Flavour Physics

A. Pich

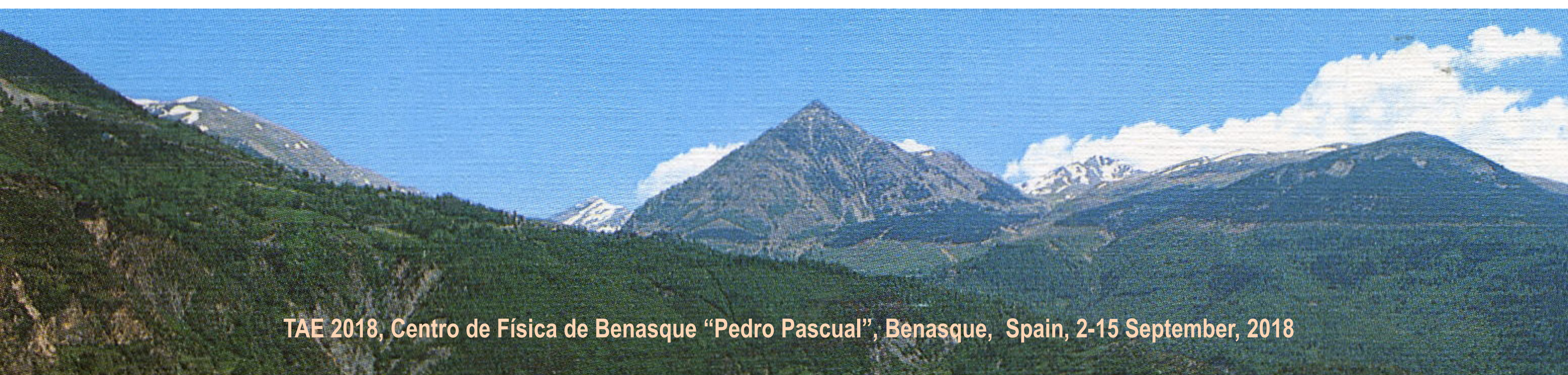
IFIC, U. València - CSIC

TAE 2018, Centro de Física de Benasque "Pedro Pascual", Benasque, Spain, 2-15 September, 2018

A. Pich, arXiv:1805.08597

Flavour Physics

1. Quark Mixing
2. CKM Structure
3. P^0-$\bar{P}^0$ Mixing & CP Violation
4. Searching for New Physics



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Quarks Leptons Bosons

Flavour Structure of the Standard Model

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

Why 3 ?

- **Pattern of masses**
- **Flavour Mixing**
- $\not{\mathcal{CP}}$

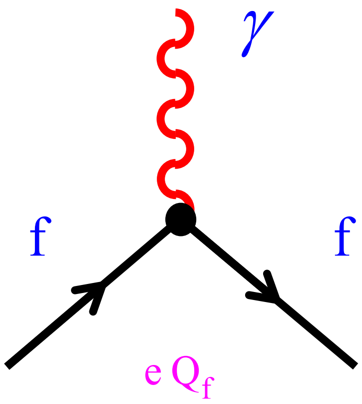
↔

Related to SSB

Scalar Sector (Higgs)

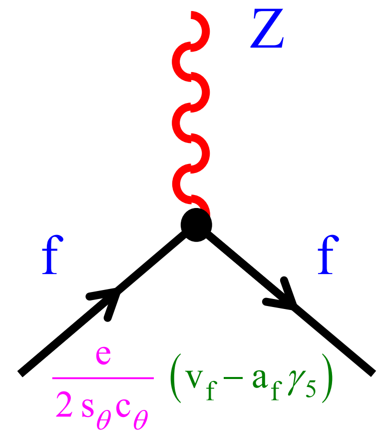
- **Kaon Factories :** u , d , s
- **τcF :** c , τ
- **BF:** b , c , τ
- **LHC :** t , b , c
- **LC :** t , b , c
- **νF :** $\nu_e , \nu_\mu , \nu_\tau$

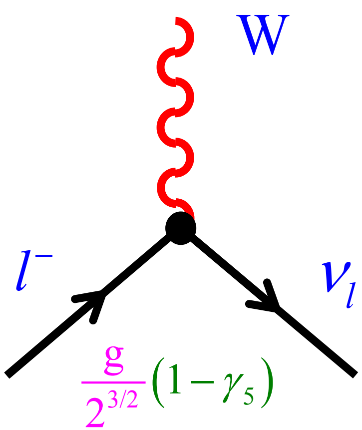
Universality: Family–Independent Couplings



NEUTRAL CURRENTS

Flavour Conserving

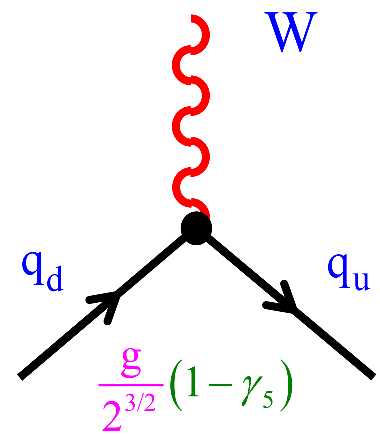


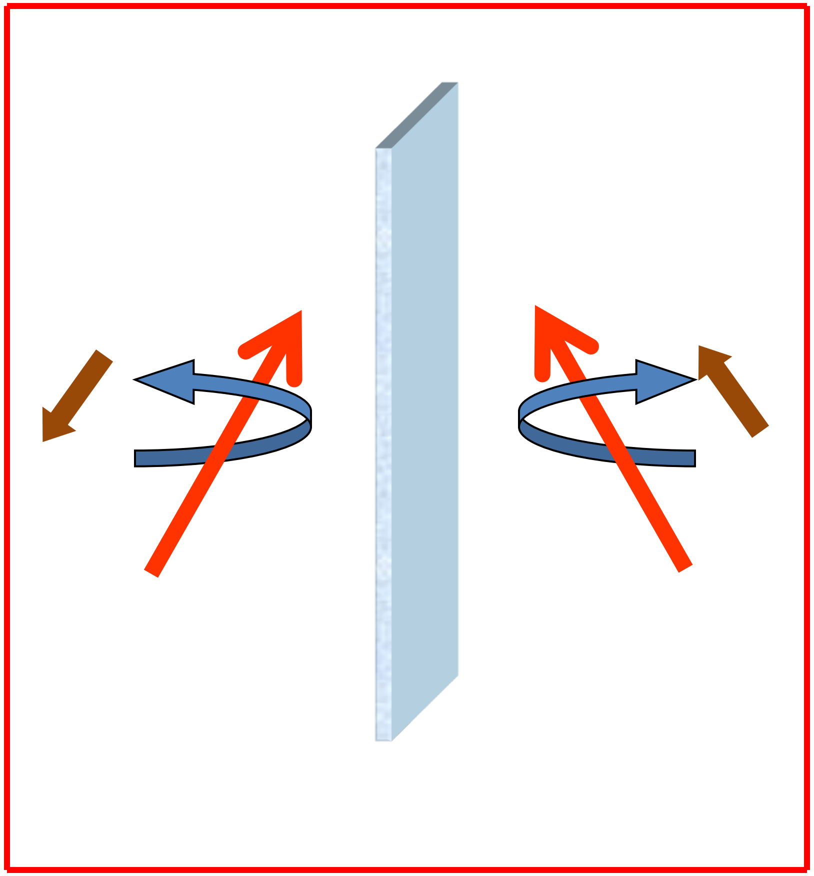


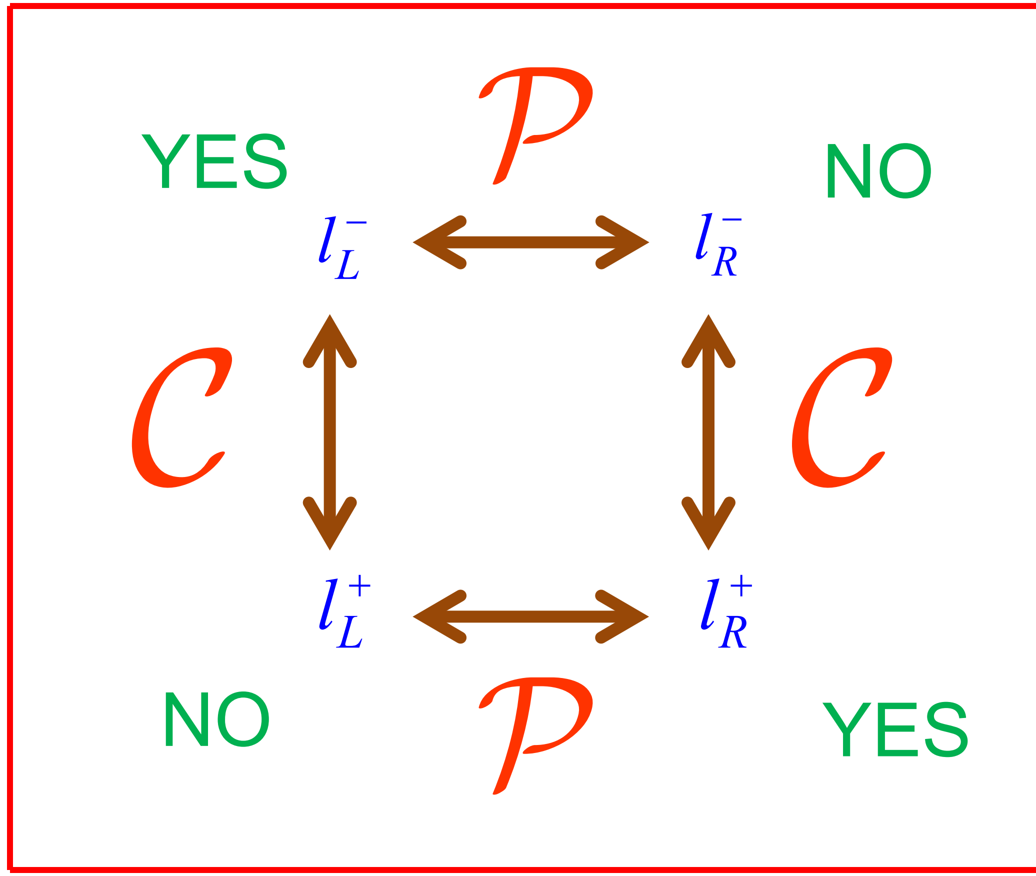
CHARGED CURRENTS

Flavour Changing

Left Handed







$\not{\mathcal{P}}$ **and** $\not{\mathcal{C}}$ **in Weak Interactions**

$\mathcal{CP}$ **still a good symmetry** **(1 family)**

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

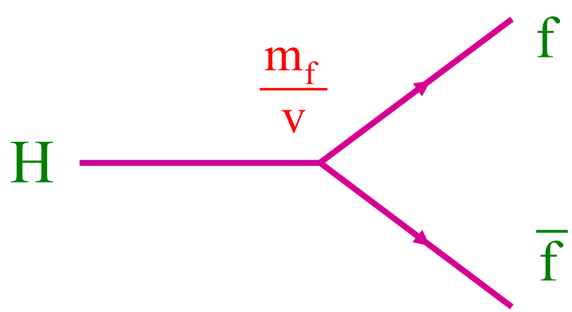
$$\mathcal{L}_Y = -\,(\bar{q}_u\,,\bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] - (\bar{\nu}_l,\bar{l}\,)_L \; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_R + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right) \left\{ m_{q_d}\; \bar{q}_d\, q_d + m_{q_u}\; \bar{q}_u\, q_u + m_l\; \bar{l}\, l \right\}$$

Fermion Masses are New Free Parameters

$$\left[m_{q_d}\,,\; m_{q_u}\,,\; m_l \right] = \left[c^{(d)}\,,\; c^{(u)}\,,\; c^{(l)} \right] \frac{\mathrm{v}}{\sqrt{2}}$$



Couplings Fixed: $g_{Hf\bar{f}} = \dfrac{m_f}{\mathrm{v}}$

FERMION GENERATIONS

$N_G = 3$ **Identical Copies** — **Masses are the only difference**

$$Q = 0 \qquad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \qquad Q = +2/3$$
$$Q = -1 \qquad\qquad\qquad\qquad Q = -1/3$$

$$(j = 1, \cdots, N_G)$$

WHY ?

