

Flavour Physics & CP

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

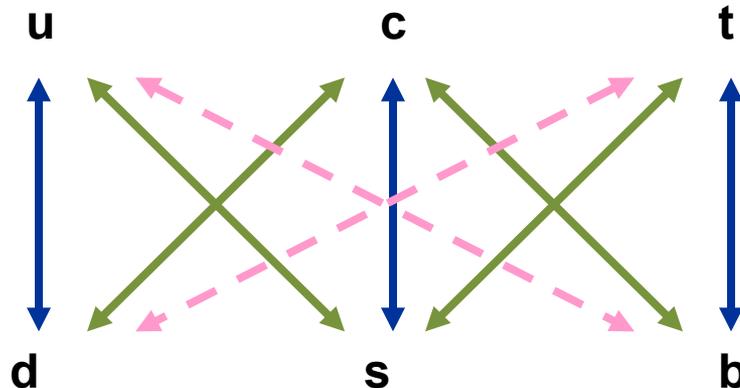
2019 CERN Latin-American School of High-Energy Physics (CLASHEP2019)
Villa General Belgrano, Córdoba, Argentina, 13-26 March 2019



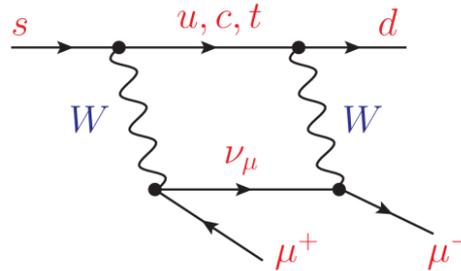
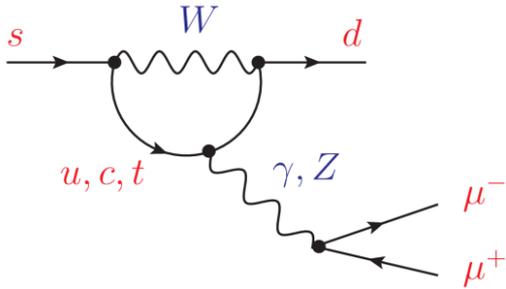
Hierarchical Structure

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

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



GIM Mechanism



$$\mathcal{M} \propto \sum_{i=u,c,t} V_{is} V_{id}^* F(m_i^2/M_W^2)$$

$$\sum_{i=u,c,t} V_{is} V_{id}^* = 0 \quad \longrightarrow \quad \mathcal{M} = 0 \quad \text{if} \quad m_u = m_c = m_t$$

$$\tilde{F}(x) \equiv F(x) - F(0)$$



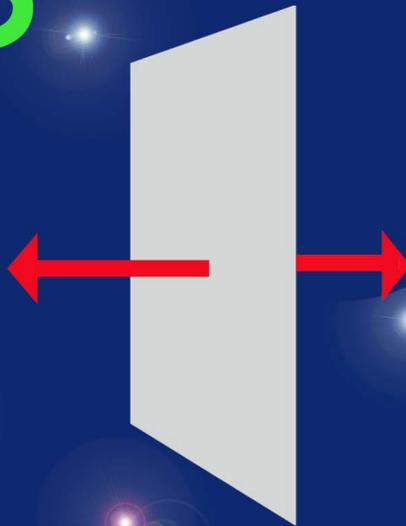
$$\begin{aligned} \mathcal{M} &\propto V_{cs} V_{cd}^* \tilde{F}(m_c^2/M_W^2) + V_{ts} V_{td}^* \tilde{F}(m_t^2/M_W^2) \\ &\approx -\lambda \tilde{F}(m_c^2/M_W^2) - \lambda^5 A^2 (1 - \rho + i\eta) \tilde{F}(m_t^2/M_W^2) \end{aligned}$$

- **Top contribution dominates. Strong suppression:** $\mathcal{M} \propto \frac{g^4}{16\pi^2} \left[\lambda^5 A^2 \frac{m_t^2}{M_W^2}, \lambda \frac{m_c^2}{M_W^2} \right]$
- **CP effects fully governed by top contribution** $\left[\text{Im}(V_{cs} V_{cd}^*) = -\text{Im}(V_{ts} V_{td}^*) \right]$

C



P



- \mathcal{C}, \mathcal{P} : Violated maximally in weak interactions
- \mathcal{CP} : Symmetry of nearly all observed phenomena
- Slight ($\sim 0.2\%$) $\cancel{\mathcal{CP}}$ in K^0 decays (1964)
- Sizeable $\cancel{\mathcal{CP}}$ in B^0 decays (2001)
- Huge Matter–Antimatter Asymmetry in our Universe
 Baryogenesis
- Small $\cancel{\mathcal{CP}}$ in D^0 decays (LHCb, 21-3-2019)

\mathcal{CPT} Theorem: $\cancel{\mathcal{CP}} \longleftrightarrow \cancel{\mathcal{T}}$

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

- Complex Phases
- Interferences

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

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

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

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

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

- Low-Energy Phenomena

- Small Effects $\sim \mathbf{J}$

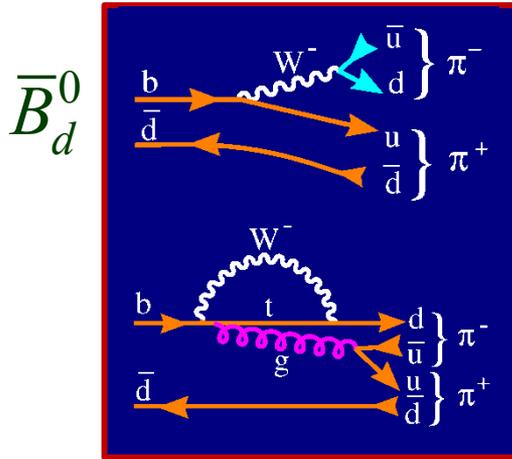
- Big Asymmetries \iff Suppressed Decays

- B Decays are an optimal place for \cancel{CP} signals

DIRECT

C/\mathcal{P}

$$|\mathbf{T}(P \rightarrow f)| \neq |\mathbf{T}(\bar{P} \rightarrow \bar{f})|$$



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

\downarrow $C\mathcal{P}$

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

$$A_{P \rightarrow f}^{\text{CP}} \equiv \frac{\Gamma(P \rightarrow f) - \Gamma(\bar{P} \rightarrow \bar{f})}{\Gamma(P \rightarrow f) + \Gamma(\bar{P} \rightarrow \bar{f})} = \frac{-2 T_1 T_2 \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1)}{T_1^2 + T_2^2 + 2 T_1 T_2 \cos(\phi_2 - \phi_1) \cos(\delta_2 - \delta_1)}$$

One needs:

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

DIRECT CP

$$A_{CP}(B \rightarrow f) \equiv \frac{\text{Br}(\bar{B} \rightarrow \bar{f}) - \text{Br}(B \rightarrow f)}{\text{Br}(\bar{B} \rightarrow \bar{f}) + \text{Br}(B \rightarrow f)}$$

$$A_{CP}(B_d^0 \rightarrow \pi^- K^+) = -0.084 \pm 0.004 \quad (21 \sigma)$$

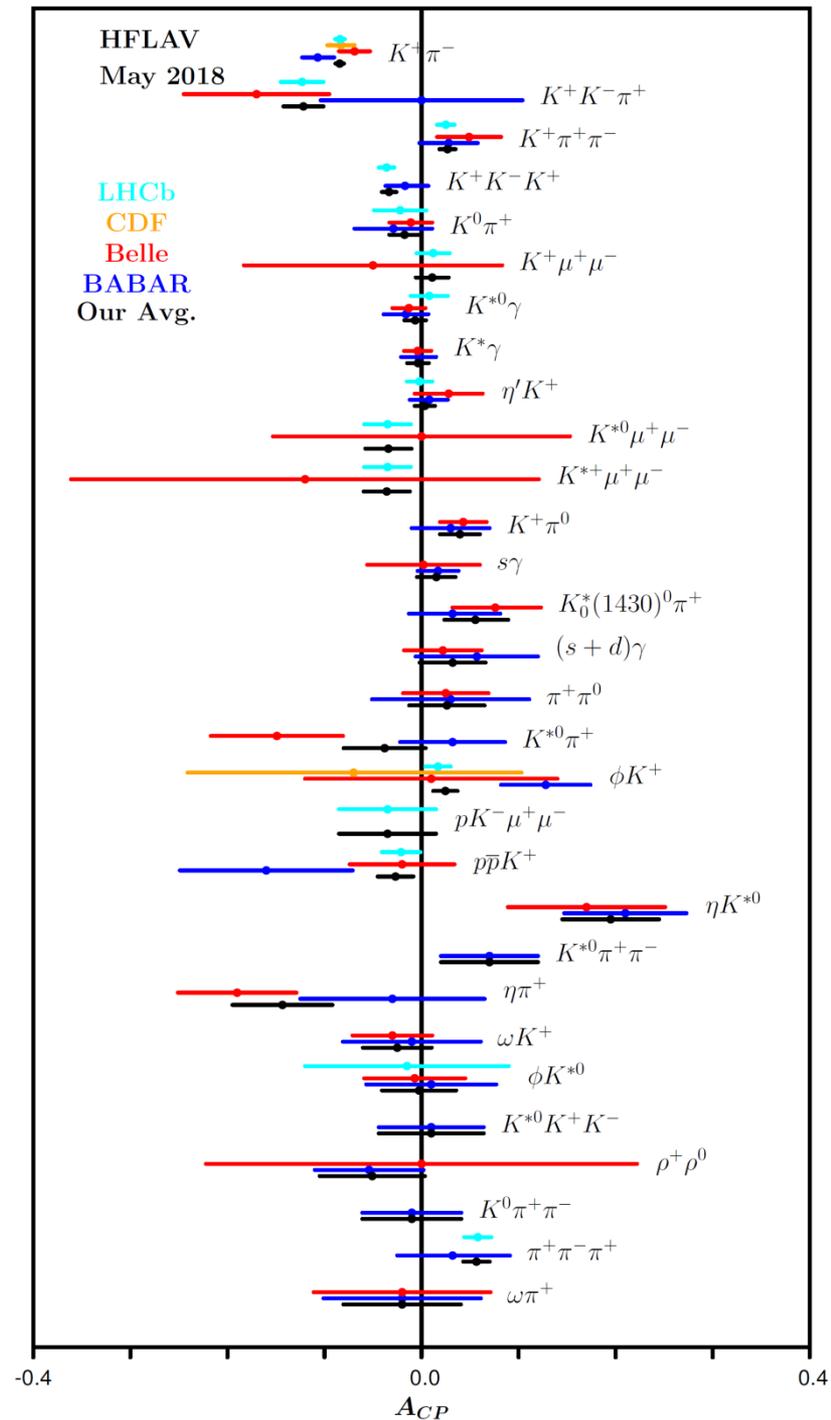
$$A(B_s^0 \rightarrow \pi^- K^+) = -0.213 \pm 0.017 \quad (12.5 \sigma)$$

$$A_{CP}(B^+ \rightarrow K^+ K^- \pi^+) = -0.122 \pm 0.021 \quad (5.8 \sigma)$$

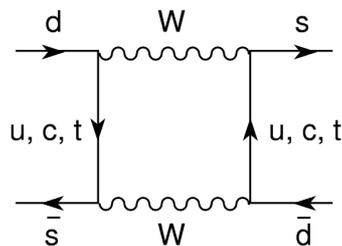
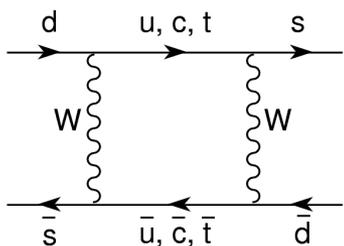
Large & Interesting Signals

Big challenge: Get reliable SM predictions

Severe hadronic uncertainties



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



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

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

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

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

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

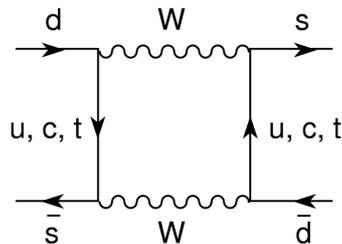
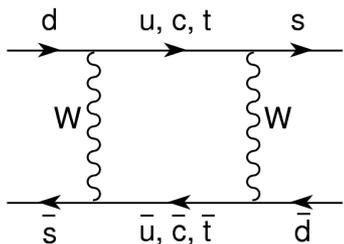
- **GIM Mechanism:** $\lambda_u + \lambda_c + \lambda_t = 0$

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

- \mathcal{CP} : $\text{Im} \lambda_t = -\text{Im} \lambda_c \simeq \eta \lambda^5 A^2$

