FERMILAB-SLIDES-19-061-T

Beauty at High $\left\{ \begin{array}{l} \text{Precision} \\ \text{Sensitivity} \end{array} \right.$

Chris Quigg

Fermilab

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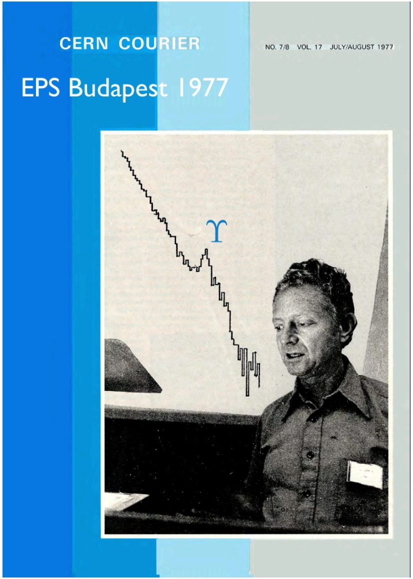
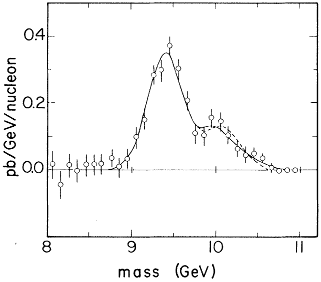
Beauty 2019 · Ljubljana · September 30, 2019

See also “Dream Machines” 1808.06036 “Perspectives and Questions” zenodo.3376597

Origin Story . . .



400-GeV $pN \to \mu^+\mu^- + X$

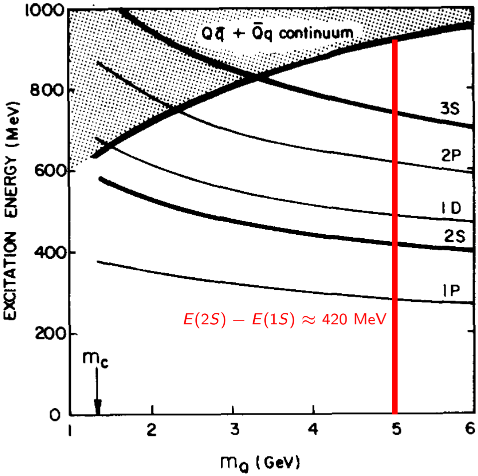


E288	$M(\Upsilon') - M(\Upsilon)$	$M(\upsilon'') - M(\Upsilon')$
Two-level fit	650 ± 30 MeV	
Three-level fit	610 ± 40 MeV	1000 ± 120 MeV
$M(\psi') - M(J/\psi)$	≈ 590 MeV	

General motivation: J/ψ, τ discoveries

Kobayashi–Maskawa CPV insight

Eichten & Gottfried: CESR Proposal (November 1976)



General: # of narrow $^3S_1$ levels $\propto \sqrt{M_Q}$

Why choose $M_Q = 5$ GeV?

Excess events at high inelasticity observed in $\bar{\nu}_\mu N \to \mu^+ +$ anything

$$V - A\text{:}\ d\sigma(\nu q)/dy \propto 1 \qquad d\sigma(\bar{\nu} q)/dy \propto (1-y)^2$$

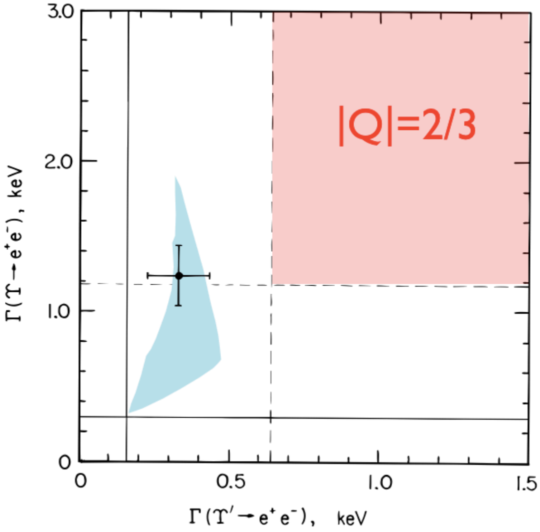
"high-y anomaly" could be explained by

$$\begin{pmatrix} u \\ b \end{pmatrix}_{\mathrm{R}} \text{with } m_b \approx 4 - 5 \text{ GeV}$$

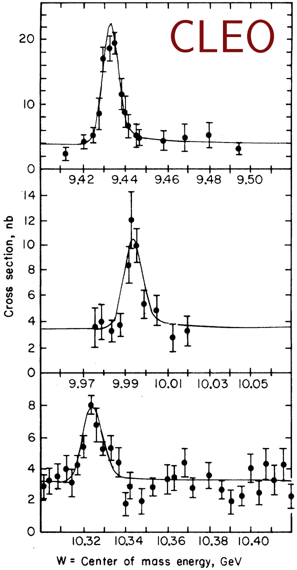
Also at Budapest 1977...

