Particle Physics II – CP violation

(also known as “Physics of Anti-matter”)

Lecture 5

N. Tuning

Plan

1) Wed 12 Feb: Anti-matter + SM
2) Mon 17 Feb: CKM matrix + Unitarity Triangle
3) Wed 19 Feb: Mixing + Master eqs. + $B^0 \rightarrow J/\psi K_s$
4) Mon 9 Mar: CP violation in $B_{(s)}$ decays (I)
5) Wed 11 Mar: CP violation in $B_{(s)}$ and K decays (II)
6) Mon 16 Mar: Rare decays + Flavour Anomalies
7) Wed 18 Mar: Exam

- Final Mark:
  - if (mark > 5.5) mark = max(exam, 0.85*exam + 0.15*homework)
  - else mark = exam
- In parallel: Lectures on Flavour Physics by prof.dr. R. Fleischer

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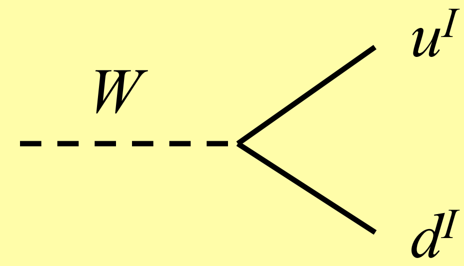
$$L_{SM} = L_{Kinetic} + L_{Higgs} + L_{Yukawa}$$

Recap

$$-L_{Yuk} = Y_{ij}^{d}\,(\overline{u_L^I}, \overline{d_L^I})_i \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_{Rj}^I + \ldots$$

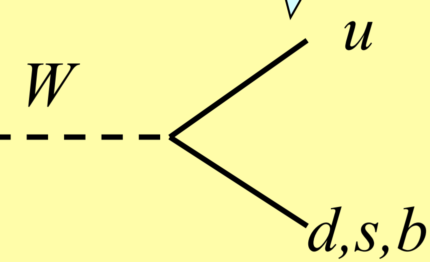
$$L_{Kinetic} = \frac{g}{\sqrt{2}} \overline{u_{Li}^I} \gamma^\mu W_\mu^- d_{Li}^I + \frac{g}{\sqrt{2}} \overline{d_{Li}^I} \gamma^\mu W_\mu^+ u_{Li}^I + \ldots$$



Diagonalize Yukawa matrix Y_{ij}

- Mass terms
- Quarks rotate
- Off diagonal terms in charged current couplings

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} \rightarrow V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$-L_{Mass} = \left(\bar{d}, \bar{s}, \bar{b}\right)_L \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R + \left(\bar{u}, \bar{c}, \bar{t}\right)_L \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \ldots$$

$$L_{CKM} = \frac{g}{\sqrt{2}} \overline{u_i} \gamma^\mu W_\mu^- V_{ij} \left(1 - \gamma^5\right) d_j + \frac{g}{\sqrt{2}} \overline{d_j} \gamma^\mu W_\mu^+ V_{ij}^* \left(1 - \gamma^5\right) u_i + \ldots$$

$$L_{SM} = L_{CKM} + L_{Higgs} + L_{Mass}$$

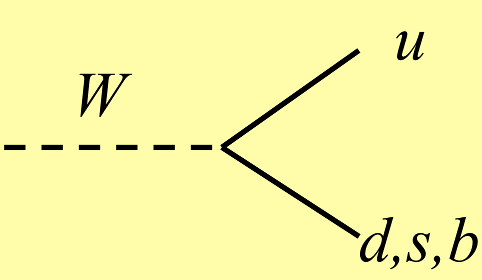
CKM-matrix: where are the phases?

- Possibility 1: simply 3 'rotations', and put phase on smallest:

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

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

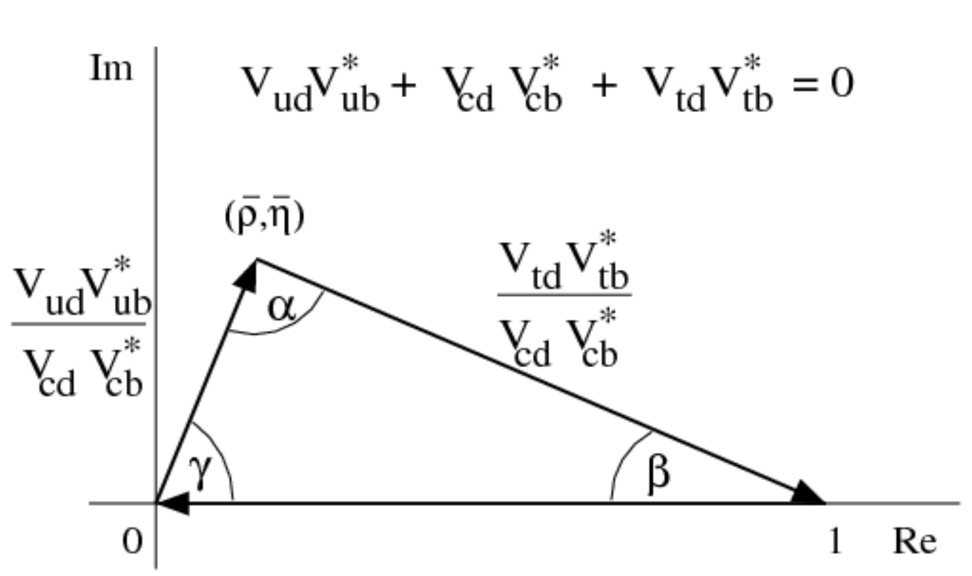
- Possibility 2: parameterize according to magnitude, in O(λ):



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

This was theory, now comes experiment

- We already saw how the moduli $|V_{ij}|$ are determined
- Now we will work towards the measurement of the imaginary part
  - Parameter: η
  - Equivalent: angles α, β, γ .



- To measure this, we need the formalism of neutral meson oscillations…

Meson Decays

- Formalism of meson *oscillations*:

$$\left|P^0(t)\right\rangle = \frac{1}{2}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t}+e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|P^0\rangle+\frac{q}{2p}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t}-e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|\bar{P}^0\rangle$$

- Subsequent: *decay*

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \left(|g_+(t)|^2+|\lambda_f|^2|g_-(t)|^2+2\Re[\lambda_f g_+^*(t)g_-(t)]\right)$$

$P^0 \to f$

$P^0 \to \bar{P}^0 \to f$

$$A(f) = \langle f|T|P^0\rangle$$

$$\bar{A}(f) = \langle f|T|\bar{P}^0\rangle$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Interference

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \frac{e^{-\Gamma t}}{2}\left(\left(1+|\lambda_f|^2\right)\cosh\frac{1}{2}\Delta\Gamma t+2\Re\lambda_f\sinh\frac{1}{2}\Delta\Gamma t+\left(1-|\lambda_f|^2\right)\cos\Delta m t-2\Im\lambda_f\sin\Delta m t\right)$$

('direct') Decay

Interference

Classification of CP Violating effects

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\text{Prob}(P^0 \to \bar{P}^0) \neq \text{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

$$\Im \lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

Remember!

Necessary ingredients for CP violation:

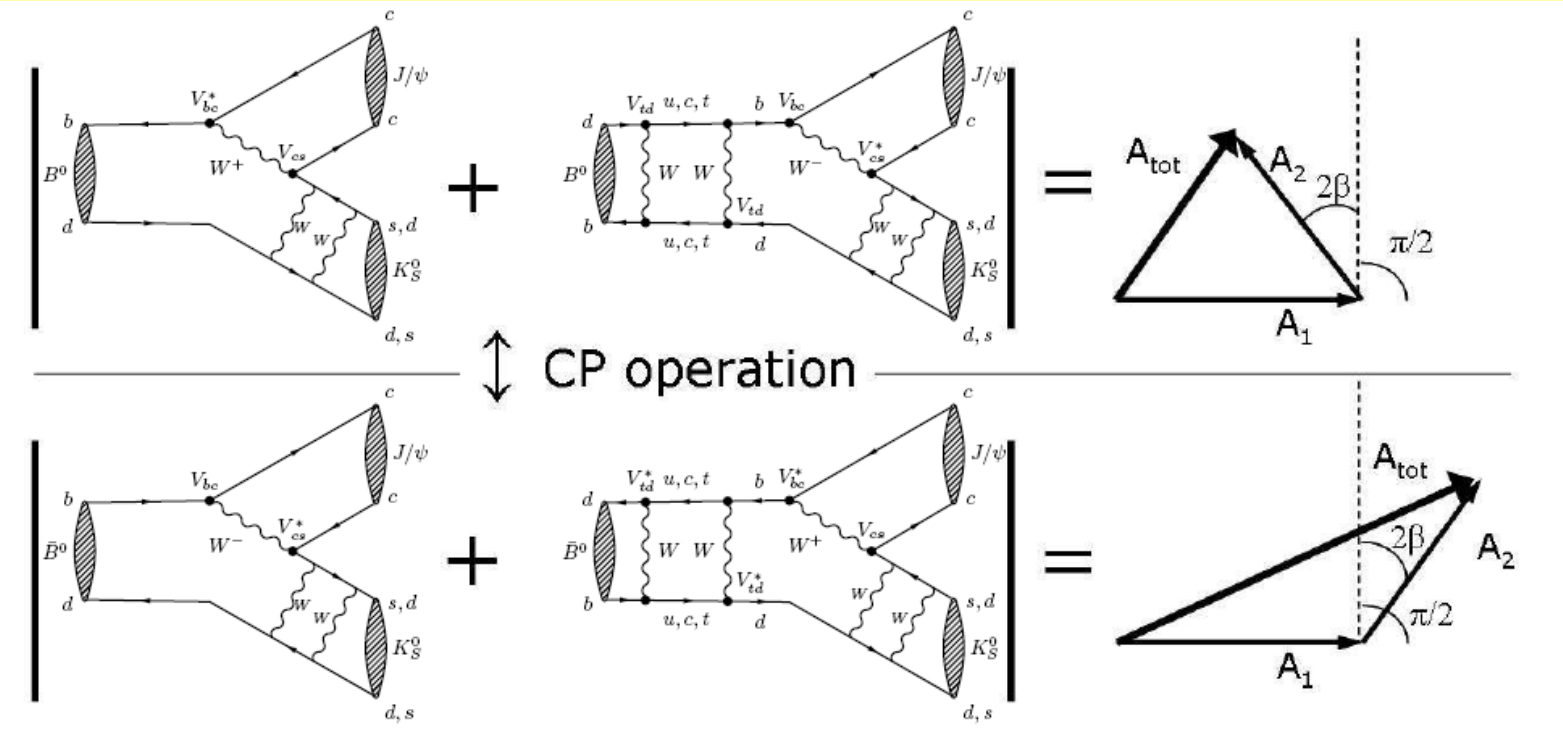
1) Two (interfering) amplitudes

2) Phase difference between amplitudes

  - one CP conserving phase ('strong' phase)
  - one CP violating phase ('weak' phase)

2 amplitudes
2 phases

Remember!



2 amplitudes
2 phases

CP violation: type 3

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

$$\boxed{\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)}$$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}}$$

$$\begin{aligned}
\Gamma_{P^0\to f}(t) &= |A_f|^2 \qquad (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f \sin\Delta m t\right)\\
\Gamma_{\bar{P}^0\to f}(t) &= |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f \sin\Delta m t\right)
\end{aligned}$$

$$D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}.$$

$$\boxed{A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f\cos\Delta m t - 2S_f\sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f\sinh\frac{1}{2}\Delta\Gamma t}}$$

Classification of CP Violating effects - Nr. 3:

Consider $f=\bar{f}$:

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f \cos\Delta m t - 2S_f \sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f \sinh\frac{1}{2}\Delta\Gamma t}$$

If one amplitude dominates the decay, then $A_f = \bar{A}_f$

$$A_{CP}(t) = \frac{-\Im\lambda_f \sin\Delta m t}{\cosh\frac{1}{2}\Delta\Gamma t + \Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t}$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

Relax: $B^0 \rightarrow J/\Psi K_s$ simplifies…

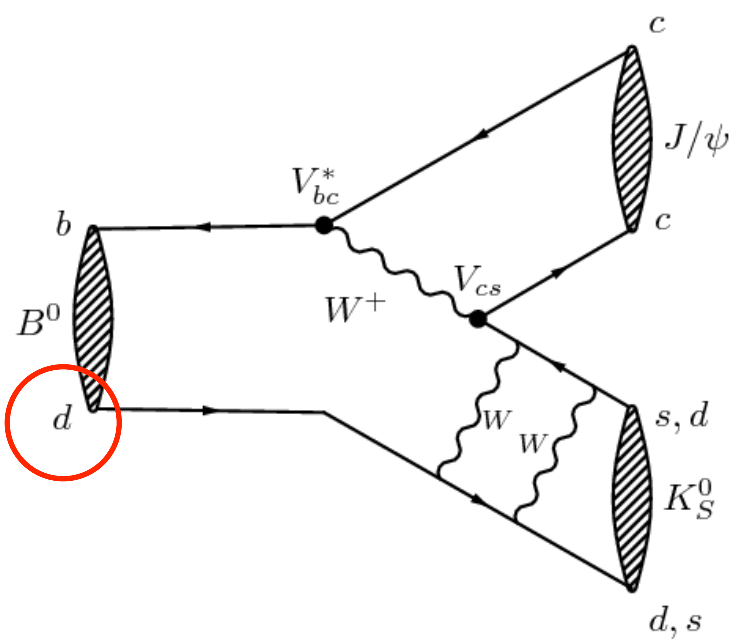
$$D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}.$$

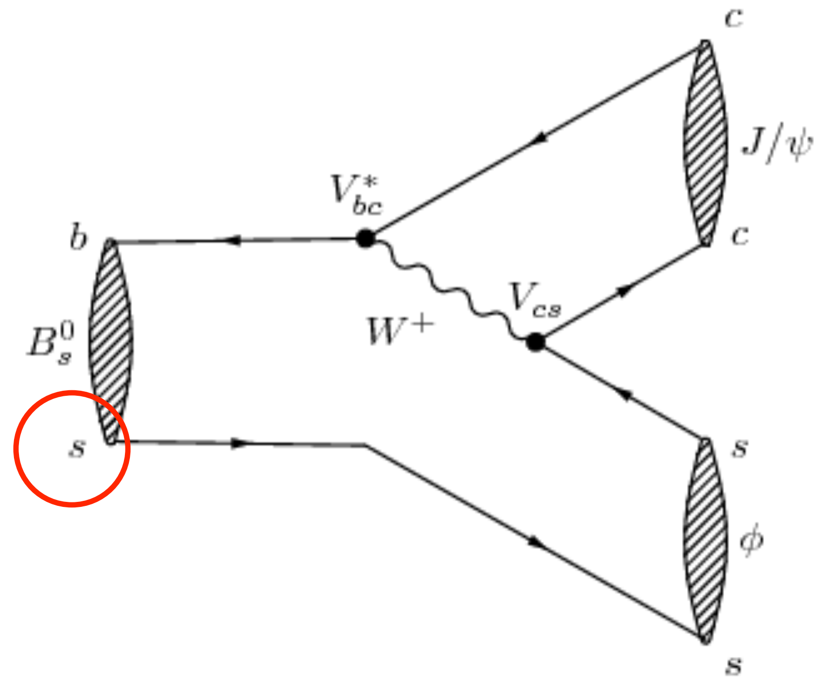
$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f \cos\Delta m t - 2S_f \sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f \sinh\frac{1}{2}\Delta\Gamma t}$$