- **Hard GIM Breaking:** $S(r_i, r_i) \sim r_i \rightarrow$ **t quark**

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



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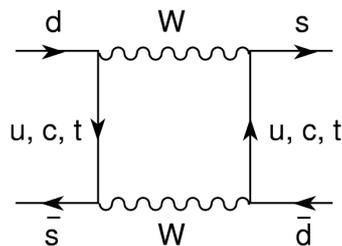
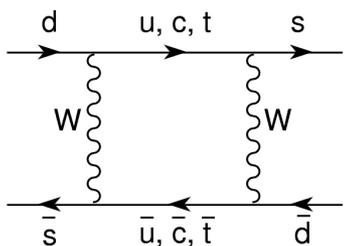
$$\lambda_i \equiv V_{id} V_{is}^* \quad ; \quad r_i \equiv m_i^2 / M_W^2 \quad (i = u, c, t)$$

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

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

$$|K_S^0\rangle \simeq |K_1^0\rangle + \bar{\epsilon}_K |K_2^0\rangle \quad , \quad |K_L^0\rangle \simeq |K_2^0\rangle + \bar{\epsilon}_K |K_1^0\rangle$$

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



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

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

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

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



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

$$\eta_{+-} \equiv \frac{T(K_L \rightarrow \pi^+ \pi^-)}{T(K_S \rightarrow \pi^+ \pi^-)} \approx \varepsilon_K$$

$$\eta_{00} \equiv \frac{T(K_L \rightarrow \pi^0 \pi^0)}{T(K_S \rightarrow \pi^0 \pi^0)} \approx \varepsilon_K$$

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

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



Buras et al

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

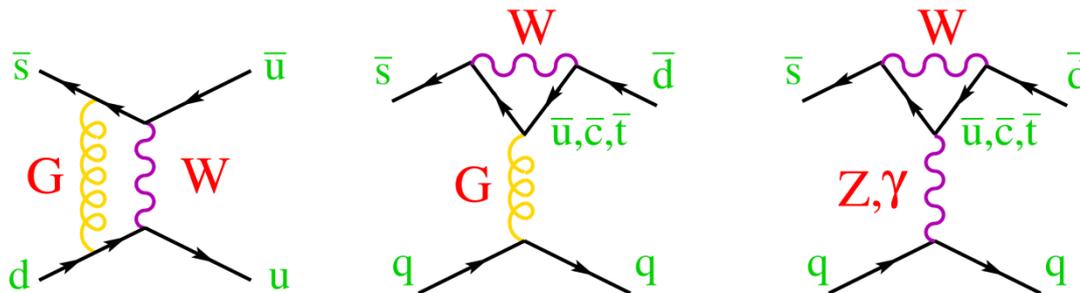
DIRECT C/P in $K \rightarrow \pi \pi$

$$\eta_{+-} \equiv \frac{T(K_L \rightarrow \pi^+ \pi^-)}{T(K_S \rightarrow \pi^+ \pi^-)} \approx \varepsilon_K + \varepsilon'_K$$

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

$$\text{Re}(\varepsilon'_K / \varepsilon_K) \approx \frac{1}{6} \left\{ 1 - \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 \right\} = (16.6 \pm 2.3) \cdot 10^{-4}$$

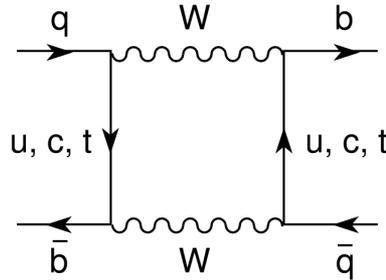
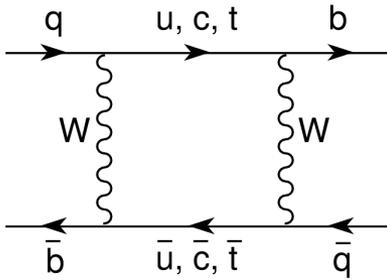
NA48, NA31
KTeV, E731



$$\text{Re}(\varepsilon'_K / \varepsilon_K)_{\text{Th}} = (15 \pm 7) \cdot 10^{-4}$$

- Short-distance OPE
Ciuchini et al, Buras et al
- Long-distance χ PT
Pallante-Pich-Scimemi
Cirigliano-Ecker-Neufeld-Pich
Gisbert-Pich, 1712.06147

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



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

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

$$\Delta M_{B_d^0} = (0.5064 \pm 0.0019) \text{ ps}^{-1}$$



$$|V_{td}|$$

- $\Delta M_{B_d^0} / \Gamma_{B_d^0} = 0.770 \pm 0.004$
- $\Delta M_{B_s^0} = (17.757 \pm 0.021) \text{ ps}^{-1}$
- $\Delta \Gamma_{B^0} / \Delta M_{B^0} \sim m_b^2 / m_t^2 \ll 1$
- $\text{Re}(\bar{\varepsilon}_{B_d^0}) = -0.0005 \pm 0.0004$

$$\Delta M_{B_s^0} / \Gamma_{B_s^0} = 26.79 \pm 0.08$$

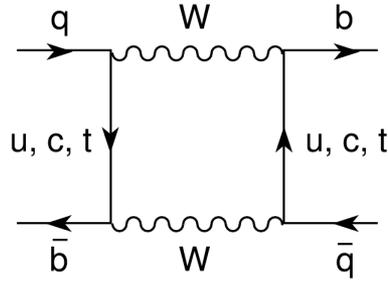
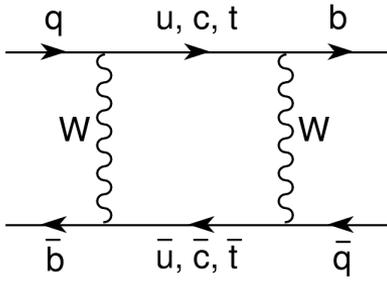
$$|V_{ts}|^2 \gg |V_{td}|^2$$

$$\Delta \Gamma_{B_s^0} / \Gamma_{B_s^0} = -0.132 \pm 0.008$$

$$\text{Re}(\bar{\varepsilon}_{B_s^0}) = -0.00015 \pm 0.00070$$

\cancel{CP} very small

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



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

$$|B_{\mp}^0\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} \left(p |B^0\rangle \mp q |\bar{B}^0\rangle \right)$$

$$\frac{q}{p} \equiv \frac{1 - \bar{\epsilon}_B}{1 + \bar{\epsilon}_B} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \right)^{1/2}$$

$$(\Delta M)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2$$

$$\Delta M \Delta\Gamma = 4 \operatorname{Re}(M_{12} \Gamma_{12}^*)$$

$$\Delta\Gamma/\Delta M \approx \Gamma_{12}/M_{12} \sim m_b^2/m_t^2 \ll 1$$



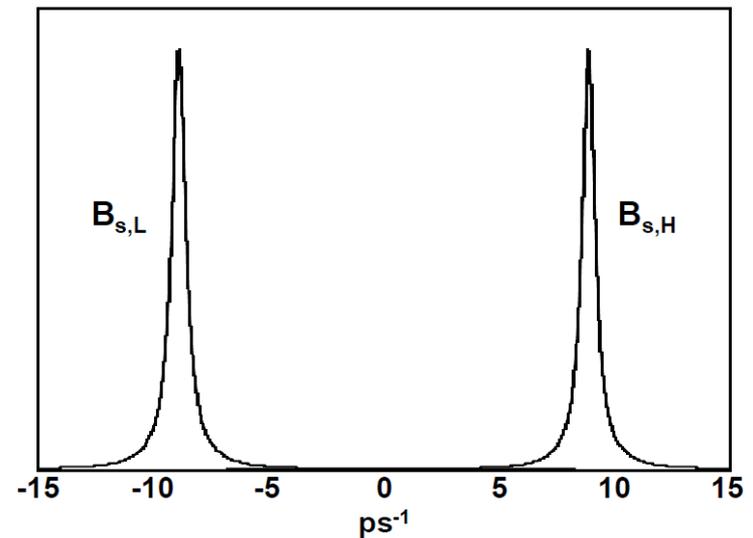
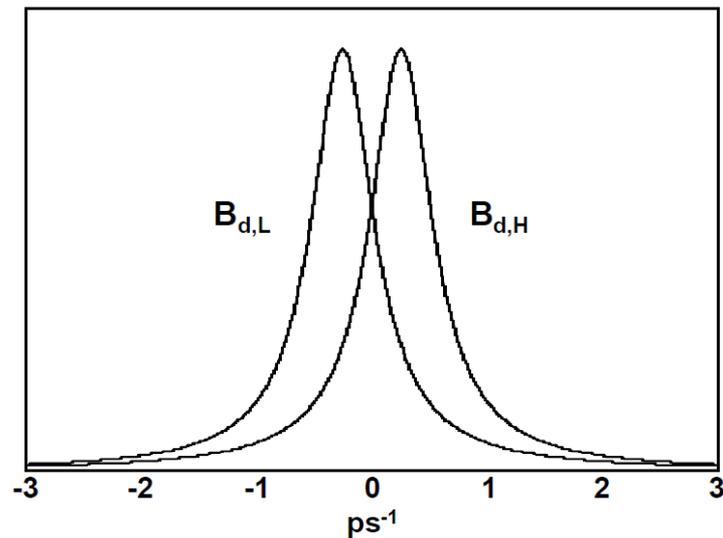
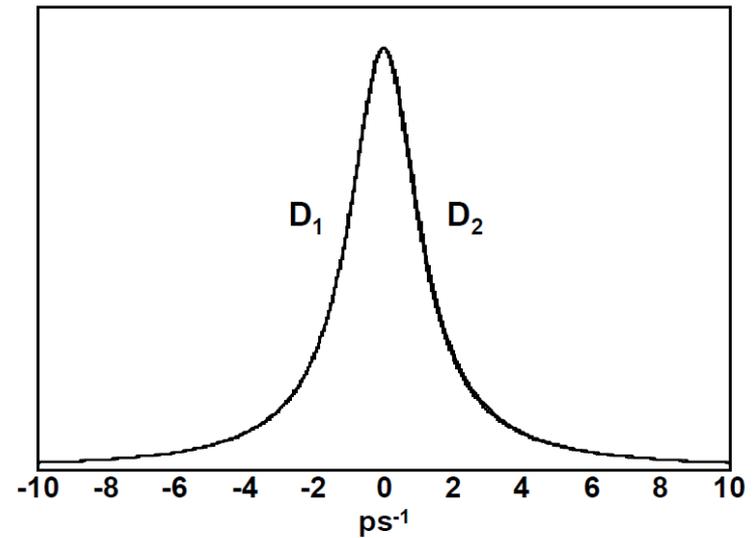
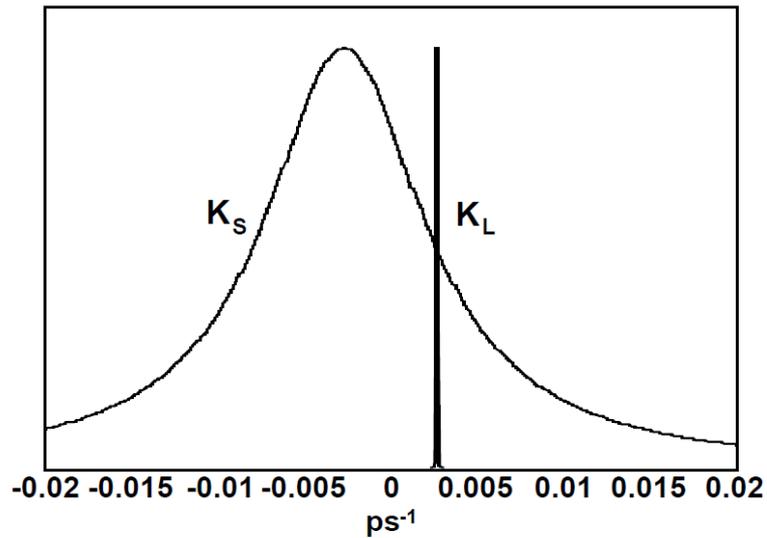
$$\left| \frac{q}{p} \right| \approx 1 + \frac{1}{2} \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin \phi_{\Delta B=2}, \quad \phi_{\Delta B=2} \equiv \arg(M_{12}/\Gamma_{12})$$

$$\Delta M \equiv M_{B_+} - M_{B_-}$$

$$\Delta\Gamma \equiv \Gamma_{B_+} - \Gamma_{B_-}$$

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

Widths & Mass Differences

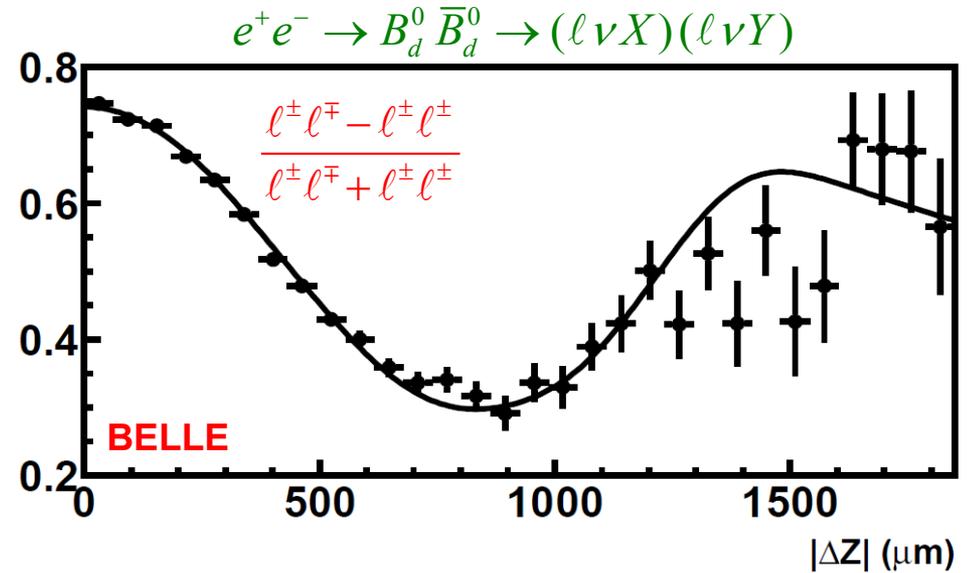


M. Gersabeck

Time Scales:

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

$$\text{Oscillation} \sim \sin \left[(x - iy) \Gamma t / 2 \right]$$



- \mathbf{K}^0 : $x \sim y \sim 1$
- \mathbf{D}^0 : $x \sim y \sim 0.01$
- \mathbf{B}_d : $x \sim 1$, $y \sim 0.01$
- \mathbf{B}_s : $x \sim 25$, $y \sim 0.05$

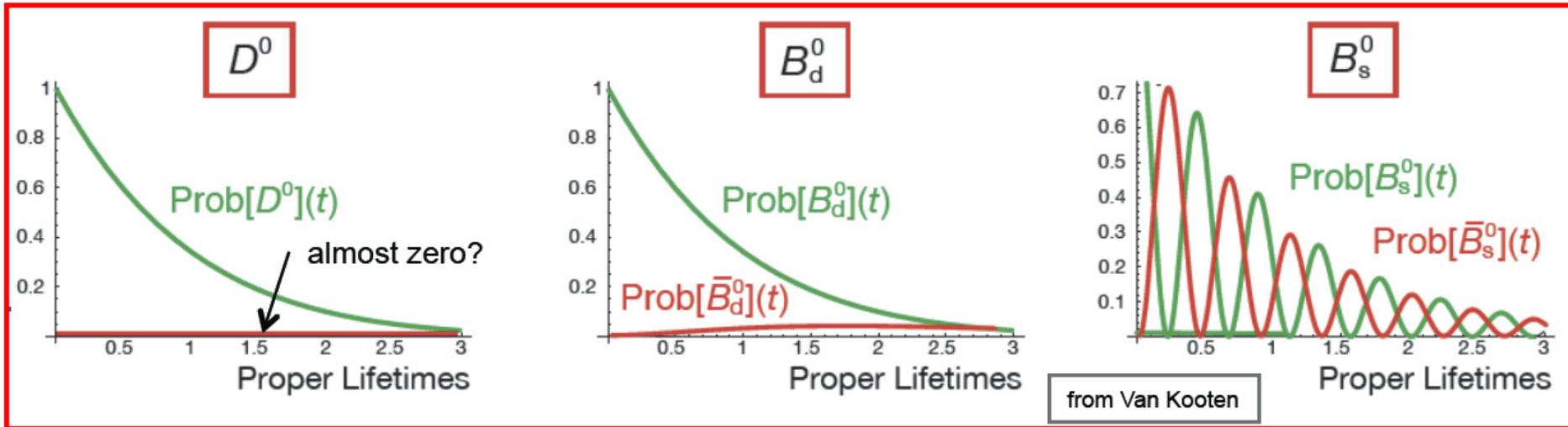
Slow oscillation (decays faster)

Fast oscillation (averages out to 0)

Time Scales:

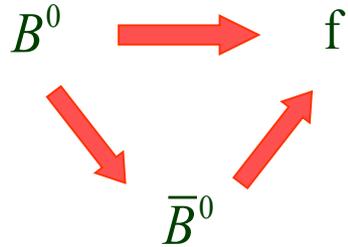
$$\text{Oscillation} \sim \sin\left[(x - iy)\Gamma t/2\right]$$

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



- \mathbf{K}^0 : $x \sim y \sim 1$
- \mathbf{D}^0 : $x \sim y \sim 0.01$ **Slow oscillation** (decays faster)
- \mathbf{B}_d : $x \sim 1$, $y \sim 0.01$
- \mathbf{B}_s : $x \sim 25$, $y \sim 0.05$ **Fast oscillation** (averages out to 0)

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



$$\begin{aligned} T_f &\equiv T[B^0 \rightarrow f] \quad ; \quad \bar{T}_f \equiv -T[\bar{B}^0 \rightarrow f] \quad ; \quad \bar{\rho}_f \equiv \bar{T}_f / T_f \\ T_{\bar{f}} &\equiv T[B^0 \rightarrow \bar{f}] \quad ; \quad \bar{T}_{\bar{f}} \equiv -T[\bar{B}^0 \rightarrow \bar{f}] \quad ; \quad \rho_{\bar{f}} \equiv T_{\bar{f}} / \bar{T}_{\bar{f}} \end{aligned}$$

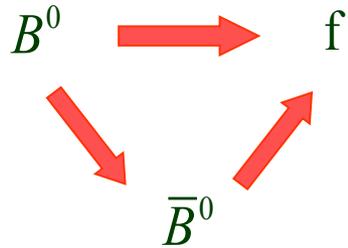
$$CP \ B^0 = -\bar{B}^0 \quad ; \quad CP \ f = \bar{f}$$

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

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

$$\Delta\Gamma \ll \Delta M \quad \longrightarrow \quad \frac{q}{p} \approx \sqrt{\frac{M_{12}^*}{M_{12}}} \approx \frac{V_{tb}^* V_{tq}}{V_{tb} V_{tq}^*} = e^{-2i\phi_M} \quad ; \quad \phi_M \approx \begin{cases} \beta & (B_d^0) \\ -\beta_s \approx -\lambda^2 \eta & (B_s^0) \end{cases}$$

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



$$\begin{aligned} T_f &\equiv T[B^0 \rightarrow f] \quad ; \quad \bar{T}_f \equiv -T[\bar{B}^0 \rightarrow f] \quad ; \quad \bar{\rho}_f \equiv \bar{T}_f / T_f \\ T_{\bar{f}} &\equiv T[B^0 \rightarrow \bar{f}] \quad ; \quad \bar{T}_{\bar{f}} \equiv -T[\bar{B}^0 \rightarrow \bar{f}] \quad ; \quad \rho_{\bar{f}} \equiv T_{\bar{f}} / \bar{T}_{\bar{f}} \end{aligned}$$

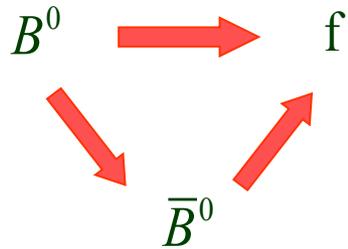
$$CP \ B^0 = -\bar{B}^0 \quad ; \quad CP \ f = \bar{f}$$

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

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

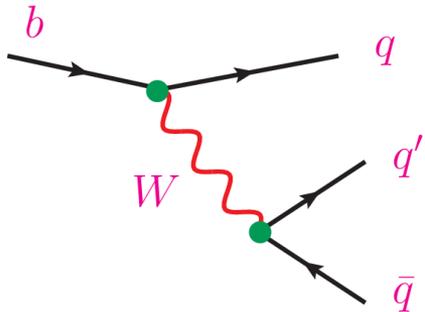
$$CP \text{ self-conjugate: } \bar{f} = \eta_f f \quad \longrightarrow \quad \begin{aligned} T_{\bar{f}} &= \eta_f T_f \quad ; \quad \bar{T}_{\bar{f}} = \eta_f \bar{T}_f \quad ; \quad \rho_{\bar{f}} \equiv 1/\bar{\rho}_f \\ C_{\bar{f}} &= C_f \quad ; \quad S_{\bar{f}} = S_f \end{aligned}$$

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



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

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



Assumption: **Only 1 decay amplitude**

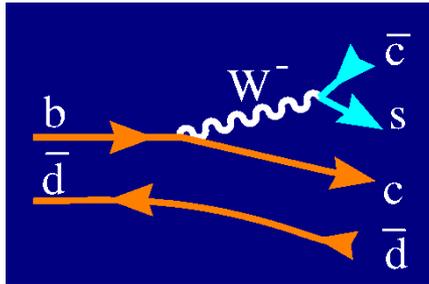
$$\frac{A_{b \rightarrow q\bar{q}q'}}{A_{\bar{b} \rightarrow \bar{q}qq'}} = \frac{V_{qb} V_{qq'}^*}{V_{qb}^* V_{qq'}} = e^{-2i\phi_D} \quad \longrightarrow \quad \begin{aligned} \rho_{\bar{f}} &= \bar{\rho}_f^* = \eta_f e^{2i\phi_D} \\ C_f &= 0 \end{aligned}$$

$$\longrightarrow \frac{\Gamma(\bar{B}^0 \rightarrow \bar{f}) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow \bar{f}) + \Gamma(B^0 \rightarrow f)} = -\eta_f \sin(2\phi) \sin(\Delta M t) \quad ; \quad \phi = \phi_M + \phi_D$$

Direct information on the CKM matrix

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

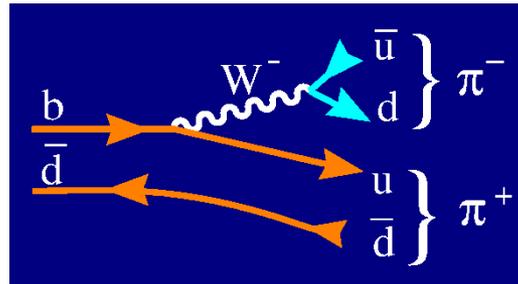
$$\phi \simeq \beta$$



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

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

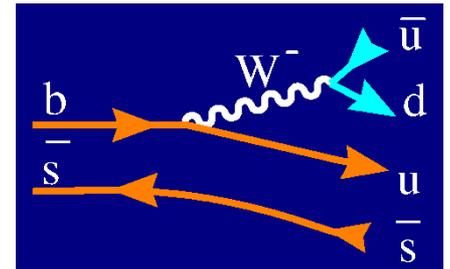
$$\phi \simeq \beta + \gamma = \pi - \alpha$$



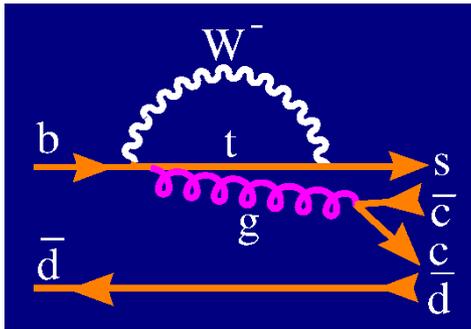
$$V_{ub} V_{ud}^* \sim A\lambda^3(\rho - i\eta)$$

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

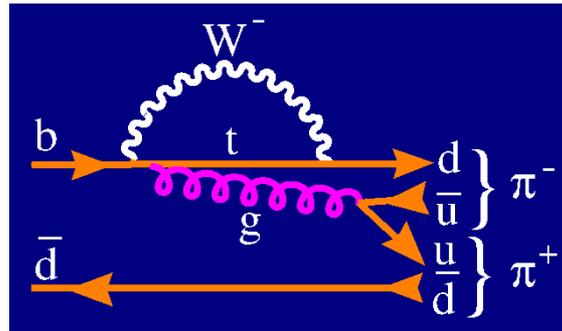
$$\phi \neq \gamma$$



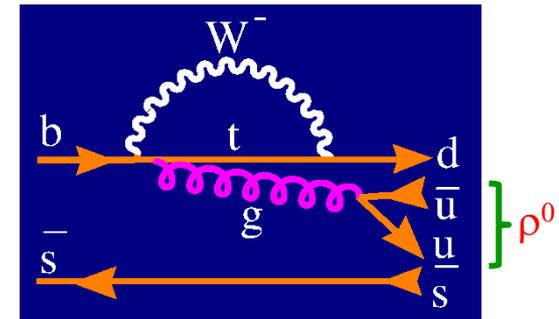
$$V_{ub} V_{ud}^* \sim A\lambda^3(\rho - i\eta)$$



