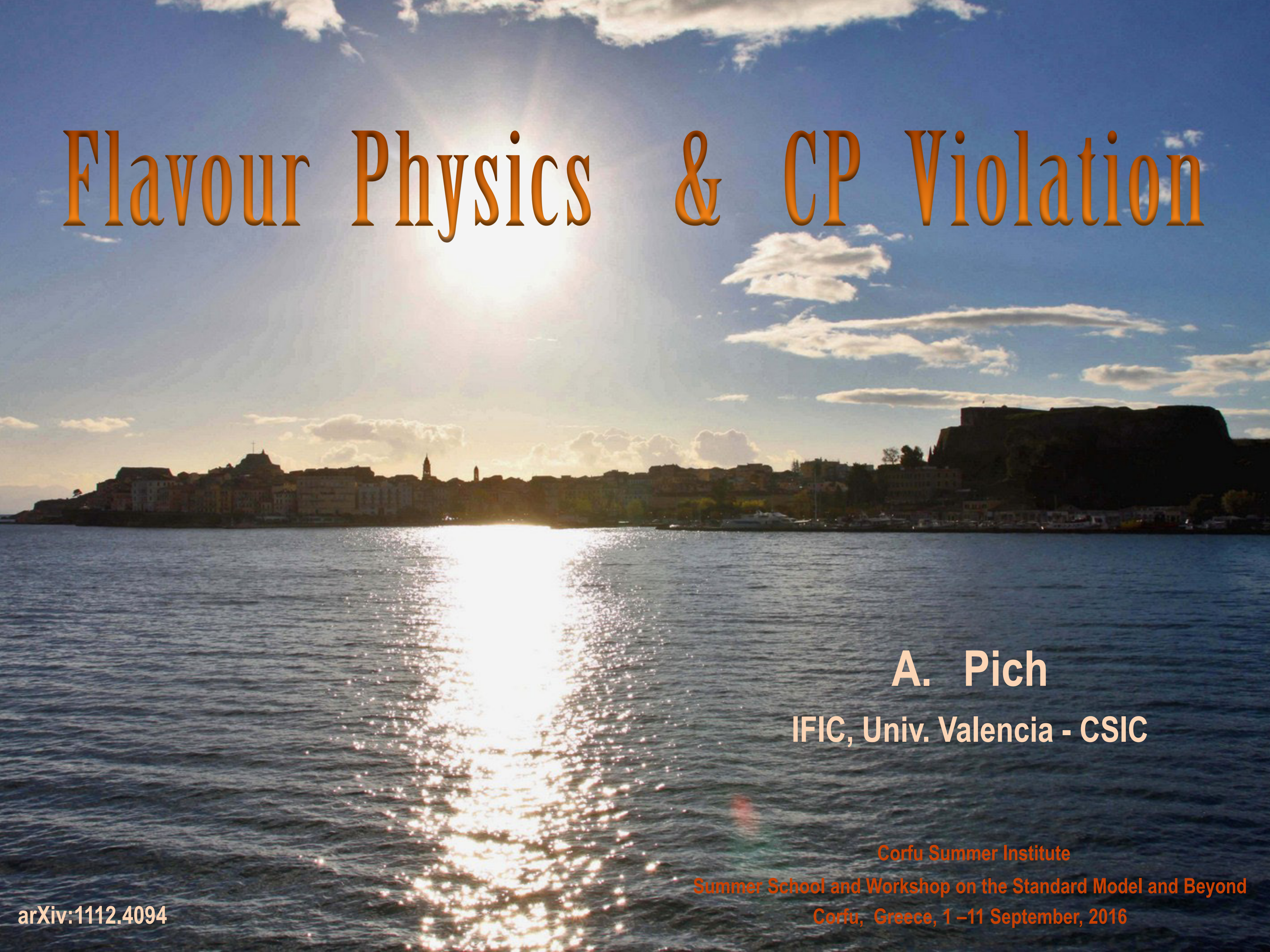

Flavour Physics & CP Violation

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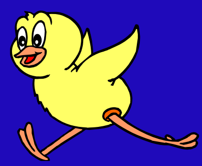
Corfu Summer Institute

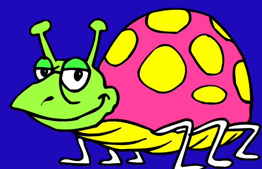
Summer School and Workshop on the Standard Model and Beyond

Corfu, Greece, 1 –11 September, 2016

arXiv:1112.4094

Quarks


up


down

charm


strange


top


beauty

Leptons

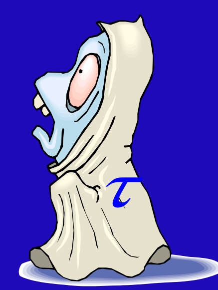

electron

neutrino e


muon

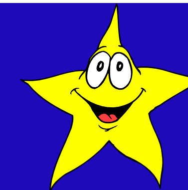
neutrino μ


tau



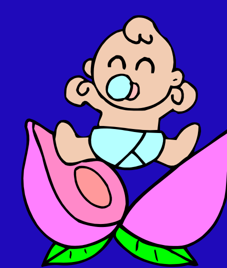
neutrino τ

Bosons


photon


gluon


Z^0 $W^{\pm}$


Higgs

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 ?

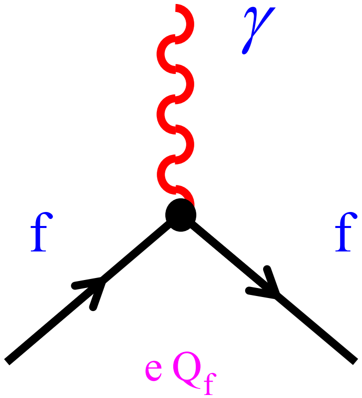
- **Pattern of masses**
- **Flavour Mixing**
- $\not{CP}$

Related to SSB

Scalar Sector (Higgs)

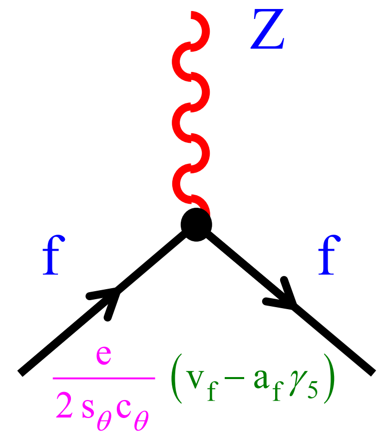
- **Kaon Factories :** u , d , s
- **τcF :** c , τ
- **BF:** b , c , τ
- **LHC :** t , b, c
- **LC :** t , …
- **νF :** ν_e , ν_μ , ν_τ

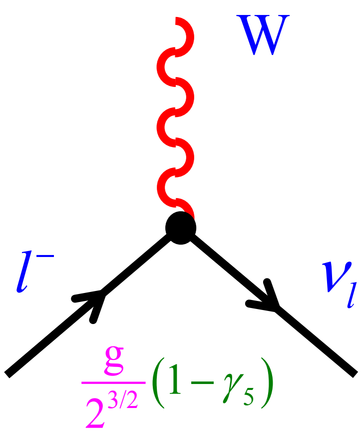
Universality: Family–Independent Couplings



NEUTRAL CURRENTS

Flavour Conserving

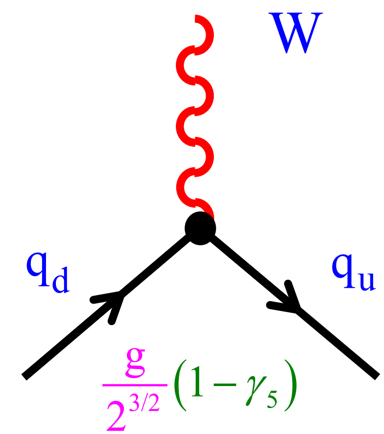


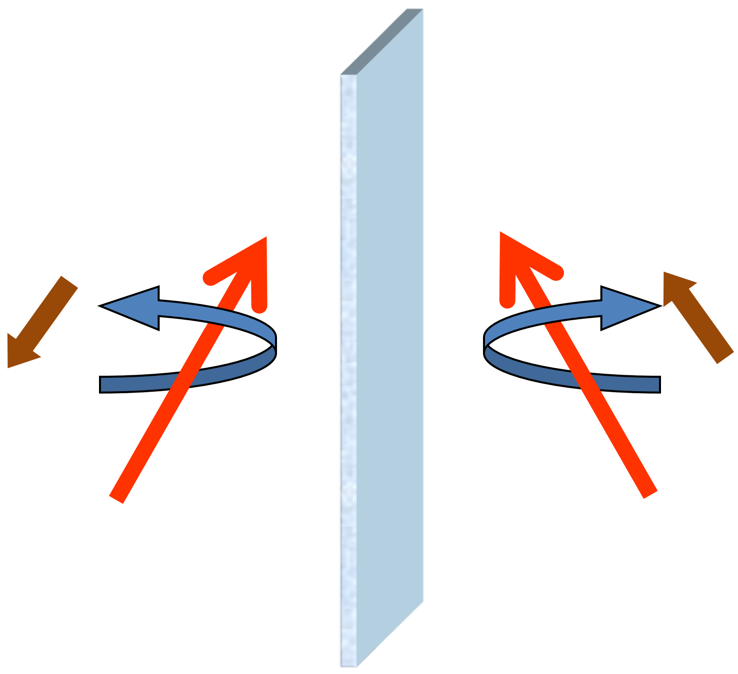


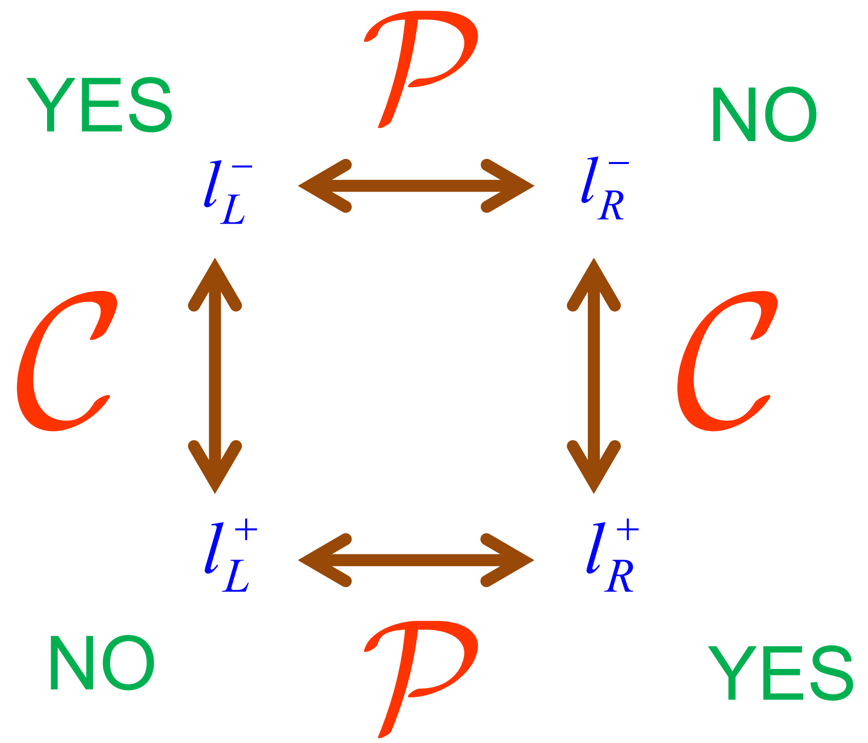
CHARGED CURRENTS

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

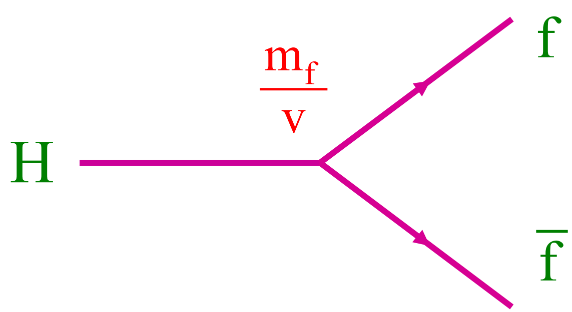
$$\mathcal{L}_Y = -\,(\bar{q}_u\,,\bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] - (\bar{\nu}_l, \bar{l}\,)_L \; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)}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

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: $g_{Hf\bar{f}} = \frac{m_f}{v}$

FERMION GENERATIONS

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

$$\begin{matrix} Q=0 \\ Q=-1 \end{matrix} \qquad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \qquad \begin{matrix} Q=+2/3 \\ Q=-1/3 \end{matrix} \qquad (j = 1, \cdots, N_G)$$

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

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

Arbitrary Non-Diagonal Complex Mass Matrices

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

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \mathcal{M}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d \qquad \mathbf{H}_f = \mathbf{H}_f^\dagger$$

$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \mathcal{M}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u \qquad \mathbf{U}_f \cdot \mathbf{U}_f^\dagger = \mathbf{U}_f^\dagger \cdot \mathbf{U}_f = 1$$

$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \mathcal{M}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l \qquad \mathbf{S}_f \cdot \mathbf{S}_f^\dagger = \mathbf{S}_f^\dagger \cdot \mathbf{S}_f = 1$$

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

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

$$d_L \equiv \mathbf{S}_d \cdot d'_L \quad ; \quad u_L \equiv \mathbf{S}_u \cdot u'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$

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

Mass Eigenstates

$\neq$

Weak Eigenstates

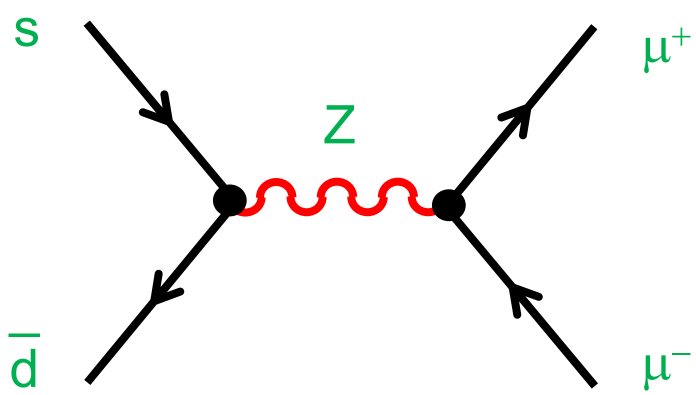
$$\bar{f}'_L\, f'_L = \bar{f}_L\, f_L \quad ; \quad \bar{f}'_R\, f'_R = \bar{f}_R\, f_R \quad \Longrightarrow \quad \mathcal{L}'_{NC} = \mathcal{L}_{NC}$$

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

QUARK MIXING

Flavour Conserving Neutral Currents (GIM)

$$\mathcal{L}_{NC}^{Z} = -\frac{e}{2\sin\theta_W\cos\theta_W}\, Z_\mu \sum_f \bar{f}\,\gamma^\mu\,[\mathrm{v}_f - \mathrm{a}_f\,\gamma_5]\,f$$



NO

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

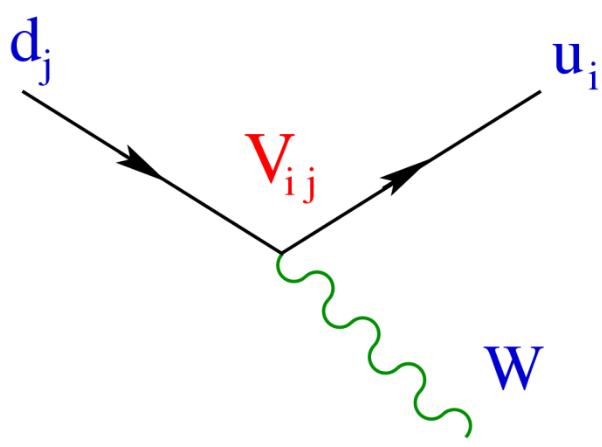
$$K_L \to \pi^{0*} \to (\gamma\,\gamma)^* \to \mu^+\mu^-$$

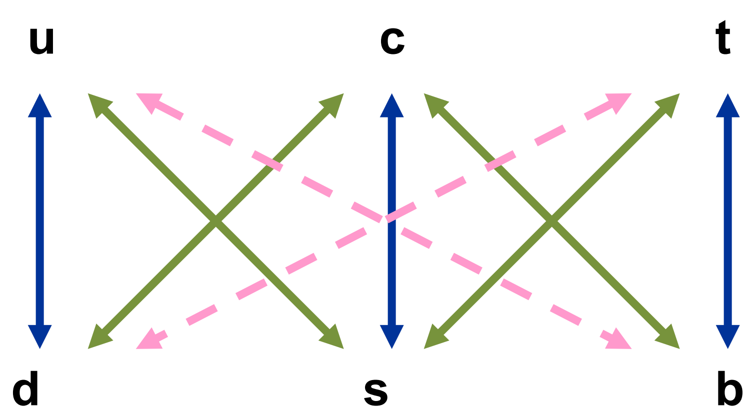
$$K_S \to (\pi^+\pi^-)^* \to (\gamma\,\gamma)^* \to \mu^+\mu^-$$

Flavour Changing Charged Currents

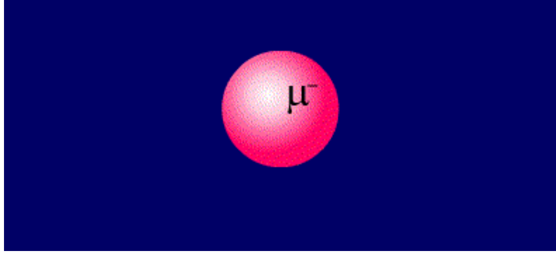
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5) \mathbf{V}_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l \right] + \text{h.c.}$$

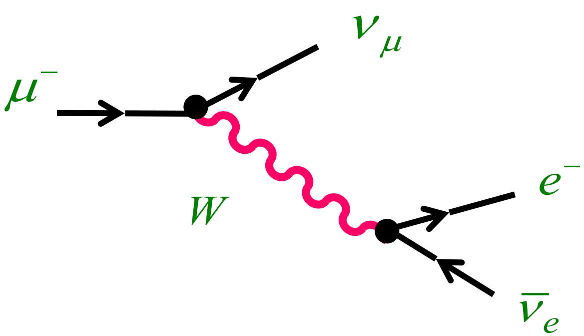
$$\left(\bar{\nu}_{l_j} \equiv \bar{\nu}_i \; \mathbf{V}_{ij}^{(l)} \right)$$

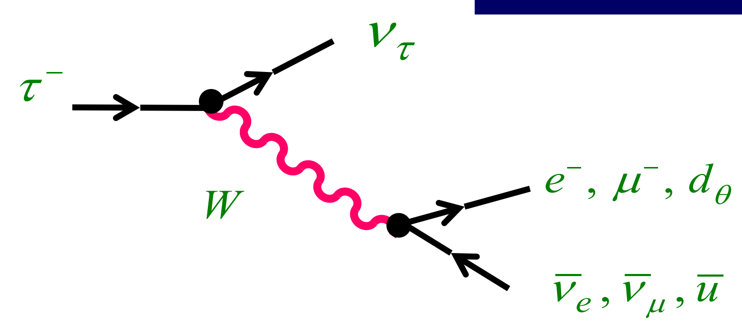




Weak Decays







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

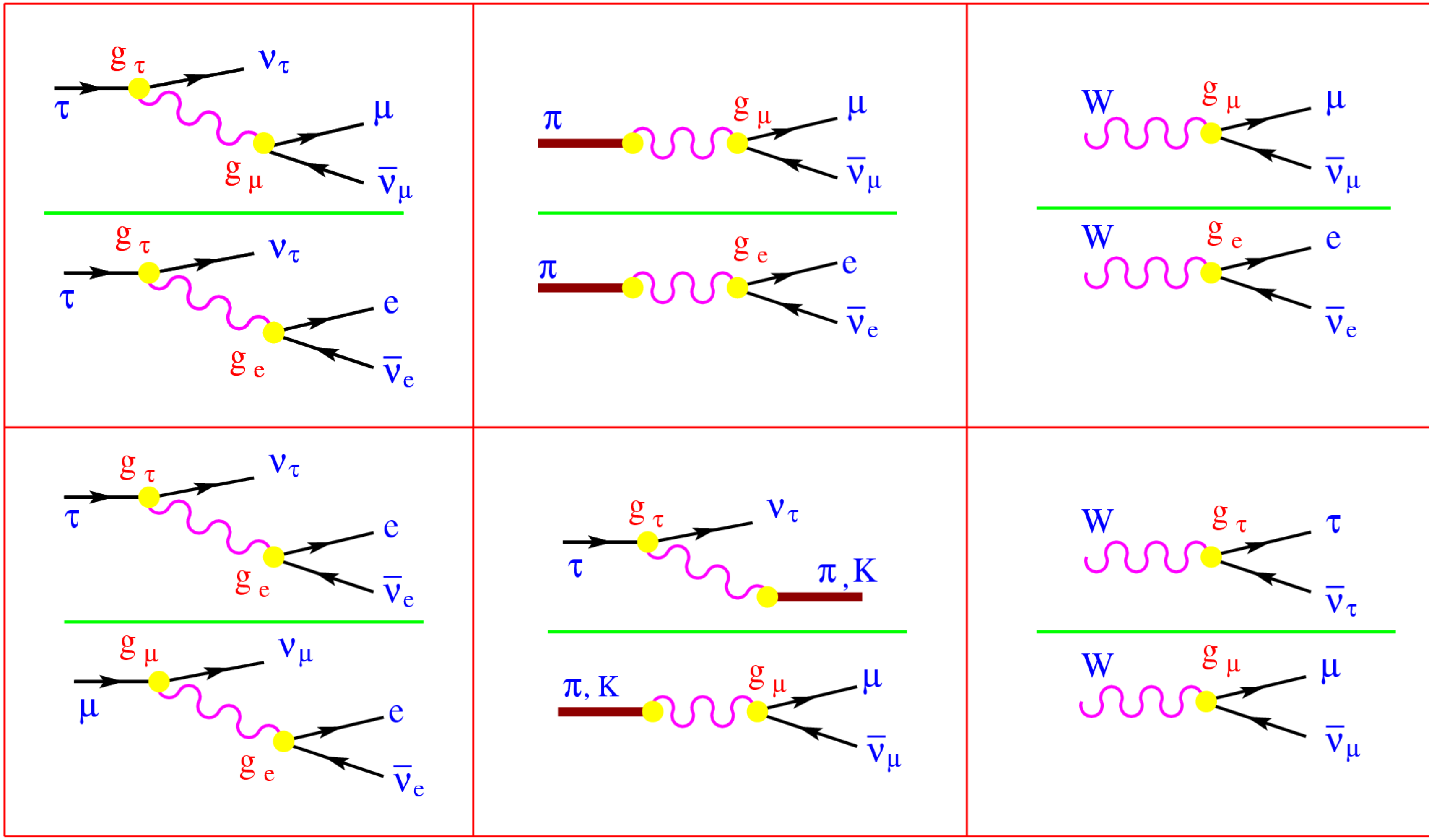
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} f(m_e^2/m_\mu^2)\, r_{EW} \quad \Longrightarrow \quad G_F = (1.166\,378\,7 \pm 0.000\,000\,6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

