Measuring $|V_{ub}|$ at LHCb

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RTG Students Lecture

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Outline

1. Lecture Today
   - CKM Meachnism
   - How to measure CKM matrix elements in general?
2. Lecture: How to measure CKM matrix elements in B-decays?
   - $|V_{cb}|$
   - $|V_{ub}|$
3. Lecture: Specific LHCb measurements
   - $\Lambda_b \to p\mu\nu$
   - $B_s^0 \to K^- \mu^+ \nu_\mu$

1. Part: CKM mechanism

Mass generation of Quarks

- In the SM quarks and leptons acquire mass through the Yukawa terms in the Lagrangian:

$$\mathcal{L}_{Yukawa} = -\frac{v}{\sqrt{2}}(\bar{d}_L Y_d d_R + \bar{u}_L Y_u u_R) + h.c.$$

left-handed quarks are coupled to right-handed ones

- q are the weak-eigenstates
- Y_u, Y_d are 3x3 complex Yukawa matrices
  $\rightarrow$ not diagonal in "generation space"

$\rightarrow$ weak eigenstates $\neq$ physical mass eigenstates

Diagonalization

- to get mass eigenstates u', d' diagonalize Yukawa matrices by unitary transformations:
  $q'_A = V_{A,q} q_A$
  - with $q = u, d$, $A = L, R$ and $V_{A,q} V^{\dagger}_{A,q} = 1$
- $V_{A,q}$ are determined by:

$$M_u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} = diag(m_u, m_c, m_t) = \frac{v}{\sqrt{2}} V_{L,u} Y_u V^{\dagger}_{R,u} \,,$$

$$M_d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} = diag(m_d, m_s, m_b) = \frac{v}{\sqrt{2}} V_{L,d} Y_d V^{\dagger}_{R,d}$$

$$\Rightarrow \mathcal{L}_{Yukawa} = -\bar{d}'_L M_d d'_R + \bar{u}'_L M_u u'_R + h.c.$$

CKM matrix

- these transformations leave all parts of SM Lagragian unchanged, except for term describing the charged current weak interaction:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}(\bar{u}_L \gamma^\mu W_\mu^+ d_L + \bar{d}_L \gamma^\mu W_\mu^- u_L)$$

$$\rightarrow \mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}(\bar{u}'_L \gamma^\mu W_\mu^+ \underbrace{V_{L,u} V_{L,d}^\dagger}_{V_{CKM}} d'_L + \bar{d}'_L \gamma^\mu W_\mu^- \underbrace{V_{L,d} V_{L,u}^\dagger}_{V_{CKM}^\dagger} u'_L)$$

$\Rightarrow$ The charged-current interaction gets a flavor structure which is encoded in the Cabibbo-Kobayashi-Maskawa (CKM) matrix
$\Rightarrow$ element $(V_{CKM})_{ij}$ connects the LH u-type quark of the ith generation with the LH d-type quark of the jth generation

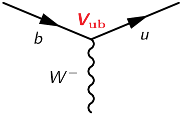
CKM matrix

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

- describes relation between weak eigenstates q and mass eigenstates q':

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

  $\rightarrow$ weak eigenstates are a mixture of mass eigenstates
- weak interaction allows for transitions between different generations of quarks through charged current interactions



Parameters of CKM matrix

in general: NxN matrix

- n^2 complex elements = $2n^2$ real parameters
- unitarity condition: $V^\dagger V = \mathbb{1}$ implies n^2 constraints
    - n unitary conditions
    - $n^2 - n$ orthogonality relations
- removing quark phases: 2n-1 constraints

$\rightarrow$ leaves $(n-1)^2$ free parameters
= $\frac{1}{2}n(n-1)$ rotation angles + $\frac{1}{2}(n-1)(n-2)$ phases

$\Rightarrow$ for 3x3 matrix: 3 rotation angles + 1 CP violating phase

Parametrization of CKM matrix

PDG parametrization: 3 Euler angles $\theta_{23}, \theta_{13}, \theta_{12}$ and 1 Phase δ

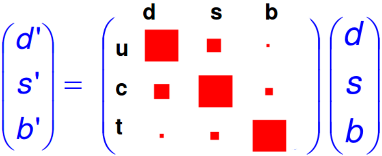
$$V_{CKM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