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\bar{u}'_j, \bar{d}'_j\right)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] - \left(\bar{\nu}'_j, \bar{l}'_j\right)_L c^{(l)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \bar{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \bar{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$\left[\mathbf{M}'_d \,,\, \mathbf{M}'_u \,,\, \mathbf{M}'_l \right]_{jk} = \left[c^{(d)}_{jk} \,,\, c^{(u)}_{jk} \,,\, c^{(l)}_{jk} \right] \frac{v}{\sqrt{2}}$$

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \mathcal{M}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d$$
$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \mathcal{M}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u$$
$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \mathcal{M}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l$$

$$\mathbf{H}_\mathrm{f} = \mathbf{H}_\mathrm{f}^\dagger$$
$$\mathbf{U}_\mathrm{f} \cdot \mathbf{U}_\mathrm{f}^\dagger = \mathbf{U}_\mathrm{f}^\dagger \cdot \mathbf{U}_\mathrm{f} = 1$$
$$\mathbf{S}_\mathrm{f} \cdot \mathbf{S}_\mathrm{f}^\dagger = \mathbf{S}_\mathrm{f}^\dagger \cdot \mathbf{S}_\mathrm{f} = 1$$

$$\mathcal{L}_Y = -\left(1+\frac{H}{v}\right)\left\{\bar{\mathrm{d}} \cdot \mathcal{M}_d \cdot \mathrm{d} + \bar{\mathrm{u}} \cdot \mathcal{M}_u \cdot \mathrm{u} + \bar{l} \cdot \mathcal{M}_l \cdot l\right\}$$

$$\mathcal{M}_u = \mathrm{diag}\,(m_u, m_c, m_t) \quad ; \quad \mathcal{M}_d = \mathrm{diag}\,(m_d, m_s, m_b) \quad ; \quad \mathcal{M}_l = \mathrm{diag}\,(m_e, m_\mu, m_\tau)$$

$$\mathrm{d}_L \equiv \mathbf{S}_d \cdot \mathrm{d}'_L \quad ; \quad \mathrm{u}_L \equiv \mathbf{S}_u \cdot \mathrm{u}'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$
$$\mathrm{d}_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot \mathrm{d}'_R \quad ; \quad \mathrm{u}_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot \mathrm{u}'_R \quad ; \quad l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

Mass Eigenstates
$\neq$
Weak Eigenstates

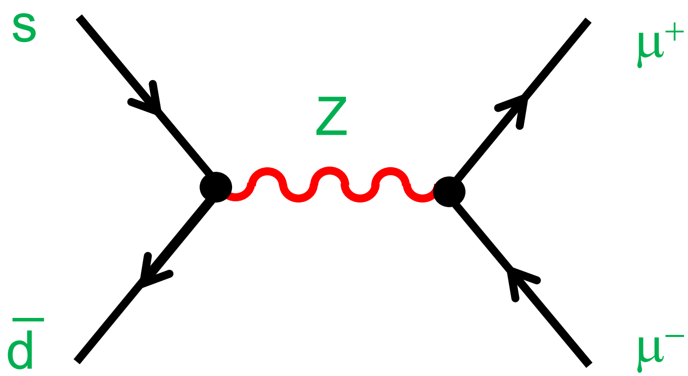
$$\bar{\mathrm{f}}'_L\, \mathrm{f}'_L = \bar{\mathrm{f}}_L\, \mathrm{f}_L \quad ; \quad \bar{\mathrm{f}}'_R\, \mathrm{f}'_R = \bar{\mathrm{f}}_R\, \mathrm{f}_R \quad \longrightarrow \quad \mathcal{L}'_{\mathrm{NC}} = \mathcal{L}_{\mathrm{NC}}$$

$$\bar{\mathrm{u}}'_L\, \mathrm{d}'_L = \bar{\mathrm{u}}_L \cdot \mathbf{V} \cdot \mathrm{d}_L \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \quad \longrightarrow \quad \mathcal{L}'_{\mathrm{CC}} \neq \mathcal{L}_{\mathrm{CC}}$$

QUARK MIXING

Flavour Conserving Neutral Currents (GIM)

$$\mathcal{L}_{NC}^{Z} = -\frac{e}{2\sin\theta_W\cos\theta_W}\, Z_\mu \sum_{f} \bar{f}\,\gamma^\mu\,[v_f - a_f\,\gamma_5]\,f$$



NO

$\mathrm{Br}(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$, $\mathrm{Br}(K_S \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ (95% CL)

LHCb, 1706.00758

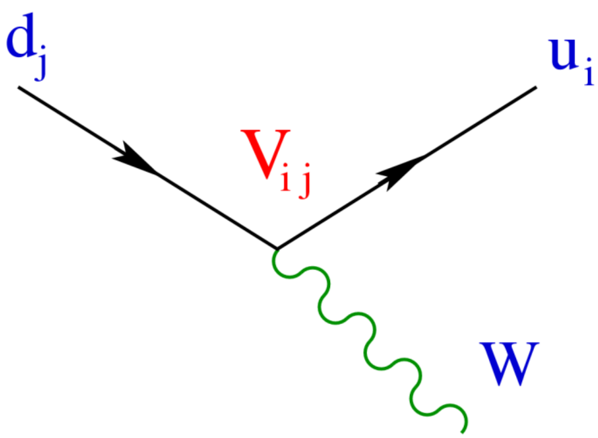
$$K_L \to \pi^{0*} \to (\gamma\gamma)^* \to \mu^+\mu^-$$

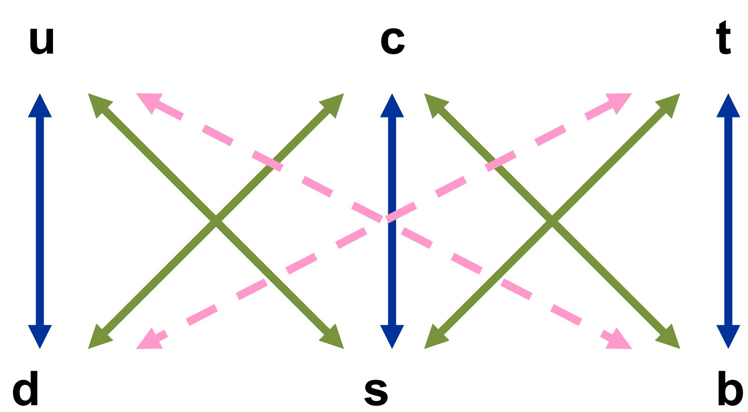
$$K_S \to (\pi^+\pi^-)^* \to (\gamma\gamma)^* \to \mu^+\mu^-$$

Flavour Changing Charged Currents

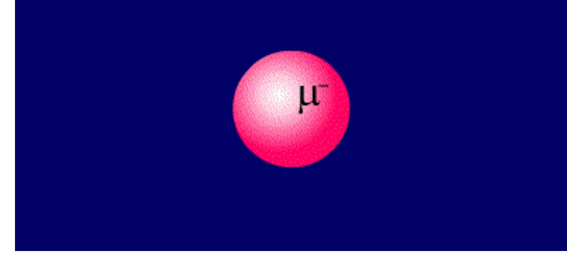
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5)\, l \right] + \text{h.c.}$$

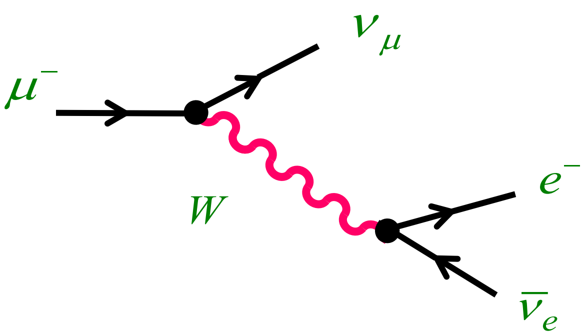
$$\left(\bar{\nu}_{l_j} \equiv \bar{\nu}_i \;\; \mathbf{V}_{ij}^{(l)} \right)$$

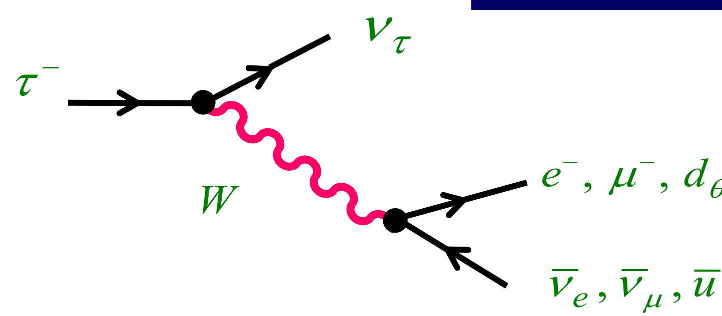




Weak Decays







$$T(l \to \nu_l\, l' \bar{\nu}_{l'}) \sim \frac{g^2}{M_W^2 - q^2} \quad \xrightarrow{q^2 \ll M_W^2} \quad \frac{g^2}{M_W^2} = 4\sqrt{2}\, G_F$$

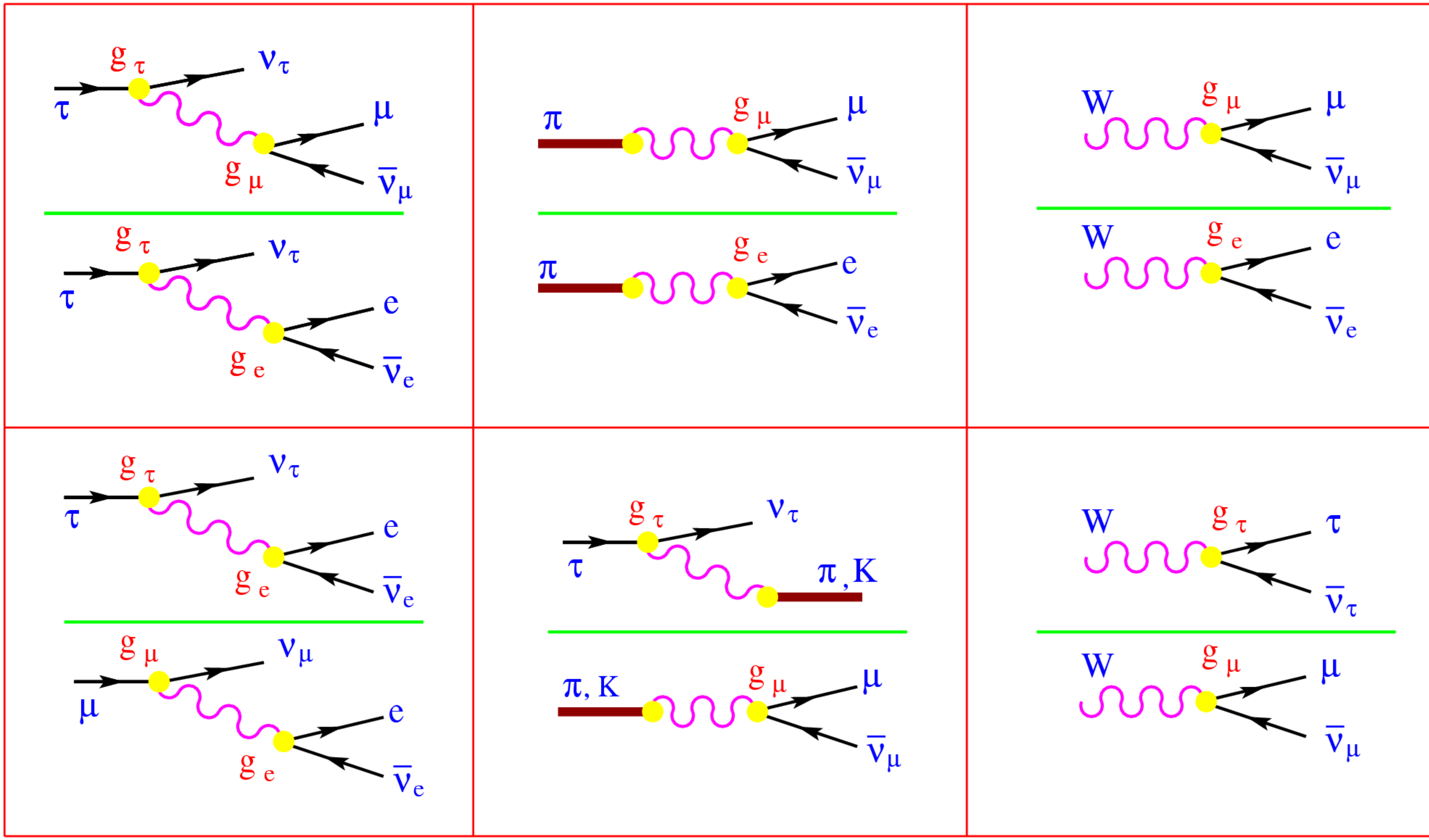
$$\frac{1}{\tau_\mu} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}\, f(m_e^2/m_\mu^2)\, r_{EW} \quad \Rightarrow \quad G_F = (1.166\,378\,7 \pm 0.000\,000\,6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right) + C_2\, \frac{\alpha(m_\mu)^2}{\pi^2}\right] = 0.9958 \qquad ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