$|\lambda_f|=1$ $\qquad$ $\Delta\Gamma=0$

$$A_{CP}(t) = -\Im\lambda_f \sin(\Delta m t)$$

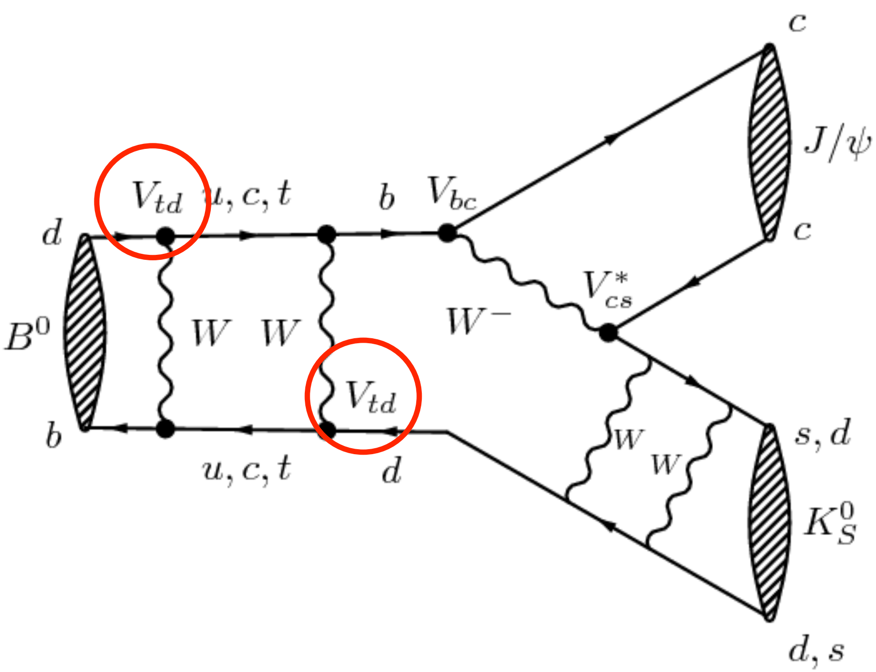
β_s: $B_s^0 \rightarrow J/\psi\varphi$: B_s^0 analogue of $B^0 \rightarrow J/\psi K^0_S$

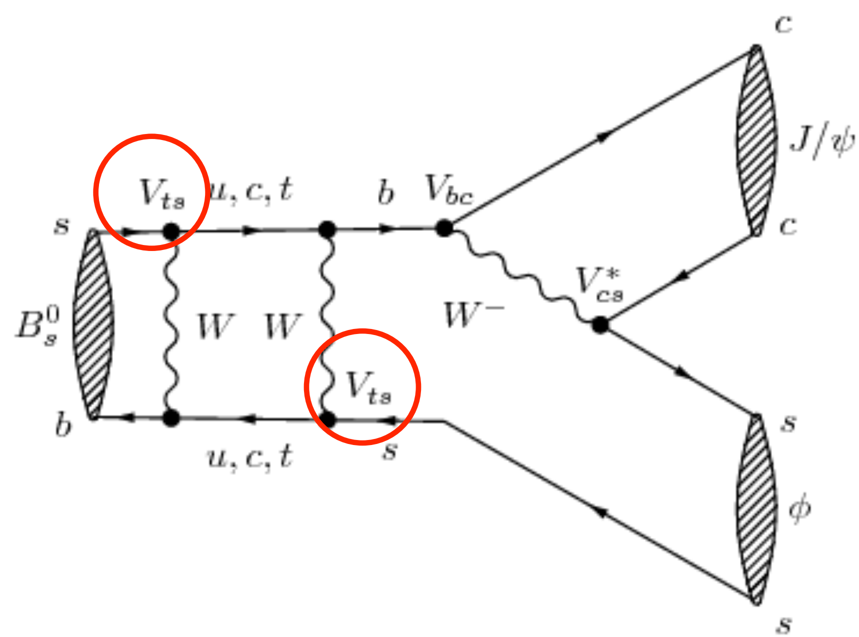




- Replace spectator quark d → s

β_s: $B_s^0 \to J/\psi\varphi$: B_s^0 analogue of $B^0 \to J/\psi K^0_S$



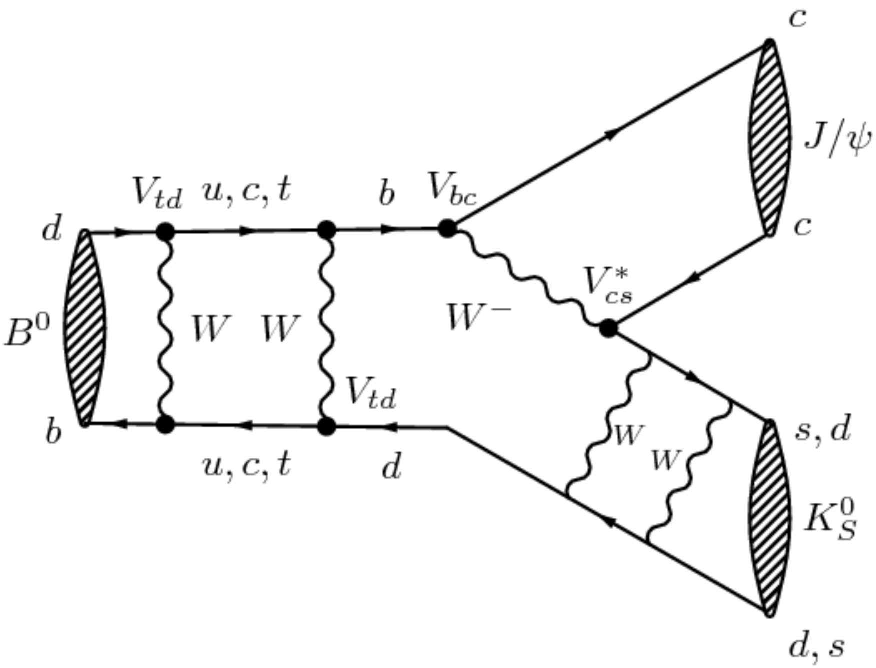


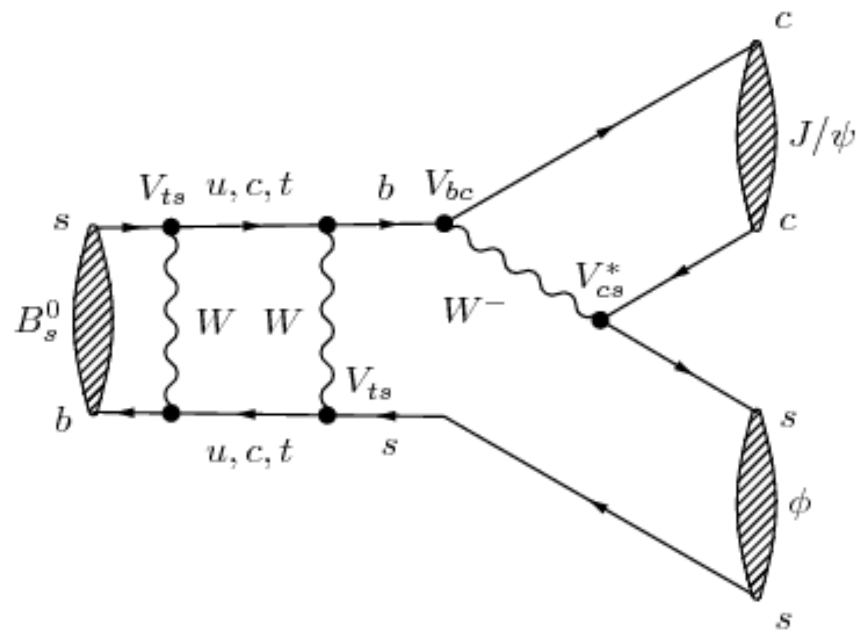
$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

$$V_{CKM,\text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

β_s: $B_s^0 \to J/\psi\varphi$: B_s^0 analogue of $B^0 \to J/\psi K^0_S$





Differences:

	B^0	B^0_s
CKM	V_{td}	V_{ts}
$\Delta\Gamma$	~0	~0.1
Final state (spin)	K^0 : s=0	φ: s=1
Final state (K)	K^0 mixing	-

β_s: $B_s^0 \rightarrow J/\psi\phi$

$$A_{CP}(t) = \frac{\Gamma_{B_s^0(t)\rightarrow J/\psi\phi} - \Gamma_{\bar{B}_s^0(t)\rightarrow J/\psi\phi}}{\Gamma_{B_s^0(t)\rightarrow J/\psi\phi} + \Gamma_{\bar{B}_s^0(t)\rightarrow J/\psi\phi}} = \frac{-\Im\lambda_{J/\psi\phi}\sin\Delta m t}{\cosh\frac{1}{2}\Delta\Gamma t + \Re\lambda_{J/\psi\phi}\sinh\frac{1}{2}\Delta\Gamma t}$$

$$\lambda_{J/\psi\phi} = \left(\frac{q}{p}\right)_{B_s^0}\left(\eta_{J/\psi\phi}\frac{\bar{A}_{J/\psi\phi}}{A_{J/\psi\phi}}\right) = (-1)^l\left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\right)\left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)$$

$$\Im\lambda_{J/\psi\phi} = (-1)^l\sin(-2\beta_s)$$

$$CP|J/\psi\phi\rangle_l = (-1)^l|J/\psi\phi\rangle_l$$

V_{ts} large, oscilations fast, need good vertex detector

3 amplitudes

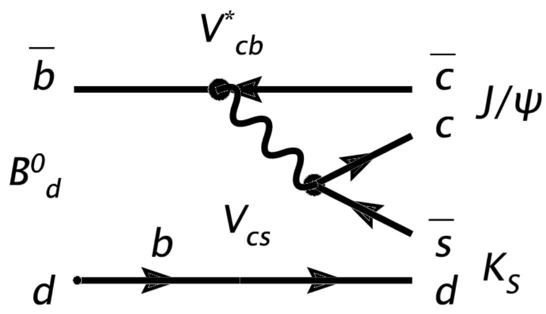
$A_\parallel$ ↑↑	*l=2*
$A_\perp$ ↑→	*l=1*
A_0 ↑↓	*l=0*

	B^0	B^0_s
CKM	V_{td}	V_{ts}
$\Delta\Gamma$	~0	~0.1
Final state (spin)	K^0 : s=0	φ: s=1
Final state (K)	K^0 mixing	-

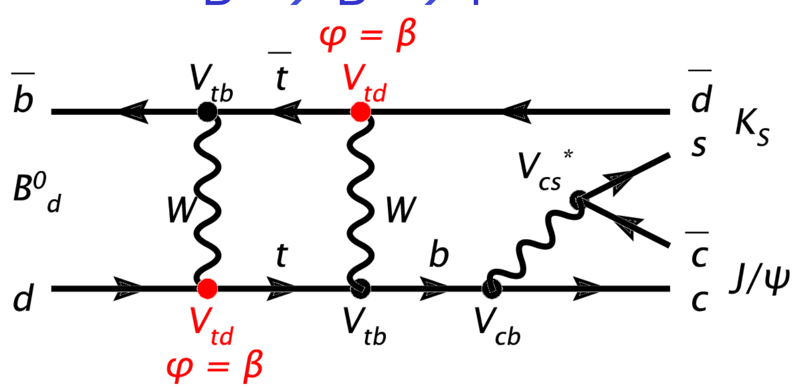
$B_s \rightarrow J/\psi\Phi$: B_s equivalent of $B \rightarrow J/\psi K_s$!

- The mixing phase (V_{td}): $\varphi_d = 2\beta$

$B^0 \rightarrow f$



$B^0 \rightarrow \overline{B^0} \rightarrow f$



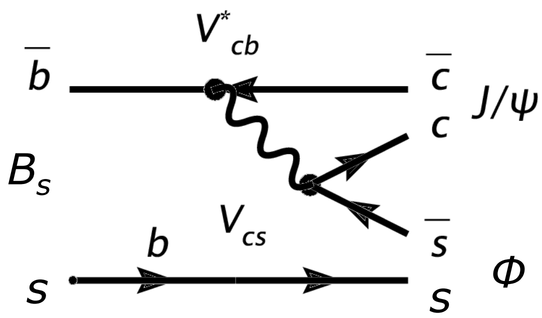
Wolfenstein parametrization to O(λ^5):

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

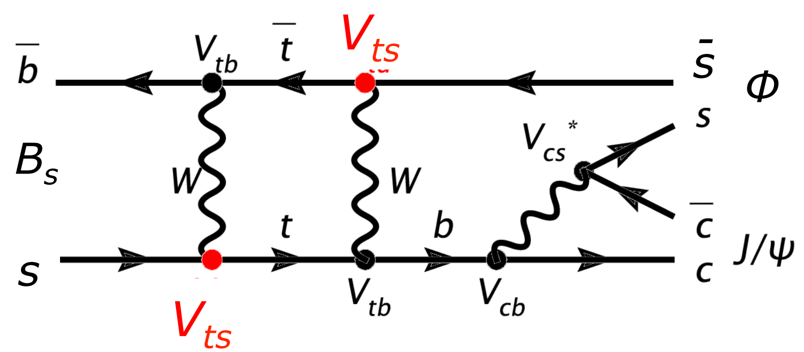
$B_s \to J/\psi\Phi$: B_s equivalent of $B \to J/\psi K_s$!

- The mixing phase (V_{ts}): $\varphi_s = -2\beta_s$

$B^0 \to f$



$B^0 \to \overline{B^0} \to f$

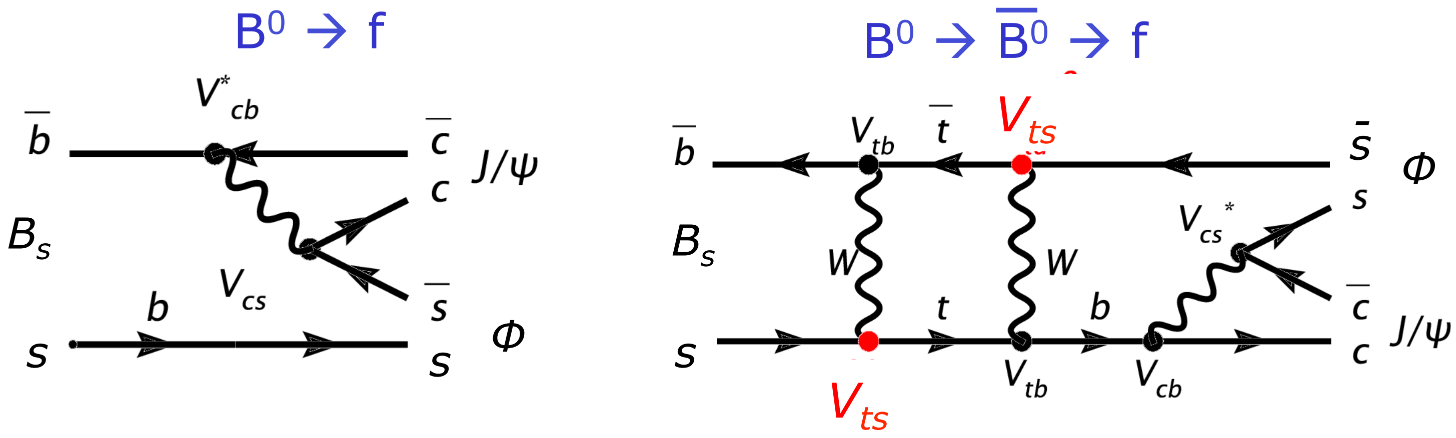


Wolfenstein parametrization to O(λ^5):

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$B_s \rightarrow J/\psi\Phi$: B_s equivalent of $B \rightarrow J/\psi K_s$!