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

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

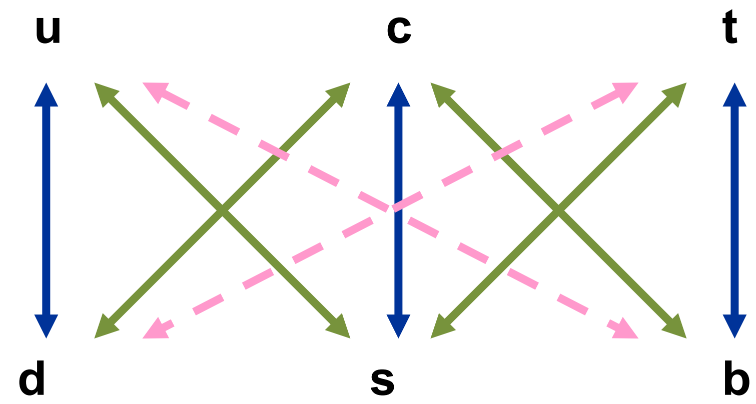
$|g_\tau / g_\mu|$

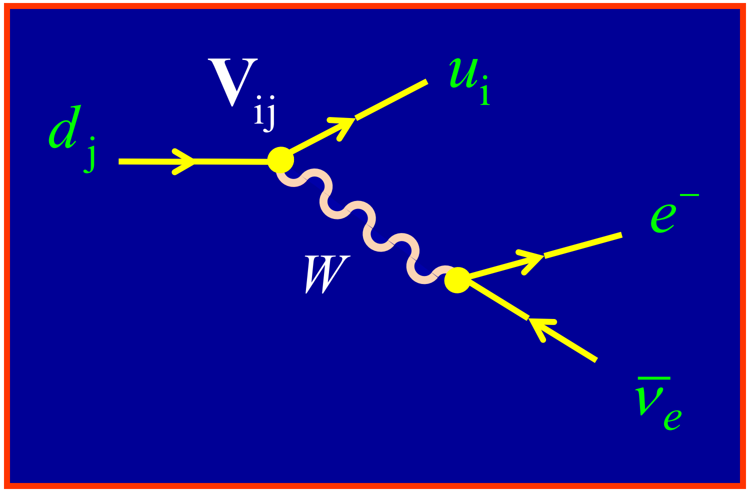
$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

$|g_\tau / g_e|$

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

Flavour Changing Charged Currents





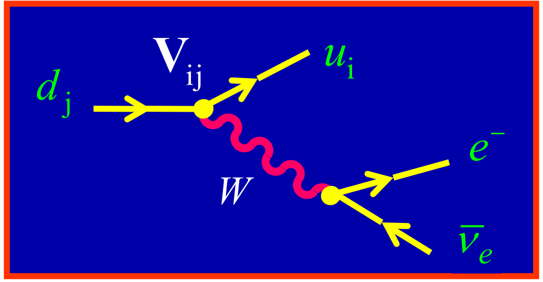
$$\Gamma(d_j \to u_i\, e^-\, \bar{\nu}_e) \propto |\mathbf{V}_{ij}|^2$$

We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

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

$K \to \pi l \nu$, $D \to K l \nu$ ...



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

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

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

$f_-(q^2)$ suppressed $(m_{u_i} - m_{d_j}, m_l)$

- 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

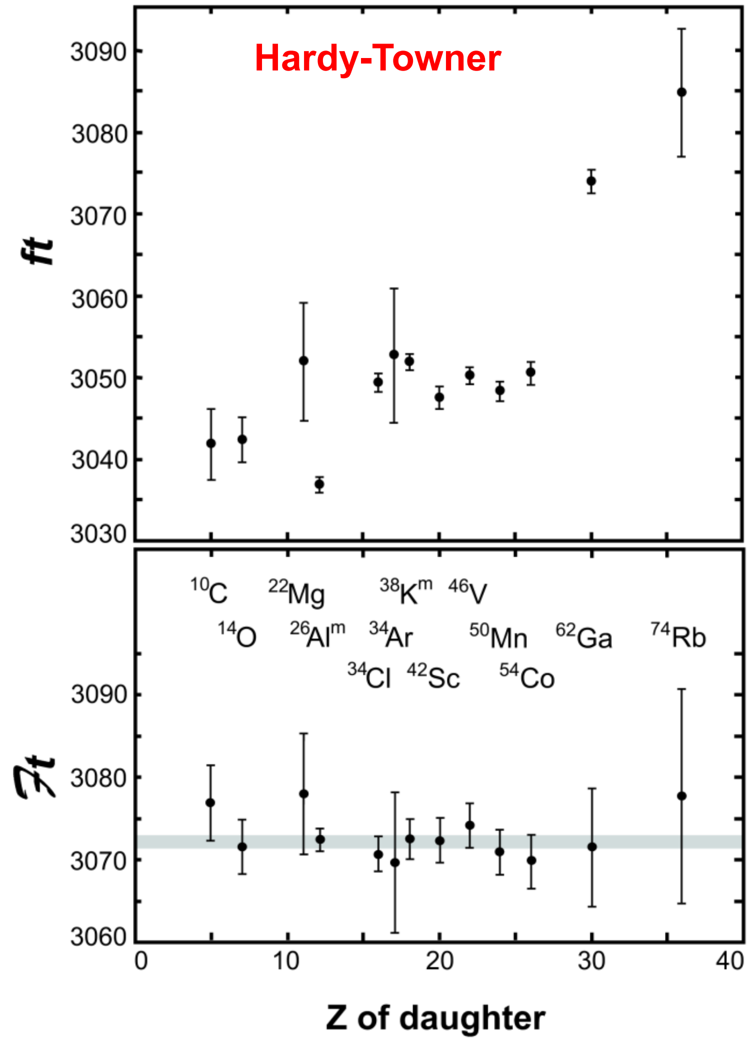
$|V_{ud}|$

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

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)



$|V_{ud}| = 0.97425 \pm 0.00022$

$|V_{ud}| = 0.97377 \pm 0.00027$ (PDG 06)

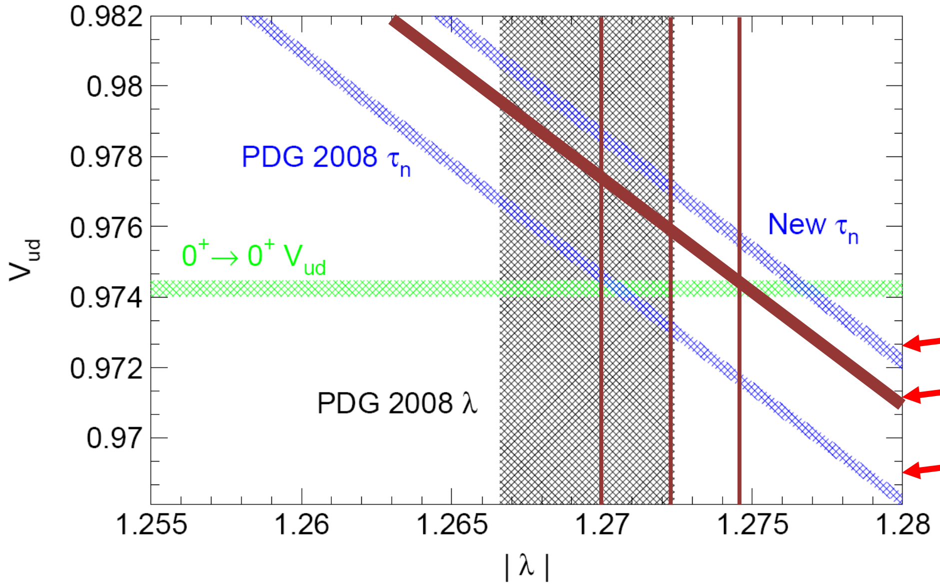
• Neutron Decay:

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

(Czarnecki – Marciano – Sirlin)

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

PDG14: $\tau_n = (880.3 \pm 1.1)$ s , $\lambda \equiv g_A / g_V = -1.2723 \pm 0.0023$



$|V_{ud}| = 0.9758 \pm 0.0016$

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

(Serebrov et al, 2005)

PDG14

PDG10

• Pion Decay:

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

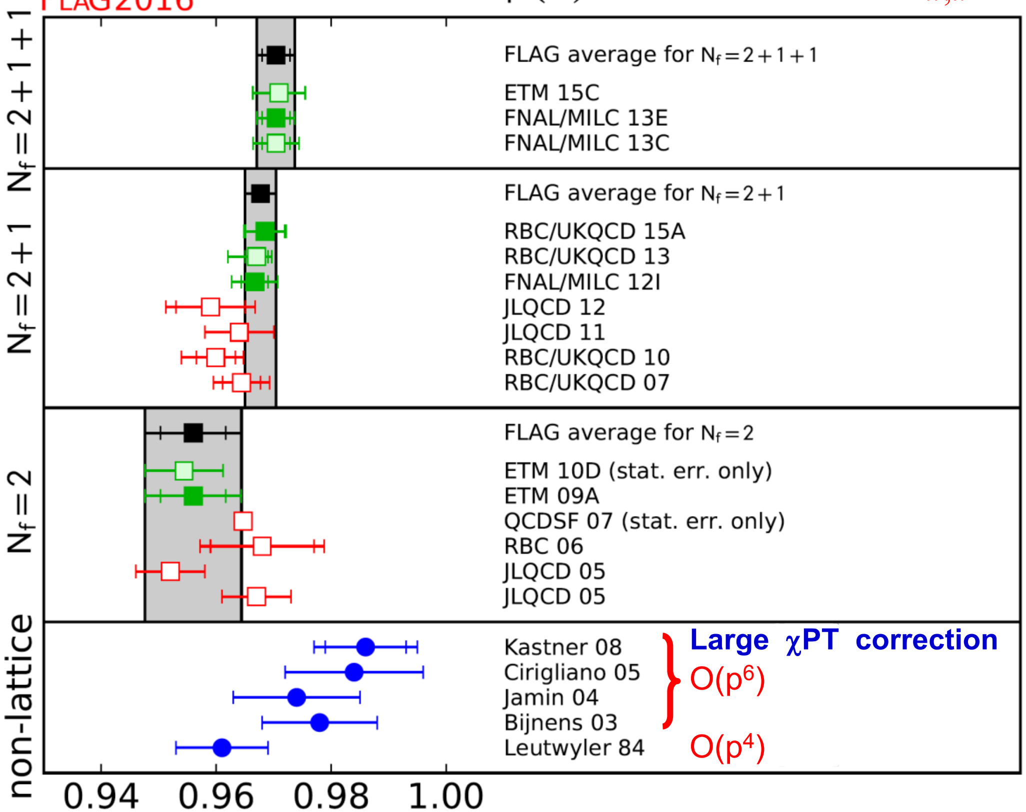
(PIBETA)

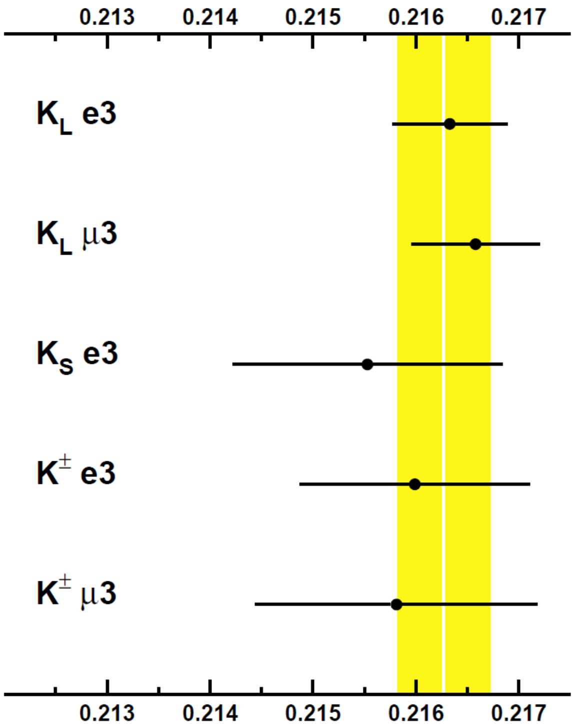
$|V_{ud}| = 0.9749 \pm 0.0026$

$K \to \pi l \nu$ Decays

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

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





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

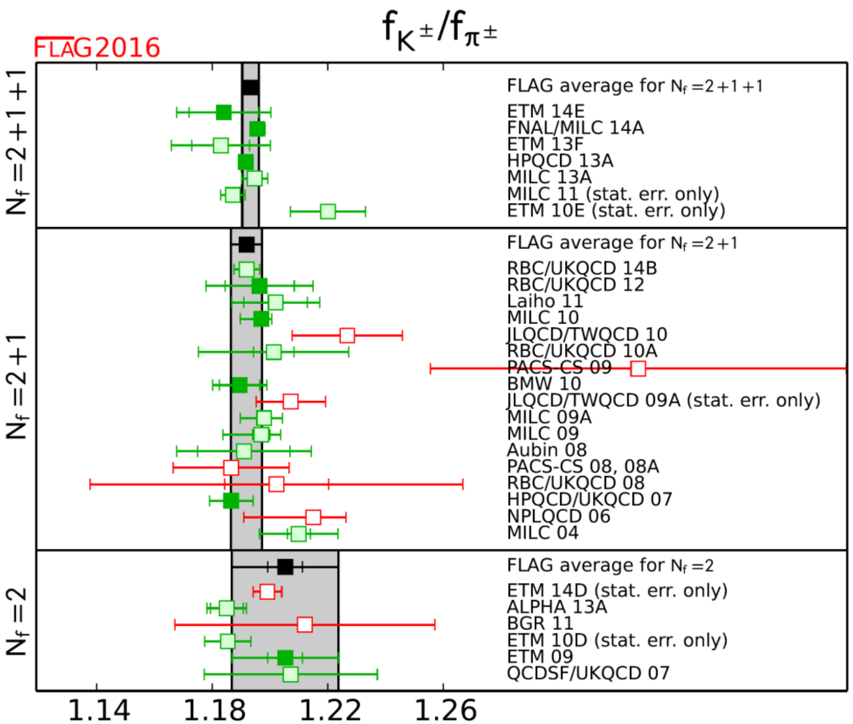
2012 : $f_+(0) = 0.959 \pm 0.005$ ➡ $|V_{us}| = 0.2255 \pm 0.0014$

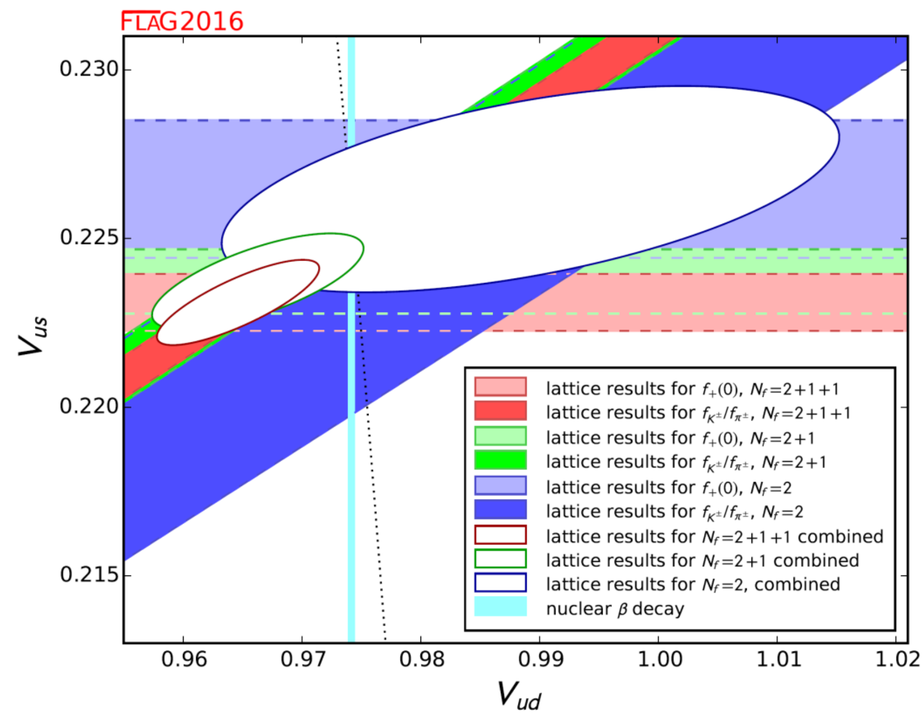
2016 : $f_+(0) = 0.970 \pm 0.003$ ➡ $|V_{us}| = 0.2232 \pm 0.0008$

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

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

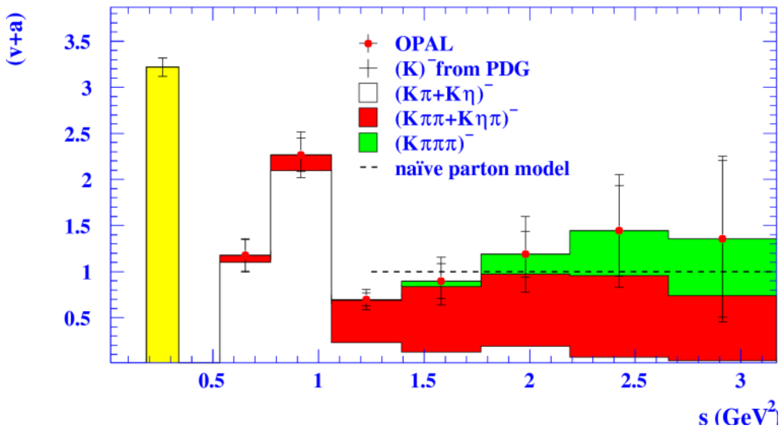
$$\langle 0 | \bar{d}_i \gamma^\mu \gamma_5 u_j | P(k) \rangle = i \, f_P \, k^\mu$$

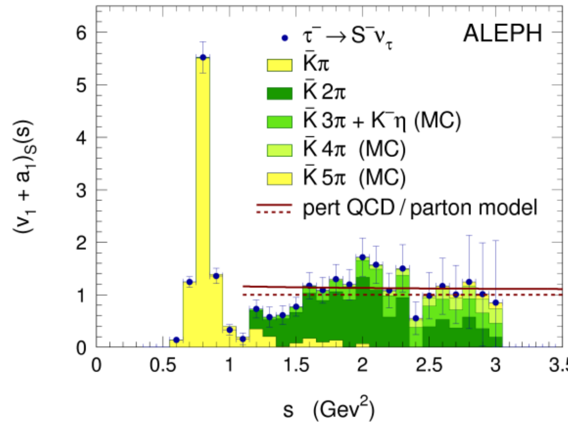




$$f_K / f_\pi = 1.1933 \pm 0.0029 \qquad \text{(FLAG 2016)}$$

$$R_{\tau,S} = \Gamma(\tau^- \to \nu_\tau S^-) / \Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)$$





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

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

$$m_s(2\,\mathrm{GeV}) = 94 \pm 6\ \mathrm{MeV}$$

Gámiz-Jamin-Pich-Prades-Schwab

$$|\mathbf{V_{us}}| = 0.2173 \pm 0.0020_{\mathrm{exp}} \pm 0.0010_{\mathrm{th}}$$

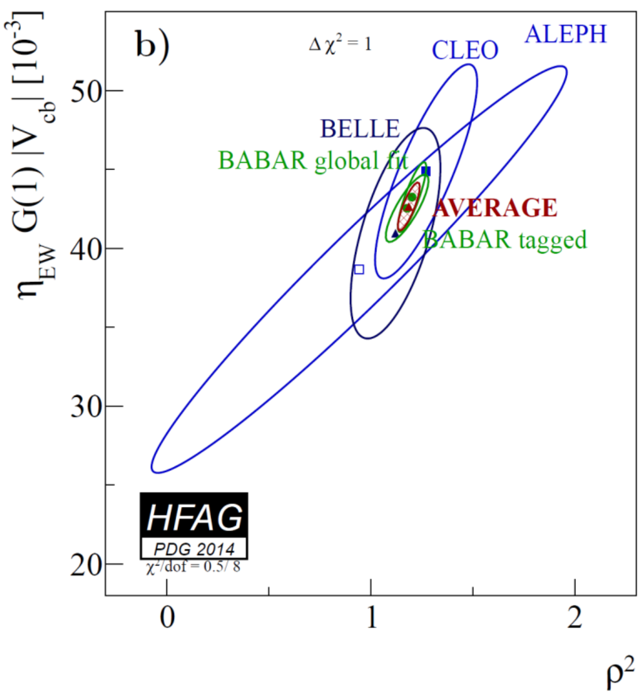
Replacing $\tau \to \nu K(\pi)$ by $K \to \nu\mu(\pi)$ data grows to **$|V_{us}|$ = 0.2207±0.0025**

