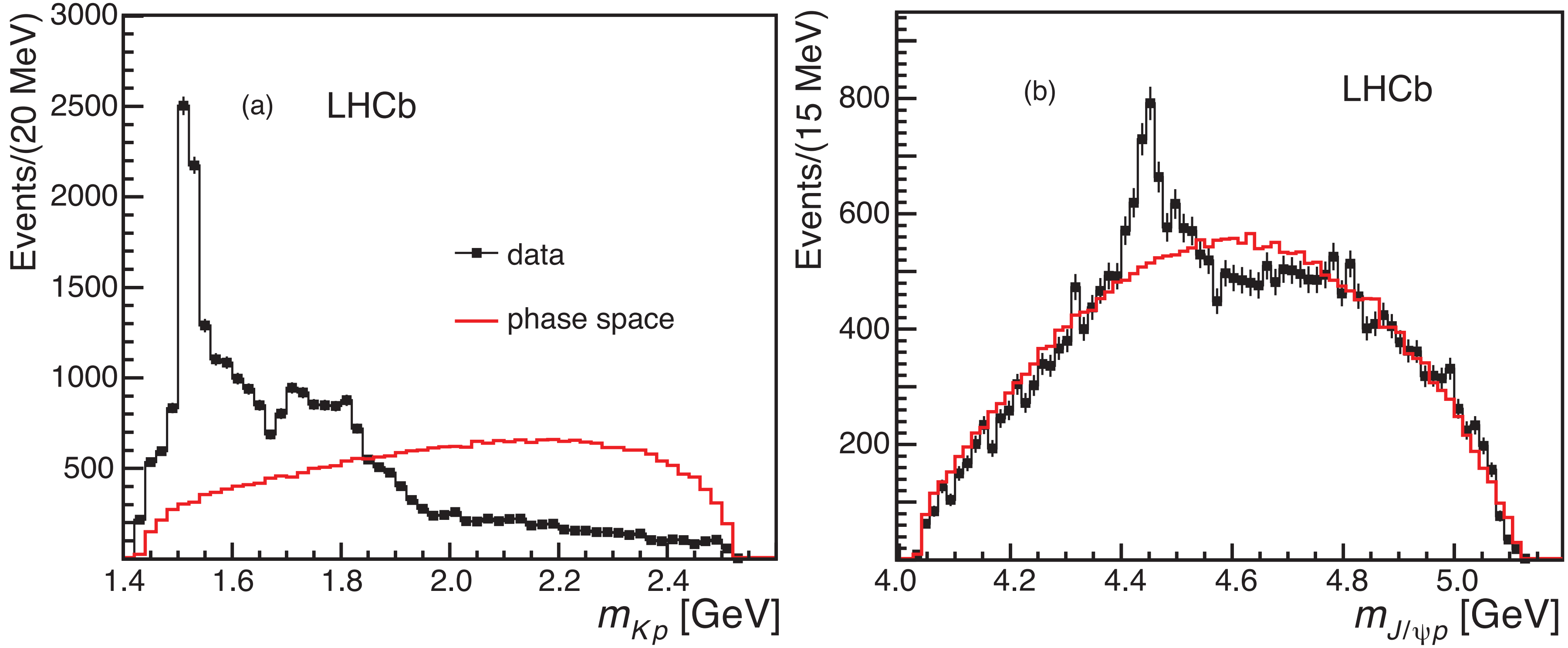
Karliner + JLR (PRL 115, 122001): Pion exchange binds $\Sigma_c(2453)$ and $D^*(2010)$ into a near-threshold bound state

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



Asymmetric behavior along $M(J/\psi\ p)$ band indicates interference with an opposite-parity state