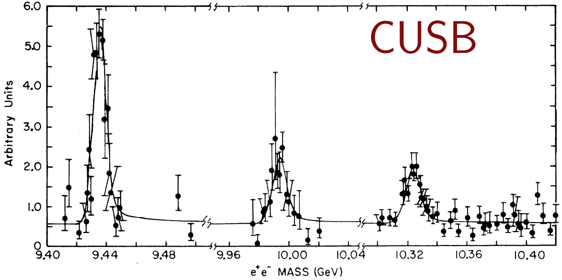
CDHS experiment ruled out the high-y anomaly

$\Upsilon(1S), \Upsilon(2S)$ leptonic widths $\rightsquigarrow Q_b = -\frac{1}{3}$ (DORIS, 1978)



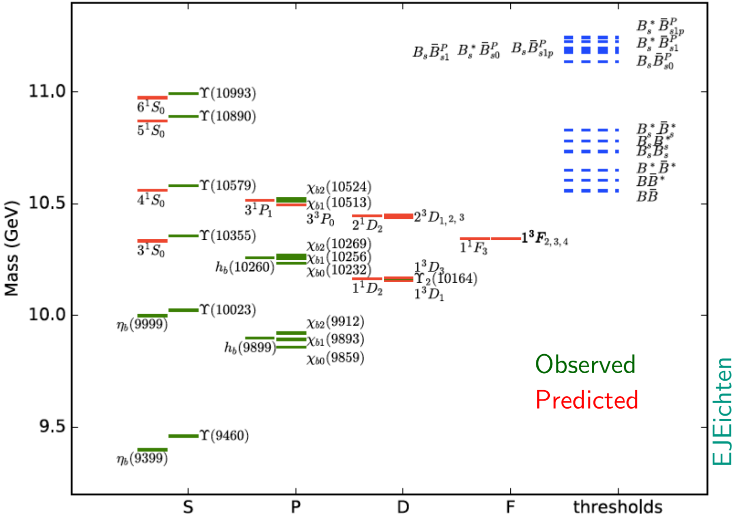
CESR resolves three narrow Υ states (1979–80)





$\Upsilon(4S)$ launches B physics (1980)

Rich spectrum of $(b\bar{b})$ levels



14 states below threshold still unobserved

Charmonium-associated states not pure charmonium

All these states near or above threshold

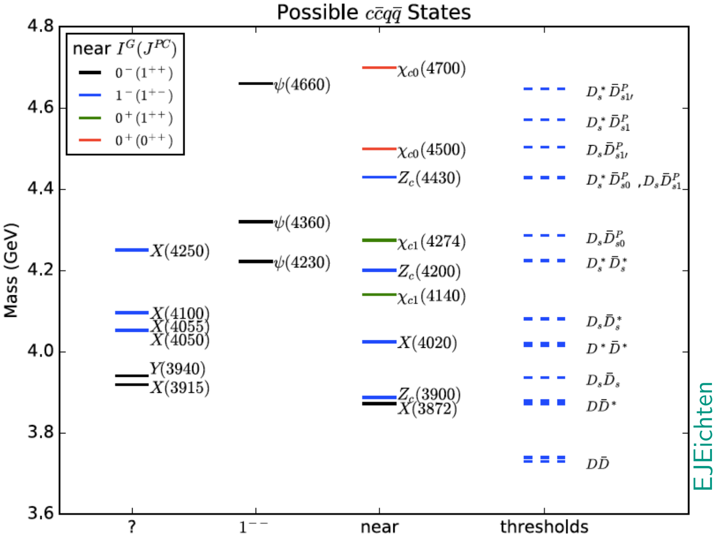
near threshold states have possible molecule component

"¿. . . ?" need more info

if $J^{PC} = 0^{++}$, ¿$X(3915)$? possible 2^3P_2

¿$\psi(4660)$? possible $5S$

$\psi(4230)$, ¿$\psi(4360)$? possible hybrids



When can we find $(b\bar{b})$ analogues?

Quarkonium-associated states: $M \gtrsim$ threshold: $X(3872)$ etc.

Mostly narrow, seen in hadronic transitions or decays

What are they?

Quarkonium (+ coupled-channels, thresholds)

Threshold effects

New body plans:

quarkonium hybrids ($q\bar{q}g$)

two-quark–two-antiquark states, including

dimeson “molecules”

tetraquarks

diquarkonium · hadroquarkonium

and superpositions!

(crypto)pentaquarks

CP violation might be large and observable (1980–81)

CP Nonconservation in Cascade Decays of B Mesons

Ashton B. Carter and A. I. Sanda
Rockefeller University, New York, New York 10021
(Received 2 June 1980)

General techniques are introduced to expose new CP-nonconserving effects in cascade decays of B mesons. These effects are computed in the Kobayashi-Maskawa model. The CP asymmetries so obtained range from 2% to 20% if the parameters are in the favorable range $s_3 < s_2 \lesssim 0.1$. Effects of this size should be observable in upcoming experiments.

NOTES ON THE OBSERVABILITY OF CP VIOLATIONS IN B DECAYS

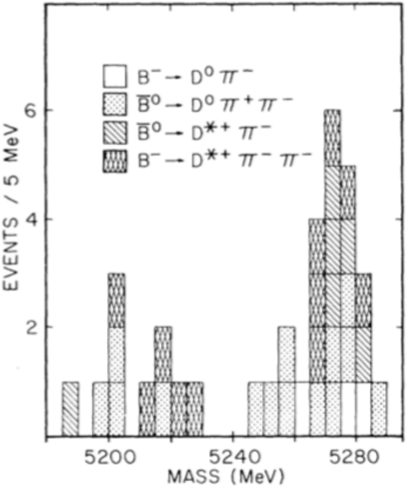
I.I. BIGI
Institut für Theor. Physik der RWTH Aachen, D-5100 Aachen, FR Germany

A.I. SANDA[1]
Rockefeller University, New York 10021, USA

Received 16 June 1981

We describe a general method of exposing CP violations in on-shell transitions of B mesons. Such CP asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large CP asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing CP tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

Reconstruction of B Mesons (CLEO, 1983)

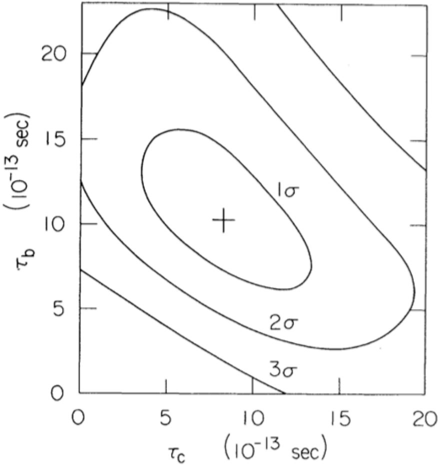


PDG: I, J, P still need confirmation!