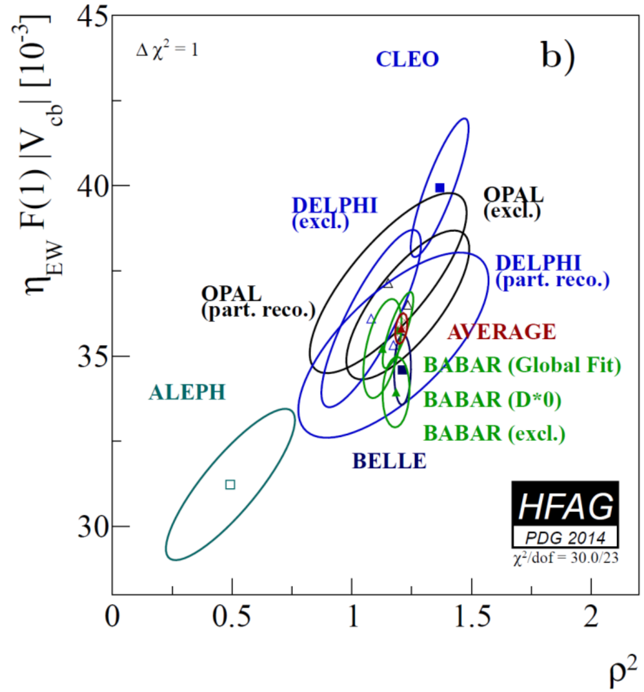
With better data, could give a very precise V_{us} determination

$B \to D\, l\, \nu$ $\quad$ $B \to D^*\, l\, \nu$

QCD Symmetries at $1/M_Q \to 0$

HQET





$$\eta_{EW}\, G(1)\, |\mathbf{V_{cb}}| = (42.65 \pm 1.53)\cdot 10^{-3}$$

$$\eta_{EW}\, F(1)\, |\mathbf{V_{cb}}| = (35.81 \pm 0.45)\cdot 10^{-3}$$

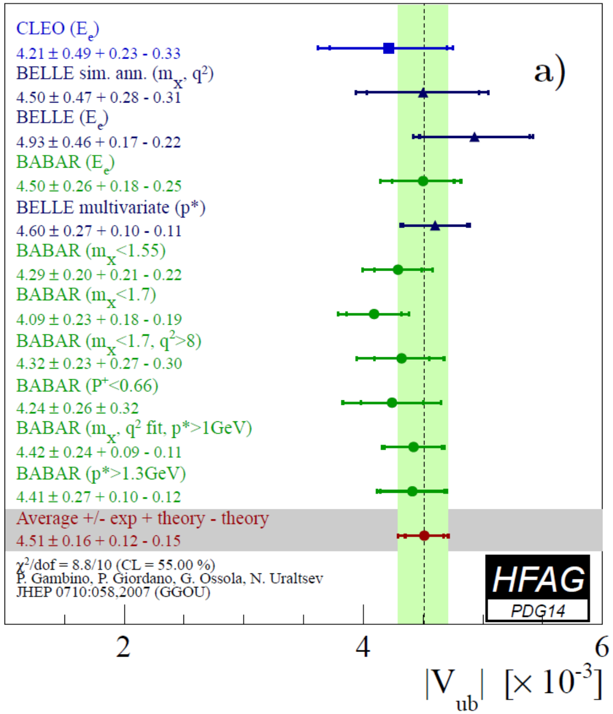
$$\eta_{EW} = 1.00662$$

$G(1) = 1.1054 \pm 0.0009$ (FNAL / MILC) $\Rightarrow$ $|\mathbf{V_{cb}}| = (40.85 \pm 0.98)\cdot 10^{-3}$

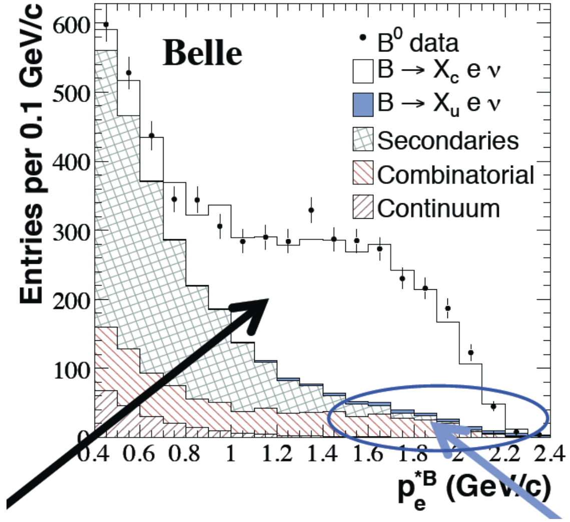
$F(1) = 0.906 \pm 0.013$ (FNAL / MILC) $\Rightarrow$ $|\mathbf{V_{cb}}| = (39.27 \pm 0.74)\cdot 10^{-3}$

$$\Rightarrow \quad \boxed{|\mathbf{V_{cb}}|_{excl} = (39.9 \pm 0.6)\cdot 10^{-3}}$$

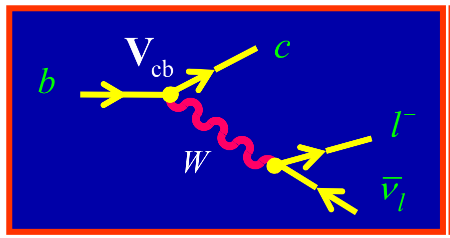
$B \to X_u \, l \, \nu$

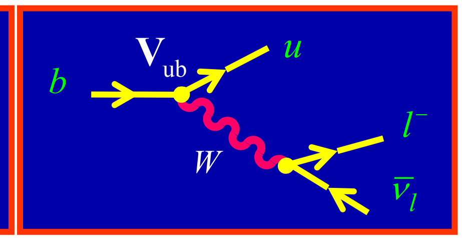


Framework	$\vert V_{ub}\vert [10^{-3}]$
BLNP	$4.45 \pm 0.15^{+0.20}_{-0.21}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.51 \pm 0.16^{+0.12}_{-0.15}$
ADFR	$4.05 \pm 0.13^{+0.18}_{-0.11}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$
LLR (*BABAR*) [486]	$4.43 \pm 0.45 \pm 0.29$
LLR (*BABAR*) [487]	$4.28 \pm 0.29 \pm 0.29 \pm 0.26 \pm 0.28$
LNP (*BABAR*) [487]	$4.40 \pm 0.30 \pm 0.41 \pm 0.23$

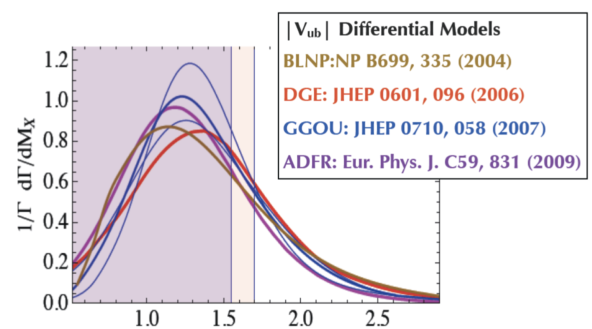


$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 \approx \frac{1}{50}$$

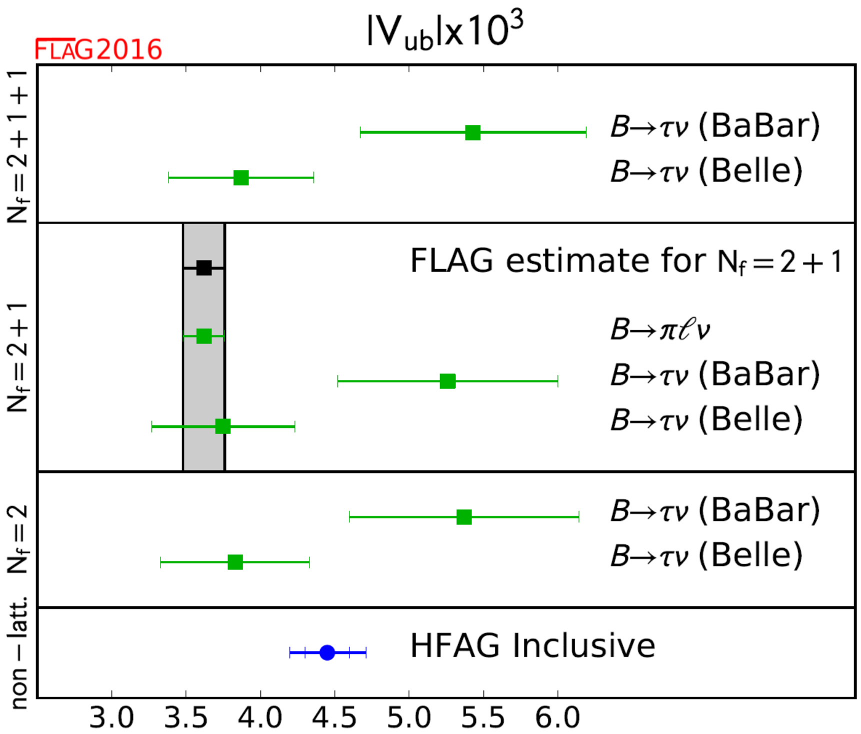


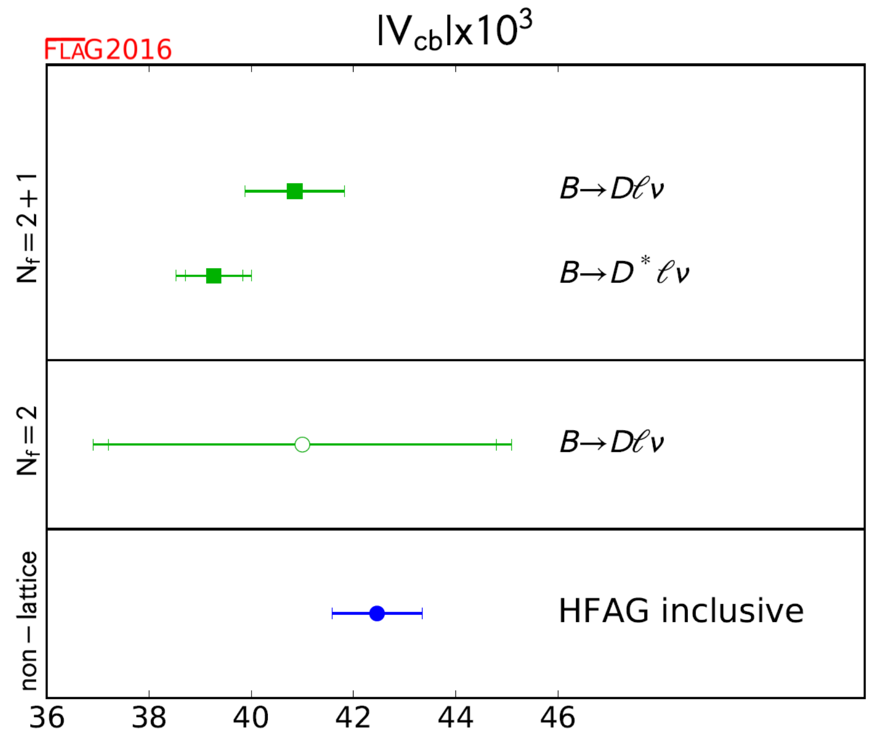


- **Large backgrounds from $B \to X_c l \nu$**
- **Strong experimental cuts**
- **Large theoretical uncertainties**



HFAG 2014: $$\left|V_{ub}\right|_{\text{incl}} = \left(4.62 \pm 0.20 \pm 0.29\right) \cdot 10^{-3}$$





$$\left|V_{ub}\right|_{excl} = (3.62 \pm 0.14) \cdot 10^{-3}$$

$$\left|V_{ub}\right|_{incl} = (4.62 \pm 0.35) \cdot 10^{-3}$$

$$\left|V_{cb}\right|_{excl} = (39.9 \pm 0.6) \cdot 10^{-3}$$

$$\left|V_{cb}\right|_{incl} = (42.5 \pm 0.9) \cdot 10^{-3}$$

$$\left|V_{ub}\right| = (3.76 \pm 0.34) \times 10^{-3}$$

$$\left|V_{cd}\right| = (40.7 \pm 1.2) \times 10^{-3}$$

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\|V_{ud}\|$	0.97425 ± 0.00022	Nuclear β decay
	0.9758 ± 0.0016	$n \to p e^- \bar{\nu}_e$
	0.9749 ± 0.0026	$\pi^+ \to \pi^0 e^+ \nu_e$
$\|V_{us}\|$	0.2232 ± 0.0008	$K \to \pi e^- \bar{\nu}_e$
	0.2253 ± 0.0007	$K/\pi \to \mu\nu$, Lattice, V_{ud}
	0.2207 ± 0.0025	τ decays
$\|V_{cd}\|$	0.230 ± 0.011	$\nu d \to c X$
	0.216 ± 0.005	$D \to \pi l \nu$, Lattice
$\|V_{cs}\|$	0.995 ± 0.014	$D \to K l \nu$, $D_s \to l \nu$, Lattice
$\|V_{cb}\|$	0.0399 ± 0.0006	$B \to D^* / D l \bar{\nu}_l$
	0.0425 ± 0.0009	$b \to c l \bar{\nu}_l$
	0.0407 ± 0.0012	
$\|V_{ub}\|$	0.00362 ± 0.00014	$B \to \pi l \bar{\nu}_l$
	0.00462 ± 0.00035	$b \to u l \bar{\nu}_l$
	0.00376 ± 0.00034	
$\|V_{tb}\| / \sqrt{\sum_q \|V_{tq}\|^2}$	> 0.92 (95% CL)	$t \to bW / t \to qW$
$\|V_{tb}\|$	1.007 ± 0.036	$p\bar{p} \to tb + X$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9990 \pm 0.0008$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.038 \pm 0.030$$

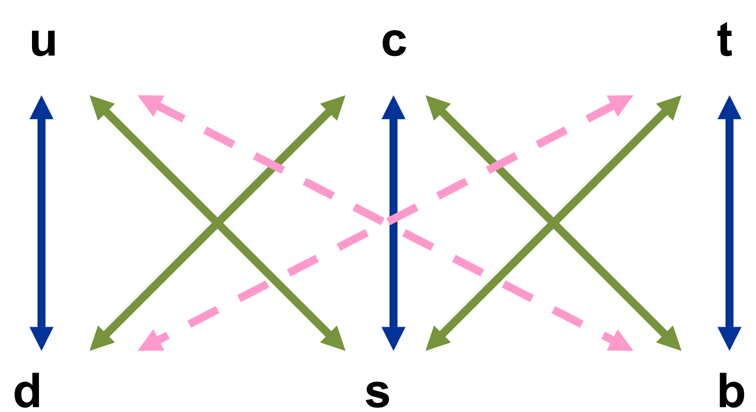
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1.016 \pm 0.073$$

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

Hierarchical Structure

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

$$\lambda \approx \sin\theta_C \approx 0.223 \quad ; \quad A \approx 0.82 \quad ; \quad \sqrt{\rho^2+\eta^2} \approx 0.41$$



QUARK MIXING MATRIX

- **Unitary** $N_G \times N_G$ **Matrix:** N_G^2 **parameters**

$$\mathbf{V} \cdot \mathbf{V}^\dagger = \mathbf{V}^\dagger \cdot \mathbf{V} = \mathbf{1}$$

- $2\, N_G - 1$ **arbitrary phases:**

$$u_i \to e^{i\phi_i}\, u_i \quad ; \quad d_j \to e^{i\theta_j}\, d_j \quad \Longrightarrow \quad \mathbf{V}_{ij} \to e^{i(\theta_j - \phi_i)}\, \mathbf{V}_{ij}$$

$\mathbf{V}_{ij}$ **Physical Parameters:**

$\frac{1}{2} N_G\, (N_G - 1)$ **Moduli** ; $\frac{1}{2} (N_G - 1)\, (N_G - 2)$ **phases**

- **$N_f = 2$: 1 angle, 0 phases (Cabibbo)**

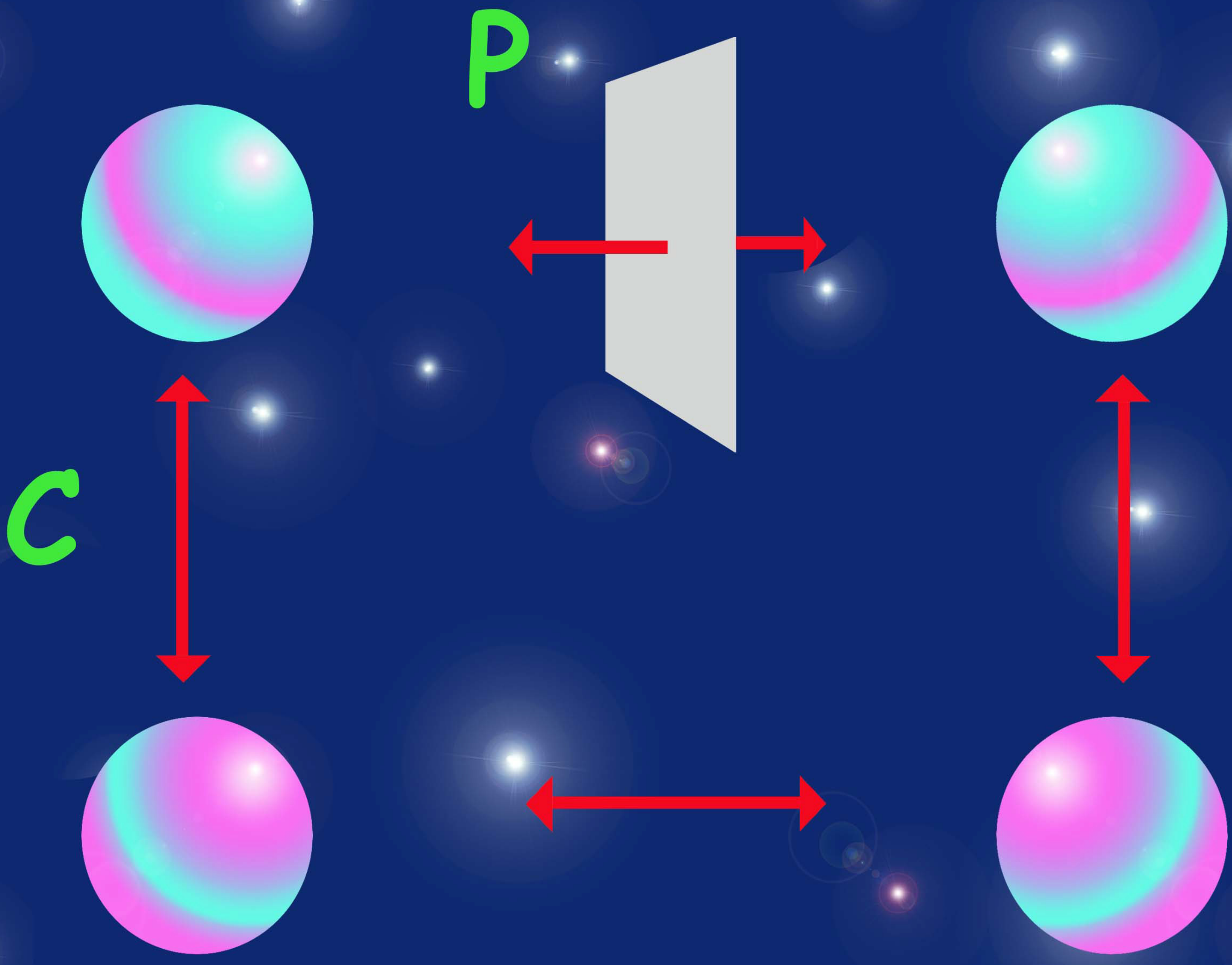
$$\mathbf{V} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \quad \Longrightarrow \quad \text{No } \not{CP}$$

- **$N_f = 3$: 3 angles, 1 phase (CKM)** $\quad c_{ij} \equiv \cos\theta_{ij} \;;\; s_{ij} \equiv \sin\theta_{ij}$

$$\mathbf{V} = \begin{bmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{13}} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & c_{23}\,c_{13} \end{bmatrix}$$

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

$\lambda \approx \sin\theta_C \approx 0.223 \;;\; A \approx 0.82 \;;\; \sqrt{\rho^2+\eta^2} \approx 0.41$ $\qquad \delta_{13} \neq 0 \quad (\eta \neq 0) \Longrightarrow \not{CP}$


P
C

- $\mathcal{C}$, $\mathcal{P}$: Violated maximally in weak interactions
- $\mathcal{CP}$: Symmetry of nearly all observed phenomena
- Slight (~ 0.2 %) $\not{\mathcal{CP}}$ in K^0 decays (1964)
- Sizeable $\not{\mathcal{CP}}$ in B^0 decays (2001)
- Huge Matter — Antimatter Asymmetry in our Universe → Baryogenesis

$\mathcal{CPT}$ Theorem: $\not{\mathcal{CP}} \Leftrightarrow \not{\mathcal{T}}$

Thus, $\not{\mathcal{CP}}$ requires:
- Complex Phases
- Interferences

Standard Model $\not{CP}$: 3 fermion families needed

$$\mathcal{CP} \quad \Longleftrightarrow \quad \mathbf{H}(M_u^2) \cdot \mathbf{H}(M_d^2) \cdot \mathbf{J} \neq 0$$

$$\mathbf{H}(M_u^2) \equiv (m_t^2 - m_c^2)\,(m_c^2 - m_u^2)\,(m_t^2 - m_u^2)$$

$$\mathbf{H}(M_d^2) \equiv (m_b^2 - m_s^2)\,(m_s^2 - m_d^2)\,(m_b^2 - m_d^2)$$

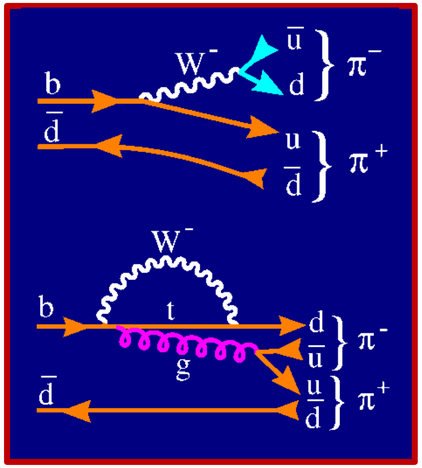
$$\mathbf{J} = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23} \sin\delta_{13} = \left| A^2 \lambda^6 \eta \right| < 10^{-4}$$

