Flavour Physics & CP Violation

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- $\mathcal{C}$, $\mathcal{P}$: Violated maximally in weak interactions
- $\mathcal{CP}$: Symmetry of nearly all observed phenomena
- Slight (~ 0.2 %) $\cancel{\mathcal{CP}}$ in K^0 decays (1964)
- Sizeable $\cancel{\mathcal{CP}}$ in B^0 decays (2001)
- Huge Matter — Antimatter Asymmetry in our Universe $\Rightarrow$ Baryogenesis

$\boxed{\mathcal{CPT}\ \textbf{Theorem:}\quad \cancel{\mathcal{CP}} \Longleftrightarrow \cancel{\mathcal{T}}}$

Thus, $\cancel{\mathcal{CP}}$ requires:

- Complex Phases
- Interferences

Standard Model $\cancel{CP}$: 3 fermion families needed

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

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

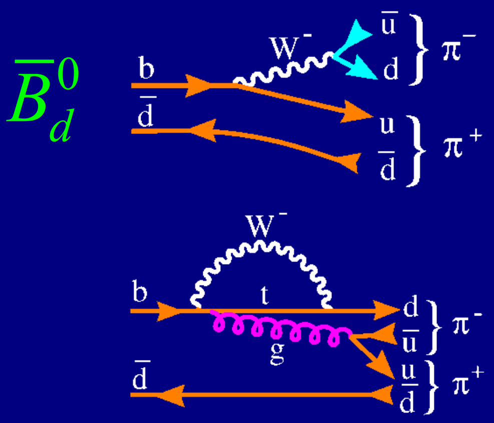
$$\mathbf{H}(M_d^2) \equiv (m_b^2 - m_s^2)\,(m_s^2 - m_d^2)\,(m_b^2 - m_d^2)$$

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

- Low-Energy Phenomena
- Small Effects ~ J
- Big Asymmetries $\Longleftrightarrow$ Suppressed Decays
- B Decays are an optimal place for $\cancel{CP}$ signals

DIRECT $\not{\mathcal{CP}}$

$$\left|\mathbf{T}\left(\mathrm{P}\to\mathrm{f}\right)\right| \neq \left|\mathbf{T}\left(\overline{\mathrm{P}}\to\overline{\mathrm{f}}\right)\right|$$



$$\mathbf{T}\left(\mathrm{P}\to\mathrm{f}\right) = \mathrm{T}_1\, e^{i\phi_1}\, e^{i\delta_1} + \mathrm{T}_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$$\Big\Downarrow\ \mathcal{CP}$$

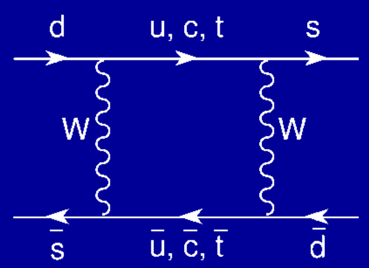
$$\mathbf{T}\left(\overline{\mathrm{P}}\to\overline{\mathrm{f}}\right) = \mathrm{T}_1\, e^{-i\phi_1}\, e^{i\delta_1} + \mathrm{T}_2\, e^{-i\phi_2}\, e^{i\delta_2}$$

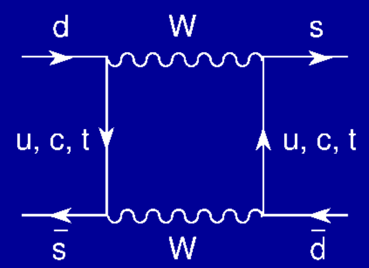
$$\boxed{\frac{\Gamma\left(\mathrm{P}\to\mathrm{f}\right)-\Gamma\left(\overline{\mathrm{P}}\to\overline{\mathrm{f}}\right)}{\Gamma\left(\mathrm{P}\to\mathrm{f}\right)+\Gamma\left(\overline{\mathrm{P}}\to\overline{\mathrm{f}}\right)} = \frac{-2\,\mathrm{T}_1\,\mathrm{T}_2\,\sin(\phi_2-\phi_1)\,\sin(\delta_2-\delta_1)}{\mathrm{T}_1^{\,2}+\mathrm{T}_2^{\,2}+2\,\mathrm{T}_1\,\mathrm{T}_2\,\cos(\phi_2-\phi_1)\,\cos(\delta_2-\delta_1)}}$$

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





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

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

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

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

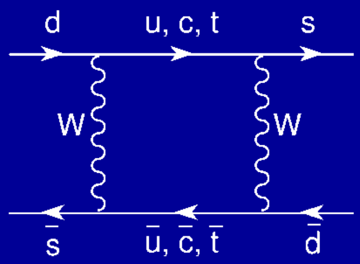
$$\lambda_i \equiv V_{id}\, V_{is}^* \qquad ; \qquad r_i \equiv m_i^2 / M_W^2 \qquad (i = u, c, t)$$

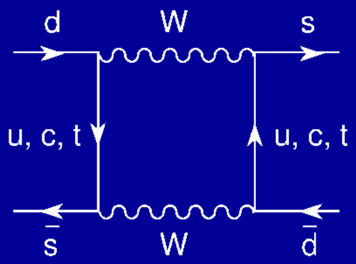
- **GIM Mechanism:** $\lambda_u + \lambda_c + \lambda_t = 0$

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

- $\not{CP}$: $\mathrm{Im}\,\lambda_t = -\,\mathrm{Im}\,\lambda_c \simeq \eta \lambda^5 A^2$
- **Hard GIM Breaking:** $S(r_i, r_i) \sim r_i$ ➡ **t quark**

INDIRECT $\cancel{CP}$: $K^0 - \bar{K}^0$ MIXING





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

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

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

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

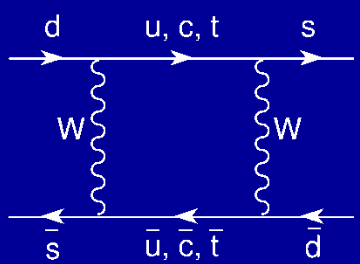
$$\lambda_i \equiv V_{id}\,V_{is}^* \quad ; \quad r_i \equiv m_i^2/M_W^2 \qquad (i=u,c,t)$$

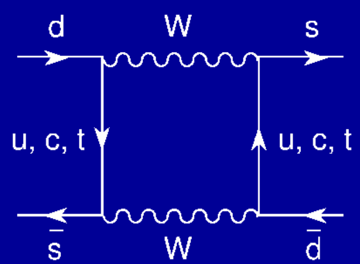
$$\mathcal{C}\,|K^0\rangle = |\bar{K}^0\rangle \quad , \quad \mathcal{P}\,|K^0\rangle = -|K^0\rangle \quad , \quad \mathcal{CP}\,|K^0\rangle = -|\bar{K}^0\rangle$$

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

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

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





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

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

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

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

$$\Rightarrow \qquad \mathrm{Re}(\bar{\varepsilon}_K) = (1.66 \pm 0.03) \cdot 10^{-3}$$

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

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

$$\phi_\varepsilon = (43.5 \pm 0.5)^\circ$$

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

Buras et al

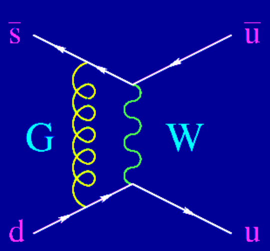
DIRECT $\not{C}\!\!\not{P}$ in $K \to \pi\,\pi$

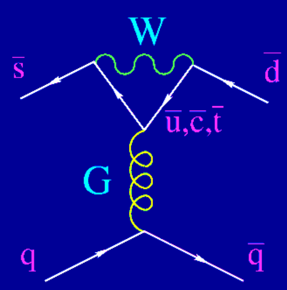
$$\eta_{+-} \equiv \frac{T(K_L \to \pi^+\pi^-)}{T(K_S \to \pi^+\pi^-)} \approx \varepsilon_K + \varepsilon'_K \qquad\qquad \eta_{00} \equiv \frac{T(K_L \to \pi^0\pi^0)}{T(K_S \to \pi^0\pi^0)} \approx \varepsilon_K - 2\,\varepsilon'_K$$

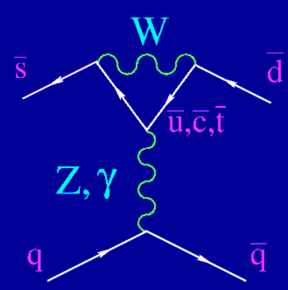
$$\mathrm{Re}\left(\varepsilon'_K / \varepsilon_K\right) \approx \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\} = (16.8 \pm 1.4)\cdot 10^{-4}$$

NA48, NA31

KTeV, E731







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

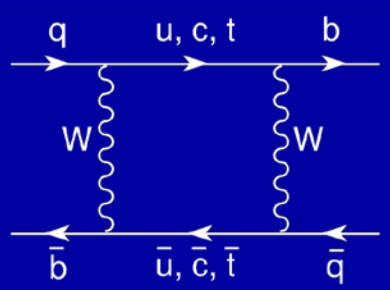
- Short-distance OPE

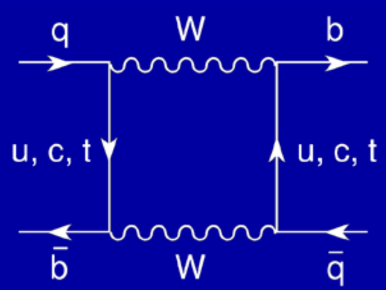
  Ciuchini et al, Buras et al

- Long-distance χPT

  Pallante-Pich-Scimemi
  Cirigliano-Ecker-Neufeld-Pich

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





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

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

$$\boxed{\Delta M_{B_d^0} = (0.508 \pm 0.004)\ \mathrm{ps}^{-1} \quad \Longrightarrow \quad |V_{td}|}$$

- $\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.771 \pm 0.007$
- $\Delta M_{B_s^0} = (17.78 \pm 0.12)\ \mathrm{ps}^{-1}$
- $\Delta \Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1$
- $\mathrm{Re}\left(\varepsilon_{B_d^0}\right) = -0.0009 \pm 0.0009$

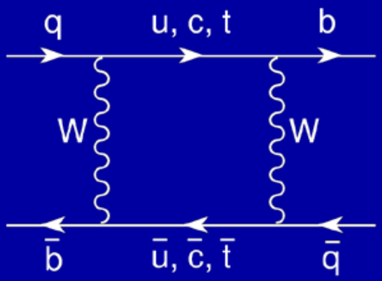
$$\Delta M_{B_s^0} / \Gamma_{B_s^0} = 26.2 \pm 0.5$$

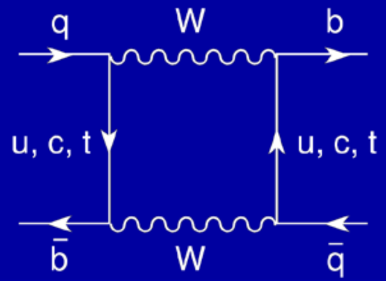
$$|V_{ts}|^2 \gg |V_{td}|^2$$

$$\Delta\Gamma_{B_s^0} / \Gamma_{B_s^0} = \left(0.092 \begin{array}{l} +0.051 \\ -0.054 \end{array}\right) \mathrm{ps}^{-1}$$