AN INTERPRETATION

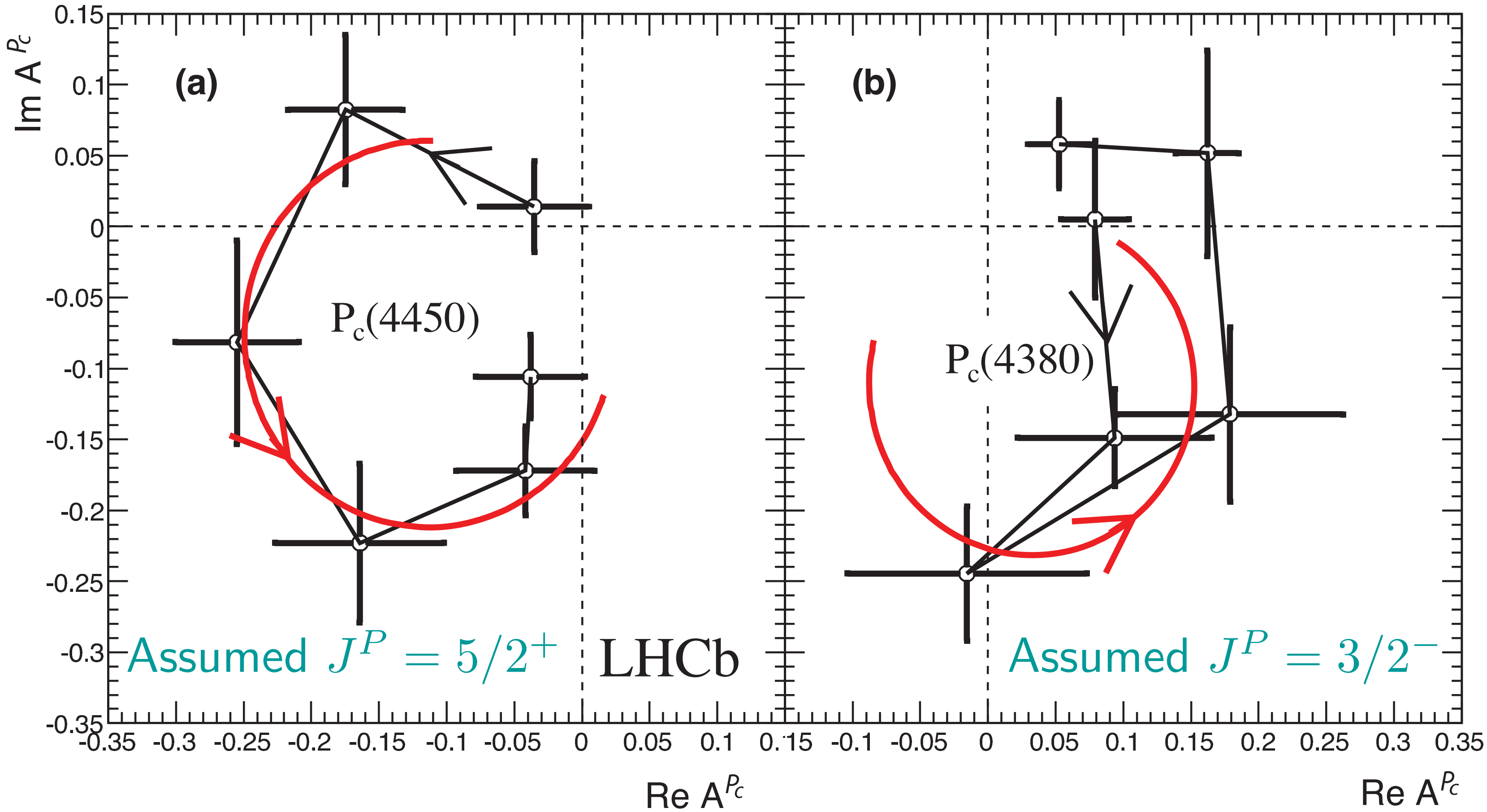


Red curves: phase space. Λ^* resonances at low $M(K^-p)$

Peak at $M(J/\psi\ p) \simeq 4450$ MeV: could be a $\Sigma_c \bar{D}^*$ S-wave bound state with $J^P = 3/2^-$; quark content $= c\bar{c}uud$

Further structure fitted by LHCb with resonance $P_c(4380)$ ($\Gamma \simeq 205$ MeV) with opposite parity to $P_c(4450)$

ARGAND PLOTS



$P_c(4450)$: classic resonant behavior; $P_c(4380)$ anomalous

No obvious molecular explanation for $P_c(4380)$

$\Sigma_c^*(2520)\bar{D}^*(2010)$ channel *above* the $P_c(4450)$ interfering *destructively* with a suitable background? (P?)

BARYONS WITH > 1 HEAVY QUARK

So far: $Q\bar{Q}q\bar{q}'$ or $Q\bar{Q}qqq'$ ($Q =$ heavy, $q, q' =$ light). Can we predict masses of (simpler) $QQ'q$ systems?

SELEX at Fermilab (2002-5) claimed $\Xi_{cc}^{++}(3520) = ccu$ and $\Xi_{cc}^{+}(3460) = ccd$; not confirmed by others

