Particle Physics II – CP violation
(also known as "Physics of Anti-matter")

Lecture 4

N. Tuning

Plan

1) Mon 2 Feb: Anti-matter + SM
2) Wed 4 Feb: CKM matrix + Unitarity Triangle
3) Mon 9 Feb: Mixing + Master eqs. + $B^0 \rightarrow J/\psi K_s$
4) Wed 11 Feb: CP violation in $B_{(s)}$ decays (I)
5) Mon 16 Feb: CP violation in $B_{(s)}$ decays (II)
6) Wed 18 Feb: CP violation in K decays + Overview
7) Mon 23 Feb: Exam on part 1 (CP violation)

- Final Mark:
  - if (mark > 5.5) mark = max(exam, 0.8*exam + 0.2*homework)
  - else mark = exam

- In parallel: Lectures on Flavour Physics by prof.dr. R. Fleischer
  - Tuesday + Thrusday

Plan

- 2 x 45 min

1) Keep track of room!

Periode SEM2 - Hoorcollege (Aanwezigheid verplicht)

Groep	Blokweken													Dag	Tijd	Gebouw	Zaal
	6	7	8	9	10	11	12	13	14	15	16	17	18				
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Periode SEM2 - Werkcollege (Aanwezigheid verplicht)

Groep	Blokweken													Dag	Tijd	Gebouw	Zaal
	6	7	8	9	10	11	12	13	14	15	16	17	18				
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1	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	Woensdag	11.00 - 12.45	BBG	061

1) Monday + Wednesday:
   - Start: 9:00 → 9:15
   - End: 11:00
   - Werkcollege: 11:00 - ?

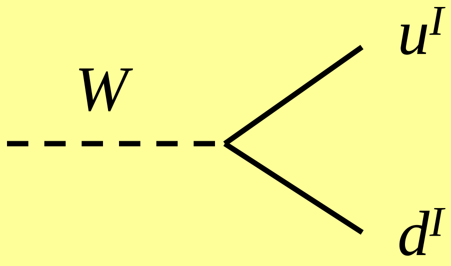
Table of contents

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

Recap

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

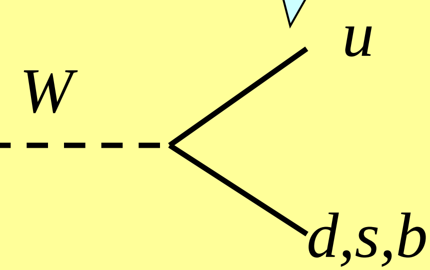
$$L_{Kinetic} = \frac{g}{\sqrt{2}} \overline{u_{Li}^I} \gamma^\mu W_\mu^- d_{Li}^I + \frac{g}{\sqrt{2}} \overline{d_{Li}^I} \gamma^\mu W_\mu^+ u_{Li}^I + \ldots$$



Diagonalize Yukawa matrix Y_{ij}

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

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



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

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

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

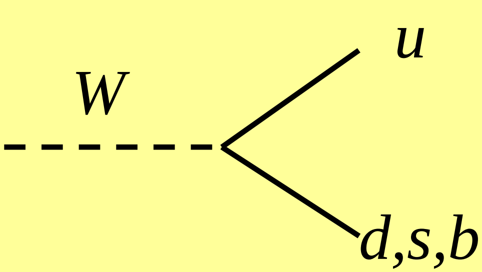
CKM-matrix: where are the phases?

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

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

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

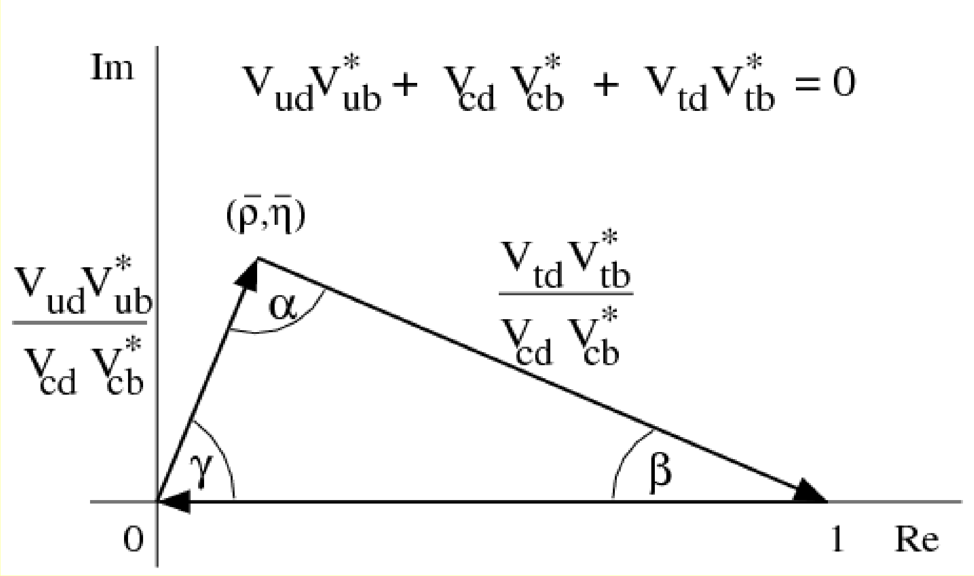
- Possibility 2: parameterize according to magnitude, in O(λ):



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

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…

Neutral Meson Oscillations (1)

- Start with Schrodinger equation:

$$i\frac{\partial\psi}{\partial t} = H\psi = (M - \frac{i}{2}\Gamma)\psi = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\psi$$

$$\psi(t) = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

(2-component state in P^0 and $\overline{P^0}$ subspace)

- Find eigenvalue:

$$\begin{vmatrix} M - \frac{i}{2}\Gamma - \lambda & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma - \lambda \end{vmatrix} = 0$$

- Solve eigenstates:

$$\psi_\pm = \begin{pmatrix} p \\ \pm q \end{pmatrix}$$

$$\begin{aligned} |P_1\rangle &= p|P^0\rangle - q|\bar{P}^0\rangle \\ |P_2\rangle &= p|P^0\rangle + q|\bar{P}^0\rangle \end{aligned}$$

we find p and q by solving

$$\begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} p \\ q \end{pmatrix} = \lambda_\pm \begin{pmatrix} p \\ q \end{pmatrix} \longrightarrow \frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- Eigenstates have diagonal Hamiltonian: mass eigenstates!

