

Weak decays of heavy flavors

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DESY, Hamburg

Workshop: Double charm tetraquarks and other exotics

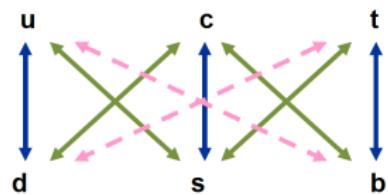
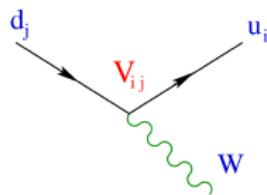
Nov. 23, 2021, Lyon

Standard Model of Particle Physics - Particle Spectrum

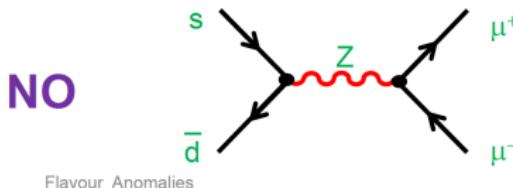
mass → $\approx 2.3 \text{ MeV}/c^2$	charge → 2/3	spin → 1/2	mass → $\approx 1.275 \text{ GeV}/c^2$	charge → 2/3	spin → 1/2	mass → $\approx 173.07 \text{ GeV}/c^2$	charge → 2/3	spin → 1/2	mass → 0	charge → 0	spin → 1	mass → $\approx 126 \text{ GeV}/c^2$	charge → 0	spin → 0
QUARKS	up		charm			top			gluon			Higgs boson		
$\approx 4.8 \text{ MeV}/c^2$	-1/3	1/2	$\approx 95 \text{ MeV}/c^2$	-1/3	1/2	$\approx 4.18 \text{ GeV}/c^2$	-1/3	1/2	γ	0	1	photon		
down			strange			bottom								
LEPTONS	electron		muon			tau			Z boson			GAUGE BOSONS		
$0.511 \text{ MeV}/c^2$	-1	1/2	$105.7 \text{ MeV}/c^2$	-1	1/2	$1.777 \text{ GeV}/c^2$	-1	1/2	$91.2 \text{ GeV}/c^2$	0	1			
electron neutrino			muon neutrino			tau neutrino			W boson					

Flavour Changing Charged Currents

$$\mathcal{L}_{\text{CC}} = - \frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1 - \gamma_5) V_{ij} d_j + \sum_l \bar{v}_l \gamma^\mu (1 - \gamma_5) l \right] + \text{h.c.}$$



Flavour Conserving Neutral Currents (GIM)



Flavour Anomalies

LHCb, 1706.00758
 $\text{Br}(K_S \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-9}$
(95% CL)

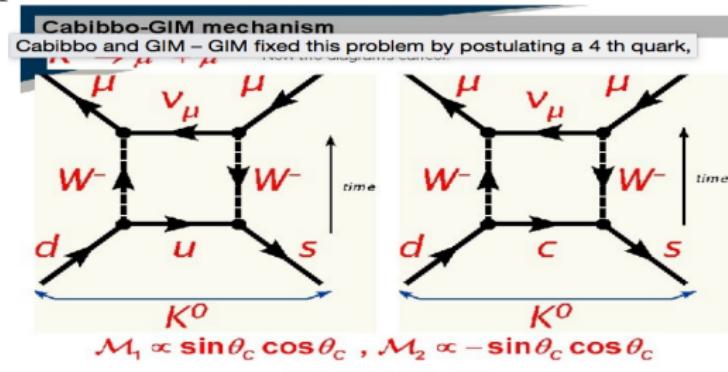
A. Pich

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Glashow-Iliopoulos-Maiani (GIM) Mechanism



Loop-induced FCNC amplitude in $s \rightarrow d\mu^+\mu^-$ decay



The Cabibbo-Kobayashi-Maskawa Matrix

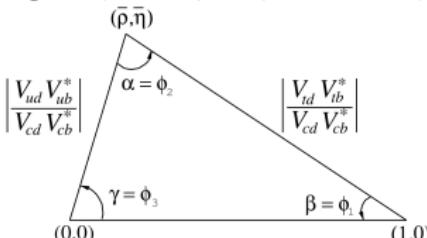
- Charged currents involving quarks: $J^\mu W_\mu^+ = -\frac{g}{\sqrt{2}} \bar{U}_L^i \gamma^\mu W_\mu^+ V_{\text{CKM}} D_L^i$

$$V_{\text{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Requires four parameters, one of which is a phase inducing CP violation; customary to use the handy Wolfenstein parametrization

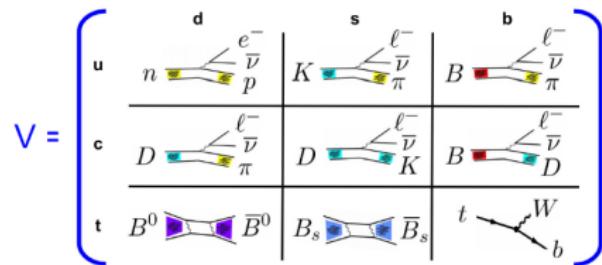
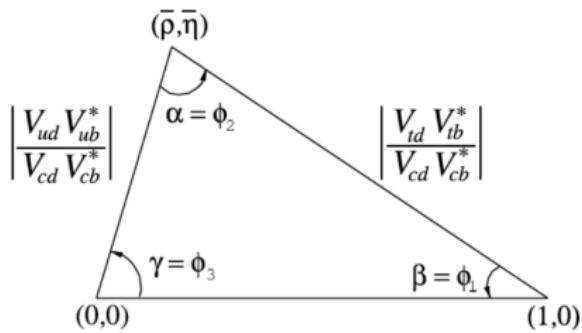
$$V_{\text{CKM}} \simeq \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda(1 + iA^2\lambda^4\eta) & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2(1 + i\lambda^2\eta) & 1 \end{pmatrix}$$

- Four parameters: A, λ, ρ, η ; $\bar{\rho} = \rho(1 - \lambda^2/2)$, $\bar{\eta} = \eta(1 - \lambda^2/2)$
- The CKM-Unitarity triangle [$\phi_1 = \beta$; $\phi_2 = \alpha$; $\phi_3 = \gamma$]



Main target of flavour physics

Precise determination of the CKM-Matrix Elements and Phases of the Unitarity Triangle!