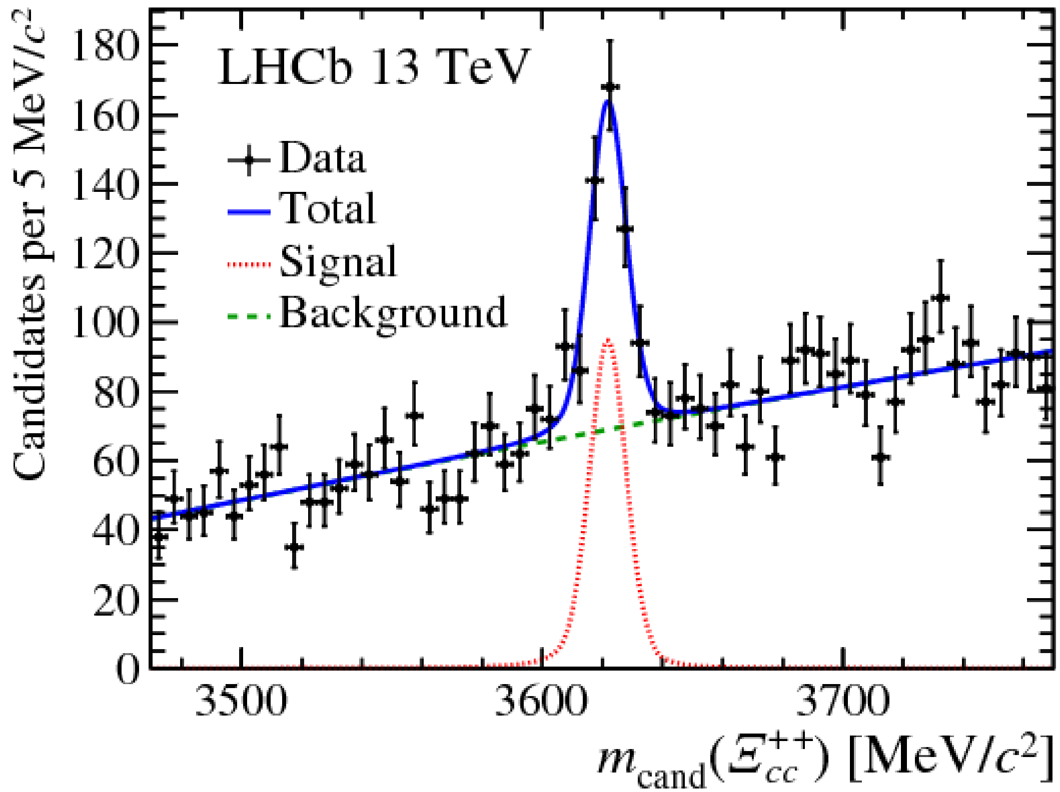
M. Karliner + JLR (PR D **90**): Constituent-quark masses, hyperfine splittings, estimates of QQ' binding ($q = u, d$):

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	–
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb PRL **119**, 112001: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV

Other estimates (> 30): spread of at least 100 MeV

$\Lambda_c K^- \pi^+ \pi^+$ SPECTRUM



Similar peak seen in 8 TeV data; no $\Lambda_c K^- \pi^+$ peak

We predicted $\tau(\Xi_{cc}^{++,+}) = (\mathbf{185}, 53)$ fs; $\Lambda_c K^- \pi^+$ peak disfavored by LHCb lifetime cut $\tau > 150$ fs

LHCb (Novosibirsk, 5/22): $\tau(\Xi_{cc}^{++}) = 256^{+24}_{-22} \pm 14$ fs

INPUTS

Describe ground-state baryons containing u, d, s taking $m_u^b = m_d^b \equiv m_q^b = 363$ MeV, $m_s^b = 538$ MeV, and hyperfine interaction term $a/(m_q^b)^2 = 50$ MeV

State (mass in MeV)	Spin	Expression for mass	Predicted mass (MeV)
$N(939)$	1/2	$3m_q^b - 3a/(m_q^b)^2$	939
$\Delta(1232)$	3/2	$3m_q^b + 3a/(m_q^b)^2$	1239
$\Lambda(1116)$	1/2	$2m_q^b + m_s^b - 3a/(m_q^b)^2$	1114
$\Sigma(1193)$	1/2	$2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$	1179
$\Sigma(1385)$	3/2	$2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$	1381
$\Xi(1318)$	1/2	$2m_s^b + m_q^b + a/(m_s^b)^2 - 4a/m_q^b m_s^b$	1327
$\Xi(1530)$	3/2	$2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_q^b m_s^b$	1529
$\Omega(1672)$	3/2	$3m_s^b + 3a/(m_s^b)^2$	1682

Describe mesons with quark masses $m_{u,d,s}^m \sim 55$ MeV less

$M(\Lambda_{c,b}) - M(\Lambda) \Rightarrow m_{c,b}^b = (1710.5, 5043.5)$ MeV

CHARMED & BOTTOM BARYONS

Above choices of mass sufficient to describe nonstrange baryons with one c or b quark

When taking account of deeper cs or bs binding in baryons with one or two strange quarks and one charm or bottom fit all baryons with one c or b

