CHARM: 55 YEARS AND COUNTING

J. Rosner (U of Chicago) – MaryK Fest – September 2019

A fourth quark has played a key role in understanding the weak and strong interactions since its proposal in 1964

Today: some early history (hep-ph/9811359 for more details) and progress over the subsequent > half-century

"Charm" bestowed by Bjorken and Glashow [PL **11**, 255 (1964)] for a fourth hadron-lepton-symmetric quark

Quartets: Gell-Mann, PL **8**, 214 (1964); Maki-Ohnuki [PTP **32**, 144 (1964)]; Hara [PR **134**, B701 (1964)]; Amati+, Nuovo Cim. **34**, 1732 (1964) & PL **11**, 190

Quartet assignment $\Rightarrow$ suppression of strangeness-changing neutral currents; good behavior of higher-order weak interactions; higher-order effects $\Rightarrow m_{\rm charm} \lesssim$ O(2 GeV): Glashow-Iliopoulos-Maiani, PR D **2**, 1285 (1970)

A SIMPLIFIED MOTIVATION

Weak charge-raising current J_μ^+: $Q^+ \equiv \int d^3x J_0^+$

Cabibbo-Gell-Mann-Lévy: In basis (u, d, s):

$$Q^+ = \begin{bmatrix} 0 & \cos\theta & \sin\theta \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} ; \quad Q^- = \begin{bmatrix} 0 & 0 & 0 \\ \cos\theta & 0 & 0 \\ \sin\theta & 0 & 0 \end{bmatrix}$$

SU(2) algebra: $Q^3 \equiv (1/2)[Q^+, Q^-]\,, \quad Q^\pm = \pm[Q^3, Q^\pm]$

Q^3 has strangeness-changing neutral currents:

$$Q^3 = \frac{1}{2}\begin{bmatrix} 1 & 0 & 0 \\ 0 & -\cos^2\theta & -\sin\theta\cos\theta \\ 0 & -\sin\theta\cos\theta & -\sin^2\theta \end{bmatrix}$$

Undesirable off-diagonal terms

Can't ignore these in a gauge theory of weak interactions

ADDING CHARM

New quark c in basis (u, c, d, s) leads to:

$$Q^+ = \begin{bmatrix} 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} ; \ Q^- = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \end{bmatrix}$$

Now $Q^3 = (1/2)[Q^+, Q^-] = (1/2)\mathrm{diag}(1, 1, -1, -1)$ and strangeness-changing neutral currents have been cancelled

Mary K and Ben Lee [PR D **10**, 897 (1974)]: charm in loop diagrams for K-$\overline{K}$ mixing, $K_L \to \mu^+\mu^-$, $K_L \to \gamma\gamma$ within electroweak unification $\Rightarrow m_c \lesssim 2$ GeV, $\gg m_u$

Rich spectroscopy implied: mesons $D^0 = c\bar{u}$, $D^+ = c\bar{d}$ [$D =$ "doublet"], $F = c\bar{s}$ ["funny"; renamed D_s by PDG], baryons like $C_0^+ = udc$ [renamed Λ_c by PDG]

GIM PREDICTIONS

Branching ratio $\mathcal{B}(D^0 = c\bar{u} \to K^-\pi^+)$ of a few %

Strong production of charm-anticharm pairs

Direct leptons in charm decays

Charm production in neutrino reactions

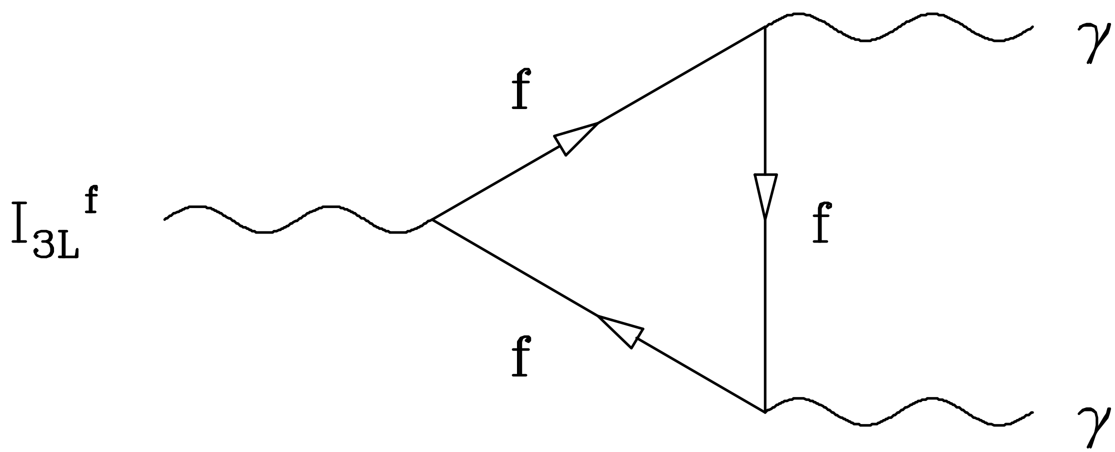
Neutral flavor-preserving currents

Z^0 observability in e^+e^- direct channel annihilations

Searches advocated by Carlson and Freund; Snow

Glashow at Meson 1974: Charm lifetimes between 10^{-13} and 10^{-12} s, similar semileptonic and hadronic decay rates, strange particles in final state, dileptons in neutrino reactions. Offered to eat his hat if charm was not found by the next Meson Conference (it was)

TRIANGLE ANOMALIES



Bouchiat-Iliopoulos-Meyer, PL **38B**, 519 (1972); Georgi-Glashow, PR D **6**, 429 (1972); Gross-Jackiw, PR D **6**, 477 (1972): $\sum_f Q_f^2 I_{3f} = 0$ ($I_{3f} =$ weak isospin):

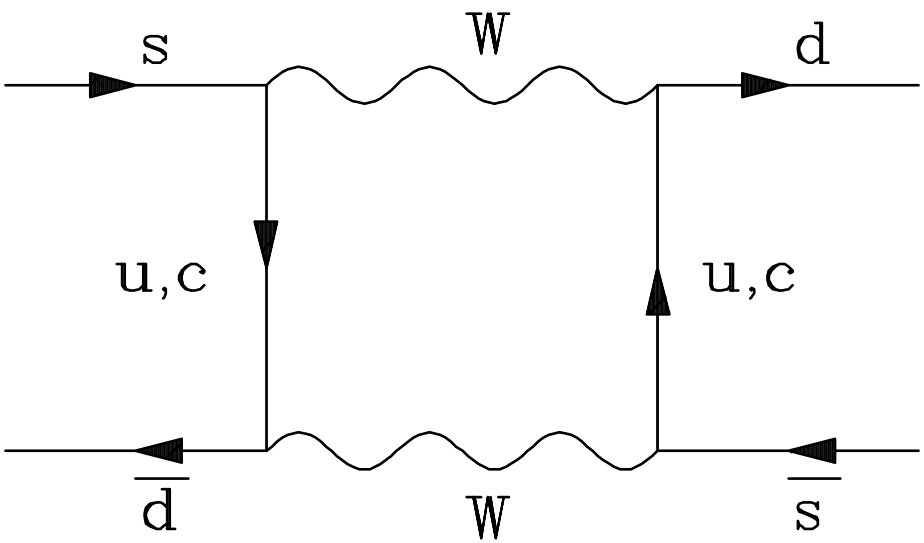
Leptons: $(0)^2\left(\frac{1}{2}\right) + (-1)^2\left(-\frac{1}{2}\right) = -\frac{1}{2}$

Quarks: $3\left[\left(\frac{2}{3}\right)^2\left(\frac{1}{2}\right) + \left(-\frac{1}{3}\right)^2\left(-\frac{1}{2}\right)\right] = \frac{1}{2}$

Cancellation within each family requires charmed quark

GAILLARD-LEE CALCULATION

Example of cancellation: $K^0 - \overline{K}^0$ mixing



plus graph with W^+W^- in t channel

Contribution $\sim (m_c^2 - m_u^2)/M_W^2$

Either $m_c^2 \sim m_u^2$ (both large) or $m_c \sim 1.5 - 2$ GeV $\gg m_u$

Prediction $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \simeq 10^{-10}$ (now $\times \sim 0.8$)

Current value $(1.7 \pm 1.1) \times 10^{-10}$ (BNL E-949);
CERN NA-62 should collect about 80 such events

Some caution was expressed in relating heavy-quark masses to those of hadrons containing the heavy quark. The link between the two was stronger than anticipated.

WAS CHARM LOST?

1974: Mary K and Ben invited me to join them; I had been involved with hadron spectroscopy and looking for charm in neutrino interactions: e.g., $\nu_\mu A \to \mu^- c\bar{s} A$

How could we have missed a whole family of hadrons with masses in the 2 GeV range?

Multiparticle decays of charm were more important than we realized; combinatorial backgrounds needed to be defeated

Charm-anticharm bound state with $J^{PC} = 1^{--}$ should show up in Drell-Yan processes and e^+e^- annihilation; Okubo-Zweig-Iizuka rule suppressing $c\bar{c}$ transitions to light-quark hadrons would make its total width small but also would suppress its production in hadronic reactions

Short-track signatures were crucial in identifying charm

A key signal was missed because of poor mass resolution

GLR CHARM SIGNATURES

M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. **47**, 277 (1975) (main text was written before J/ψ)

"Direct" lepton production

Large numbers of strange particles

Narrow peaks in mass spectra of hadrons

Apparent strangeness violations

Short tracks . . . lifetimes of order 10^{-13} s

Di-lepton production in neutrino reactions

Narrow peaks in e^+e^- or $\mu^+\mu^-$ mass spectra

Transient threshold . . . in deep inelastic leptoproduction

$\sigma(e^+e^- \rightarrow \text{ hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) \Rightarrow 3\frac{1}{3}\ldots$

GLR CHARM SIGNATURES

"Direct" lepton production: $\surd$ but other sources too

Large numbers of strange particles: τ "dilution"

Narrow peaks in mass spectra of hadrons $\surd$

Apparent strangeness violations: Good particle ID needed

Short tracks ... lifetimes of order 10^{-13} s: Some longer

Di-lepton production in neutrino reactions: $\surd$

Narrow peaks in e^+e^- or $\mu^+\mu^-$ mass spectra $\surd$ $(J/\psi, \ldots)$!