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

$\cancel{CP}$ very small





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

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

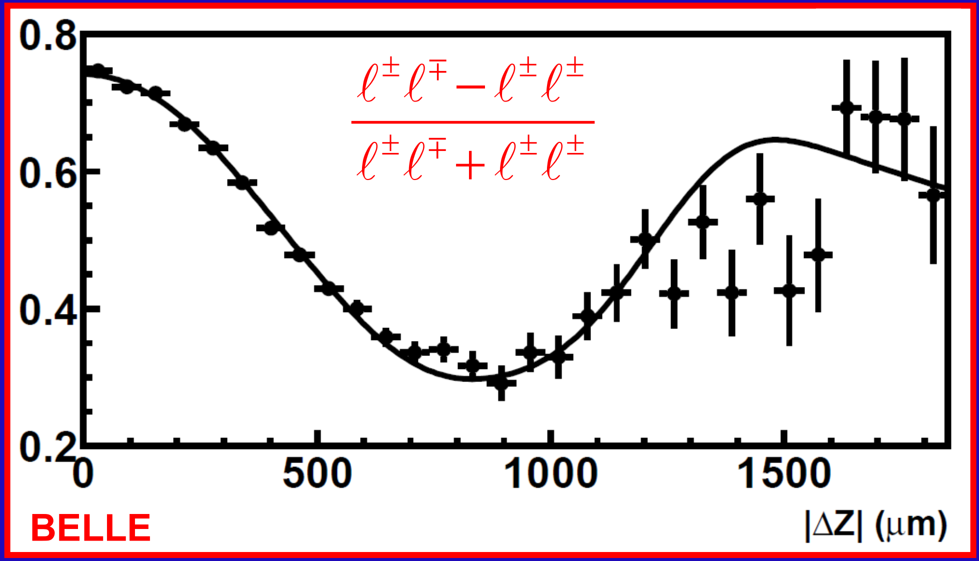
$$\Delta\Gamma/\Delta M \approx \Gamma_{12}/M_{12} \sim m_b^2/m_t^2 \ll 1 \quad \Rightarrow \quad \left|\frac{q}{p}\right| \approx 1 + \frac{1}{2}\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{\Delta B=2} \quad , \quad \phi_{\Delta B=2} \equiv \arg(M_{12}/\Gamma_{12})$$

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

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

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

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



- **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)

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

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & & f \\ & \bar{B}^0 \arrow[ur] & \end{tikzcd}$$

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

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

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

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

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

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

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

$$\begin{tikzcd}[column sep=small] B^0 \arrow[rr] \arrow[dr] & & \mathrm{f} \\ & \bar{B}^0 \arrow[ur] & \end{tikzcd}$$

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

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

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

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

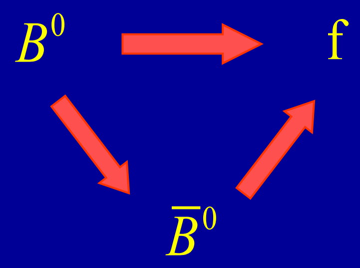
$$\mathbf{C_f} \equiv \frac{1 - |\bar{\rho}_{\mathrm{f}}|^2}{1 + |\bar{\rho}_{\mathrm{f}}|^2} \quad ; \quad \mathbf{S_f} \equiv \frac{2\,\mathrm{Im}\left(\frac{q}{p}\, \bar{\rho}_{\mathrm{f}} \right)}{1 + |\bar{\rho}_{\mathrm{f}}|^2} \quad ; \quad \mathbf{C_{\bar{f}}} \equiv -\frac{1 - |\rho_{\bar{\mathrm{f}}}|^2}{1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

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

$$T_{\bar{\mathrm{f}}} = \eta_{\mathrm{f}}\, T_{\mathrm{f}} \quad ; \quad \bar{T}_{\bar{\mathrm{f}}} = \eta_{\mathrm{f}}\, \bar{T}_{\mathrm{f}} \quad ; \quad \rho_{\bar{\mathrm{f}}} \equiv 1/\bar{\rho}_{\mathrm{f}}$$

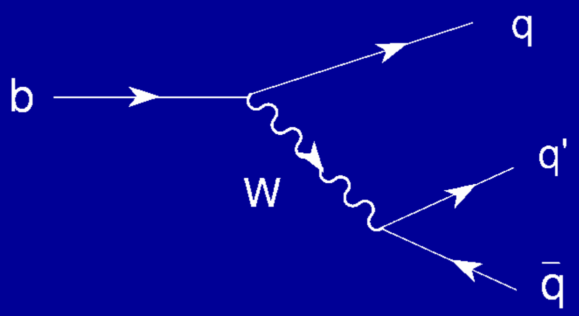
$$\mathbf{C_{\bar{f}}} = \mathbf{C_f} \qquad ; \qquad \mathbf{S_{\bar{f}}} = \mathbf{S_f}$$

$B^0 - \bar{B}^0$ MIXING AND DIRECT $\cancel{CP}$



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

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



Assumption: Only 1 decay amplitude

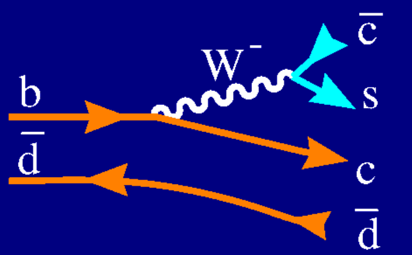
$$\frac{A_{b\to q\bar{q}q'}}{A_{\bar{b}\to\bar{q}q\bar{q}'}} = \frac{\mathbf{V}_{qb}\ \mathbf{V}_{qq'}^{*}}{\mathbf{V}_{qb}^{*}\ \mathbf{V}_{qq'}} = e^{-2i\phi_D}$$

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

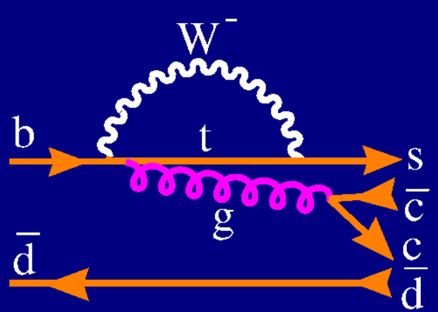
Direct information on the CKM matrix

$\bar{B}_d^0 \to J/\Psi\, K_S^0$

$\phi \simeq \beta$



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

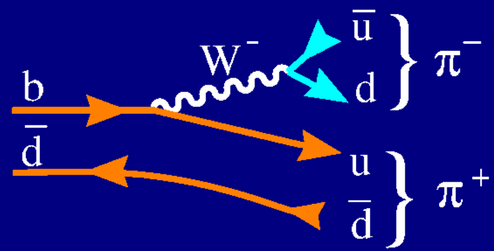


$V_{tb}\, V_{ts}^* \sim -A\lambda^2$

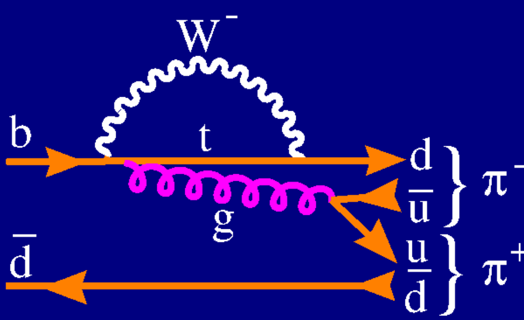
***

$\bar{B}_d^0 \to \pi^+\pi^-$

$\phi \simeq \beta + \gamma = \pi - \alpha$



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

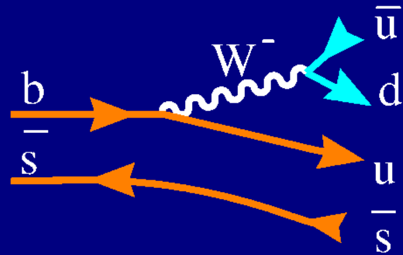


$V_{tb}\, V_{td}^* \sim A\lambda^3(1 - \rho + i\eta)$

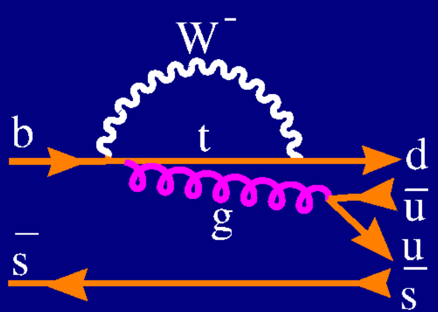
**

$\bar{B}_s^0 \to \rho^0 K_S^0$

$\phi \neq \gamma$



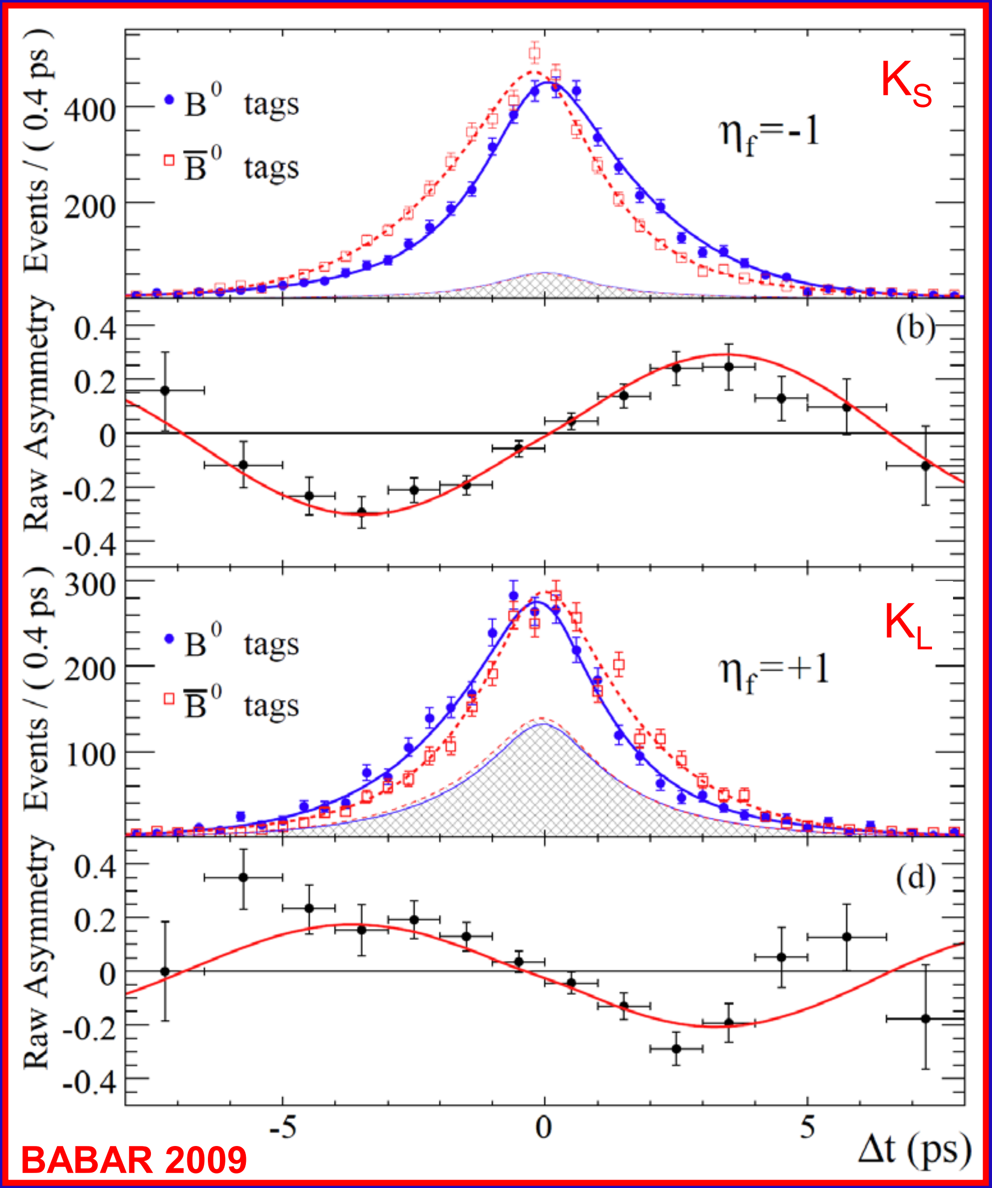
$V_{ub}\, V_{ud}^* \sim A\lambda^3(\rho - i\eta)$