Neutral Meson Oscillations (2)

- Two mass eigenstates

$$\begin{aligned} |P_H\rangle &= p|P^0\rangle + q|\bar{P}^0\rangle \\ |P_L\rangle &= p|P^0\rangle - q|\bar{P}^0\rangle \end{aligned}$$

- Time evolution:

$$\begin{aligned} |P_H(t)\rangle &= e^{-im_H t - \frac{1}{2}\Gamma_H t}|P_H(0)\rangle \\ |P_L(t)\rangle &= e^{-im_L t - \frac{1}{2}\Gamma_H L}|P_L(0)\rangle \end{aligned}$$

$$\begin{aligned} |P^0\rangle &= \frac{1}{2p}\left[|P_H\rangle + |P_L\rangle\right] \\ |\bar{P}^0\rangle &= \frac{1}{2q}\left[|P_H\rangle - |P_L\rangle\right] \end{aligned}$$

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

- Probability for $|P^0\rangle \rightarrow |\overline{P^0}\rangle$!
- Express in $M = m_H + m_L$ and $\Delta m = m_H - m_L$ → Δm dependence

Meson Decays

- Formalism of meson *oscillations*:

$$\left|P^0(t)\right\rangle = \frac{1}{2}\left(e^{-im_Ht-\frac{1}{2}\Gamma_Ht}+e^{-im_Lt-\frac{1}{2}\Gamma_Lt}\right)|P^0\rangle+\frac{q}{2p}\left(e^{-im_Ht-\frac{1}{2}\Gamma_Ht}-e^{-im_Lt-\frac{1}{2}\Gamma_Lt}\right)|\bar{P}^0\rangle$$

- 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

('direct') Decay

Interference

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

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

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

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

3. CP violation in interference

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

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

Now: Im(λ_f)

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

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

We will investigate λ_f for various final states f

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

CP violation: type 3

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

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

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

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

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

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

Classification of CP Violating effects - Nr. 3:

Consider $f=\bar{f}$:

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

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

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

3. CP violation in interference

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

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

Final state f : $J/\Psi K_s$

- Interference between $B^0 \to f_{CP}$ and $B^0 \to \overline{B}^0 \to f_{CP}$
  - For example: $B^0 \to J/\Psi K_s$ and $B^0 \to \overline{B}^0 \to J/\Psi K_s$
  - Lets' s simplify ☺...

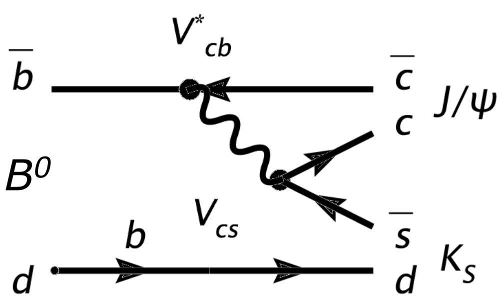
1) For B^0 we have:

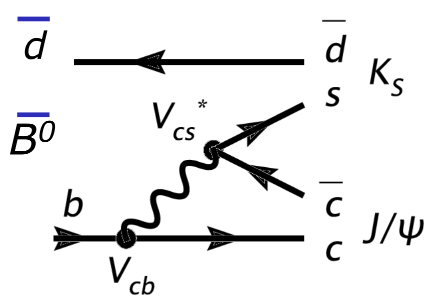
$$\left|\frac{q}{p}\right| = 1$$

2) Since $f_{CP} = \overline{f}_{CP}$ we have:

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = \frac{q}{p}\frac{\overline{A}_{\overline{f}}}{A_{\overline{f}}} \equiv \lambda_{\overline{f}}$$

3) The amplitudes $|A(B^0 \to J/\psi K_s)|$ and $|A(\overline{B}^0 \to J/\psi K_s)|$ are equal:





$$\left|A_{f_{CP}}\right| = \left|\overline{A}_{f_{CP}}\right|$$

$$|\lambda_f| = 1$$

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

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

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

$|\lambda_f|=1$

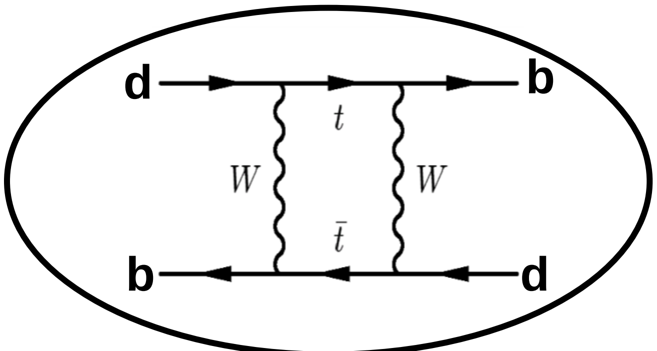
$\Delta\Gamma=0$

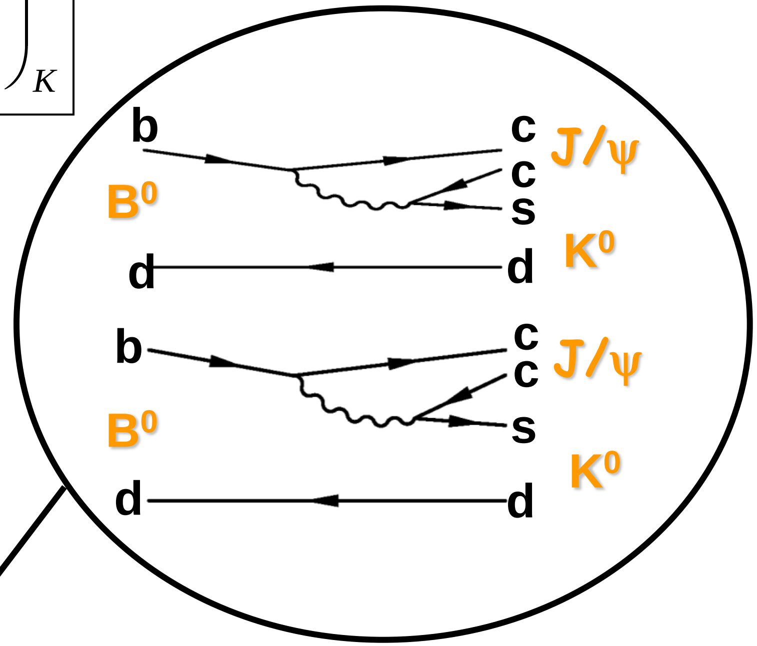
$$A_{CP}(t) = -\Im\lambda_f \sin(\Delta m t)$$