Transient threshold ... in deep inelastic leptoproduction:

$R = \sigma(e^+e^- \to \mathrm{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) \Rightarrow 3\frac{1}{3} \ldots$: τ too

Many of these realized only with measurement progress: short tracks, particle ID, soft pion in $D^{*+} \to D^0\pi^+, \ldots$

EARLY HINTS OF CHARM

Christenson +, BNL: 3.5 GeV shoulder in $\mu^+\mu^-$ spectrum; Lederman at a BNL seminar in July 1971: "Looks like a resonance to me!" (He was talked out of it)

K. Niu and collaborators at Nagoya U.: short tracks in emulsions exposed to cosmic rays. One event consistent with $D^+ \to \pi^+\pi^0$, mass ~ 2 GeV, lifetime $\sim 10^{-14}$ s.

Dimuon events in neutrino interactions: semileptonic charmed particle decays such as $\nu_\mu d \to \mu^- c \to \mu^- s \mu^+ \nu_\mu$ (B. Lee, comment to D. Cundy at London ICHEP, 1974)

Simultaneous announcement of J and ψ, $c\bar{c}$ candidate at 3.1 GeV, and subsequent radial excitation candidate ψ' at 3.7 GeV, greatly narrowed possible charm parameters

Those who were convinced it was charm included Appelquist and Politzer; De Rújula, Georgi, and Glashow (DGG); and Eichten *et al.*; not all (Jan. 6, 1975 PRL)

SORTING OUT CHARM (1975-6)

"Don't give up the ship. It has just begun to sink."

$D^0 = c\bar{u} \to K^-\pi^+$ expected; branching ratio only a few % because of many possible decay modes

Rise in $R = \sigma(e^+e^- \to \mathrm{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ was larger than expected: Contribution $\Delta R = 1$ of $\sigma(e^+e^- \to \tau^+\tau^-)$ needed to be taken into account.

Increase in strange particle production above charm threshold offset by dearth of strange particles in τ decays

Possible charmed baryon production by neutrinos: E. G. Cazzoli +, PRL **34**, 1125 (1975)

Charm discovery at SLAC: $D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$ [PRL **37**, 255 (1976)] aided by soft-pion signature in $D^{*+} \to \pi^+D^0$ [Nussinov, PRL **35**, 1672 (1975)], time-of-flight

SHORT-TRACK DETECTION

Emulsion: Niu+, PTP **46**, 1644 (1971); FNAL E531, E653

Charm photoproduction: Fermilab E516, E691, E687, E831: short tracks from picosecond lifetimes (1983 –)

Charm hadroproduction a difficult task: J. Ritchie, thesis, University of Rochester, 1983, & references therein

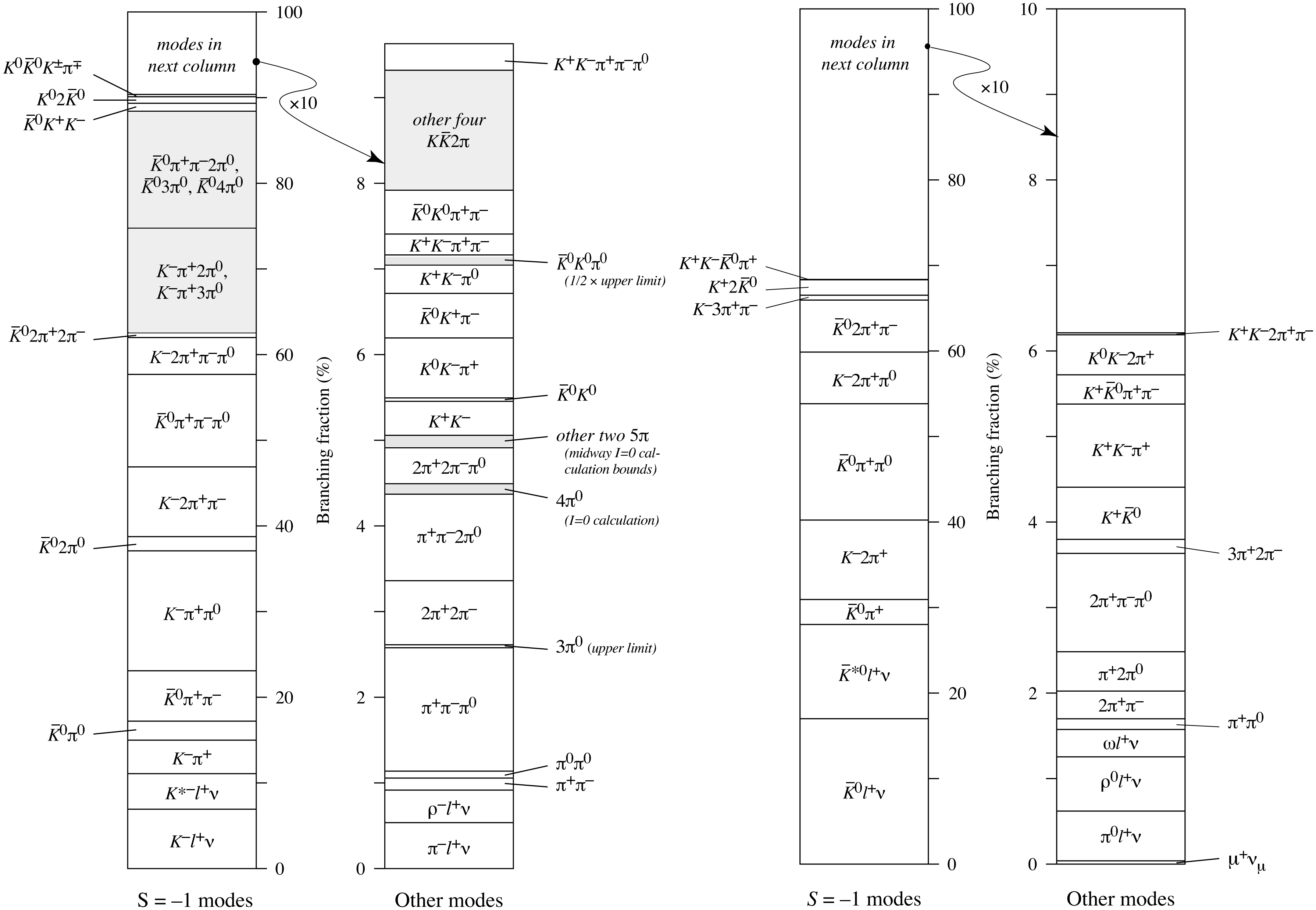
Initially charmed hadrons were not reconstructed but their presence was inferred from direct leptons

Review of early hadroproduction successes: J. Appel, Ann. Rev. Nucl. Part. Sci. **42**, 367 (1992)

Pioneers: e.g., LEBC (rapid-cycling high-resolution bubble chamber); ACCMOR Collab. [R. Butler+, NIM **213**, 201 (1983)], first use of CCDs in a hadron beam

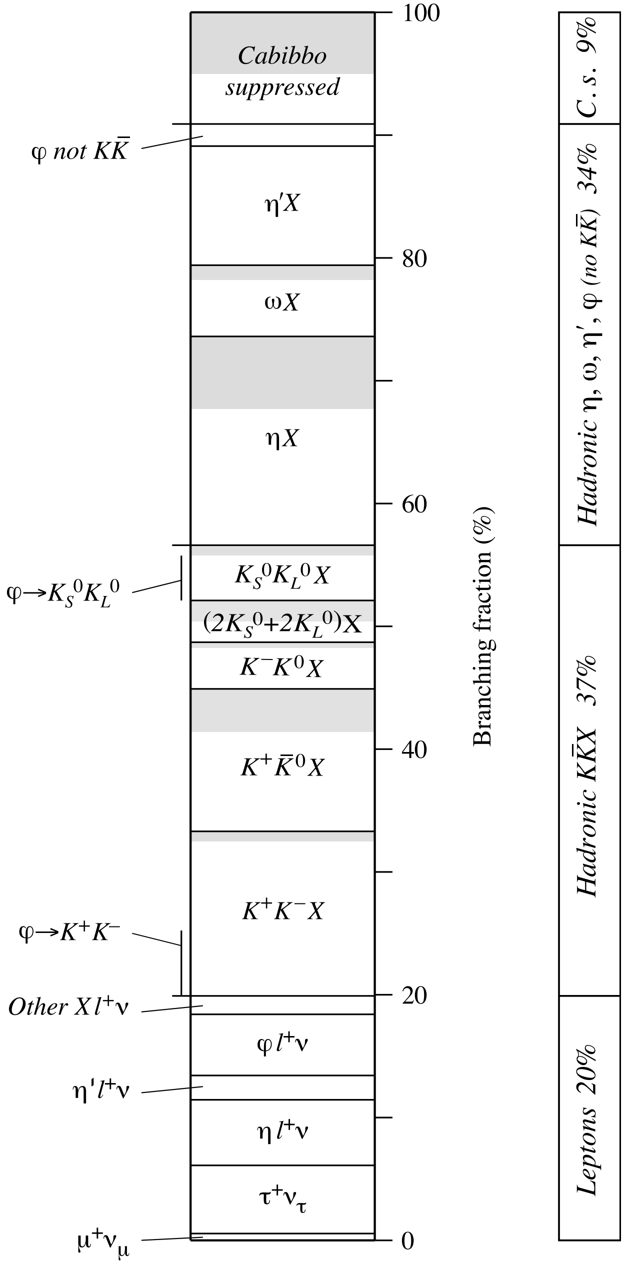
Also, e.g., FNAL E769, E791; CERN WA82, WA89, WA92