- Low-Energy Phenomena
- Small Effects ~ J
- Big Asymmetries ⟷ Suppressed Decays
- B Decays are an optimal place for $\not{CP}$ signals

DIRECT $\not{CP}$

$$\left|T(P\to f)\right| \neq \left|T(\bar{P}\to \bar{f})\right|$$

$\bar{B}_d^0$



$$T(P\to f) = T_1\, e^{i\phi_1}\, e^{i\delta_1} + T_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$\mathcal{CP}$

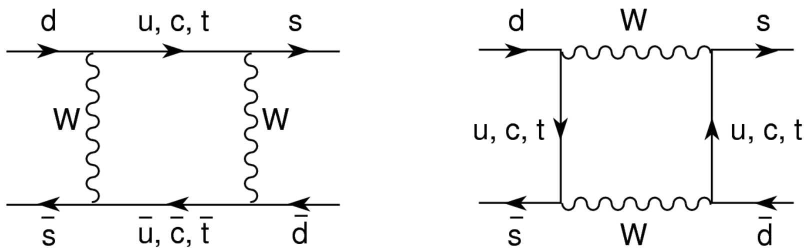
$$T(\bar{P}\to \bar{f}) = T_1\, e^{-i\phi_1}\, e^{i\delta_1} + T_2\, e^{-i\phi_2}\, e^{i\delta_2}$$

$$A^{CP}_{P\to f} \equiv \frac{\Gamma(P\to f) - \Gamma(\bar{P}\to\bar{f})}{\Gamma(P\to f) + \Gamma(\bar{P}\to\bar{f})} = \frac{-2\, T_1\, T_2\, \sin(\phi_2-\phi_1)\, \sin(\delta_2-\delta_1)}{T_1^2 + T_2^2 + 2\, T_1\, T_2\, \cos(\phi_2-\phi_1)\, \cos(\delta_2-\delta_1)}$$

One needs:

- **2 Interfering Amplitudes**
- **2 Different Weak Phases** $\left[\sin(\phi_2-\phi_1)\neq 0\right]$
- **2 Different FSI Phases** $\left[\sin(\delta_2-\delta_1)\neq 0\right]$

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING



$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$\langle \bar{K}^0 | \mathbf{H} | K^0 \rangle \sim \sum_{ij} \lambda_i \lambda_j \, S(r_i, r_j)\, \eta_{ij} \;\; \langle O_{\Delta S=2} \rangle$$

$$\langle O_{\Delta S=2} \rangle = \alpha_s(\mu)^{-2/9} \langle \bar{K}^0 | (\bar{s}_L \gamma^\alpha d_L)(\bar{s}_L \gamma_\alpha d_L) | K^0 \rangle \equiv \left(\frac{4}{3} M_K^2 f_K^2\right) \hat{B}_K$$

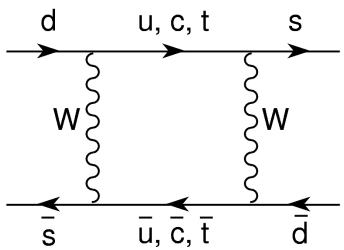
$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \quad (i = u, c, t)$$

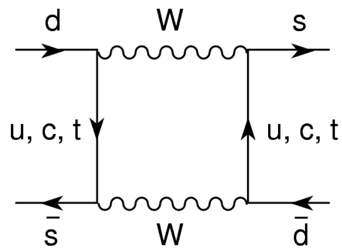
- **GIM Mechanism:** $\lambda_u + \lambda_c + \lambda_t = 0$

$$(M_{K_L} - M_{K_S})/M_{K^0} = (7.00 \pm 0.01) \times 10^{-15}$$

- $\mathcal{CP}$ **:** $\mathrm{Im}\,\lambda_t = -\mathrm{Im}\,\lambda_c \simeq \eta \lambda^5 A^2$
- **Hard GIM Breaking:** $S(r_i, r_i) \sim r_i$ ➡ **t quark**

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING





$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$\langle \bar{K}^0|\mathbf{H}|K^0\rangle \sim \sum_{ij} \lambda_i\,\lambda_j\; S(r_i,r_j)\;\eta_{ij}\quad \langle O_{\Delta S=2}\rangle$$

$$\langle O_{\Delta S=2}\rangle = \alpha_s(\mu)^{-2/9}\,\langle \bar{K}^0|(\bar{s}_L\gamma^\alpha d_L)(\bar{s}_L\gamma_\alpha d_L)|K^0\rangle \equiv \left(\frac{4}{3}M_K^2 f_K^2\right)\hat{B}_K$$

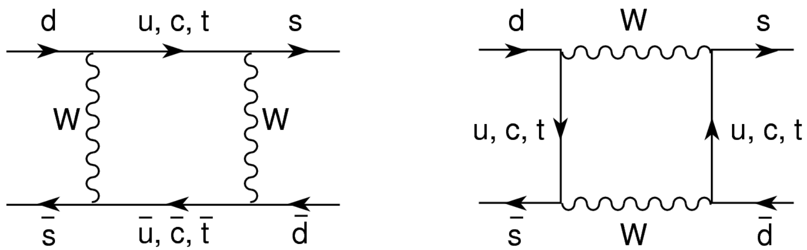
$$\lambda_i \equiv V_{id}\,V_{is}^* \qquad ; \qquad r_i \equiv m_i^2/M_W^2 \qquad (i=u,c,t)$$

$$\mathcal{C}\,|K^0\rangle = |\bar{K}^0\rangle \quad , \quad \mathcal{P}\,|K^0\rangle = -|K^0\rangle \quad , \quad \mathcal{CP}\,|K^0\rangle = -|\bar{K}^0\rangle$$

$$|K^0_{1,2}\rangle = \frac{1}{\sqrt{2}}\left(\,|K^0\rangle \mp |\bar{K}^0\rangle\,\right) \qquad , \qquad \mathcal{CP}\,|K^0_{1,2}\rangle = \pm\,|K^0_{1,2}\rangle$$

$$|K^0_S\rangle \simeq |K^0_1\rangle + \bar{\varepsilon}_K\,|K^0_2\rangle \qquad , \qquad |K^0_L\rangle \simeq |K^0_2\rangle + \bar{\varepsilon}_K\,|K^0_1\rangle$$

INDIRECT $\not{CP}$: $K^0 - \bar{K}^0$ MIXING



$$|K^0_{S,L}\rangle \sim p\,|K^0\rangle \mp q\,|\bar{K}^0\rangle$$

$$q/p \equiv (1-\bar{\varepsilon}_K)/(1+\bar{\varepsilon}_K)$$

$$K^0 \to \pi^- l^+ \nu_l \quad (\bar{s} \to \bar{u}) \qquad ; \qquad \bar{K}^0 \to \pi^+ l^- \bar{\nu}_l \quad (s \to u)$$

$$\frac{\Gamma\left(K_L^0 \to \pi^- l^+ \nu_l\right) - \Gamma\left(K_L^0 \to \pi^+ l^- \bar{\nu}_l\right)}{\Gamma\left(K_L^0 \to \pi^- l^+ \nu_l\right) + \Gamma\left(K_L^0 \to \pi^+ l^- \bar{\nu}_l\right)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2\,\mathrm{Re}(\bar{\varepsilon}_K)}{1+|\bar{\varepsilon}_K|^2} = (0.332 \pm 0.006)\%$$

➡ $\mathbf{Re}(\bar{\varepsilon}_K) = (1.66 \pm 0.03) \cdot 10^{-3}$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K \qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K$$

$$\varepsilon_K = (2.228 \pm 0.011) \cdot 10^{-3}\, e^{i\phi_\varepsilon}$$

$$\phi_\varepsilon = (43.52 \pm 0.05)^\circ$$

➡ Buras et al

$$\eta\left[(1-\rho)A^2 + 0.22\right] A^2\,\hat{B}_K = 0.143$$

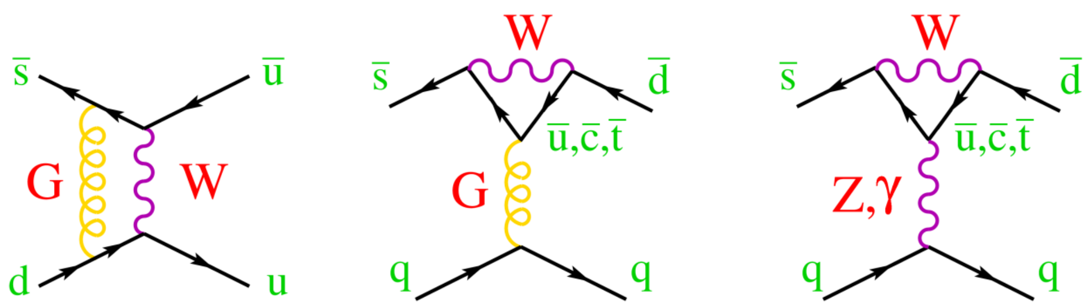
DIRECT $\not{CP}$ in $K \to \pi\pi$

$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K + \varepsilon'_K \qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K - 2\,\varepsilon'_K$$

$$\mathrm{Re}\left(\varepsilon'_K / \varepsilon_K\right) \approx \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\} = (16.8 \pm 1.4)\cdot 10^{-4}$$

NA48, NA31

KTeV, E731



$$\mathrm{Re}\left(\varepsilon'_K / \varepsilon_K\right)_{\mathrm{Th}} = \left(19\ ^{+11}_{-9}\right)\cdot 10^{-4}$$

- Short-distance OPE

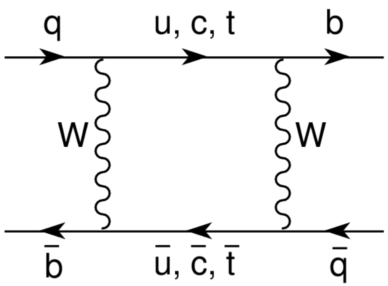
  Ciuchini et al, Buras et al

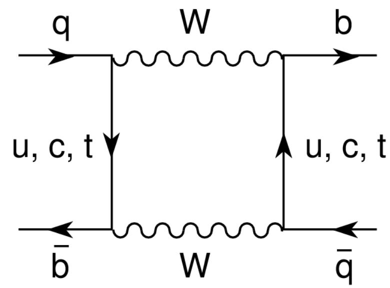
- Long-distance χPT

  Pallante-Pich-Scimemi

  Cirigliano-Ecker-Neufeld-Pich

$B^0 - \bar{B}^0$ MIXING





$$V_{ud}\, V_{ub}^* \sim V_{cd}\, V_{cb}^* \sim V_{td}\, V_{tb}^* \sim A\lambda^3$$

$$\langle \bar{B}^0 | \mathrm{H} | B^0 \rangle \sim |V_{td}|^2 \; S(r_t, r_t) \left(\frac{4}{3} M_B^2 f_B^2 \right) \hat{B}_B$$

$$\Delta M_{B_d^0} = (0.5065 \pm 0.0019)\ \mathrm{ps}^{-1} \quad \Rightarrow \quad |V_{td}|$$

- $\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.770 \pm 0.004$
- $\Delta M_{B_s^0} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$
- $\Delta \Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1$
- $\mathrm{Re}\left(\varepsilon_{B_d^0}\right) = -0.0004 \pm 0.0004$

$\not{CP}$ very small

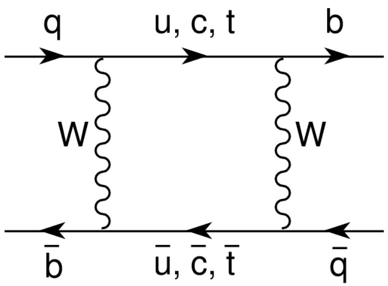
$$\Delta M_{B_s^0} / \Gamma_{B_s^0} = 26.73 \pm 0.09$$

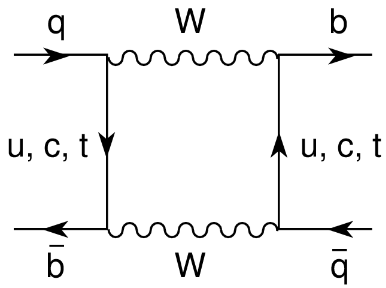
$$|V_{ts}|^2 \gg |V_{td}|^2$$

$$\Delta \Gamma_{B_s^0} / \Gamma_{B_s^0} = -0.124 \pm 0.009$$

$$\mathrm{Re}\left(\varepsilon_{B_s^0}\right) = -0.0019 \pm 0.0011$$

$$|q/p| - 1 \sim m_c^2 / m_t^2$$





$$\mathbf{M} = \begin{pmatrix} M & M_{12} \\ M_{12} & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12} & \Gamma \end{pmatrix}$$

$$\left|B^0_{\mp}\right\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} \left(p \left|B^0\right\rangle \mp q \left|\bar{B}^0\right\rangle \right) \quad , \quad \frac{q}{p} \equiv \frac{1-\varepsilon_B}{1-\varepsilon_B} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \right)^{1/2}$$

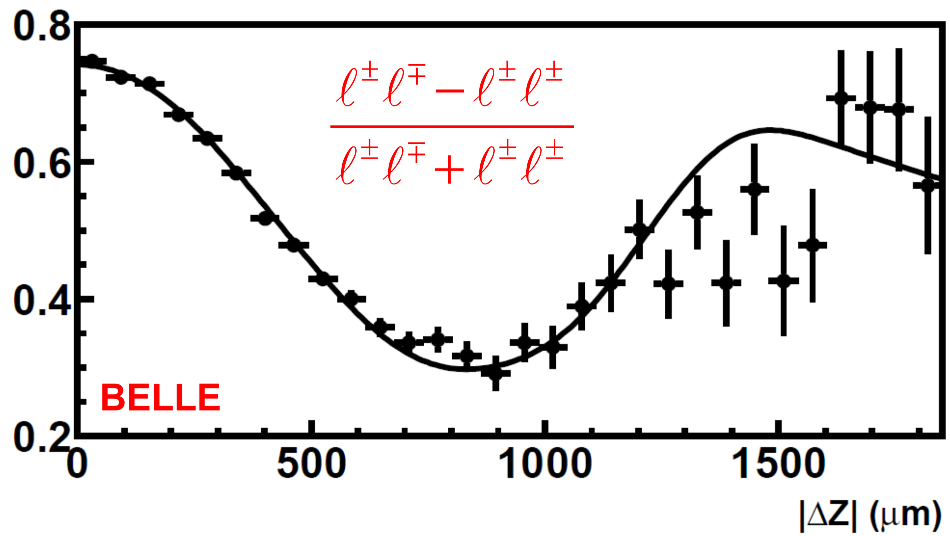
$$\Delta\Gamma/\Delta M \approx \Gamma_{12}/M_{12} \sim m_b^2/m_t^2 \ll 1 \quad \Rightarrow \quad \left|\frac{q}{p}\right| \approx 1 + \frac{1}{2}\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{\Delta B=2} \quad , \quad \phi_{\Delta B=2} \equiv \arg\left(M_{12}/\Gamma_{12}\right)$$

$$\Delta M \equiv M_{B_+} - M_{B_-} \quad , \quad \Delta\Gamma \equiv \Gamma_{B_+} - \Gamma_{B_-}$$

$$\begin{pmatrix} \left|B^0(t)\right\rangle \\ \left|\bar{B}^0(t)\right\rangle \end{pmatrix} = \begin{pmatrix} g_1(t) & \frac{q}{p} g_2(t) \\ \frac{p}{q} g_2(t) & g_1(t) \end{pmatrix} \begin{pmatrix} \left|B^0\right\rangle \\ \left|\bar{B}^0\right\rangle \end{pmatrix} \quad , \quad \begin{pmatrix} g_1(t) \\ g_2(t) \end{pmatrix} = e^{-iMt}\, e^{-\Gamma t/2} \begin{pmatrix} \cos\left[\left(\Delta M - \frac{i}{2}\Delta\Gamma\right)\frac{t}{2}\right] \\ -i\sin\left[\left(\Delta M - \frac{i}{2}\Delta\Gamma\right)\frac{t}{2}\right] \end{pmatrix}$$

Time Scales: Oscillation $\sim \sin\left[(x - iy)\Gamma t/2\right]$

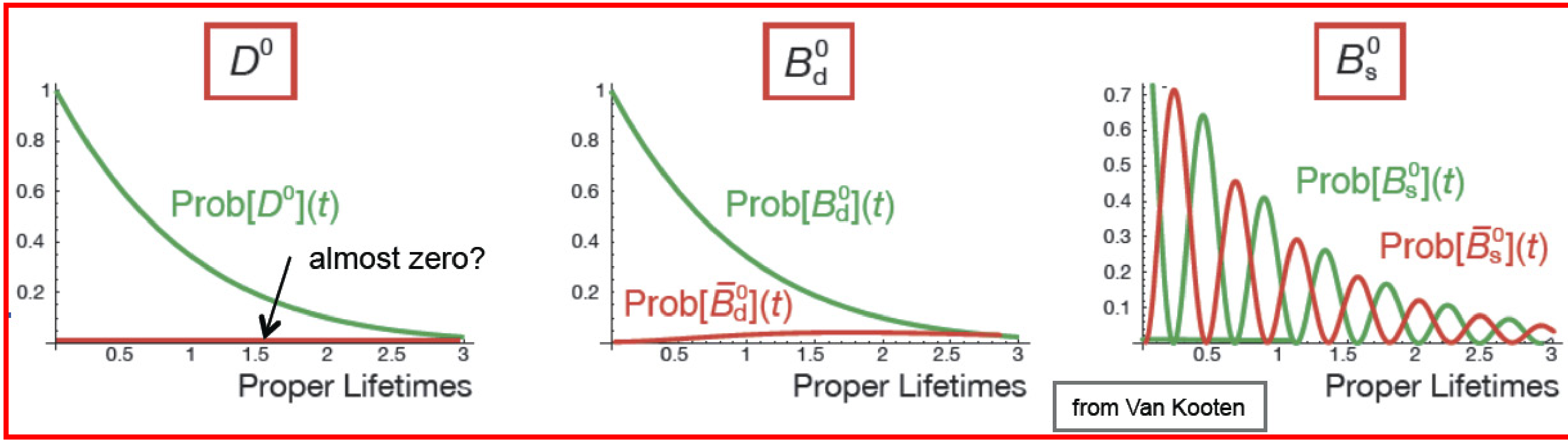
$$x \equiv \frac{\Delta M}{\Gamma} \quad , \quad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$



- **K^0 :** $x \sim y \sim 1$
- **D^0 :** $x \sim y \sim 0.01$ Slow oscillation (decays faster)
- **B_d :** $x \sim 1$, $y \sim 0.01$
- **B_s :** $x \sim 25$, $y \leq 0.01$ Fast oscillation (averages out to 0)

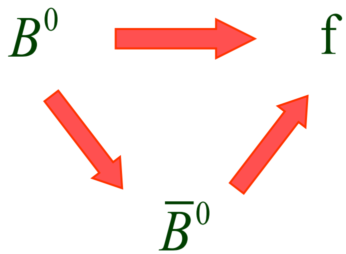
Time Scales: Oscillation $\sim \sin\left[(x-iy)\Gamma t/2\right]$

$$x \equiv \Delta M/\Gamma \quad , \quad y \equiv \Delta\Gamma/2\Gamma$$



- **K^0 :** x ~ y ~ 1
- **D^0 :** x ~ y ~ 0.01 — Slow oscillation (decays faster)
- **B_d :** x ~ 1 , y ~ 0.01
- **B_s :** x ~ 25 , y ≤ 0.01 — Fast oscillation (averages out to 0)

