Determinations of $|V_{cb}|$ and $|V_{ub}|$ from Λ_b decays

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EPJC77, 714 (2017)
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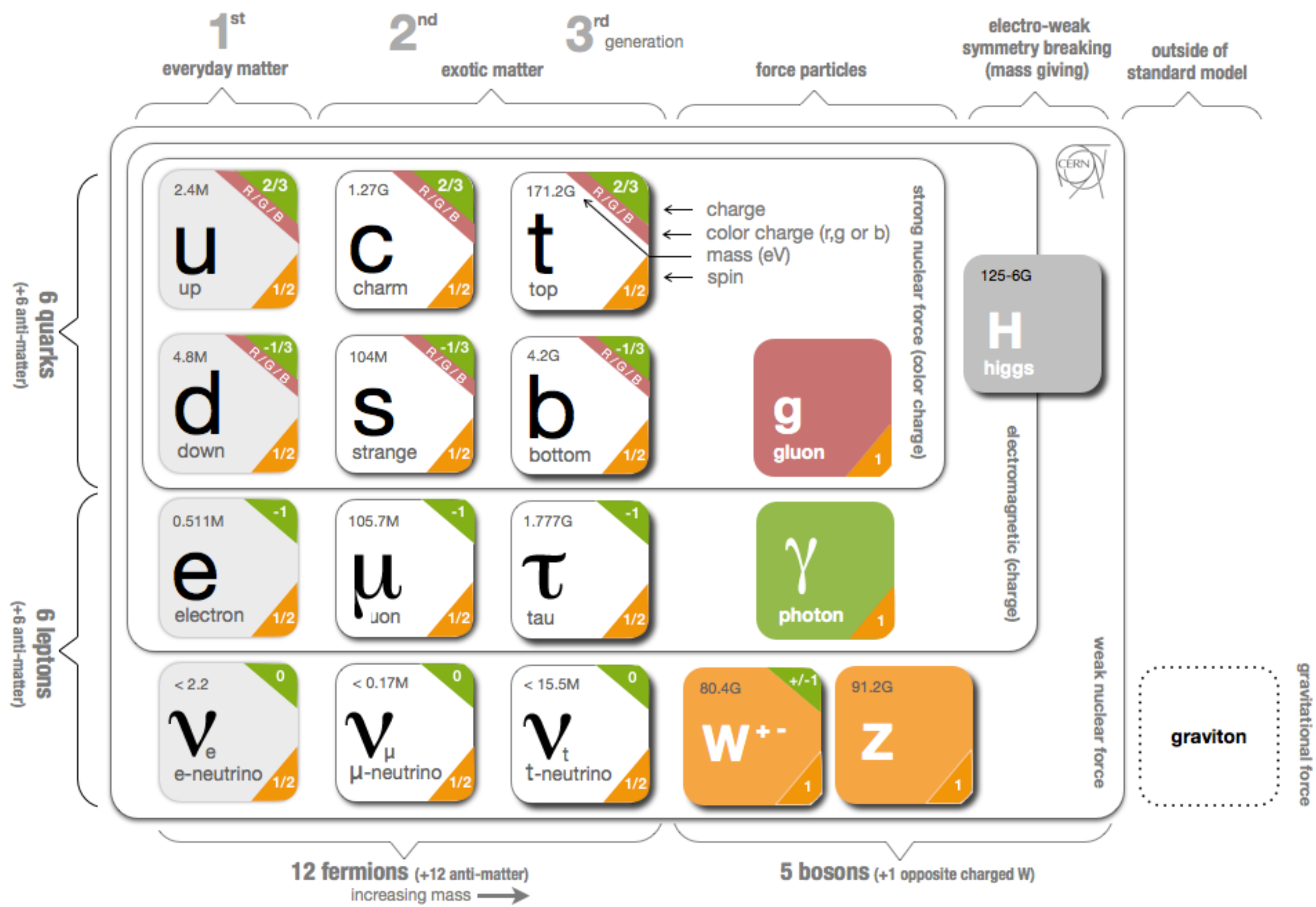
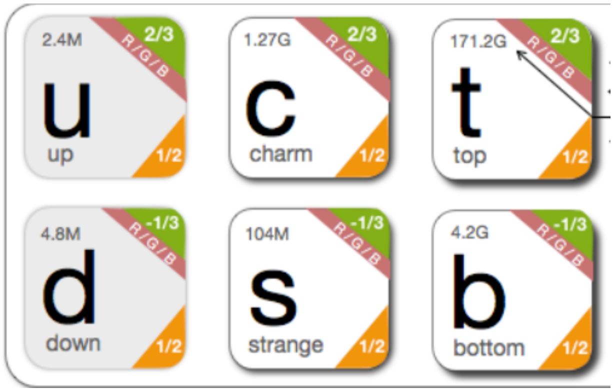
Outline:

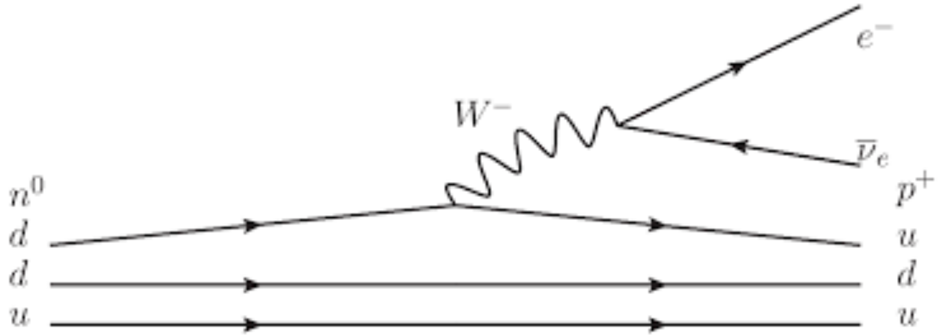
1. Introduction
2. Formalism
3. Results
4. Summary

Standard Model



quark mixing





- CKM (Cabibbo-Kobayashi-Maskawa) matrix elements:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Kobayashi and Maskawa, Nobel prize in 2008

CKM matrix elements

- Wolfenstein parameterization:

(A, λ, ρ, η)

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$V_{ub} = A\lambda^3(\rho - i\eta)$$

with the CP-odd phase for CP violation

$\lambda = 0.2257\,^{+0.0009}_{-0.0010}$, $A = 0.814\,^{+0.021}_{-0.022}$, $\rho = 0.135\,^{+0.031}_{-0.016}$, and $\eta = 0.349\,^{+0.015}_{-0.017}$.

Extractions of CKM matrix elements

- Long-standing discrepancy for $|V_{cb}|$, (2-3)σ:

$$|V_{cb}| = (39.18 \pm 0.99) \times 10^{-3}, \quad (B \to D\ell\bar{\nu}_\ell)$$

$$|V_{cb}| = (38.71 \pm 0.75) \times 10^{-3}, \quad (B \to D^*\ell\bar{\nu}_\ell)$$

$$|V_{cb}| = (42.11 \pm 0.74) \times 10^{-3}. \quad (B \to X_c\ell\bar{\nu}_\ell)$$

- Solution:

the more flexible $B \to D^{(*)}$ transition form factors

D. Bigi, P. Gambino and S. Schacht, PLB769, 441 (2017).

B. Grinstein and A. Kobach, PLB771, 359 (2017).

- Long-standing discrepancy for $|V_{ub}|$, (3-4)σ:

$$|V_{ub}|_{in} = (4.49 \pm 0.16^{+0.16}_{-0.18}) \times 10^{-3} \ ,$$

$$|V_{ub}|_{ex} = (3.72 \pm 0.19) \times 10^{-3} \ .$$

- Determinations of $|V_{cb}|$ and $|V_{ub}|$ from Λ_b decays,

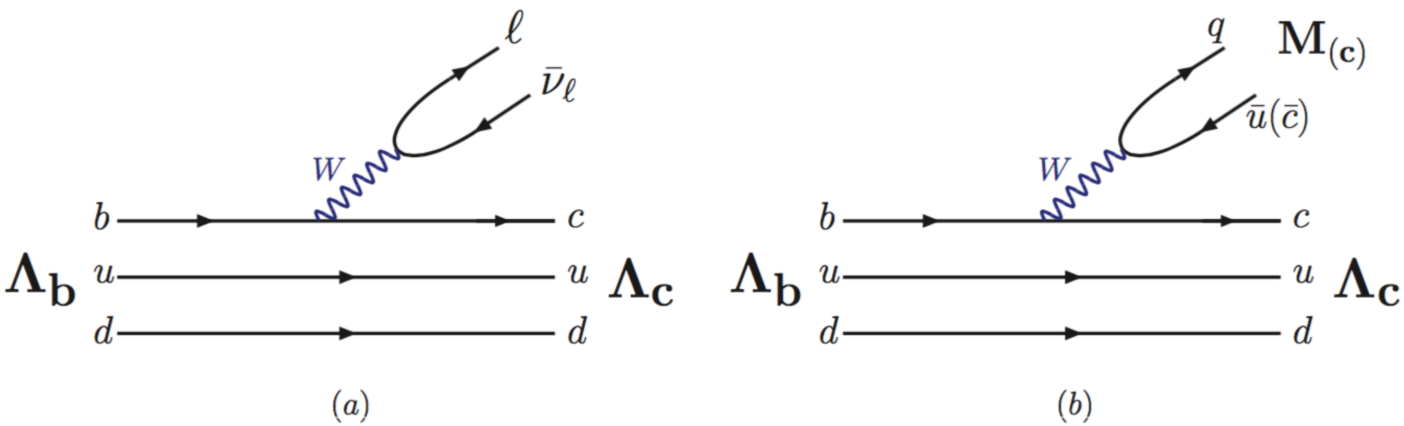
to ease the tensions between

the exclusive and inclusive determinations.