Charmed baryons			Bottom baryons		
State (M in MeV)	Spin	Predicted M (MeV)	State (M in MeV)	Spin	Predicted M (MeV)
$\Lambda_c(2286.5)$	1/2	Input	$\Lambda_b(5619.5)$	1/2	Input
$\Sigma_c(2453.4)$	1/2	2444.0	$\Sigma_b(5814.3)$	1/2	5805.1
$\Sigma_c^*(2518.1)$	3/2	2507.7	$\Sigma_b^*(5833.8)$	3/2	5826.7
$\Xi_c(2469.3)$	1/2	2475.3	$\Xi_b(5792.7)$	1/2	5801.5
$\Xi_c'(2575.8)$	1/2	2565.4	$\Xi_b'(-)$	1/2	5921.3
$\Xi_c^*(2645.9)$	3/2	2628.6	$\Xi_b^*(5949.7)$	3/2	5944.1
$\Omega_c(2695.2)$	1/2	2692.1	$\Omega_b(6046.4)$	1/2	6042.8
$\Omega_c^*(2765.9)$	3/2	2762.8	$\Omega_b^*(-)$	3/2	6066.7

HEAVY QUARK PAIR BINDING

Quark pair more deeply bound when neither is u or d

$B(c\bar{s}) = [3M(D_s^*) + M(D_s)]/4 - m_s^m - m_c^m = -69.9$ MeV

Assume $B(cs)/B(c\bar{s}) = 1/2$ as for single-gluon exchange

Then $B(cs) = -35$ MeV; also find $B(bs) = -41.8$ MeV

Rescale hyperfine interactions when neither quark is u or d; take a cue from $M(D_s^*) - M(D_s) \simeq M(D^*) - M(D)$

Now we are ready to deal with cc, cb, bb

Charm-anticharm binding: $B(c\bar{c}) = [3M(J/\psi) + M(\eta_c)]/4 - 2m_c^m = -258$ MeV, so $B(cc) = -129$ MeV

Similar calculations give $B(bb) = -281.4$ MeV and $B(bc) = -167.8 \pm 3.0$ MeV (uncertainty in B_c^* mass)

STABLE $bb\bar{u}\bar{d}$ TETRAQUARK

We looked at $QQ'\bar{u}\bar{d}$ systems ($Q = c$ or b) (PRL **119**)

We found $cc\bar{u}\bar{d}$ unbound; it could decay to DD^* or $DD\gamma$

Lowest-lying $bc\bar{u}\bar{d}$ state was near $BD\gamma$ threshold and we could not tell for sure whether it was bound or unbound

Predicted $M(bb\bar{u}\bar{d}) = 10,389 \pm 12$ MeV, 215 MeV below B^-B^{*0} threshold and 170 MeV below $B^-B^0\gamma$ threshold

Regard bb as a color-3^* diquark (transforming under QCD as an antiquark); fermi statistics require its spin to be 1

Lightest $\bar{q}\bar{q}'$ state $(q, q' = u, d)$ is a color-3 $\bar{u}\bar{d}$ state with isospin zero; fermi statistics require its spin to be zero

Mass prediction then relies on accounting for constituent-quark masses, hyperfine interactions, and binding effects

TETRAQUARKS $QQ'\bar{u}\bar{d}$

Contributions (MeV) to mass of lightest tetraquark:

$cc\bar{u}\bar{d},\ J^P = 1^+$		$bc\bar{u}\bar{d},\ J^P = 0^+$		$bb\bar{u}\bar{d},\ J^P = 1^+$	
Contribution	Value	Contribution	Value	Contribution	Value
$2m_c^b$	3421.0	$m_b + m_c$	6754.0	$2m_b^b$	10087.0
$2m_q^b$	726.0	$2m_q^b$	726.0	$2m_q^b$	726.0
cc hyperfine	14.2	bc hyperfine	-25.5	bb hyperfine	7.8
$-3a/(m_q^b)^2$	-150.0	$-3a/(m_q^b)^2$	-150.0	$-3a/(m_q^b)^2$	-150.0
cc binding	-129.0	bc binding	-170.8	bb binding	-281.4
Total	3882±12	Total	7134±13	Total	10389 ± 12