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



$$T_f \to T[B^0 \to f] \quad ; \quad \bar{T}_f \to -T[\bar{B}^0 \to f] \quad ; \quad \bar{\rho}_f \equiv \bar{T}_f / T_f$$

$$T_{\bar{f}} \to T[B^0 \to \bar{f}] \quad ; \quad \bar{T}_{\bar{f}} \to -T[\bar{B}^0 \to \bar{f}] \quad ; \quad \rho_{\bar{f}} \equiv T_{\bar{f}} / \bar{T}_{\bar{f}}$$

$$\mathcal{CP}\; B^0 = -\bar{B}^0 \qquad ; \qquad \mathcal{CP}\; f = \bar{f}$$

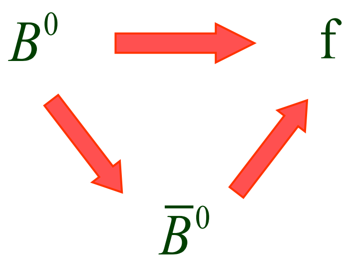
$$\Gamma[B^0(t) \to f] \sim \frac{1}{2}\, e^{-\Gamma t} \left(|T_f|^2 + |\bar{T}_f|^2\right) \left\{1 + \mathbf{C_f}\, \cos(\Delta M\, t) - \mathbf{S_f}\, \sin(\Delta M\, t)\right\}$$

$$\Gamma[\bar{B}^0(t) \to \bar{f}] \sim \frac{1}{2}\, e^{-\Gamma t} \left(|\bar{T}_{\bar{f}}|^2 + |T_{\bar{f}}|^2\right) \left\{1 - \mathbf{C_{\bar{f}}}\, \cos(\Delta M\, t) + \mathbf{S_{\bar{f}}}\, \sin(\Delta M\, t)\right\}$$

$$\mathbf{C_f} \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{S_f} \equiv \frac{2\,\mathrm{Im}\left(\frac{q}{p}\,\bar{\rho}_f\right)}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{C_{\bar{f}}} \equiv -\frac{1 - |\rho_{\bar{f}}|^2}{1 + |\rho_{\bar{f}}|^2} \quad ; \quad \mathbf{S_{\bar{f}}} \equiv \frac{-2\,\mathrm{Im}\left(\frac{p}{q}\,\rho_{\bar{f}}\right)}{1 + |\rho_{\bar{f}}|^2}$$

$$\Delta\Gamma \ll \Delta M \quad \Longrightarrow \quad \frac{q}{p} \approx \frac{\mathbf{V}_{tb}^*\, \mathbf{V}_{tq}}{\mathbf{V}_{tb}\, \mathbf{V}_{tq}^*} = e^{-2i\phi_M} \quad ; \quad \phi_M \approx \begin{cases} \beta & (B_d^0) \\ -\beta_s \approx -\lambda^2 \eta & (B_s^0) \end{cases}$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



$$T_{f} \to T[B^0 \to f] \quad ; \quad \bar{T}_{f} \to -T[\bar{B}^0 \to f] \quad ; \quad \bar{\rho}_{f} \equiv \bar{T}_{f} / T_{f}$$

$$T_{\bar{f}} \to T[B^0 \to \bar{f}] \quad ; \quad \bar{T}_{\bar{f}} \to -T[\bar{B}^0 \to \bar{f}] \quad ; \quad \rho_{\bar{f}} \equiv T_{\bar{f}} / \bar{T}_{\bar{f}}$$

$$\mathcal{CP}\; B^0 = -\bar{B}^0 \qquad ; \qquad \mathcal{CP}\; f = \bar{f}$$

$$\Gamma[B^0(t) \to f] \;\sim\; \frac{1}{2}\, e^{-\Gamma t} \left(|T_f|^2 + |\bar{T}_f|^2 \right) \left\{ 1 + \mathbf{C_f} \cos(\Delta M\, t) - \mathbf{S_f} \sin(\Delta M\, t) \right\}$$

$$\Gamma[\bar{B}^0(t) \to \bar{f}] \;\sim\; \frac{1}{2}\, e^{-\Gamma t} \left(|\bar{T}_{\bar{f}}|^2 + |T_{\bar{f}}|^2 \right) \left\{ 1 - \mathbf{C_{\bar{f}}} \cos(\Delta M\, t) + \mathbf{S_{\bar{f}}} \sin(\Delta M\, t) \right\}$$

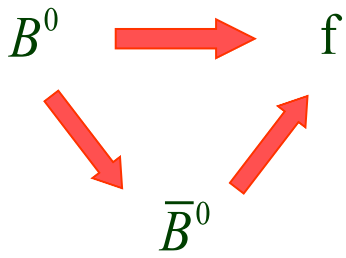
$$\mathbf{C_f} \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{S_f} \equiv \frac{2\, \mathrm{Im}\left(\frac{q}{p}\, \bar{\rho}_f \right)}{1 + |\bar{\rho}_f|^2} \quad ; \quad \mathbf{C_{\bar{f}}} \equiv -\frac{1 - |\rho_{\bar{f}}|^2}{1 + |\rho_{\bar{f}}|^2} \quad ; \quad \mathbf{S_{\bar{f}}} \equiv \frac{-\,2\, \mathrm{Im}\left(\frac{p}{q}\, \rho_{\bar{f}} \right)}{1 + |\rho_{\bar{f}}|^2}$$

CP self-conjugate: $\bar{f} = \eta_f\, f$ $\Longrightarrow$

$$T_{\bar{f}} = \eta_f\, T_f \quad ; \quad \bar{T}_{\bar{f}} = \eta_f\, \bar{T}_f \quad ; \quad \rho_{\bar{f}} \equiv 1 / \bar{\rho}_f$$

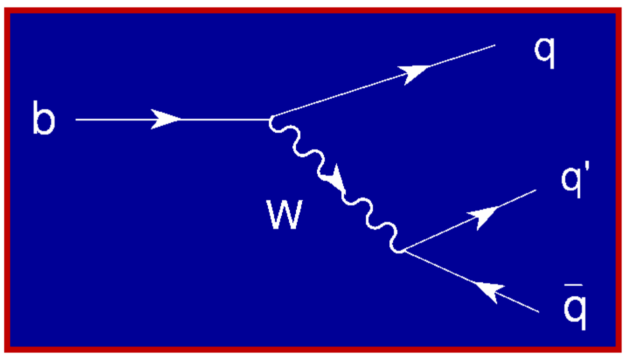
$$\mathbf{C_{\bar{f}}} = \mathbf{C_f} \qquad ; \qquad \mathbf{S_{\bar{f}}} = \mathbf{S_f}$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\not{CP}$



CP self-conjugate: $\bar{\mathrm{f}} = \eta_{\mathrm{f}}\ \mathrm{f}$

$$\frac{q}{p} \approx \frac{\mathbf{V}_{tb}^* \, \mathbf{V}_{tq}}{\mathbf{V}_{tb} \, \mathbf{V}_{tq}^*} = e^{-2i\phi_M} \quad ; \qquad \phi_M \approx \begin{cases} \beta & \left(B_d^0\right) \\ -\beta_s \approx -\lambda^2 \eta & \left(B_s^0\right) \end{cases}$$



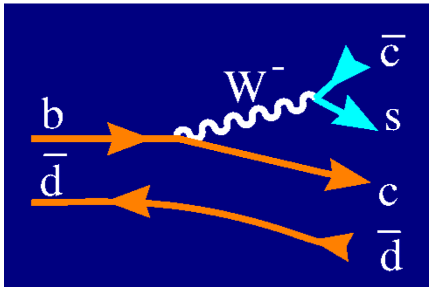
Assumption: **Only 1 decay amplitude**

$$\frac{A_{b\to q\bar{q}q'}}{A_{\bar{b}\to\bar{q}q\bar{q}'}} = \frac{\mathbf{V}_{qb} \, \mathbf{V}_{qq'}^*}{\mathbf{V}_{qb}^* \, \mathbf{V}_{qq'}} = e^{-2i\phi_D}$$

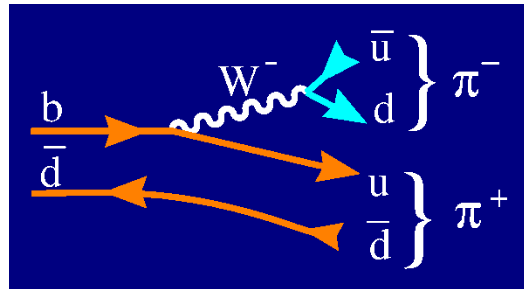
$$\frac{\Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right) - \Gamma\left(B^0 \to \mathrm{f}\right)}{\Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right) + \Gamma\left(B^0 \to \mathrm{f}\right)} = -\eta_{\mathrm{f}}\ \sin(2\phi)\ \sin(\Delta M\, t) \qquad ; \qquad \phi = \phi_M + \phi_D$$

Direct information on the CKM matrix

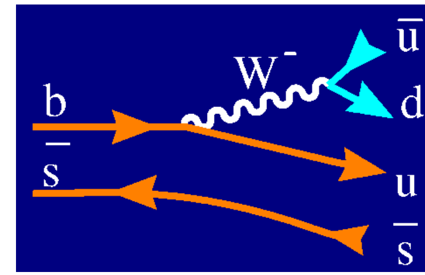
$\bar{B}_d^0 \to J/\Psi\, K_S^0$	$\bar{B}_d^0 \to \pi^+\pi^-$	$\bar{B}_s^0 \to \rho^0 K_S^0$
$\phi \simeq \beta$	$\phi \simeq \beta + \gamma = \pi - \alpha$	$\phi \neq \gamma$



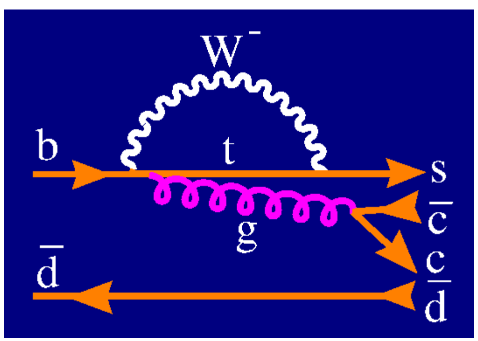
$V_{cb}\, V_{cs}^* \sim A\lambda^2$



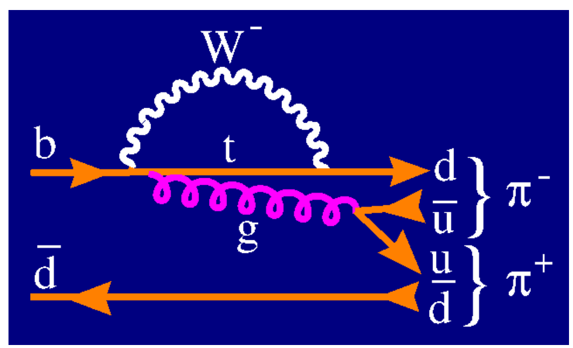
$V_{ub}\, V_{ud}^* \sim A\lambda^3(\rho - i\eta)$



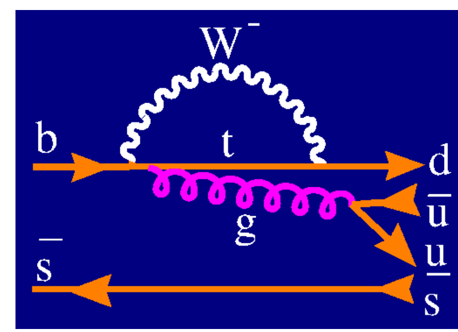
$V_{ub}\, V_{ud}^* \sim A\lambda^3(\rho - i\eta)$



$V_{tb}\, V_{ts}^* \sim -A\lambda^2$



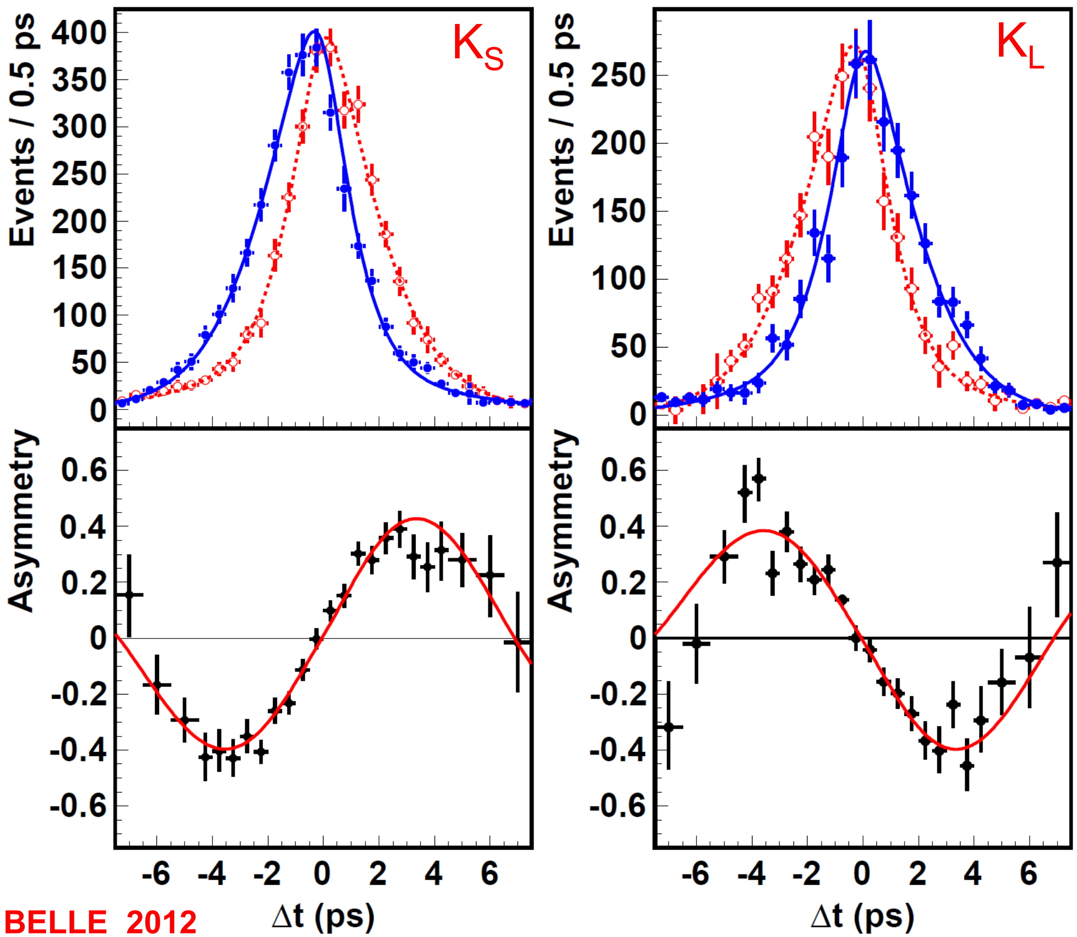
$V_{tb}\, V_{td}^* \sim A\lambda^3(1 - \rho + i\eta)$



$V_{tb}\, V_{td}^* \sim A\lambda^3(1 - \rho + i\eta)$

***	**	**BAD**

$$\frac{\Gamma(\bar{B}^0 \to J/\psi\, K_S) - \Gamma(B^0 \to J/\psi\, K_S)}{\Gamma(\bar{B}^0 \to J/\psi\, K_S) + \Gamma(B^0 \to J/\psi\, K_S)} = -\eta_f \;\sin(2\beta)\;\sin(\Delta M\, t)$$

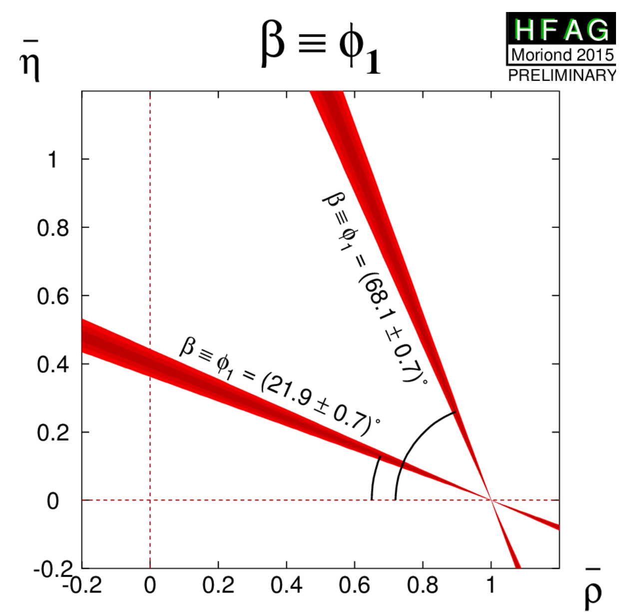


BELLE 2012

HFAG:

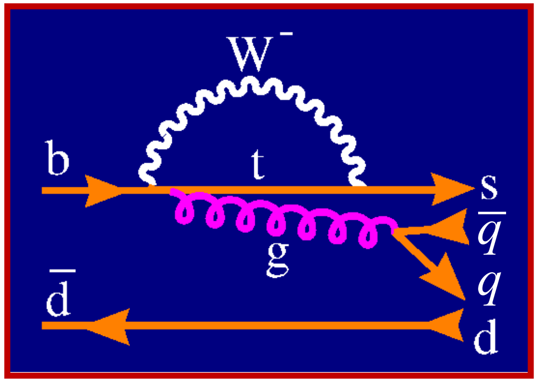
sin(2β) = 0. 679 ± 0.020

$B^0 \to J/\psi\, K_{S,L}\,, \psi(2S)\, K_S\,, \chi_c\, K_S\,, \eta_c\, K_S$



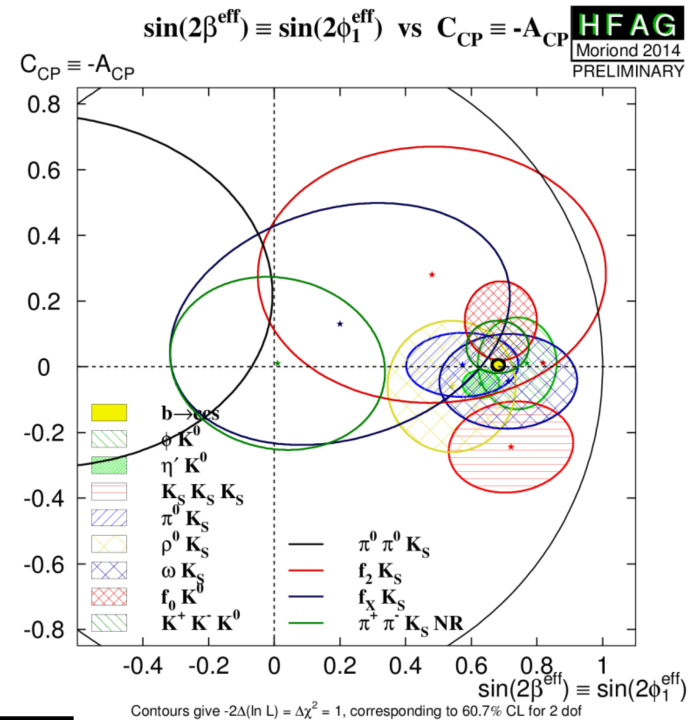
$\not{CP}$ **Signal**

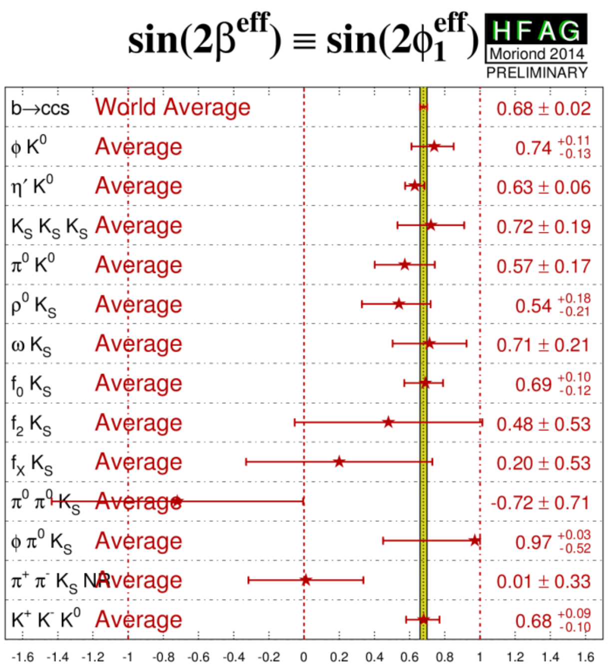
$b \to q\bar{q}s$

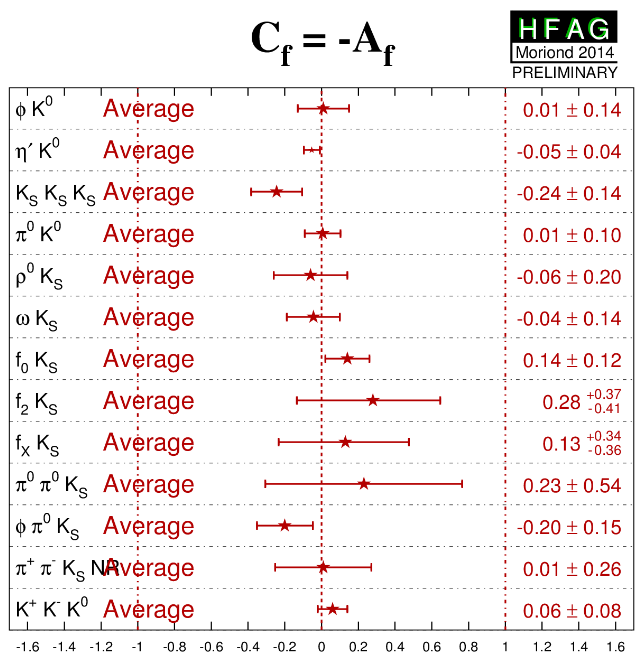


$$V_{tb} V_{ts}^* \sim -A\lambda^2$$

Sensitive to New Physics in Penguin diagram







Agreement with

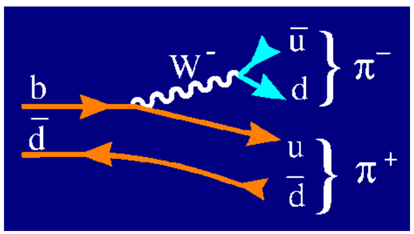
$$B^0 \to J/\Psi\, K_S \quad (b \to c\bar{c}s)$$

No signal of direct $\not{C}\!\!\not{P}$

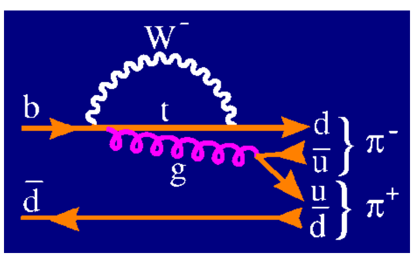
$B^0 \to \pi\pi$

$$\frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)} = -C_f \cos(\Delta M\, t) + S_f \sin(\Delta M\, t)$$