LEPTON UNIVERSALITY

$$\frac{g_\mu}{g_e}$$

$$\frac{g_\tau}{g_\mu}$$



CHARGED CURRENT UNIVERSALITY

$|g_\mu / g_e|$

$B_{\tau\to\mu} / B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu} / B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu} / B_{K\to e}$	0.9978 ± 0.0020
$B_{K\to\pi\mu} / B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu} / B_{W\to e}$	0.996 ± 0.010

$|g_\tau / g_\mu|$

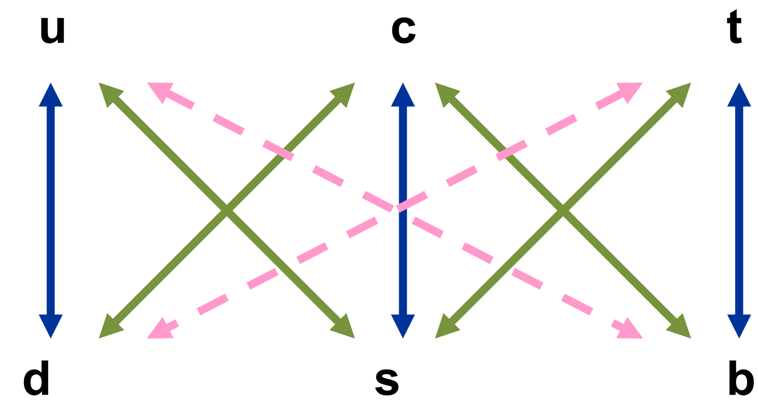
$B_{\tau\to e}\ \tau_\mu / \tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi} / \Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K} / \Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau} / B_{W\to\mu}$	1.034 ± 0.013

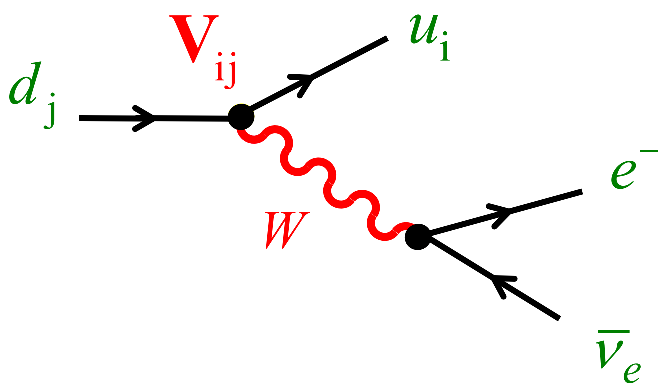
$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu / \tau_\tau$	1.0030 ± 0.0015
$B_{W\to\tau} / B_{W\to e}$	1.031 ± 0.013

A. Pich, arXiv:1310.7922

Flavour Changing Charged Currents



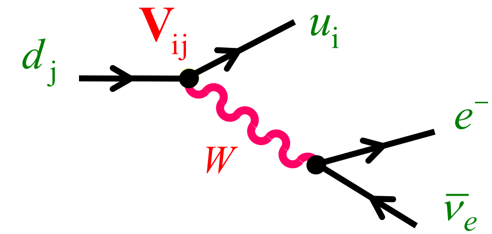


$$\Gamma(d_j \to u_i\, e^-\, \bar{\nu}_e) \propto |V_{ij}|^2$$

We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

$\mathbf{V_{ij}}$ Determination $(0^- \to 0^-)$



K→π ℓ ν , D→K ℓ ν...

$$\langle P'(k')|\bar{u}_i\gamma^\mu d_j|P(k)\rangle = C_{PP'}\left\{(k+k')^\mu\, f_+(q^2) + (k-k')^\mu\, f_-(q^2)\right\}$$

$$\Gamma(P\to P'l\nu) = \frac{G_F^2 M_P^5}{192\,\pi^3}\,|\mathbf{V_{ij}}|^2\, C_{PP'}^2\,|f_+(0)|^2\,\mathbf{I}\,(1+\delta_{\mathrm{RC}})$$

$$\mathbf{I} \approx \int_0^{(M_P-M_{P'})^2} \frac{dq^2}{M_P^8}\,\lambda^{3/2}(q^2,M_P^2,M_{P'}^2)\left|\frac{f_+(q^2)}{f_+(0)}\right|^2$$

$f_-(q^2)$ suppressed

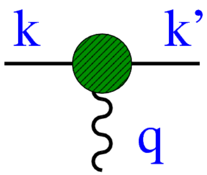
$(k-k')^\mu\ \bar{l}\,\gamma_\mu(1-\gamma_5)\,\nu_l \sim m_l$

- Measure the q^2 distribution ➡ $\mathbf{I}$
- Measure Γ ➡ $f_+(0)\,|\mathbf{V_{ij}}|$
- Get a theoretical prediction for $f_+(0)$ ➡ $|\mathbf{V_{ij}}|$

Theory is always needed: Symmetries

Symmetry (CVC): $\partial_\mu V^\mu_{ij} \equiv \partial_\mu \left(\bar{u}_i \gamma^\mu d_j\right) \sim m_{u_i} - m_{d_j} = 0$

$V^\mu_{ij}(x) = e^{iP\cdot x}\, V^\mu_{ij}(0)\, e^{-iP\cdot x}$



$$\left\langle P_i'(k') \middle| V^\mu_{ij}(x) \middle| P_j(k) \right\rangle = e^{iq\cdot x}\, C_{PP'}\, (k+k')^\mu\, f_+^{ij}(q^2)$$

Clebsh-Gordan: $C_{PP'} = 1/\sqrt{2}\;\; (P' = \pi^0),\;\; 1\;\; (\text{otherwise})$

$$\partial_\mu V^\mu_{ij} = 0 \quad \Rightarrow \quad N_{ij} = \int d^3x\, V^0_{ij}(x) = \int d^3x\, u_i^\dagger(x)\, d_j(x)$$

$$C_{PP'}\, \Delta_{\vec{k}\vec{k}'} = \left\langle P_i'(k') \middle| N_{ij} \middle| P_j(k) \right\rangle = \left\langle P_i'(k') \middle| \int d^3x\, V^0_{ij}(x) \middle| P_j(k) \right\rangle$$

$$= C_{PP'}\, (2\pi)^3\, \delta^3(\vec{q})\, 2k^0\, f_+^{ij}(0) = C_{PP'}\, \Delta_{\vec{k}\vec{k}'}\, f_+^{ij}(0)$$

$$\Rightarrow \quad \boxed{f_+^{ij}(0) = 1}$$

$|V_{ud}|$

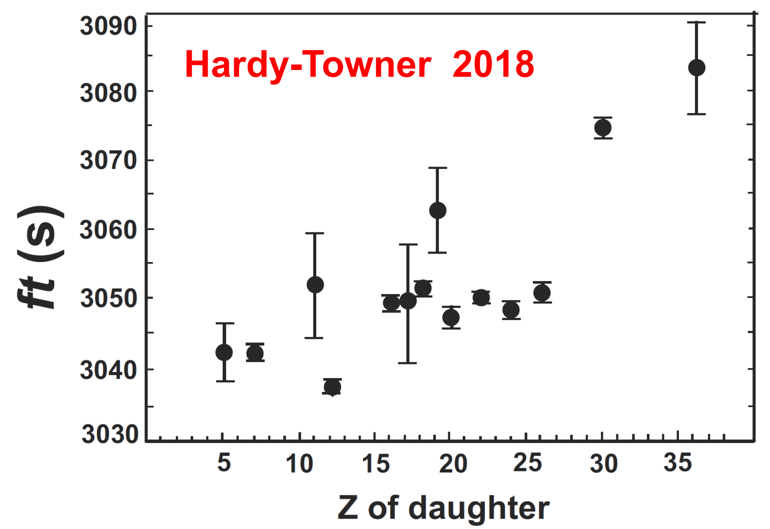
$$f_+(0) = 1 + O[(m_u - m_d)^2]$$

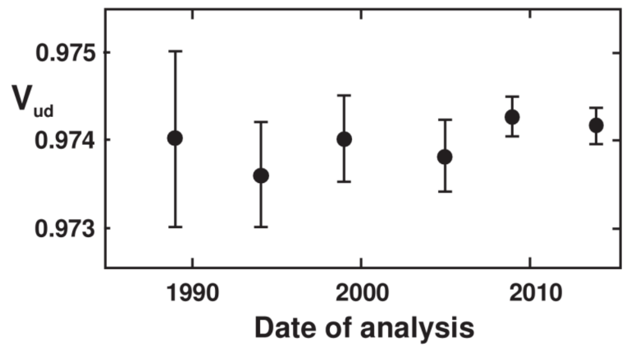
Superallowed Nuclear β Transitions $(0^+ \to 0^+)$

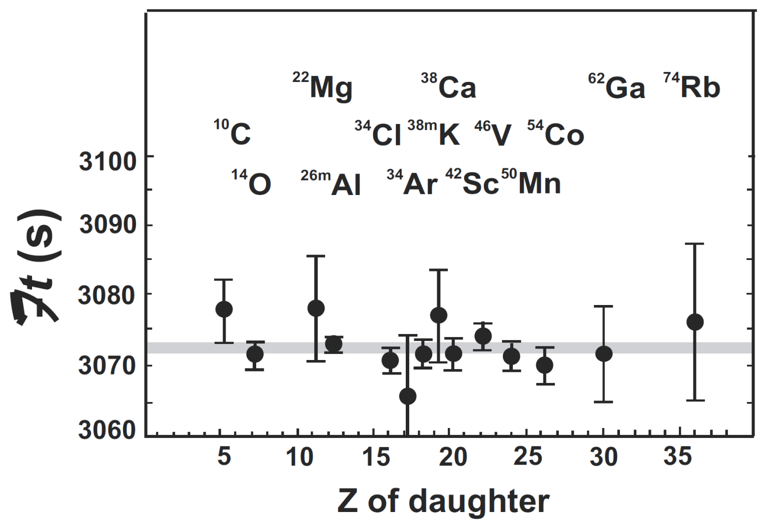
$$|V_{ud}|^2 = \frac{\pi^3 \ln 2}{ft\, G_F^2 m_e^5\, (1+\delta_{RC})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\, (1+\delta_{RC})}$$

(Marciano – Sirlin)