$|V_{cb}|$ from Inclusive decays $B \rightarrow X_c \ell \bar{\nu}_\ell$

Theoretical Method

Heavy Quark Mass Expansion and Operator Product Expansion (OPE)

[Chay, Georgi, Grinstein; Voloshin, Shifman; Bigi et al.; Manohar, Wise; Blok et al.]

- Perform an OPE: m_b is the largest scale

- Decay rate for $B \rightarrow X_c \ell \bar{\nu}_\ell$

$$\Gamma = \Gamma_0 + \frac{1}{m_b} \Gamma_1 + \frac{1}{m_b^2} \Gamma_2 + \frac{1}{m_b^3} \Gamma_3 + \dots$$

- Γ_i are power series in $\alpha_s(m_b)$ → Perturbation theory
- Γ_0 is the decay of a free quark ("Parton Model")
- Γ_1 vanishes due to the absence of dimension-5 operators
- Γ_2 is expressed in terms of two non-perturbative parameters

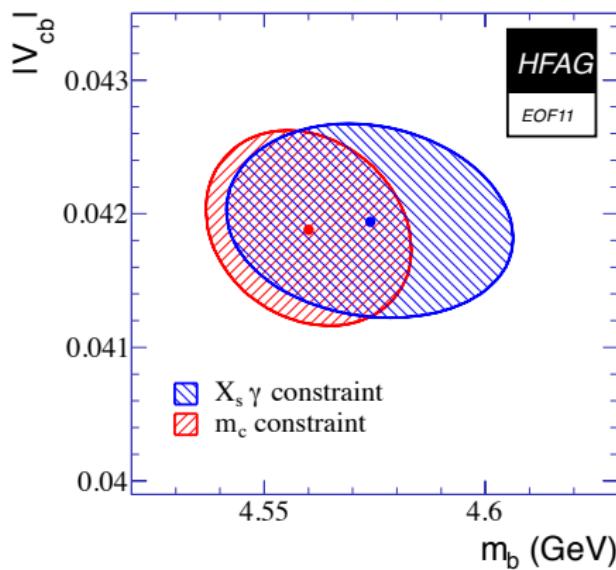
$$2M_B \lambda_1 = \langle B(v) | \bar{Q}_v (iD)^2 Q_v | B(v) \rangle$$

$$6M_B \lambda_2 = \langle B(v) | \bar{Q}_v \sigma_{\mu\nu} [iD^\mu, iD^\nu] Q_v | B(v) \rangle$$

λ_1 : Kinetic energy, λ_2 : Chromomagnetic moment (also called μ_π^2 and μ_G^2)

- Γ_3 involves several new parameters

$|V_{cb}|$ vs. m_b : $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (PDG 2020)



- HQET has yielded precise determinations of the matrix elements V_{cb} and V_{ub} (PDG 2020)

$|V_{cb}|$ from $B \rightarrow D^* \ell \nu_\ell$ decays

$B \rightarrow D^* \ell \nu_\ell$ decays

$$\frac{d\Gamma}{d\omega} = \frac{G_F^2}{4\pi^3} (\omega^2 - 1)^{1/2} m_{D^*}^3 (m_B - m_{D^*})^2 \mathcal{G}(\omega) |V_{cb}|^2 |\mathcal{F}(\omega)|^2$$

- $\mathcal{F}(\omega)$ = Isgur–Wise function: $\mathcal{G}(\omega)$ phase space factor:

$$\mathcal{G}(1) = \mathcal{F}(1) = 1,$$

- Leading Λ_{QCD}/m_b corrections absent (Luke's theorem)

- Need second order correction to $\mathcal{F}(\omega = 1)$, and slope ρ^2

$$\mathcal{F}(\omega) = \mathcal{F}(1) [1 - 8\rho^2 z + + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3]$$

where $z = (\sqrt{\omega+1} - \sqrt{2})/(\sqrt{\omega+1} + \sqrt{2})$, $\mathcal{F}(1) = \eta_A [1 + \delta_{1/m^2} + \dots]$

- strong correlation between $\mathcal{F}(1)$ and ρ^2

$$\mathcal{F}(1)|V_{cb}| =$$

$$(35.27 \pm 0.52) \times 10^{-3} [\text{Grinstein \& Kobach, PLB771, 359 (2017)}]$$

$$|V_{cb}| = (38.4 \pm 0.7 \pm 0.5) \times 10^{-3} [\text{Lattice QCD (Fermilab, MILC, 2017), E}]$$

$|V_{ub}|$

- Use of OPE to calculate inclusive spectra:

From End-point spectra in $B \rightarrow X_u \ell \nu_\ell$ and $B \rightarrow X_s \gamma$

- Decay rate in the cut-region depends on the shape function $f(\omega)$

$$2M_B f(\omega) = \langle B | \bar{Q}_v \delta(\omega + \mathbf{n} \cdot (\mathbf{i}D)) Q_v | B \rangle; \quad (n.v = 1, n^2 = 0)$$

- Leading Shape Function in $B \rightarrow X_s \gamma$; ($x = \frac{2E_\gamma}{m_b}$)

[Neubert; Bigi et al.]