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



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

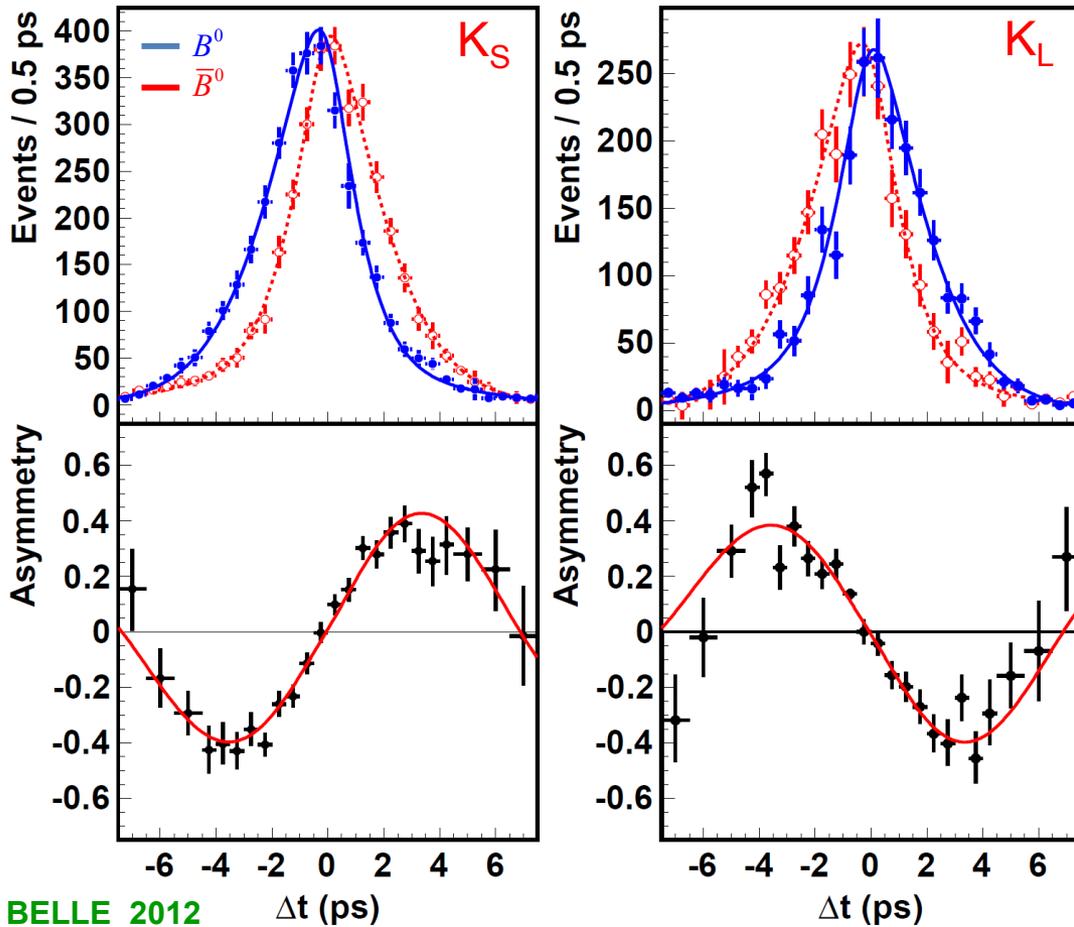


$$V_{tb} V_{td}^* \sim A\lambda^3(1 - \rho + i\eta)$$

**

BAD

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



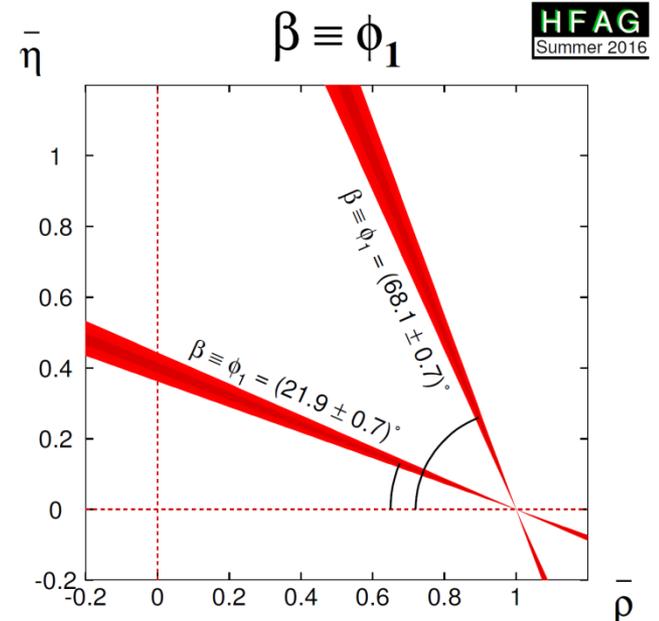
BELLE 2012

~~CP~~ Signal

PDG 2018:

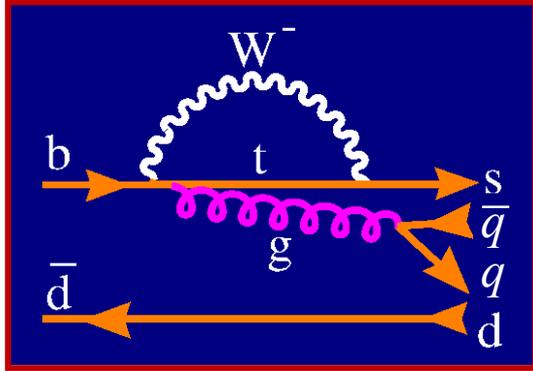
$$\sin(2\beta) = 0.699 \pm 0.017$$

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



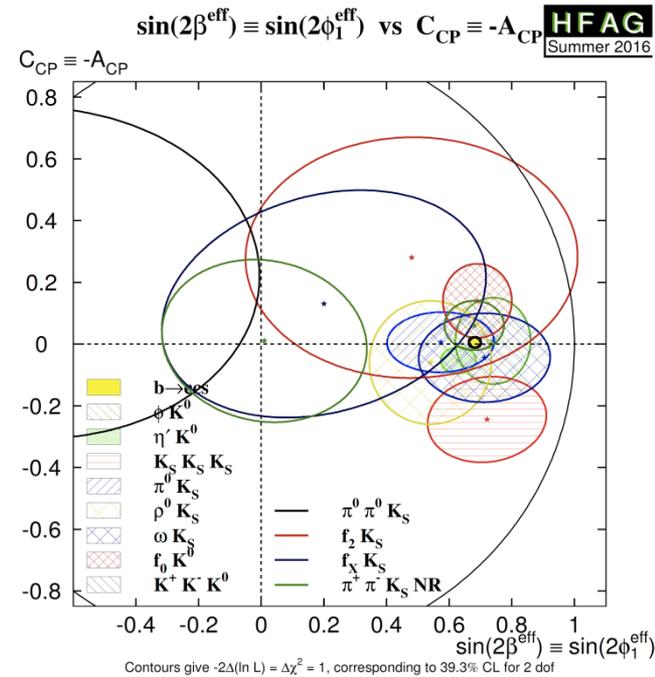
$b \rightarrow q\bar{q}s$

$q = d, s$



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

Sensitive to New Physics in Penguin diagram



$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$

HFAG Summer 2016

$b \rightarrow ccs$	World Average	
ϕK^0	Average	$0.74^{+0.11}_{-0.13}$
$\eta' K^0$	Average	0.63 ± 0.06
$K_S K_S K_S$	Average	0.72 ± 0.19
$\pi^0 K^0$	Average	0.57 ± 0.17
$\rho^0 K_S$	Average	$0.54^{+0.18}_{-0.21}$
ωK_S	Average	0.71 ± 0.21
$f_0 K_S$	Average	$0.69^{+0.10}_{-0.12}$
$f_2 K_S$	Average	0.48 ± 0.53
$f_X K_S$	Average	0.20 ± 0.53
$\pi^0 \pi^0 K_S$	Average	-0.72 ± 0.71
$\phi \pi^0 K_S$	Average	$0.97^{+0.03}_{-0.52}$
$\pi^+ \pi^- K_S \text{ NR}$	Average	0.01 ± 0.33
$K^+ K^- K^0$	Average	$0.68^{+0.09}_{-0.10}$

$$C_f = -A_f$$

HFAG Summer 2016

ϕK^0	Average	0.01 ± 0.14
$\eta' K^0$	Average	-0.05 ± 0.04
$K_S K_S K_S$	Average	-0.24 ± 0.14
$\pi^0 K^0$	Average	0.01 ± 0.10
$\rho^0 K_S$	Average	-0.06 ± 0.20
ωK_S	Average	-0.04 ± 0.14
$f_0 K_S$	Average	0.14 ± 0.12
$f_2 K_S$	Average	$0.28^{+0.37}_{-0.41}$
$f_X K_S$	Average	$0.13^{+0.34}_{-0.36}$
$\pi^0 \pi^0 K_S$	Average	0.23 ± 0.54
$\phi \pi^0 K_S$	Average	-0.20 ± 0.15
$\pi^+ \pi^- K_S \text{ NR}$	Average	0.01 ± 0.26
$K^+ K^- K^0$	Average	0.06 ± 0.08

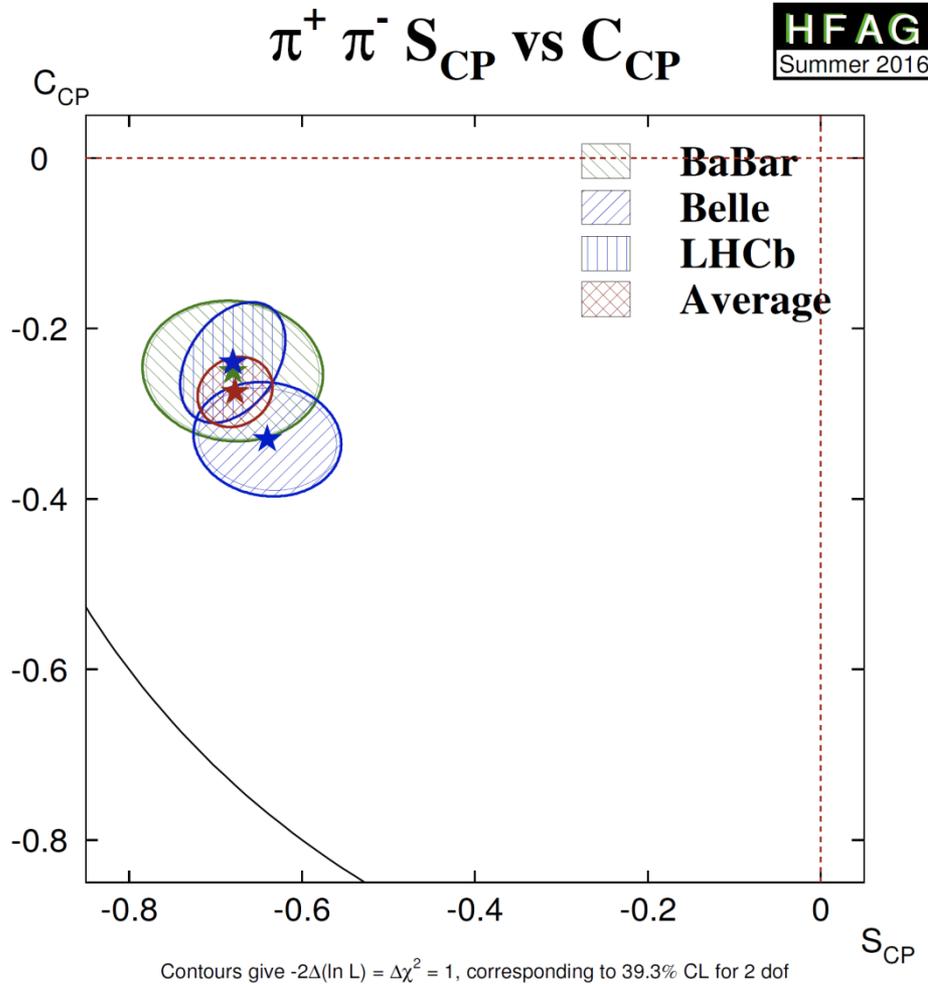
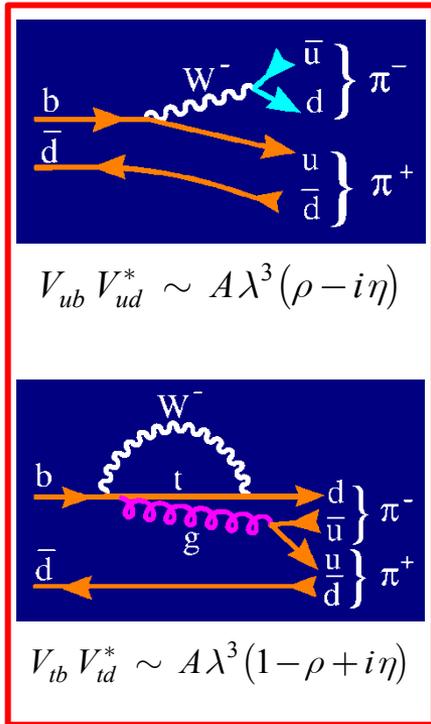
Agreement with $B^0 \rightarrow J/\Psi K_S$ ($b \rightarrow c\bar{c}s$)