Wolfenstein Parametrization

Reflects the hierarchical structure of the CKM matrix:



λ, A, ρ, η with $\lambda = 0.22$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$|V_{ub}| \times e^{-i\gamma}$

$|V_{td}| \times e^{-i\beta}$

with $\lambda = \sin\theta_{12}$, $A\lambda^2 = \sin\theta_{23}$ and $\sin\theta_{23} e^{i\delta} = A\lambda^3(\rho + i\eta)$

Unitarity Condition

$$V^\dagger V = VV^\dagger = \mathbb{1}$$

$$\Leftrightarrow \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

leads to following three unitary relations:

$$V_{ud} V_{ud}^* + V_{us} V_{us}^* + V_{ub} V_{ub}^* = 1$$
$$V_{cd} V_{cd}^* + V_{cs} V_{cs}^* + V_{cb} V_{cb}^* = 1$$
$$V_{td} V_{td}^* + V_{ts} V_{ts}^* + V_{tb} V_{tb}^* = 1$$

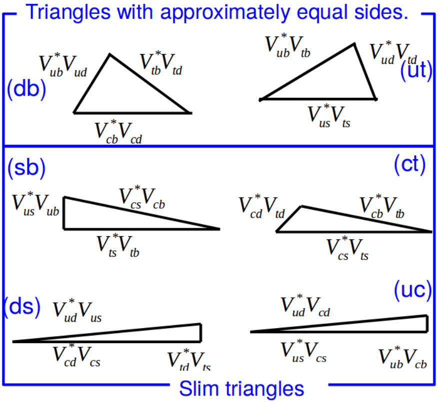
- *weak universality*: squared sum of coupling strengths of u-quark to d, s and b-quarks is equal to overall charged coupling of c and t-quark
- adding up to 1, no probability remaining to couple to 4th down-type quark

Unitarity Triangles

remaining orthogonality conditions can be described by an triangle relations in the complex plane:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{(db)}$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad \text{(sb)}$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad \text{(ds)}$$

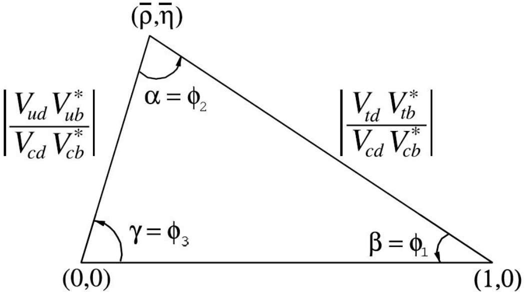
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \quad \text{(ut)}$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0 \quad \text{(ct)}$$
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad \text{(uc)}$$



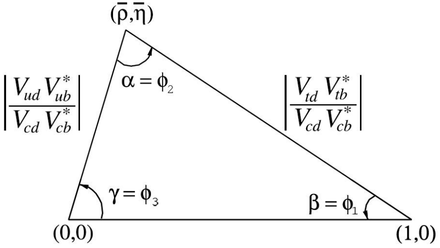
$\rightarrow$ all 6 triangles have same area $J_{CP}/2$, called the Jarlskog invariant, measure of CP violation of the SM

Unitarity Triangle

- (db) and (ut) have both sides with similar length, terms of order λ^3, better to visualize
  $\rightarrow$ (db) triangle used as 'the unitarity triangle' for historic reasons (b-factories Belle & Babar):
  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- divide each side by best-known one $V_{cd}V_{cb}^*$ gives:



The Unitarity Triangle

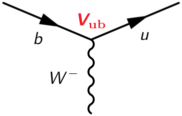


- angles of unitarity triangle:
  $\alpha \equiv arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$, $\beta \equiv arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$, $\gamma \equiv arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$
- CKM matrix elements are fundamental parameters of the SM
  $\rightarrow$ no theory predictions!
  $\Rightarrow$ precise determination of parameters very important
- **Goal of flavour physics:** overconstrain unitarity triangle by complementary measurements & search for New Physics

2.Part: How to measure CKM matrix elements in general?

How to measure CKM matrix elements in general?