$|V_{ud}| = 0.97420 \pm 0.00021$







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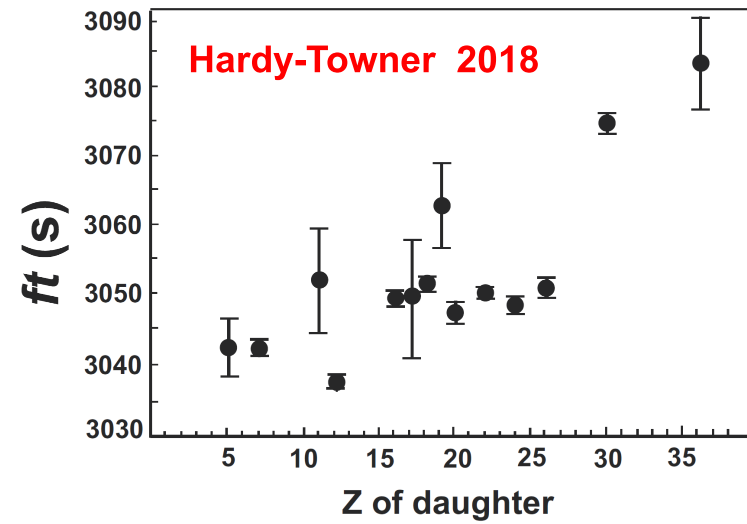
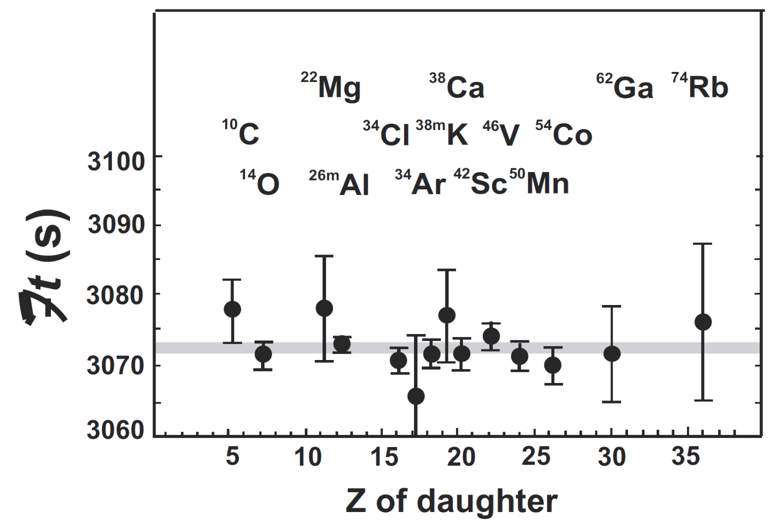
$$\delta_{RC} = \Delta_R^V + \Delta_{Nucl} \quad , \quad \mathcal{F}t = ft\left(1+\Delta_{Nucl}\right) = 3072.27\ (72)\ \text{s}$$

$$\Delta_R^V = \begin{cases} 0.02361\,(38) & \text{Marciano-Sirlin, 2006} \\ 0.02467\,(22) & \text{Seng et al, 1807.10197} \end{cases}$$

↓

$$|V_{ud}| = \begin{cases} \mathbf{0.97420\ (21)} & \text{Marciano-Sirlin} \\ \mathbf{0.97366\ (15)} & \text{Seng et al} \end{cases}$$





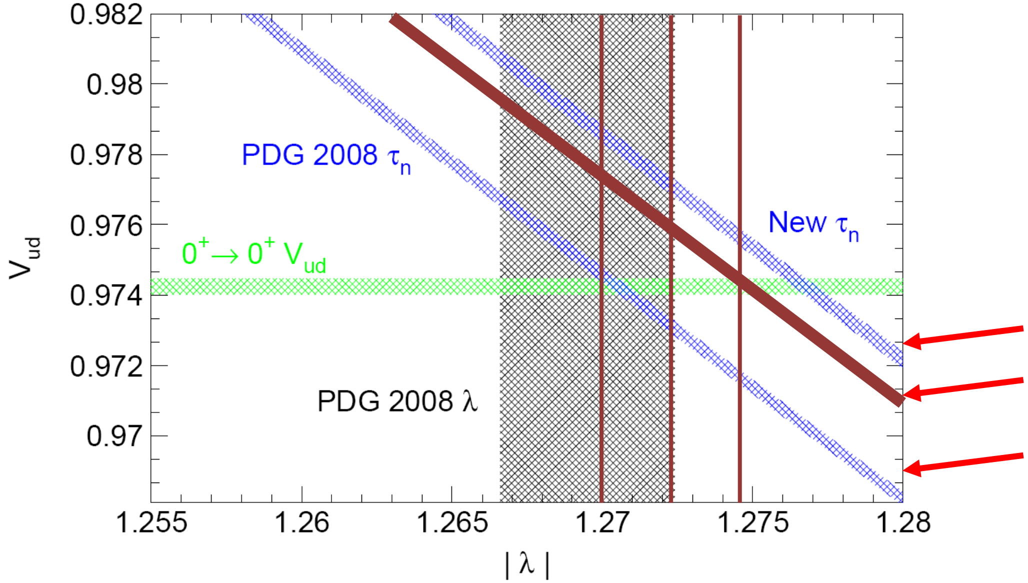
• Neutron Decay:

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\ \mathrm{s}}{\tau_n (1 + 3\lambda^2)}$$

(Czarnecki – Marciano – Sirlin)

PDG10: $\tau_n = (885.7 \pm 0.8)$ s , $\lambda \equiv g_A / g_V = -1.2694 \pm 0.0028$

PDG18: $\tau_n = (879.3 \pm 0.9)$ s , $\lambda \equiv g_A / g_V = -1.2724 \pm 0.0023$



PDG16

PDG10

$|V_{ud}| = 0.9763 \pm 0.0016$

$\tau_n = (878.5 \pm 0.7 \pm 0.3)$ s

(Serebrov et al, 2005)

• Pion Decay:

$$\mathrm{Br}(\pi^+ \to \pi^0 e^+ \nu_e) = (1.036 \pm 0.006) \times 10^{-8}$$

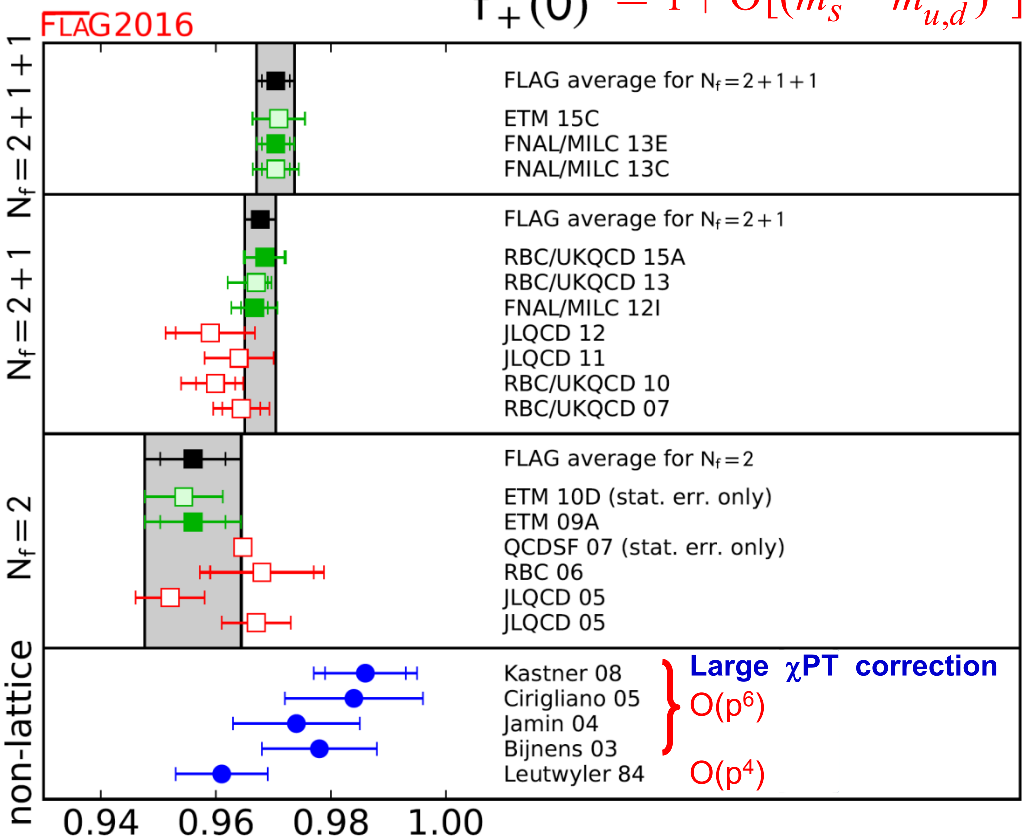
(PIBETA)

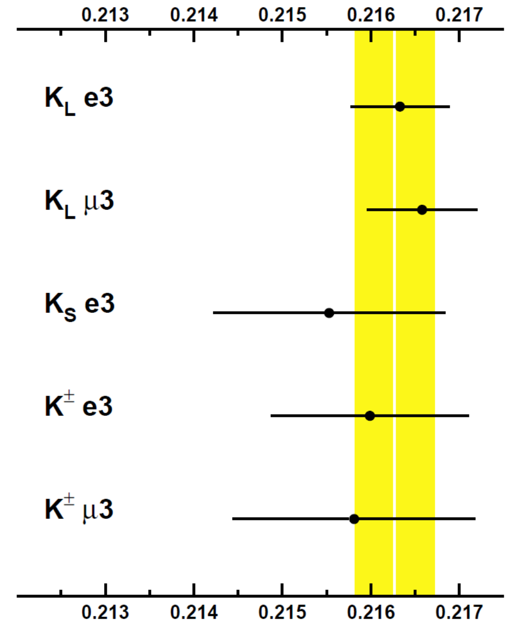
$|V_{ud}| = 0.9749 \pm 0.0026$

$K \to \pi \ell \nu$ Decays

Flavianet, arXiv:1005.2323 [hep-ph]
Moulson, arXiv:1411.5252 [hep-ph]

$$f_+(0) = 1 + O[(m_s - m_{u,d})^2]$$





$$|f_+(0)\, V_{us}| = 0.2165 \pm 0.0004$$

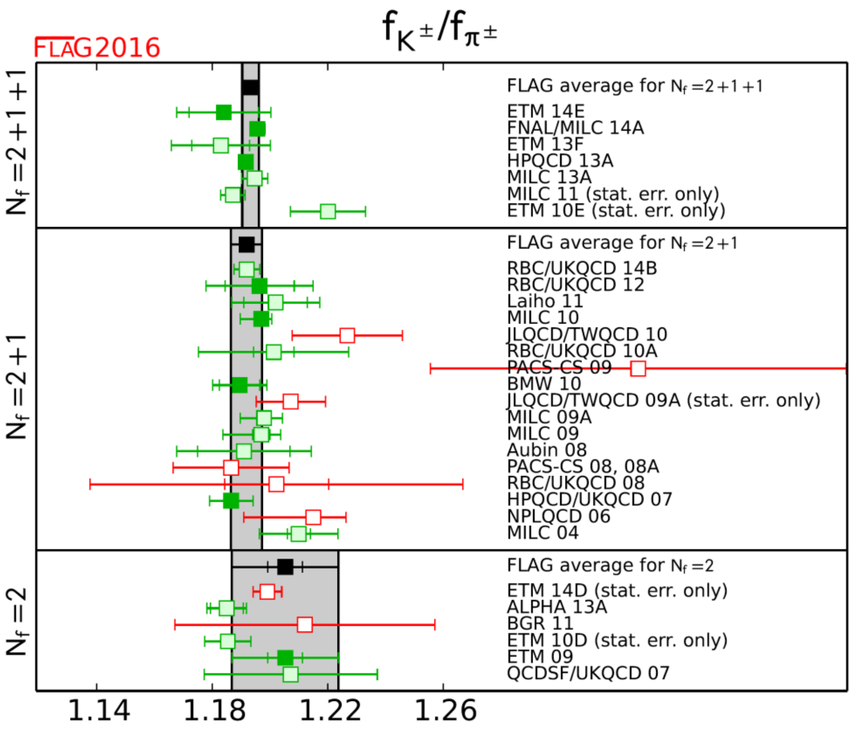
2012 : $f_+(0) = 0.959 \pm 0.005$ → $|V_{us}| = 0.2255 \pm 0.0014$