- The mixing phase (V_{ts}): $\varphi_s = -2\beta_s$



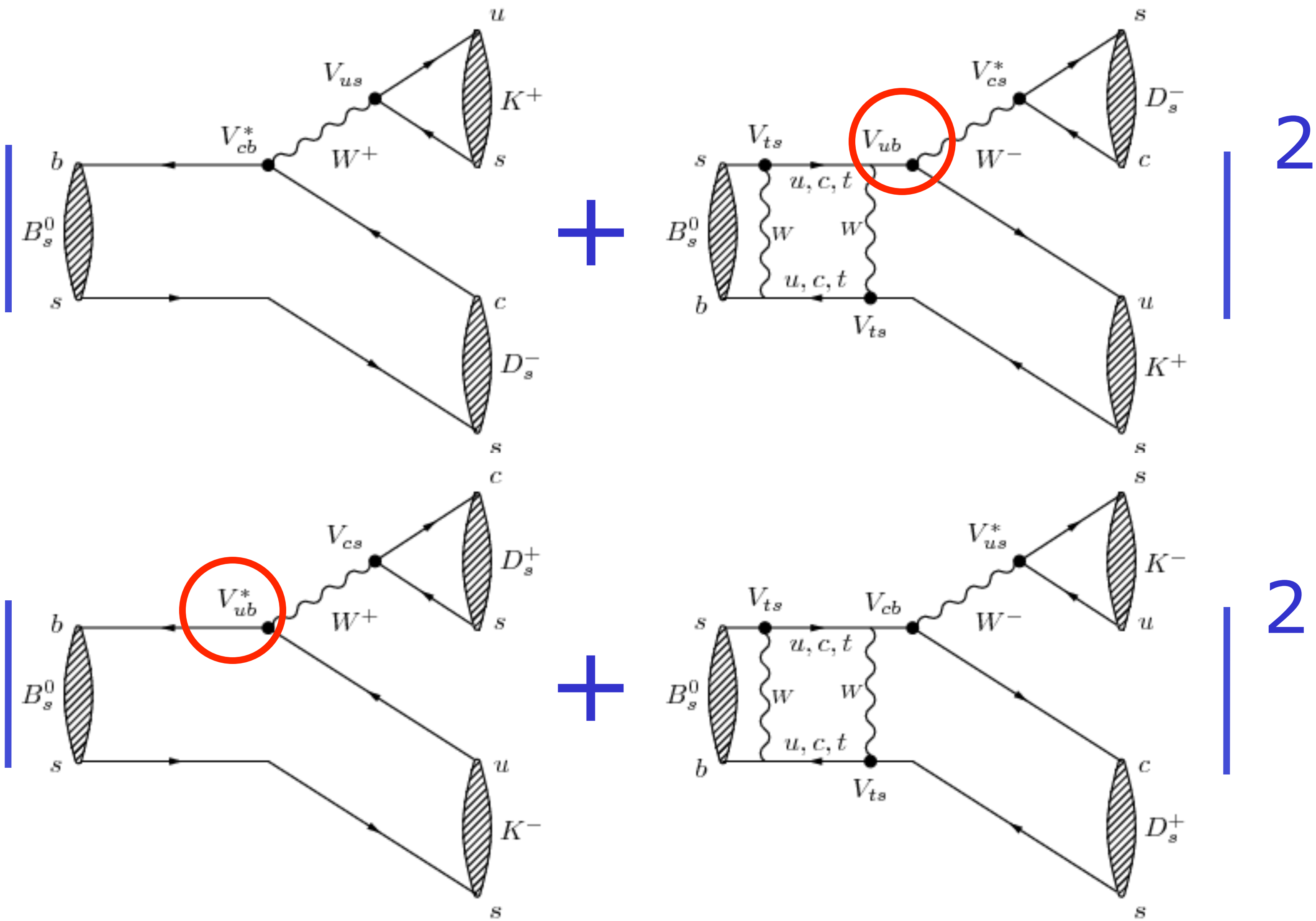
$$V_{CKM,\text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

Other angles

Measure γ: $B^0_s \rightarrow D_s^{\pm}K^{-/+}$: both λ_f and $\lambda_{\bar{f}}$

$\Gamma(B\rightarrow f)=$

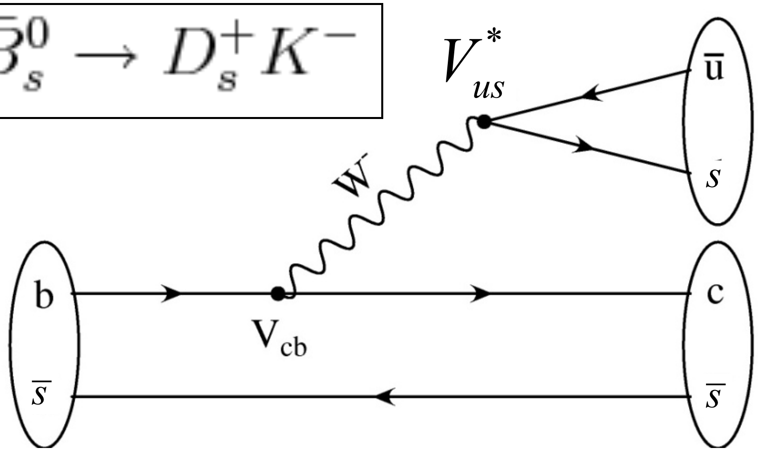
$\Gamma(B\rightarrow \bar{f})=$



NB: In addition $\bar{B}_s \rightarrow D_s^{\pm}K^{-/+}$: both $\bar{\lambda}_f$ and $\bar{\lambda}_{\bar{f}}$

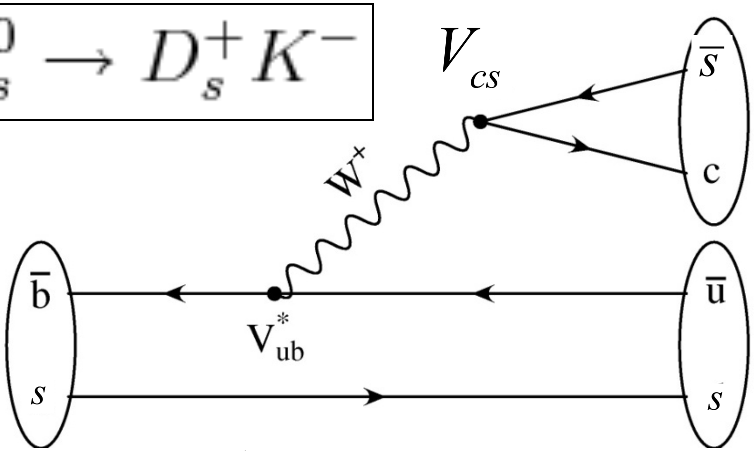
Measure γ: $B_s \rightarrow D_s^{\pm}K^{-/+}$ --- first one f: $D_s^+K^-$

$\bar{B}_s^0 \rightarrow D_s^+ K^-$



$V_{cb}V_{us}^* \propto \lambda^3$

$B_s^0 \rightarrow D_s^+ K^-$



$V_{ub}^*V_{cs} \propto \lambda^3 e^{i\gamma}$

- This time $|A_f| \neq |\bar{A}_f|$, so $|\lambda| \neq 1$!

$$\left(\frac{\bar{A}_{D_s^-K^+}}{A_{D_s^-K^+}}\right) = \left(\frac{V_{ub}V_{cs}^*}{V_{cb}^*V_{us}}\right)\left(\frac{A_2}{A_1}\right) \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- In fact, not only magnitude, but also phase difference:

$$\frac{A_{D_s^-K^+}}{\bar{A}_{D_s^-K^+}} = \frac{|A_{D_s^-K^+}|}{|\bar{A}_{D_s^-K^+}|}e^{i(\delta_s-\gamma)}$$

Measure γ: $B_s \rightarrow D_s^{\pm}K^{-/+}$

- $B^0_s \rightarrow D_s^- K^+$ has phase difference (δ - γ):

$$\frac{A_{D_s^- K^+}}{\bar{A}_{D_s^- K^+}} = \frac{|A_{D_s^- K^+}|}{|\bar{A}_{D_s^- K^+}|} e^{i(\delta_s - \gamma)}$$

- Need $B^0_s \rightarrow D_s^+ K^-$ to disentangle δ and γ:

$$\lambda_{D_s^- K^+} = \left(\frac{q}{p}\right)_{B_s^0} \left(\frac{\bar{A}_{D_s^- K^+}}{A_{D_s^- K^+}}\right) = \left|\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right| \left|\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}}\right| \left|\frac{A_2}{A_1}\right| e^{i(-2\beta_s - \gamma + \delta_s))}$$

$$\lambda_{D_s^+ K^-} = \left(\frac{q}{p}\right)_{B_s^0} \left(\frac{\bar{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}}\right) = \left|\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right| \left|\frac{V_{us}^* V_{cb}}{V_{cs} V_{ub}^*}\right| \left|\frac{A_1}{A_2}\right| e^{i(-2\beta_s - \gamma - \delta_s))}$$

Next

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

$$\Im \lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

γ

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

1) $B^- \to \overset{(-)}{D^0} K^-$ (Time integrated)

2) $B_s^0 \to D_s^{\pm} K^{+-}$ (Time dependent)

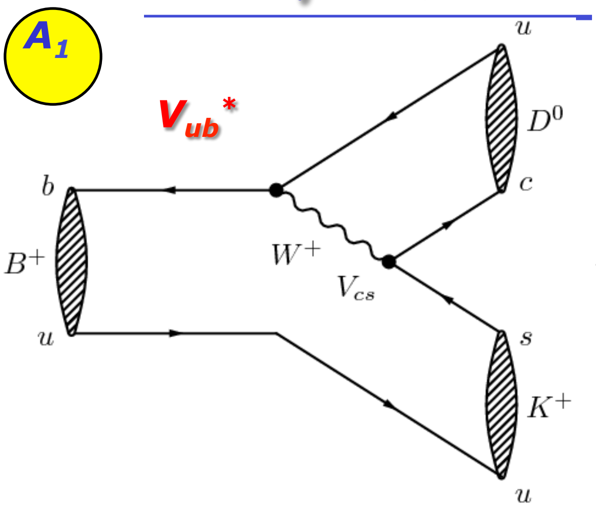
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

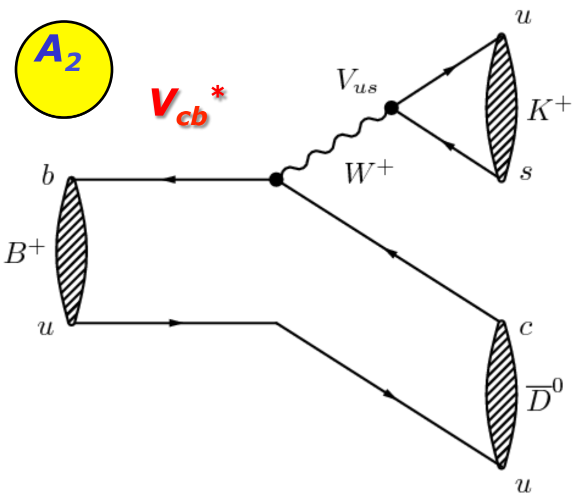
Necessary ingredients for CP violation:

1) Two (interfering) amplitudes
2) Phase difference between amplitudes
   - ***one CP conserving phase ('strong' phase)***
   - ***one CP violating phase ('weak' phase)***

γ (GLW)

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



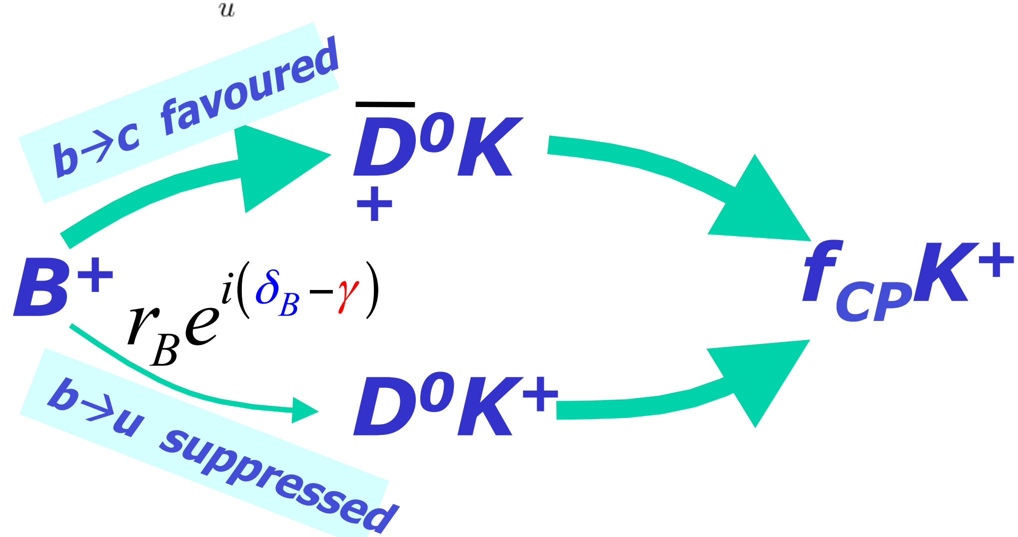


$B^- \to D^0(\overline{D}^0)K^-$

- Relative phase: γ

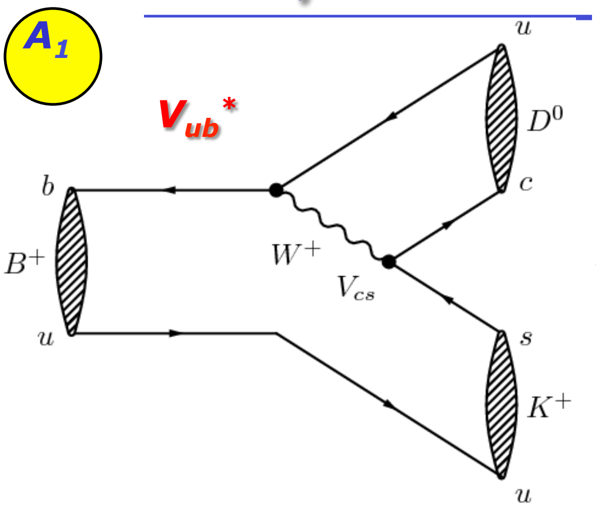
GLW:

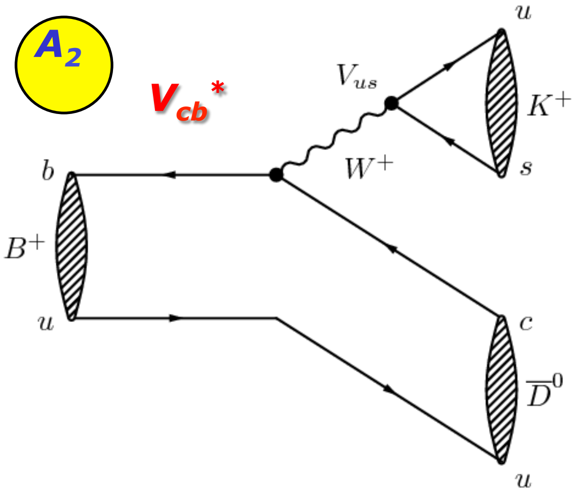
CP eigenstate: $D^0 \to K^+K^-(\pi\pi)$



γ (GLW)

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



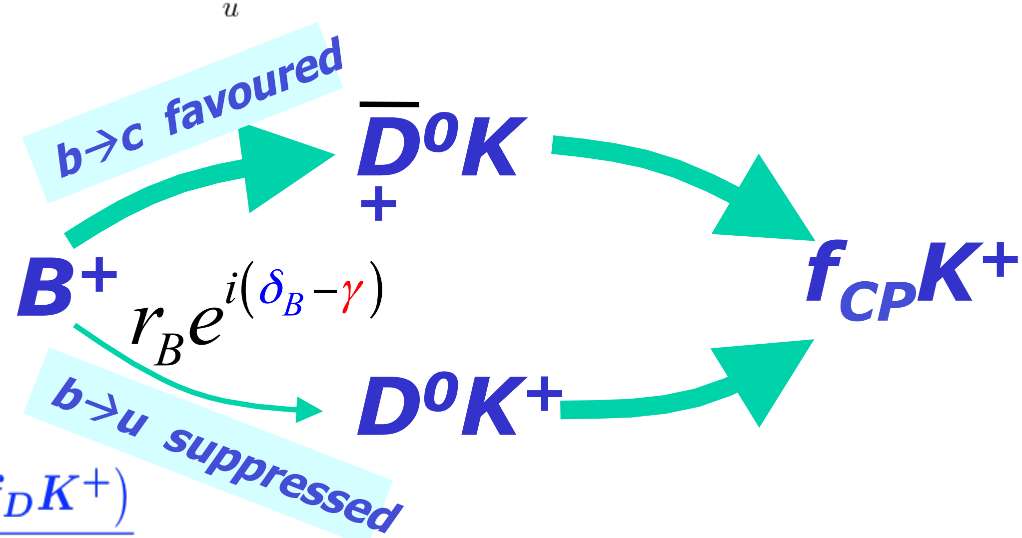


$B^- \to D^0(\overline{K^-})$

- **Relative phase:** γ

GLW:

CP eigenstate: $D^0 \to K^+K^-(\pi\pi)$

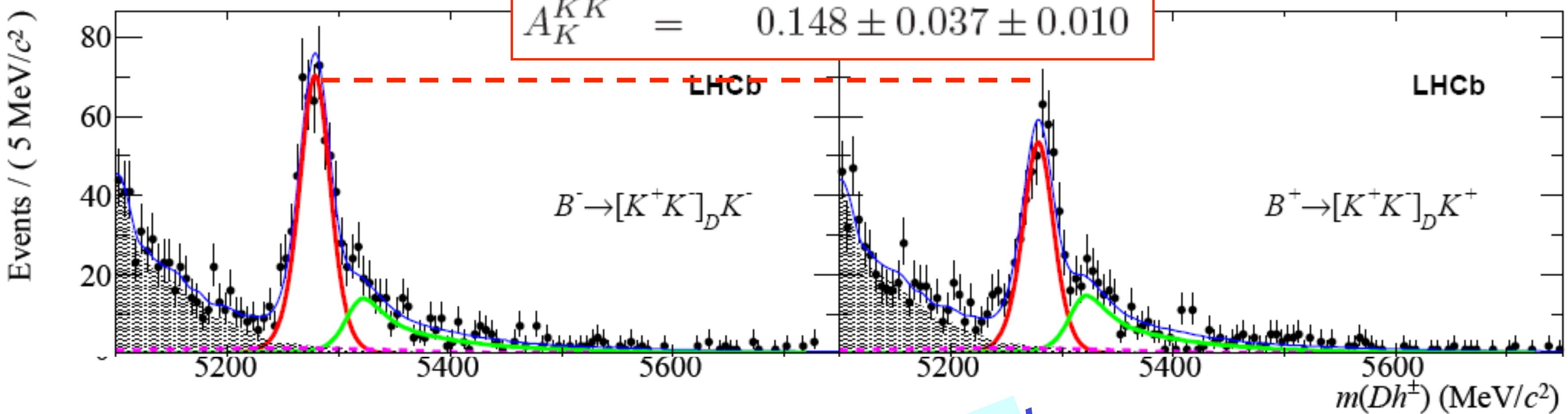


$$A_{CP+} = \frac{\Gamma(B^- \to f_D K^-) - \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)}$$

$$R_{CP+} = \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to D^0 K^+)}$$

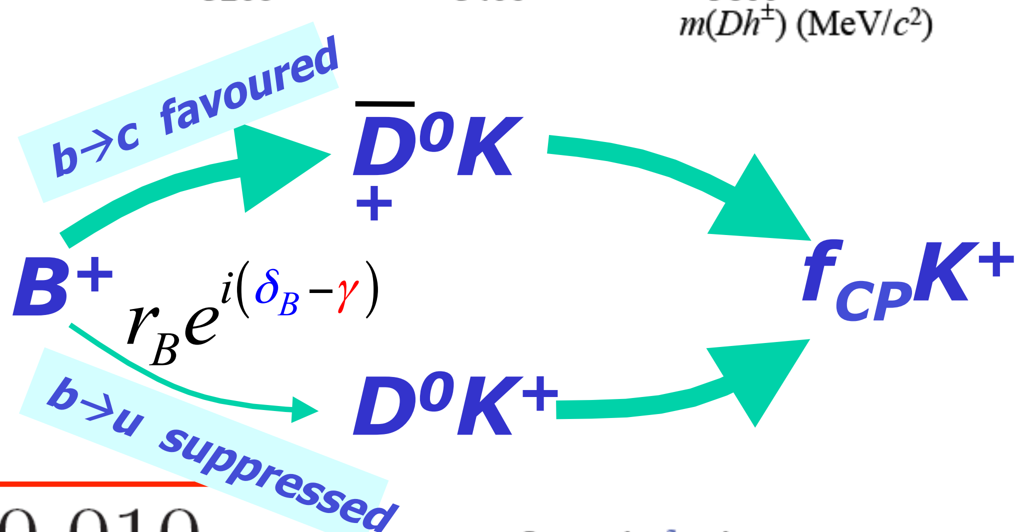
γ (GLW)

$A_K^{KK} = 0.148 \pm 0.037 \pm 0.010$



GLW:

CP eigenstate: $D^0 \to K^+K^-(\pi\pi)$



$A_{CP+} = 0.145 \pm 0.032 \pm 0.010$

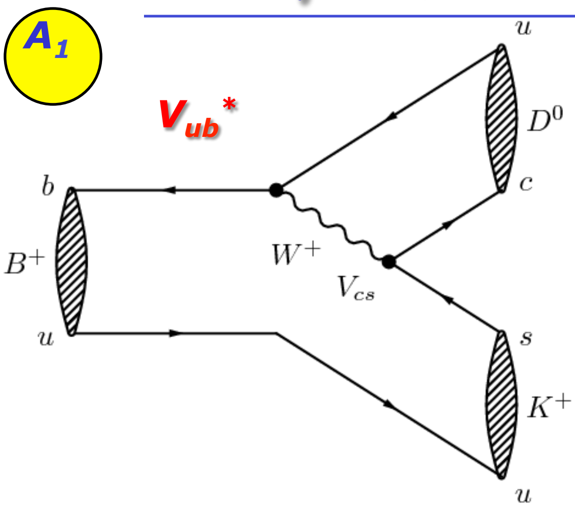
$R_{CP+} = 1.007 \pm 0.038 \pm 0.012$

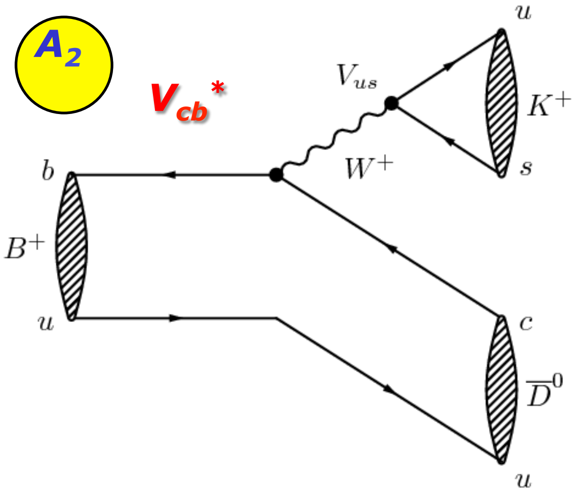
$$A_{CP+} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{R_{CP+}}$$

$$R_{CP+} = 1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma$$

γ (ADS)

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



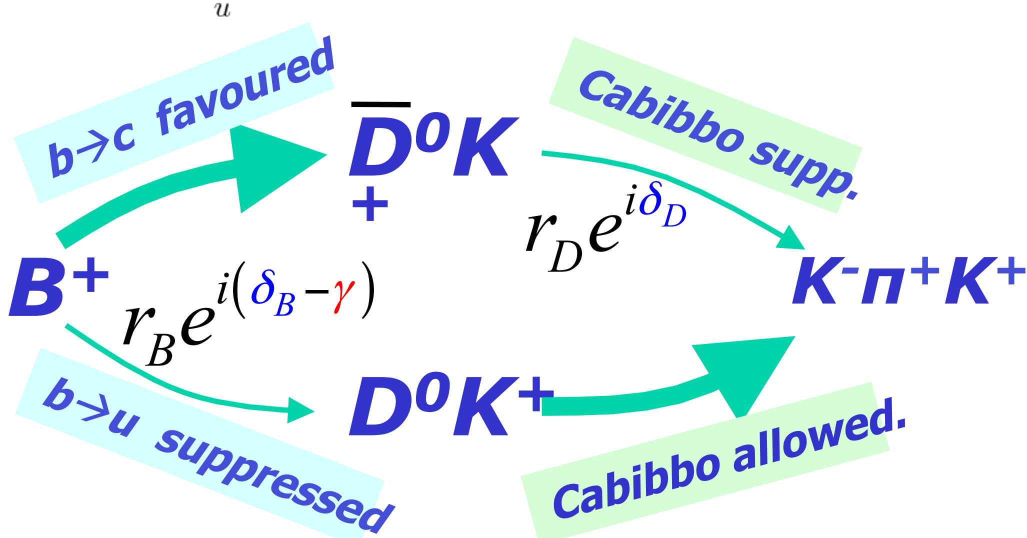


$B^- \to \overset{(-)}{D^0} K^-$

- Relative phase: γ

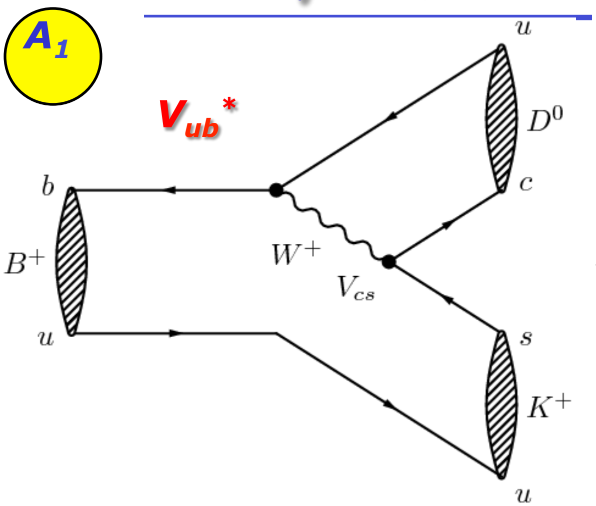
ADS:

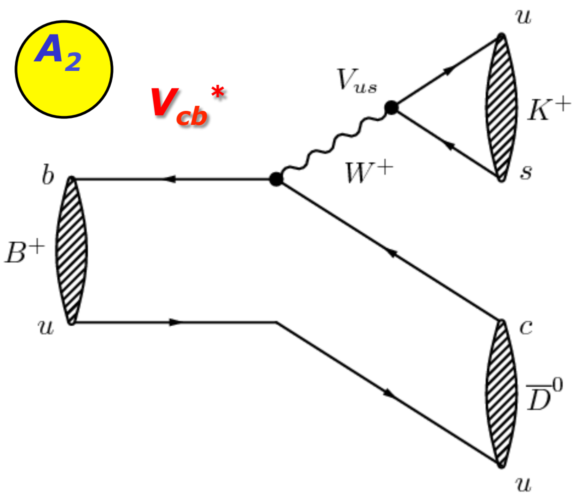
B or D Cabibbo favoured: $D^0 \to K^+\pi^-$



γ (ADS)

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



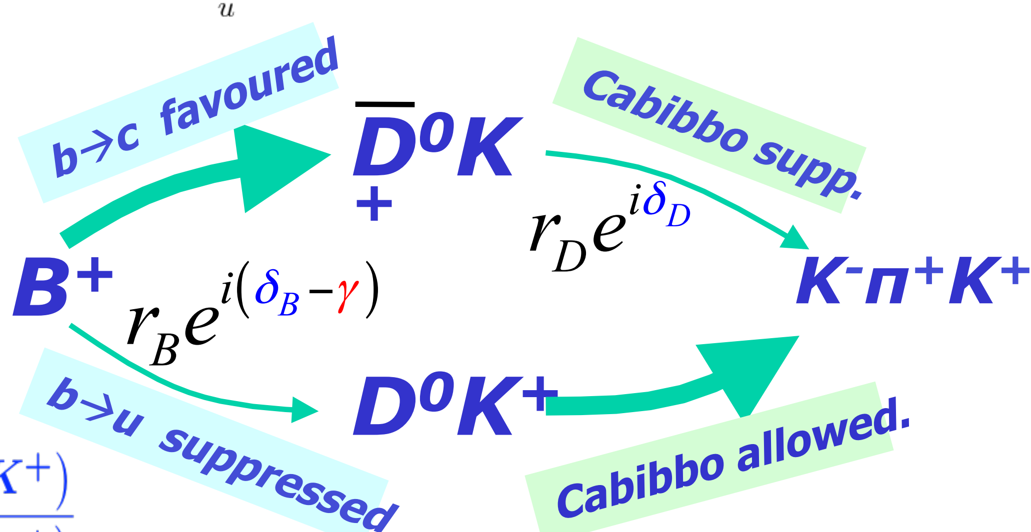


$B^- \to D^0 K^-$

- **Relative phase: γ**

ADS:

B or D Cabibbo favoured: $D^0 \to K^+\pi^-$



$$A_{ADS} = \frac{\Gamma\left(B^- \to f_D K^-\right) - \Gamma\left(B^+ \to \overline{f_D} K^+\right)}{\Gamma\left(B^- \to f_D K^-\right) + \Gamma\left(B^+ \to \overline{f_D} K^+\right)}$$

"Difference in suppression"

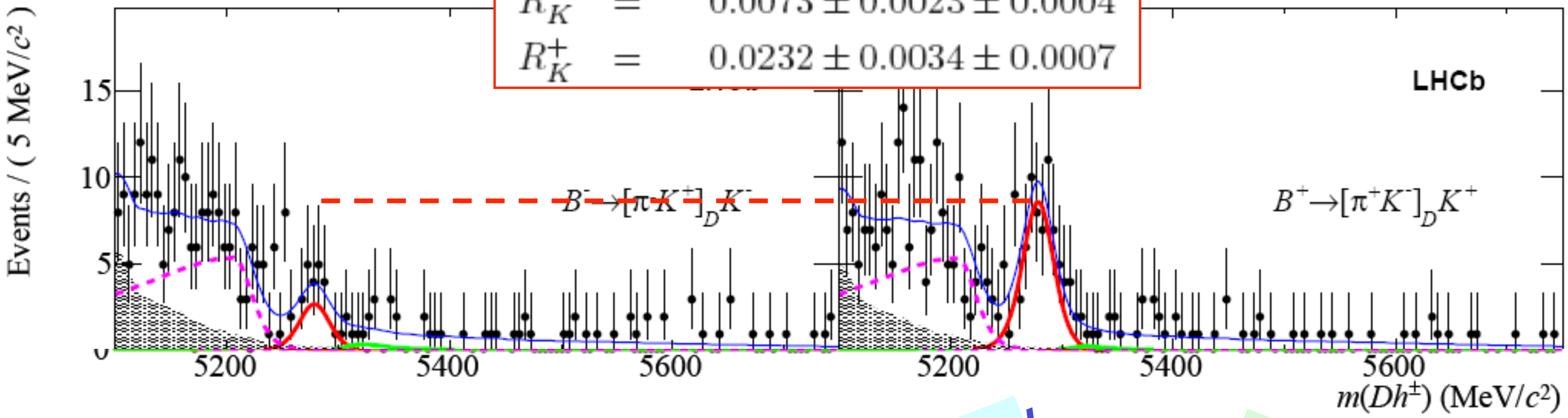
$$R_{ADS} = \frac{\Gamma\left(B^- \to f_D K^-\right) + \Gamma\left(B^+ \to \overline{f_D} K^+\right)}{\Gamma\left(B^- \to \overline{f_D} K^-\right) + \Gamma\left(B^+ \to f_D K^+\right)}$$