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

BAD

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



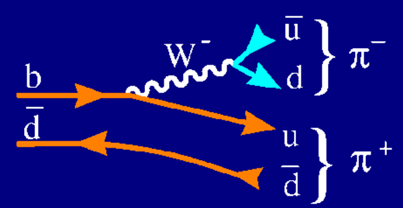
$\cancel{CP}$ Signal

HFAG: $J/\psi\, K_{S,L}\, ,\, \psi(2S)\, K_S\, ,\, \chi_c\, K_S\, ,\, \eta_c\, K_S$

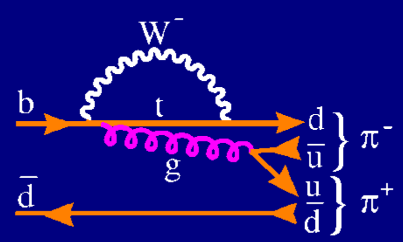
$\sin(2\beta) = 0.672 \pm 0.023$

$B^0 \to \pi\pi$

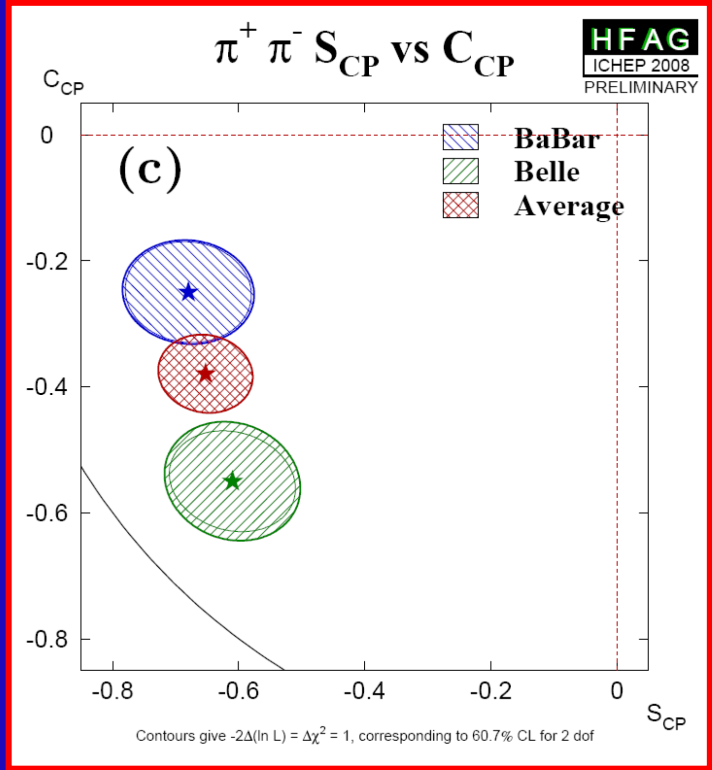
$$\frac{\Gamma\left(B^0 \to \mathrm{f}\right) - \Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right)}{\Gamma\left(B^0 \to \mathrm{f}\right) + \Gamma\left(\bar{B}^0 \to \bar{\mathrm{f}}\right)} = C_f \, \cos(\Delta M\, t) - S_f \, \sin(\Delta M\, t)$$



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



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



$$C_\mathrm{f} \equiv \frac{1 - |\bar{\rho}_\mathrm{f}|^2}{1 + |\bar{\rho}_\mathrm{f}|^2} \neq 0$$

Direct $\not{C}\!\!\not{P}$

Penguins

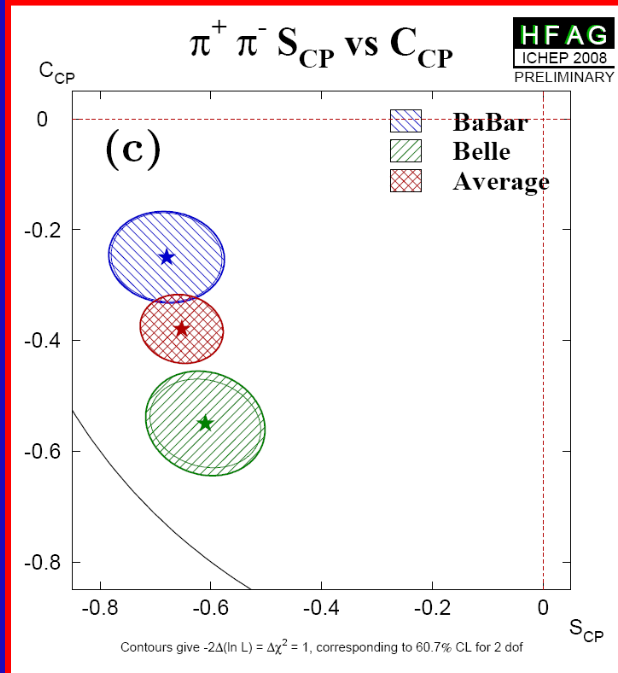
$$S_f \approx -\sin(2\alpha) \quad ?$$

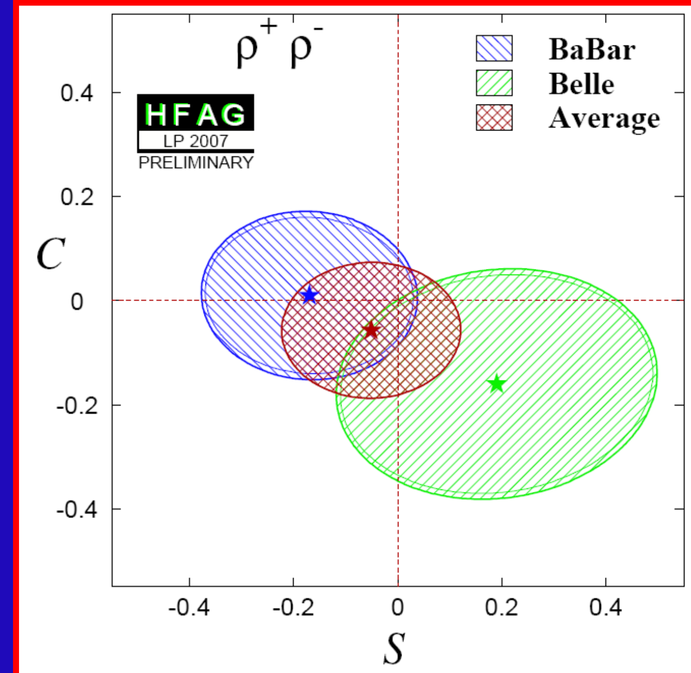
$B^0 \to \pi\pi, \rho\rho, \rho\pi$

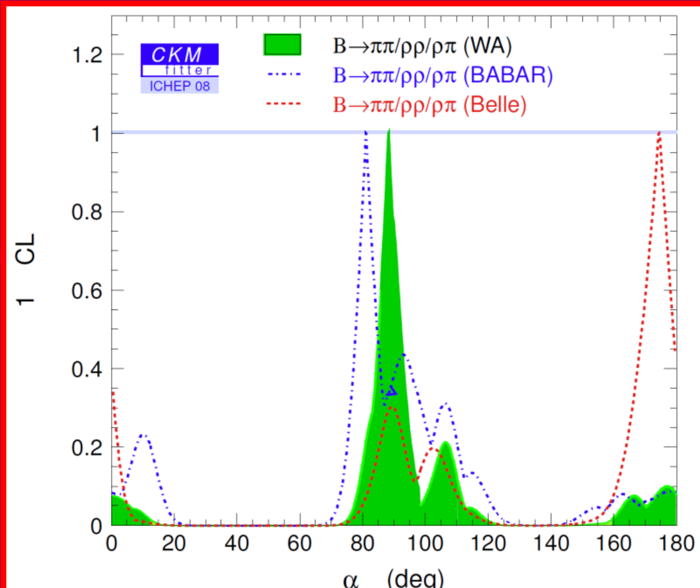
$$C_f \equiv \frac{1-|\bar\rho_f|^2}{1+|\bar\rho_f|^2} \neq 0$$