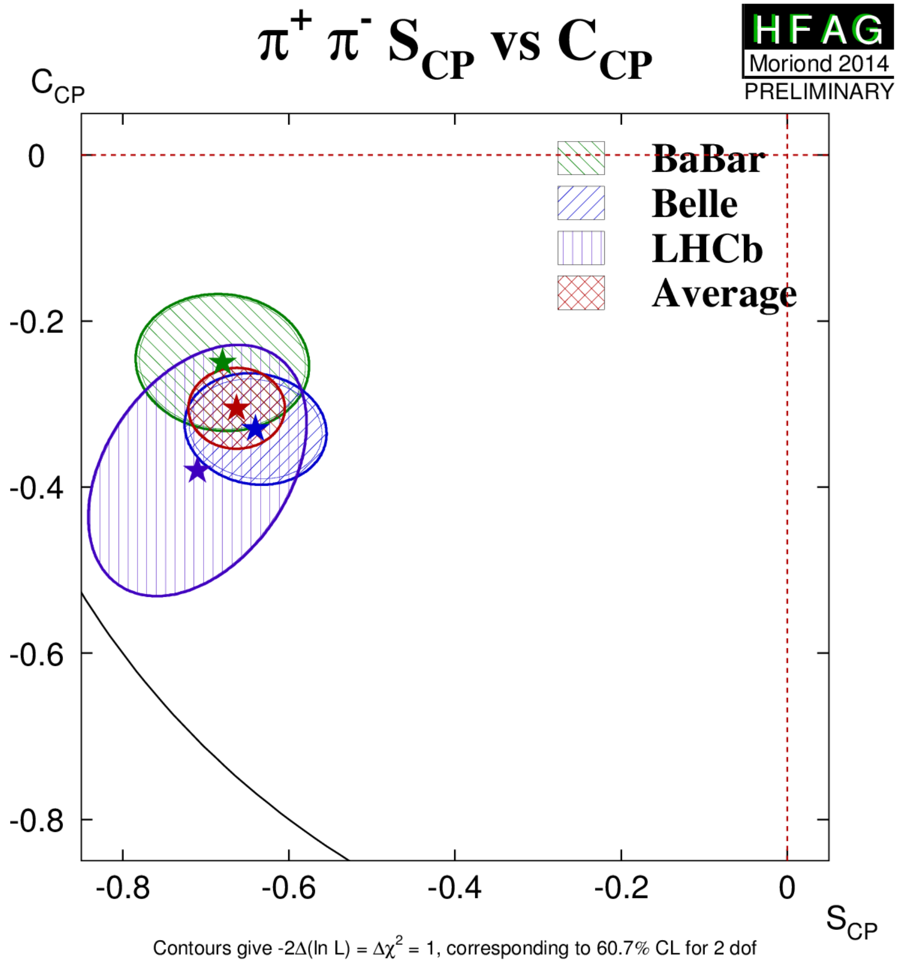
$$\alpha \equiv \arg\left[-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*}\right]$$



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



$$V_{tb} V_{td}^* \sim A\lambda^3(1 - \rho + i\eta)$$



$$C_f \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \neq 0$$

Direct CP̸

Penguins

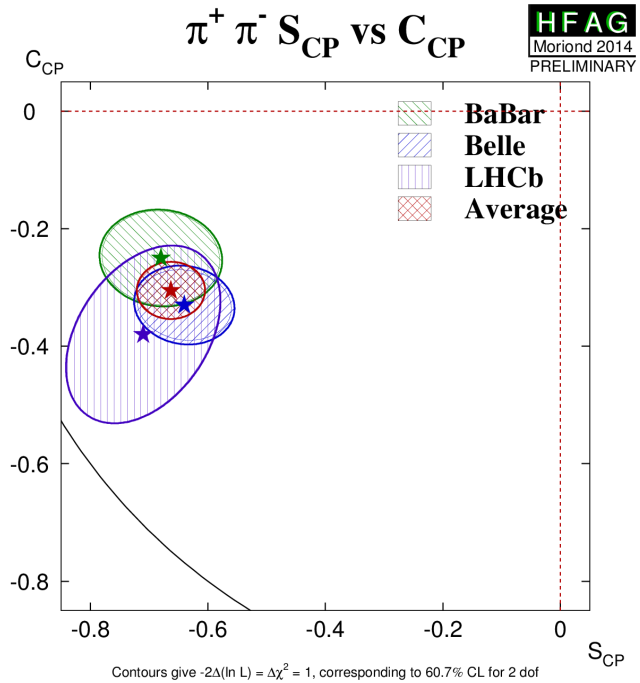
$$S_f \approx -\sin(2\alpha) \quad ?$$

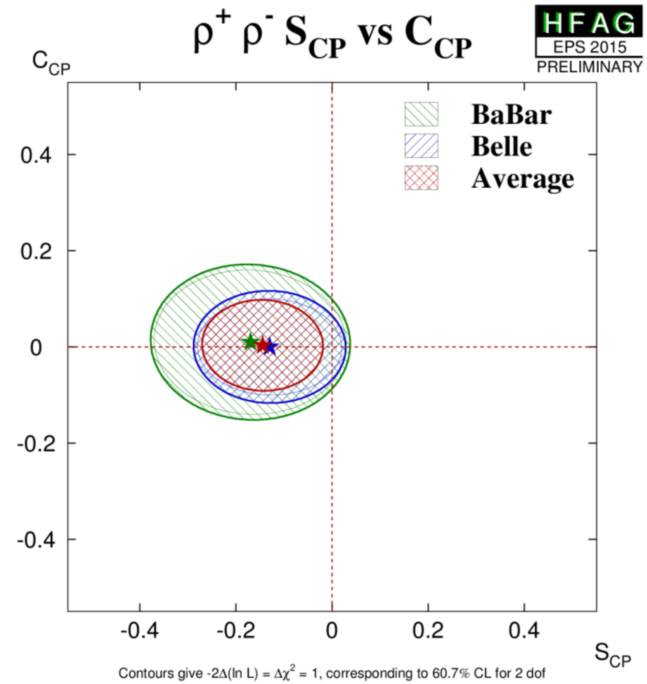
$B^0 \to \pi\pi, \rho\rho, \rho\pi$

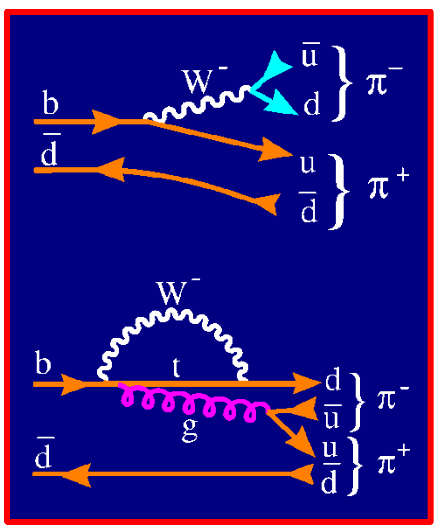
$$C_f \equiv \frac{1-|\bar{\rho}_f|^2}{1+|\bar{\rho}_f|^2} \neq 0$$

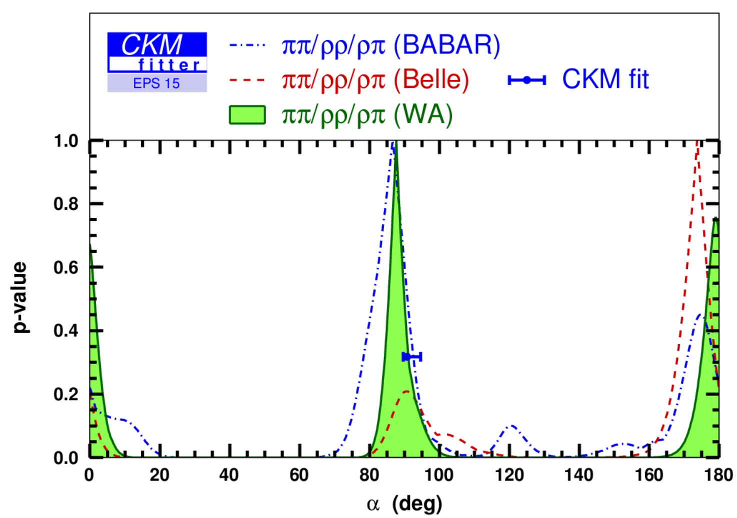
Direct $\not{CP}$

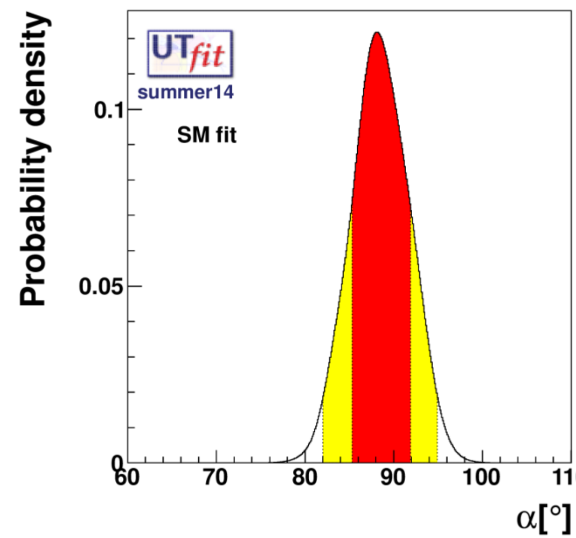
Penguins











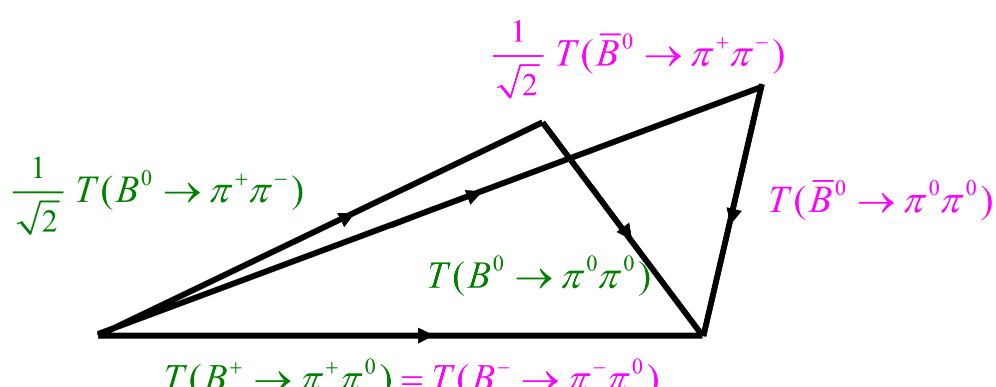
MEASURING HADRONIC CONTAMINATIONS

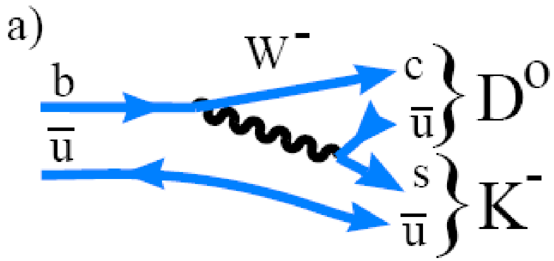
- **Time Evolution**
- **Transversity Analysis:** **$B \to V\,V$**
- **Isospin Relations** (Gronau-London)
- **D^0-$\bar{D}^0$ Mixing** (Gronau-London-Wyler, Atwood-Dunietz-Soni)

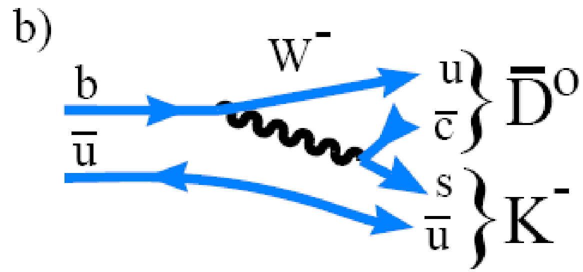
$$\sqrt{2}\,\mathrm{T}(B^+ \to D^0_+ K^+) = \mathrm{T}(B^+ \to D^0 K^+) + \mathrm{T}(B^+ \to \bar{D}^0 K^+)$$

$$\sqrt{2}\,\mathrm{T}(B^0_d \to D^0_+ K_S) = \mathrm{T}(B^+ \to D^0 K_S) + \mathrm{T}(B^+ \to \bar{D}^0 K_S)$$

- **Dalitz Analysis**
- **SU(3) Relations:** **$B \to \pi K\,,\ \pi\pi\,,\ \ldots$**
- …







D^0-$\bar{D}^0$ Mixing

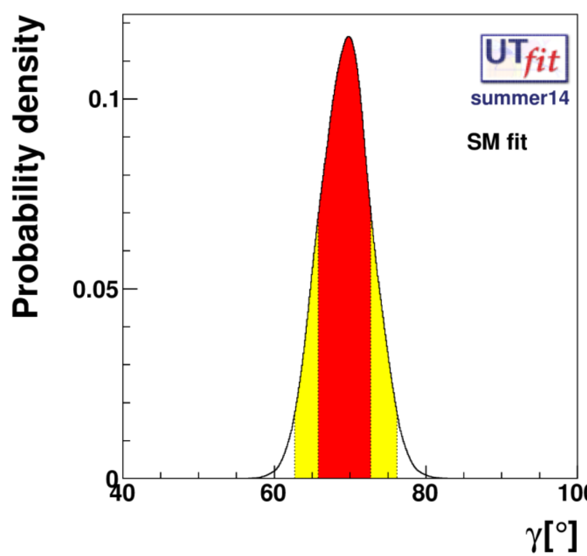
Gronau-London-Wyler

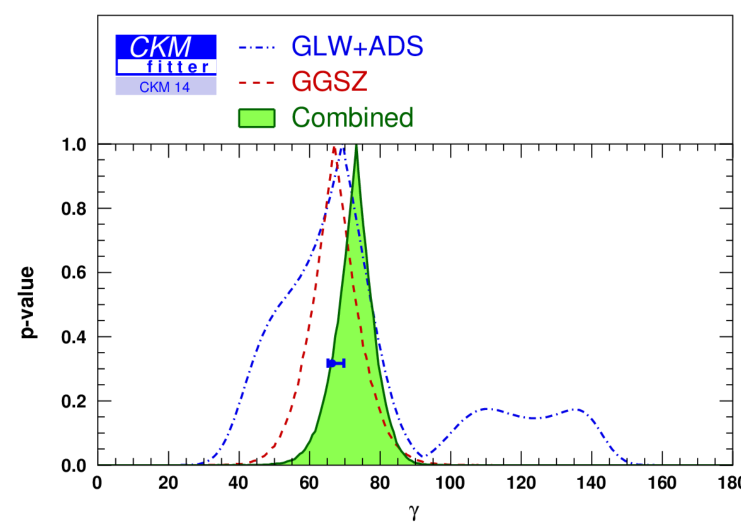
Atwood-Dunietz-Soni

$$\sqrt{2}\, T(B^+ \to D^0_+ K^+) = T(B^+ \to D^0 K^+) + T(B^+ \to \bar{D}^0 K^+)$$

$$\sqrt{2}\, T(B^0_d \to D^0_+ K_S) = T(B^+ \to D^0 K_S) + T(B^+ \to \bar{D}^0 K_S)$$

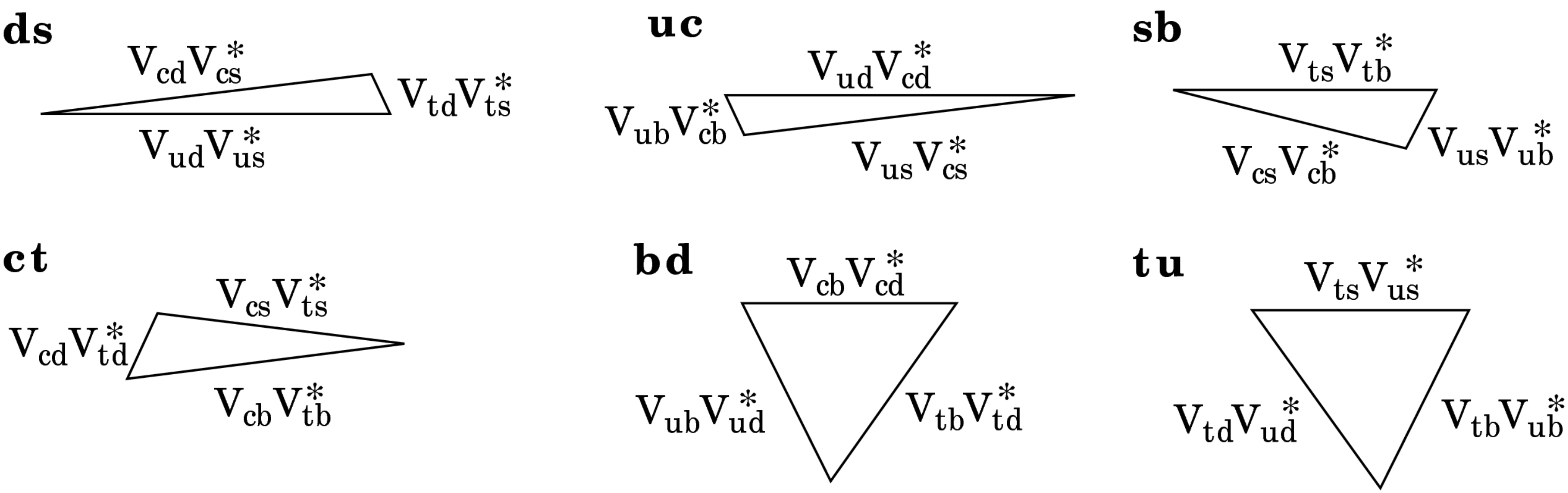
$$\Rightarrow \quad \gamma \equiv \arg\left[-\frac{\mathbf{V}_{ud}\,\mathbf{V}^*_{ub}}{\mathbf{V}_{cd}\,\mathbf{V}^*_{cb}}\right] = \left(68.0\,{}^{+8.0}_{-8.5}\right)^\circ$$





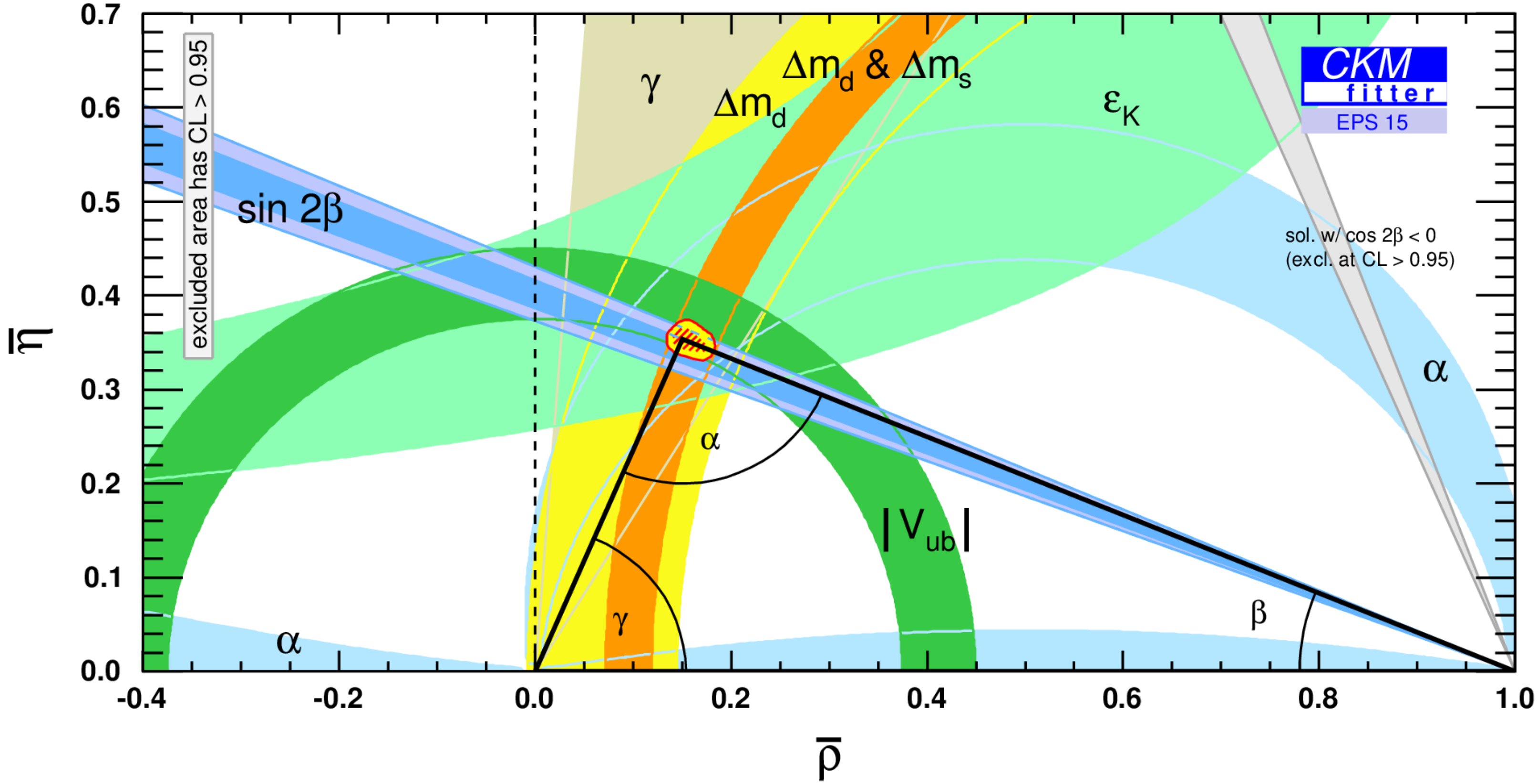
UNITARITY TRIANGLES

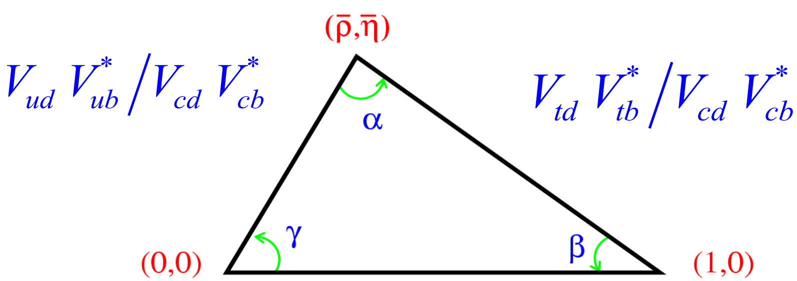
$$\mathbf{V_{ui}\, V_{uj}^* + V_{ci}\, V_{cj}^* + V_{ti}\, V_{tj}^* = 0} \qquad (i \neq j)$$