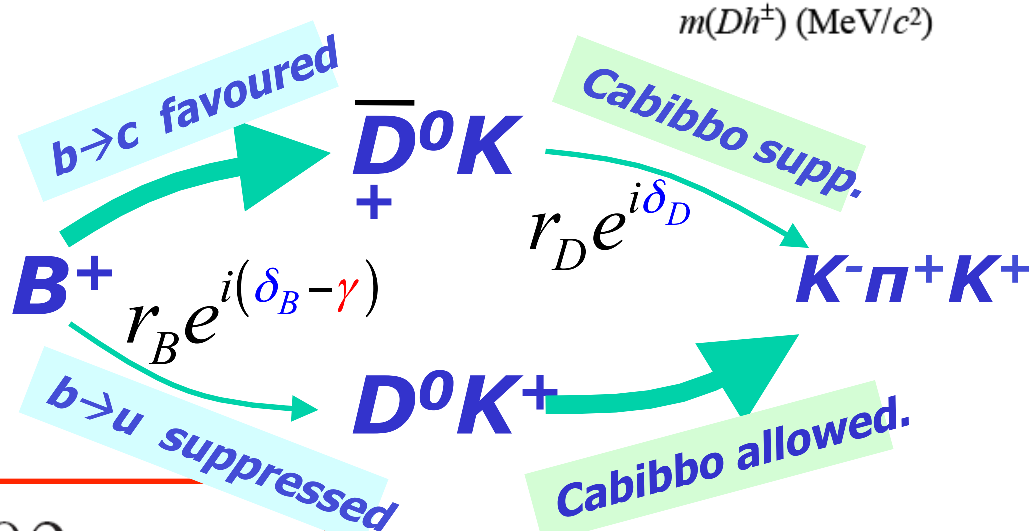
"Average suppression"

γ (ADS)

Suppressed mode for the B^- is relatively more suppressed than for the B^+...

$$R_K^- = 0.0073 \pm 0.0023 \pm 0.0004$$
$$R_K^+ = 0.0232 \pm 0.0034 \pm 0.0007$$





ADS:

B or D Cabibbo favoured: $D^0 \to K^+\pi^-$

BR~ 2 x 10^{-7}

$$A_{ADS} = -0.52 \pm 0.15 \pm 0.02 \quad = 2\kappa r_B r \sin(\delta_B + \delta_D)\sin\gamma / \mathcal{R}_s^{ADS}$$

$$R_{ADS} = 0.0152 \pm 0.0020 \pm 0.0004 \quad = r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

Another example of CP violation in decay

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

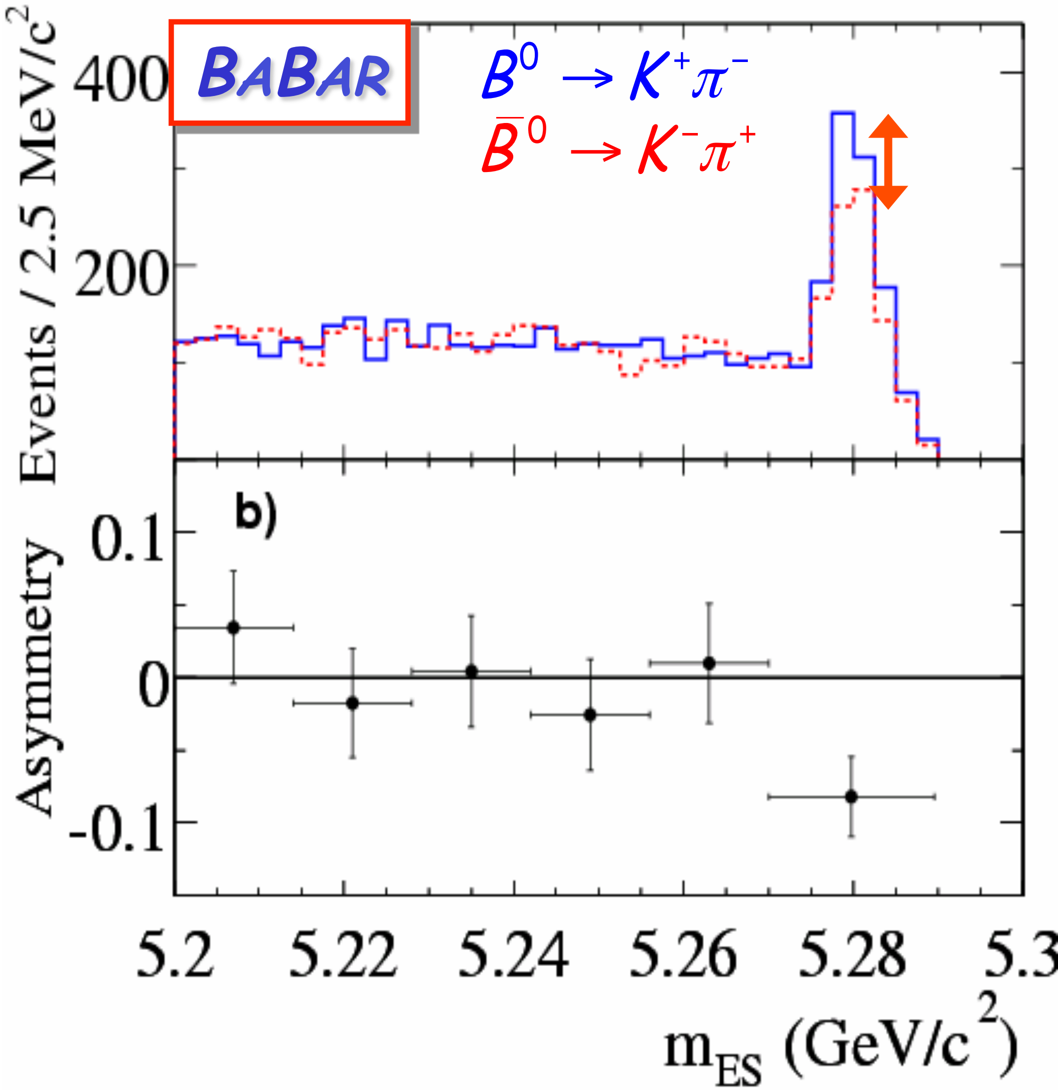
$$\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

$$\Im \lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

CP violation in Decay? *(also known as: "direct CPV")*

First observation of Direct CPV in B decays (2004):

$$A_{CP} = \frac{\Gamma_{\bar{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\bar{B}\to\bar{f}} + \Gamma_{B\to f}}$$



BABAR

hep-ex/0407057
Phys.Rev.Lett.93:131801,2004

$A_{CP} = -0.133 \pm 0.030 \pm 0.009$

4.2σ

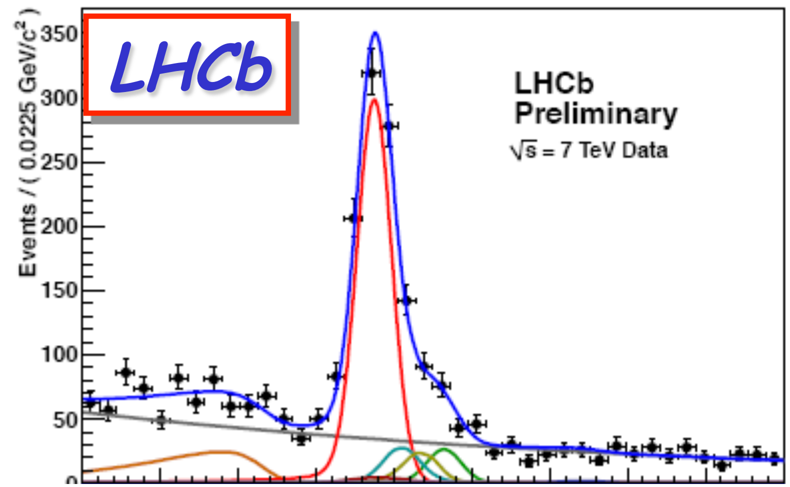
HFAG:

$A_{CP} = -0.098 \pm 0.012$

CP violation in Decay? *(also known as: "direct CPV")*

First observation of Direct CPV in B decays at LHC (2011):

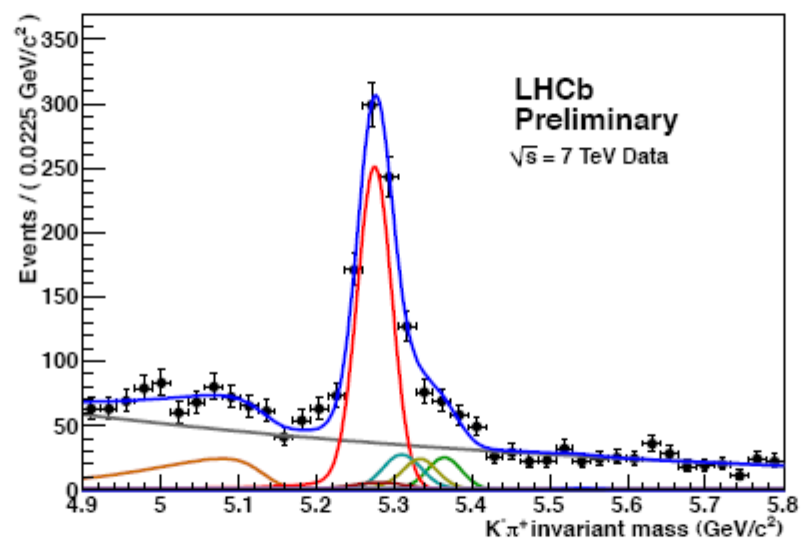
$$A_{CP} = \frac{\Gamma_{\bar{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\bar{B}\to\bar{f}} + \Gamma_{B\to f}}$$



LHCb

LHCb-CONF-2011-011

$$A_{CP}(B^0 \to K^+\pi^-) = -0.074 \pm 0.033 \pm 0.008$$



Remember!

Necessary ingredients for CP violation:

1) Two (interfering) amplitudes

2) Phase difference between amplitudes

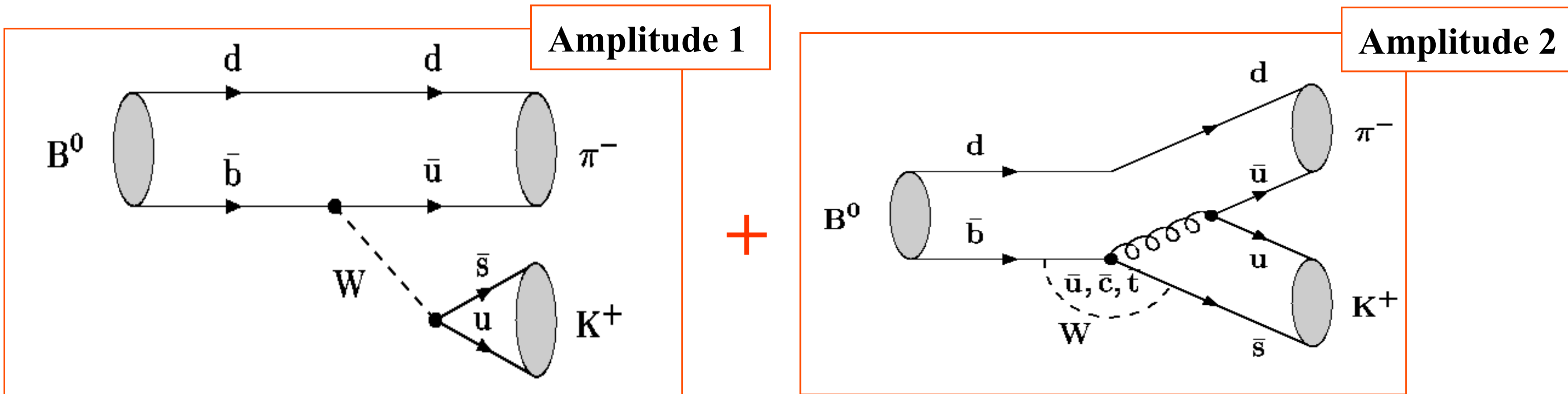
- one CP conserving phase (‘strong’ phase)
- one CP violating phase (‘weak’ phase)

2 amplitudes
2 phases

Direct CP violation: $\Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow \bar{f})$

CP violation if $\Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow \bar{f})$

But: need 2 amplitudes → interference



$$\Gamma(B^0 \rightarrow K^+\pi^-) \propto \left| V_{ub}^* V_{us} e^{i\delta} + V_{tb}^* V_{ts} \right|^2 \approx \left| \lambda^4 e^{+i\gamma+i\delta} + \lambda^2 \right|^2$$

$$\Gamma(\bar{B}^0 \rightarrow K^-\pi^+) \propto \left| V_{ub} V_{us}^* e^{i\delta} + V_{tb} V_{ts}^* \right|^2 \approx \left| \lambda^4 e^{-i\gamma+i\delta} + \lambda^2 \right|^2$$

Only different if both δ and γ are ≠0 !

→ $\Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow \bar{f})$

Hint for new physics? $B^0 \rightarrow K\pi$ and $B^\pm \rightarrow K^\pm\pi^0$

Redo the experiment with $B^\pm$ instead of B^0…

d or **u** spectator quark: what's the difference ??

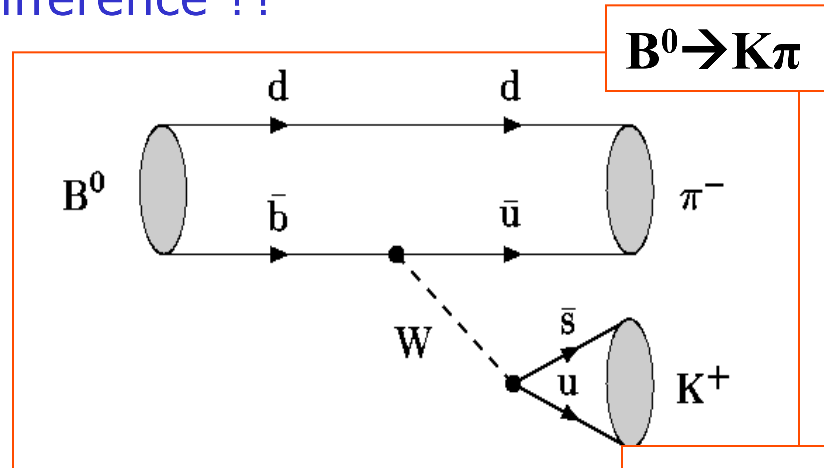
$B^0 \rightarrow K^+\pi^-$

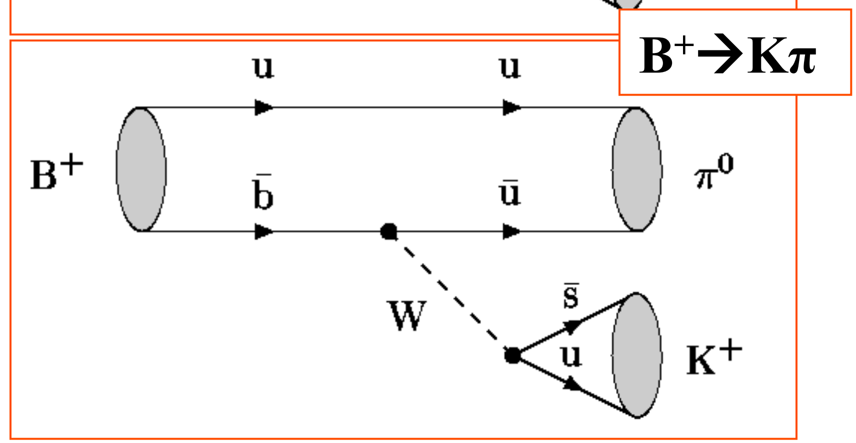
Average $A_{CP} = -0.114 \pm 0.020$

3.6σ ?