MAC & Mark II find unexpectedly long b-hadron lifetime (1983)

Charm lifetimes [fs]

D^+ : 1040 ± 7
D^0 : 410.1 ± 1.5
D_s : 504 ± 4
Λ_c : 200 ± 6
Ξ_c^+ : 442 ± 26
Ξ_c^0 : 112^{+13}_{-10}
Ω_c : 268^{+10}_{-26}

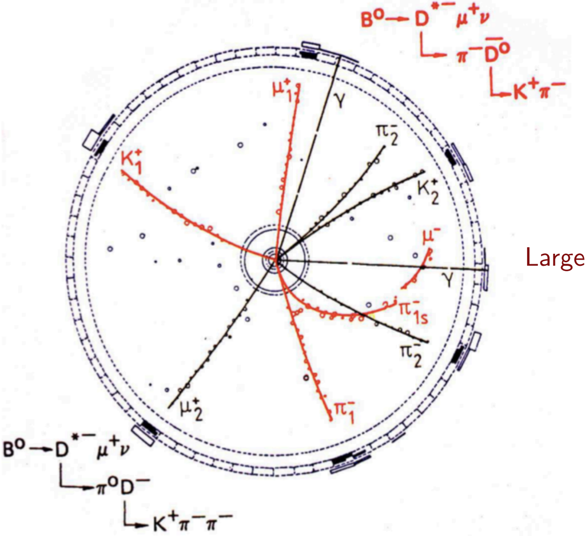


Beauty lifetimes [fs]

B^+ : 1638 ± 4
B^0 : 1519 ± 4
B_s : 1510 ± 4
Λ_b : 1471 ± 9
Ξ_b^- : 1572 ± 40
Ξ_b^0 : 1480 ± 30
Ω_b : 1640^{+180}_{-170}

Evidence for small $|V_{cb}| \approx 0.05$

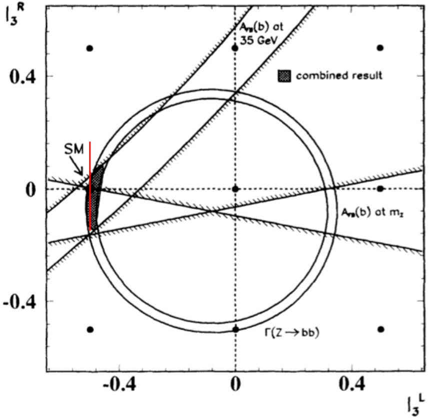
B^0-$\bar{B}^0$ Mixing: the golden event from ARGUS (1987)



Large mixing $\rightsquigarrow$ large m_t

UA1 same-sign dimuons $\rightsquigarrow$ $B_s^0 - \bar{B}_s^0$ mixing (1987)

b properties imply top-quark partner must exist (1992)

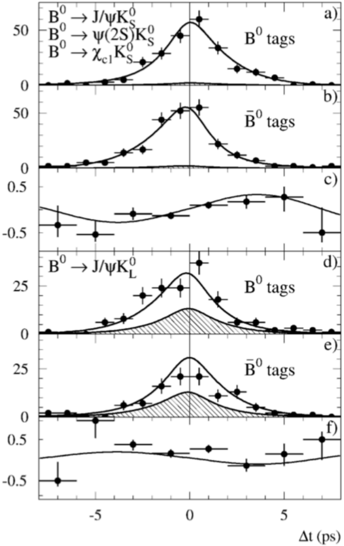


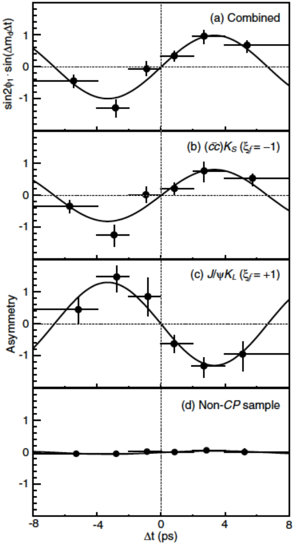
$$L_b \equiv 2I_{3L} - 2Q_b \sin^2\theta_W, \; R_b \equiv 2I_{3R} - 2Q_b \sin^2\theta_W$$

$\Gamma(Z^0 \to b\bar{b})$ measures $(L_b^2 + R_b^2)$, $A_{\text{peak}}^{(b\bar{b})}$ $(L_b^2 - R_b^2)/(L_b^2 + R_b^2)$, LE FB asym $A(b\bar{b}) \propto (R_b - L_b)$

$$\boxed{I_{3L} = -\tfrac{1}{2}; \; I_{3R} = 0}$$

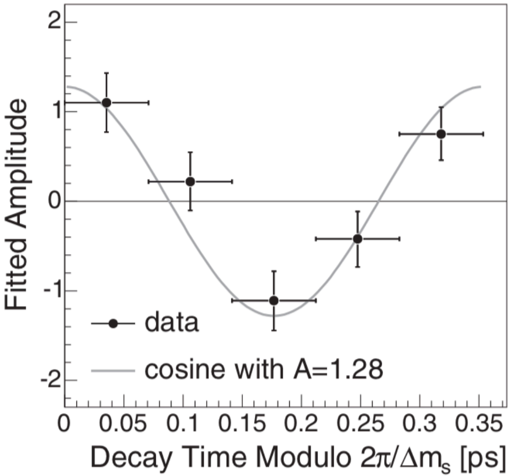
Observation of *large* CP violation in B^0 decays (*BABAR* & Belle, 2001)