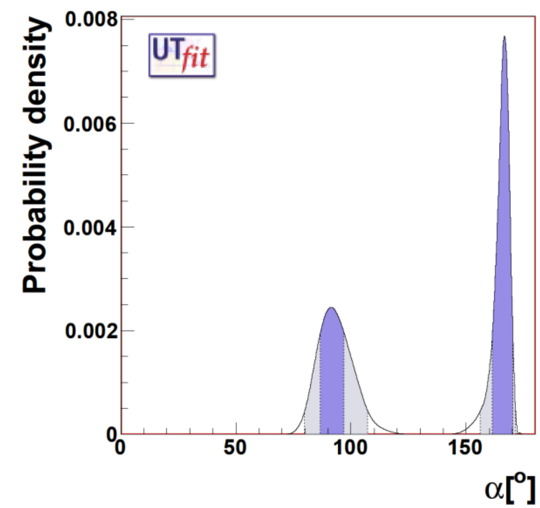
Direct $\not{C}\!\!\not{P}$

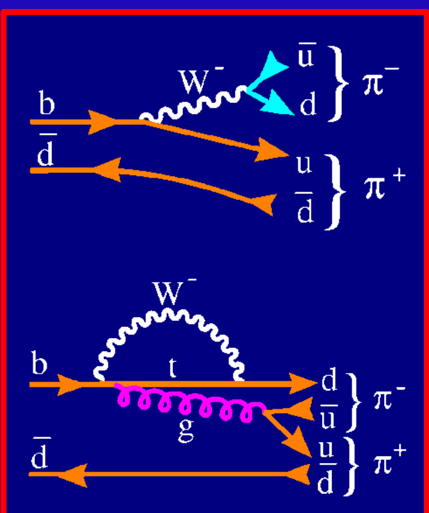
Penguins











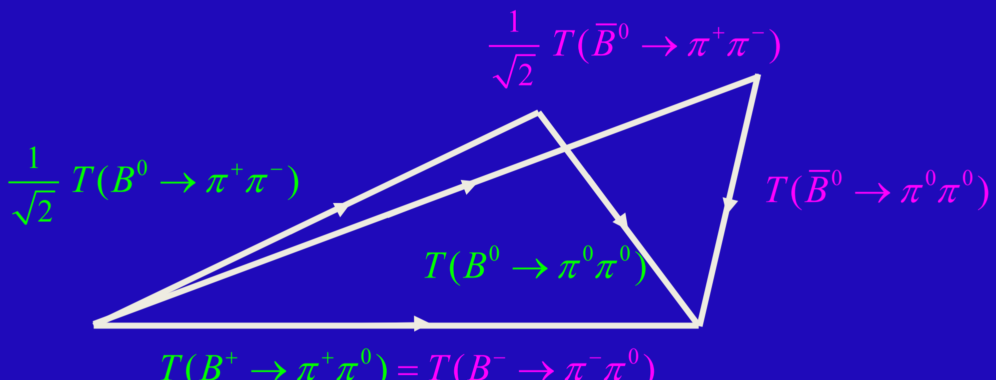
MEASURING HADRONIC CONTAMINATIONS

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

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

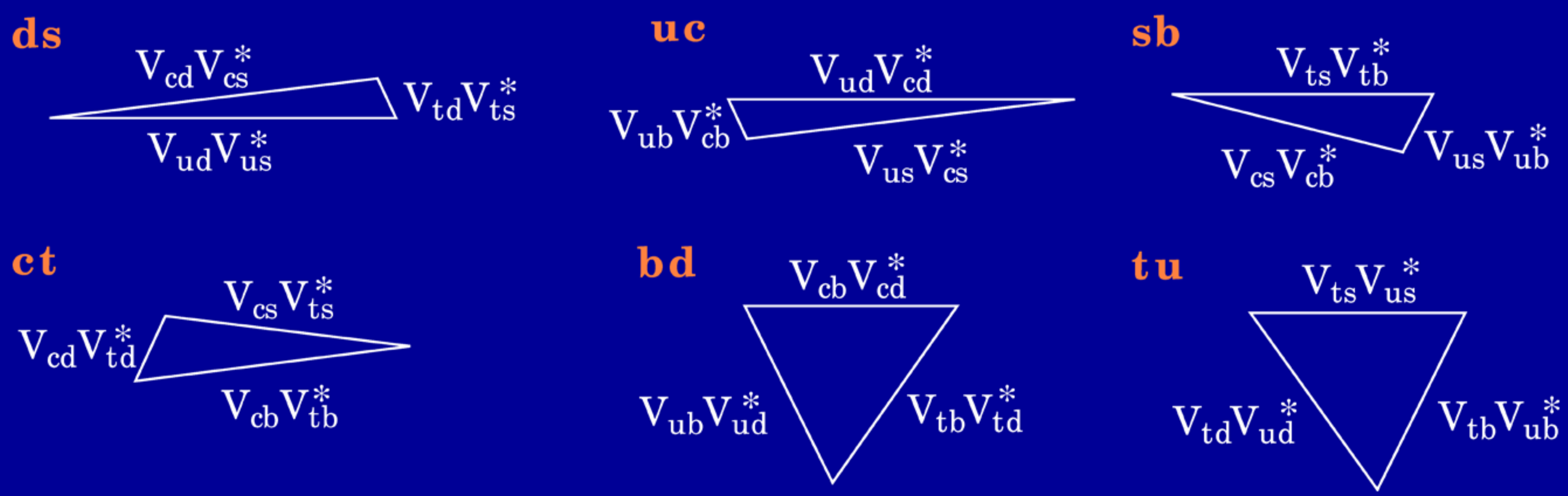
$$\sqrt{2}\,\mathrm{T}(B^0_d \to D^0_+ K_S) = \mathrm{T}(B^+ \to D^0 K_S) + \mathrm{T}(B^+ \to \bar{D}^0 K_S)$$

- Dalitz Analysis
- SU(3) Relations: B → π K , π π , ...
- ...



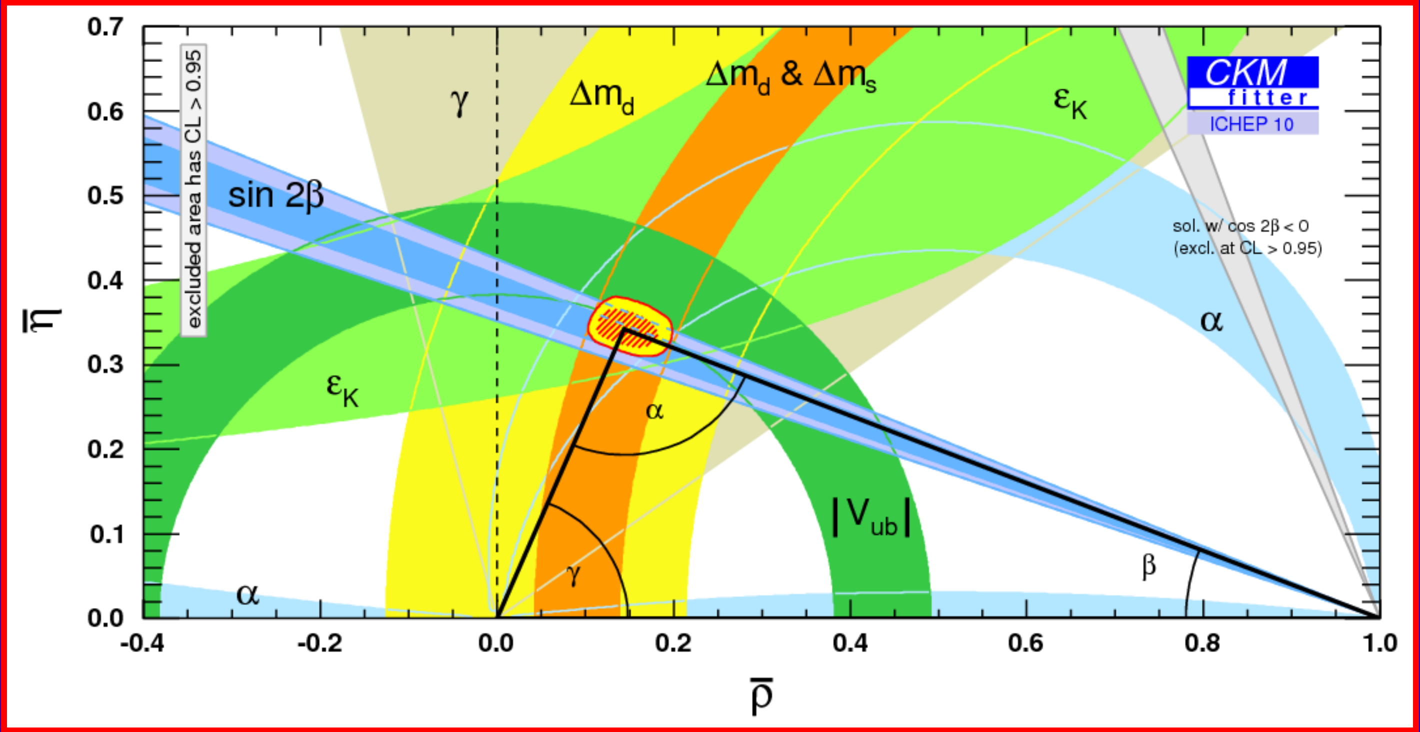
UNITARITY TRIANGLES

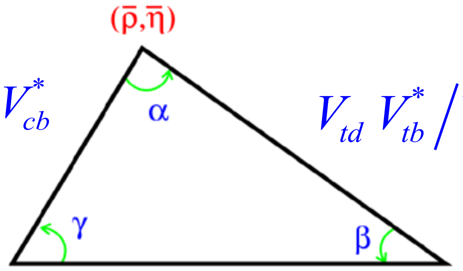
$$V_{ui}\, V_{uj}^* + V_{ci}\, V_{cj}^* + V_{ti}\, V_{tj}^* = 0 \qquad (i \neq j)$$



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

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





$V_{ud}\,V_{ub}^{*}\,/\,V_{cd}\,V_{cb}^{*}$

$V_{td}\,V_{tb}^{*}\,/\,V_{cd}\,V_{cb}^{*}$

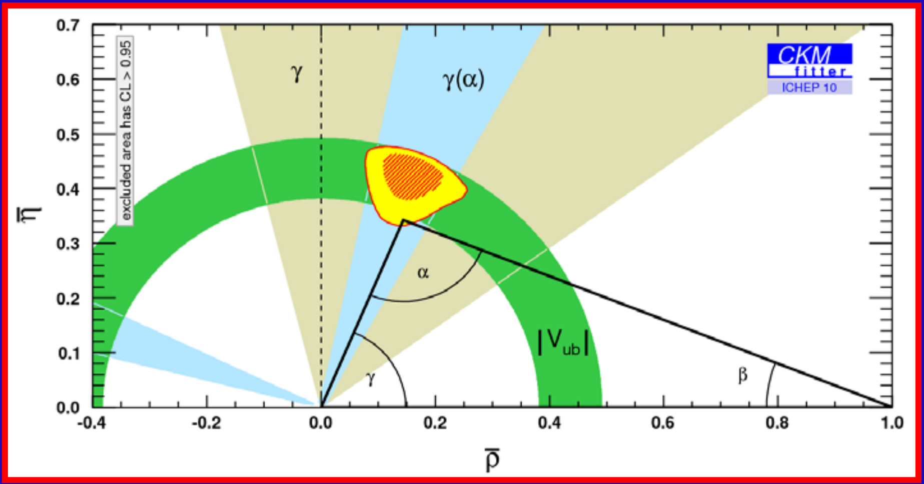
UT$_{fit}$

$$\bar{\eta} \equiv \eta\left(1-\frac{1}{2}\lambda^2\right) = 0.358\pm0.012$$

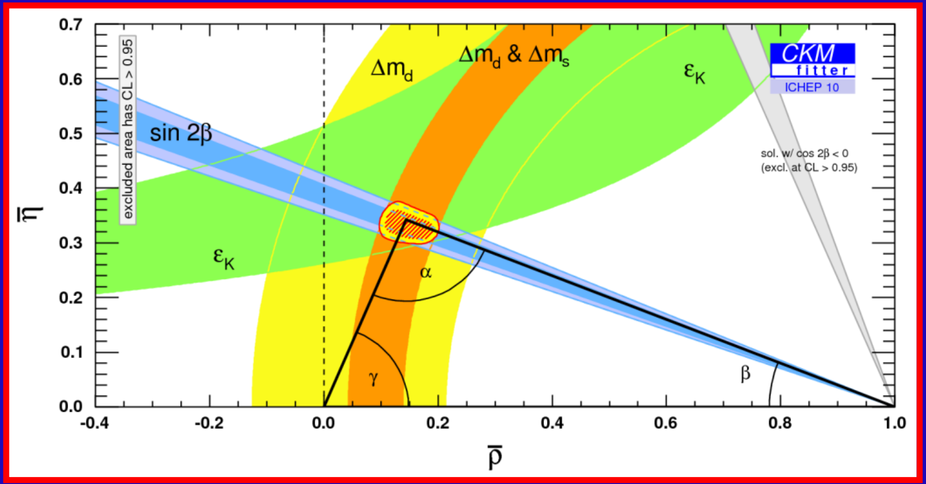
$$\bar{\rho} \equiv \rho\left(1-\frac{1}{2}\lambda^2\right) = 0.135\pm0.021$$

$$\alpha = 87.8\pm3.0^\circ\ ;\ \beta = 22.4\pm0.7^\circ\ ;\ \gamma = 69.8\pm3.0^\circ$$