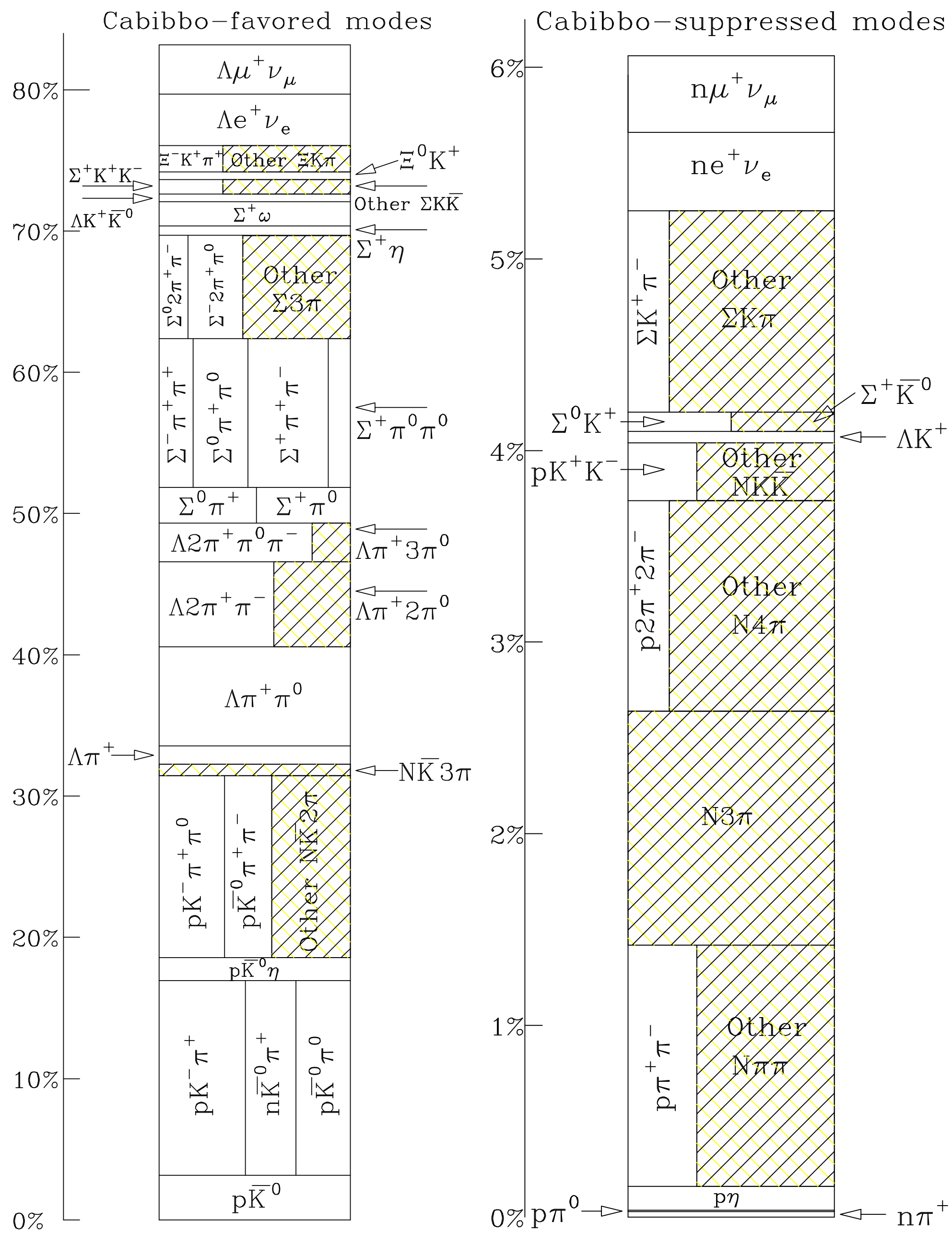
D^0 AND D^+ DECAYS



This and related plots: with M. Gronau, C. Wohl

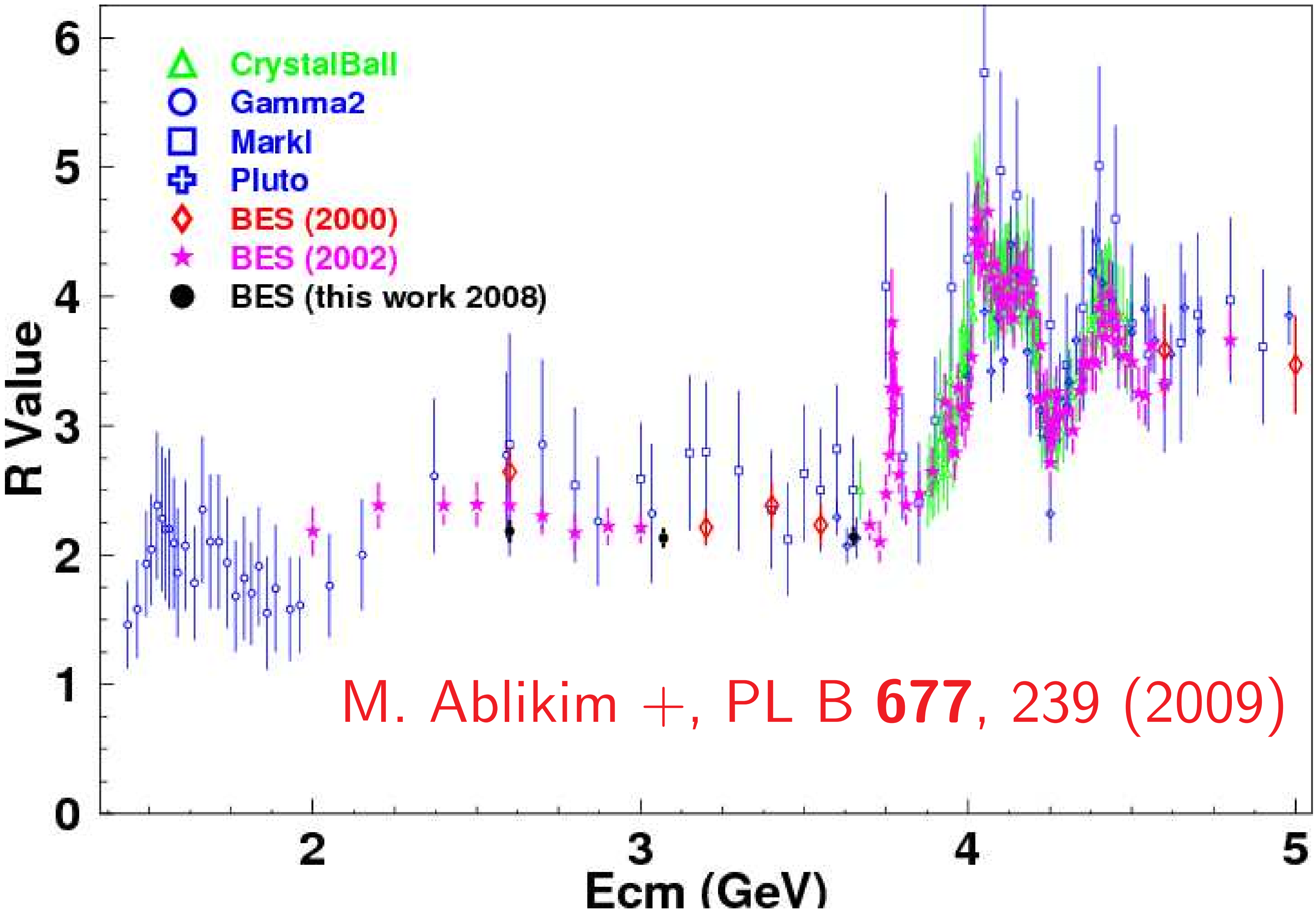
D_s DECAYS Λ_c DECAYS





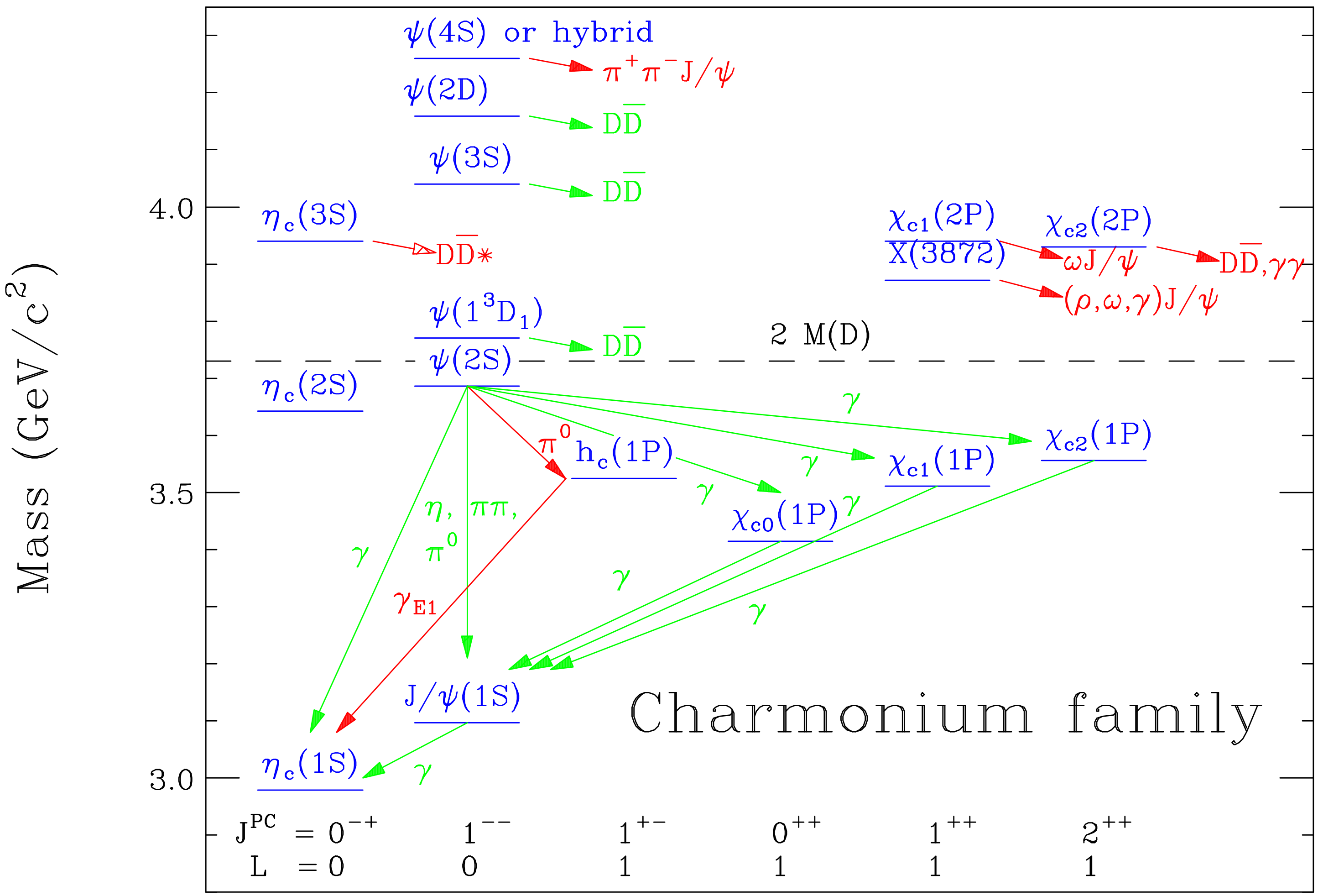
Substantial progress in identifying most decay modes