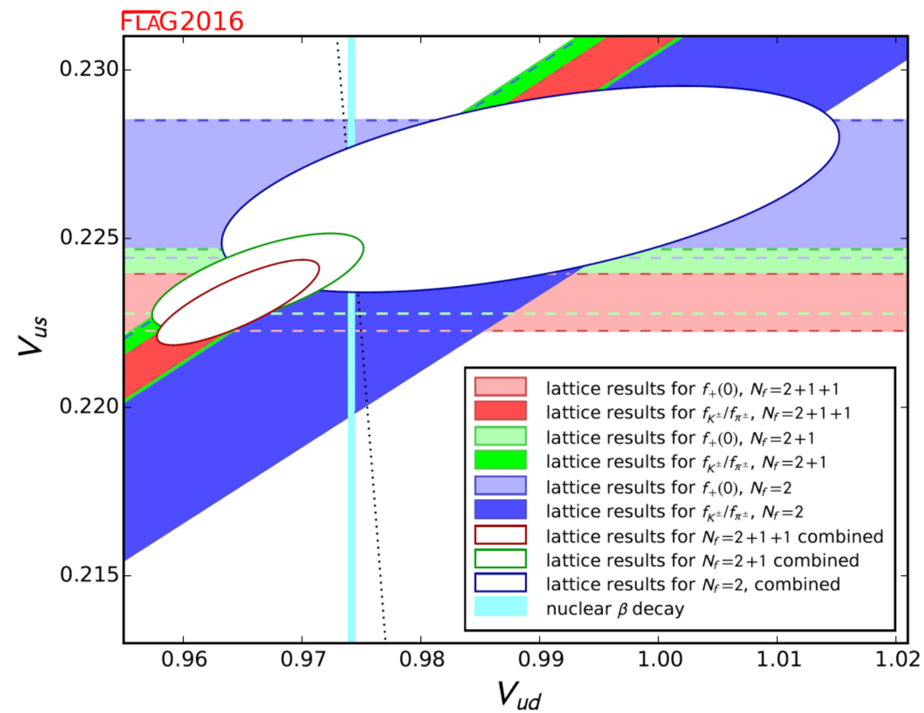
2016 : $f_+(0) = 0.9706 \pm 0.0027$ → $|V_{us}| = 0.2231 \pm 0.0007$

$\Gamma(K^+ \to \mu^+ \nu_\mu) \,/\, \Gamma(\pi^+ \to \mu^+ \nu_\mu)$

$$\frac{f_K}{f_\pi}\frac{|V_{us}|}{|V_{ud}|} = 0.2760 \pm 0.0004 \quad \Rightarrow \quad \frac{|V_{us}|}{|V_{ud}|} = 0.2313 \pm 0.007$$

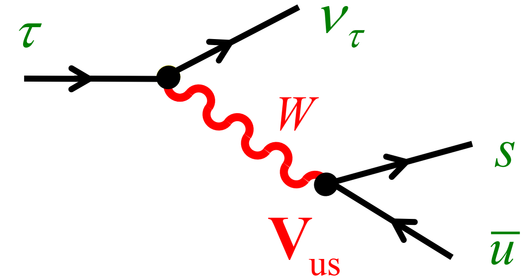
$$\langle 0 | \bar{d}_i \gamma^\mu \gamma_5 u_j | P(k) \rangle = i\, f_P\, k^\mu$$





$$f_K / f_\pi = 1.1933 \pm 0.0029 \qquad \text{(FLAG 2016)}$$

$$R_{\tau,us} = \frac{\Gamma(\tau^- \to \nu_\tau X_s^-)}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}$$



Gámiz-Jamin-Pich-Prades-Schwab

$$\delta R_\tau \equiv \frac{R_{\tau,ud}}{|\mathbf{V_{ud}}|^2} - \frac{R_{\tau,us}}{|\mathbf{V_{us}}|^2} \approx 24\, \frac{m_s^2(m_\tau^2)}{m_\tau^2}\, \Delta(\alpha_s) = 0.240 \pm 0.032$$

$$|\mathbf{V_{us}}|^2 = \frac{R_{\tau,S}}{\frac{R_{\tau,ud}}{|\mathbf{V_{ud}}|^2} - \delta R_\tau^{\mathrm{th}}}$$

HFAG 2016: $R_{\tau,ud} = 3.4718 \pm 0.0072$; $R_{\tau,S} = 0.1633 \pm 0.0027$

$$|\mathbf{V_{us}}| = 0.2186 \pm 0.0018_{\mathrm{exp}} \pm 0.0010_{\mathrm{th}}$$

Replacing $\tau \to \nu K(\pi)$ by $K \to \nu \mu(\pi)$ data: **$|V_{us}| = 0.2213 \pm 0.0023$**

With better data, could give a very precise V_{us} determination

Heavy Quark Symmetry

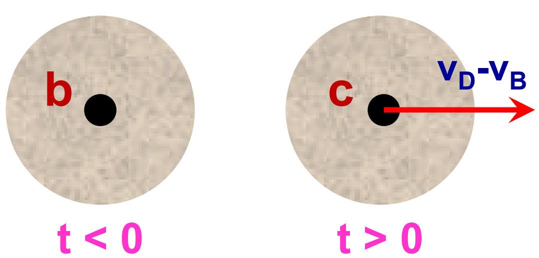
- **Atomic Physics:** $\mu \equiv m_e M_N/(m_e+M_N) \simeq m_e \ll M_N \quad , \quad \vec{S}_N / M_N$
  - **Flavour Symmetry:** Same chemical properties for different isotopes $(Z = Z' \,,\, M_N \neq M_{N'})$
  - **Spin Symmetry:** Atoms with nuclear spin J are (2J+1) degenerate

- **Heavy-Light Mesons $Q\bar{q}$:** $M_Q \gg m_q , \Lambda \quad ; \quad \delta P_Q \sim \Lambda \quad ; \quad \delta v_Q \sim \Lambda / M_Q \ll 1$
  - Q is practically at rest and acts as a static source of gluons $(\lambda_Q \sim 1/M_Q \ll R_{had} \sim 1/\Lambda)$
  - The interaction is M_Q and J_Q independent ➡ **Flavour and Spin Symmetries**

    $B \leftrightarrow D \qquad B \leftrightarrow B^*$

- **$B \to D \ell \nu$:** $P_Q^\mu \equiv M_Q v^\mu + k^\mu \quad , \quad v^2 = 1 \quad , \quad k \sim \Lambda \quad , \quad Q(x) \approx e^{-iM_Q v\cdot x}\, h_v^{(Q)}(x) \quad , \quad |M(P)\rangle \equiv \sqrt{M_P}\, |\tilde{M}(v)\rangle$

$$\langle D | \bar{c}\gamma^\mu b | B \rangle \quad \Longrightarrow \quad \left\langle \tilde{D}(v_D) \left| \bar{h}_{v_D}^{(c)} \gamma^\mu h_{v_B}^{(b)} \right| \tilde{B}(v_B) \right\rangle = \xi(v_D \cdot v_B)\,(v_D + v_B)^\mu$$

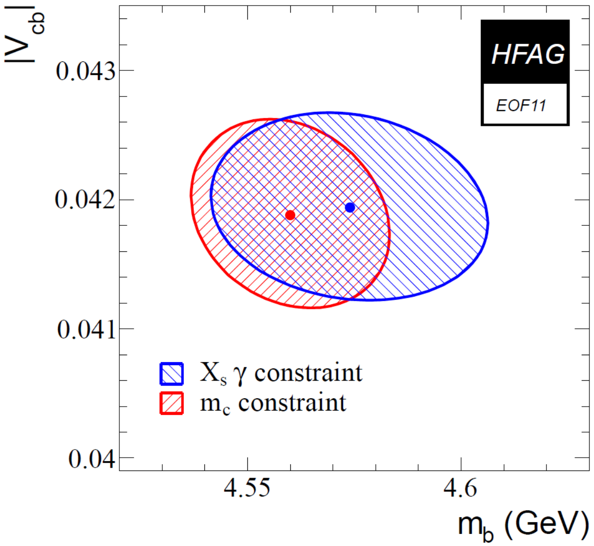


Nothing changes at zero recoil: $v_D = v_B \qquad [(q^2)_{max} = (M_B - M_D)^2\,]$

➡ $\boxed{\xi(1) = 1}$

Inclusive B Decays (OPE, HQET)

$$\Gamma(\bar{B} \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \left\{ f(\rho) + k(\rho) \frac{\mu_\pi^2}{2m_b^2} + g(\rho) \frac{\mu_G^2}{2m_b^2} \right\}$$



Fits to lepton energy, hadronic invariant mass and photon energy moments

HFAG 2016: $|V_{cb}|_{incl} = \begin{cases} (42.19 \pm 0.78) \cdot 10^{-3} & \text{Kinetic mass} \\ (41.98 \pm 0.45) \cdot 10^{-3} & \text{1S mass} \end{cases}$

PDG 2018: $|V_{cb}|_{incl} = (42.2 \pm 0.8) \cdot 10^{-3}$

Gambino- Healey-Turczyk, 1606.06174

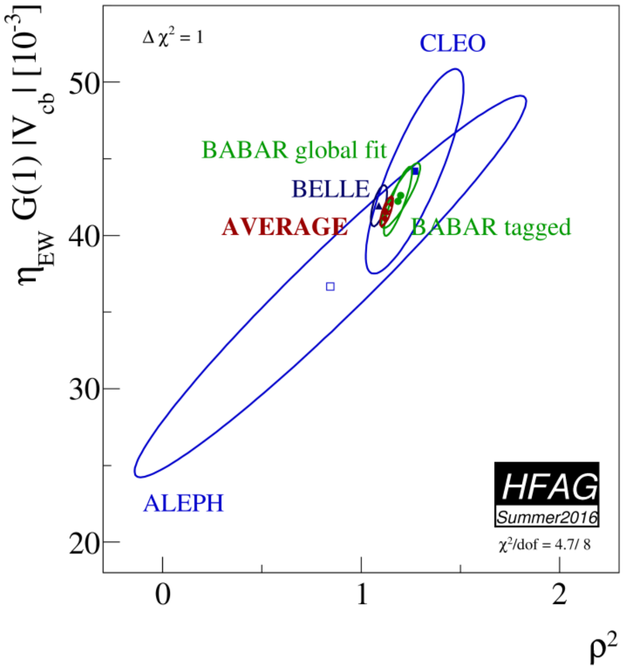
Higher Power Corrections

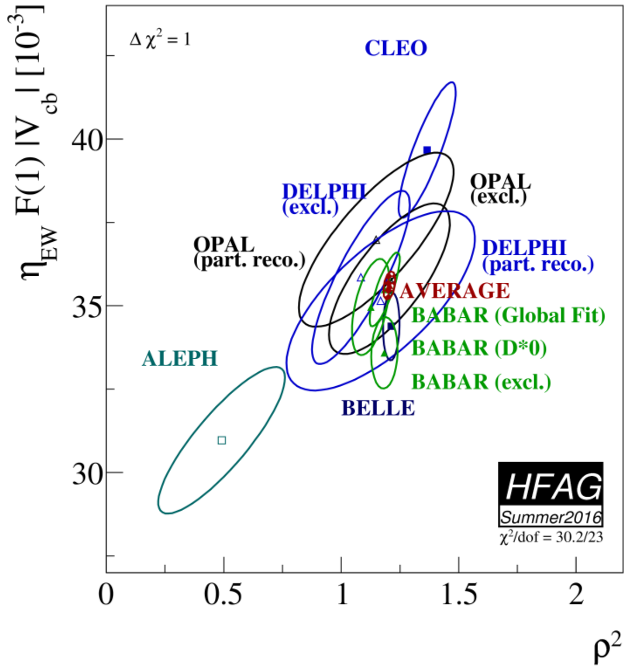
$|V_{cb}| = (42.00 \pm 0.63) \times 10^{-3}$