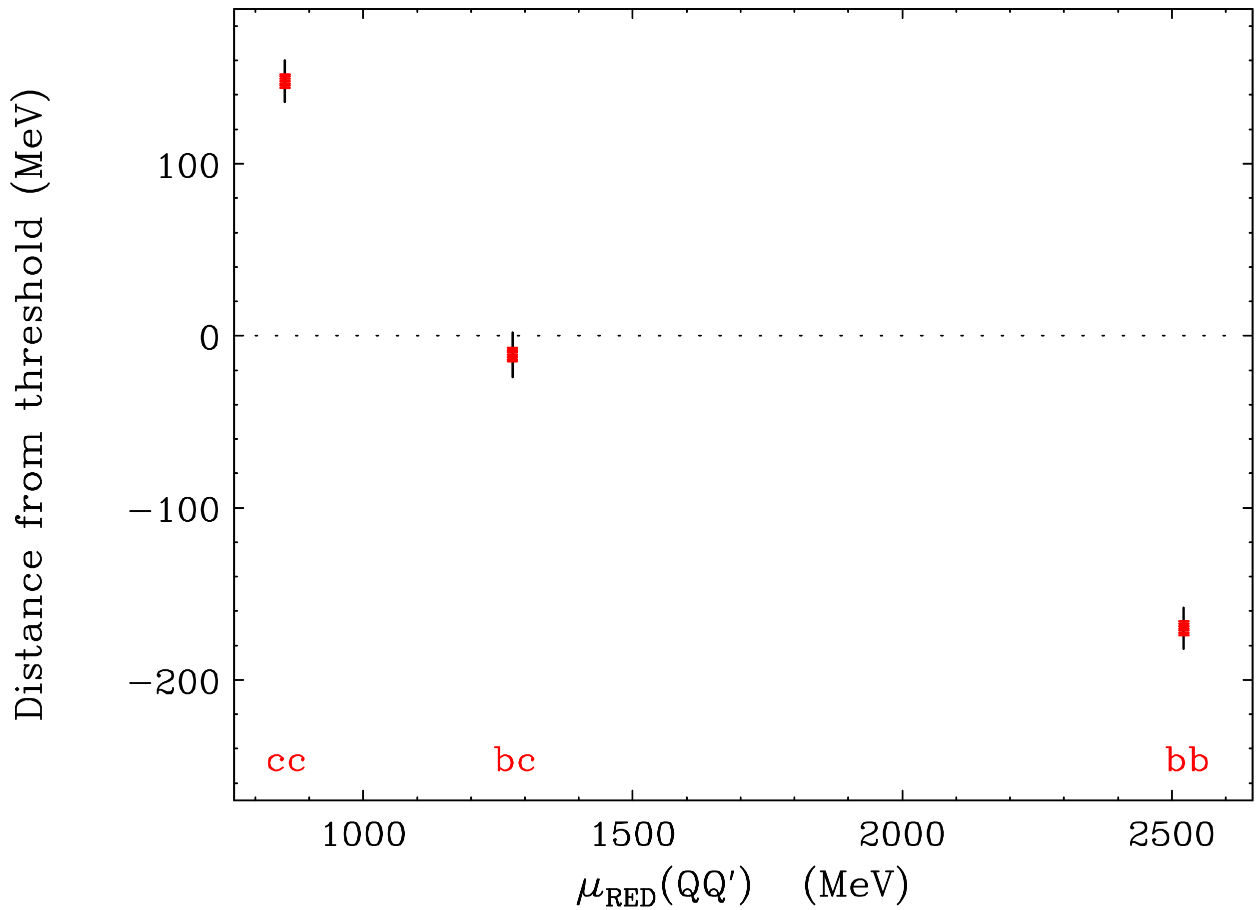
Spin zero allowed for the $bc\bar{u}\bar{d}$ state, taking advantage of the attractive bc hyperfine interaction

Since $M(cc\bar{u}\bar{d}) > M(D^0) + M(D^+) = 3734$ MeV, it can decay to $D^0D^+\gamma$ (decay to D^0D^+ is forbidden)

$M(bc\bar{u}\bar{d}) < M(D^0) + \bar{M}(B^0) = 7144$ MeV?