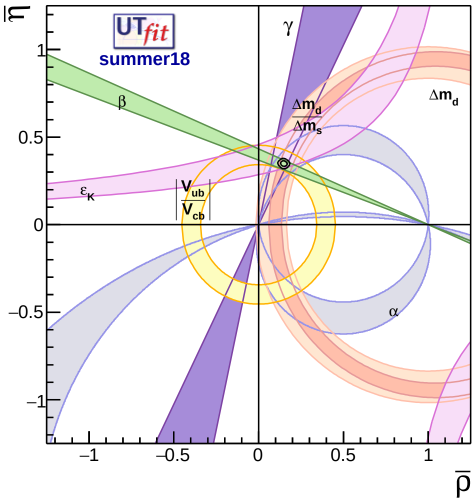
$\sin 2\beta \approx 0.59$ $\sin 2\phi_1 \approx 0.99$

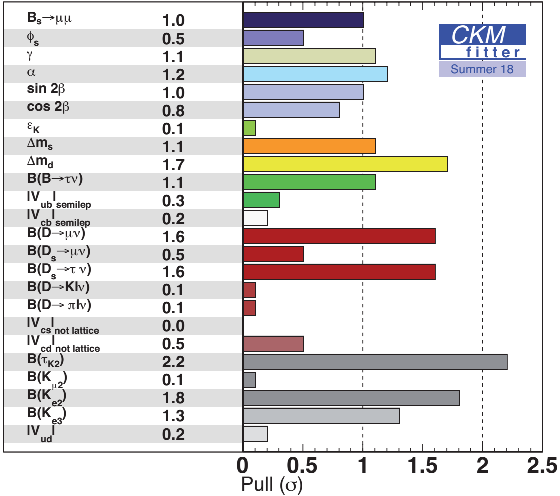
Observation of $B_s^0 - \bar{B}_s^0$ Oscillations (CDF, 2006)



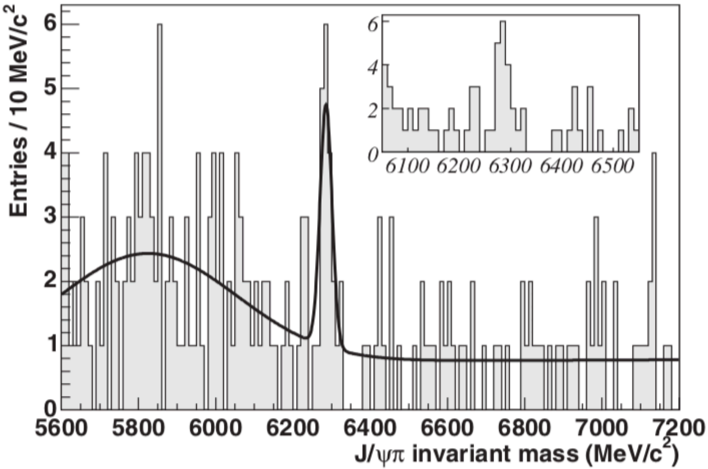
$$\Delta m_s \approx 17.77 \text{ ps}^{-1}$$

Precision tests of the CKM paradigm





Reconstruction of B_c meson (CDF, 2006)



$M(B_c) = 6274.9 \pm 0.8$ MeV (Test of lattice QCD prediction)

Mesons with beauty and charm: stress test for NRQM, LQCD

B_c: weak decays only

$b \to c \qquad c \to s \qquad b\bar{c} \to W^-$

$B_c \to J/\psi\pi$: $(Q\bar{Q})$ transmutation

Rich $(b\bar{c})$ excitation spectrum; interpolates $J/\psi, \Upsilon$ ($\neq$ masses)

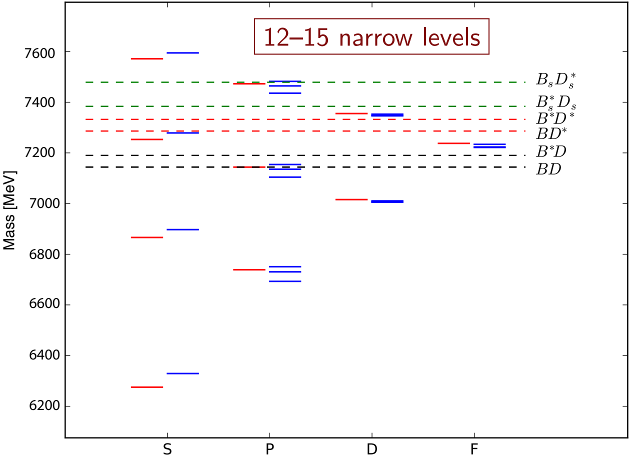
Excited states below $BD \to B_c + \ldots$

$B_c(2S) \to B_c(1S) + \pi\pi$

P states: γ transitions

Many states observable at LHC, Tera$Z$

Update: Eichten & CQ (2019) using "frozen-α_s" potential, new approach to spin splittings



Observing the B_c spectrum: $\pi\pi$ transitions

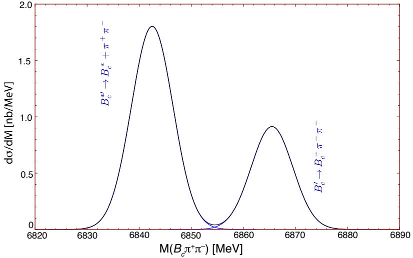
Combine predicted production rates (BCVEGPY2.2) with calculated branching fractions to obtain expectations for $\pi\pi$ transition rates
$\rightsquigarrow$ *peak heights:* $B_c^{*\prime}/B_c' \approx 2.5$