$B \to D \ell \nu$ $B \to D^* \ell \nu$

QCD Symmetries at $1/M_Q \to 0$

HQET





Caprini-Lellouch-Neubert parametrization

$$\eta_{EW}\, G(1)\ |\mathbf{V_{cb}}| = (41.57 \pm 1.00)\cdot 10^{-3}$$

$$\eta_{EW}\, F(1)\ |\mathbf{V_{cb}}| = (35.61 \pm 0.43)\cdot 10^{-3}$$

FNAL / MILC :

$$\eta_{EW}\, G(1) = 1.061 \pm 0.010 \quad \Rightarrow \quad |\mathbf{V_{cb}}| = (39.18 \pm 0.94_{exp} \pm 0.36_{th})\cdot 10^{-3}$$

$$\eta_{EW}\, F(1) = 0.912 \pm 0.014 \quad \Rightarrow \quad |\mathbf{V_{cb}}| = (39.05 \pm 0.47_{exp} \pm 0.58_{th})\cdot 10^{-3}$$

$$\Rightarrow \quad \boxed{|\mathbf{V_{cb}}|_{excl} = (39.10 \pm 0.60)\cdot 10^{-3}}$$

3.3 σ discrepancy with inclusive measurement

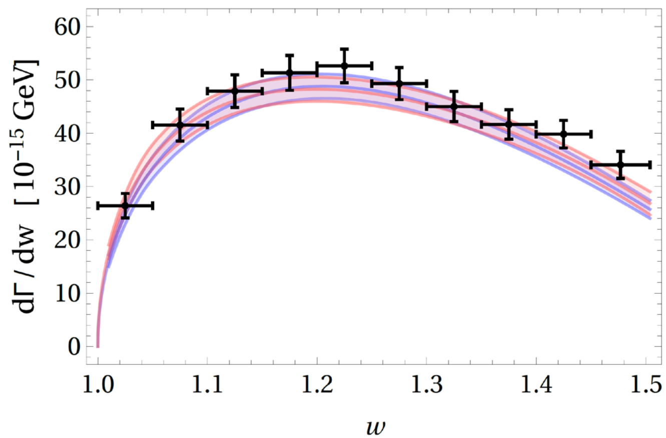
Parametrization Dependence

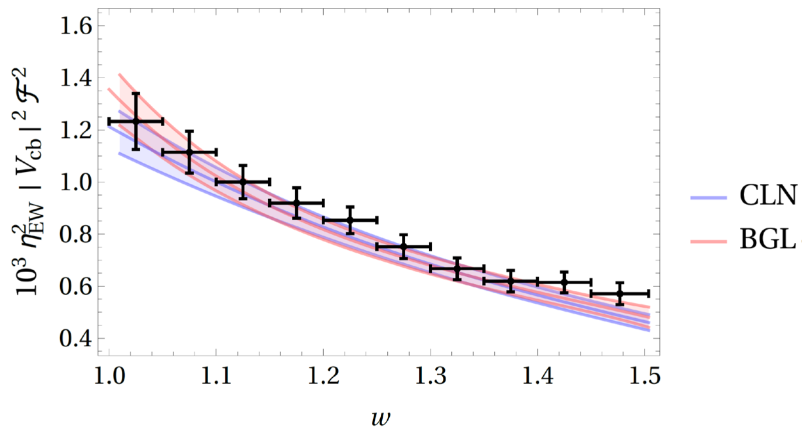
Analyticity, Unitarity
Crossing Symmetry →
- Boyd-Grinstein-Lebed (BGL)
- Caprini-Lellouch-Neubert (CLN) (HQET relations valid within 2%)

● $B \to D^* \ell \nu$

Belle data (1702.01521) + Lattice + LCSRs

Bigi-Gambino-Schacht, 1703.06124, 1707.09509



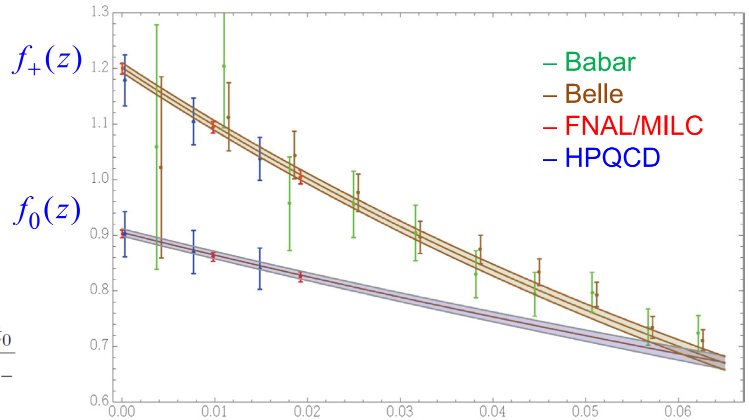


$10^{-3} \cdot \lvert V_{cb} \rvert$
39.2 ± 1.1
40.6 ± 1.3

$w = v_B \cdot v_D$

See also Grinstein-Kobach, 1703.08170; Bernlochner-Ligeti-Papucci-Robinson, 1703.05330, 1708.07134

● $B \to D \ell \nu$



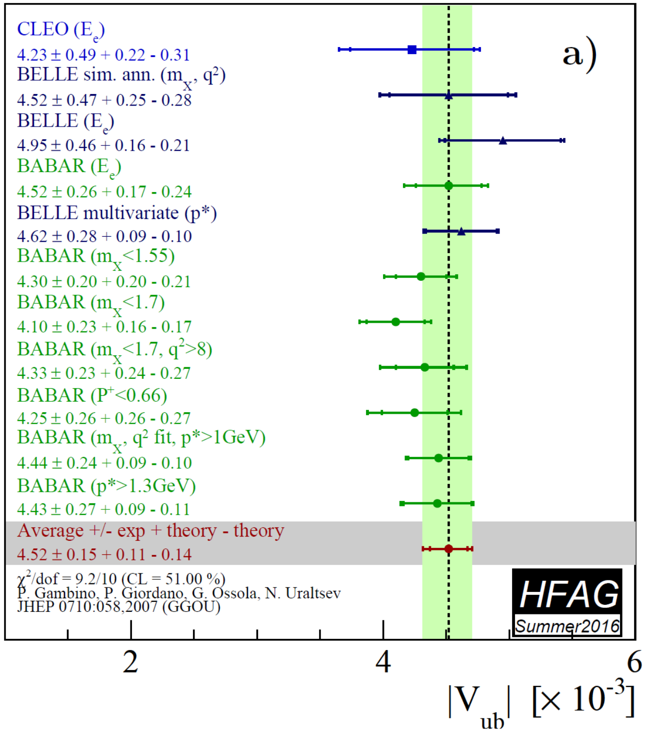
Bigi-Gambino-Schacht, 1606.08030

$$\lvert V_{cb} \rvert = (40.49 \pm 0.97) \cdot 10^{-3}$$

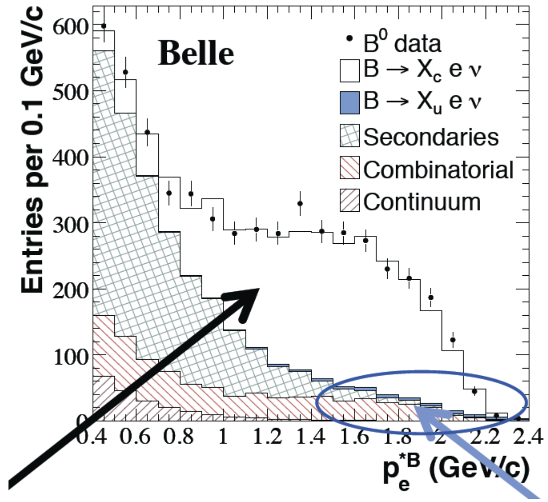
$$t_+ = (m_B + m_D)^2, \qquad t_- = (m_B - m_D)^2,$$

$$z(w, \mathcal{N}) = \frac{\sqrt{1+w} - \sqrt{2\mathcal{N}}}{\sqrt{1+w} + \sqrt{2\mathcal{N}}}, \qquad \mathcal{N} = \frac{t_+ - t_0}{t_+ - t_-}$$

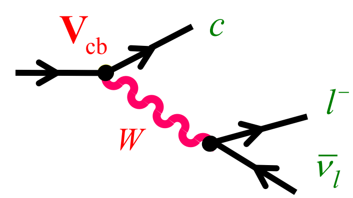
$B \to X_u \ell \nu$

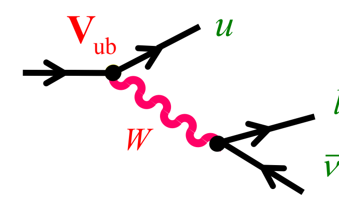


Framework	$\lvert V_{ub}\rvert [10^{-3}]$
BLNP	$4.44 \pm 0.15^{+0.21}_{-0.22}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.52 \pm 0.15^{+0.11}_{-0.14}$
ADFR	$4.08 \pm 0.13^{+0.18}_{-0.12}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$
LLR (*BABAR*) [531]	$4.43 \pm 0.45 \pm 0.29$
LLR (*BABAR*) [532]	$4.28 \pm 0.29 \pm 0.29 \pm 0.26 \pm 0.28$
LNP (*BABAR*) [532]	$4.40 \pm 0.30 \pm 0.41 \pm 0.23$