$$\frac{d\Gamma}{dx} = \frac{G_F^2 \alpha m_b^5}{32\pi^4} |V_{ts} V_{tb^*}|^2 |C_7|^2 f(1-x)$$

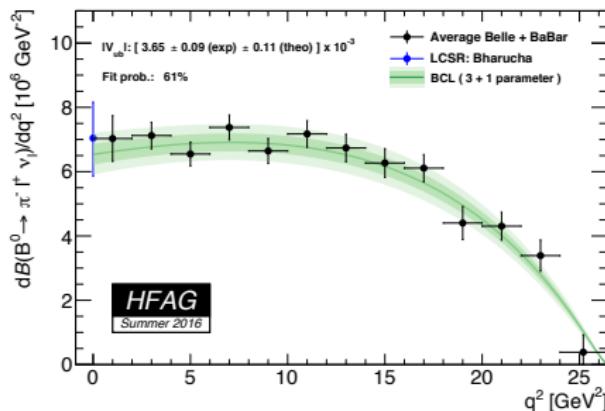
- E_ℓ - and M_{X_u} -spectra in $B \rightarrow X_u \ell \nu_\ell$ governed also by $f(x)$
- $f(x)$ can be measured in $B \rightarrow X_s \gamma$
- $|V_{ub}| = (4.25 \pm 0.12^{+0.15}_{-0.14}) \times 10^{-3}$

$|V_{ub}|$ from exclusive decays $B \rightarrow \pi \ell \nu_\ell$

$$\langle \pi(p_\pi) | \bar{b} \gamma_\mu q | B(p_B) \rangle = \left((p_B + p_\pi)_\mu - \frac{m_B^2 - m_\pi^2}{q^2} q_\mu \right) F_+(q^2) + \frac{m_B^2 - m_\pi^2}{q^2} F_0(q^2) q_\mu$$

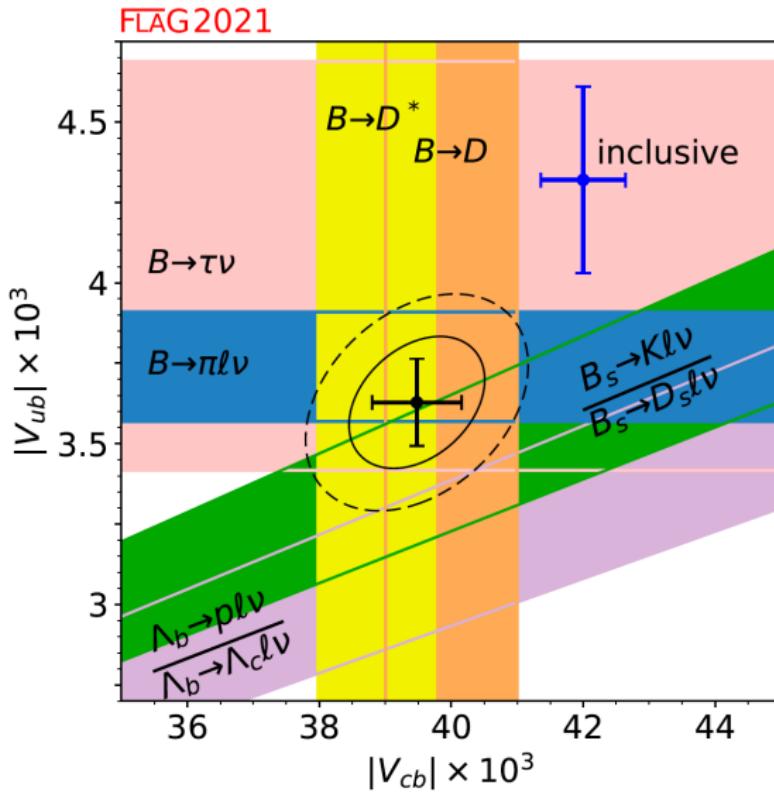
Techniques used to determine $F_+(q^2)$, $F_0(q^2)$

- Light-cone QCD sum rules [A. Bharucha, JHEP 1205 (2012), 092]
- Lattice-QCD (Unquenched) [HPQCD, FNAL/MILC, FLAG]

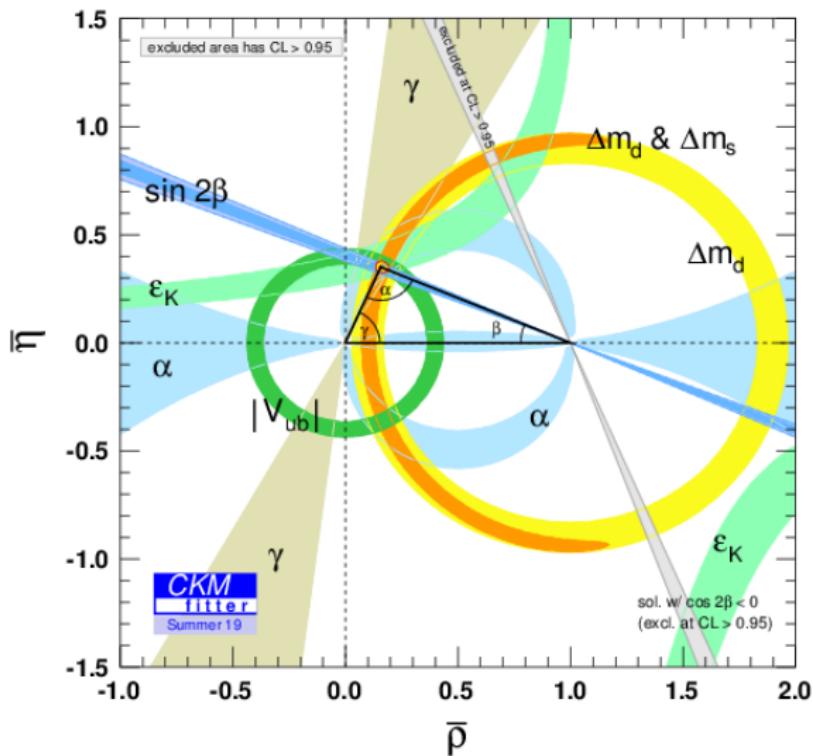


- $|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$

$|V_{cb}| - |V_{ub}|$:current status



Current Status of the CKM-Unitarity Triangle [CKMfitter]