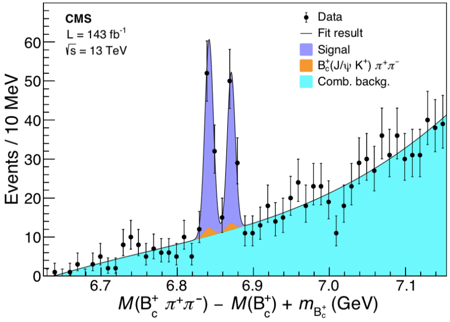
M1 $B_c^* \to \cancel{\gamma} B_c$ unobserved

$[M(B_c^{*\prime}) - M(B_c')] - [M(B_c^*) - M(B_c)]$
≈ -23 MeV: $B_c^{*\prime}$ lower peak

2S $\to \pi\pi +$ 1S transitions observed by ATLAS, CMS, LHC*b*

CMS separation: -29 MeV





Observing the B_c spectrum: E1 transitions

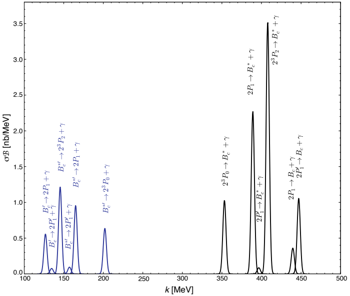
E1 spectroscopy in the $(b\bar{b})$ family:
LHC experiments discovered χ''_{b1}, χ''_{b2}.

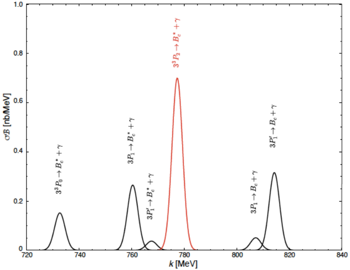
Incentive for the search: $2S \to 2P$ and $2P \to 1S$ transitions, assuming missing $B_c^* \to B_c \not\gamma$ in the reconstruction.

$3S, 3P$ yields $\approx \frac{1}{4} \times$ $2P \to 1S$ lines, but higher γ energies may aid detection.

$$\boxed{3^3P_2(7154) \to B_c^*\gamma(777\ \text{MeV})}$$

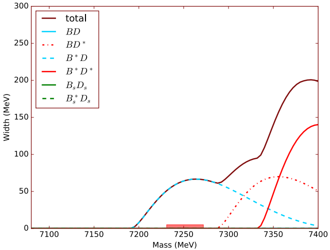
Encourage search for $(3,2)P(b\bar{c})$.

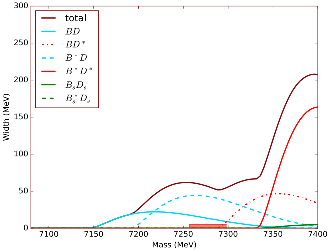




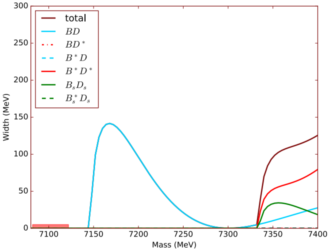
Mesons with beauty and charm: states above flavor threshold

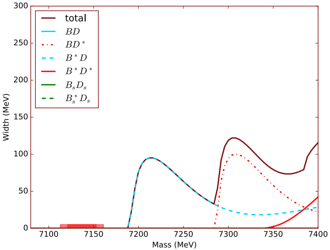
$3S$ states above threshold have significant decay widths

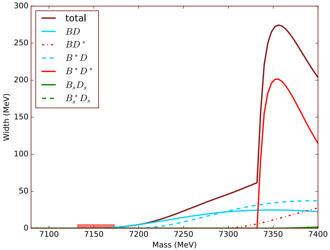




$3P$ states just below threshold; $J = 1$ may have significant mixing







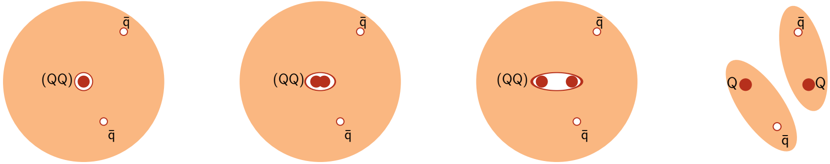
Strong dynamics greatly simplifies for $M_Q \gg \Lambda_{\mathrm{QCD}}$

Symmetry independent of dynamics of light degrees of freedom

Heavy-light systems: $(c\bar{q}), (b\bar{q}), (cqq), (bqq), (ccq), (cbq), (bbq)$ $(q = u, d, s)$
HQET: systematic expansion in powers of $\Lambda_{\mathrm{QCD}}/M_Q$
HQS relations among spectra in $[(c\bar{q}), (b\bar{q}), (ccq), (bcq), (bbq)]$ and $[(cqq), (bqq)]$
QED analogue: hydrogen atom $(e^- p^+)$

Nonrelativistic $(Q\bar{Q})$: bound-state masses $\mathcal{M} \approx 2M_Q$
NRQCD: systematic expansion in powers of v/c
Quarkonium systems: $(c\bar{c}), (b\bar{b}), (b\bar{c})$
heavy quark velocity: $p_Q/M_Q \approx v/c \ll 1$
binding energy: $2M_Q - \mathcal{M} \approx M_Q v^2/c^2$
QED analogs: positronium (e^+e^-), "true" muonium $(\mu^+\mu^-)$, muonium (μ^+e^-)

Heavy quark symmetry $\Rightarrow$ stable heavy tetraquarks $Q_i Q_j \bar{q}_k \bar{q}_l$



HQS relates DHTQ mass to masses of QQq, Qqq, $Q\bar{q}$.