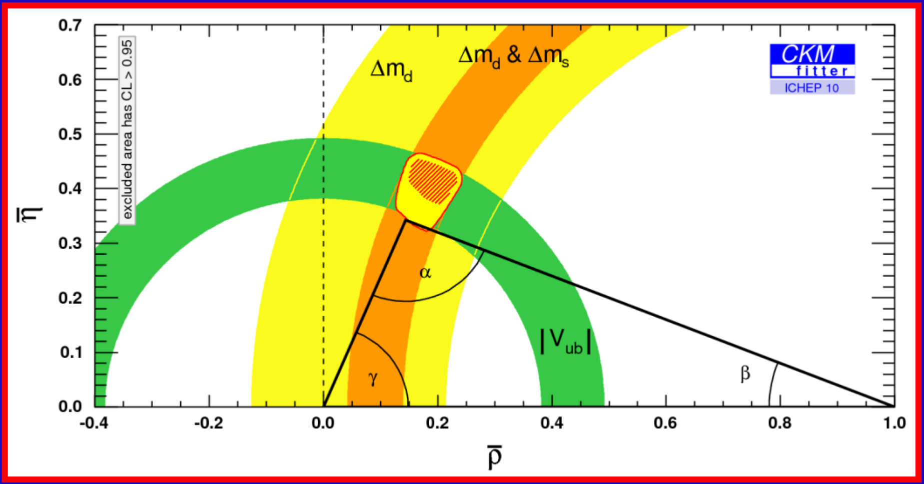
Tree-level determinations



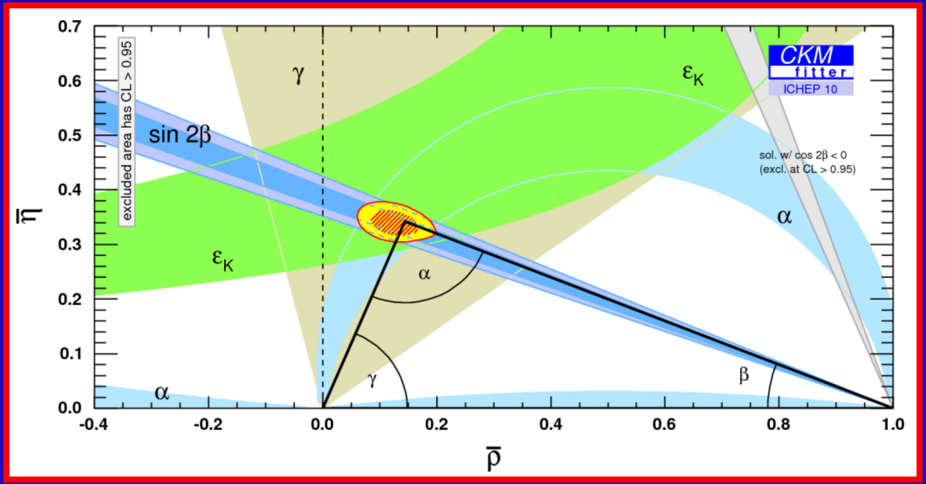
Loop processes



CP Conserving



CP Violating



DIRECT $\not{CP}$ 7.5 σ signal

$$A(B_d^0 \to \pi^\mp K^\pm) \equiv \frac{\mathrm{Br}(B_d^0 \to \pi^- K^+) - \mathrm{Br}(\overline{B}_d^0 \to \pi^+ K^-)}{\mathrm{Br}(B_d^0 \to \pi^- K^+) + \mathrm{Br}(\overline{B}_d^0 \to \pi^+ K^-)} = 0.098 \pm 0.013$$

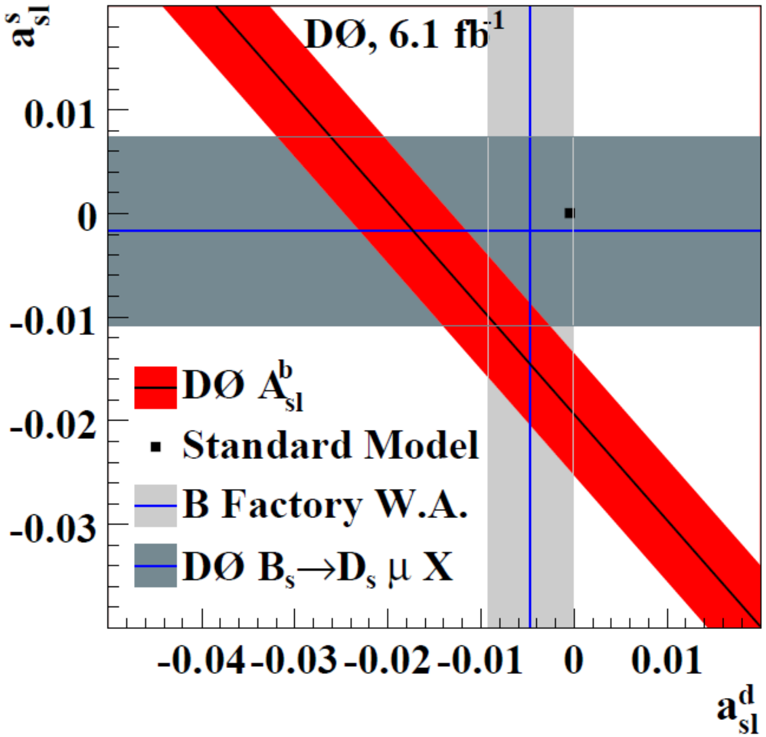
$$A(B^\pm \to \pi^0 K^\pm) \equiv \frac{\mathrm{Br}(B^+ \to \pi^0 K^+) - \mathrm{Br}(B^- \to \pi^0 K^-)}{\mathrm{Br}(B^+ \to \pi^0 K^+) + \mathrm{Br}(B^- \to \pi^0 K^-)} = -0.051 \pm 0.025$$

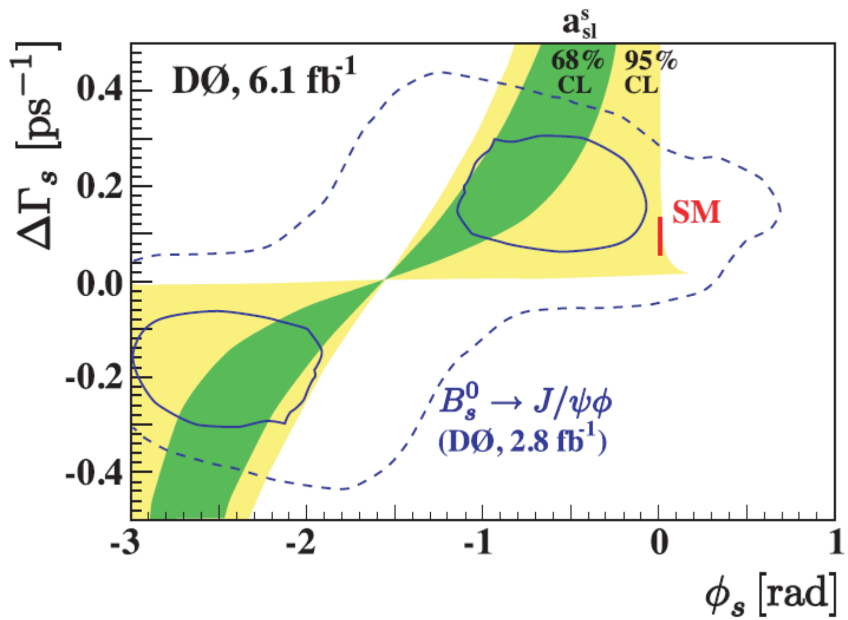
$$A(B_d^0 \to \pi^\mp K^\pm) - A(B^\pm \to \pi^0 K^\pm) = 0.149 \pm 0.028$$

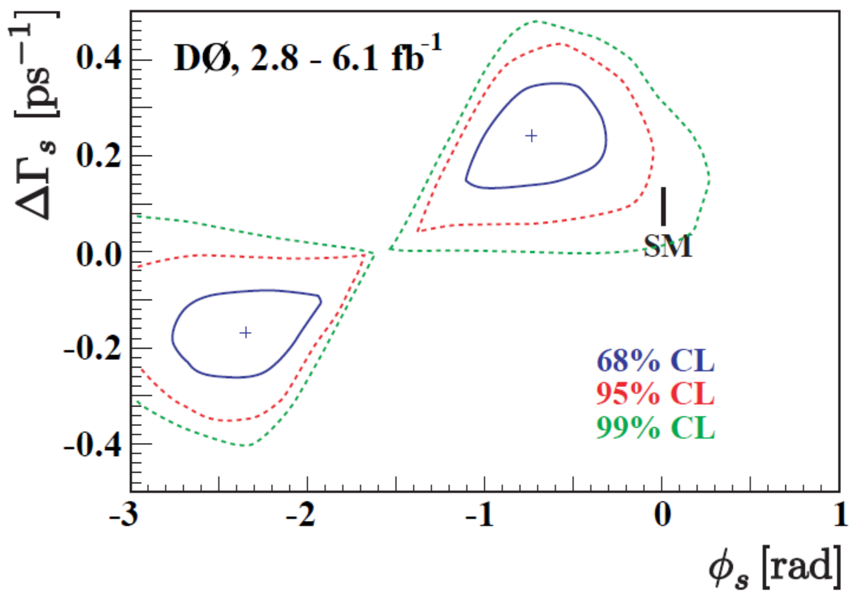
Difficult to accommodate in the Standard Model (but huge uncertainties)

New Physics ?

D0: $\mu^\pm\mu^\pm$ Asymmetry



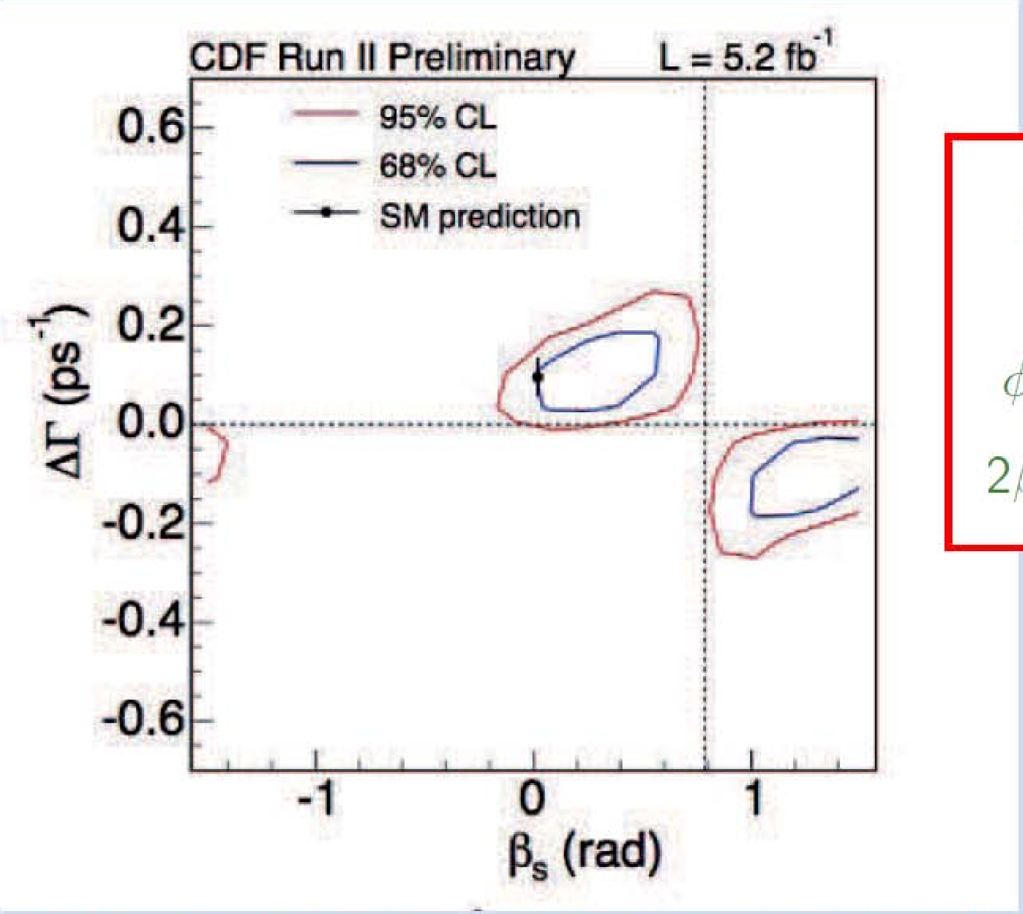




$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

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

New CDF measurement of β_s



$B_s^0 \to J/\psi\,\phi$

$\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$

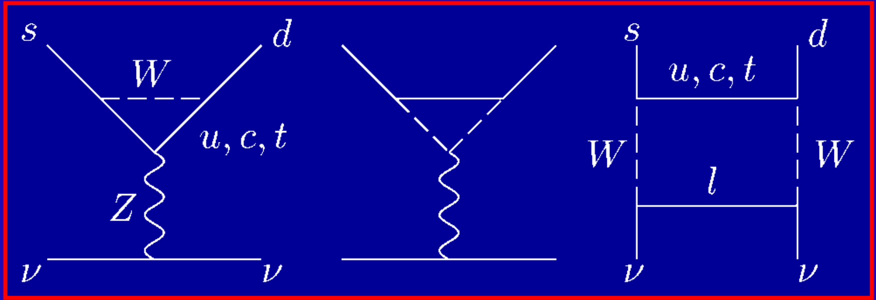
$2\beta_s = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$

Coverage adjusted 2D likelihood contours for β_s and $\Delta\Gamma$

P-value for SM point: 44%
(0.8σ deviation)

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

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



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

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

Buras et al

Long-distance contributions are negligible

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

- **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:** $\mathrm{Br}\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 6.7 \times 10^{-8}$ (90% C.L.)