Estimated lifetime of $bb\bar{u}\bar{d}$ state: 367 fs

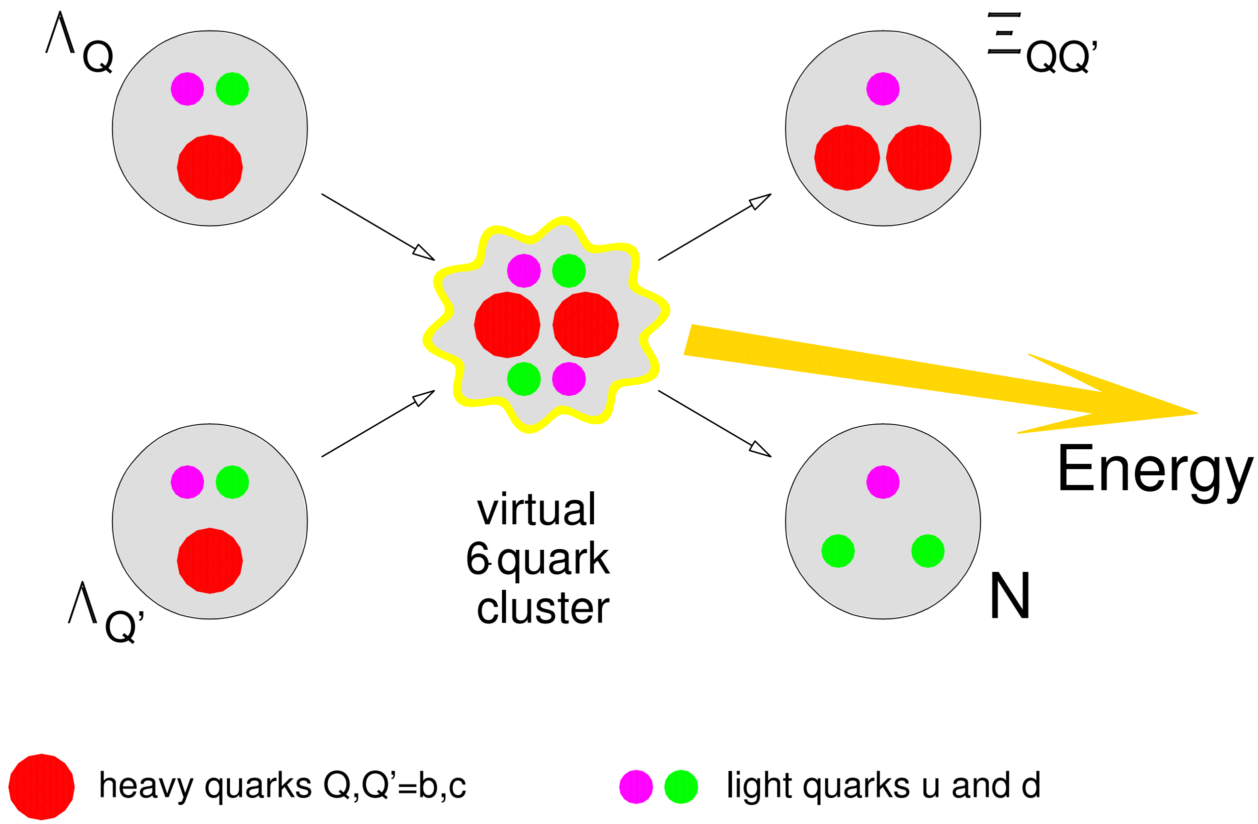
COMPARISON OF TQ MASSES



Distance in MeV of the $cc\bar{u}\bar{d}$, $bc\bar{u}\bar{d}$ and $bb\bar{u}\bar{d}$ tetraquark masses from corresponding thresholds $D^0 D^+ \gamma$, $\bar{B}^0 D^0$, and $\bar{B}^0 B^- \gamma$, plotted against reduced masses of the doubly-heavy diquarks $\mu(QQ')$, $Q, Q' = c, b$.

HEAVY QUARK FUSION

MK + JLR, *Nature* **551**, 89 (2017): $\Lambda_Q + \Lambda_{Q'} \to \Xi_{QQ'} + N$



Q, Q'	s, s	c, c	b, c	b, b
$\Xi_{QQ'}$	Ξ	Ξ_{cc}	Ξ_{bc}	Ξ_{bb}
ΔE (MeV)	-23	12	50	138 ± 12

$QQ\bar{Q}\bar{Q}$ STATES

M. Karliner, S. Nussinov, JLR: Masses, production, decays of $cc\bar{c}\bar{c}$ and $bb\bar{b}\bar{b}$ states (PR D **95**, 034011 (2017))

Compensate 55 MeV difference in effective quark masses in mesons and baryons with 165 MeV per "string junction"

$M_{(cc)(\bar{c}\bar{c})} = 6192 \pm 25$ MeV, 225 ± 25 MeV above $2M(\eta_c)$

$M_{(bb)(\bar{b}\bar{b})} = 18826 \pm 25$ MeV, 28 ± 25 MeV above $2M(\eta_b)$, could exhibit non-hadronic decays if estimate is $> 1\sigma$ high

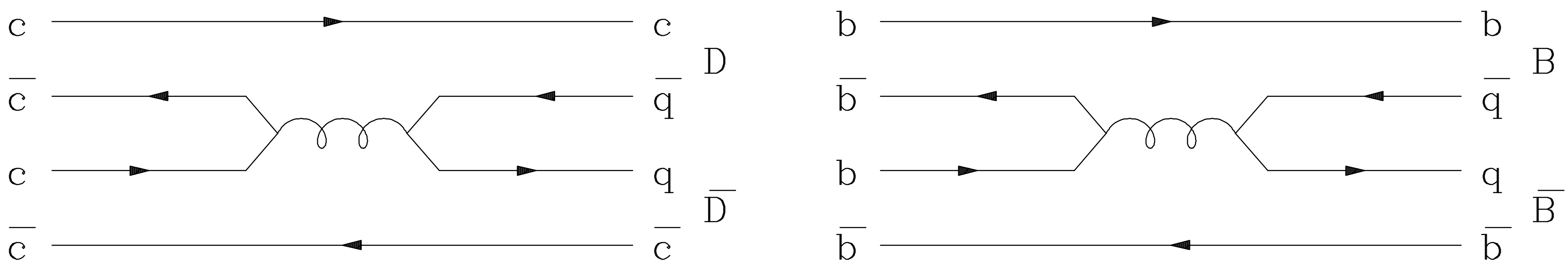
Hadronic production of an extra $Q\bar{Q}$: probability $\sim 0.1\%$