- Extraction of $|V_{cb}|$ from Λ_b decays

$$\mathcal{A}(\Lambda_b \to \Lambda_c^+ \ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{cb} \langle \Lambda_c^+ | \bar{c}\gamma_\mu (1-\gamma_5) b | \Lambda_b \rangle \bar{\ell}\gamma^\mu (1-\gamma_5)\nu_\ell$$

$$\mathcal{A}(\Lambda_b \to \Lambda_c^+ M_{(c)}) = \frac{G_F}{\sqrt{2}} V_{cb} V_{\alpha\beta}^* a_1^{M_{(c)}} i f_{M_{(c)}} q^\mu \langle \Lambda_c^+ | \bar{c}\gamma_\mu (1-\gamma_5) b | \Lambda_b \rangle$$



branching ratios	experimental data PDG
$10^2\mathcal{B}(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell)$	$6.2^{+1.4}_{-1.3}$
$10^3\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)$	4.9 ± 0.4
$10^4\mathcal{B}(\Lambda_b \to \Lambda_c^+ K^-)$	3.6 ± 0.3
$10^4\mathcal{B}(\Lambda_b \to \Lambda_c^+ D^-)$	4.6 ± 0.6
$10^2\mathcal{B}(\Lambda_b \to \Lambda_c^+ D_s^-)$	1.1 ± 0.1

• The helicity-based definition

Feldmann&Yip, PRD85, 014035 (2012); 86, 079901(E) (2012)

$$\langle\Lambda_c|\bar{c}\gamma_\mu b|\Lambda_b\rangle = \bar{u}_{\Lambda_c}(p',s')\Big[f_0(q^2)(m_{\Lambda_b}-m_{\Lambda_c})\frac{q^\mu}{q^2} + f_+(q^2)\frac{m_{\Lambda_b}+m_{\Lambda_c}}{s_+}$$
$$\times\left(p^\mu + p'^\mu - (m^2_{\Lambda_b}-m^2_{\Lambda_c})\frac{q^\mu}{q^2}\right) + f_\perp(q^2)\left(\gamma^\mu - \frac{2m_{\Lambda_c}}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right)\Big]u_{\Lambda_b}(p,s)$$

$$\langle\Lambda_c|\bar{c}\gamma_\mu\gamma_5 b|\Lambda_b\rangle = -\bar{u}_{\Lambda_c}(p',s')\gamma_5\Big[g_0(q^2)(m_{\Lambda_b}+m_{\Lambda_c})\frac{q^\mu}{q^2} + g_+(q^2)\frac{m_{\Lambda_b}-m_{\Lambda_c}}{s_-}$$
$$\times\left(p^\mu + p'^\mu - (m^2_{\Lambda_b}-m^2_{\Lambda_c})\frac{q^\mu}{q^2}\right) + g_\perp(q^2)\left(\gamma^\mu + \frac{2m_{\Lambda_c}}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right)\Big]u_{\Lambda_b}(p,s)$$

$q = p - p'$, $s_\pm = (m_{\Lambda_b} \pm m_{\Lambda_c})^2 - q^2$

• Lattice QCD

Detmold, Lehner, Meinel, PRD92, 034503 (2015)

$$f(t) = \frac{1}{1-t/(m_{pole}^f)^2} \sum_{n=0}^{n_{max}} a_n^f \left[\frac{\sqrt{t_+ - t_0} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}} \right]^n$$

$$(n_{max}, t_+, t_0) = (1, (m_{pole}^f)^2, (m_{\Lambda_b} - m_{\Lambda_c})^2)$$

$$(\Delta^{f_{+,\perp}}, \Delta^{f_0}, \Delta^{g_{+,\perp}}, \Delta^{g_0}) = (0.056, 0.449, 0.492, 0) \text{ GeV}$$