$B^+ \rightarrow K^+\pi^0$

Average $A_{CP} = +0.049 \pm 0.040$





Mode	$\mathcal{A}_{CP}$	$\mathcal{S}(\sigma)$
$K^+\pi^-$	$-0.093 \pm 0.018 \pm 0.008$	4.7
$K^+\pi^0$	$+0.07 \pm 0.03 \pm 0.01$	2.3

Hint for new physics? $B^0 \to K\pi$ and $B^\pm \to K^\pm\pi^0$

$B \to K\pi$ PUZZLE

- with small *arg(C/T)* (or just small *C*)

$$A_{CP}(B^0 \to K^+\pi^-) \simeq A_{CP}(B^+ \to K^+\pi^0)$$

- experimentally

$$A_{CP}(B^+ \to K^+\pi^0) = 0.050 \pm 0.025$$
$$A_{CP}(B^0 \to K^+\pi^-) = -0.098^{+0.012}_{-0.011}$$

- so large *C* and large *arg(C/T)*
  - problematic for SCET/QCDF
  - large $1/m_b$?
  - in pQCD the large phase claimed from Glauber gluons

Li, Mishima, 0901.1272

- or NP?: presence of isospin violating NP can be tested precisely

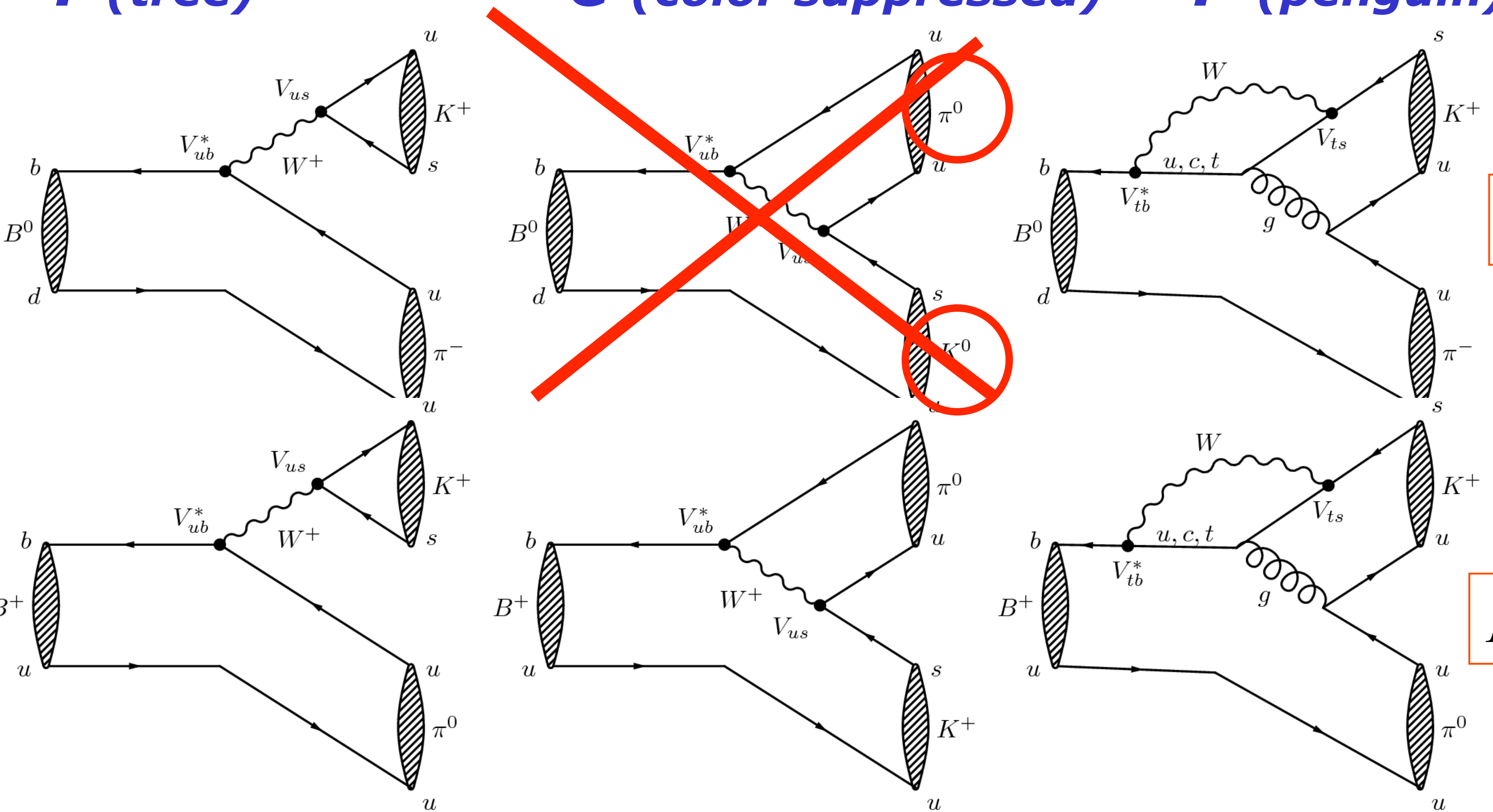
Hint for new physics? $B^0 \to K\pi$ and $B^\pm \to K^\pm\pi^0$

- with small $arg(C/T)$ (or just small C)

$$A_{CP}(B^0 \to K^+\pi^-) \simeq A_{CP}(B^+ \to K^+\pi^0)$$

- so large C and large $arg(C/T)$

T (tree) ***C (color suppressed)*** ***P (penguin)***



$B^0 \to K^+\pi^-$

$B^+ \to K^+\pi^0$

Next

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\text{Prob}(P^0 \to \bar{P}^0) \neq \text{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\leadsto \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\leadsto P^0)} \to f)(t)$$

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

CP violation in Mixing? *(also known as: "indirect CPV": ε≠0 in K-system)*

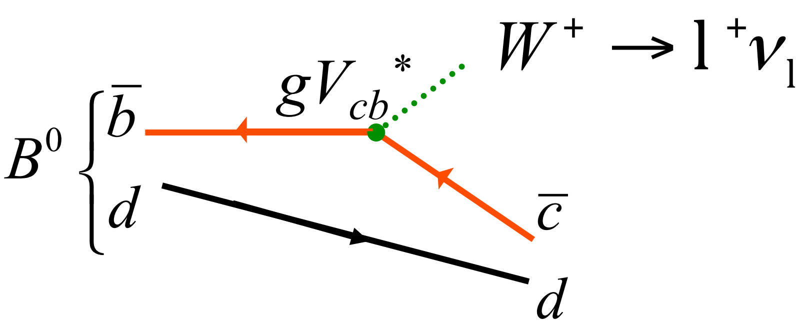
$$P\left(B^0 \rightarrow \overline{B}^0\right) \stackrel{?}{=} P\left(\overline{B}^0 \rightarrow B^0\right)$$

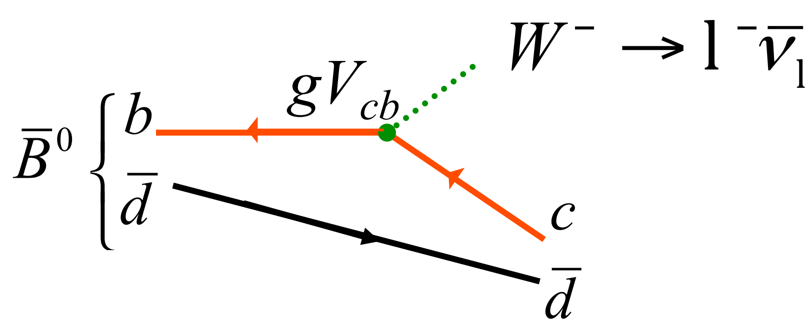
t=0	t	Decay
$B^0\overline{B}^0$	$B^0\overline{B}^0$	$\rightarrow l^+l^-X$
	$B^0 B^0$	$\rightarrow l^+l^+X$
	$\overline{B}^0\overline{B}^0$	$\rightarrow l^-l^-X$
	$\overline{B}^0 B^0$	$\rightarrow l^-l^+X$

Look for like-sign lepton pairs:

$l^+l^+X \propto P\left(\overline{B}^0 \rightarrow B^0\right)$

$l^-l^-X \propto P\left(B^0 \rightarrow \overline{B}^0\right)$





(limit on) CP violation in B^0 mixing

Search for T and CP Violation in B^0-$\overline{B}^0$ Mixing with Inclusive Dilepton Events

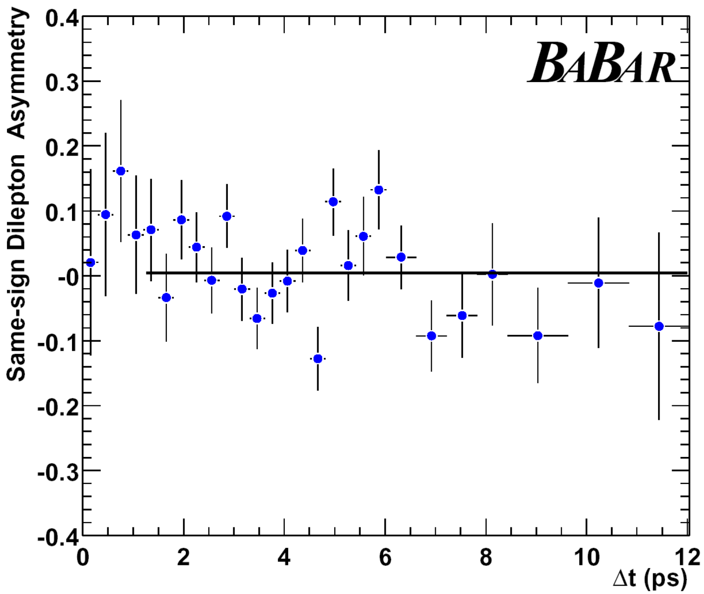


FIG. 3: Corrected same-sign dilepton asymmetry as a function of Δt. The line shows the result of the fit for the dileptons with $\Delta z > 200\ \mu$m.

Look for a like-sign asymmetry:

$$A_T(\Delta t) = \frac{N_{++}(\Delta t) - N_{--}(\Delta t)}{N_{++}(\Delta t) + N_{--}(\Delta t)} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

As expected, no asymmetry is observed…

$$\left|\frac{q}{p}\right| = 1$$

We report the results of a search for T and CP violation in B^0-$\overline{B}^0$ mixing using an inclusive dilepton sample collected by the BABAR experiment at the PEP-II B Factory. The asymmetry between $\ell^+\ell^+$ and $\ell^-\ell^-$ events allows us to compare the probabilities for $\overline{B}^0 \to B^0$ and $B^0 \to \overline{B}^0$ oscillations and thus probe T and CP invariance. Using a sample of 23 million $B\overline{B}$ pairs, we measure a same-sign dilepton asymmetry of $A_{T/CP} = (0.5 \pm 1.2(\text{stat}) \pm 1.4(\text{syst}))\,\%$. For the modulus of the ratio of complex mixing parameters p and q, we obtain $|q/p| = 0.998 \pm 0.006(\text{stat}) \pm 0.007(\text{syst})$.

Remember!

Necessary ingredients for CP violation:

1) Two (interfering) amplitudes

2) Phase difference between amplitudes

- one CP conserving phase ('strong' phase)
- one CP violating phase ('weak' phase)

2 amplitudes
2 phases

CP violation in B_s^0 Mixing??

D0 Coll.,
Phys.Rev.D82:032001,2010.
arXiv:1005.2757

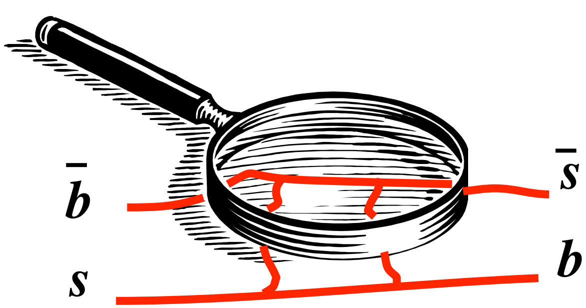
Fermilab-Pub-10/114-E

Evidence for an anomalous like-sign dimuon charge asymmetry

V.M. Abazov,[36] B. Abbott,[74] M. Abolins,[63] B.S. Acharya,[29] M. Adams,[49] T. Adams,[47] E. Aguilo,[6] G.D. Alexeev,[36]

$$B^0\bar{B}^0 \to \begin{cases} B^0\bar{B}^0 \to l^+l^-X \\ B^0B^0 \to l^+l^+X & \propto P\left(\bar{B}^0 \to B^0\right) \\ \bar{B}^0\bar{B}^0 \to l^-l^-X & \propto P\left(B^0 \to \bar{B}^0\right) \\ \bar{B}^0B^0 \to l^-l^+X \end{cases}$$

"Box" diagram: ΔB=2



$$\Delta M_q = 2\left|M_q^{12}\right|, \qquad \Delta\Gamma_q = 2\left|\Gamma_q^{12}\right|\cos\phi_q$$

$$a = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi$$

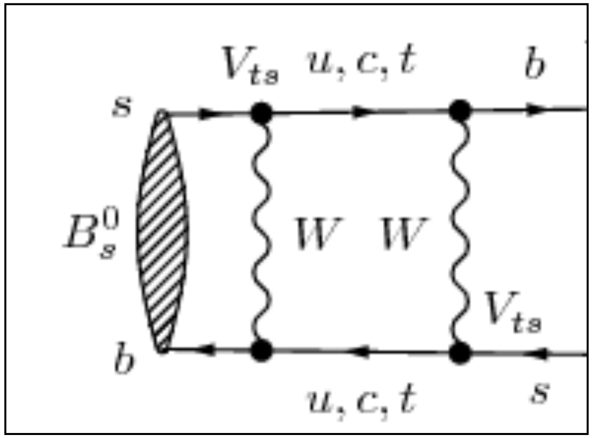
$$\phi = \phi_M - \arg(-\Gamma_{12})$$

$\varphi_s^{SM} \sim 0.004$
$\varphi_{s\,M}^{SM} \sim 0.04$

CP violation from Semi-leptonic decays

- ***SM:*** $P(B^0_s \rightarrow \bar{B}^0_s) = P(B^0_s \leftarrow \bar{B}^0_s)$
- ***DØ:*** $P(B^0_s \rightarrow \bar{B}^0_s) \neq P(B^0_s \leftarrow \bar{B}^0_s)$

?