CMS (JHEP 05 (2017) 013): double $\Upsilon(1S)$ production; 38 events, each $\Upsilon \to \mu^+\mu^-$, [20.7 fb^{-1}, $\sqrt{s} = 8$ TeV]

S. Durgut (CMS, thesis, U. of Iowa, April 2018 APS Meeting): Excess in $\Upsilon(1S)\ell^+\ell^-$ at $18.5 \pm 0.1 \pm 0.2$ GeV

$QQ\bar{Q}\bar{Q}$ DECAY

If $M(0^+) < 2m(\eta_Q)$, main decay to flavored meson pair:



$Q\bar{Q} \to q\bar{q}$ partial width of α_s^2 order (tens of MeV)

Wave function overlap uncertain; could be very small

$$\sigma(pp \to X_{bb\bar{b}\bar{b}}[0^{++}] \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-) \leq 4\,\text{fb} \quad (\text{LHC},\ 13\ \text{TeV})\,;$$

upper limit attained only if little competition from

$$X_{bb\bar{b}\bar{b}}[0^{++}] \to B\bar{B}X\ .$$

PREDICTIONS FOR $\Omega_{cc} = ccs$

Strange quark is about 175 MeV heavier than nonstrange but more deeply bound to cc diquark than nonstrange

$\Xi_{cc} = ccq$		$\Omega_{cc} = ccs$	
Contribution	Value (MeV)	Contribution	Value (MeV)
$2m_c^b + m_q^b$	3789.0	$2m_c^b + m_s^b$	3959.0
cc binding	-129.0	cc binding	-129.0
$a_{cc}/(m_c^b)^2$	14.2	$a_{cc}/(m_c^b)^2$	14.2
$-4a/m_q^b m_c^b$	-42.4	$-4a'/m_s^b m_c^b$	-42.4
Total	3626.8 ± 12	Subtotal	3801.8 ± 12

Additional binding of s to cc: -109.4 ± 10.5 MeV, giving $M(\Omega_{cc}) = 3692 \pm 16$ MeV, $M(\Omega_{cc}^*) = 3756 \pm 16$ MeV

Superscripts on quark masses: value in a baryon

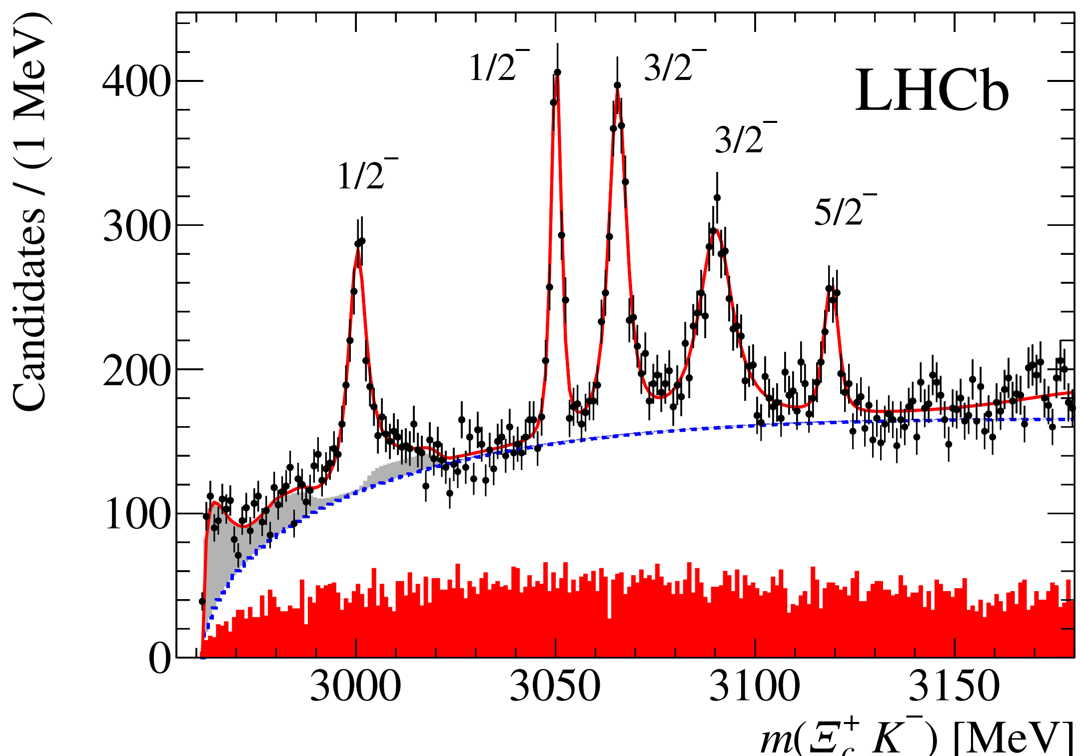
Universal quark masses and 165 MeV "string junction" term for baryons: predict $M(\Omega_{cc}) \sim 40$ MeV higher