STRUCTURE IN R



Charm and $\tau^+\tau^-$ thresholds; excited $c\bar{c}$ levels

CHARMONIUM ($c\bar{c}$) SPECTRUM



I joined CLEO in 2003 during sabbatical

Helped find the $h_c(3525)$

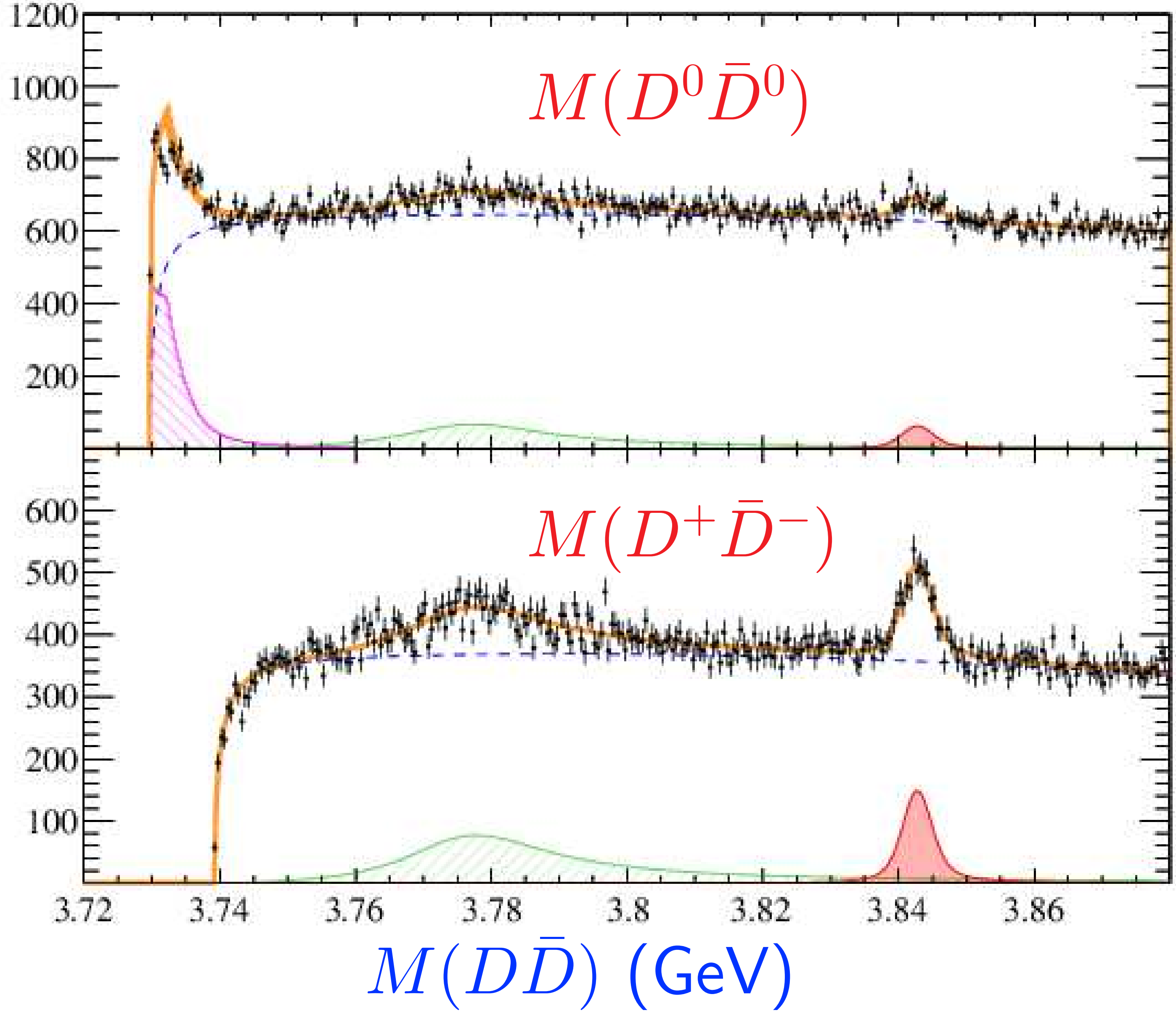
Late addition: $^3D_3$ candidate at 3843 (LHCb) (1903.12240v2)

$c\bar{c}$ potentials (e.g., Cornell) $\Rightarrow$ cartoon of levels

Linear potential ($\sim r$) at long distance: quark-confining

Gluon exchange (Coulomb-like, $\sim -1/r$) at short distance

$^3D_3$ CANDIDATE AT 3843 MEV



Hadronic production $\Rightarrow$ wider range of quarkonium states

THE THIRD FAMILY

Discovery of τ suggested a third neutrino

Quark-lepton symmetry then required a third doublet (t, b)

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

b discovered at Fermilab in 1977: $\Upsilon(1S, 2S, [3S])$ as $b\bar{b}$

Top quark t discovered at Fermilab in 1995: $t \to Wb$

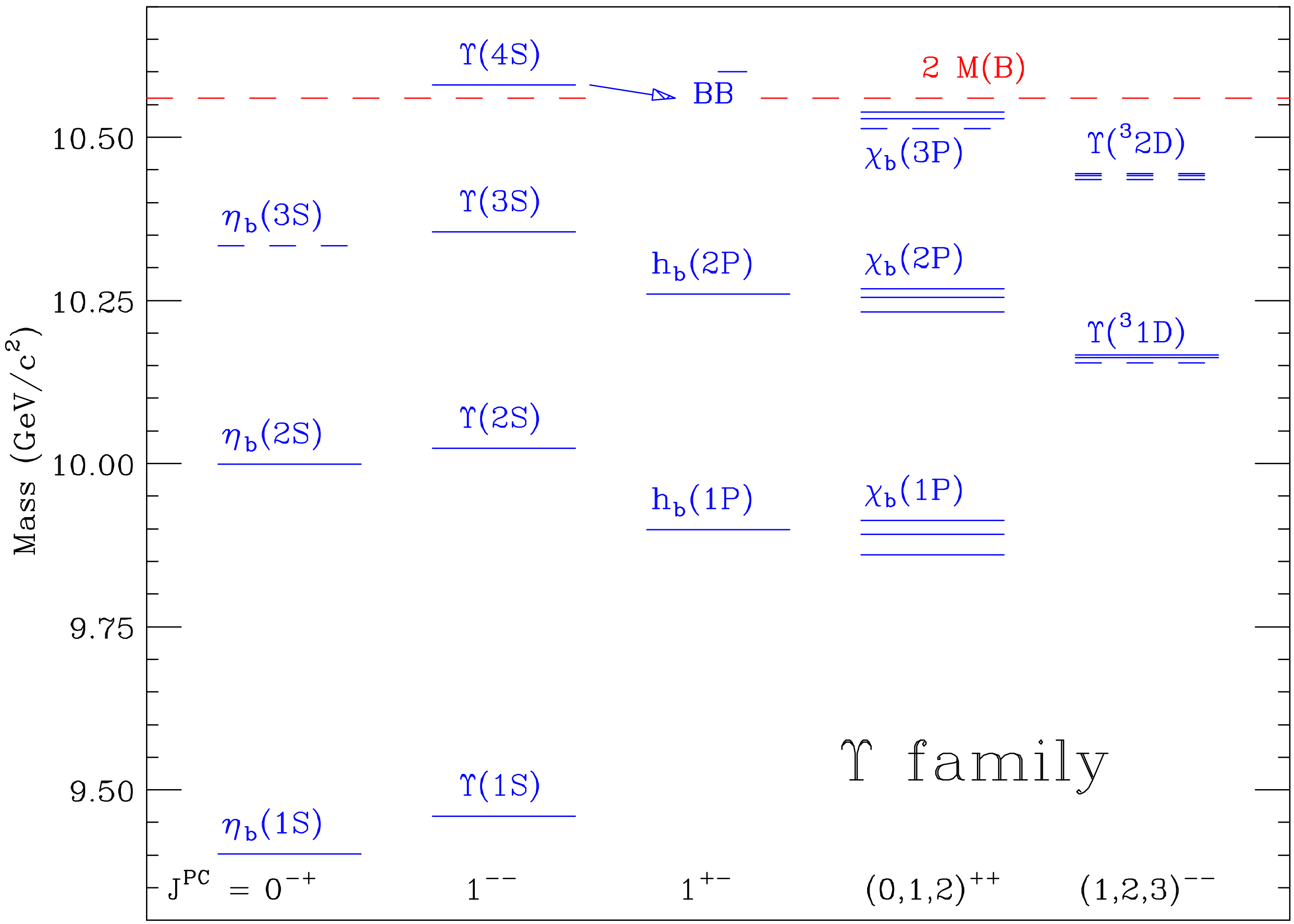
ν_τ discovered at Fermilab in 2000 (emulsion target)