$$m_{pole}^f = m_{B_c} + \Delta^f$$

$(a_0^{f_+}, a_1^{f_+})$	$(0.8146 \pm 0.0167, -4.8990 \pm 0.5425)$
$(a_0^{f_0}, a_1^{f_0})$	$(0.7439 \pm 0.0125, -4.6480 \pm 0.6084)$
$(a_0^{f_\perp}, a_1^{f_\perp})$	$(1.0780 \pm 0.0256, -6.4170 \pm 0.8480)$
$(a_0^{g_+}, a_1^{g_+})$	$(0.6847 \pm 0.0086, -4.4310 \pm 0.3572)$
$(a_0^{g_0}, a_1^{g_0})$	$(0.7396 \pm 0.0143, -4.3660 \pm 0.3314)$
$(a_0^{g_\perp}, a_1^{g_\perp})$	$(0.6847 \pm 0.0086, -4.4630 \pm 0.3613)$

• Extraction of $|V_{ub}|$ from baryonic decays

LHCb, Nature Phys. **11**, 743 (2015),

"Determination of the quark coupling strength $|V_{ub}|$ using baryonic decays"

$$\frac{\mathcal{B}(\Lambda_b \to p\mu\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2}} = (1.00 \pm 0.09) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Lambda_b \to p\mu\bar{\nu})_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2}} = \frac{|V_{ub}|^2/|V_{cb}|^2}{R_{FF}}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

with the input of $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$

$(B \to D^{(*)}\ell\bar{\nu}_\ell)$

- The minimum χ^2 fit:

$$\chi^2 = \sum_{i=1}^{5} \left(\frac{\mathcal{B}^i_{th} - \mathcal{B}^i_{ex}}{\sigma^i_{ex}} \right)^2 + \sum_j \left(\frac{\mathcal{F}^j_{fit} - \mathcal{F}^j_{th}}{\sigma^j_{\mathcal{F}_{th}}} \right)^2$$

1. Theoretical inputs:

$$(|V_{cd}|, |V_{cs}|) = (0.220 \pm 0.005, 0.995 \pm 0.016)$$

$$(|V_{ud}|, |V_{us}|) = (0.97417 \pm 0.00021, 0.2248 \pm 0.0006)$$

$$(f_\pi, f_K) = (130.2 \pm 1.7, 155.6 \pm 0.4)\ \text{MeV}$$

$$(f_D, f_{D_s}) = (203.7 \pm 4.7, 257.8 \pm 4.1)\ \text{MeV}$$

$$a_1^{M(c)} = 1.05 \pm 0.12$$

2. Test of FFs:

$$\mathcal{F}(\Lambda_b \to \Lambda_c) = \frac{1}{|V_{cb}|^2} \int_{q^2} \frac{\hat{\tau}_{\Lambda_b}}{(2\pi)^3\, 32\, m^3_{\Lambda_b}} \frac{d\Gamma(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell)}{dq^2} dq^2$$

3. Two scenarios:

(S1) $\mathcal{B}(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell) + \mathcal{B}(\Lambda_b \to \Lambda_c M_{(c)})$

(S2) $\mathcal{B}(\Lambda_b \to \Lambda_c M_{(c)})$

- Results:

$$|V_{cb}| = (44.6 \pm 3.2) \times 10^{-3}$$

$$(a_1^M, a_1^{M_c}) = (1.19 \pm 0.08, 0.87 \pm 0.06)$$

$$\mathcal{F}(\Lambda_b \to \Lambda_c) = 31.18 \pm 0.64$$

$$\chi^2/d.o.f = 7.3/4 \simeq 1.8$$

Fit results for |Vcb| and |Vub|

	$\chi^2/d.o.f$	$\lvert V_{cb}\rvert \times 10^3$	$\lvert V_{ub}\rvert \times 10^3$	$\mathcal{F}(\Lambda_b \to \Lambda_c)$
$S1$	1.8	44.6 ± 3.2	4.3 ± 0.4	31.18 ± 0.64
$S2$	2.3	45.1 ± 4.5	4.3 ± 0.5	31.23 ± 0.64
$B \to D\ell\bar{\nu}_\ell$ [1]		39.18 ± 0.99		
$B \to D^*\ell\bar{\nu}_\ell$ [1]		38.71 ± 0.75		
$B \to X_c\ell\bar{\nu}_\ell$ [2]		42.11 ± 0.74		
$B \to \pi\ell\bar{\nu}_\ell$ [17]			3.72 ± 0.19	
$B \to X_u\ell\bar{\nu}_\ell$ [17]			4.49 ± 0.24	
LQCD [16]				31.19 ± 1.33

Conclusions

- Besides the B decays,
the Λ_b decays can be used
to study the CKM matrix elements.

- $|V_{cb}|$ and $|V_{ub}|$ are extracted
to agree with those from the inclusive B decays.

Thanks!