- as shown before CKM matrix elements included in charged current weak interaction Lagrangian
- magnitude can be measured from rates of respective flavour changing transitions



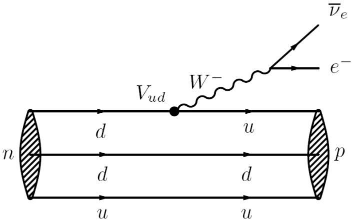
$\rightarrow$ emission of W boson

- rate of that is proportional to the coupling strength $|V_{ij}|^2$:

$$\frac{d\Gamma}{dq^2} \propto G_F^2 |V_{ij}|^2 |f^+(q^2)|$$

$\rightarrow$ needs as input non-perturbative Form factor ($f^+(q^2)$) calculations from LQCD or QCD sum rules

$|V_{ud}|$



Experimental measurements:

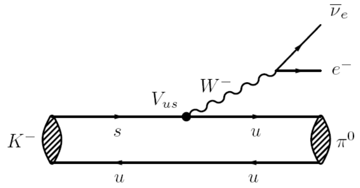
- measured from nuclear β decay: $n \to pe^-\bar{\nu}_e$

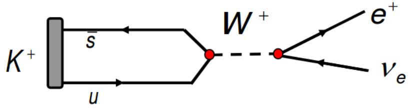
$$|V_{ud}| = 0.97417 \pm 0.00021$$

- error dominated by theoretical uncertainties due to binding energy corrections in nuclei

- also from neutron lifetime
- measure $\pi^+ \to \pi^0 e^+ \nu_e$ branching ratio (PIBETA experiment)

$|V_{us}|$





- from **semileptonic Kaon decays** (many different experiments): $K_L^0 \to \pi\mu\nu$, $K^\pm \to \pi^0 e^\pm \nu$,$K^\pm \to \pi^0\mu^\pm\nu$ and $K_S^0 \to \pi e\nu$ can extract $|V_{us}|f_+(0)$ $\to$ need to know form factor (FF) $f_+(0)$ from Lattice calculations (LQCD)
- also from **fully leptonic decays** (KLOE experiment): $|V_{us}/V_{ud}|$ from $K \to \mu\nu(\gamma)$ and $\pi \to \mu\nu(\gamma)$ together with ratio of decay constants f_K/f_π from LQCD

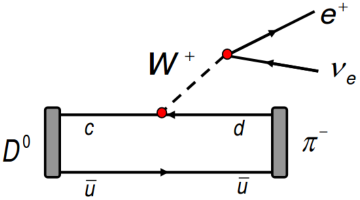
average of both gives:

$$|V_{us}| = 0.2248 \pm 0.0006$$

- also from Hyperon decays and hadronic tau decays $\tau \to h\nu$ $(h = \pi, K)$

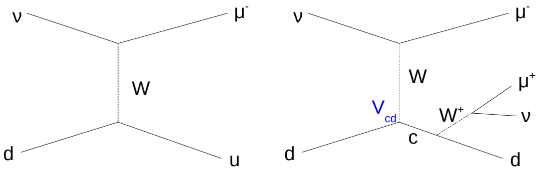
$|V_{cd}|$

- from **semileptonic charm decays** (BaBar, Belle, BESIII, CLEO-c):
  $D \to \pi l \nu$, $D \to K l \nu$ together with FFs $f_+^{D\pi}(0)$ from LQCD
- from **leptonic charm decays** (BESIII, CLEO):
  $D^+ \to \mu^+ \nu$ and decay constant f_D from LQCD



$|V_{cd}|$

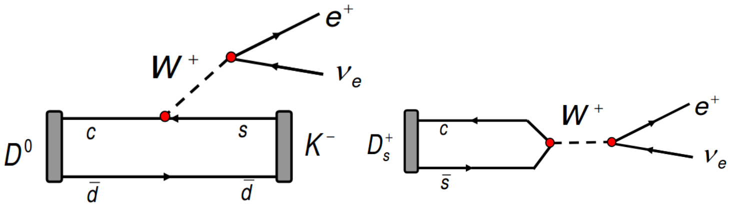
- from **neutrino scattering data** (CDHS, CCFR, CHARM II): The difference of the ratio of double-muon to single-muon production by neutrino and antineutrino beams is proportional to the charm cross section off valence d quarks, and therefore to $|V_{cd}|^2$



gives total average of all 3 methods:

$$|V_{cd}| = 0.220 \pm 0.005$$

$|V_{cs}|$



- from **semileptonic D decays** (Belle, BABAR, CLEO-c, BESIII): $D \to Kl\nu$ together with FFs $f_+^{DK}(0)$ from LQCD
- from **leptonic D_s decays** (Belle, BABAR, CLEO-c): $D_s \to \mu\nu, \tau\nu$ using the PDG values for mass and lifetime of the D_s, the masses of the leptons and f_{Ds} from LQCD