λ_f for $B^0 \to J/\psi K^0_S$

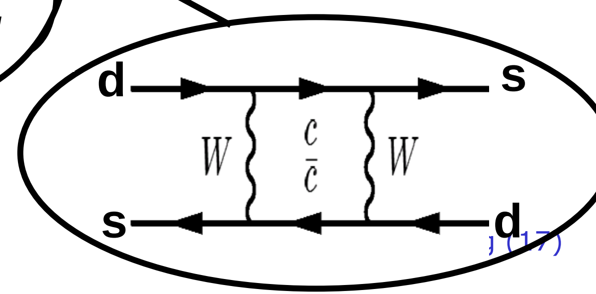
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

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





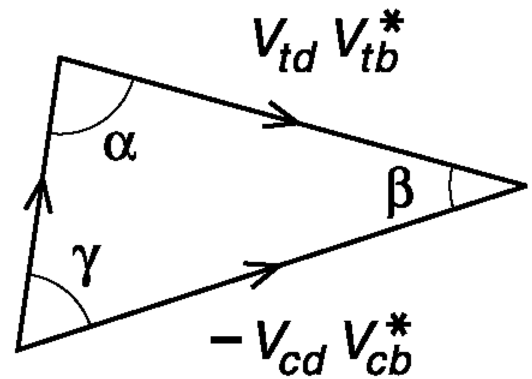
$$\lambda_{J/\psi K_s} = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)\left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right)$$



λ_f for $B^0 \to J/\psi K^0_S$

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

$$= -e^{-2i\beta}$$



Time-dependent *CP* asymmetry

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

- Theoretically clean way to measure β
- Clean experimental signature
- Branching fraction: $O(10^{-4})$
    - "Large" compared to other CP modes!

Remember: C and P eigenvalue

- C and P are good symmetries (not involving the weak interaction)
  - Can associate a conserved value with them (Noether Theorem)
- Each hadron has a conserved P and C quantum number
  - What are the values of the quantum numbers
  - Evaluate the eigenvalue of the P and C operators on each hadron
    $\mathbf{P}|\psi\rangle = p|\psi\rangle$
- What values of C and P are possible for hadrons?
  - Symmetry operation squared gives unity so eigenvalue squared must be 1
  - Possible C and P values are +1 and -1.
- Meaning of P quantum number
  - If P=1 then $P|\psi\rangle = +1|\psi\rangle$ (wave function symmetric in space)
    if P=-1 then $P|\psi\rangle = -1\,|\psi\rangle$ (wave function anti-symmetric in space)

Remember: P eigenvalues for hadrons

- The π^+ meson
  - Quark and anti-quark composite: intrinsic P = (1)*(-1) = -1
  - Orbital ground state → no extra term
  - **$P(\pi^+)=-1$**

Meaning: $P|\pi^+\rangle = -1|\pi^+\rangle$

- The neutron
  - Three quark composite: intrinsic P = (1)*(1)*(1) = 1
  - Orbital ground state → no extra term
  - **P(n) = +1**

- The $K_1(1270)$
  - Quark anti-quark composite: intrinsic P = (1)*(-1) = -1
  - Orbital excitation with L=1 → extra term $(-1)^1$
  - **$P(K_1) = +1$**

Intermezzo: CP eigenvalue

- Remember:
  - $P^2 = 1$ ($x \rightarrow -x \rightarrow x$)
  - $C^2 = 1$ ($\psi \rightarrow \bar{\psi} \rightarrow \psi$)
  - $\rightarrow CP^2 = 1$
- $CP\,|\,f> = \pm\,|\,f>$
- Knowing this we can evaluate the effect of CP on the K^0

  $CP|\bar{K}^0> = -1|K^0>$

  $CP|K^0> = -1|\bar{K}^0>$

  ➢ K^0 is not CP eigenstate, but flavour eigenstate (sd) !
- Mass eigenstates:

  $|K_S> = p|K^0> + q|\bar{K}^0>$

  $|K_L> = p|K^0> - q|\bar{K}^0>$ ($S(K)=0 \rightarrow L(\pi\pi)=0$)

  $|K_s>$ $(CP=+1) \longrightarrow \pi\,\pi$ $(CP = (-1)(-1)(-1)^{l=0} = +1)$

  $|K_L>$ $(CP=-1) \longrightarrow \pi\,\pi\,\pi$ $(CP = (-1)(-1)(-1)(-1)^{l=0} = -1)$

CP eigenvalue of final state $J/\psi K^0_S$

- CP $|J/\psi\rangle = +1\ |J/\psi\rangle$ ***(S(J/ψ)=1)***
- CP $|K^0_S\rangle = +1\ |K^0_S\rangle$
- CP $|J/\psi K^0_S\rangle = (-1)^l\ |J/\psi K^0_S\rangle$ ***(S(B)=0 → L(J/ψK⁰S)=1)***

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

$$= -e^{-2i\beta}$$

Relative minus-sign between state and CP-conjugated state:

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

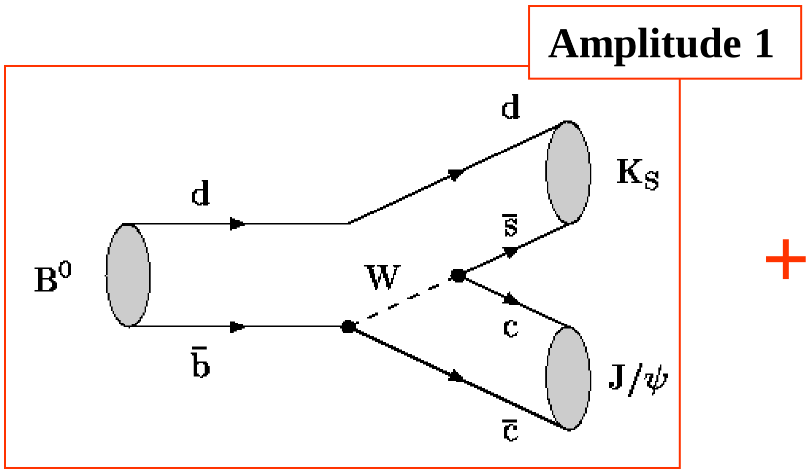
$$A_{CP}(t) = -\sin 2\beta\ \sin(\Delta m t)$$

Time dependent CP violation

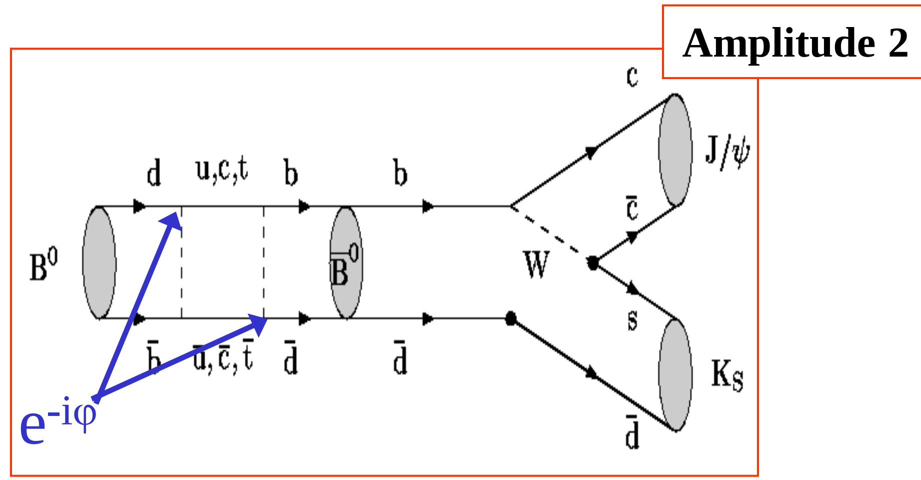
- If final state is CP eigenstate then 2 amplitudes (w/o mixing):

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

- B^0 - $\overline{B}^0$ oscillation is periodic in time → CP violation time dependent



+



$(i=e^{i\pi/2} \rightarrow \delta=90^o)$
$(\varphi=2\beta)$

$$A_{CP}(t) = \frac{\Gamma\left(B^0 \rightarrow J/\psi K_S\right) - \Gamma\left(\overline{B}^0 \rightarrow J/\psi K_S\right)}{\Gamma\left(B^0 \rightarrow J/\psi K_S\right) + \Gamma\left(\overline{B}^0 \rightarrow J/\psi K_S\right)} = -\sin 2\beta \sin \Delta m t$$

Time dependent CP violation

- If final state is CP eigenstate then 2 amplitudes (w/o mixing):

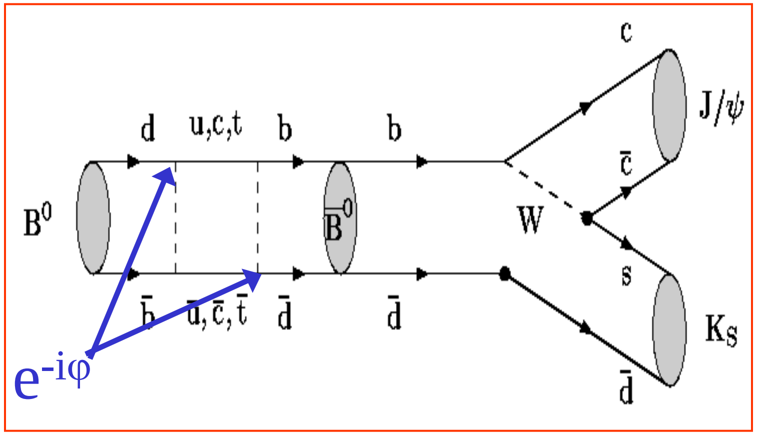
  $B^0 \to f$ and $B^0 \to \overline{B}^0 \to f$

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

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left(1 \pm \cos\Delta m t\right)$$

$$g_+^*(t) g_-(t) = \frac{e^{-\Gamma t}}{2}\left(+ i \sin\Delta m t\right)$$

$$g_+(t) g_-^*(t) = \frac{e^{-\Gamma t}}{2}\left(- i \sin\Delta m t\right)$$



$$\Gamma\left(B^0 \to J/\psi K_S\right) = \left| A e^{-imt-\Gamma t}\left(\cos\frac{\Delta m t}{2} + e^{-i\phi} i \sin\frac{\Delta m t}{2}\right)\right|^2$$

$$A_{CP}(t) = \frac{\Gamma\left(B^0 \to J/\psi K_S\right) - \Gamma\left(\overline{B}^0 \to J/\psi K_S\right)}{\Gamma\left(B^0 \to J/\psi K_S\right) + \Gamma\left(\overline{B}^0 \to J/\psi K_S\right)} = -\sin 2\beta \sin\Delta m t$$

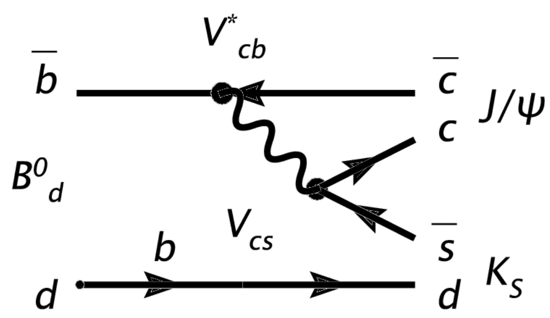
($i = e^{i\pi/2} \to \delta = 90^o$)

($\varphi = 2\beta$)

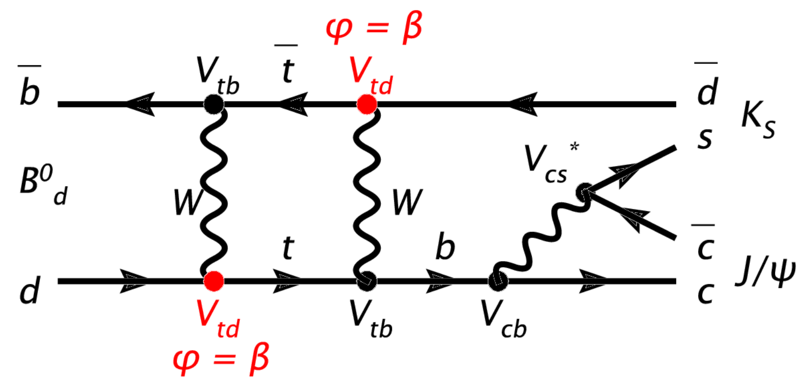
Sum of 2 amplitudes: sensitivity to phase

- What do we know about the relative phases of the diagrams?