Six quarks anticipated by Kobayashi-Maskawa in 1973; generalized Cabibbo theory to allow CP violation

Weak charge-changing transitions between left-handed fermions now described by $(u, c, t)^T \leftarrow V_{CKM}(d, s, b)^T$

V_{CKM} a 3×3 unitary matrix with three angles and a phase

BOTTOMONIUM ($b\bar{b}$) SPECTRUM



Level spacings almost independent of reduced mass

C. Quigg + JLR: log r interpolates between $-1/r$ and r

CARTOON OF HADRON MASSES

Zeldovich-Sakharov, DGG: Constituent quarks with masses several hundred MeV, hyperfine splittings

M. Karliner + JLR: Additional binding of heavy quarks

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

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

CHARMED & BOTTOM BARYONS

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

Above choices of mass sufficient to describe nonstrange ground state 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 (with M. Karliner)

Charmed baryons			Bottom baryons		
State (M in MeV)	Spin	Predicted M (MeV)	State (M in MeV)	Spin	Predicted M (MeV)
$\Lambda_c(2286.5) = cud$	1/2	Input	$\Lambda_b(5619.5) = bud$	1/2	Input
$\Sigma_c(2453.4) = cuu, \ldots$	1/2	2444.0	$\Sigma_b(5814.3) = buu, \ldots$	1/2	5805.1
$\Sigma^*_c(2518.1) = cuu, \ldots$	3/2	2507.7	$\Sigma^*_b(5833.8) = buu, \ldots$	3/2	5826.7
$\Xi_c(2469.3) = csu, csd$	1/2	2475.3	$\Xi_b(5792.7) = bsu, bsd$	1/2	5801.5
$\Xi'_c(2575.8) = csu, csd$	1/2	2565.4	$\Xi'_b(-) = bsu, bsd$	1/2	5921.3
$\Xi^*_c(2645.9) = csu, csd$	3/2	2628.6	$\Xi^*_b(5949.7) = bsu, bsd$	3/2	5944.1
$\Omega_c(2695.2) = css$	1/2	2692.1	$\Omega_b(6046.4) = bss$	1/2	6042.8
$\Omega^*_c(2765.9) = css$	3/2	2762.8	$\Omega^*_b(-) = bss$	3/2	6066.7

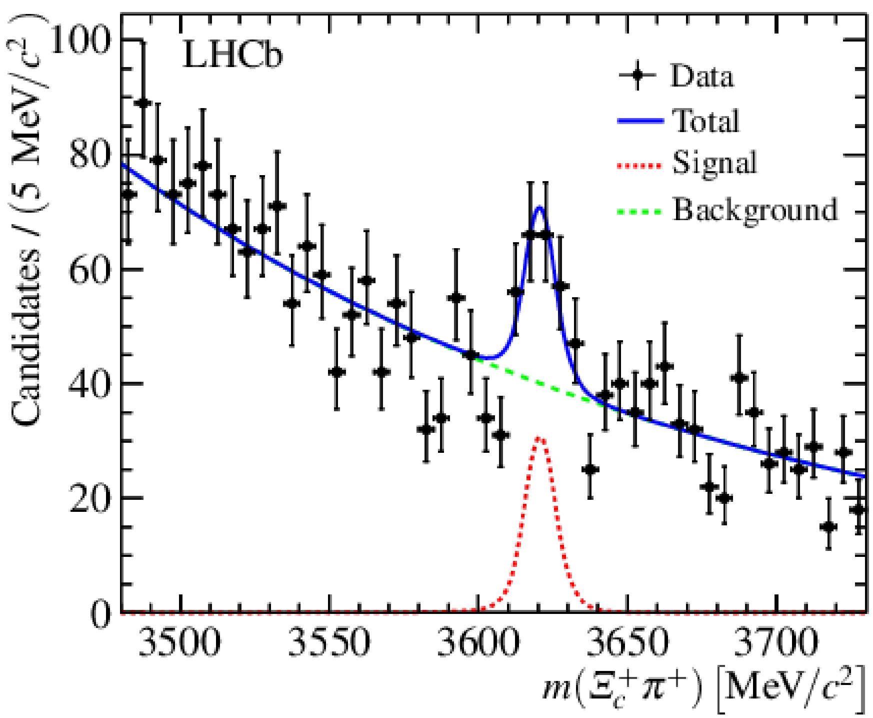
Predict masses of baryons with more than one heavy quark?

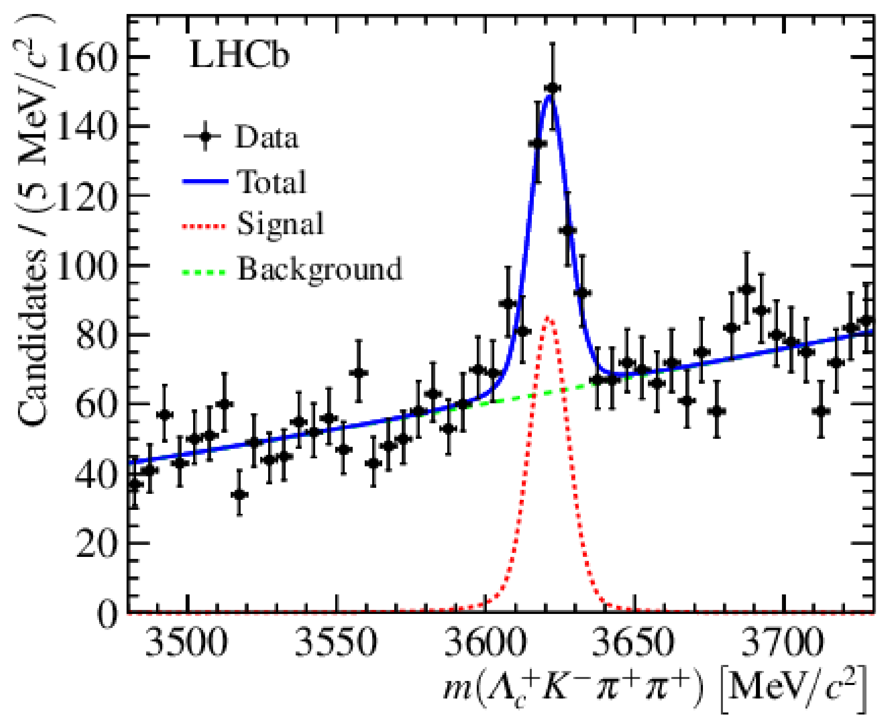
BARYONS WITH > 1 HEAVY QUARK

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 ($q = u, d$): $M(\Xi_{cc}, \Xi_{cc}^{*}) = (3627 \pm 12,\ 3690 \pm 12)$ MeV

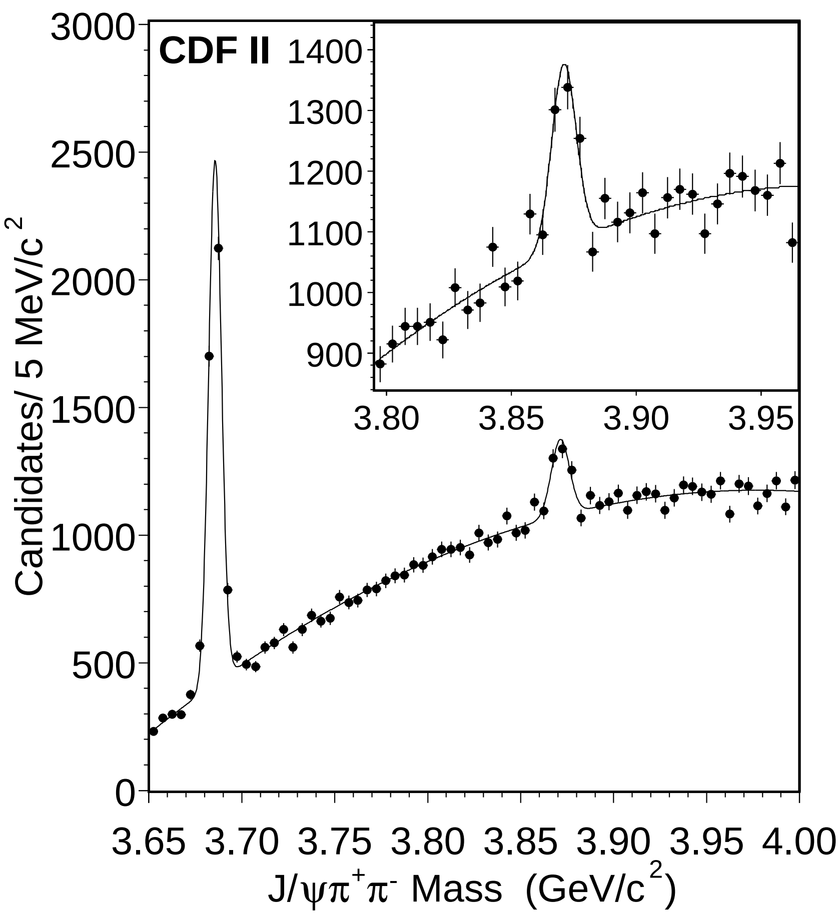
LHCb PRL **119**, 112001: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV

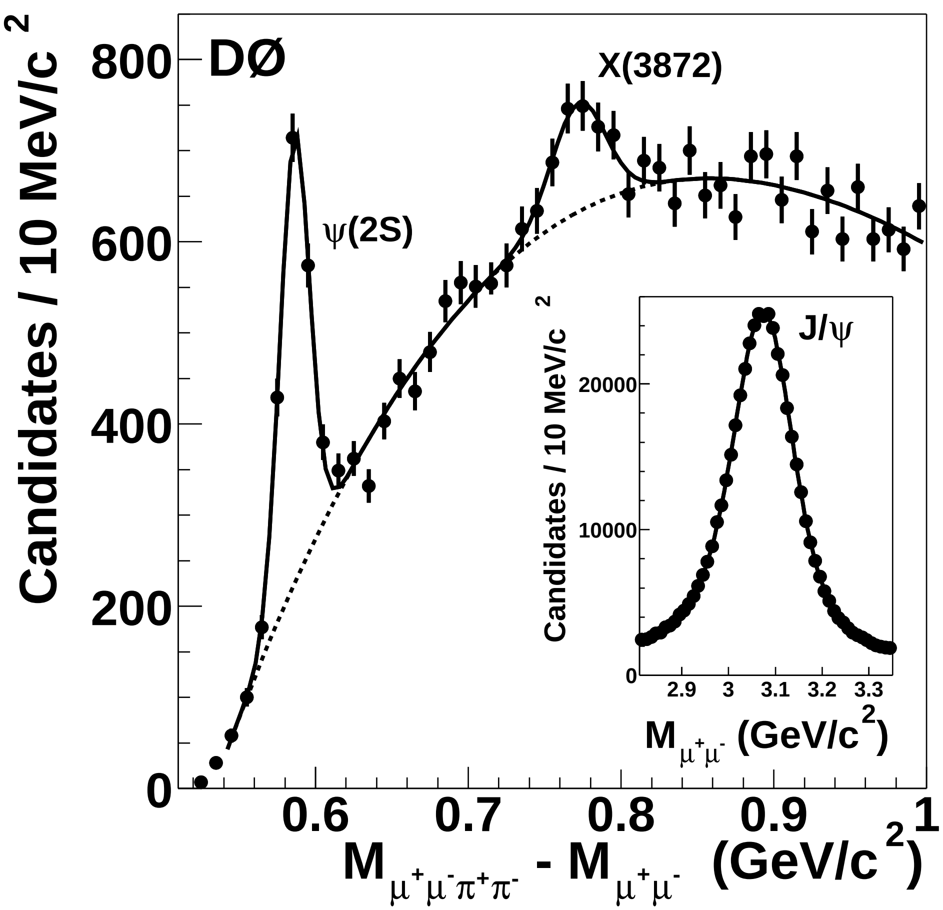




$X(3872)$: $c\bar{c}u\bar{u}$ STATE

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 (2005)





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

$X(3872)$ 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

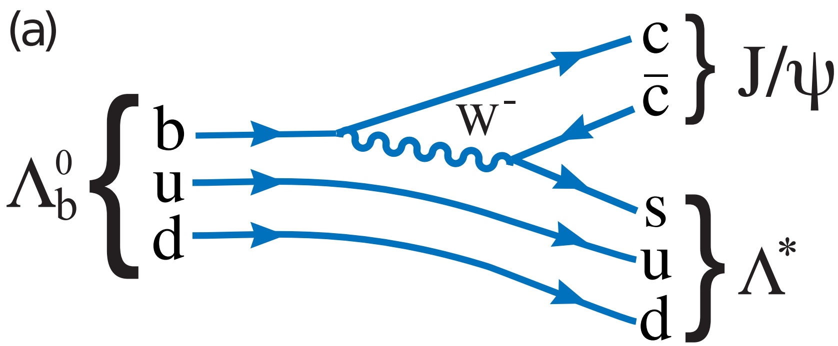
Large $M(D^{(*)+} - D^{(*)0}) \Rightarrow$ little $D^{(*)\pm}$ in wave function

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

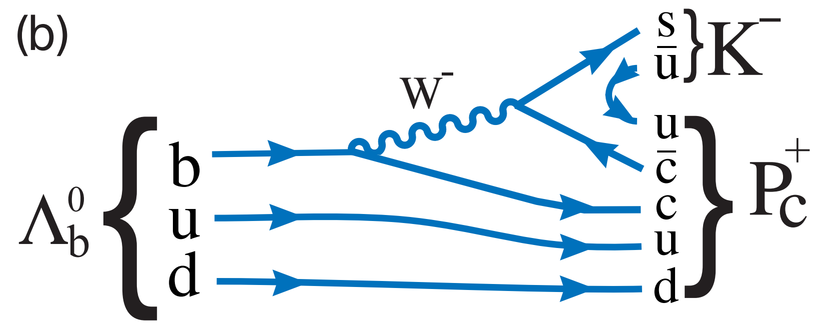
In addition to $X(3872)$ (mixture of 2^3P_1 $c\bar{c}$ state and $J^{PC} = 1^{++}$ $c\bar{c}u\bar{u}$ state) one expects an orthogonal mixture (potential models: probably > 3900 MeV)

PENTAQUARKS P_c

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



Λ^* excitation



P_c excitation

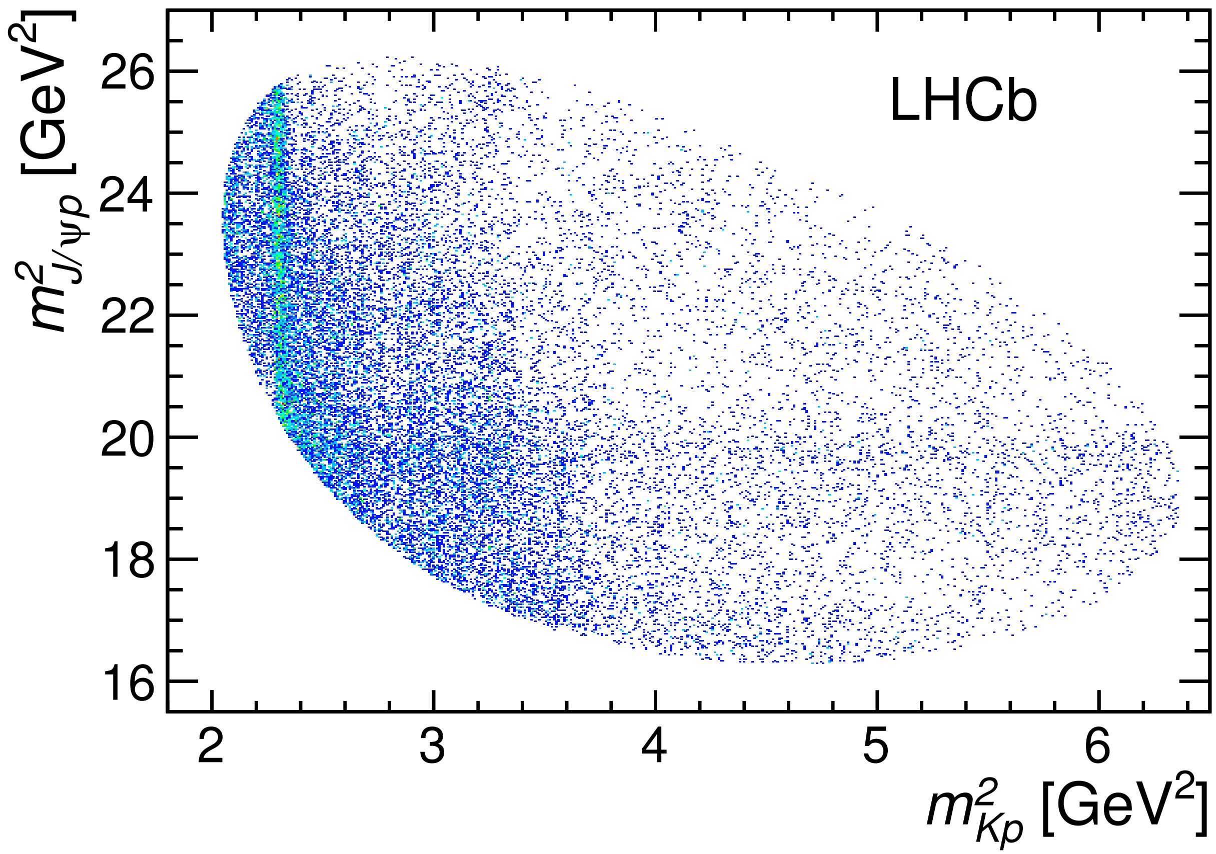
Dalitz plot: many $I = 0\ K^- p$ states $(\Delta I[b \to c\bar{c}s] = 0)$.

Updated result: *Three* narrow J/ψ resonances: 4311.9, 4440.3, 4457.3 MeV; widths 9.8, 20.6, 6.4 MeV

Near $\Sigma_c \bar{D}$ and $\Sigma_c \bar{D}^*$ thresholds; binding mechanism?