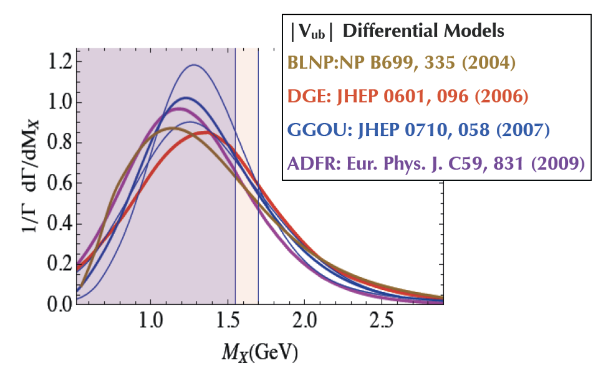


$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 \approx \frac{1}{50}$$



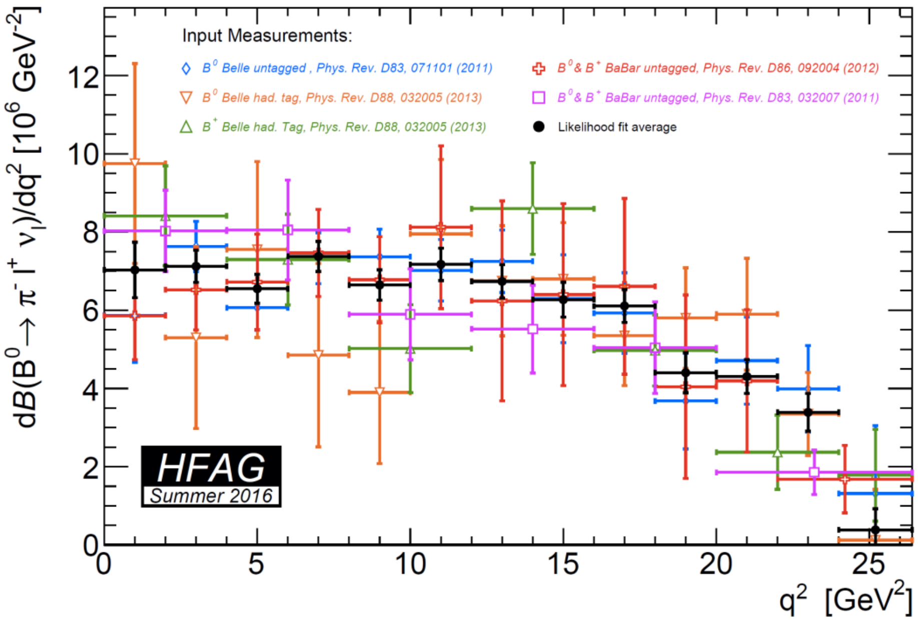


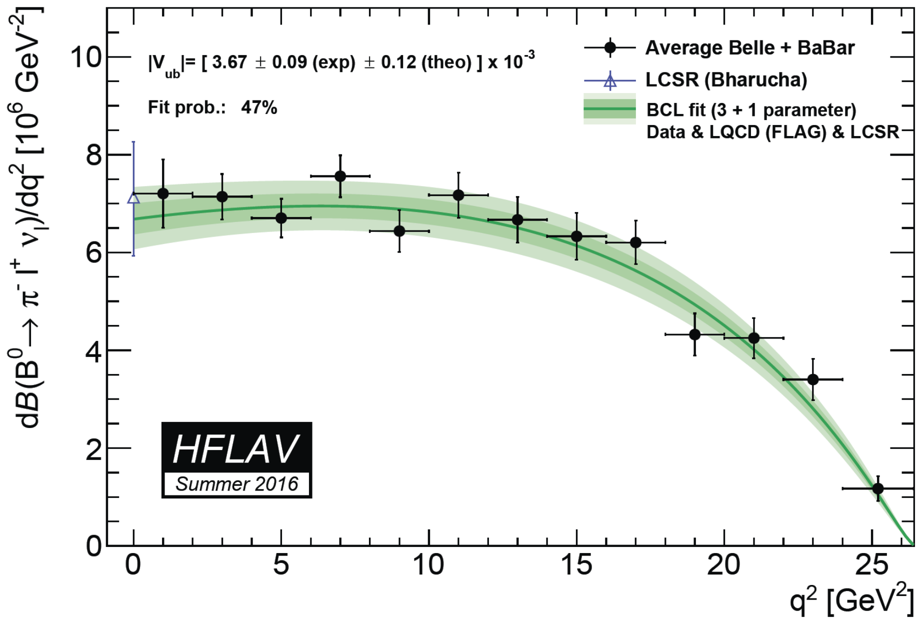
- **Large backgrounds from $B \to X_c l \nu$**
- **Strong experimental cuts**
- **Large theoretical uncertainties**



HFAG 2016: $$\left|V_{ub}\right|_{\mathrm{incl}} = \left(4.52 \pm 0.15 \,{}^{+0.11}_{-0.14}\right) \cdot 10^{-3}$$

$B \to \pi \ell \nu$





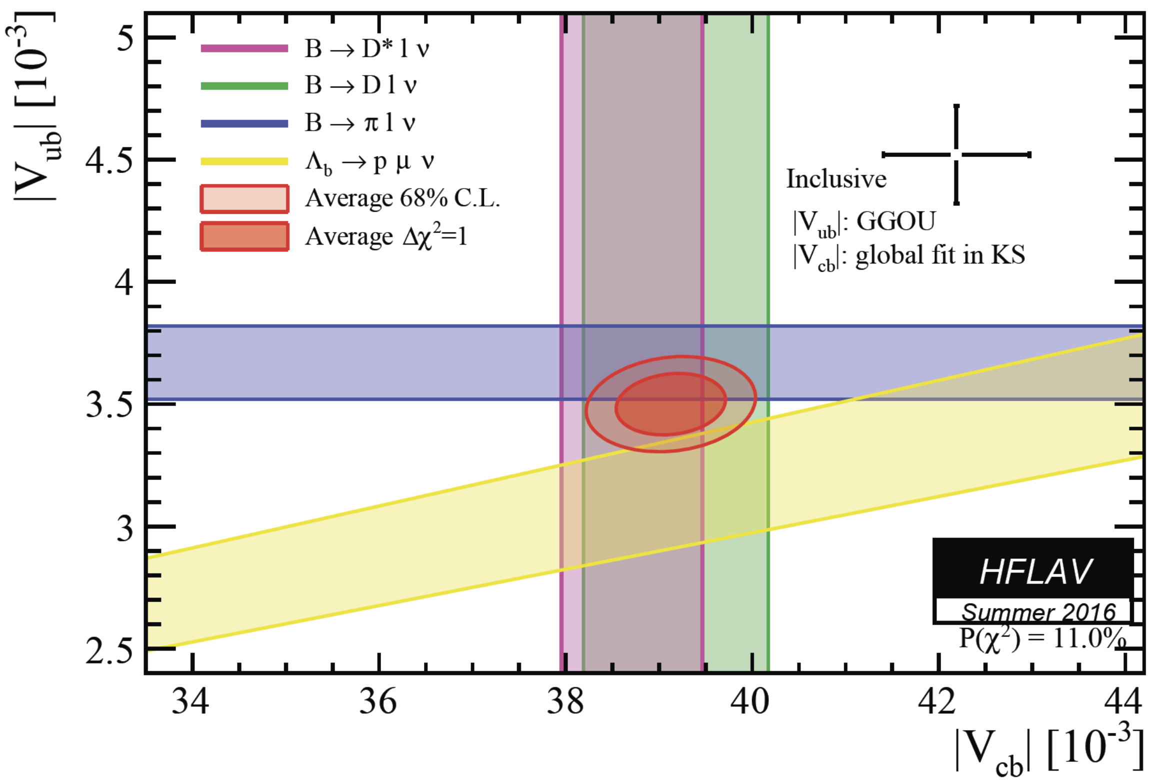
HFAG 2016: $$\left|V_{ub}\right|_{\text{excl}} = \left(3.67 \pm 0.09_{\text{exp}} \pm 0.12_{\text{th}}\right)\cdot 10^{-3}$$

3.4 σ discrepancy with inclusive measurement

$$\rightarrow \quad \left|V_{ub}\right| = (3.98 \pm 0.40) \times 10^{-3}$$

LHCb : 1504.01568

$$R = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)_{q^2>15\ GeV^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\ GeV^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

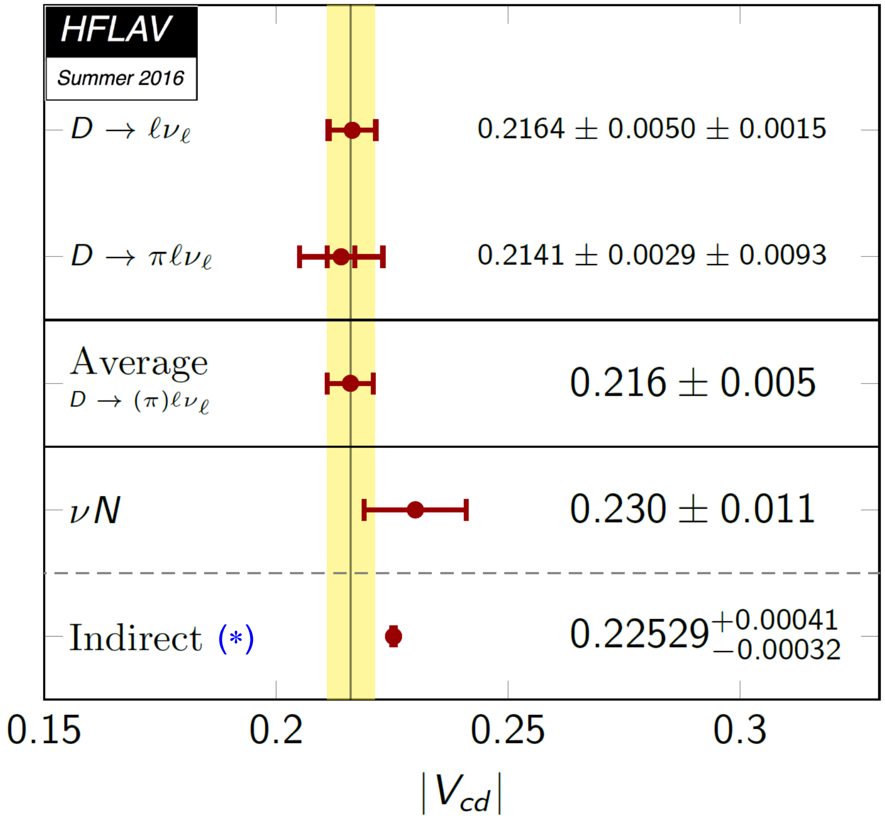


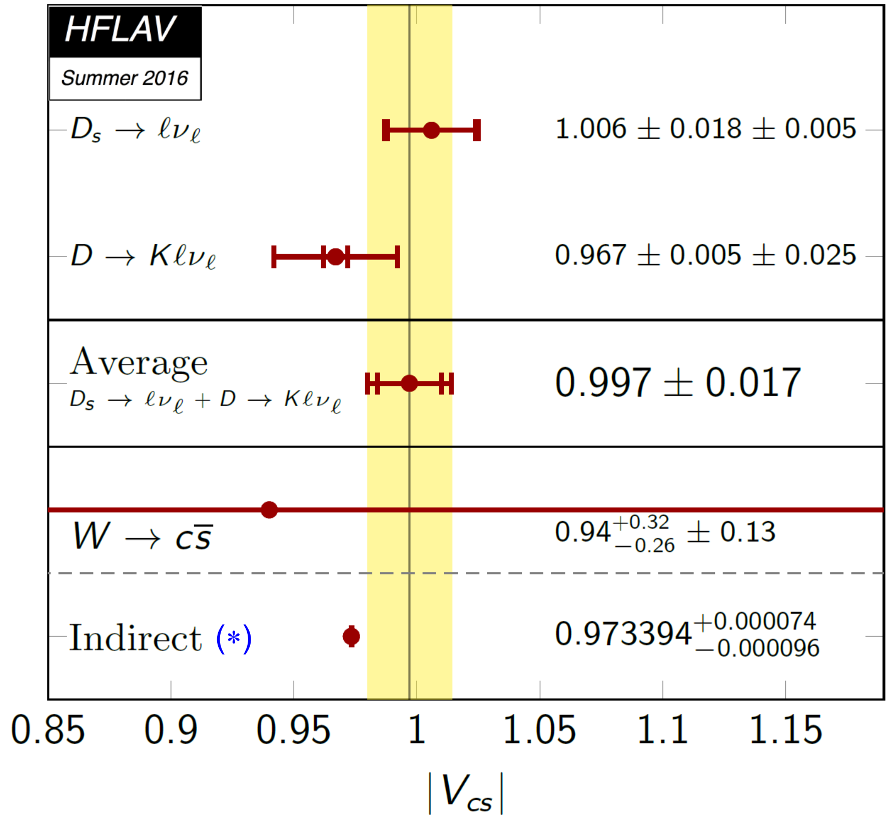
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.080 \pm 0.004_{\text{exp}} \pm 0.004_{\text{F.F.}}$$

Combination exclusive + LHCb: (HFAG 2016)

$$|V_{cb}| = (39.13 \pm 0.59) \cdot 10^{-3} \qquad , \qquad |V_{ub}| = (3.50 \pm 0.13) \cdot 10^{-3}$$

$|V_{cd}|$ & $|V_{cs}|$





(*) Global CKM fit (unitarity assumed)

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\|V_{ud}\|$	**0.97420 ± 0.00021**	Nuclear β decay
	0.9763 ± 0.0016	$n \to p\, e^- \bar{\nu}_e$
	0.9749 ± 0.0026	$\pi^+ \to \pi^0 e^+ \nu_e$
$\|V_{us}\|$	**0.2231 ± 0.0007**	$K \to \pi\, e^- \bar{\nu}_e$
	0.2253 ± 0.0007	$K/\pi \to \mu\nu$, Lattice, V_{ud}
	0.2213 ± 0.0023	τ decays
$\|V_{cd}\|$	0.230 ± 0.011	$\nu\, d \to c\, X$
	0.216 ± 0.005	$D \to (\pi)\, l\, \nu$, Lattice
$\|V_{cs}\|$	**0.997 ± 0.017**	$D \to K\, l\, \nu$, $D_s \to l\, \nu$, Lattice
$\|V_{cb}\|$	0.0405 ± 0.0010	$B \to D^* l\, \bar{\nu}_l$, $D\, l\, \bar{\nu}_l$
	0.0420 ± 0.0006	$b \to c\, l\, \bar{\nu}_l$
$\|V_{ub}\|$	0.00367 ± 0.00015	$B \to \pi\, l\, \bar{\nu}_l$
	0.00451 ± 0.00020	$b \to u\, l\, \bar{\nu}_l$
	0.00398 ± 0.00040	
$\|V_{tb}\| / \sqrt{\sum_q \|V_{tq}\|^2}$	> 0.975 (95% CL)	$t \to bW / t \to qW$
$\|V_{tb}\|$	**1.019 ± 0.025**	$p\bar{p} \to tb + X$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \mathbf{0.9989 \pm 0.0005}$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = \mathbf{1.040 \pm 0.051}$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = \mathbf{1.042 \pm 0.034}$$