New Experiments Needed: NA62, J-Parc, …

Standard Model Mechanism of $\cancel{CP}$

Complex phases in Yukawa couplings only:

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

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

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

$c^{(q)}_{jk}$ diagonalization

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

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W^\dagger_\mu \sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \text{h.c.}$$

The CKM matrix $\mathbf{V}_{ij}$ is the only source of $\cancel{CP}$

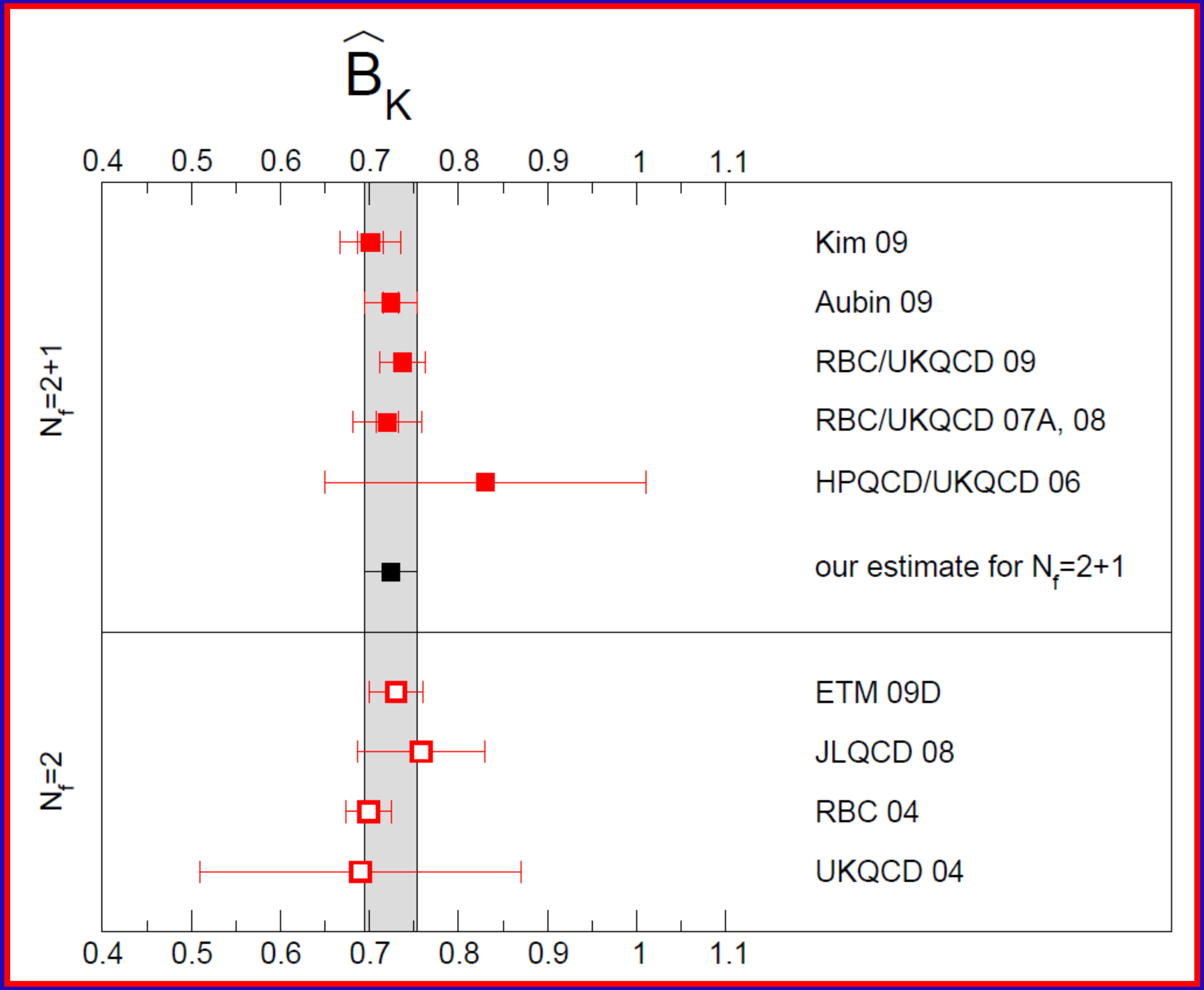
SUMMARY

- 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, Super-B, …

Quarks Leptons Bosons

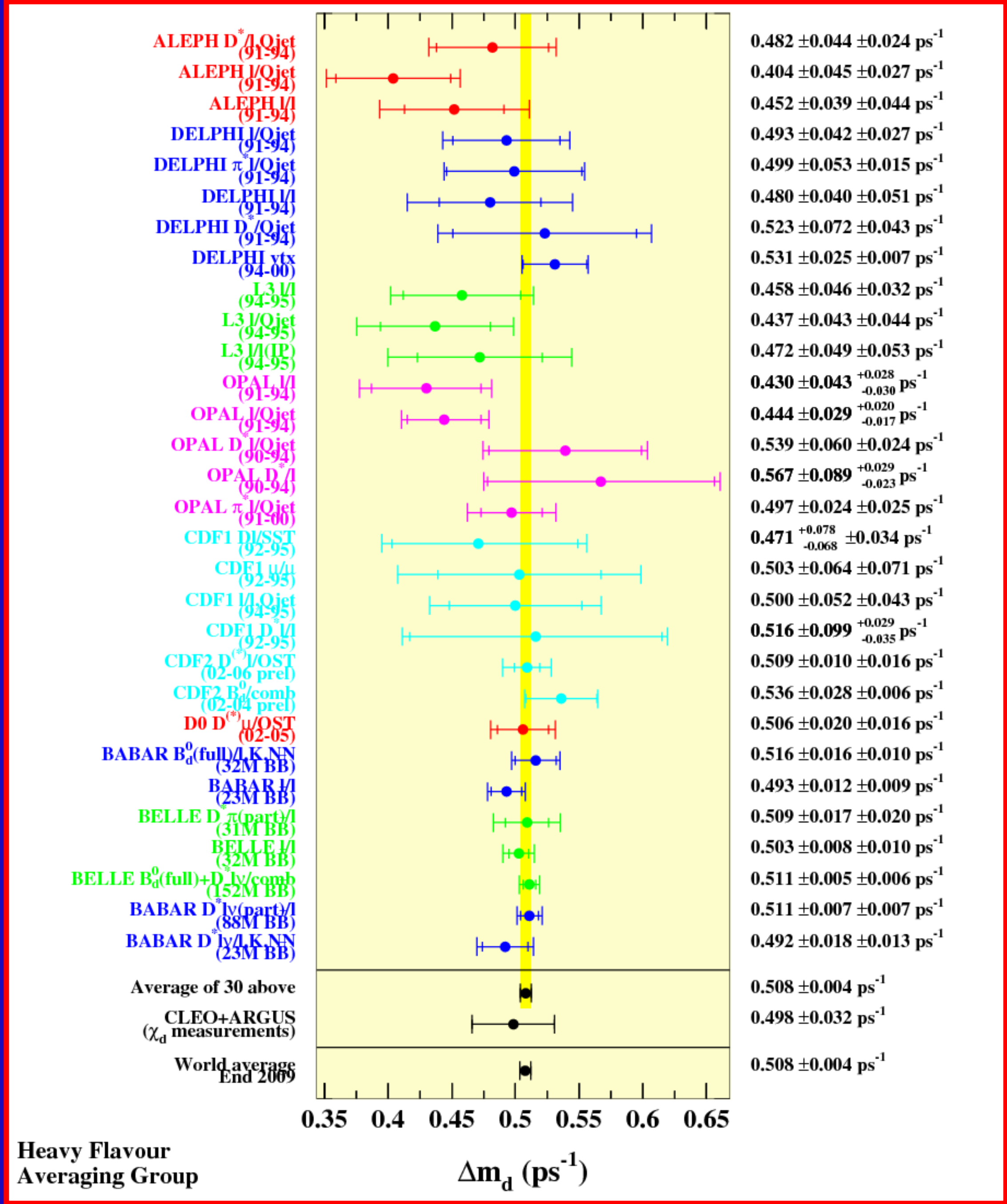
Lattice Results for $\hat{B}_K$



Flavianet Lattice Averaging Group

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

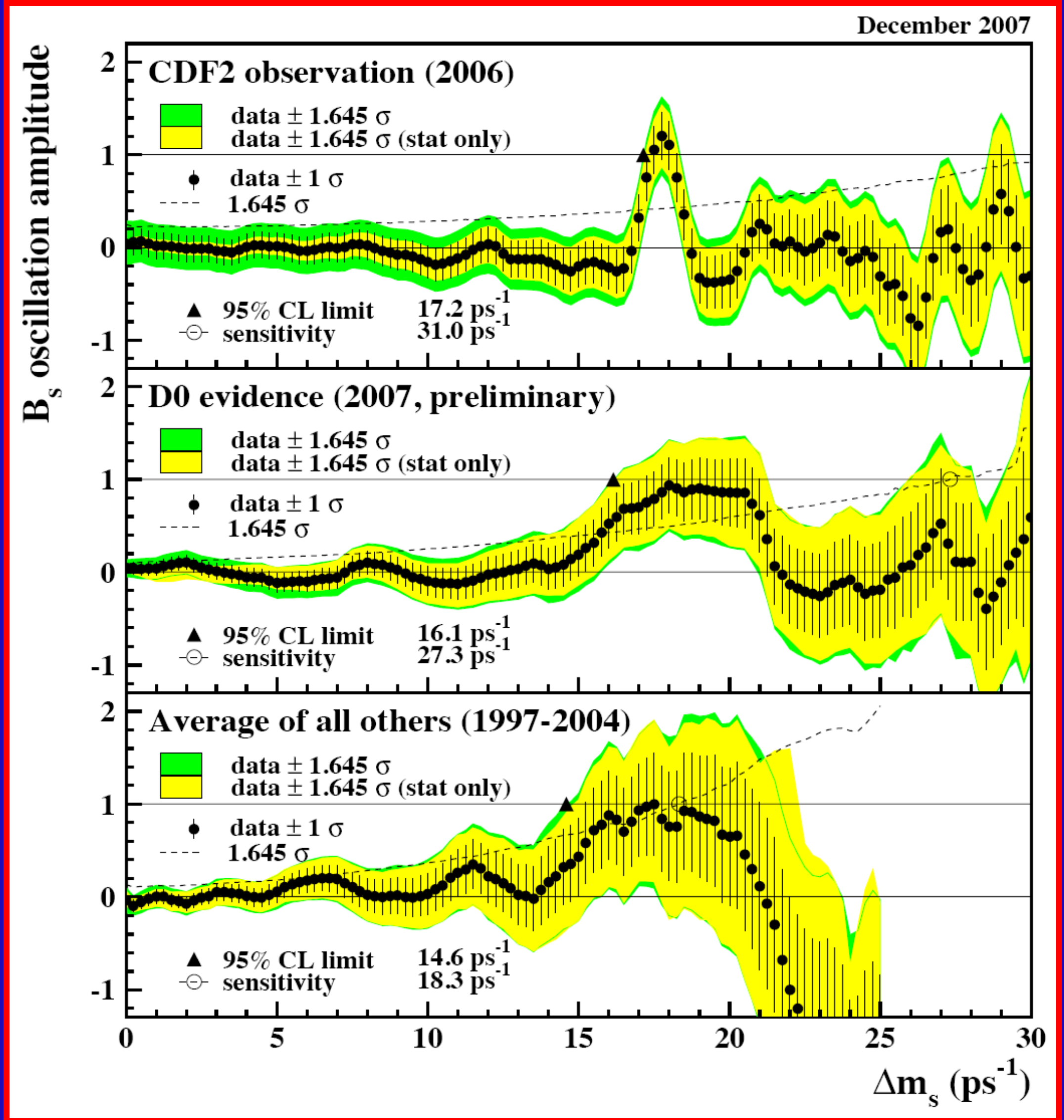
$$\Delta M_{B_d^0} = (0.508 \pm 0.004)\ \mathrm{ps}^{-1}$$