Inclusive decays of heavy quarks

- Concentrating on hadrons with a b quark, the starting point is the transition operator $\mathcal{T}(b \rightarrow f \rightarrow b)$, describing the forward scattering amplitude of b quarks via an intermediate state f

$$\Gamma(H_b) = \frac{1}{2M_{H_b}} \langle H_b | \mathcal{T}(b \rightarrow f \rightarrow b) | H_b \rangle$$

- To second order in the weak interaction,

$$\mathcal{T}(b \rightarrow f \rightarrow b) = i \operatorname{Im} \int \{ \mathcal{L}_W(x) \mathcal{L}_W(0) \}_T$$

$\mathcal{L}_W(x) = \frac{G_F}{\sqrt{2}} [J_\mu J^{\mu\dagger} + h.c.]$ denotes the effective weak Lagrangian, and $\{.\}_T$ denotes the time-ordered product

- Treating m_b as a large parameter, a Wilson OPE allows to express the non-local operator \mathcal{T} as an infinite sum of local operators with increasing dimensions of $1/m_b$

$$\mathcal{T}(b \rightarrow f \rightarrow b) = \sum_n C_n(\mu) \mathcal{O}_n(\mu)$$

Inclusive decay widths

- To order $1/m_b^3$, one has

$$\Gamma(H_b \rightarrow f) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{CKM}|^2 \left[c_{3,b} \langle H_b | \bar{b}b | H_b \rangle + \frac{c_{5,b}}{m_b^2} \langle H_b | \bar{b} i\sigma_{\mu\nu} G^{\mu\nu} b | H_b \rangle \right. \\ \left. + 2 \sum_i \frac{c_{6,b}}{m_b^3} \langle H_b | (\bar{\Gamma}_i b q)(\bar{q}\Gamma_i b) | H_b \rangle + \dots \right]$$

- The lowest (dimension-3) operator for b -quarks is $\bar{b}b$. In the $m_b \rightarrow \infty$ limit all b -hadrons will have identical lifetimes
- Note: The first term is the Noether current for the heavy flavor quatum number, and hence its expectation value is determined by the beauty content of H_b :

$$\langle H_b | \bar{b}b | H_b \rangle = 1 + O(1/m_b^2)$$

- Using equation of motion, the operator $\bar{b}b$ is expanded in a series in $1/m_b$ (v_μ denotes the four-velocity of the heavy hadron H_b)

$$\langle H_b | \bar{b}b | H_b \rangle = \langle H_b | v_\mu \bar{b} \gamma_\mu b - \frac{1}{2m_b^2} \bar{b} [(iv.D)^2 - (iD)^2] b + \frac{1}{4m_b^2} \bar{b} i\sigma.Gb | H_b \rangle + \dots$$

Chromomagnetic and kinetic energy operators

- The difference in the lifetimes of the B meson and Λ_b baryon are proportional to $1/m_b^2$ and essentially determined by the expectation values of the chromomagnetic and kinetic energy operators
- The chromomagnetic operator $\bar{b}i\sigma_{\mu\nu}G^{\mu\nu}b$ appears in the expression for $\Gamma(H_b \rightarrow f)$ and in the expansion of $\bar{b}b$. Its expectation value vanishes for the baryon Λ_b : $\langle \Lambda_b | \bar{b}i\sigma_{\mu\nu}G^{\mu\nu}b | \Lambda_b \rangle = 0$
- For the B mesons, hyperfine splitting of the B^* and B gives:
$$\langle B | \bar{b}i\sigma_{\mu\nu}G^{\mu\nu}b | B \rangle = \frac{3}{2}(M_{B^*}^2 - M_B^2) \simeq 0.74 \text{ GeV}^2.$$
 This yields
$$G_B \equiv \frac{\langle B | \bar{b}i\sigma_{\mu\nu}G^{\mu\nu}b | B \rangle}{2m_b^2} \simeq 0.015$$
- The second term in the expansion of $\bar{b}b$ describes the kinetic energy of the b quark in the hadron H_b :

$$\langle H_b | \bar{b}[(iv.D)^2 - (iD)^2]b | H_b \rangle \simeq \langle H_b | \bar{b}(i\vec{D})^2b | H_b \rangle \equiv \langle (\vec{p}_b)^2 \rangle_{H_b}$$

- This is estimated as $K_{\Lambda_b} \simeq K_B \equiv \frac{\langle \vec{p}_b^2 \rangle_B}{m_b^2} \simeq 0.015$
- Expectations based on HQE are borne out by data (PDG 2021):
 $\tau(B^0) = (1.519 \pm .004) \times 10^{-12} \text{ s}; \tau(\Lambda_b) = (1.471 \pm .009) \times 10^{-12} \text{ s}$

Dimension-6 operators and $B^+ - B_d^0$ lifetime difference

- For the $B^+ - B_d^0$ lifetime difference, the $\mathcal{O}(1/m_b^2)$ chromomagnetic and kinetic operators are innocuous, as strong interactions obey isospin symmetry
- At $\mathcal{O}(1/m_b^3)$, one encounters dimension-6 operators, encoding interactions between the valence b and the light spectator quarks. For the dominant charge current $b \rightarrow c$ transition, they are given by the following $\Delta B = 1$ effective Hamiltonian