One-pion exchange can't couple to $D\bar{D}$; $\pi^+\pi^-$ may favor $\Sigma_c \bar{D}$ over $D\bar{D}$: lowest intermediate state is $\Lambda_c \bar{D}^*$ vs. $D^* \bar{D}^*$

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



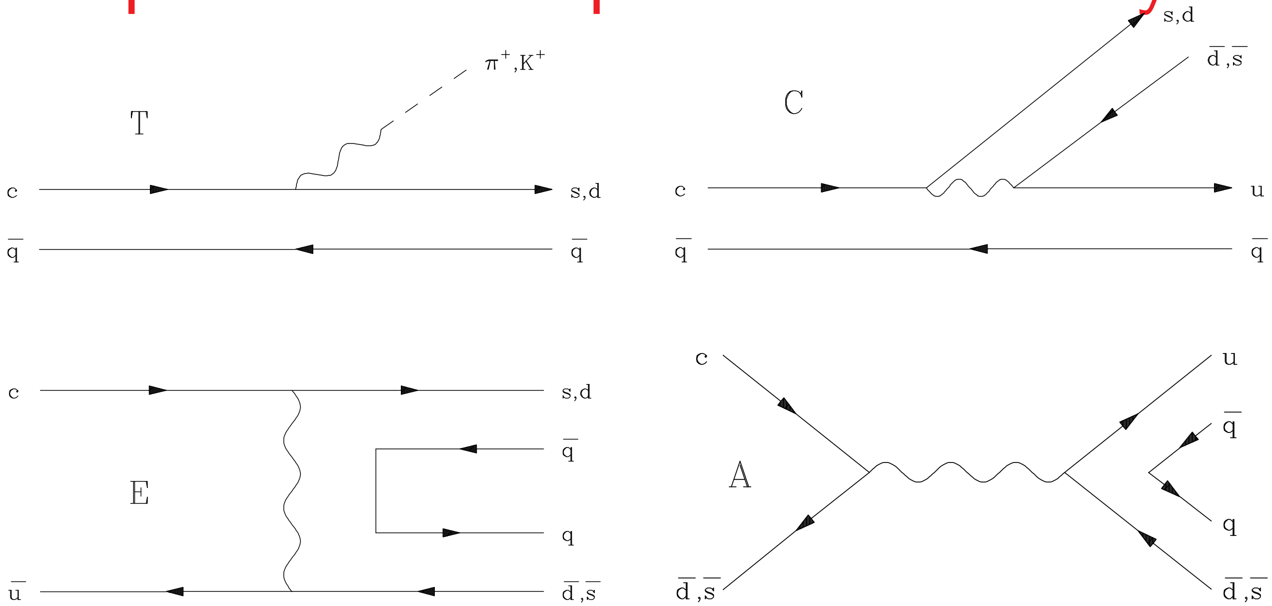
Asymmetric behavior along $M(J/\psi\ p)$ bands indicates interference with opposite-parity amplitude(s)

arXiv:1903.11503: Possible isospin impurity of $P_c(4457)$

arXiv:1903.11560: Total of 7 $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecules

CHARMED MESON DECAYS

Amplitude decomposition for decays to two pseudoscalars



With M. Gronau, B. Bhattacharya

$T = 2.927$,

$C = 2.337\, e^{-i\ 151.66^\circ}$,

$E = 1.573\, e^{i\ 120.56^\circ}$,

$A = 0.33\, e^{i\ 70.47^\circ}$

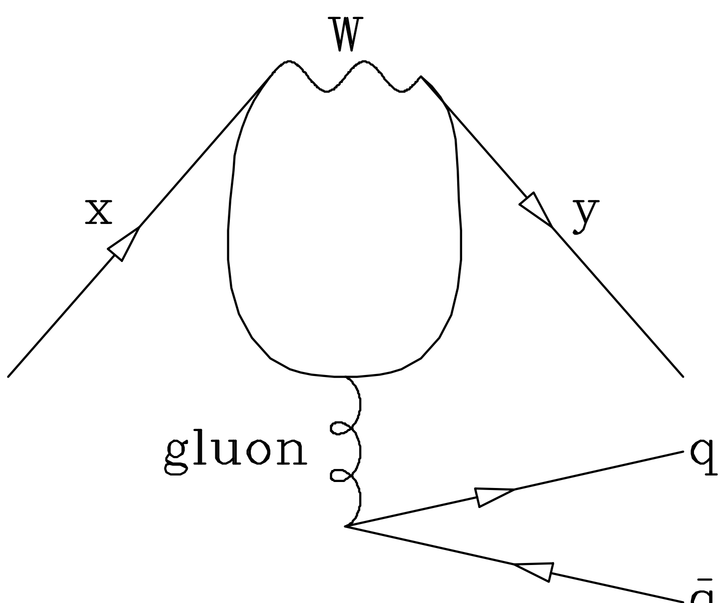
Meson	Decay mode	$\mathcal{B}$ [PDG] (%)	p^* (MeV)	$\lvert\mathcal{A}\rvert$ $(10^{-6} GeV)$	Rep.	Predicted $\mathcal{B}$ (%)
D^0	$K^-\pi^+$	3.891 ± 0.077	861.1	2.52 ± 0.03	$T + E$	3.905
	$\overline{K}^0\pi^0$	2.380 ± 0.092	860.4	1.97 ± 0.04	$(C - E)/\sqrt{2}$	2.347
	$\overline{K}^0\eta$	0.962 ± 0.060	771.9	1.32 ± 0.04	$C/\sqrt{3}$	1.002
	$\overline{K}^0\eta'$	1.900 ± 0.108	564.9	2.17 ± 0.06	$-(C + 3E)/\sqrt{6}$	1.920
D^+	$\overline{K}^0\pi^+$	3.074 ± 0.097	862.4	1.41 ± 0.02	$C + T$	3.090
D_s^+	$\overline{K}^0K^+$	2.98 ± 0.17	850.3	2.12 ± 0.06	$C + A$	2.939
	$\pi^+\eta$	1.84 ± 0.15	902.3	1.62 ± 0.07	$(T - 2A)/\sqrt{3}$	1.810
	$\pi^+\eta'$	3.95 ± 0.34	743.2	2.61 ± 0.11	$2(T + A)/\sqrt{6}$	3.603

CP VIOLATION IN $\Delta S = 0$ CHARM DECAYS

Leading-order CKM matrix $\Rightarrow$ more CP violation in b decays than in charm decays (phase mainly for 3rd family):

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

LHCb PRL **122**, 211803 (2019)] has seen CP violation in difference between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ CP asymmetries: $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

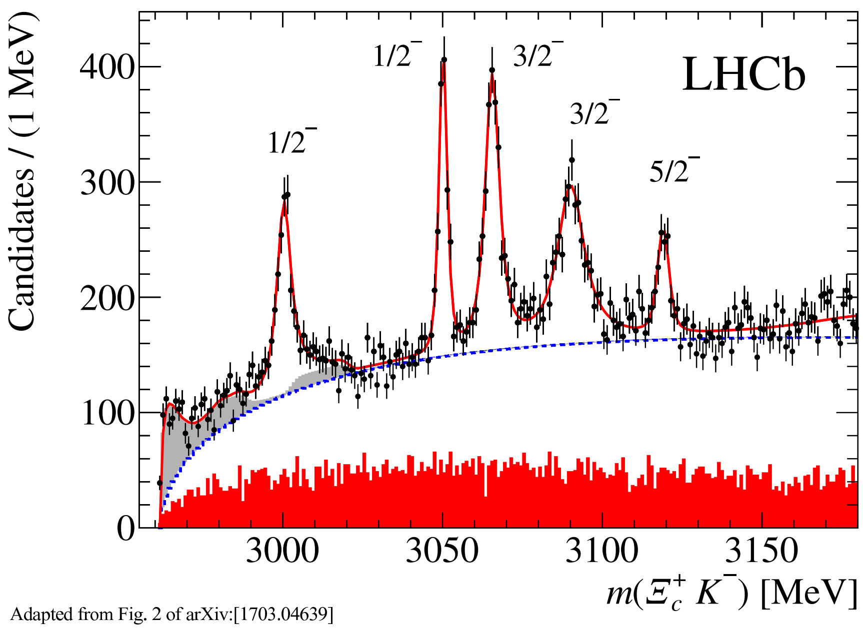


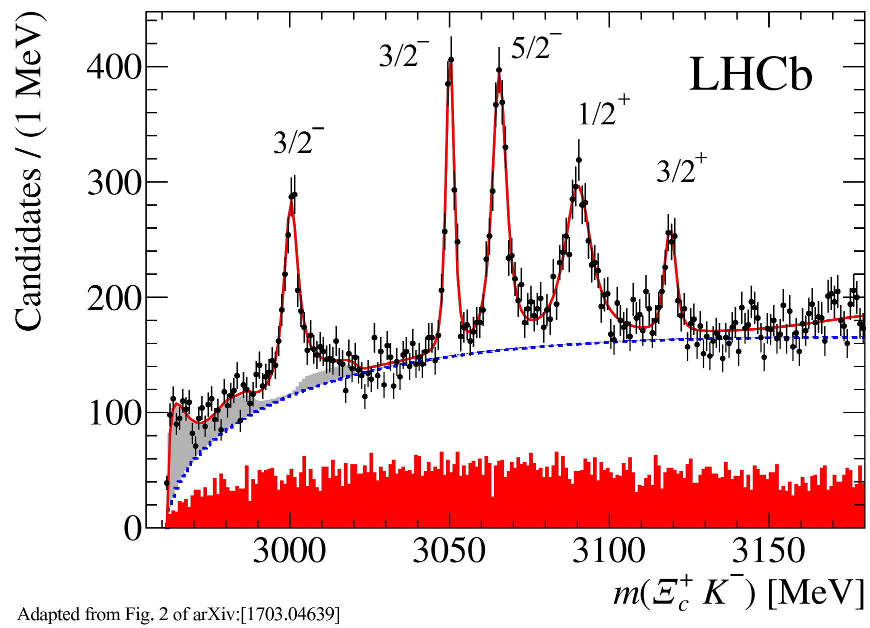
Most likely cause: small $c \to u$ penguin with b quark in the loop utilizing nonzero phase of V_{ub}
1903.10490: No; 1903.10(638,952): Yes

If so, expect CP asymmetries in other $\Delta S = 0$ charm decays to two pseudoscalar mesons

EXCITED $\Omega_c = css$ STATES

LHCb, PRL **118**, 182001 (2017):





Two possible spin-parity assignments. Narrowness is a consequence of absence of nonstrange (u, d) quarks

If two highest-mass states have positive parity, they are radial excitations of $1/2^+$ and $3/2^+$ ground states, and two more negative-parity states are expected at lower masses [M. Karliner + JLR, PR D **95**, 114012 (2017)]

CHARMED BARYON LIFETIMES

LHCb: PRL **121**, 092003 (2018); PRD **100**, 032001
Theory: H. Y. Cheng, Front. Phys. **10**, 101406 (2015)