No signal of direct CP

$B^0 \rightarrow \pi\pi$

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

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



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



Direct ~~CP~~

Penguins

$$\frac{\Gamma(B^0 \rightarrow \pi^0 \pi^0)}{\Gamma(B^0 \rightarrow \pi^+ \pi^-)} = 0.31(5)$$



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



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

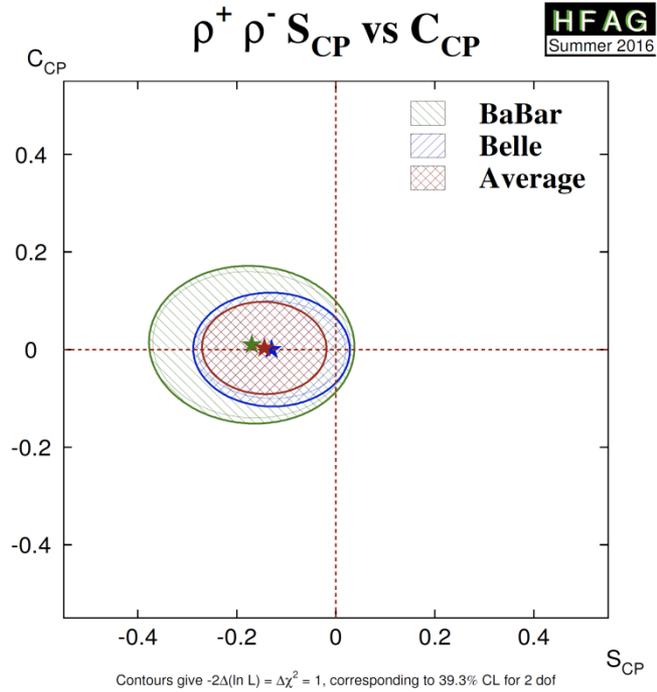
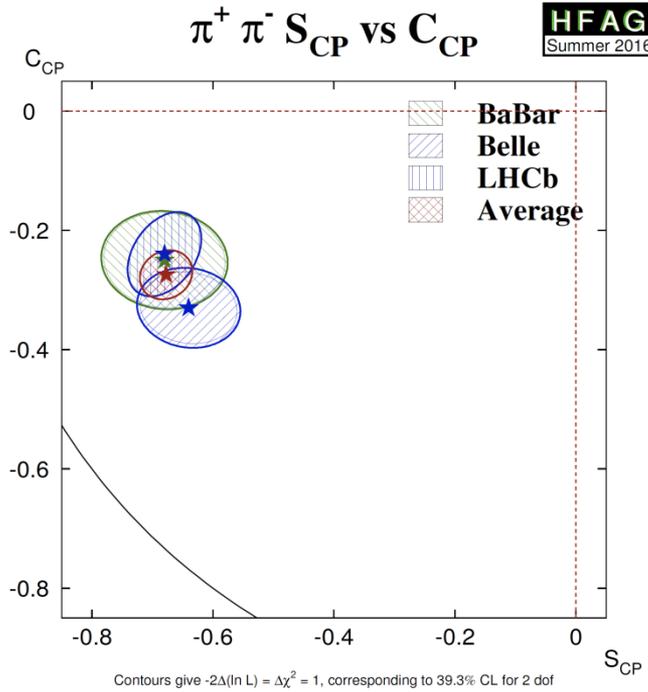
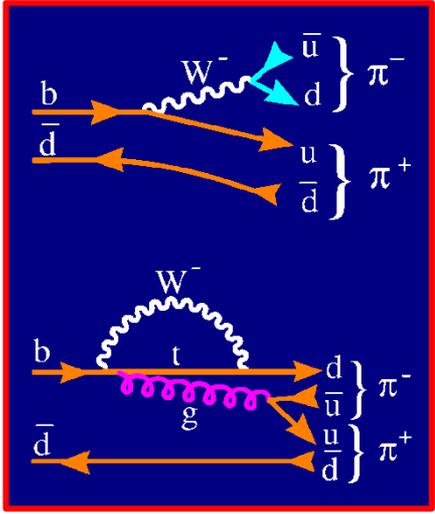
$$C_f \equiv \frac{1 - |\bar{\rho}_f|^2}{1 + |\bar{\rho}_f|^2} \neq 0$$



Direct CP

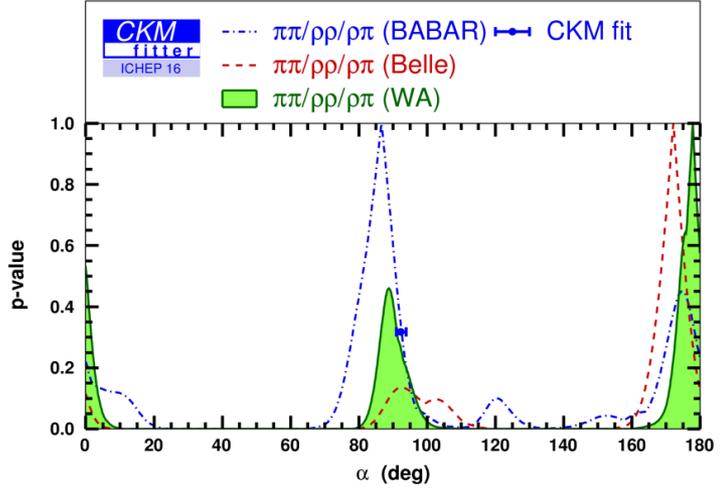
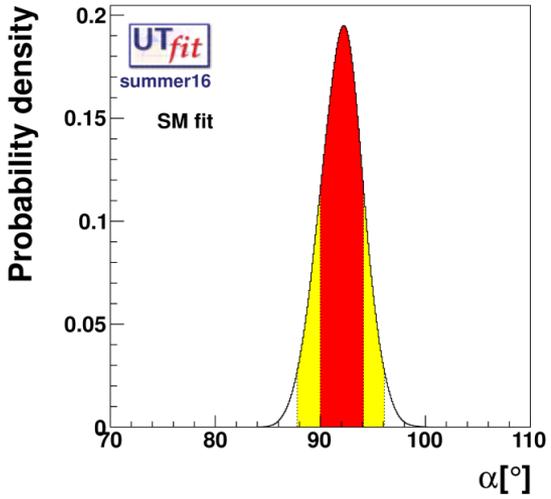
Penguins

$$\frac{\Gamma(B^0 \rightarrow \rho^0 \rho^0)}{\Gamma(B^0 \rightarrow \rho^+ \rho^-)} = 0.035 \quad (6)$$



HFAG 2017:

$$\alpha \equiv \arg \left[-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right] = (88 \pm 5)^\circ$$



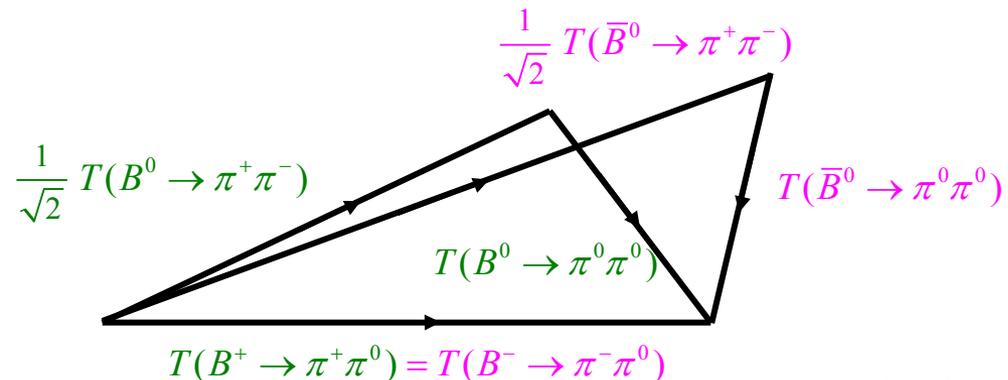
MEASURING HADRONIC CONTAMINATIONS

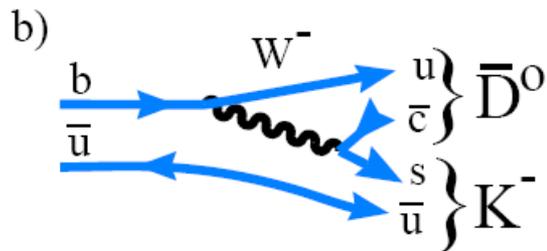
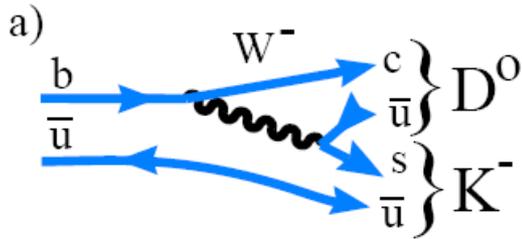
- Time Evolution
- Transversity Analysis: $\mathbf{B} \rightarrow \mathbf{V V}$
- Isospin Relations (Gronau-London)
- \mathbf{D}^0 - $\bar{\mathbf{D}}^0$ Mixing (Gronau-London-Wyler, Atwood-Dunietz-Soni)

$$\sqrt{2} T(B^+ \rightarrow D_+^0 K^+) = T(B^+ \rightarrow D^0 K^+) + T(B^+ \rightarrow \bar{D}^0 K^+)$$

$$\sqrt{2} T(B_d^0 \rightarrow D_+^0 K_S) = T(B_d^0 \rightarrow D^0 K_S) + T(B_d^0 \rightarrow \bar{D}^0 K_S)$$

- Dalitz Analysis
- SU(3) Relations: $\mathbf{B} \rightarrow \pi \mathbf{K}, \pi \pi, \dots$
- ...



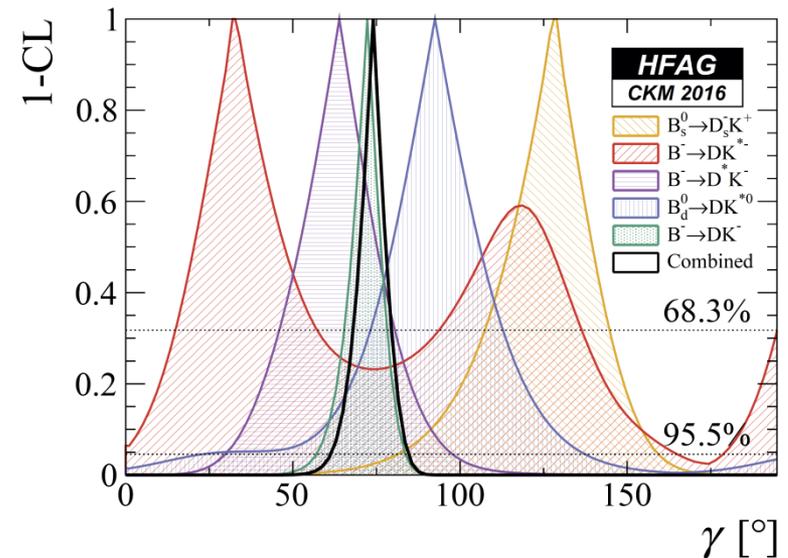
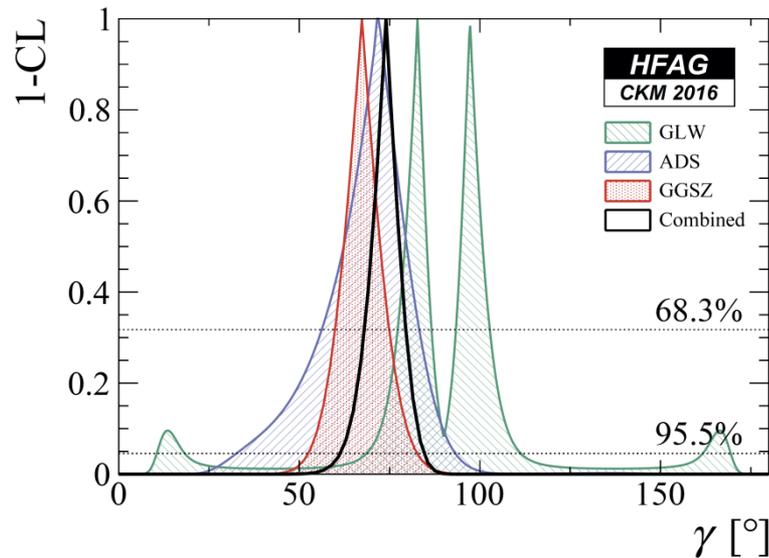