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

$$V_{ud}\,V_{ub}^{*} + V_{cd}\,V_{cb}^{*} + V_{td}\,V_{tb}^{*} = 0$$





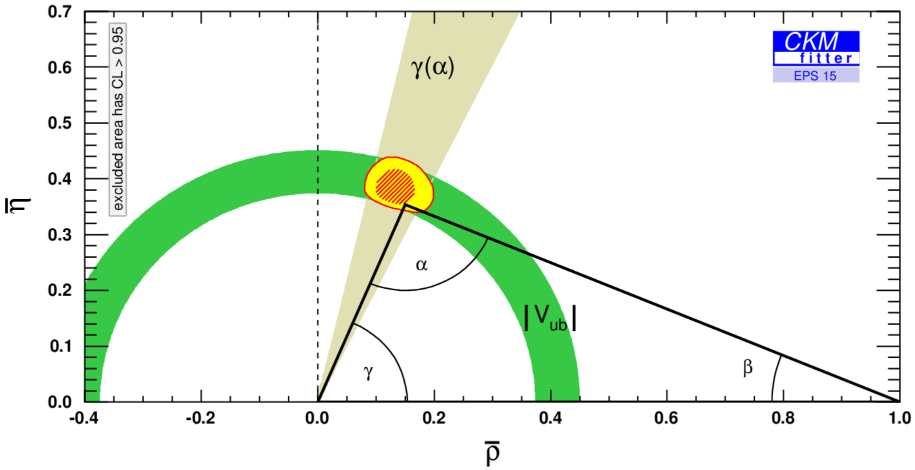
UT*fit*

$$\bar\eta \equiv \eta\left(1-\frac{1}{2}\lambda^2\right) = 0.352 \pm 0.014$$

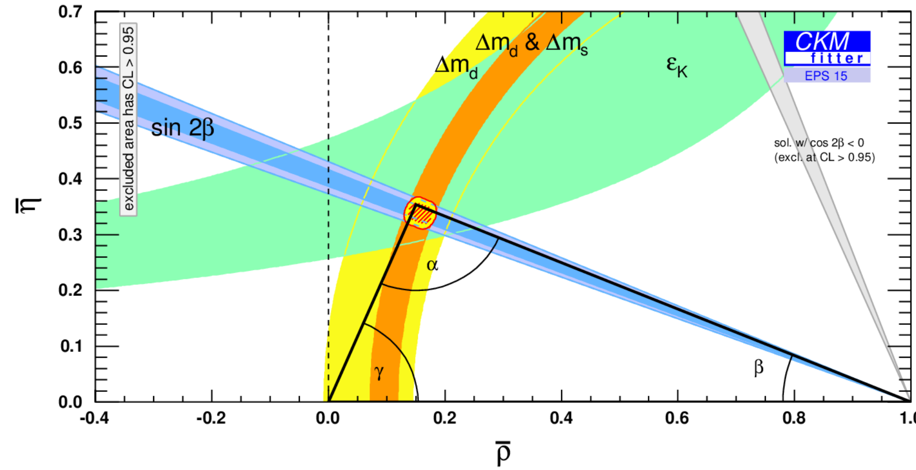
$$\bar\rho \equiv \rho\left(1-\frac{1}{2}\lambda^2\right) = 0.132 \pm 0.023$$

$\alpha = 88.6 \pm 3.3^\circ$; $\beta = 22.03 \pm 0.86^\circ$; $\gamma = 69.2 \pm 3.4^\circ$

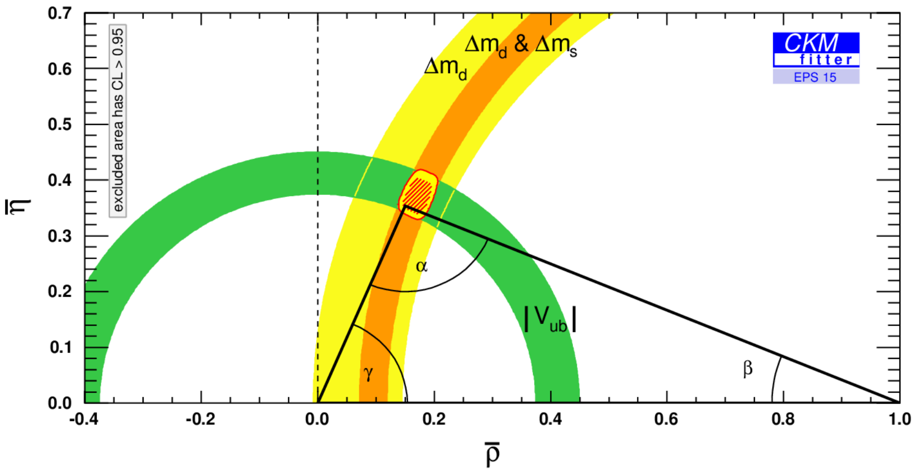
Tree-level determinations



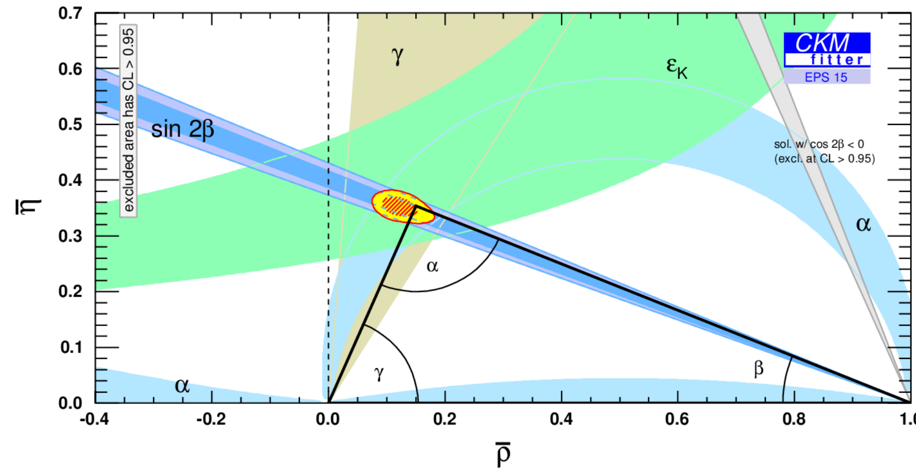
Loop processes



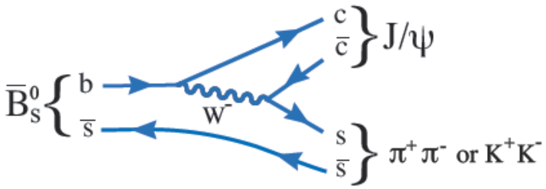
CP Conserving



CP Violating

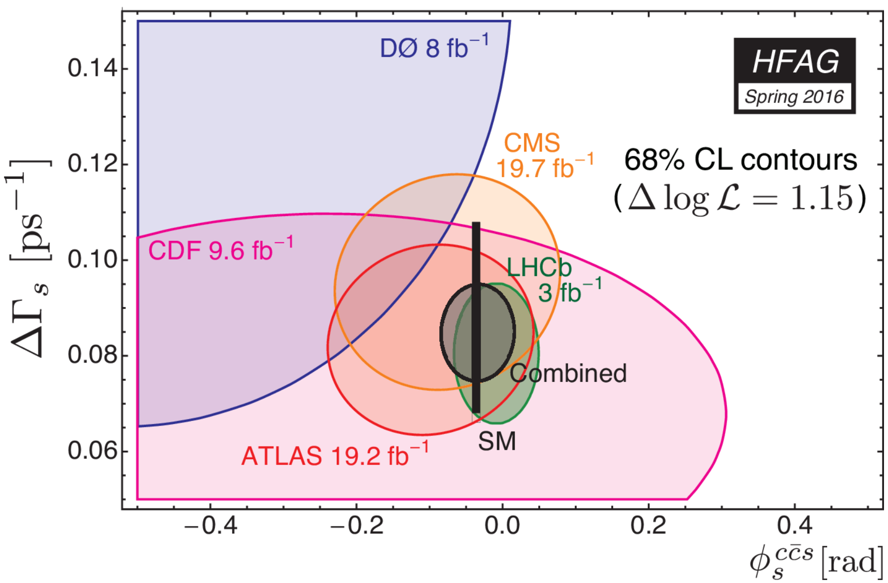


B_s Asymmetries



$$\phi_s^{c\bar{c}s} \equiv 2\left(\phi_s^M + \phi_s^D\right)$$

$$\phi_s^{c\bar{c}s}\Big|_{SM} \approx -2\beta_s \equiv -2\,\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

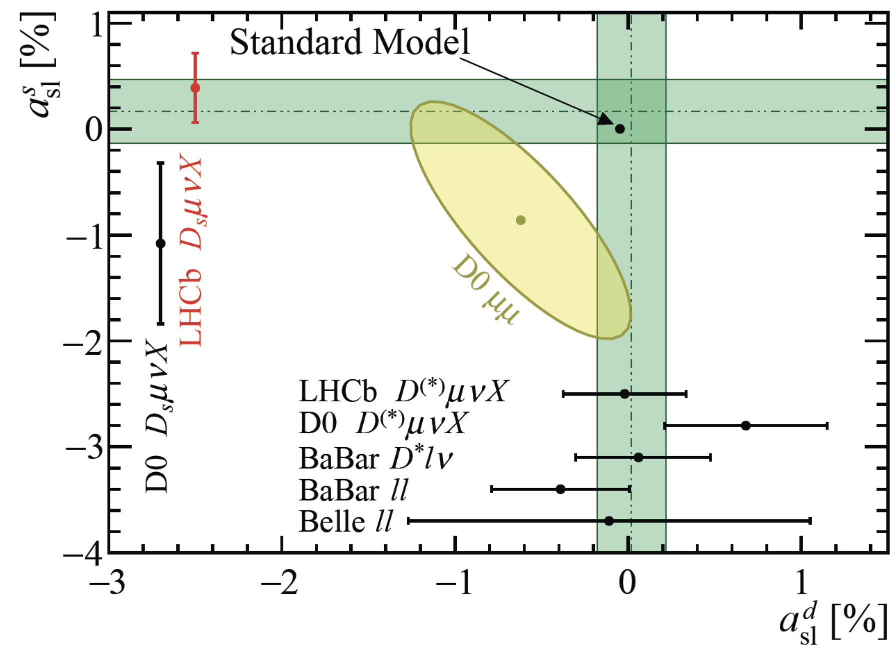


$$\phi_s^{c\bar{c}s}\Big|_{SM} = \left(-0.033 \pm 0.033\right)\ \text{rad} \qquad \text{(HFAG 2016)}$$

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$a^q_{sl} \equiv \frac{\Gamma(\bar{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\bar{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q$$

$$\phi_q \equiv \arg\left(-M^q_{12}/\Gamma^q_{12}\right) \sim \frac{m_c^2}{m_b^2}$$



DIRECT $\not{CP}$

$$A(\bar{B}_d^0 \to \pi^+ K^-) \equiv \frac{\mathrm{Br}(\bar{B}_d^0 \to \pi^+ K^-) - \mathrm{Br}(B_d^0 \to \pi^- K^+)}{\mathrm{Br}(\bar{B}_d^0 \to \pi^+ K^-) + \mathrm{Br}(B_d^0 \to \pi^- K^+)} = -0.082 \pm 0.006$$

(13.7 σ)

$$A(\bar{B}_s^0 \to \pi^- K^+) = 0.263 \pm 0.035$$

(7.5 σ)

Large & Interesting Signals

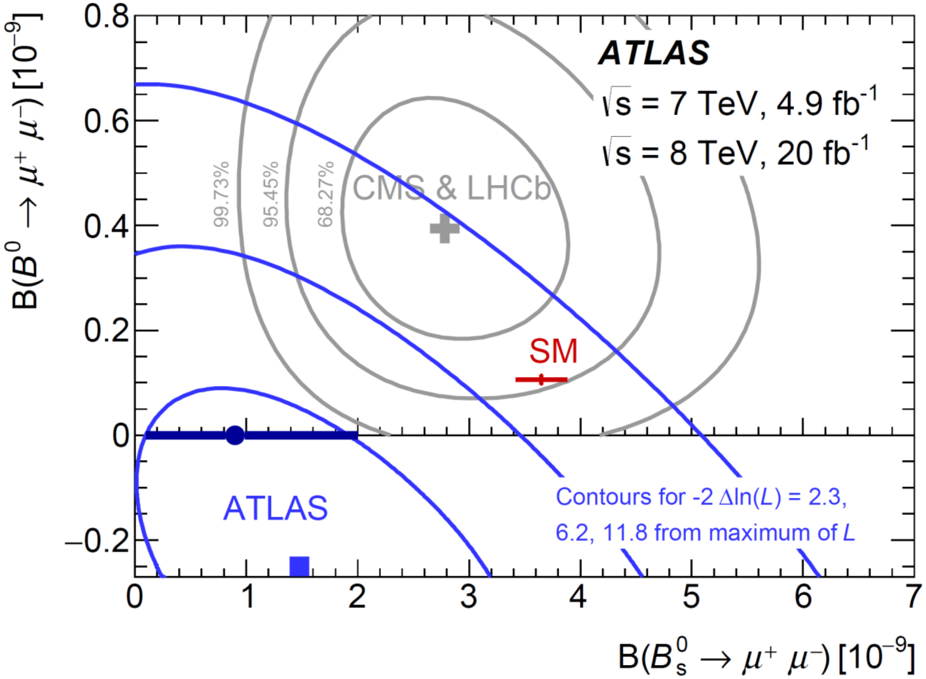
Big challenge: **Get reliable Standard Model predictions**

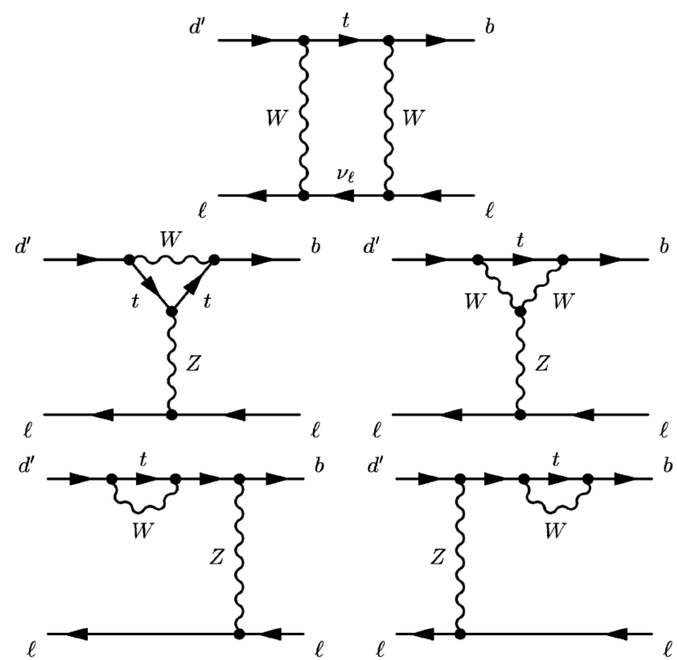
Severe hadronic uncertainties

Rare Decays

Loop & CKM suppression → **NP sensitivity**

$B_{s,d} \to \mu^+\mu^-$





$W^\pm \to H^\pm$, $Z \to H^0, A^0$

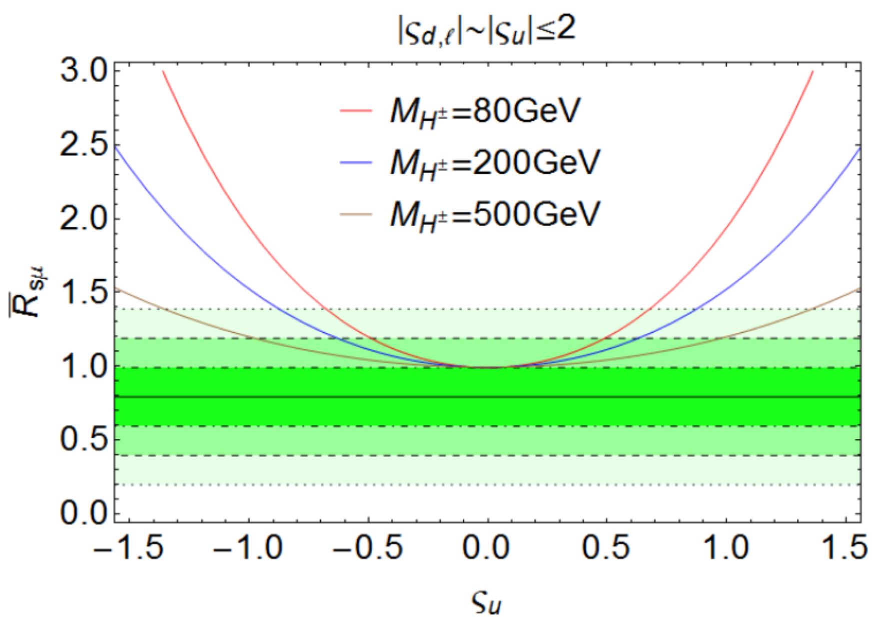
Sensitive to (pseudo) scalar contributions

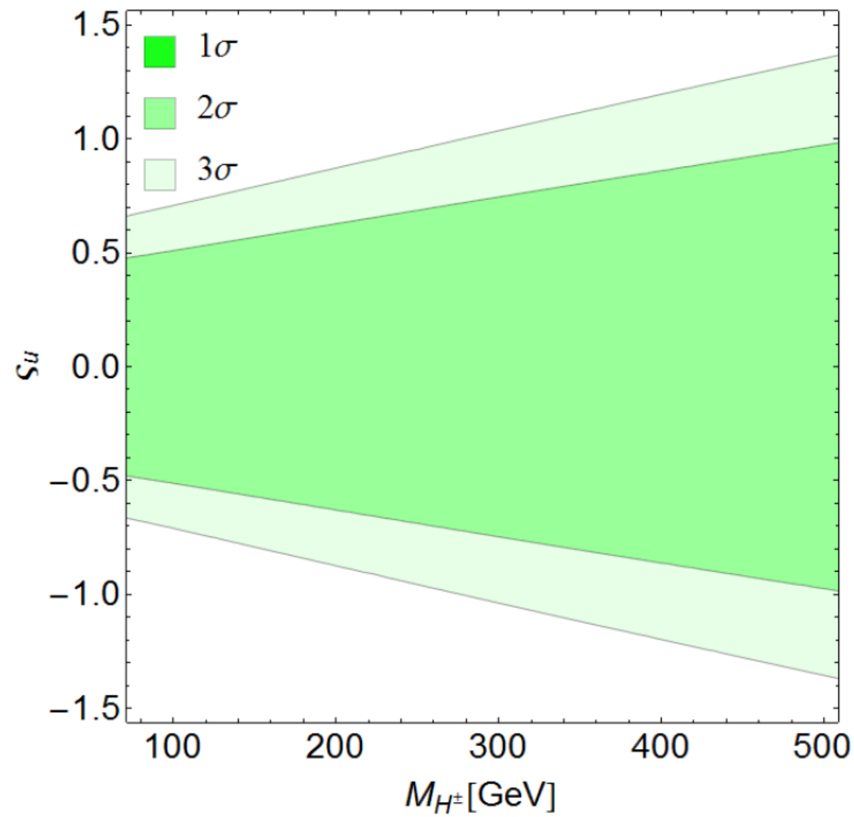
Li-Lu-A.P. 1404.5865

$B_{s,d} \to \mu^+\mu^-$

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \bar{u} \left[\varsigma_d V_{\rm CKM} M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V_{\rm CKM} \mathcal{P}_L\right] d$$

Li-Lu-A.P. 1404.5865





$$\bar{R}_{s\mu} \equiv \overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)/\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)_{\rm SM}$$

CMS & LHCb: $\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)_{\rm exp.} = (2.8 \pm 0.7) \times 10^{-9}$ [SM: $(3.65 \pm 0.23) \times 10^{-9}$]

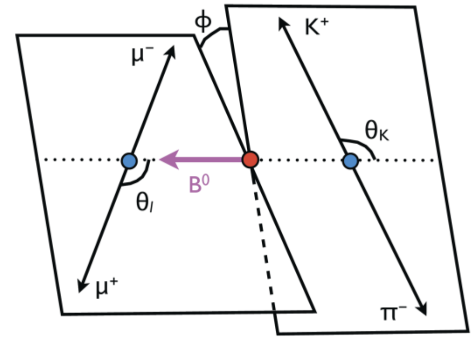
$\overline{\mathcal{B}}(B_d^0 \to \mu^+\mu^-)_{\rm exp.} = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$ [SM: $(1.06 \pm 0.09) \times 10^{-10}$]