Lightest $bb\bar{u}\bar{d}$, $bb\bar{u}\bar{s}$, $bb\bar{d}\bar{s}$ states: (likely) no strong decays.

Heavier $bb\bar{q}_k\bar{q}_l$, $cc\bar{q}_k\bar{q}_l$, $bc\bar{q}_k\bar{q}_l \to Q\bar{q} + Q\bar{q}$ might be seen as "double-flavor" resonances near threshold.

Observing a weakly decaying double-beauty state would establish the existence of tetraquarks and illuminate the role of heavy color-$\bar{\mathbf{3}}$ diquarks as hadron constituents.

Eichten & CQ 1707.09575

HQS relations for ground-state tetraquark masses

$$m(Q_iQ_j\bar{q}_k\bar{q}_l) - m(Q_iQ_jq_m) = m(Q_xq_kq_l) - m(Q_x\bar{q}_m)$$

$+$ finite-mass corrections RHS is determined from data

One doubly heavy baryon observed, Ξ_{cc}; others from model calculations*

LHCb: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV

*We adopt Karliner & Rosner, *PRD* **90**, 094007 (2014)

Strong decays $(Q_iQ_j\bar{q}_k\bar{q}_l) \not\to (Q_iQ_jq_m) + (\bar{q}_k\bar{q}_l\bar{q}_m)$ $\forall$ ground states

Consider decays to pairs of heavy–light mesons case-by-case

Expectations for ground-state tetraquark masses, in MeV

State	J^P	$m(Q_i Q_j \bar{q}_k \bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	$D^+ D^{*0}$ 3876	102
$\{cc\}[\bar{q}_k \bar{s}]$	1^+	4156	$D^+ D_s^{*+}$ 3977	179
$\{cc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	4146, 4167, 4210	$D^+ D^0, D^+ D^{*0}$ 3734, 3876	412, 292, 476
$[bc][\bar{u}\bar{d}]$	0^+	7229	$B^- D^+ / B^0 D^0$ 7146	83
$[bc][\bar{q}_k \bar{s}]$	0^+	7406	$B_s D$ 7236	170
$[bc]\{\bar{q}_k \bar{q}_l\}$	1^+	7439	$B^* D / B D^*$ 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	$B^* D / B D^*$ 7190/7290	82
$\{bc\}[\bar{q}_k \bar{s}]$	1^+	7445	$D B_s^*$ 7282	163
$\{bc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	7461, 7472, 7493	$B D / B^* D$ 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	1^+	10482	$B^- \bar{B}^{*0}$ 10603	$\boxed{\mathbf{-121}}$
$\{bb\}[\bar{q}_k \bar{s}]$	1^+	10643	$\bar{B} \bar{B}_s^* / \bar{B}_s \bar{B}^*$ 10695/10691	$\boxed{\mathbf{-48}}$
$\{bb\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	10674, 10681, 10695	$B^- B^0, B^- B^{*0}$ 10559, 10603	115, 78, 136

Cf. M. Karliner & J. L. Rosner model, Phys. Rev. Lett. **119**, 202001 (2017) [arXiv:1707.07666].
Estimate deeper binding, so additional *bc* and *cc* candidates.

Real-world candidates for stable tetraquarks

$J^P = 1^+$ $\{bb\}[\bar{u}\bar{d}]$ meson, bound by 121 MeV

(77 MeV below $B^-\bar{B}^0\gamma$)

$$\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{d}]}(10482)^- \to \Xi^0_{bc}\bar{p},\ B^-D^+\pi^-, \text{ and } \underbrace{B^-D^+\ell^-\bar{\nu}}_{\text{manifestly weak!}}$$

$J^P = 1^+$ $\{bb\}[\bar{u}\bar{s}]$ and $\{bb\}[\bar{d}\bar{s}]$ mesons, bound by 48 MeV

(3 MeV below $BB_s\gamma$)

$$\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{s}]}(10643)^- \to \Xi^0_{bc}\overline{\Sigma}^- \qquad \mathcal{T}^{\{bb\}}_{[\bar{d}\bar{s}]}(10643)^0 \to \Xi^0_{bc}(\bar{\Lambda}, \overline{\Sigma}^0)$$

Unstable doubly heavy tetraquarks

Resonances in "wrong-sign" (double flavor) combinations DD, DB, BB?

$J^P = 1^+\ \mathcal{T}^{\{cc\}++}_{[\bar{d}\bar{s}]}(4156) \to D^+ D_s^{*+}$: *prima facie evidence* for non-$q\bar{q}$ level

Double charge / double charm

(New kind of resonance: no attractive force at the meson–meson level.)

Also, $1^+\ \mathcal{T}^{\{bb\}}_{\{\bar{q}_k\bar{q}_l\}}(10681)^{0,-,--}$, $\mathcal{Q} = +78$ MeV $\quad 1^+\ \mathcal{T}^{\{bc\}}_{[\bar{u}\bar{d}]}(7272)^0$, $\mathcal{Q} = +82$ MeV

$0^+\ \mathcal{T}^{[bc]}_{[\bar{u}\bar{d}]}(7229)^0$, $\mathcal{Q} = +83$ MeV $\quad 1^+\ \mathcal{T}^{\{cc\}}_{[\bar{u}\bar{d}]}(3978)^+$, $\mathcal{Q} = +102$ MeV

Aside: $^3\mathrm{D}_3$ *and* $^3\mathrm{F}_4$ $c\bar{c}$ *mesons still to be identified in* $D\bar{D}$, *etc.*

LHC*b* $^3\mathrm{D}_3$ candidate (2019)

Homework for experiment

$\mathcal{T}1.$ Look for double-flavor resonances near threshold.