$B^0 \rightarrow f$



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



ϕ(strong)=ϕ	*Decays are identical*	***ϕ(strong)=ϕ***
ϕ(weak)=0	*K^0 mixing exactly cancels V_{cs}*	***ϕ(weak)=2β***
		ϕ(mixing)=π/2

$$|\psi(t)\rangle :$$

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\overline{B^0}\rangle$$

$$|\overline{B^0}(t)\rangle = g_+(t)|\overline{B^0}\rangle + \frac{p}{q} g_-(t)|B^0\rangle$$

$$g_+(t) = e^{-imt} e^{-\Gamma t/2} \cos\frac{\Delta mt}{2}$$

$$g_-(t) = e^{-imt} e^{-\Gamma t/2} i \sin\frac{\Delta mt}{2}$$

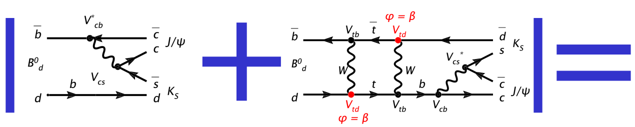
$$\Psi_0(x,t) = e^{-imt - t/2\tau}\left(|B^0\rangle \cos(\Delta mt/2) + i\left(\frac{q}{p}\right)|\overline{B}^0\rangle \sin(\Delta mt/2)\right)$$

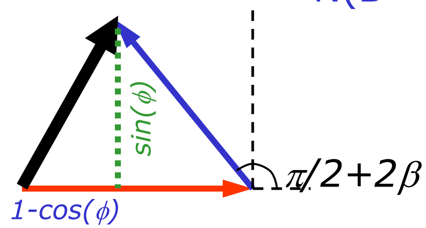
There is a phase difference of i between the B^0 and $\overline{B}^0$

Sum of 2 amplitudes: sensitivity to phase

- Now also look at CP-conjugate process
- Investigate situation at time t, such that $|A_1| = |A_2|$:

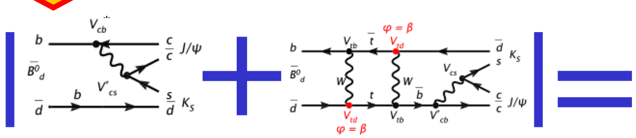
$\Gamma(B \rightarrow f) =$

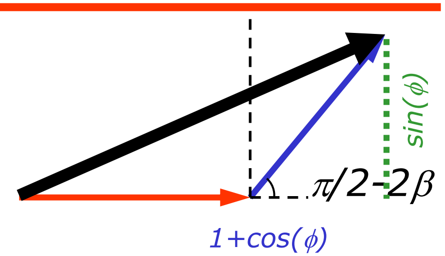




CP

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





$$N(B^0 \rightarrow f) \propto |A|^2 \propto (1-\cos\phi)^2 + \sin^2\phi$$
$$= 1 - 2\cos\phi + \cos^2\phi + \sin^2\phi$$
$$= 2 - 2\cos(\pi/2 - 2\beta)$$
$$\propto 1 - \sin(2\beta)$$

$$A_{CP} = \frac{N_{\overline{B^0} \rightarrow f} - N_{B^0 \rightarrow f}}{N_{B^0 \rightarrow f} + N_{\overline{B^0} \rightarrow f}} = \sin(2\beta)$$

$$N(\overline{B^0} \rightarrow f) \propto (1+\cos\phi)^2 + \sin^2\phi$$
$$= 2 + 2\cos(\pi/2 - 2\beta)$$
$$\propto 1 + \sin(2\beta)$$

- Directly observable result (essentially just from counting) measure CKM phase β directly!

$$A_{CP}(t = \pi / 2\Delta m) = \frac{N_{\overline{B^0} \rightarrow f} - N_{B^0 \rightarrow f}}{N_{B^0 \rightarrow f} + N_{\overline{B^0} \rightarrow f}} = \sin(2\beta)$$

Remember!

Necessary ingredients for CP violation:

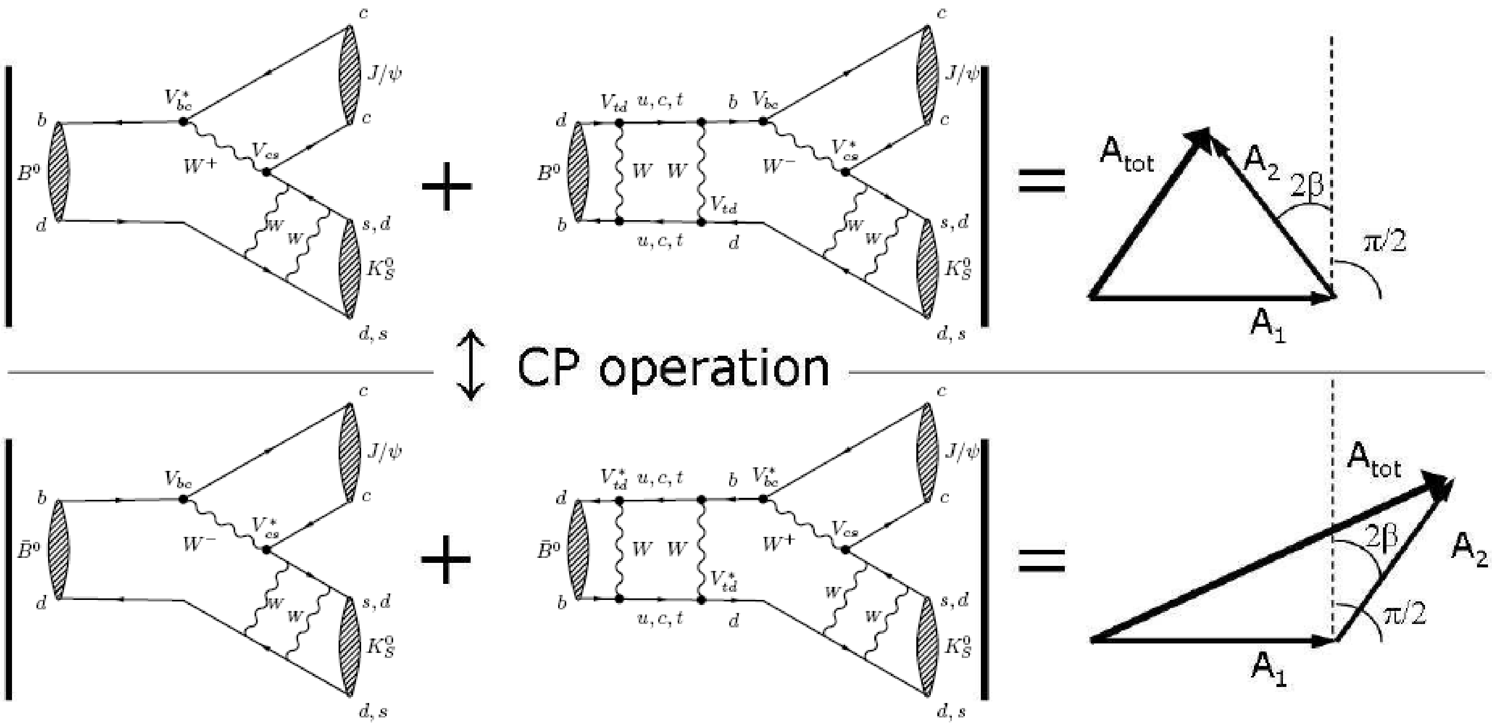
1) Two (interfering) amplitudes

2) Phase difference between amplitudes

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

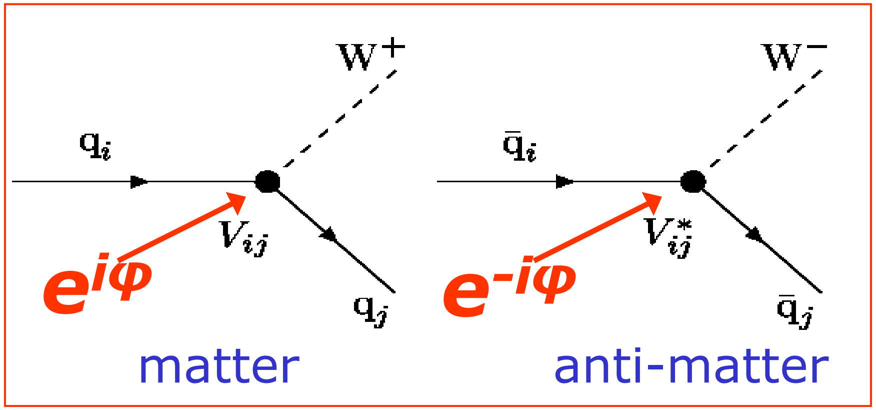
2 amplitudes
2 phases

Remember!



2 amplitudes
2 phases

What do we measure?



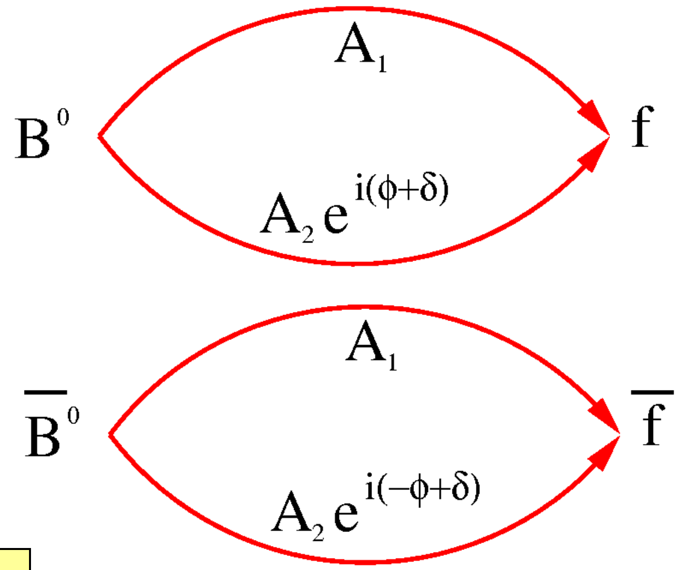
We measure quark couplings

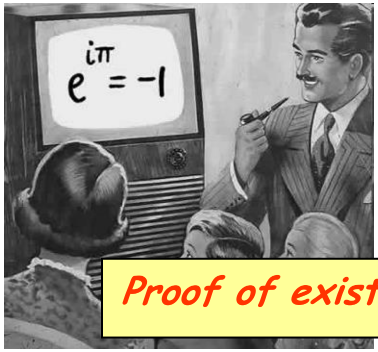
There is a complex phase in couplings!