D^0 - \bar{D}^0 Mixing

Gronau-London-Wyler
Atwood-Dunietz-Soni
Giri-Grossman-Soffer-Zupan

$$\sqrt{2} T(B^+ \rightarrow D_+^0 K^+) = T(B^+ \rightarrow D^0 K^+) + T(B^+ \rightarrow \bar{D}^0 K^+)$$

$$\sqrt{2} T(B_d^0 \rightarrow D_+^0 K_S) = T(B_d^0 \rightarrow D^0 K_S) + T(B_d^0 \rightarrow \bar{D}^0 K_S)$$



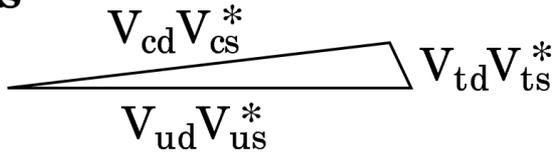
➔

$$\gamma \equiv \arg \left[-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right] = (74.0^{+5.8}_{-6.4})^\circ$$

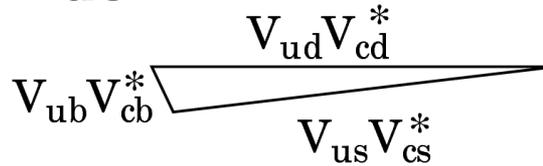
UNITARITY TRIANGLES

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

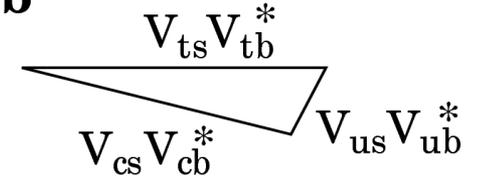
ds



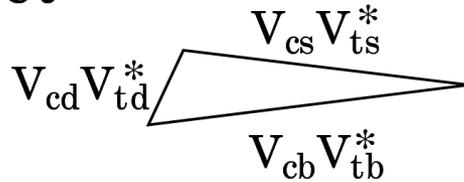
uc



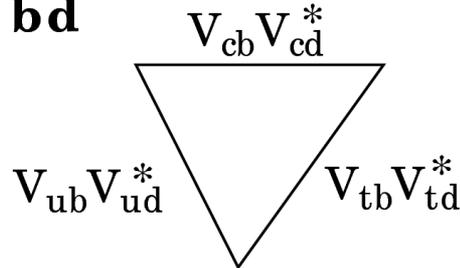
sb



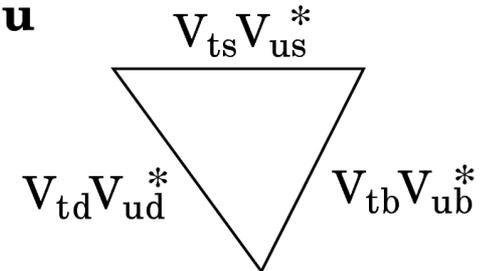
ct



bd

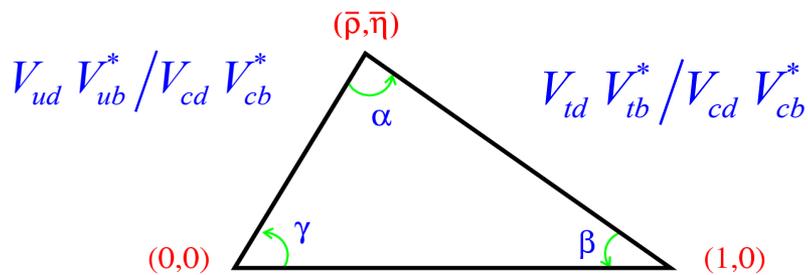
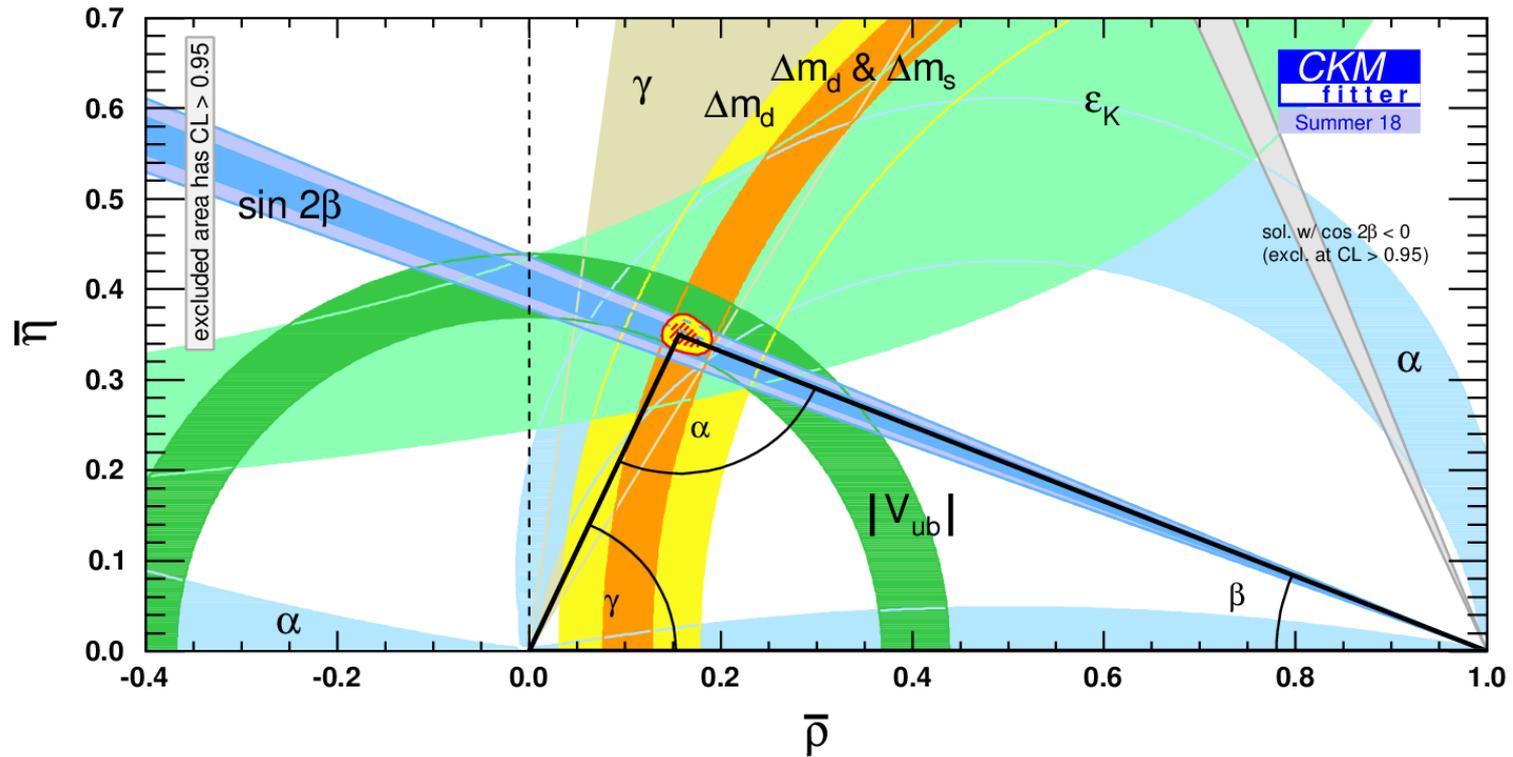


tu



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

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

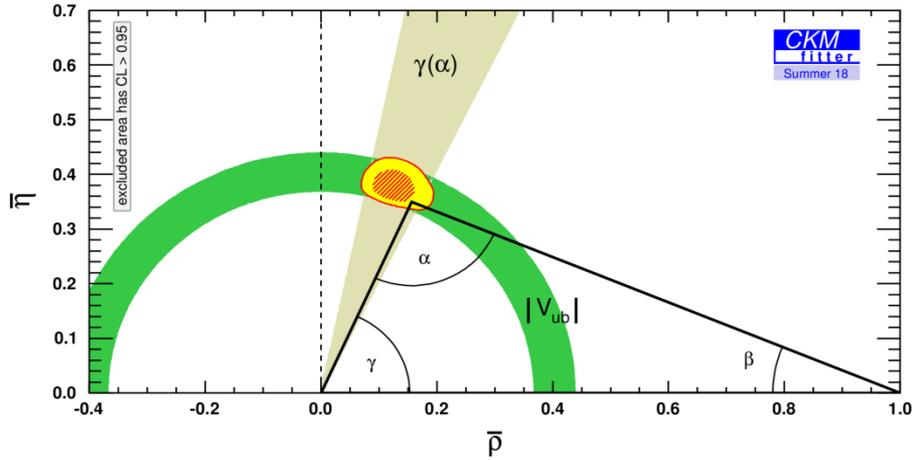


$$\text{UT}_{fit} \quad \bar{\eta} \equiv \eta \left(1 - \frac{1}{2} \lambda^2\right) = 0.348 \pm 0.010$$

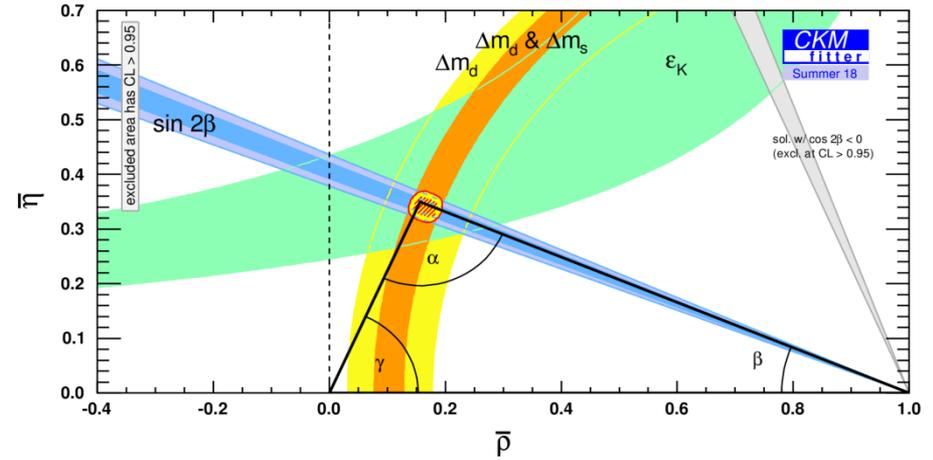
$$\bar{\rho} \equiv \rho \left(1 - \frac{1}{2} \lambda^2\right) = 0.148 \pm 0.013$$

$$\alpha = 90.1 \pm 2.2^\circ ; \beta = 23.8 \pm 1.3^\circ ; \gamma = 65.8 \pm 2.2^\circ$$