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

$$\Delta M_{B_s^0} = (17.77 \pm 0.10 \pm 0.07)\ \mathrm{ps}^{-1}$$

$$P(t) \;=\; \frac{1}{2}\Gamma_s\, e^{-\Gamma_s t}\left[1 + \cos\left(\Delta M_s t\right)\right]$$



Fit to function:

$$P(t) \;=\; \frac{1}{2}\Gamma_s\, e^{-\Gamma_s t}\left[1 + A\cos\left(\quad t\right)\right]$$

$B^0 \to \rho^+ \rho^-$

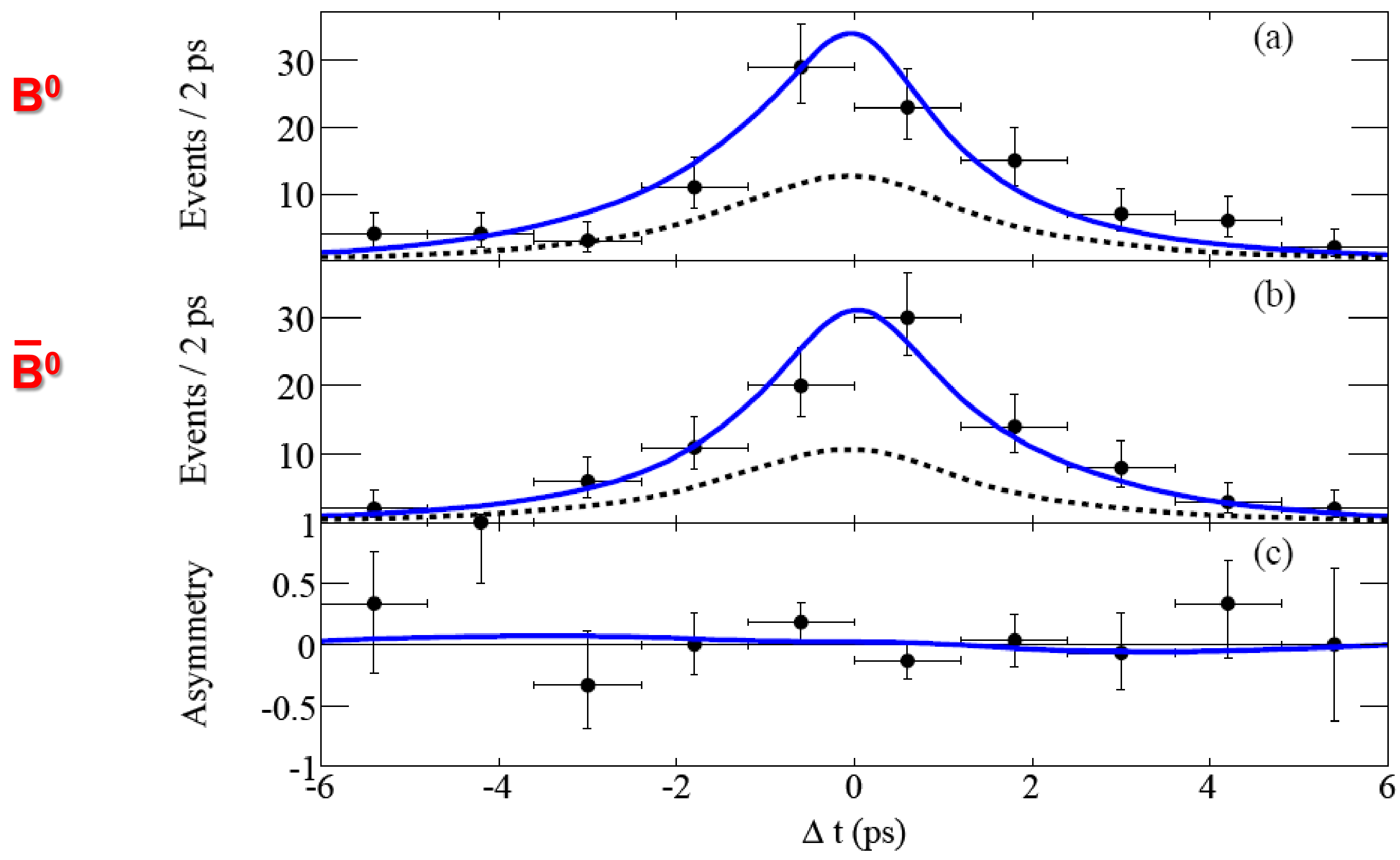
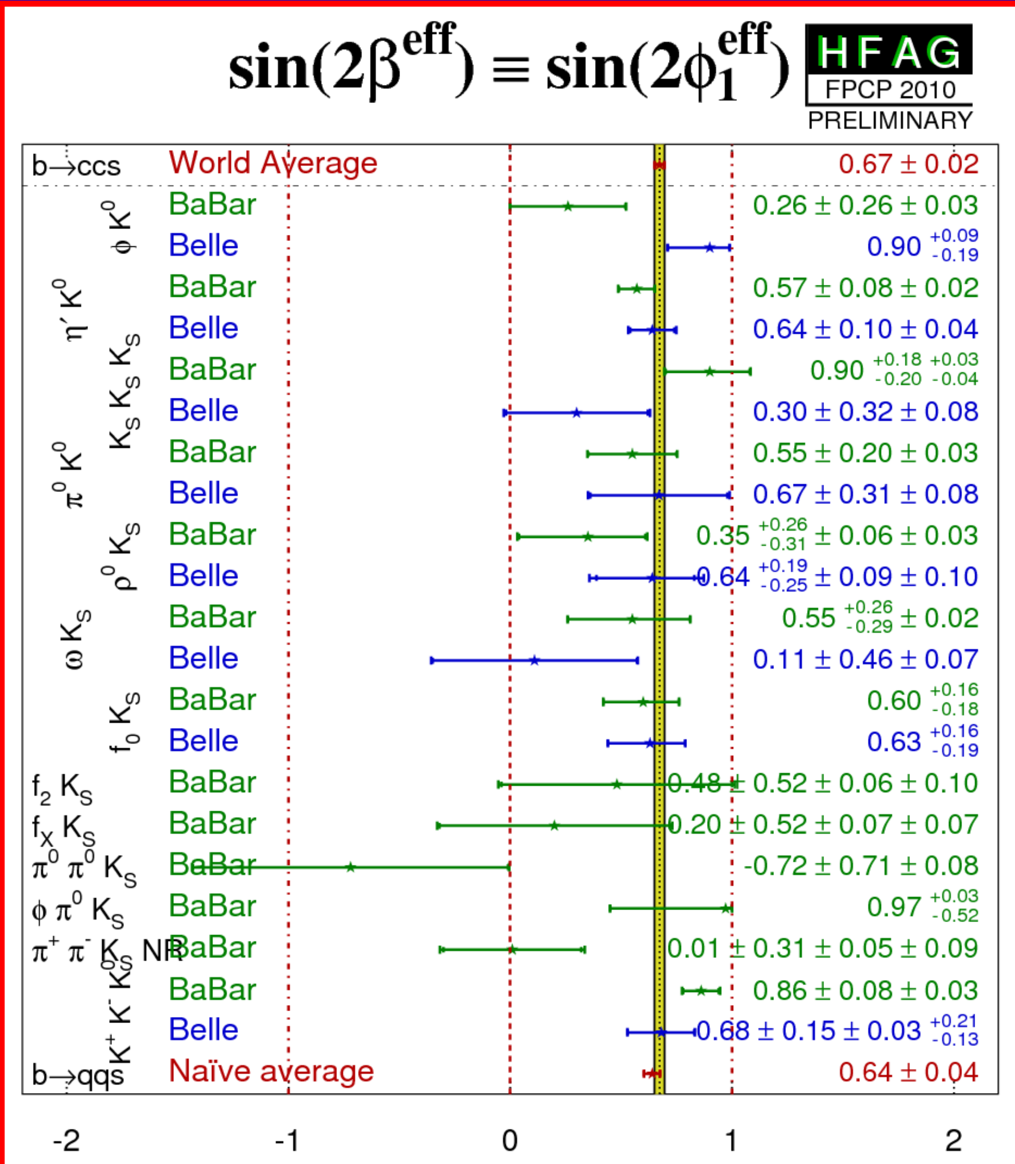
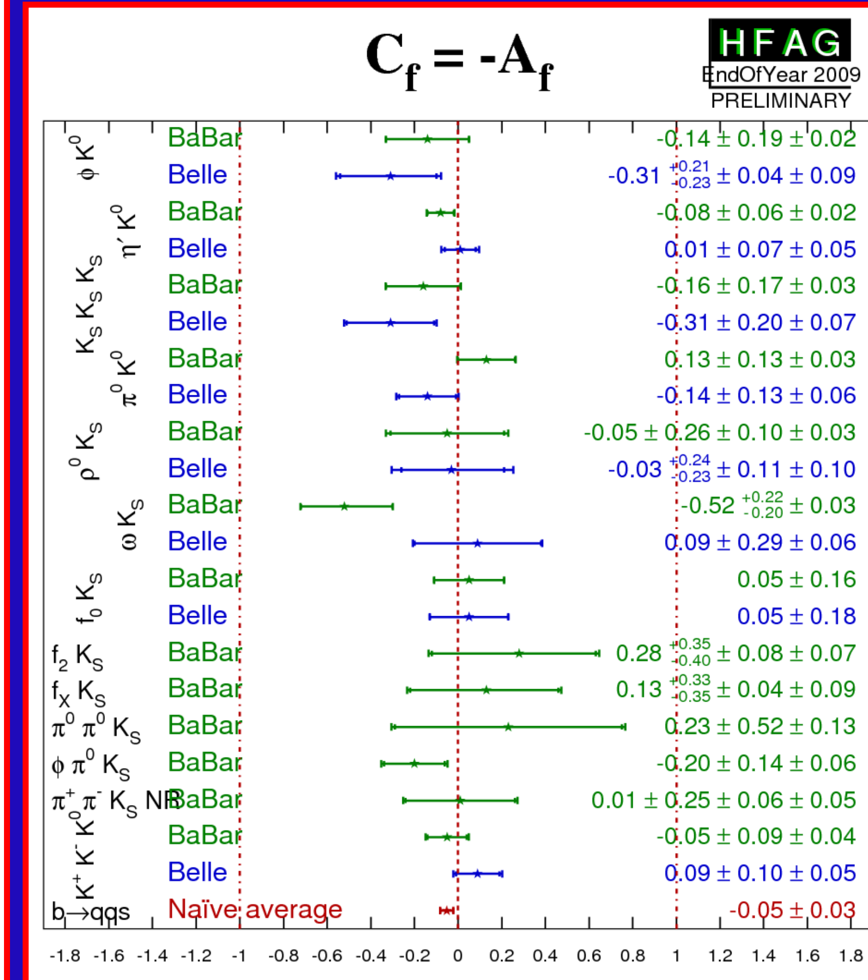


Fig. 86. Decay time distributions from *BABAR* [1110]. *(a)* $\overline{B}^0 \to \rho^+\rho^-$ decays *(b)* $B^0 \to \rho^+\rho^-$ decays, and *(c)* the asymmetry $(\overline{N} - N)/(\overline{N} + N)$, where $\overline{N}$ (N) is the number of signal $\overline{B}^0 \to \rho^+\rho^-$ $(B^0 \to \rho^+\rho^-)$ decays. The dashed curve shows the fit result for all backgrounds, and the solid curve shows the fit result for the total.