Visible when there are 2 amplitudes:

$$\Gamma(B \rightarrow f) = |A_1 + A_2 e^{i(\varphi+\delta)}|^2$$

$$\Gamma(\bar{B} \rightarrow \bar{f}) = |A_1 + A_2 e^{i(-\varphi+\delta)}|^2$$



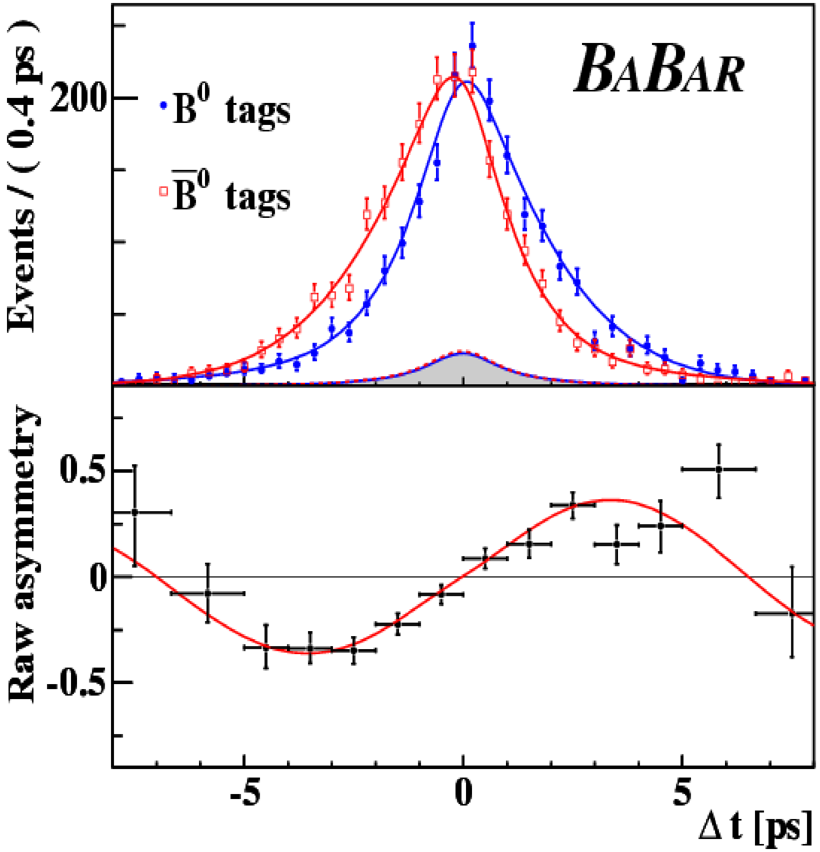


Proof of existence of complex numbers…

B-system - Time-dependent CP asymmetry

$B^0 \to J/\psi K_s$

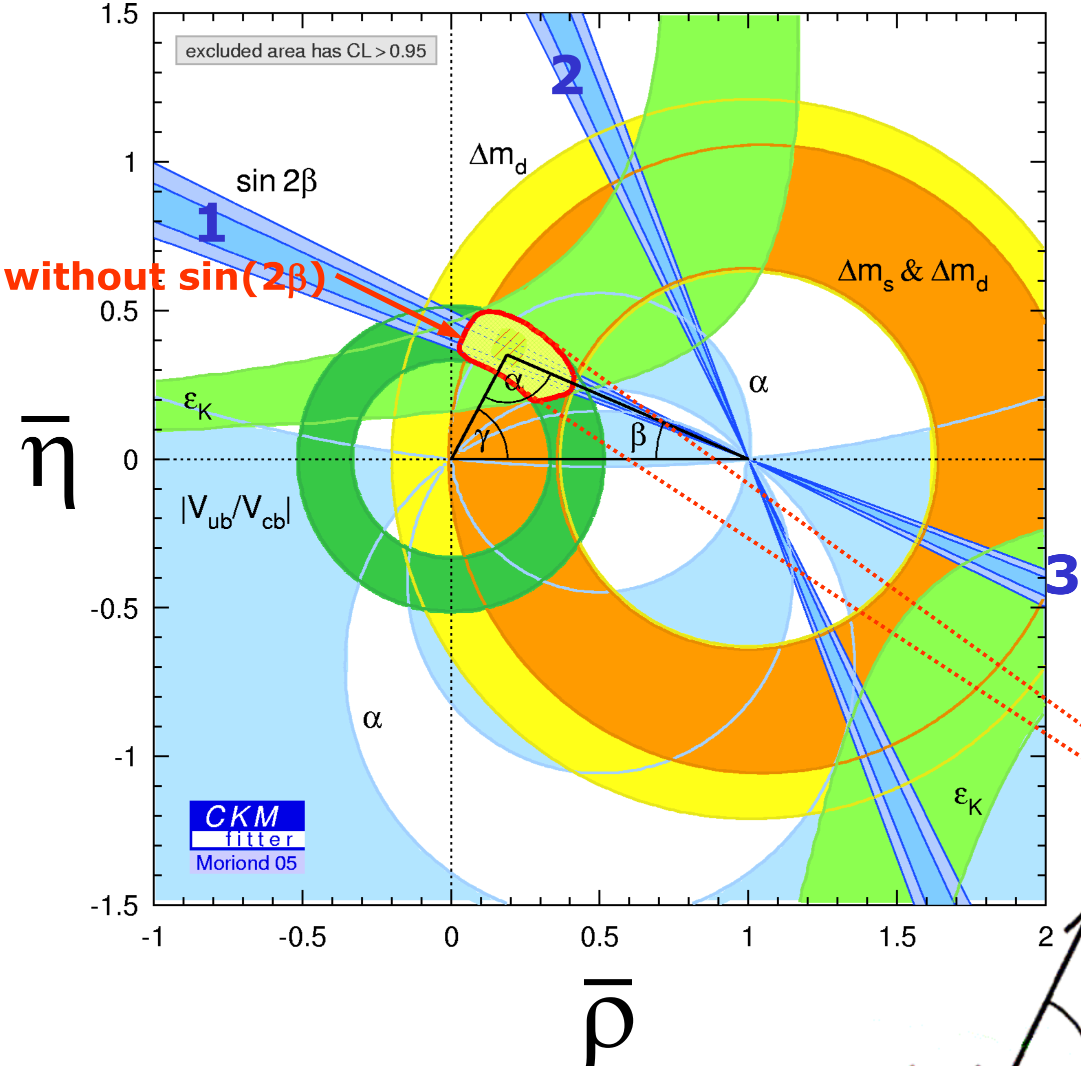
$$A_{CP}(t) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)\sin(\Delta m t)$$



BaBar (2002)