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* \sum_{d'=d,s; u'=u,c} V_{u'd'} [C_1(\mu) Q_1^{u',d'}(\mu) + C_2(\mu) Q_2^{u',d'}(\mu)] + h.c.$$

- The Wilson coefficients $C_i(\mu)$ contain the short-distance physics associated with the scale above the renormalization scale μ , and the weak interactions are encoded in the four-quark operators (i and j are color indices):

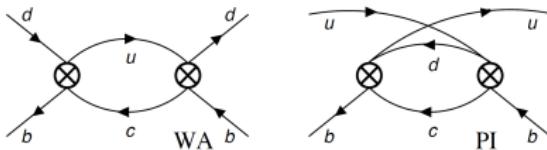
$$\begin{aligned} Q_1^{u',d'} &= \bar{b}_i \gamma_\mu (1 - \gamma_5) c_j \bar{u}'_j \gamma^\mu (1 - \gamma_5) d'_i \\ Q_2^{u',d'} &= \bar{b}_i \gamma_\mu (1 - \gamma_5) c_i \bar{u}'_j \gamma^\mu (1 - \gamma_5) d'_j \end{aligned}$$

Weak Annihilation and Pauli Interference Effects in H_b decays

- The so-called weak annihilation (WA) and Pauli interference (PI) effects, \mathcal{T}_3 , being suppressed by $O(1/m_b^3)$ are: $\mathcal{T}_3 = \mathcal{T}_u + \mathcal{T}_d$

$$\begin{aligned}\mathcal{T}^u &= \frac{G_F^2 m_b^2 |V_{cb}|^2}{6\pi} \left[|V_{ud}|^2 \left(F^u Q^d + F_S^u Q_S^d + G^u T^d + G_S^u T_S^d \right) \right. \\ &\quad \left. + |V_{cd}|^2 \left(F^c Q^d + F_S^c Q_S^d + G^c T^d + G_S^c T_S^d \right) \right] + (d \rightarrow s) \\ \mathcal{T}^d &= \frac{G_F^2 m_b^2 |V_{cb}|^2}{6\pi} \left[F^d Q^u + F_S^d Q_S^u + G^d T^u + G_S^d T_S^u \right].\end{aligned}$$

- The superscript F^q, F_S^q, G^q, G_S^q refer to the cq intermediate state



- Q^q, Q_S^q, T^q, T_S^q are the local dim-6 $\Delta B = 0$ operators (T^a are $SU(3)$ generators)

$$Q^q = \bar{b} \gamma_\mu (1 - \gamma_5) q \bar{q} \gamma^\mu (1 - \gamma_5) b,$$

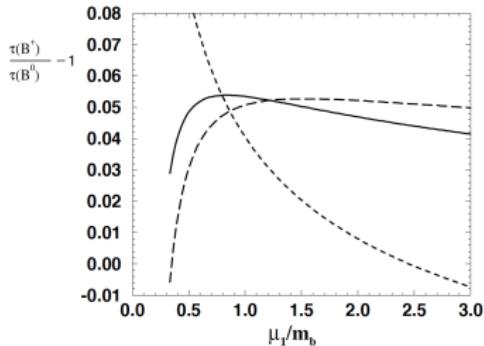
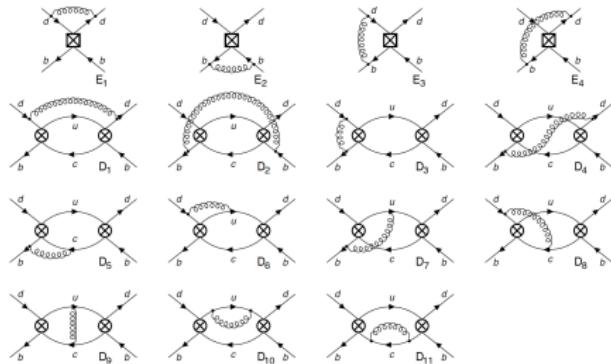
$$T^q = \bar{b} \gamma_\mu (1 - \gamma_5) T^a q \bar{q} \gamma^\mu (1 - \gamma_5) T^a b,$$

$$Q_S^q = \bar{b} (1 - \gamma_5) q \bar{q} (1 + \gamma_5) b,$$

$$T_S^q = \bar{b} (1 - \gamma_5) T^a q \bar{q} (1 + \gamma_5) T^a b$$

The $B^+ - B_d^0$ Lifetime difference in NLL accuracy

[M. Beneke *et al.*, Nucl.Phys. B639 (2002) 389]

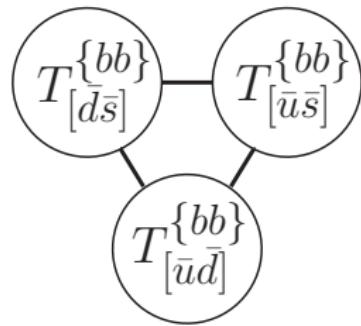
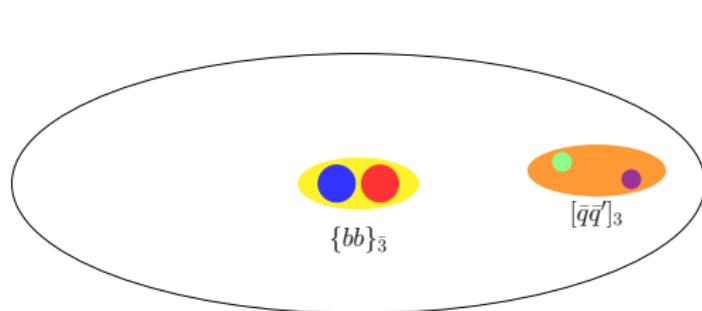