$B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$

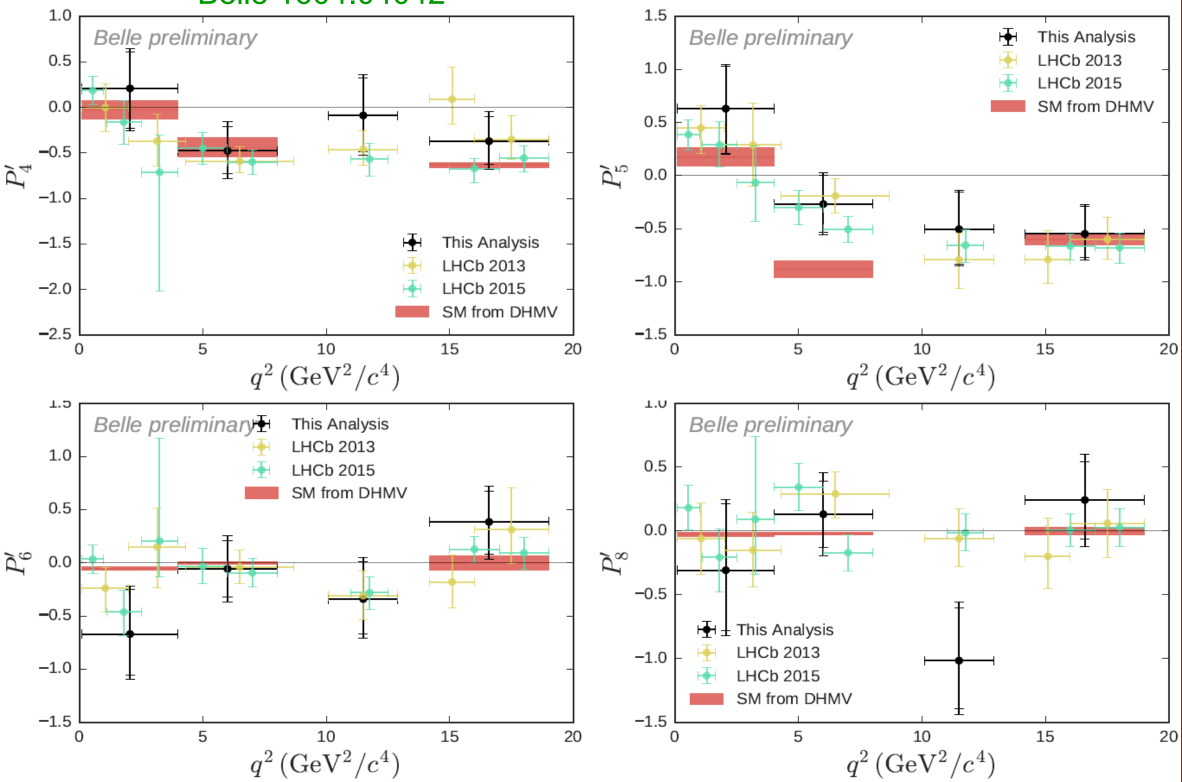
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$q^2 = s_{\mu^+\mu^-}$$

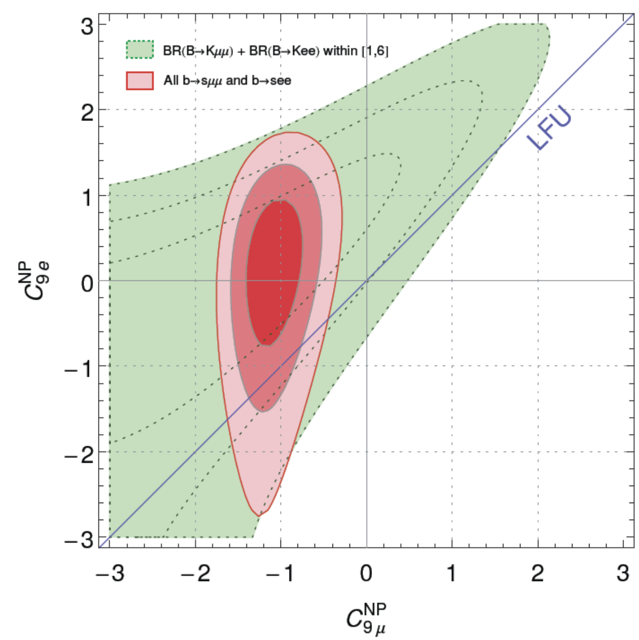
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



Belle 1604.04042

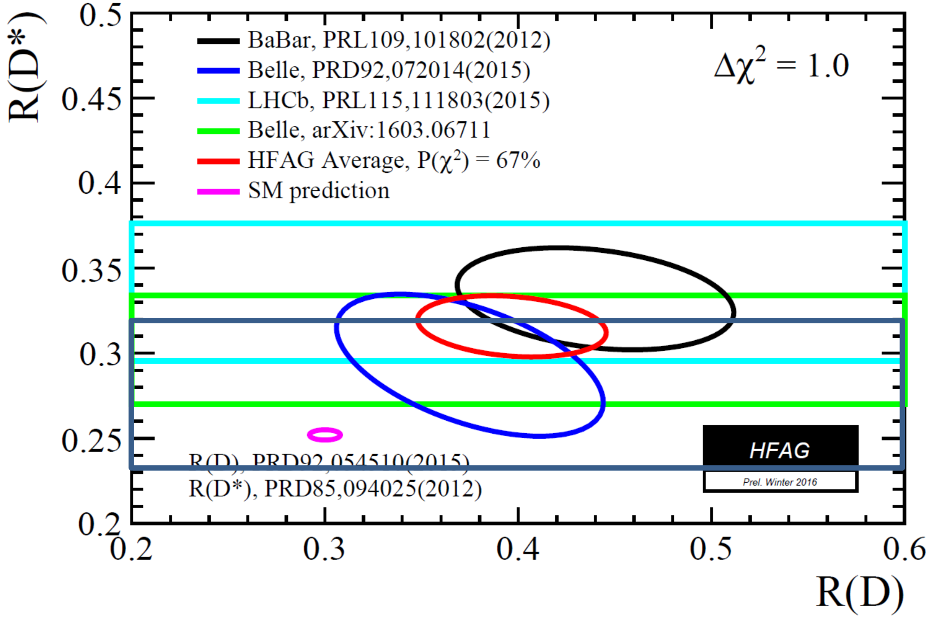


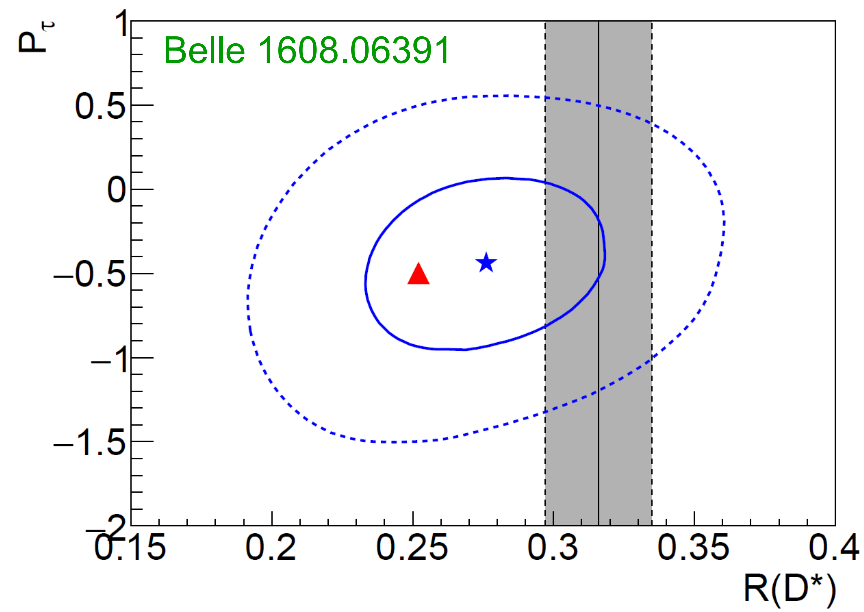
Descotes-Genon et al



$$O_9 = \frac{\alpha}{4\pi}\, m_b \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\gamma^\mu\ell\right)$$

$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}$$





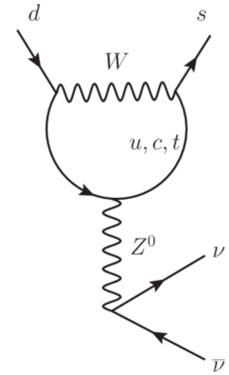
LHCb: $(q^2 \in [1,6]\ \mathrm{GeV}^2)$

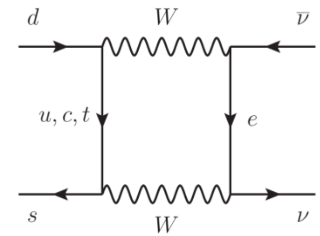
$$\frac{\mathrm{Br}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}(B^+ \to K^+e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

2.6 σ below the SM

Violation of Lepton Flavour

$K \to \pi \nu \bar{\nu}$





$$\mathbf{T} \sim F\left(V_{is}^* V_{id}, m_i^2/M_W^2\right) \left(\bar{\nu}_L \gamma_\mu \nu_L\right) \left\langle \pi \middle| \bar{s}_L \gamma_\mu d_L \middle| K \right\rangle$$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = (7.8 \pm 0.8) \times 10^{-11} \sim A^4 \left[\eta^2 + (1.4 - \rho)^2\right]$$

$$\mathrm{Br}\left(K_L \to \pi^0 \nu \bar{\nu}\right) = (2.4 \pm 0.4) \times 10^{-11} \sim A^4 \, \eta^2$$

Buras et al

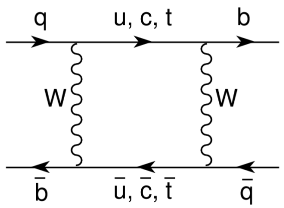
Long-distance contributions are negligible

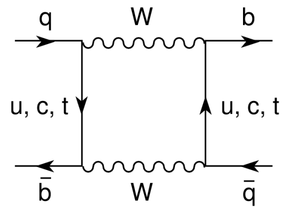
$$\mathrm{T}\left(K_L \to \pi^0 \nu \bar{\nu}\right) \neq 0 \quad \Rightarrow \quad \not{CP}$$

- **BNL-E949:** **few events!** ➡ $\mathrm{Br}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = \left(1.73\,^{+1.15}_{-1.05}\right) \cdot 10^{-10}$
- **KEK-E391a:** $\mathrm{Br}\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 2.6 \times 10^{-8}$ (90% C.L.)

New Experiments Needed: **NA62, K0TO** **(ORKA, Project-X)**

Bounds on New Flavour Physics





$$L_{\rm eff} = L_{\rm SM} + \sum_{D>4} \sum_k \frac{c_k^{(D)}}{\Lambda_{\rm NP}^{D-4}} O_k^{(D)}$$

Isidori, 1302.0661

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Bounds on Λ in TeV ($c_{\rm NP}=1$) Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Im	Observables
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar s_R\, d_L)(\bar s_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_R\, d_L)(\bar b_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar b_R\, s_L)(\bar b_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

- **Generic flavour structure [c_{NP}~O(1)] ruled out at the TeV scale**
- **Λ_{NP} ~ 1 TeV requires c_{NP} to inherit the strong SM suppressions (GIM)**

Minimal Flavour Violation: The up and down Yukawa matrices are the only source of quark-flavour symmetry breaking

D'Ambrosio et al, Buras et al

Two-Higgs Doublet Models

5 scalar fields: $H^\pm,\ \varphi_i^0 = (h, H, A)$ [3x3 mixing R_{ij}] $\quad \mathrm{v} = \sqrt{\mathrm{v}_1^2 + \mathrm{v}_2^2}\ ,\quad \tan\beta = \mathrm{v}_2/\mathrm{v}_1$

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = \left(g_{hVV}^{\mathrm{SM}}\right)^2$$

CP-conserving potential: $R = \begin{bmatrix} \cos\tilde\alpha & \sin\tilde\alpha & 0 \\ -\sin\tilde\alpha & \cos\tilde\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$ $\quad g_{\varphi_i^0 VV} / g_{\varphi_i^0 VV}^{\mathrm{SM}} = R_{i1} = \cos\tilde\alpha \equiv \sin(\beta - \alpha)$

Yukawas: $L_Y = -\bar Q'_L \left(\Gamma_1 \phi_1 + \Gamma_2 \phi_2\right) d'_R + \cdots$ → (EWSB) $L_Y = -\frac{\sqrt{2}}{\mathrm{v}} \bar Q'_L \left(M'_d \Phi_1 + Y'_d \Phi_2\right) d'_R + \cdots$

M'_f & Y'_f unrelated **(not simultaneously diagonal)** → **FCNCs**

Solutions:

(same for u_R and ℓ_R Yukawas)

- **Natural Flavour Conservation:** $\Gamma_1 = 0$ or $\Gamma_2 = 0$ (Z_2 models) Glashow-Weinberg...
- **Alignment:** $\Gamma_1 \propto \Gamma_2$ → $Y_{d,l} = \varsigma_{d,l} M_{d,l}\ ,\quad Y_u = \varsigma_u^* M_u$ AP-Tuzón
- **BGL Models:** "controlled" FCNC (symmetries) Branco et al

Aligned 2HDM

Pich-Tuzón, 0908.1554

Yukawa alignment in Flavour Space: $Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \quad , \quad Y_u = \varsigma_u^*\, M_u$

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u}\left[\varsigma_d\, V_{\mathrm{CKM}} M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V_{\mathrm{CKM}} \mathcal{P}_L\right] d \;+\; \varsigma_l\, \left(\bar{\nu}\, M_l\, \mathcal{P}_R\, l\right)\right\}$$

$$-\frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0}\, \varphi_i^0\, \left(\bar{f}\, M_f\, \mathcal{P}_R\, f\right) \quad + \quad \mathrm{h.c.}$$

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3})\,\varsigma_{d,l} \qquad , \qquad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\,\mathcal{R}_{i3})\,\varsigma_u^*$$

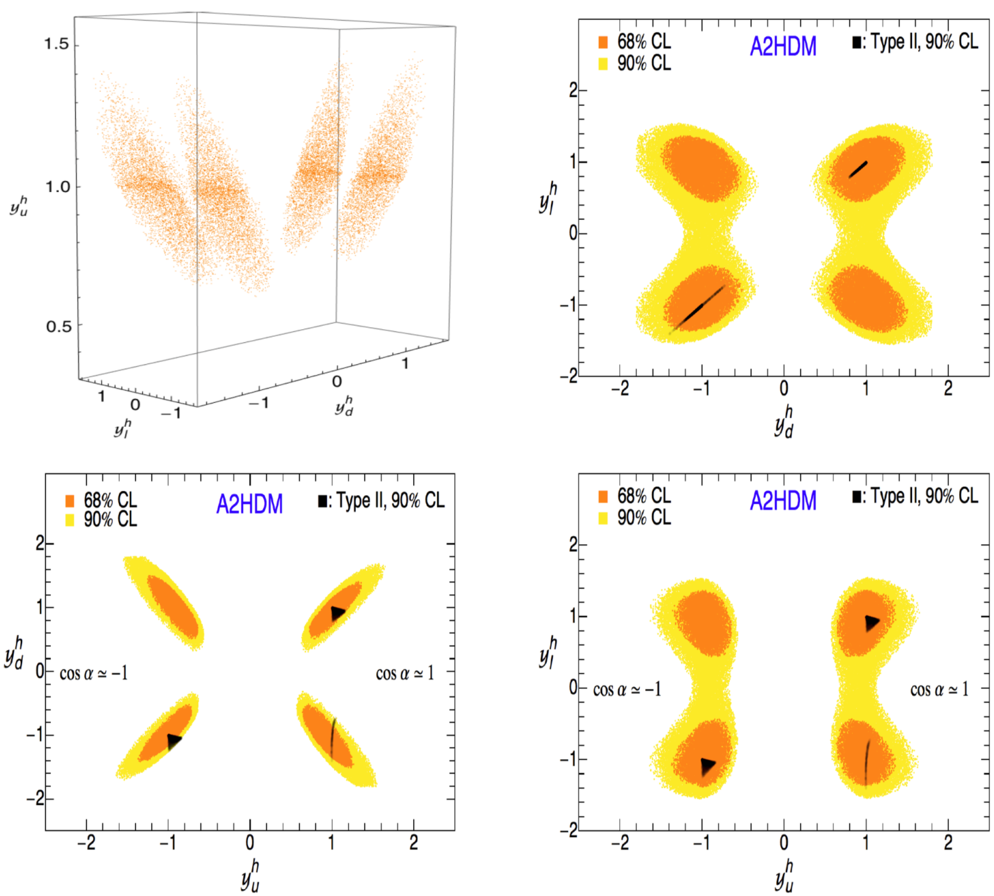
ς_f → **New sources of CP violation without tree-level FCNCs**

$\mathcal{Z}_2$ models:

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Flavour Alignment (Aligned 2HDM) AP-Tuzón

Celis-Ilisie-AP, 1302.4022, 1310.7941



$$|\cos\tilde{\alpha}| > 0.80 \quad (90\%\ \mathrm{CL})$$

General setting without FCNCs & new sources of CP violation

$$Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \quad , \quad Y_u = \varsigma_u^*\, M_u$$

- **Rich phenomenology @ LHC**

  Altmannshofer et al, Barger et al, Celis et al, Cervero-Gerard, López-Val et al...

  Many allowed possibilities

  Search for light $H^\pm$, H, A

  CP violation

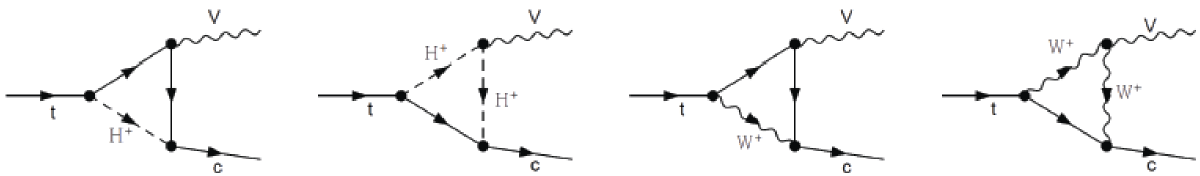
- **Flavour constraints fulfilled**

  Celis et al, Jung et al, Li et al

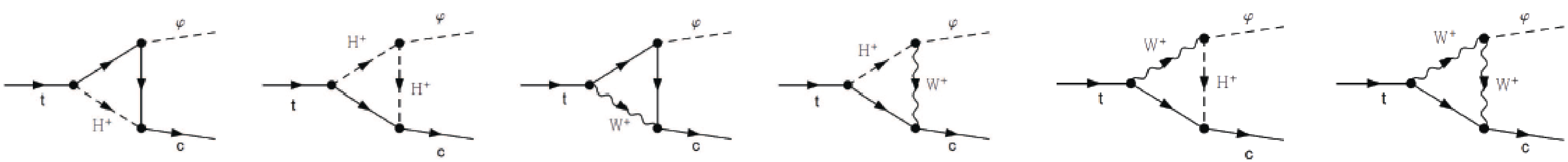
- **EDMs** Jung-AP, 1308.6283

- **Usual Z_2 models recovered in particular (CP-conserving) limits**

$t \to c\, V \qquad (V = \gamma, Z)$



$t \to c\, \varphi_i^0 \qquad (\varphi_i^0 = h, H, A)$



$M_{H^\pm}$ (GeV)	$\mathrm{Br}(t \to c\gamma)$	$\mathrm{Br}(t \to cZ)$	$\mathrm{Br}(t \to ch)$
100	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-13}$	$\lesssim 6 \times 10^{-9}$
200	$\lesssim 10^{-10}$	$\lesssim 3 \times 10^{-11}$	$\lesssim 3 \times 10^{-8}$
300	$\lesssim 10^{-11}$	$\lesssim 5 \times 10^{-12}$	$\lesssim 2 \times 10^{-8}$
400	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-12}$	$\lesssim 5 \times 10^{-9}$
500	$\lesssim 10^{-12}$	$\lesssim 10^{-12}$	$\lesssim 2 \times 10^{-9}$
Exp. limit	$< 1.8 \times 10^{-3}$	$< 5 \times 10^{-4}$	$< 5.6 \times 10^{-3}$

Abbas-Celis-Li-Lu-Pich, 1503.06423

Standard Model Mechanism of $\not{\!\!\mathcal{CP}}$

Complex phases in Yukawa couplings only:

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

SSB $\left[\langle \phi^{(0)} \rangle = \mathrm{v}/\sqrt{2} \right]$

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\mathrm{v}}\right) \frac{\mathrm{v}}{\sqrt{2}} \left\{ \bar{d}'_{\mathrm{jL}}\, c^{(d)}_{\mathrm{jk}}\, d'_{\mathrm{kR}} + \bar{u}'_{\mathrm{jL}}\, c^{(u)}_{\mathrm{jk}}\, u'_{\mathrm{kR}} + \mathrm{h.c.} \right\}$$

$c^{(q)}_{\mathrm{jk}}$ **diagonalization**

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\mathrm{v}}\right) \left\{ \bar{d}_{\mathrm{jL}}\, m_{d_{\mathrm{j}}}\, d_{\mathrm{jR}} + \bar{u}_{\mathrm{jL}}\, m_{u_{\mathrm{j}}}\, u_{\mathrm{jR}} + \mathrm{h.c.} \right\}$$

$$\mathcal{L}_{\mathrm{CC}} = \frac{g}{2\sqrt{2}}\, W^{\dagger}_{\mu} \sum_{\mathrm{ij}} \bar{u}_{\mathrm{i}}\, \gamma^{\mu} (1 - \gamma_5)\, \mathbf{V}_{\mathrm{ij}}\, d_{\mathrm{j}} + \mathrm{h.c.}$$

The CKM matrix $\mathbf{V}_{\mathrm{ij}}$ is the only source of $\not{\!\!\mathcal{CP}}$

SUMMARY

- **Flavour Structure and** $\not{CP}$ are major pending questions
- **Related to SSB** → **Scalar Sector** (Higgs)
- Important **cosmological implications** (Baryogenesis)
- Sensitive to **New Physics**
- $\not{CP}$ is highly constrained in the SM: **1 phase only**
- Many interesting $\not{CP}$ signals within experimental reach
- Better control of **QCD** effects urgently needed
- **Challenging future ahead:**

  BES-III, LHCb, NA62, J-Parc, Super-Belle, τcF, …

Quarks Leptons Bosons