$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = \mathbf{2.002 \pm 0.027} \quad \text{(LEP)}$$

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\|V_{ud}\|$	**0.97366 ± 0.00015**	Nuclear β decay
Seng et al	0.9763 ± 0.0016	$n \to p\, e^- \bar{\nu}_e$
	0.9749 ± 0.0026	$\pi^+ \to \pi^0 e^+ \nu_e$
$\|V_{us}\|$	**0.2231 ± 0.0007**	$K \to \pi\, e^- \bar{\nu}_e$
	0.2252 ± 0.0007	$K/\pi \to \mu\nu$, Lattice, V_{ud}
	0.2213 ± 0.0023	τ decays
$\|V_{cd}\|$	0.230 ± 0.011	$\nu d \to c X$
	0.216 ± 0.005	$D \to (\pi) l \nu$, Lattice
$\|V_{cs}\|$	**0.997 ± 0.017**	$D \to K l \nu$, $D_s \to l \nu$, Lattice
$\|V_{cb}\|$	0.0405 ± 0.0010	$B \to D^* l \bar{\nu}_l$, $D l \bar{\nu}_l$
	0.0420 ± 0.0006	$b \to c\, l \bar{\nu}_l$
$\|V_{ub}\|$	0.00367 ± 0.00015	$B \to \pi\, l \bar{\nu}_l$
	0.00451 ± 0.00020	$b \to u\, l \bar{\nu}_l$
	0.00398 ± 0.00040	
$\|V_{tb}\| / \sqrt{\sum_q \|V_{tq}\|^2}$	> 0.975 (95% CL)	$t \to bW / t \to qW$
$\|V_{tb}\|$	**1.019 ± 0.025**	$p\bar{p} \to tb + X$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \mathbf{0.9978 \pm 0.0004}$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = \mathbf{1.042 \pm 0.034}$$

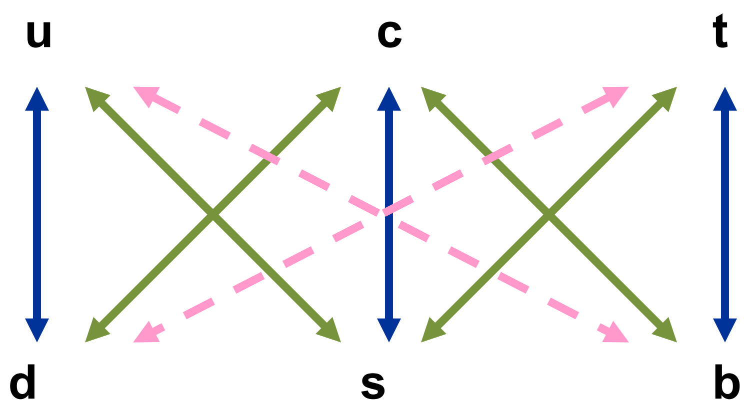
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = \mathbf{1.040 \pm 0.051}$$

$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = \mathbf{2.002 \pm 0.027} \quad \text{(LEP)}$$

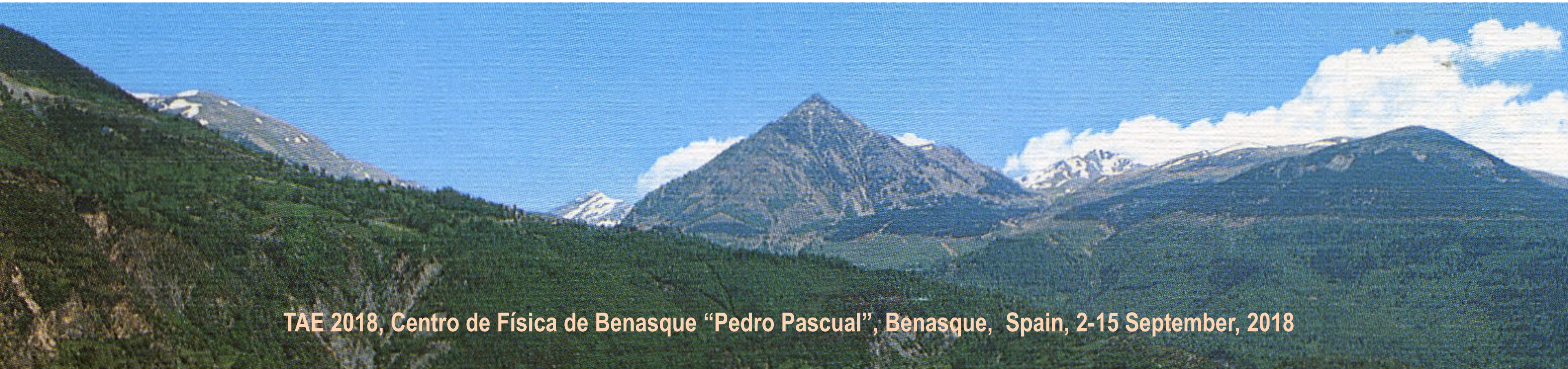
Hierarchical Structure

$$\mathbf{V} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

$$\lambda \approx \sin\theta_C \approx 0.223 \quad ; \quad A \approx 0.84 \quad ; \quad \sqrt{\rho^2+\eta^2} \approx 0.4$$



Backup



$D \to K l \nu$: $\left| f_+^{DK}(0)\, V_{cs} \right| = 0.7226 \pm 0.0022 \pm 0.0026$ HFAG 2017

FLAG 2016 ($N_f = 2+1$): $f_+^{DK}(0) = 0.747 \pm 0.019$ ➡ $\left| \mathbf{V_{cs}} \right| = \mathbf{0.967 \pm 0.005 \pm 0.025}$

$D_s \to l \nu$: $\left| f_{D_s}\, V_{cs} \right| = (250.3 \pm 4.5)$ MeV HFAG 2017

FLAG 2016 ($N_f = 2+1+1$): $f_{D_s} = (248.83 \pm 1.27)$ MeV ➡ $\left| \mathbf{V_{cs}} \right| = \mathbf{1.006 \pm 0.018 \pm 0.005}$

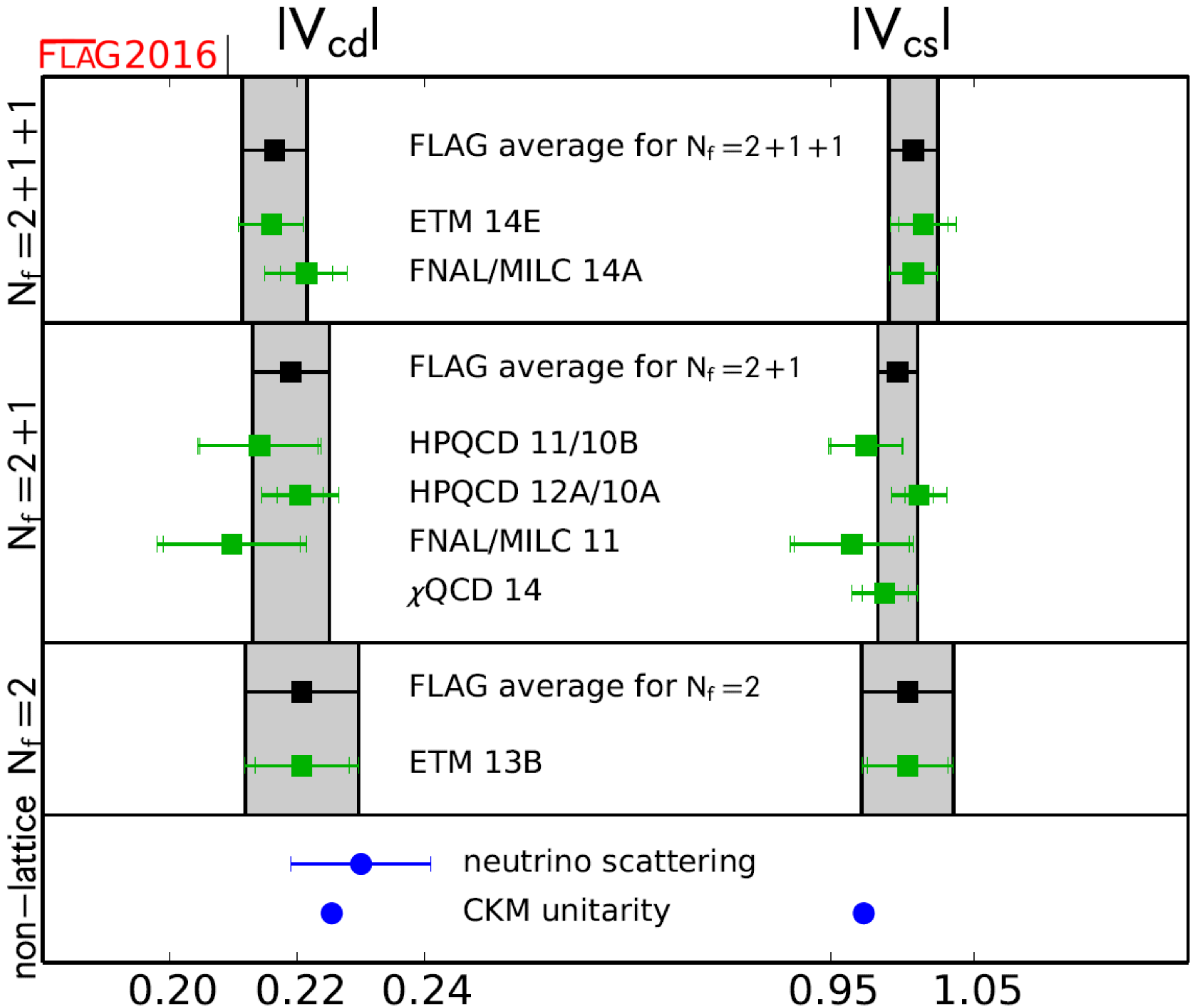
$D \to \pi l \nu$: $\left| f_+^{D\pi}(0)\, V_{cd} \right| = 0.1426 \pm 0.0017 \pm 0.0008$ HFAG 2017

FLAG 2016 ($N_f = 2+1$): $f_+^{D\pi}(0) = 0.666 \pm 0.029$ ➡ $\left| \mathbf{V_{cd}} \right| = \mathbf{0.2141 \pm 0.0029 \pm 0.0093}$

$D \to l \nu$: $\left| f_D\, V_{cd} \right| = (45.9 \pm 1.1)$ MeV HFAG 2017

FLAG 2016 ($N_f = 2+1+1$): $f_D = (212.15 \pm 1.45)$ MeV ➡ $\left| \mathbf{V_{cd}} \right| = \mathbf{0.2164 \pm 0.0050 \pm 0.0015}$

➡ $\left| \mathbf{V_{cs}} \right| = \mathbf{0.997 \pm 0.017}$ $\left| \mathbf{V_{cd}} \right| = \mathbf{0.216 \pm 0.005}$



FLAG2016
|Vcd|
|Vcs|
Nf =2+1+1
FLAG average for Nf =2+1+1
ETM 14E
FNAL/MILC 14A
Nf =2+1
FLAG average for Nf =2+1
HPQCD 11/10B
HPQCD 12A/10A
FNAL/MILC 11
χQCD 14
Nf =2
FLAG average for Nf =2
ETM 13B
non−lattice
neutrino scattering
CKM unitarity
0.20
0.22
0.24
0.95
1.05