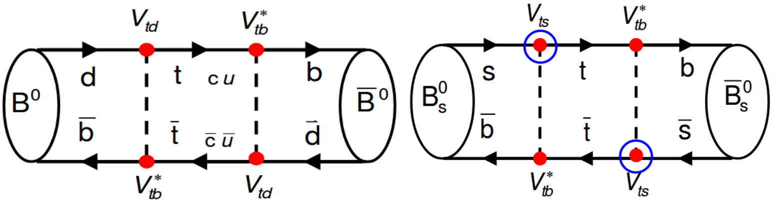
averaging both gives:

$$|V_{cs}| = 0.995 \pm 0.016$$

- also from tagged on-shell $W^+ \to c\bar{s}$ decays at LEPII

$|V_{td}|$ and $|V_{ts}|$

- in general measurable in tree level top decays, but not precise enough
- can be measured via virtual effects:
  1. from $B - \bar{B}$, $B_s - \bar{B}_s$ oscillations mediated by box diagrams with top quarks and LQCD input for f_{B_d} and f_{B_s}



$$\Delta m_d = (0.5064 \pm 0.0019) ps^{-1} \sim (V_{td}^* V_{tb})^2, \quad \Delta m_s = (17.757 \pm 0.021) ps^{-1} \sim (V_{ts}^* V_{tb})^2$$

$$|V_{td}| = (8.2 \pm 0.6) \times 10^{-3}, \qquad |V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$$

$|V_{td}|$ and $|V_{ts}|$

can be measured via virtual effects:

1. from $B - \bar{B}$ oscillations mediated by box diagrams with top quarks
2. loop-mediated rare K and B decays
   - $B \to X_s\gamma$ penguin process $\sim |V_{ts}^* V_{tb}|^2$
   - $B_s \to \mu\mu$ box diagram

- theoretical uncertainties in hadronic effects limit accurancy of current determinations, reduced when measuring $|V_{td}/V_{ts}|$ instead:

$$|V_{td}/V_{ts}| = 0.215 \pm 0.001 \pm 0.011$$

- theoretically clean determination of $|V_{ts}^* V_{td}|$ from $K^+ \to \pi^+\nu\bar{\nu}$, so far only 7 events observed from E949 & E787 Collaboration (*arXiv:0903.0030*), NA62 expected to improve that

$|V_{tb}|$

- top decays at hadron colliders CDF, D0, ATLAS, CMS:

  $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq) = |V_{tb}|^2/(\sum_q |V_{tq}|^2)$ with q=b,s,d
  $\Rightarrow R = |V_{tb}|^2$ assuming unitarity
- direct determination from single top-quark production cross section through *Wtb* vertex

combination of both:

$$|V_{tb}| = 1.009 \pm 0.031$$

dominated by experimental systematic uncertainties

Putting it all together

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

$$= \begin{pmatrix} 0.97417 \pm 0.00021 & 0.2248 \pm 0.0006 & V_{ub} \\ 0.220 \pm 0.005 & 0.995 \pm 0.016 & V_{cb} \\ 0.0082 \pm 0.0006) & 0.04 \pm 0.0027 & 1.009 \pm 0.031 \end{pmatrix}$$

clear hierarchy visible as described in Wolfenstein parametrization:

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & V_{ub} \\ \lambda & 1 & V_{cb} \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

with $\lambda \sim 0.22$

Take Home Message

- CKM matrix encodes the flavour structure of charged-current interaction
- weak interaction allows for transition between quark generations
- CKM matrix is unitary, complex 3x3 matrix
  $\rightarrow$ 4 free paramters: 3 rotation angles & 1 CP violating phase
- CKM matrix elements are fundamental parameters of the SM $\rightarrow$ need to be extracted from several different measurements
- from unitarity condition get the unitarity triangle
- **Goal of Flavour Physics** to over constrain this by complementary measurements