$\mathcal{T}2.$ Measure cross sections for final states containing 4 heavies: $Q_i\bar{Q}_i Q_j \bar{Q}_j$.

$\mathcal{T}3.$ Discover and determine masses of doubly-heavy baryons.

needed to implement HQS calculation of tetraquark masses

intrinsic interest in these states:

compare heavy–light mesons, possible core excitations

Resolve Ξ_{cc}^{+} uncertainty (SELEX/LHCb)

$\mathcal{T}4.$ Find stable tetraquarks through weak decays. Lifetime: $\sim \frac{1}{3}$ ps ??

Homework for theory

$\mathcal{T}5$. Develop expectations for production. A. Ali et al., "Prospects of discovering stable double-heavy tetraquarks at a Tera-Z factory," arXiv:1805.02535 $\rightarrow$ PLB.

$\mathcal{T}6$. Refine lifetime estimates for stable states.

$\mathcal{T}7$. Understand how color configurations evolve with QQ (and $\bar{q}\bar{q}$) masses. J.-M. Richard, et al., "Few-body quark dynamics for doubly-heavy baryons and tetraquarks," arXiv:1803.06155, Phys. Rev. C **97**, 035211 (2018).

$\mathcal{T}8$. Investigate stability of different body plans in the heavy-quark limit.
. . . up to $(Q_iQ_j)(Q_kQ_l)(Q_mQ_n)$: $B = 2$, but $Q_pQ_qQ_r$ color structure?

Flavor: the problem of identity

What makes an electron an electron, a top quark a top quark, . . . ?

We do not have a clear view of how to approach the
diverse character of the constituents of matter

CKM paradigm: extraordinarily fruitful framework in hadron sector

BUT—many parameters: no clue what determines them,
nor at what energy scale they are set

Even if Higgs mechanism explains *how* masses and mixing angles arise,
we do not know *why* they have the values we observe

$\boxed{\text{Physics beyond the standard model!}}$

Flavor: the problem of identity (continued)

Parameters of the Standard Model

3	Coupling parameters, α_{s}, α_{em}, $\sin^2\theta_{\mathsf{W}}$
2	Parameters of the Higgs potential
1	Vacuum phase (QCD)
6	Quark masses
3	Quark mixing angles
1	CP-violating phase
3	Charged-lepton masses
3	Neutrino masses
3	Leptonic mixing angles
1	Leptonic CP-violating phase ($+$ Majorana phases?)
26^+	Arbitrary parameters

Questions concerning the problem of identity

F1. Can we find evidence of right-handed charged-current interactions? Is nature built on a fundamentally asymmetrical plan, or are the right-handed weak interactions simply too feeble for us to have observed until now, reflecting an underlying hidden symmetry?

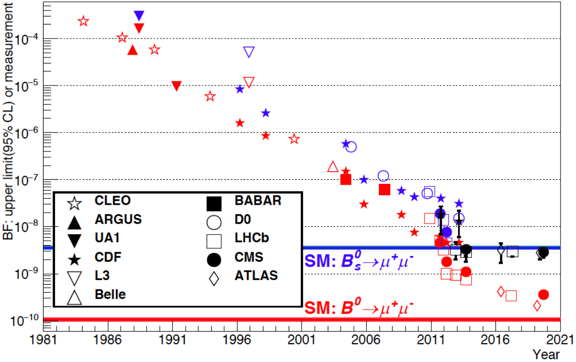
F2. What is the relationship of left-handed and right-handed fermions?

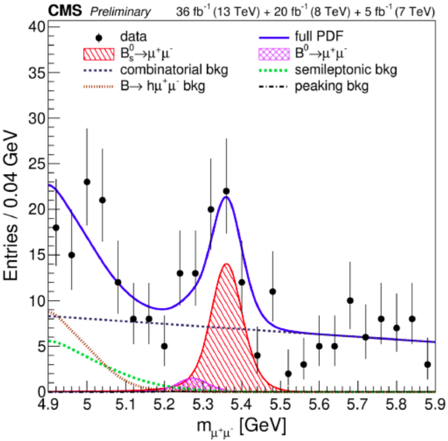
F3. Are there additional electroweak gauge bosons, beyond $W^{\pm}$ and Z?

F4. Are there additional kinds of matter?

F5. Is charged-current universality exact?
What about lepton-flavor universality?

$B_{(s,d)} \to \ell^+\ell^-$ search and observation





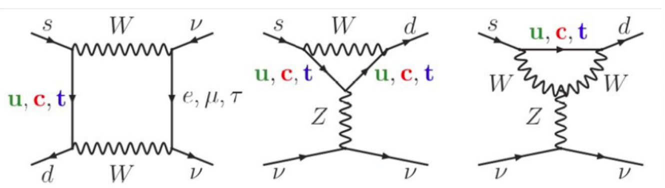
SM: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

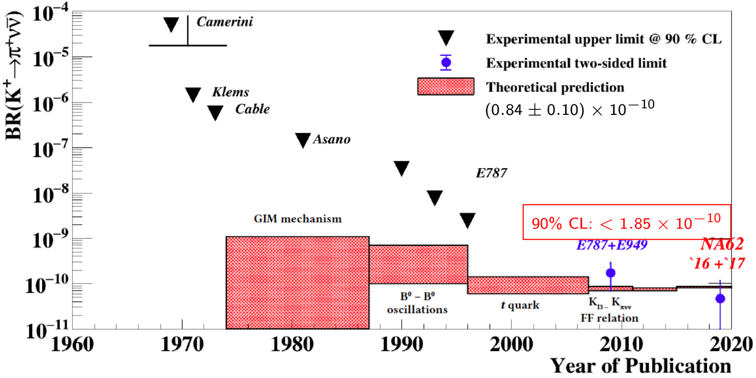
$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Recent CMS: $\mathcal{B}(B_s \to \mu^+\mu^-) = [2.9^{+0.7}_{-0.4} \pm 0.2(f_s/f_d)] \times 10^{-9}$