EXCITED Ω_c STATES

Ground css states: $\Omega_c(2695, 1/2^+)$, $\Omega_c^*(2766, 3/2^+)$ (PDG)

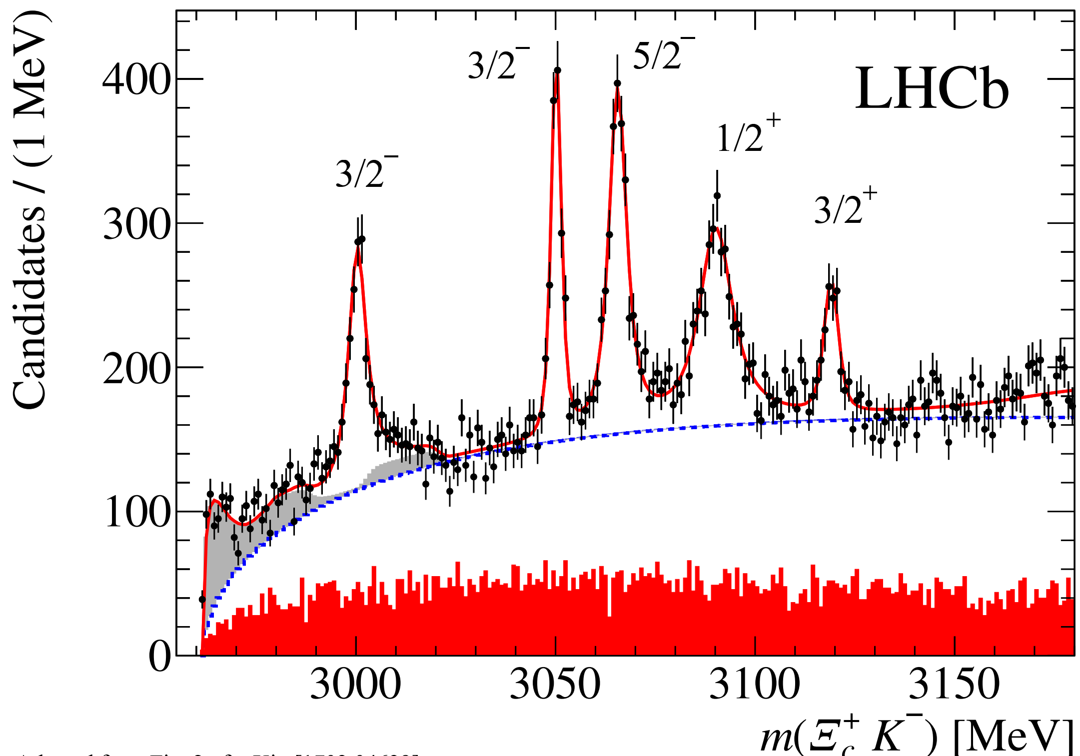
LHCb (PRL **118**): Five narrow Ω_c^* states $\to \Xi_c^+ K^-$

Karliner + JLR (PR D **95**): Five P-wave excitations?



Adapted from Fig. 2 of arXiv:[1703.04639]

ALTERNATIVE ASSIGNMENT



Adapted from Fig. 2 of arXiv:[1703.04639]

In this case two $J^P = 1/2^-$ states yet to be seen

One around 2904 MeV decaying to $\Omega_c\gamma$ and/or $\Omega_c\pi^0$

The other around 2978 MeV $\rightarrow \Xi_c^+ K^-$ in S-wave

PROSPECTS

Exotic mesons and baryons (beyond $q\bar{q}$ and qqq) *do* exist; molecular configurations are at least part of the story

Heavy quarks have a lower kinetic energy and help to stabilize exotic configurations containing them

Techniques for mass estimation (constituent-quark masses, hyperfine interactions, binding effects) relatively straightforward and starting to be tested for $QQ'q$ baryons

Frontier: $Q_1 Q_2 \bar{Q}_3 \bar{Q}_4$; any $cc\bar{c}\bar{c}$ lighter than $2M(\eta_c)$? Any $bb\bar{b}\bar{b}$ lighter than $2M(\eta_b)$?

Can quark-level analogue of nuclear fusion be put to use?

Still to be known: What does it cost to produce one or more extra heavy quarks via strong interactions? When do two heavy quarks end up in the same hadron?

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