$\rightarrow$ next week discussion on V_{cb} and V_{ub}

Sources

- Physics at the Terrascale, Ian Brock, Thomas Schörner-Sadenius, 2011, Chapter Quark Flavour Physics
- Review of Particle Physics, C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update, http://pdg.lbl.gov/2017/reviews/rpp2017-rev-ckm-matrix.pdf, http://pdg.lbl.gov/2017/reviews/rpp2017-rev-vud-vus.pdf
- Quark and Lepton Flavor Physics Lectures by Ulrich Uwer https://www.physi.uni-heidelberg.de/ uwer/lectures/Flavor/notes.html
- Standard Model Lecture by Ulrich Uwer https://www.physi.uni-heidelberg.de/ uwer/lectures/StandardModel/notes.html
- The Standard Model of Particle Physics Lectures by Andre Schöning and https://www.mpi-hd.mpg.de/manitop/StandardModel/lectures/Lecture_SM_22.pdf
- Lectures on CP violation, Particle Physics II January 2015, P. Kooijman & N. Tuning, https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Thanks for your attention!

Backup Slides

$|V_{ud}|$

superallowed ($\Delta I = 0$) nuclear, neutron, and pion decays

$\rightarrow$ most precise determination from **superallowed nuclear beta-decays** ($0^+ \rightarrow 0^+$ transitions):

- with half-lives, t, and Q values (total energy released in a given nuclear decay) that give the decay rate factor, f:

$$ft = \frac{K}{2G_V^2(1+\Delta)}, \quad |V_{ud}| = G_V/G_F, \quad \Rightarrow |V_{ud}|^2 = \frac{2984.48(5)sec}{ft(1+\Delta)}$$

- Δ denotes the electroweak radiative corrections (RC), nuclear structure, and isospin violating nuclear effects $\rightarrow$ nucleus dependent
- most recent analysis of 14 precisely measured superallowed transitions gives a weighted average:

$$|V_{ud}| = 0.97420(10)_{exp.,nucl.}(18)_{RC}(superallowed)$$

$|V_{ud}|$

Neutron lifetime:

- together the ratio of axial-vector/vector couplings, $g_A \equiv G_A/G_V$ via neutron decay asymmetries gives:

$$|V_{ud}|^2 = \frac{4908.7(1.9)sec}{\tau_n(1+3g_A^2)}$$

- error from uncertainties in the electroweak radiative corrections due to hadronic loop effects
- Using world averages for $\tau_n^{ave} = 879.3(9)sec$ and $g_A^{ave} = 1.2723(23)$ gives:

$$|V_{ud}| = 0.9763(5)_{\tau_n}(15)_{g_A}(2)_{RC}$$

- error dominated by g_A uncertainties
- value of $|V_{ud}|$ is high by 1.3 sigma wrt. superallowed nuclear beta-decay

$|V_{ud}|$

pion decay:

- PIBETA experiment at PSI measured the very small ($\mathcal{O}(10^{-8})$) branching ratio for $\pi^+ \to \pi^0 e^+ \nu_e$ with about $\pm 0.5\%$ precision, gives:

$$|V_{ud}| = 0.9749(26) \left[\frac{BR(\pi^+ \to e^+ \nu_e(\gamma))}{1.2352 \times 10^{-4}} \right]^{1/2}$$

- Theoretical uncertainties in the pion β-decay determination are very small
- much higher statistics required to make this approach competitive with others

$|V_{us}|$

from **kaon decays**, hyperon decays, and tau decays

$$\Gamma_{Kl3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1 + \delta_K^l + \delta_{SU2}) C^2 |V_{us}|^2 f_+^2(0) I_K^l$$

M_K kaon mass, S_{EW} short-distance radiative correction, δ_K^l mode-dependent long-distance radiative correction, $f_+^2(0)$ calculated form factor at zero momentum transfer for the $l\nu$ system, I_K^l phase-space integral, δ_{SU2} for charged kaon decays deviation from one of the ratio of $f_+(0)$ for the charged to neutral kaon decay, C^2 is 1 (1/2) for neutral (charged) kaon decays