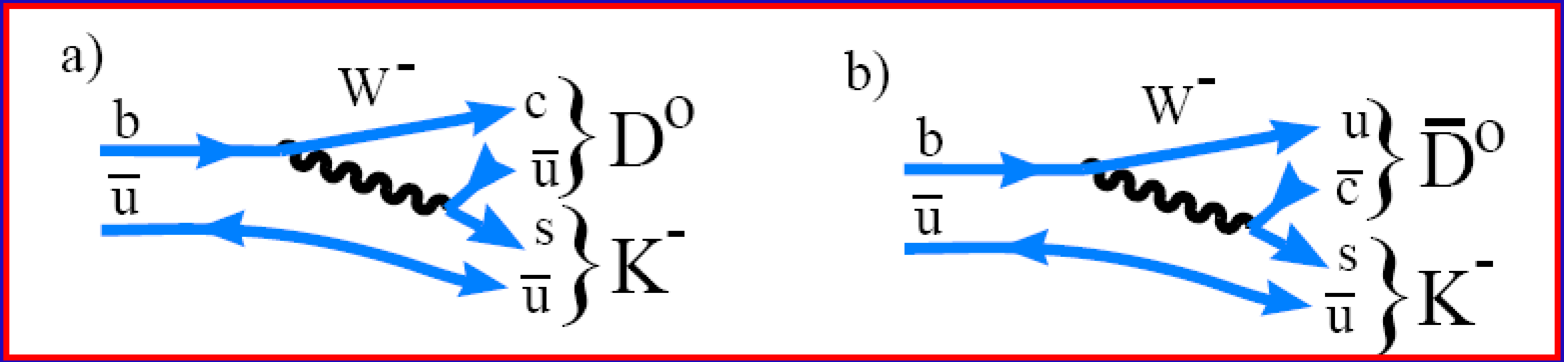
b → ccs

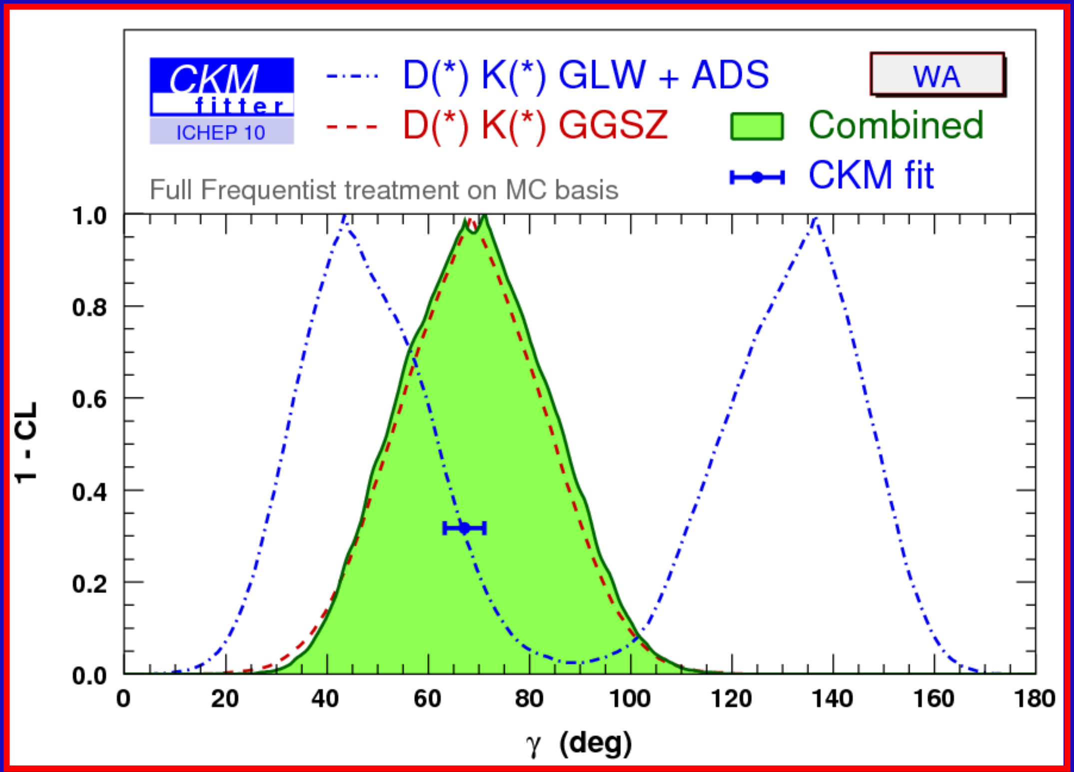


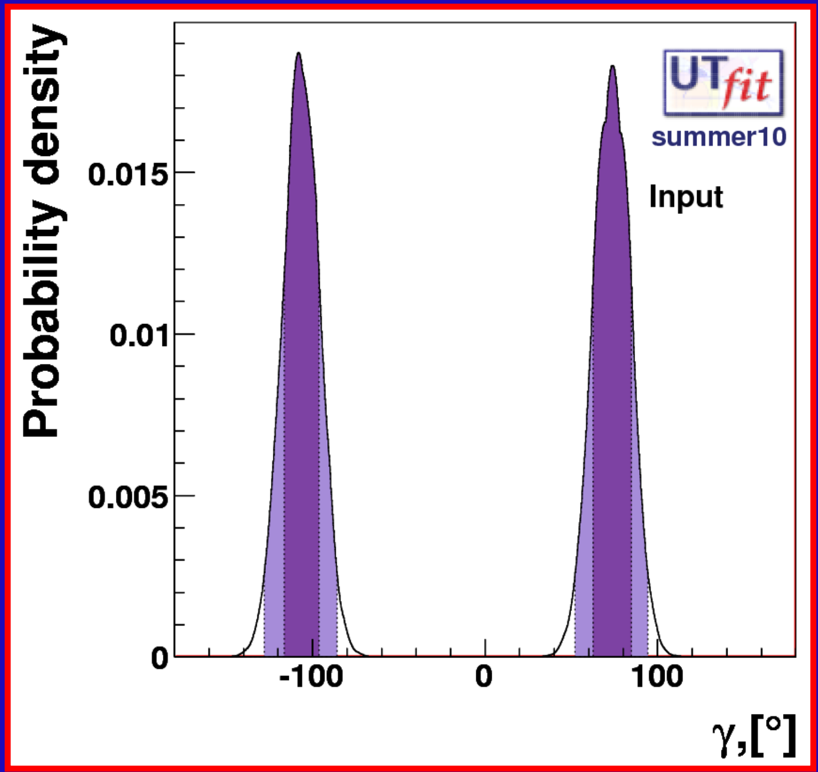
$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$
HFAG
FPCP 2010
PRELIMINARY
b→ccs World Average 0.67 ± 0.02
ϕK^0 BaBar 0.26 ± 0.26 ± 0.03
Belle 0.90 $^{+0.09}_{-0.19}$
$\eta' K^0$ BaBar 0.57 ± 0.08 ± 0.02
Belle 0.64 ± 0.10 ± 0.04
$K_S K_S K_S$ BaBar 0.90 $^{+0.18}_{-0.20}$ $^{+0.03}_{-0.04}$
Belle 0.30 ± 0.32 ± 0.08
$\pi^0 K^0$ BaBar 0.55 ± 0.20 ± 0.03
Belle 0.67 ± 0.31 ± 0.08
$\rho^0 K_S$ BaBar 0.35 $^{+0.26}_{-0.31}$ ± 0.06 ± 0.03
Belle 0.64 $^{+0.19}_{-0.25}$ ± 0.09 ± 0.10
ωK_S BaBar 0.55 $^{+0.26}_{-0.29}$ ± 0.02
Belle 0.11 ± 0.46 ± 0.07
$f_0 K_S$ BaBar 0.60 $^{+0.16}_{-0.18}$
Belle 0.63 $^{+0.16}_{-0.19}$
$f_2 K_S$ BaBar 0.48 ± 0.52 ± 0.06 ± 0.10
$f_X K_S$ BaBar 0.20 ± 0.52 ± 0.07 ± 0.07
$\pi^0 \pi^0 K_S$ BaBar -0.72 ± 0.71 ± 0.08
$\phi \pi^0 K_S$ BaBar 0.97 $^{+0.03}_{-0.52}$
$\pi^+ \pi^- K_S$ NR BaBar 0.01 ± 0.31 ± 0.05 ± 0.09
$K^+ K^- K^0$ BaBar 0.86 ± 0.08 ± 0.03
Belle 0.68 ± 0.15 ± 0.03 $^{+0.21}_{-0.13}$
b→qqs Naïve average 0.64 ± 0.04
-2 -1 0 1 2



$C_f = -A_f$
HFAG
EndOfYear 2009
PRELIMINARY
ϕK^0 BaBar -0.14 ± 0.19 ± 0.02
Belle -0.31 $^{+0.21}_{-0.23}$ ± 0.04 ± 0.09
$\eta' K^0$ BaBar -0.08 ± 0.06 ± 0.02
Belle 0.01 ± 0.07 ± 0.05
$K_S K_S K_S$ BaBar -0.16 ± 0.17 ± 0.03
Belle -0.31 ± 0.20 ± 0.07
$\pi^0 K^0$ BaBar 0.13 ± 0.13 ± 0.03
Belle -0.14 ± 0.13 ± 0.06
$\rho^0 K_S$ BaBar -0.05 ± 0.26 ± 0.10 ± 0.03
Belle -0.03 $^{+0.24}_{-0.23}$ ± 0.11 ± 0.10
ωK_S BaBar -0.52 $^{+0.22}_{-0.20}$ ± 0.03
Belle 0.09 ± 0.29 ± 0.06
$f_0 K_S$ BaBar 0.05 ± 0.16
Belle 0.05 ± 0.18
$f_2 K_S$ BaBar 0.28 $^{+0.35}_{-0.40}$ ± 0.08 ± 0.07
$f_X K_S$ BaBar 0.13 $^{+0.33}_{-0.35}$ ± 0.04 ± 0.09
$\pi^0 \pi^0 K_S$ BaBar 0.23 ± 0.52 ± 0.13
$\phi \pi^0 K_S$ BaBar -0.20 ± 0.14 ± 0.06
$\pi^+ \pi^- K_S$ NR BaBar 0.01 ± 0.25 ± 0.06 ± 0.05
$K^+ K^- K^0$ BaBar -0.05 ± 0.09 ± 0.04
Belle 0.09 ± 0.10 ± 0.05
b→qqs Naïve average -0.05 ± 0.03
-1.8 -1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8


a)
b
$\bar{u}$
W^-
c
$\bar{u}$
D^0
s
$\bar{u}$
K^-
b)
b
$\bar{u}$
W^-
u
$\bar{c}$
$\bar{D}^0$
s
$\bar{u}$
K^-


CKM fitter
ICHEP 10
D(*) K(*) GLW + ADS
D(*) K(*) GGSZ
WA
Combined
CKM fit
Full Frequentist treatment on MC basis
1 - CL
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
160
180
γ (deg)


Probability density
UTfit
summer10
Input
0.015
0.01
0.005
0
-100
0
100
γ,[°]