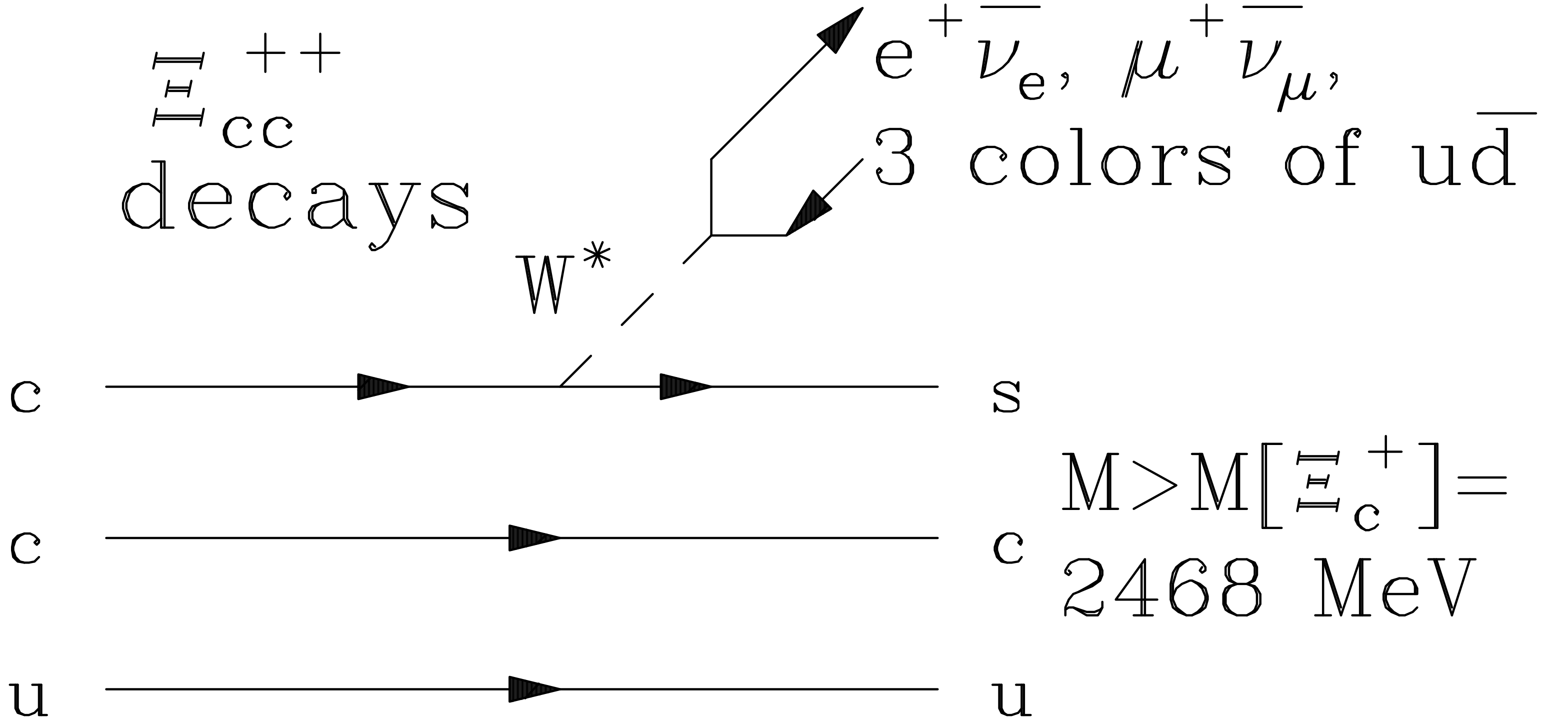
	PDG 2018	LHCb	Theory
$\Lambda_c = cud$	200 ± 6	$203.5 \pm 1.0 \pm 1.3 \pm 1.4$	264
$\Xi_c^+ = csu$	442 ± 26	$456.8 \pm 3.5 \pm 2.9 \pm 3.1$	368
$\Xi_c^0 = csd$	112^{+13}_{-10}	$154.5 \pm 1.7 \pm 1.6 \pm 1.0$	193
$\Omega_c = css$	69 ± 12	$268 \pm 24 \pm 10 \pm 2$	171

Λ_c and Ξ_c^0 lifetimes short: subprocess $cd \to su$

Operator product expansion overestimated the enhancement of Ω_c decay rate due to constructive interference of two strange quarks

Still some open questions for theorists!

Ξ_{cc}^{++} LIFETIME



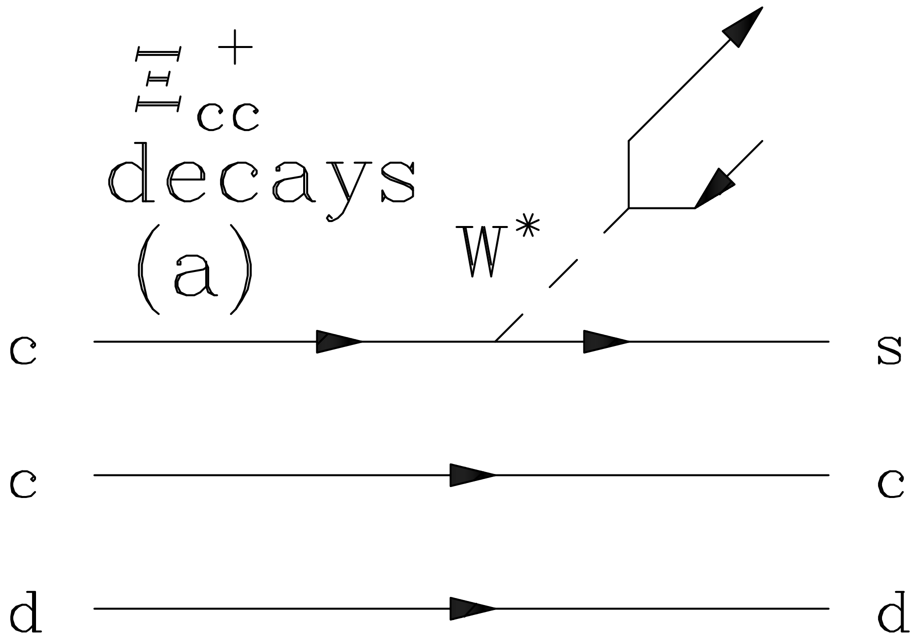
Dominant process: $c \to s[W^* \to e^+\nu_e, \mu^+\nu_\mu,$ 3 colors of $u\bar{d}]$

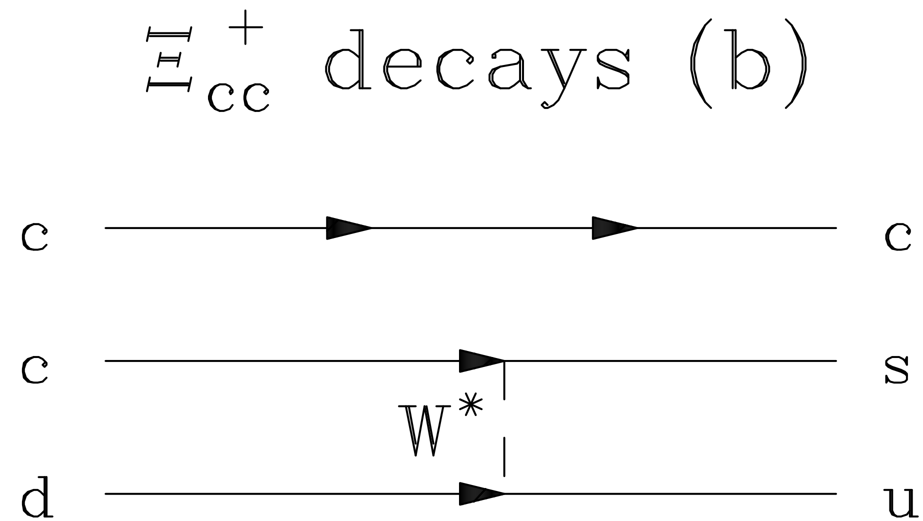
Emulate kinematic suppression with $x_{cc} \equiv [M(\Xi_c/M(\Xi_{cc})]^2$:

$$F(x) = 1 - 8x + 8x^3 - x^4 + 12\ln(1/x)$$

$$\Gamma(\Xi_{cc}^{++}) = \frac{10G_F^2 M(\Xi_{cc}^{++})^5}{192\pi^3} F(x_{cc}) \Rightarrow \tau(\Xi_{cc}^{++}) = 188 \text{ fs}$$

Ξ_{cc}^{+} LIFETIME





(a) "Spectator" (b) "Exchange"

$\Gamma_a = \hbar/\tau(\Xi_{cc}^{++}) = \hbar/(256 \text{ fs}) = 2.57 \times 10^{-12}$ GeV

$\Gamma_b = 2[\hbar/\tau(\Xi_c^0) - \hbar/\tau(\Xi_c^+)] = 5.64 \times 10^{-12}$ GeV

$\tau(\Xi_c^0) = 154.5 \pm 1.7 \pm 1.6 \pm 1.0$ fs ;
$\tau(\Xi_c^+) = 458.8 \pm 3.6 \pm 2.9 \pm 3.1$ fs

LHCb arXiv: 1906:08350

$\Gamma_a + \Gamma_b = 8.21 \times 10^{-12}$ GeV $\Rightarrow$ $\tau(\Xi_{cc}^{+}) = 80$ fs

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

THANKS

To MaryK and Ben Lee: for an enjoyable collaboration

To the organizers: for the chance to celebrate MaryK's 80th while reliving some exciting moments in physics

To my collaborators Bhujyo Bhattacharya, Cheng-Wei Chiang, Michael Gronau, Marek Karliner, Waikwok Kwong, David London, Zumin Luo, Chris Quigg, Rick Robinett, Tomasz Skwarnicki, Sheldon Stone, . . .

To the experimentalists at BES, Brookhaven, CERN, CESR, DESY, Fermilab, KEK, and SLAC, who have provided such valuable data over more than half a century, with further prospects from Belle-II, BES, LHC, . . .

To the funding agencies who made all this possible

To the Guggenheim Foundation (Cornell sabbatical)

To the Enrico Fermi Institute of the University of Chicago