- Many measurements during last decade have resulted in a significant shift in $|V_{us}|$ due to difference in $K \to \pi e^+ \nu$ branching fraction as a result of inadequate treatment of radiation in older experiments

$|V_{us}|$

- experiments: BNL E865, KTeV, KLOE, NA48, ISTRA+
- new measurements of branching fractions, of lifetimes and form factors resulted in improved precision for all of the experimental inputs, gives:

$$f_+(0)|V_{us}| = 0.2165(4)$$

- using recent FLAG averages:

$$\begin{aligned} |V_{us}| &= 0.2238(4)_{exp+RC}(6)_{lattice} \quad (N_f = 2+1, K_{l3} \quad decays) \\ &= 0.2231(4)_{exp+RC}(7)_{lattice} \quad (N_f = 2+1+1, K_{l3} \quad decays) \end{aligned}$$

$|V_{us}|$

from a comparison of the radiative inclusive decay rates for $K \to \mu\nu(\gamma)$ and $\pi \to \mu\nu(\gamma)$ together with lattice calculation of f_{K^+}/f_{π^+} gives:

$$\frac{|V_{us}|f_{K^+}}{|V_{ud}|f_{\pi^+}} = 0.23871(20)\left[\frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}\right]^{1/2}$$

small error coming from electroweak radiative corrections and isospin breaking effects, using experimental measurements for Γ together with FLAG averages gives:

$$\begin{aligned} |V_{us}| &= 0.2256(10) \quad (N_f = 2+1, K_{\mu 2} \quad decays) \\ &= 0.2253(7) \quad (N_f = 2+1+1, K_{\mu 2} \quad decays) \end{aligned}$$

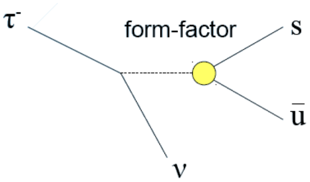
give similar results as from Kl3 decays

$|V_{us}|$

from **hyperon beta decays**:
$\Lambda \to pe^-\bar{\nu}$, $\Sigma^- \to ne^-\bar{\nu}$, $\Xi^- \to \Lambda e^-\bar{\nu}$, $\Xi^0 \to \Sigma^+ e^-\bar{\nu}$
gives:

$$|V_{us}| = 0.2250(27)$$

which neglects SU(3) breaking effects



from **tau decays**: $\tau \to \nu KX$
averaging both inclusive and exclusive measurements, gives:

$$|V_{us}| = 0.2202(15)$$

differs by about 3 sigma from the kaon determination, mainly from inclusive determination

CKM Unitarity Constraints

Unitarity Requirement should be fulfilled:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

using PDG averages of $|V_{us}|$ (using only kaon decays)

$$\begin{aligned} |V_{us}| &= 0.2244(6) \quad (N_f = 2+1) \\ &= 0.2243(5) \quad (N_f = 2+1+1) \end{aligned}$$

and $|V_{ud}|$ (using only superallowed nuclear beta decays)

$$|V_{ud}| = 0.97420(10)_{exp.,nucl.}(18)_{RC}$$

($|V_{ub}|^2 \simeq 1.7 \times 10^{-5}$ is negligibly small, ignored here) gives:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(5)$$

$\Rightarrow$ strong confirmation of SM, better than 50 σ, implies constraints on NP

$|V_{cs}|$

Measurements of on-shell $W^{\pm}$ decays sensitive to $|V_{cs}|$ were made by LEP-2

- W branching ratio to each lepton flavour is:

$$1/\mathcal{B}(W \to l\bar{\nu}_l) = 3\left[1 + \Sigma_{u,c,d,s,b}|V_{ij}|^2(1 + \alpha_s(m_W)/\pi) + ...\right]$$

- Assuming lepton universality, the measurement $\mathcal{B}(W \to l\bar{\nu}_l) = (10.83 \pm 0.07 \pm 0.07)\%$ implies $\Sigma_{u,c,d,s,b}|V_{ij}|^2 = 2.002 \pm 0.027$
- only flavour-tagged W-decays determine $|V_{cs}|$ directly, DELPHI's tagged $W^+ \to c\bar{s}$ analysis, yielding

$$|V_{cs}| = 0.94^{+0.32}_{-0.26} \pm 0.13$$