- $\frac{\tau(B^+)}{\tau(B_d^0)} = 1.053 \pm 0.016 \pm 0.017 [= 1.078 \pm 0.004 (\text{PDG2021})]$

Objects of Interest

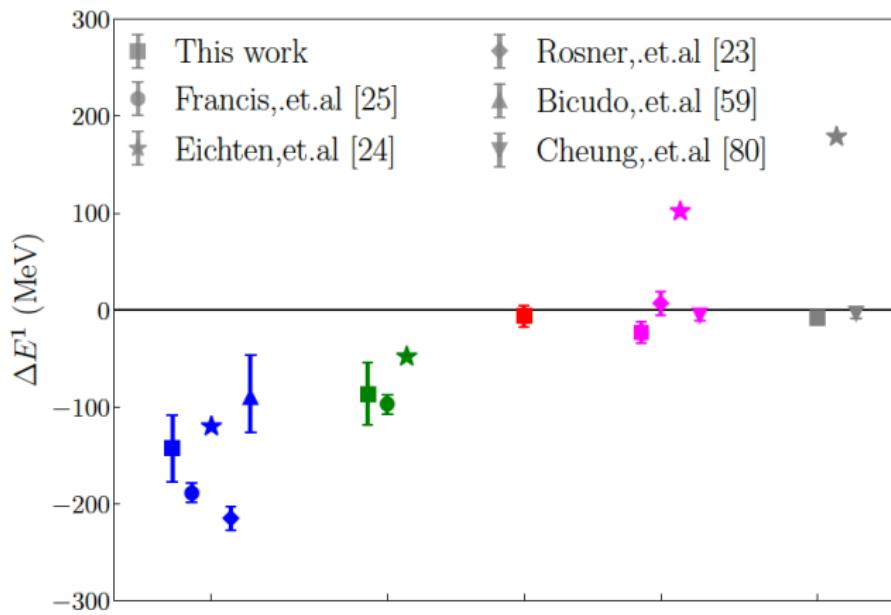
$SU(3)_F$ -Triplet of Stable Double-Bottom Tetraquarks

- Double-heavy diquark: color $\bar{3}$, spin $S_{\{bb\}} = 1$
- Light antidiquark: color 3 , spin $S_{[\bar{q}\bar{q}']} = 0$
- Ground DHTQ states: $L = 0$
- Spin-parity of DHTQ: $J^P = 1^+$



Global results for the binding energy ΔE on spin-1 doubly-heavy tetraquarks

[P. Junnarkar, N. Mathur, M. Padmanath, PR D99 (2019) 034507]



- Consensus that $J^P = 1^+$ doubly-bottom tetraquarks lie below their resp. strong thresholds

Estimates of the lifetime for $T_{[\bar{u}\bar{d}]}^{\{bb\}}$ using heavy quark expansion
 [AA, A. Parkhomenko, Qin Qin, Wei Wang, Phys.Lett. B782, 412 (2018).]

- HQE simplifies the inclusive decay widths. Up to dimension 6 :

$$\mathcal{T} = \frac{G_F^2 m_b^5}{192\pi^3} |V_{CKM}|^2 \left[c_{3,b} \bar{b}b + \frac{c_{5,b}}{m_b^2} \bar{b} g_s \sigma_{\mu\nu} G^{\mu\nu} b + 2 \frac{c_{6,b}}{m_b^3} (\bar{b}q) \Gamma(\bar{q}b) \Gamma + \dots \right]$$

- At leading order in $1/m_b$, only the $\bar{b}b$ operator contributes:

$$\Gamma(T_{[\bar{q}\bar{q}']}^{\{bb\}}) = \frac{G_F m_b^5}{192\pi^3} |V_{CKM}|^2 c_{3,b} \frac{1}{3} \sum_{\lambda} \frac{\langle T_{[\bar{q}\bar{q}']}^{\{bb\}} | \bar{b}b | T_{[\bar{q}\bar{q}']}^{\{bb\}} \rangle}{2m_{T_{[\bar{q}\bar{q}']}^{\{bb\}}}}$$

- $\frac{\langle T_{[\bar{q}\bar{q}']}^{\{bb\}} | \bar{b}b | T_{[\bar{q}\bar{q}']}^{\{bb\}} \rangle}{2m_{T_{[\bar{q}\bar{q}']}^{\{bb\}}}}$ corresponds to the bottom-quark number in $T_{[\bar{q}\bar{q}']}^{\{bb\}}$, and is twice the matrix element for B meson and Λ_b baryon

- Hence, expect $\tau(T_{[\bar{u}\bar{d}]}^{\{bb\}}) \simeq 1/2\tau(B)$:

$$\tau(T_{[\bar{q}\bar{q}']}^{\{bb\}}) \sim \frac{1}{2} \times 1.6 \times 10^{-12} s = 800 \times 10^{-15} s$$

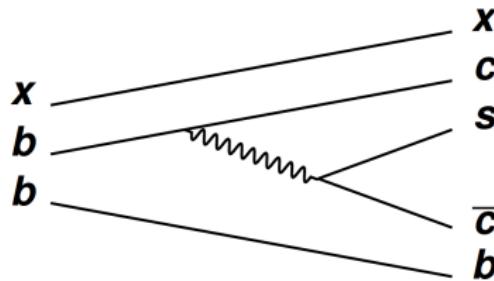
Detached B_c -vertices as a sign of double-bottom hadrons

[T. Gershon, A. Poluektov, JHEP, 1901 (2019) 019]

- Key observation

Weakly decaying double beauty hadrons are the only possible source of displaced B_c mesons