- ***b→Xμ⁻ν, b→Xμ⁺ν***
- ***$\bar{b}$→b → Xμ⁺ν, b→ $\bar{b}$ → Xμ⁻ν***

➢ Compare events with like-sign μμ

➢ Two methods:
  - ➢ Measure asymmetry of events with 1 muon
  - ➢ Measure asymmetry of events with 2 muons

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

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

- Switching magnet polarity helps in reducing systematics
- But…:
  - ➢ Decays in flight, e.g. $K \rightarrow \mu$
  - ➢ K^+/K^- asymmetry

$$A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

CP violation from Semi-leptonic decays

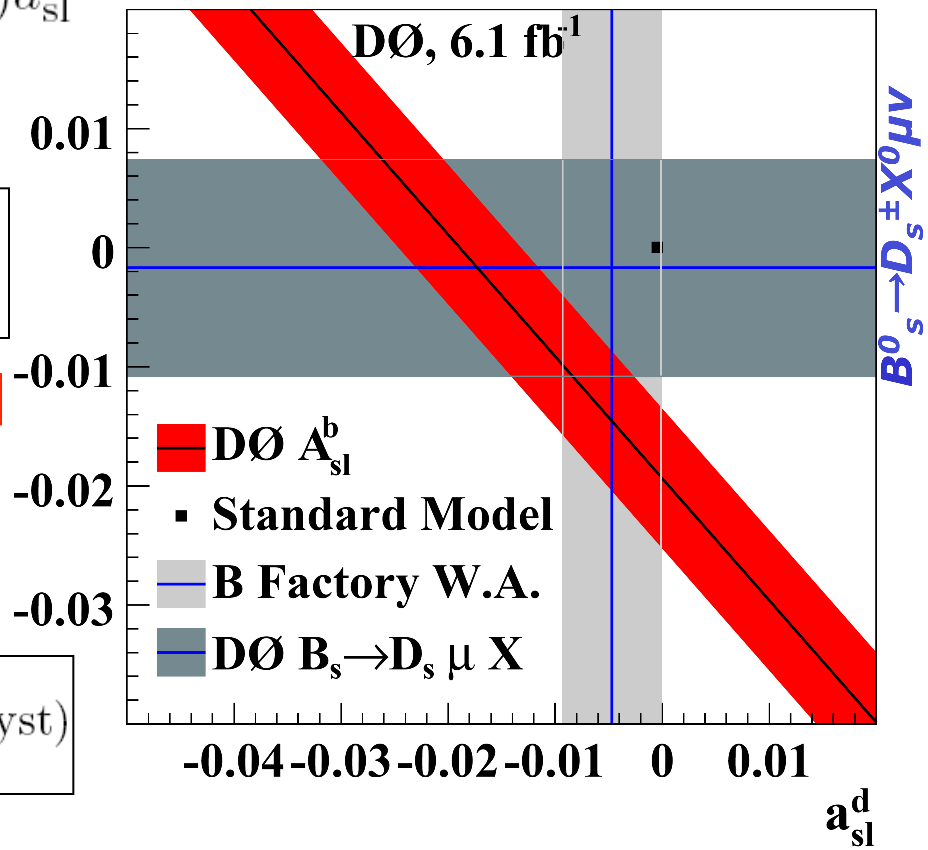
- ***SM:*** $P(B^0_s \rightarrow \bar{B}^0_s) = P(B^0_s \leftarrow \bar{B}^0_s)$
- ***DØ:*** $P(B^0_s \rightarrow \bar{B}^0_s) \neq P(B^0_s \leftarrow \bar{B}^0_s)$

?

$$A^b_{sl} = (0.506 \pm 0.043) a^d_{sl} + (0.494 \pm 0.043) a^s_{sl}$$

We measure the charge asymmetry $A \equiv (N^{++} - N^{--})/(N^{++} + N^{--})$ of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{sl} = -0.00957 \pm 0.00251\,(\text{stat}) \pm 0.00146\,(\text{sys})$. It differs by 3.2 standard deviations from the standard model prediction $A^b_{sl}(\text{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$, and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

3.2 standard deviations from the standard model

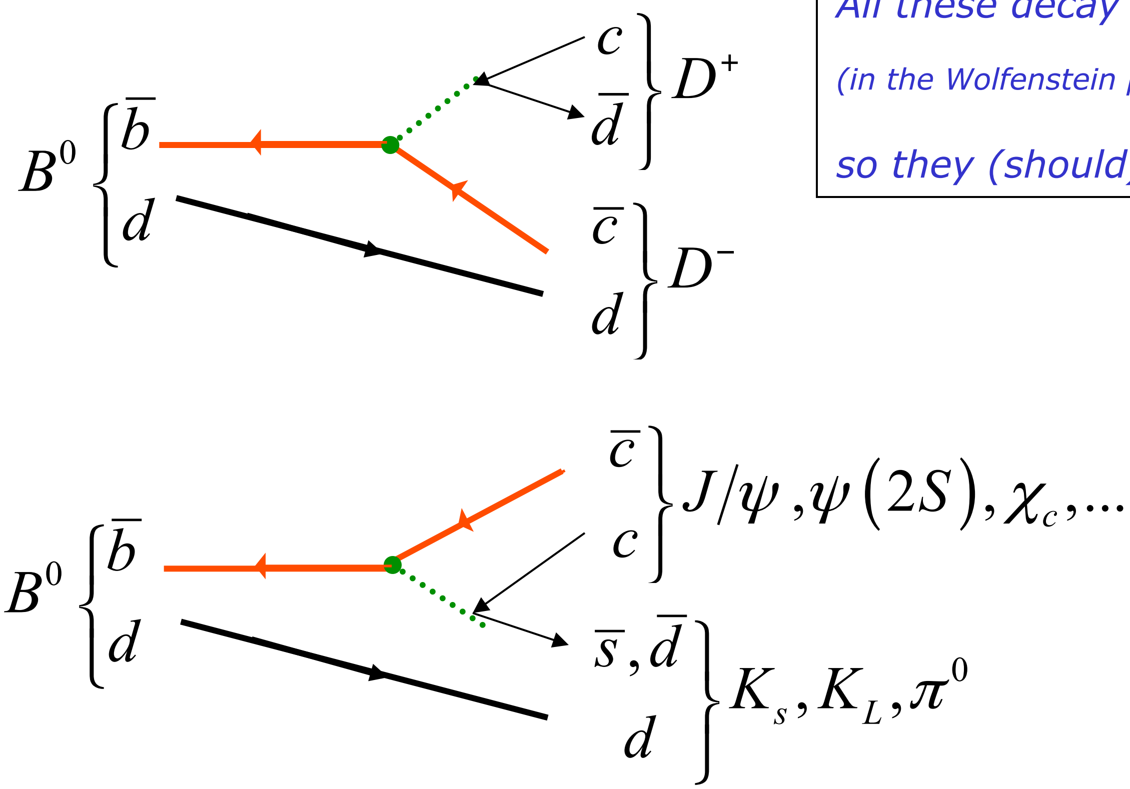


$$A^b_{sl} = -0.00957 \pm 0.00251\ (\text{stat}) \pm 0.00146\ (\text{syst})$$

More β…

Other ways of measuring sin2β

- Need interference of b→c transition and $B^0 - \overline{B}^0$ mixing
- Let's look at other b→c decays to CP eigenstates:



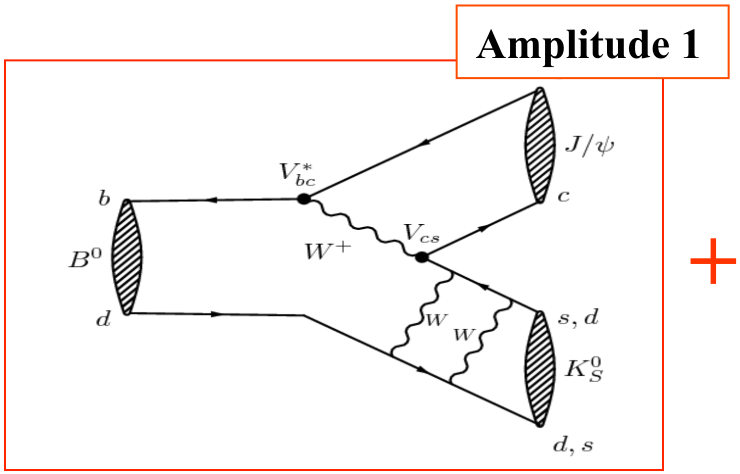
All these decay amplitudes have the same phase

(in the Wolfenstein parameterization)

so they (should) measure the same CP violation

CP in interference with B→φK$_s$

- Same as $B^0 \rightarrow J/\psi K_s$:
- Interference between $B^0 \rightarrow f_{CP}$ and $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$
  - For example: $B^0 \rightarrow J/\Psi K_s$ and $B^0 \rightarrow \bar{B}^0 \rightarrow J/\Psi K_s$
  - For example: $B^0 \rightarrow \varphi K_s$ and $B^0 \rightarrow \bar{B}^0 \rightarrow \varphi K_s$



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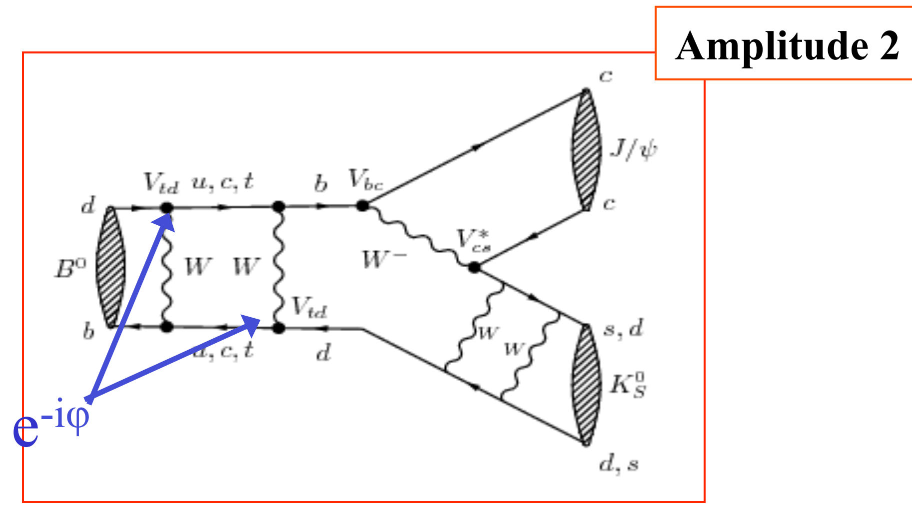


$$\lambda_{J/\psi K_s} = \left(\frac{q}{p}\right)_{B^0} \frac{\bar{A}_{J/\psi K_s}}{A_{J/\psi K_s}} = \left(\frac{q}{p}\right)_{B^0} \frac{\bar{A}_{J/\psi K^0}}{A_{J/\psi K^0}} \left(\frac{p}{q}\right)_K$$

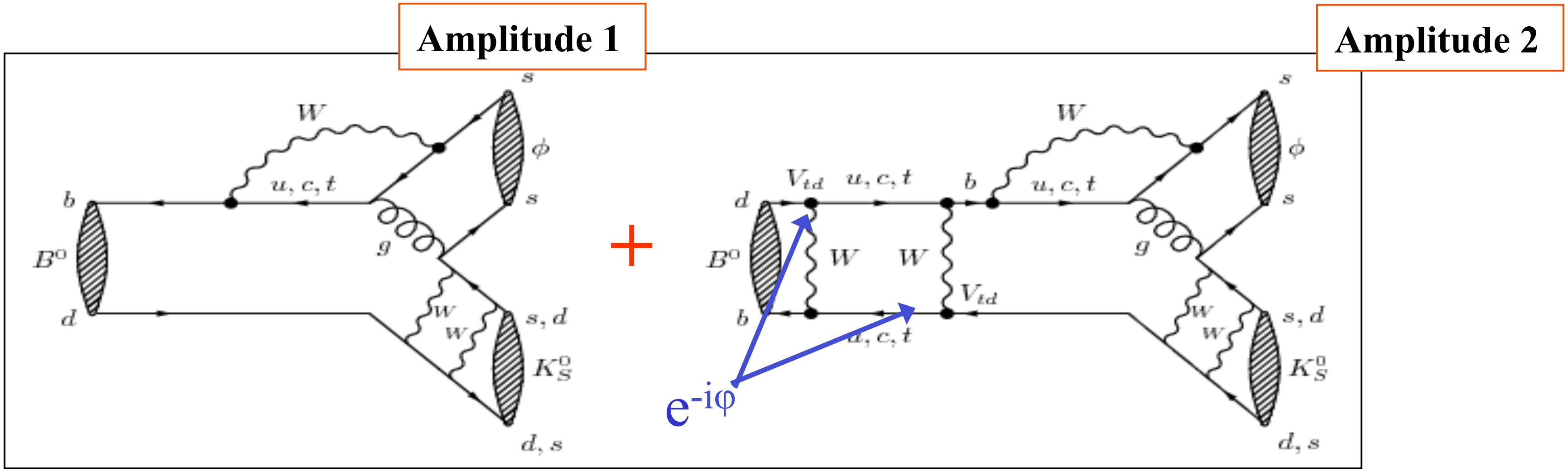
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\rightarrow f}(t) - \Gamma_{B\rightarrow f}(t)}{\Gamma_{\bar{B}\rightarrow f}(t) + \Gamma_{B\rightarrow f}(t)} = \mathrm{Im}(\lambda_f)\sin\Delta m t$$

$$\lambda_{J/\psi K_s} = -\left(\frac{V_{tb}^{\ *}V_{td}}{V_{tb}V_{td}^{\ *}}\right)\left(\frac{V_{cb}V_{cs}^{\ *}}{V_{cb}^{\ *}V_{cs}}\right)\left(\frac{V_{cs}V_{cd}^{\ *}}{V_{cs}^{\ *}V_{cd}}\right)$$

$$A_{CP}(t) = -\sin 2\beta \ \sin(\Delta m t)$$

CP in interference with B→φK$_s$: what is different??

- Same as $B^0 \rightarrow J/\psi K_s$:
- Interference between $B^0 \rightarrow f_{CP}$ and $B^0 \rightarrow \overline{B}^0 \rightarrow f_{CP}$
  - For example: $B^0 \rightarrow J/\Psi K_s$ and $B^0 \rightarrow \overline{B}^0 \rightarrow J/\Psi K_s$
  - For example: $B^0 \rightarrow \varphi K_s$ and $B^0 \rightarrow \overline{B}^0 \rightarrow \varphi K_s$



$$A_{CP}(t) = \frac{\Gamma_{\overline{B}\rightarrow f}(t) - \Gamma_{B\rightarrow f}(t)}{\Gamma_{\overline{B}\rightarrow f}(t) + \Gamma_{B\rightarrow f}(t)} = \mathrm{Im}(\lambda_f)\sin\Delta m t$$

$$A_{CP}(t) = -\sin 2\beta \ \sin(\Delta m t)$$

Penguin diagrams

THE PHENOMENOLOGY OF THE NEXT LEFT - HANDED QUARKS

Nucl. Phys. B131:285 1977

J. Ellis, M.K. Gaillard *), D.V. Nanopoulos +) and S. Rudaz ")

CERN - Geneva

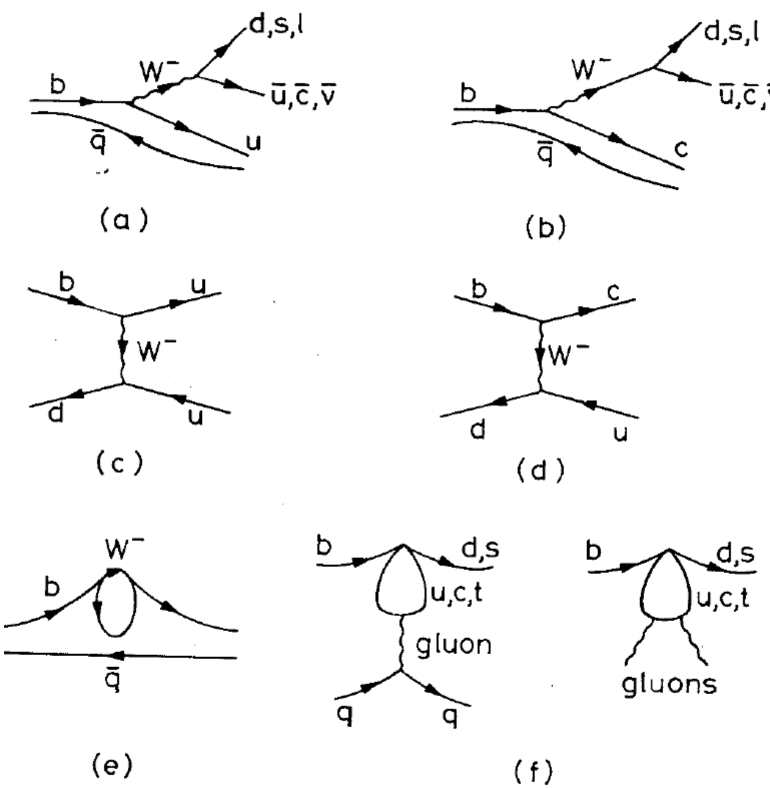
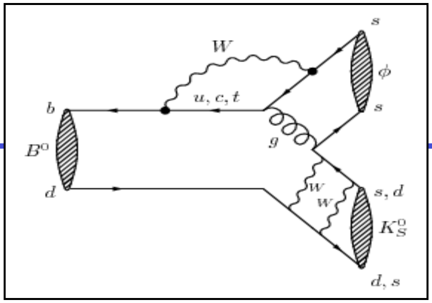


Fig. 2

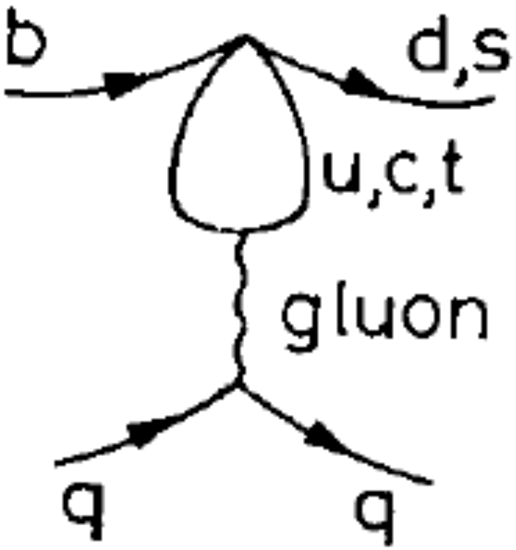
1.1 *History of Penguins*

The curious name penguin goes back to a game of darts in a Geneva pub in the summer of 1977, involving theorists John Ellis, Mary K. Gaillard, Dimitri Nanopoulos and Serge Rudaz (all then at CERN) and experimentalist Melissa Franklin (then a Stanford student, now a Harvard professor). Somehow the telling of a joke about penguins evolved to the resolution that the loser of the dart game would use the word penguin in their next paper. It seems that Rudaz spelled Franklin at some point, beating Ellis (otherwise we might now have a detector named penguin); sure enough the seminal 1977 paper on loop diagrams in B decays [3] refers to such diagrams as penguins. This paper contains a whimsical acknowledgment to Franklin for "useful discussions" [4].