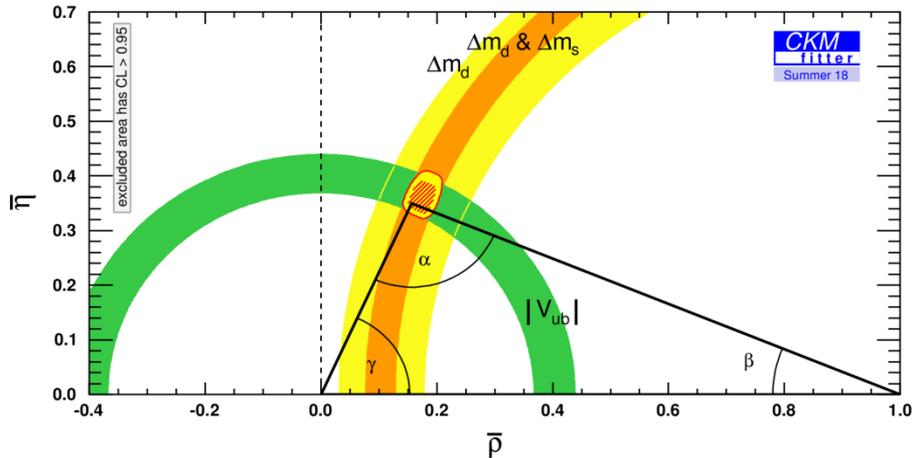
Tree-level determinations



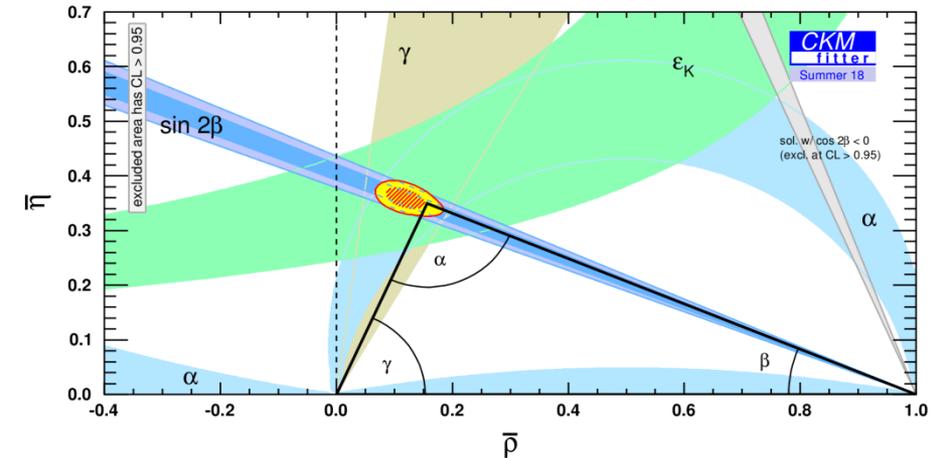
Loop processes



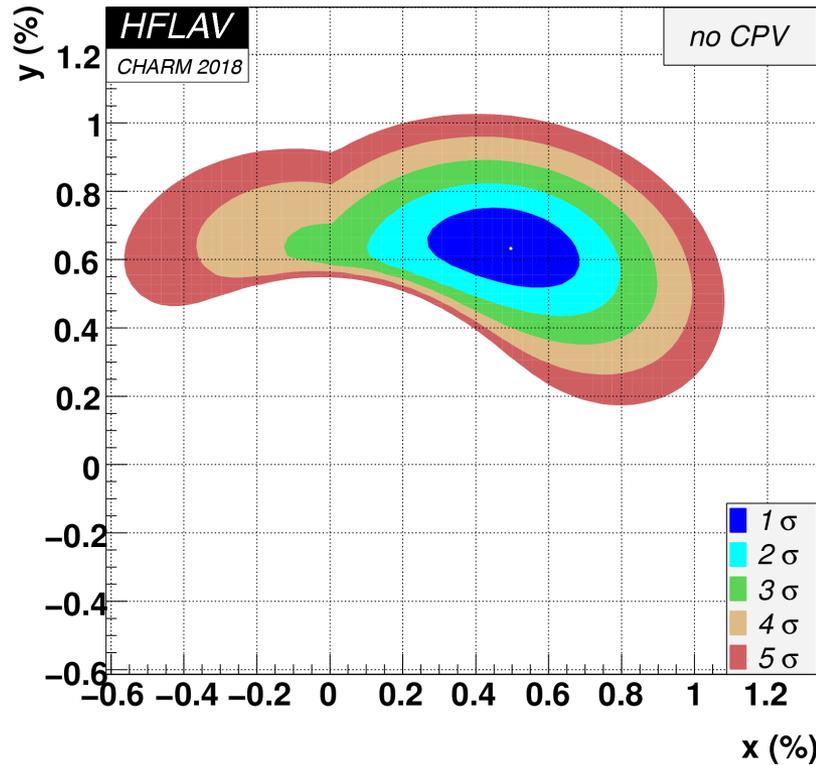
CP Conserving



CP Violating



D⁰ – D̄⁰ MIXING

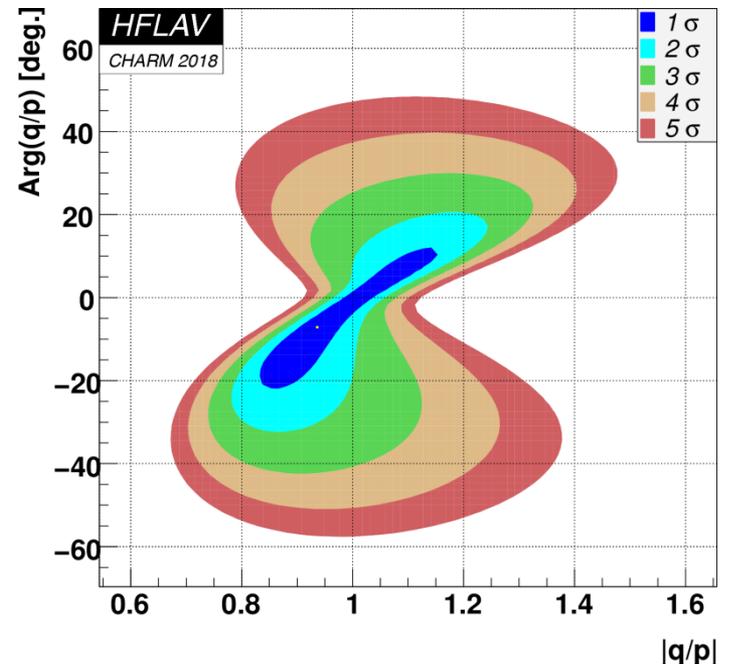
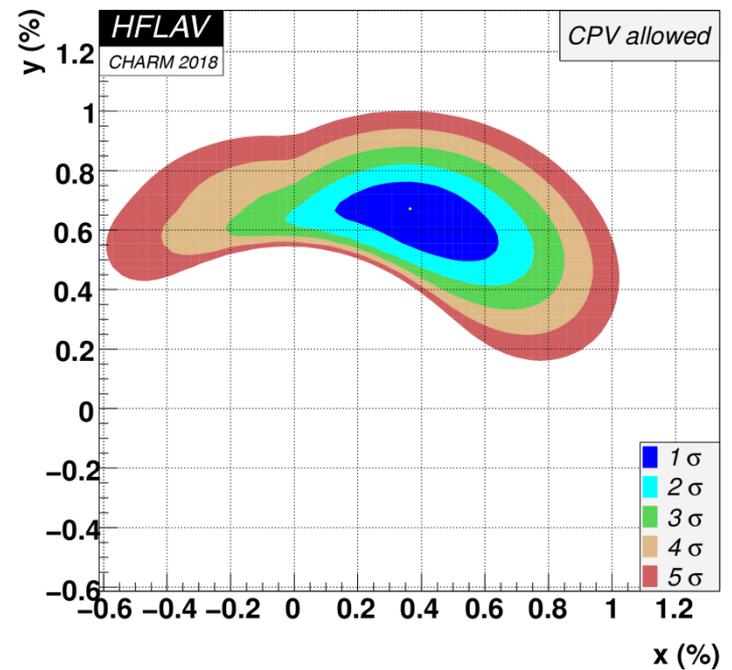


$$x \equiv -\frac{\Delta M}{\Gamma} \quad , \quad y \equiv -\frac{\Delta \Gamma}{2\Gamma}$$

LHCb 1903.03074:

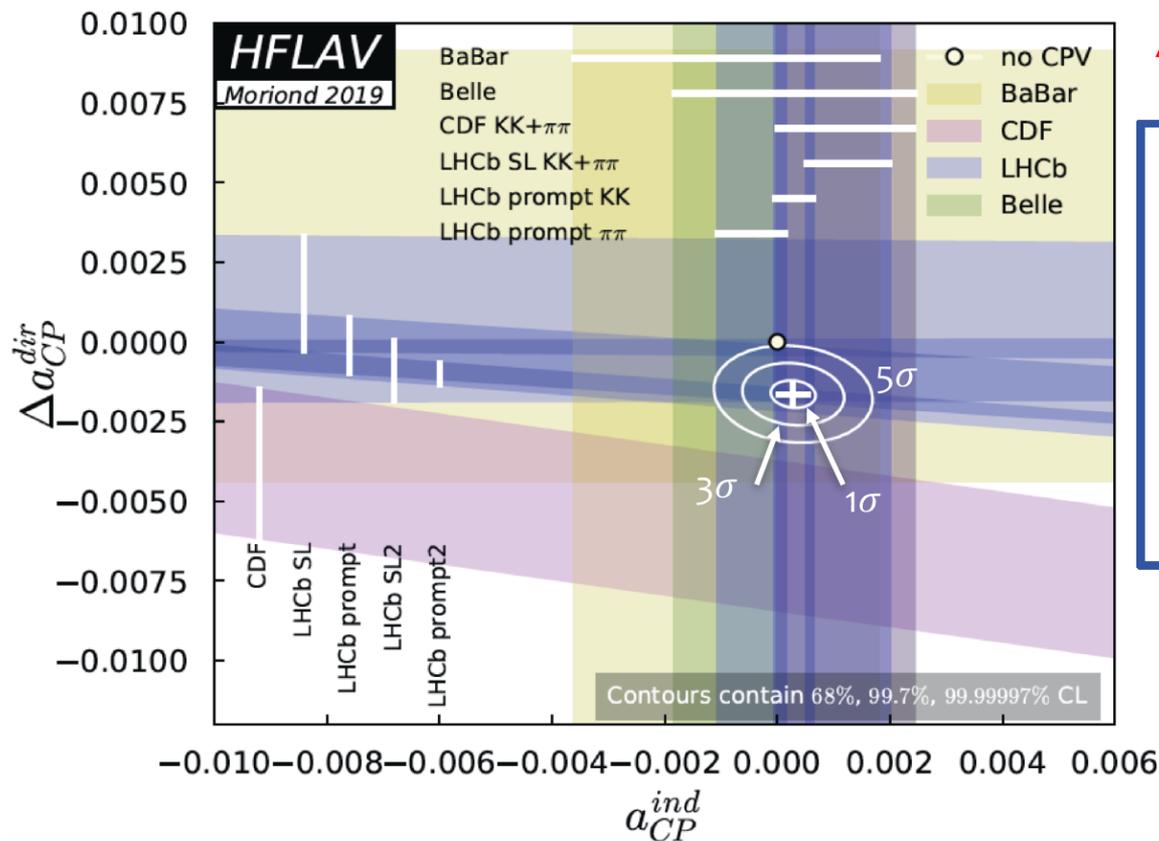
$$x = \begin{pmatrix} 0.27^{+0.17} \\ -0.15 \end{pmatrix} \cdot 10^{-2}$$

World Average: $x = (0.38 \pm 0.12) \cdot 10^{-2}$



$D^0 - \bar{D}^0$ MIXING: First evidence of \mathcal{CP} (5.3 σ)

LHCb-PAPER-2019-006: $\Delta a_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$, $\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9) \cdot 10^{-4}$



$$\Delta a_{CP} = a_{CP}(K^+K^-) - a_{CP}(\pi^+\pi^-)$$

HFLAV combination

$a_{CP}^{\text{ind}} = (0.028 \pm 0.026)\%$

$\Delta a_{CP}^{\text{dir}} = (-0.164 \pm 0.028)\%$

Consistency with NO CPV hypothesis: 5×10^{-8}

$$a_{CP} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}$$

World average dominated by LHCb results

Backup



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

Phase convention: $\mathcal{CP} |P^0\rangle = -|\bar{P}^0\rangle$

$$|\psi(t)\rangle = a(t)|P^0\rangle + b(t)|\bar{P}^0\rangle$$

$$i\frac{d}{dt}|\psi(t)\rangle = \mathbf{M}|\psi(t)\rangle$$

$$\mathcal{CPT}: \quad \mathbf{M} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

$$\mathcal{CP}: \quad M_{12} = M_{12}^* \quad , \quad \Gamma_{12} = \Gamma_{12}^*$$

▪ **Dispersive:**
$$M_{12} = \frac{1}{2M} \left\{ \langle P^0 | H_{\Delta P=2} | \bar{P}^0 \rangle + PP \int \frac{ds}{M^2 - s} \sum_X dQ_X \langle P^0 | H_{\Delta P=1} | X \rangle \langle X | H_{\Delta P=1} | \bar{P}^0 \rangle \right\}$$

▪ **Absorptive:**
$$\Gamma_{12} = \frac{\pi}{M} \int ds \sum_X dQ_X \delta(s - M^2) \langle P^0 | H_{\Delta P=1} | X \rangle \langle X | H_{\Delta P=1} | \bar{P}^0 \rangle$$