- Require $b \rightarrow c$ transitions



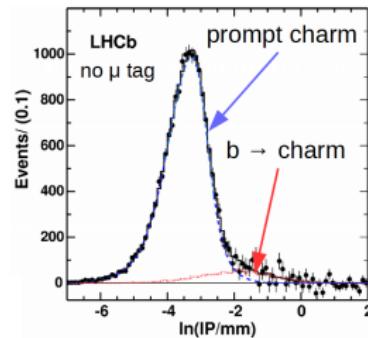
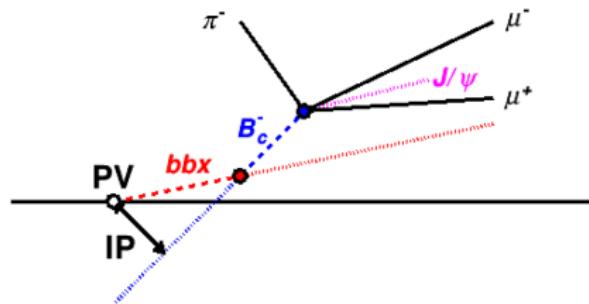
Detached B_c -vertices as a sign of double-bottom hadrons

[T. Gershon, A. Poluektov, JHEP, 1901 (2019) 019]

Working example: Displaced charm

Signature of displaced charm used to measure
inclusive $pp \rightarrow bbX$ production cross-section
LHCb-PAPER-2010-002

Muon tag from semileptonic decay helps to
suppress background from prompt charm
→ not possible for displaced B_c analysis
→ $(b \rightarrow \bar{c})$ instead of $(b \rightarrow c)$



signal:background $\sim 1:20$
still able to distinguish
displaced charm with 2.9 nb^{-1}
IP resolution since improved

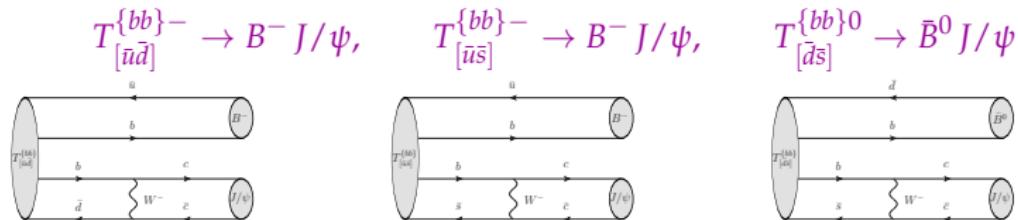
Rate Estimates for Detached B_c -vertices

- $\mathcal{B}(\Xi_{bbq} \rightarrow \bar{B}_c^{(*)} + X) = 0.8 \times 10^{-3}$
- $\mathcal{B}(T_{[\bar{q}\bar{q}']}^{\{bb\}-} \rightarrow \bar{B}_c^{(*)} + X) \simeq \mathcal{B}(\Xi_{bbq} \rightarrow \bar{B}_c^{(*)} + X)$ [Ridgway, Wise, PL B793 (2019) 181]
- $\mathcal{B}(\bar{B}_c \rightarrow J/\psi \pi^- \rightarrow \mu^+ \mu^- \pi^-) \simeq 2 \times 10^{-4}$ [C.F. Qiao et al., PRD 89 (2014) 034008]
- $\sigma(pp \rightarrow H_{\{bb\}} + X) \simeq 15 \text{ nb}$ [AA, Qin, Wang; PL B785 (2018) 605]
- With 9 (fb)^{-1} yield $\sim 10^2$ detached $\mu^+ \mu^- \pi^-$ events at LHCb
- Yield an order of magnitude higher for the ATLAS & CMS; worth an attempt with current data!

Weak Annihilation Decays of Stable DHTQs

[AA, A. Parkhomenko, Qin Qin, Wei Wang, Phys.Lett. B782, 412 (2018).]

- Weak annihilation decays are determined by W -exchange diagrams
- Of interest for LHC are modes with J/ψ -meson production



- Described by factorizable amplitudes

$$\mathcal{M}(T_{[u\bar{s}]}^{bb} -> B^- J/\psi) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2^{\text{eff}} m_\psi f_\psi \varepsilon_\psi^{*\mu} \langle B^- | \bar{s} \gamma_\mu (1 - \gamma_5) b | T_{[u\bar{s}]}^{bb} \rangle$$

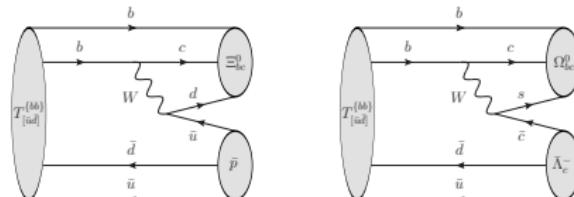
- The general decomposition of $T_{[u\bar{s}]}^{bb} -> B$ transition is similar to $B \rightarrow A$ transition matrix element; one needs to know form factors
- Decay $T_{[u\bar{d}]}^{bb} -> B^- J/\psi$ is suppressed due to the CKM factor V_{cd}^* by approximately a factor of 25

Weak Decays of $T_{[\bar{u}\bar{d}]}^{\{bb\}}$

- Tell-Tale signatures: Decays into "wrong-sign" heavy mesons
[A. Esposito *et al.*, Phys. Rev. D88, 054029 (2013); S.Q. Luo *et al.*, EPJC 77, 709 (2017)]
- Effective Weak Hamiltonian

$$\begin{aligned} \mathcal{H}_{\text{eff}}^{(cc)} &= \frac{4G_F}{\sqrt{2}} V_{cb} V_{ud}^* \left\{ C_1 [\bar{c}_\alpha \gamma_\mu P_L b^\alpha] [\bar{d}_\beta \gamma^\mu P_L u^\beta] \right. \\ &\quad \left. + C_2 [\bar{c}_\beta \gamma_\mu P_L b^\alpha] [\bar{d}_\alpha \gamma^\mu P_L u^\beta] \right\} \\ &+ \frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left\{ C_1 [\bar{c}_\alpha \gamma_\mu P_L b^\alpha] [\bar{s}_\beta \gamma^\mu P_L c^\beta] \right. \\ &\quad \left. + C_2 [\bar{c}_\beta \gamma_\mu P_L b^\alpha] [\bar{s}_\alpha \gamma^\mu P_L c^\beta] \right\} + \text{h. c.} \end{aligned}$$