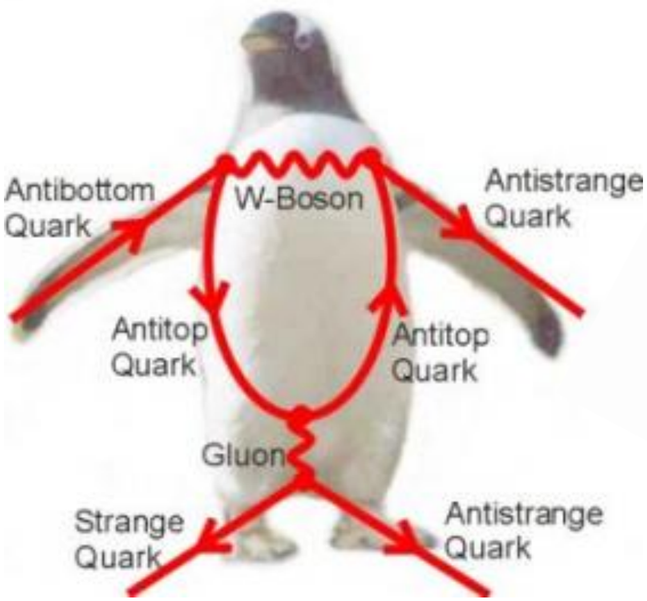
Penguins??



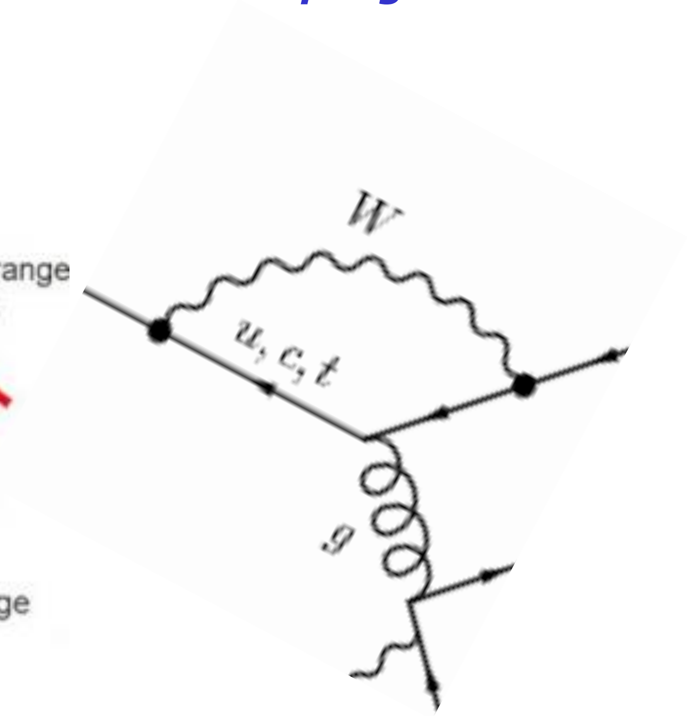
The original penguin:



A real penguin:



Our penguin:

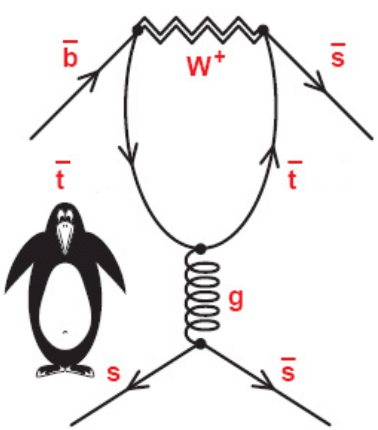


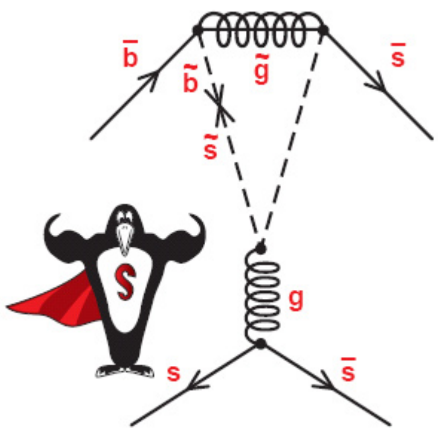
Funny

Dead Penguin

Flying Penguin

Super Penguin:



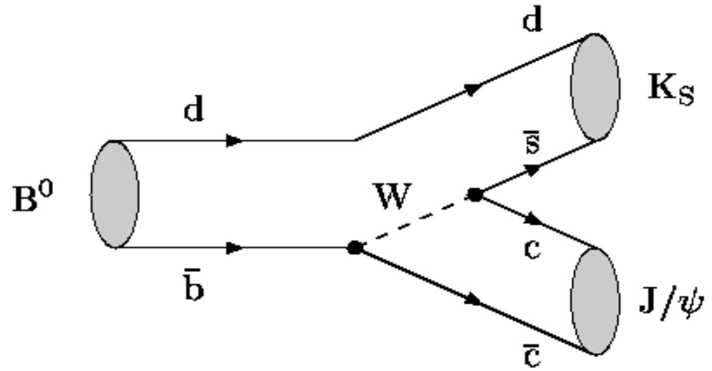


Penguin T-shirt:

The "b-s penguin"

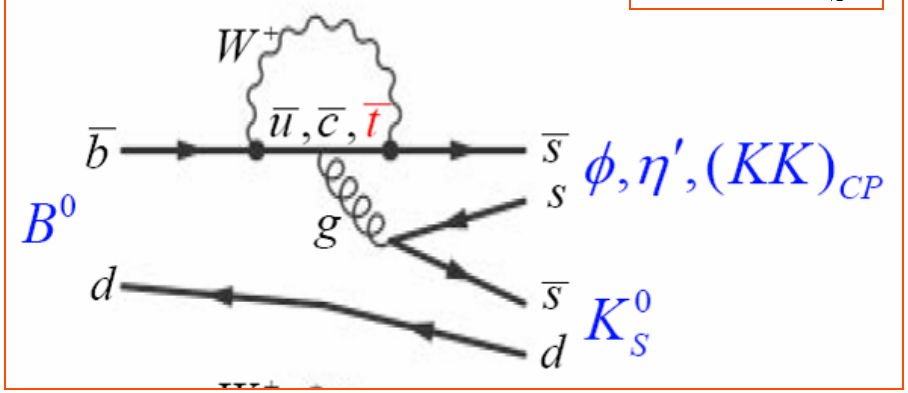
Asymmetry in SM

$B^0 \rightarrow J/\psi K_S$

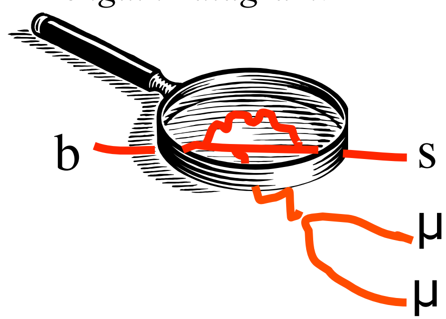


≈

$B^0 \rightarrow \varphi K_S$



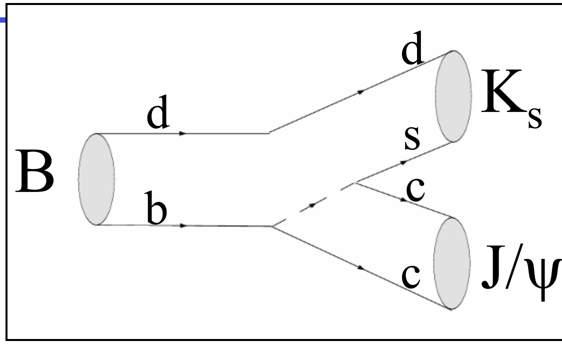
"Penguin" diagram: ΔB=1



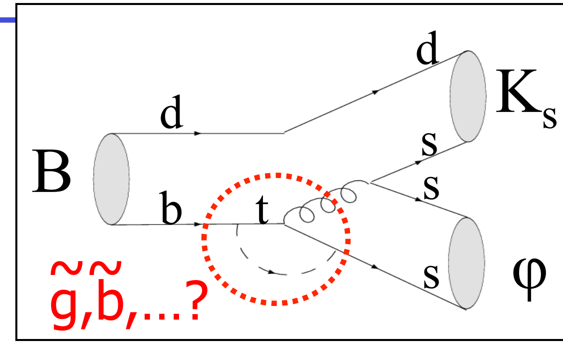
… unless there is new physics!

- New particles (also heavy) can show up in loops:
  - Can affect the branching ratio
  - And can introduce <u>additional phase</u> and affect the asymmetry

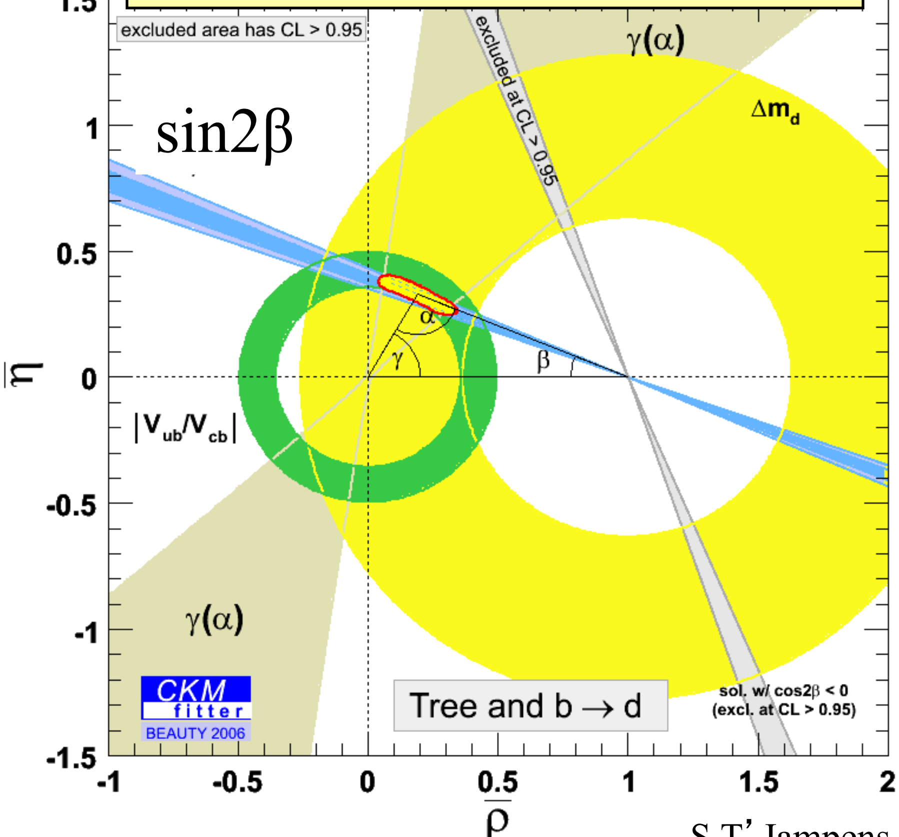
Hint for new physics??

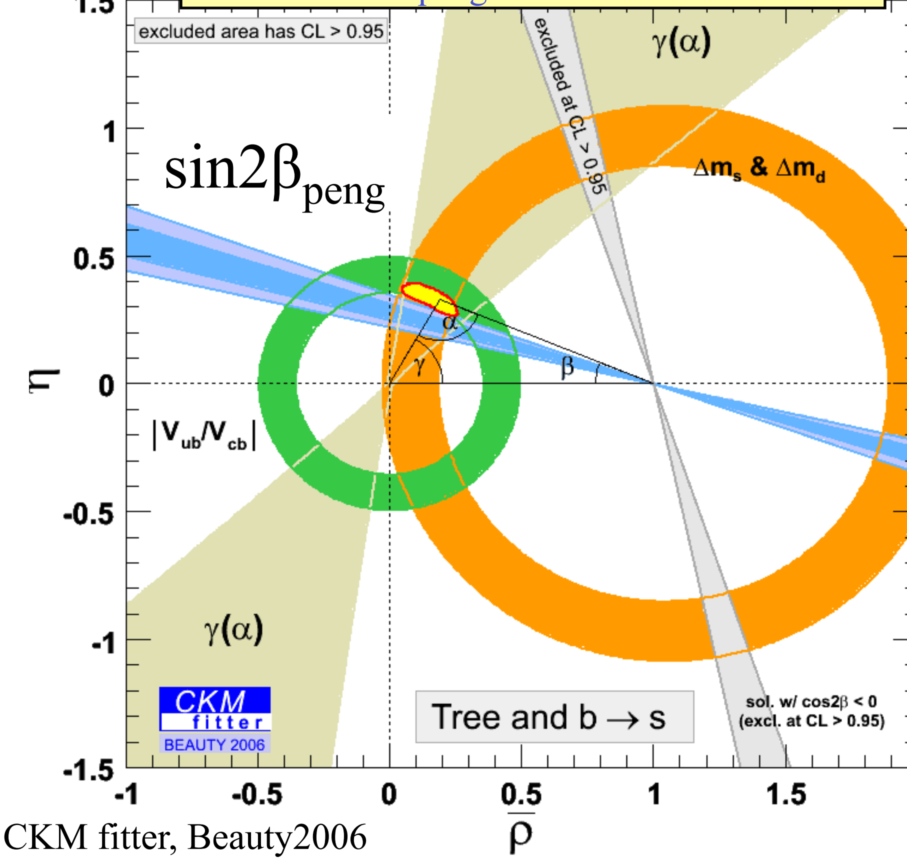


?



- $\sin 2\beta_{b \to ccs} = 0.68 \pm 0.03$
- $\sin 2\beta_{peng} = 0.52 \pm 0.05$





S.T' Jampens, CKM fitter, Beauty2006

Table of contents

Kaons…

- Different notation: confusing!

$K_1, K_2, K_L, K_S, K_+, K_-, K^0$

$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$
$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

$$|K_L\rangle = p\,|K^0\rangle - q\,|\overline{K^0}\rangle$$
$$|K_S\rangle = p\,|K^0\rangle + q\,|\overline{K^0}\rangle$$

- Smaller CP violating effects

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

$$\delta V = \begin{pmatrix} -\frac{1}{8}\lambda^4 & 0 & 0 \\ \frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) & -\frac{1}{8}\lambda^4(1+4A^2) & 0 \\ \frac{1}{2}A\lambda^5(\rho+i\eta) & \frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) & -\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

- But historically important!
  - Concepts same as in B-system, so you have a chance to understand…