Coming: $\tau(B_s \to \mu^+\mu^-)$, $B_{(d,s)} \to e^+e^-$ searches

$K^+ \to \pi^+ \nu\bar{\nu}$ search and observation





Searches for flavor-changing neutral currents

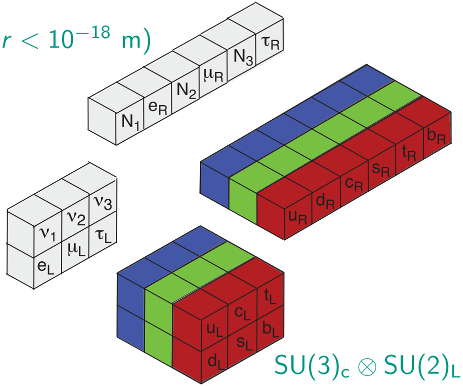
F6. Where are flavor-changing neutral currents in quark transitions? In the standard model, these are absent at tree level and highly suppressed by the Glashow–Iliopouolos–Maiani mechanism. They arise generically in proposals for physics beyond the standard model, and need to be controlled. And yet we have made no sightings!
Why not? $B_{s,d} \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, ...

F7. Can we detect flavor-violating decays $H(125) \to \tau^\pm\mu^\mp, \ldots$?

F8. How well can we test the standard-model correlation among $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, $\mathcal{B}(B_s \to \mu^+\mu^-)$, and the quark-mixing matrix parameter γ?

Have we found the "periodic table" of elementary particles?

Pointlike spin-1/2 constituents ($r < 10^{-18}$ m)



$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_c \otimes U(1)_{em}$

F9. What do generations mean? Is there a family symmetry?

F10. Why are there three families of quarks and leptons? (Is it so?)

F11. Are there new species of quarks and leptons? exotic charges?

More questions concerning the problem of identity

F12. Is there any link to a dark sector?

F13. What will resolve the disparate values of $|V_{ub}|$ and $|V_{cb}|$ measured in inclusive and exclusive decays?

F14. Is the 3×3 (CKM) quark-mixing matrix unitary?

F15. Why is isospin a good symmetry? What does it mean?

F16. Can we find evidence for charged-lepton flavor violation?

F17. Will we establish and diagnose a break in the SM?

F18. Do flavor parameters *mean* anything at all?
Contrast the landscape perspective.

F19. If flavor parameters have meaning (beyond engineering information), what is the meta-question?

The top quark touches many topics in particle physics

t1. How well can we constrain V_{tb} in single-top production, ...?

t2. How well can we constrain the top-quark lifetime? How free is t?

Recent ATLAS: $\Gamma(t) = 1.9 \pm 0.5$ GeV (SM 1.32 GeV)

t3. Are there $t\bar{t}$ resonances?

t4. Can we find evidence of flavor-changing top decays $t \to (Z, \gamma)(c, u)$?

Questions about EWSB and the Higgs Sector

H1. Is $H(125)$ the only member of its clan? Might there be others—charged or neutral—at higher or lower masses?

H2. Does $H(125)$ fully account for electroweak symmetry breaking? Does it match standard-model branching fractions to gauge bosons? Are absolute couplings to W and Z as expected in the standard model?

H3. Are all production rates as expected? Any surprise sources of $H(125)$?

H4. What accounts for the immense range of fermion masses?

H5. Is the Higgs field the only source of fermion masses?
Are fermion couplings proportional to fermion masses? $\mu^+\mu^-$ soon?
How can we detect $H \to c\bar{c}$? e^+e^-?? (basis of chemistry)

H6. What role does the Higgs field play in generating neutrino masses?

More questions about EWSB and the Higgs Sector

*H*7. Can we establish or exclude decays to new particles? Does $H(125)$ act as a portal to hidden sectors? When can we measure Γ_H?

*H*8. Can we detect flavor-violating decays $(\tau^{\pm}\mu^{\mp}, \ldots)$?

*H*9. Do loop-induced decays $(gg, \gamma\gamma, \gamma Z)$ occur at standard-model rates?

*H*10. What can we learn from rare decays $(J/\psi\,\gamma, \Upsilon\,\gamma, \ldots)$?

*H*11. Does the EW vacuum seem stable, or suggest a new physics scale?

*H*12. Can we find signs of new strong dynamics or (partial) compositeness?

*H*13. Can we establish the *HHH* trilinear self-coupling?

*H*14. How well can we test the notion that *H* regulates Higgs–Goldstone scattering, i.e., tames the high-energy behavior of *WW* scattering?

*H*15. Is the electroweak phase transition first-order?

See Dawson, Englert, Plehn, arXiv:1808.01324 $\rightsquigarrow$ *Phys. Rep.*

An exercise for all of us

How do *you* assess the scientific potential *for Beauty and in general* of

(a) The High-Luminosity LHC?
(b) The High-Energy LHC?
(c) A 100-TeV pp Collider (FCC-hh)?
(d) A 250-GeV ILC?
(e) A circular Higgs factory (FCC-ee or CEPC)?
(f) A 380-GeV CLIC?
(g) A $\mu^+\mu^- \to H$ Higgs factory?
(h) LHeC / FCC-eh? (or an electron–ion collider?)
(i) A muon-storage-ring neutrino factory?
(j) A multi-TeV muon collider?
(k) The instrument of your dreams?