- Two-Body Baryonic Decays from $b \rightarrow c + d + \bar{u}$ and $b \rightarrow c + s + \bar{c}$



An order of magnitude estimate

- Involve non-factorizable Amplitudes . For the $J^P = 1^+$ tetraquark, the general form of the decay amplitude is:

$$\begin{aligned} \mathcal{M}(T_{[\bar{u}\bar{d}]}^{\{bb\}-} \rightarrow \Xi_{bc}^0 \bar{p}) = & \bar{v}(p_p) \left[f_1^{\Xi_{bc}\bar{p}} q_\mu + f_2^{\Xi_{bc}\bar{p}} \gamma_\mu \right. \\ & + f_3^{\Xi_{bc}\bar{p}} \sigma_{\mu\nu} \frac{q^\nu}{M_T} + g_1^{\Xi_{bc}\bar{p}} \gamma_5 q_\mu + g_2^{\Xi_{bc}\bar{p}} \gamma_\mu \gamma_5 \\ & \left. + g_3^{\Xi_{bc}\bar{p}} \sigma_{\mu\nu} \gamma_5 \frac{q^\nu}{M_T} \right] u(p_{\Xi_{bc}}) \epsilon_T^\mu(p_T) \end{aligned}$$

- Inspired by the B meson decay data

$$\begin{aligned} \mathcal{B}(\bar{B}^0 \rightarrow D^+ \pi^-) &= (2.52 \pm 0.13) \times 10^{-3} \\ \mathcal{B}(\bar{B}^0 \rightarrow D^+ D_s^-) &= (7.2 \pm 0.8) \times 10^{-3} \end{aligned}$$

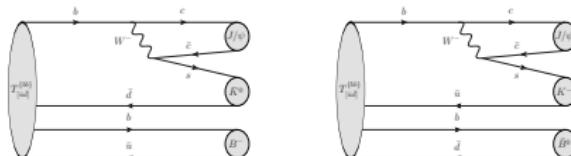
- Infer that $\mathcal{B}(T_{[\bar{u}\bar{d}]}^{\{bb\}-} \rightarrow \Xi_{bc}^0 \bar{p})$ and $\mathcal{B}(T_{[\bar{u}\bar{d}]}^{\{bb\}-} \rightarrow \Omega_{bc}^0 \bar{\Lambda}_c^-)$ are of $O(10^{-3})$
- Needs reconstructing the doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0 , such as through $\Xi_{bc}^0 \rightarrow \Lambda_b K^- \pi^+$, expect the two-body baryonic decay modes of $T_{[\bar{u}\bar{d}]}^{\{bb\}-}$ can have branching fractions of order 10^{-6}

Hidden-Charm final states in $T_{[\bar{u}\bar{d}]}^{\{bb\}-}$ decays

- In some decays hidden-charm mesons, such as $J/\psi, \psi'$, can be produced

$$T_{[\bar{u}\bar{d}]}^{\{bb\}-} \rightarrow J/\psi \bar{K}^0 B^-,$$

$$T_{[\bar{u}\bar{d}]}^{\{bb\}-} \rightarrow J/\psi K^- \bar{B}^0$$



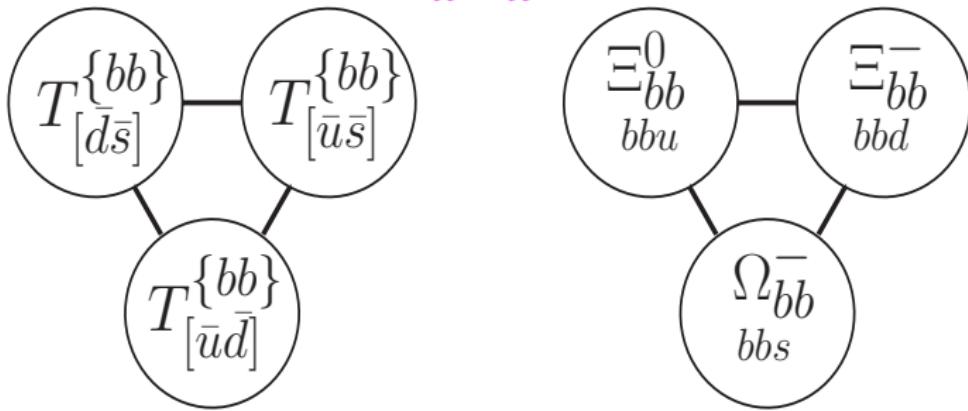
- Their decay branching ratios can be comparable with the $\mathcal{B}(B \rightarrow J/\psi K)$:

$$\mathcal{B}(\bar{B}^0 \rightarrow J/\psi \bar{K}^0) = (8.73 \pm 0.32) \times 10^{-4}$$

- Expect that the product branching ratios to establish $T_{[\bar{u}\bar{d}]}^{\{bb\}-}$ are at most of $O(10^{-6})$

Outlook

- Great potential of discovering double-bottom tetraquarks $T_{[\bar{q}\bar{q}']}^{\{bb\}}$ and double-bottom baryons $\Xi_{bb}^0, \Xi_{bb}^-, \Omega_{hh}^-$ at the LHC and Tera-Z!



- Hope: Will establish heavy-heavy (Coulomb) diquarks as fundamental constituents of hadronic matter!!