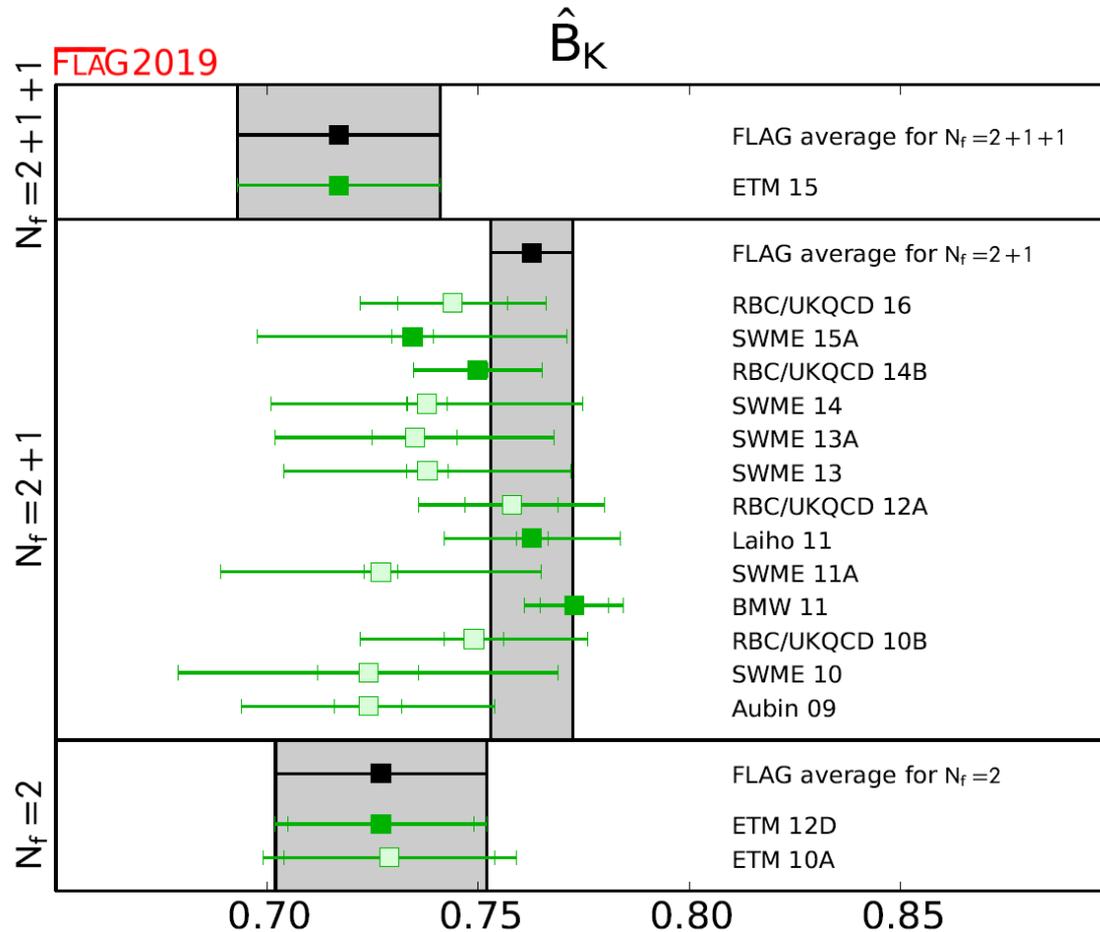
▪ **Eigenvalues:**
$$|P_{\mp}^0\rangle = \frac{p|P^0\rangle \mp q|\bar{P}^0\rangle}{\sqrt{|p|^2 + |q|^2}} \quad , \quad \frac{q}{p} \equiv \frac{1 - \bar{\varepsilon}}{1 + \bar{\varepsilon}} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \right)^{1/2}$$

$$\langle P_- | P_+ \rangle = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2 \operatorname{Re}(\bar{\varepsilon})}{1 + |\bar{\varepsilon}|^2}$$

$$\mathcal{CP} \longrightarrow q/p = 1 \longrightarrow |P_{1,2}\rangle = \frac{1}{\sqrt{2}} (|P^0\rangle \mp |\bar{P}^0\rangle) \quad , \quad \mathcal{CP} |P_{1,2}\rangle = \pm |P_{1,2}\rangle$$

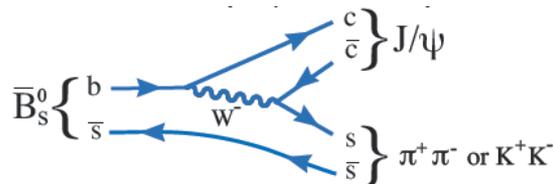
Lattice Results for \hat{B}_K

$$B_K^{\overline{\text{MS}}}(2\text{ GeV}) = 0.557 \pm 0.007 \quad , \quad \hat{B}_K = 0.763 \pm 0.010 \quad (N_f = 2+1)$$



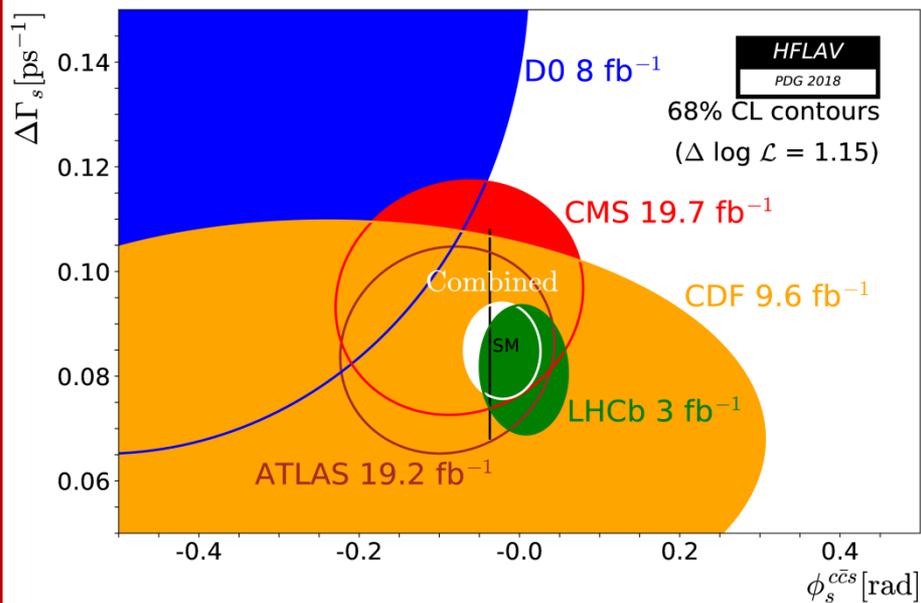
Flavianet Lattice Averaging Group

B_s Asymmetries



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

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

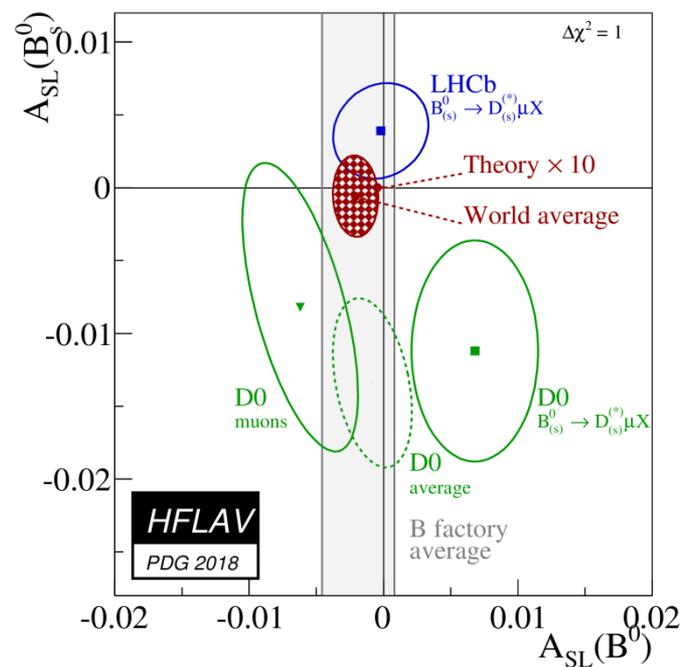


$$\Delta\Gamma_s = (0.088 \pm 0.006) \text{ ps}^{-1}, \quad \phi_s^{c\bar{c}s} = (-0.021 \pm 0.031) \text{ rad}$$

$$A_{\text{SL}}(B_q^0) \equiv \frac{\Gamma(\bar{B}_q^0 \rightarrow \ell^+ X) - \Gamma(B_q^0 \rightarrow \ell^- X)}{\Gamma(\bar{B}_q^0 \rightarrow \ell^+ X) + \Gamma(B_q^0 \rightarrow \ell^- X)} = \frac{|p|^4 - |q|^4}{|p|^4 + |q|^4}$$

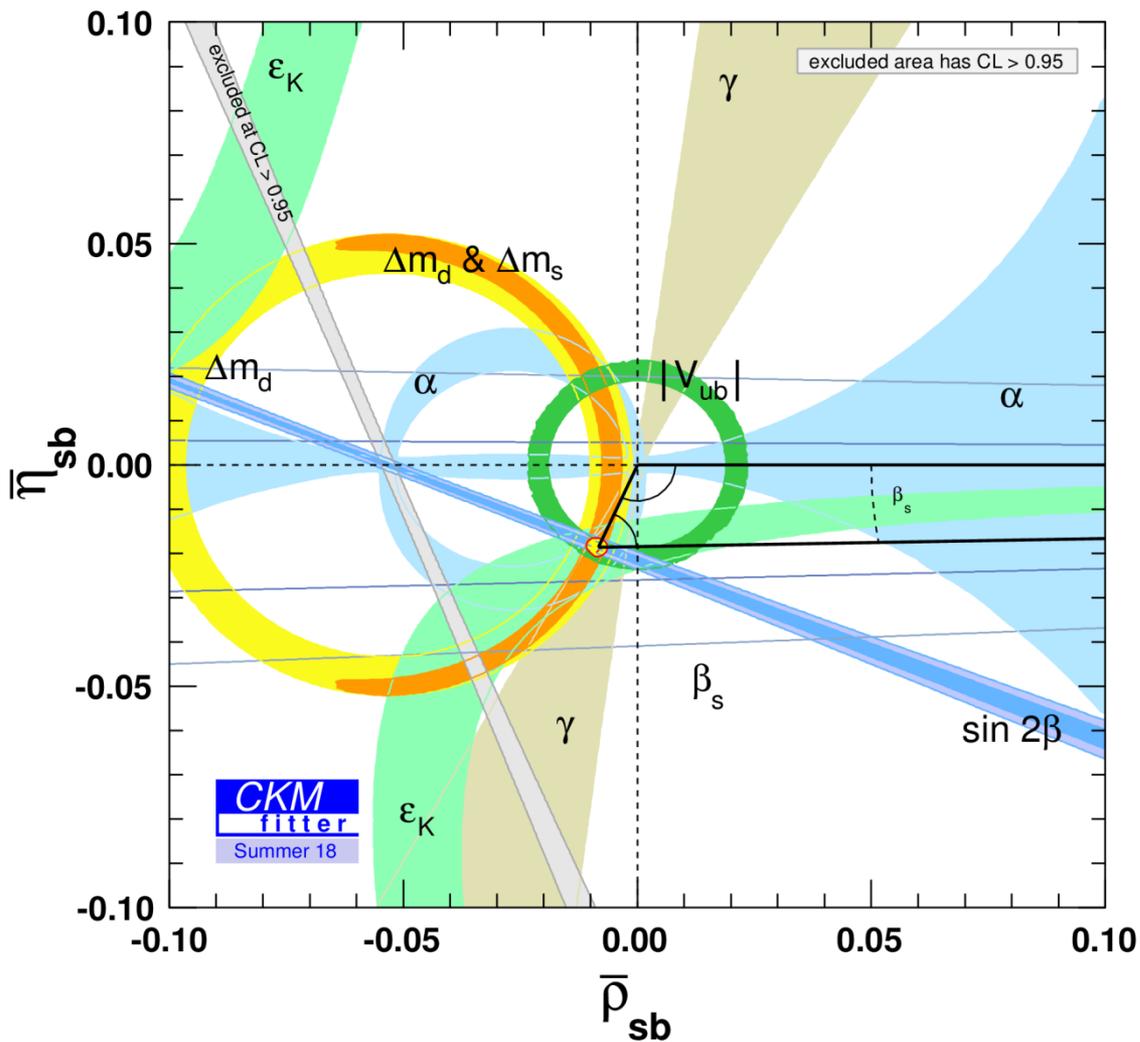
$$\approx 4 \text{Re}(\bar{\varepsilon}_{B_q^0}) \approx \frac{|\Gamma_{12}|}{|M_{12}|} \sin \phi_q \approx \frac{|\Delta\Gamma_{B_q^0}|}{|\Delta M_{B_q^0}|} \tan \phi_q$$

$$\phi_q \equiv \arg(-M_{12}^q/\Gamma_{12}^q) \sim \frac{m_c^2}{m_b^2}$$



$$A_{\text{SL}}(B_d^0) = -0.0021 \pm 0.0017, \quad A_{\text{SL}}(B_s^0) = -0.0006 \pm 0.0028$$

$$\underbrace{V_{us} V_{ub}^*}_{\lambda^4} + \underbrace{V_{cs} V_{cb}^*}_{\lambda^2} + \underbrace{V_{ts} V_{tb}^*}_{\lambda^2} = 0$$



$$\bar{\rho}_{sb} + i \bar{\eta}_{sb} = -V_{us} V_{ub}^* / V_{cs} V_{cb}^*$$