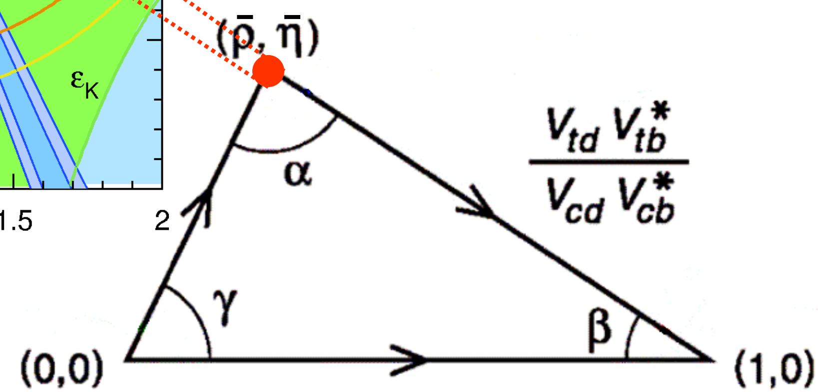
Consistency with other measurements in (ρ,η) plane

4-fold ambiguity because we measure sin(2β), not β



Prices measurement of sin(2β) agrees perfectly with other measurements and CKM model assumptions

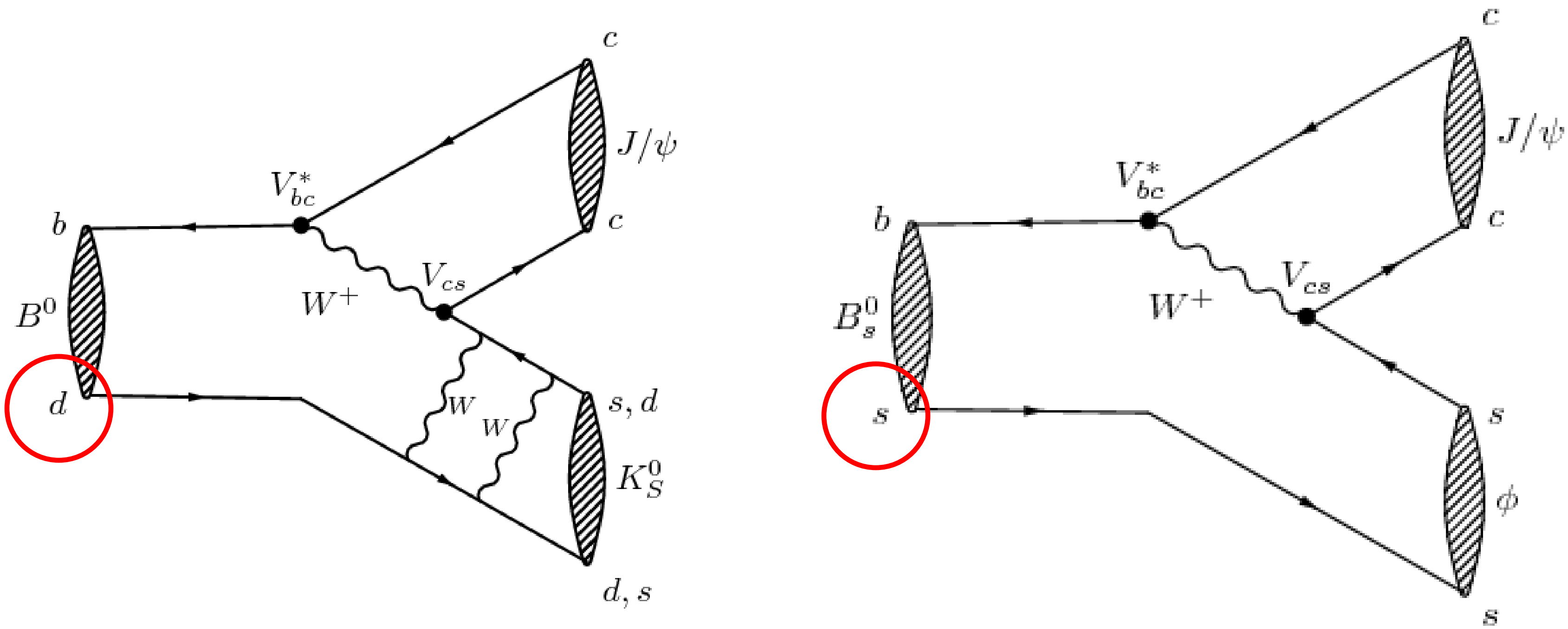
The CKM model of CP violation experimentally confirmed with high precision!



Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001

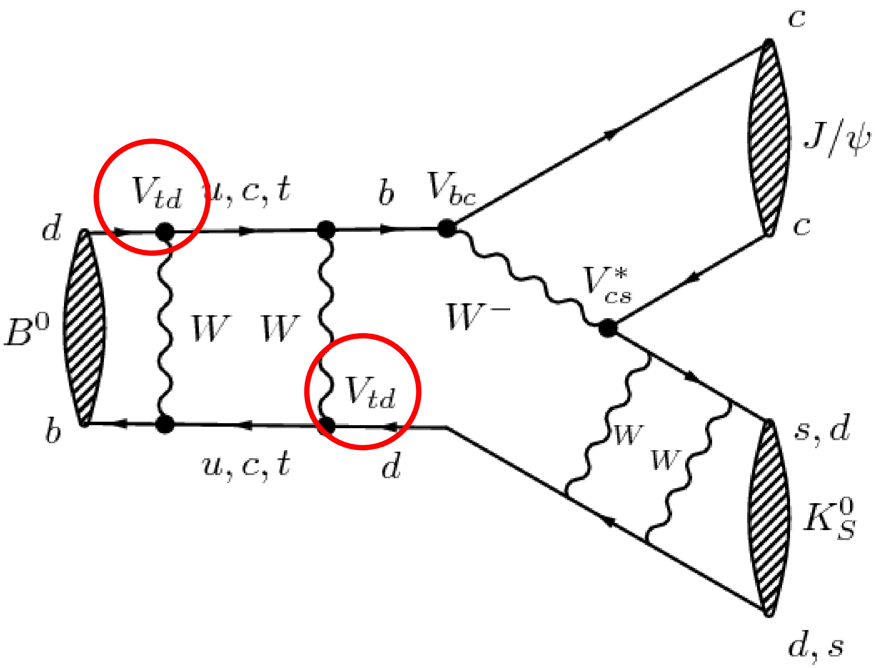
Break

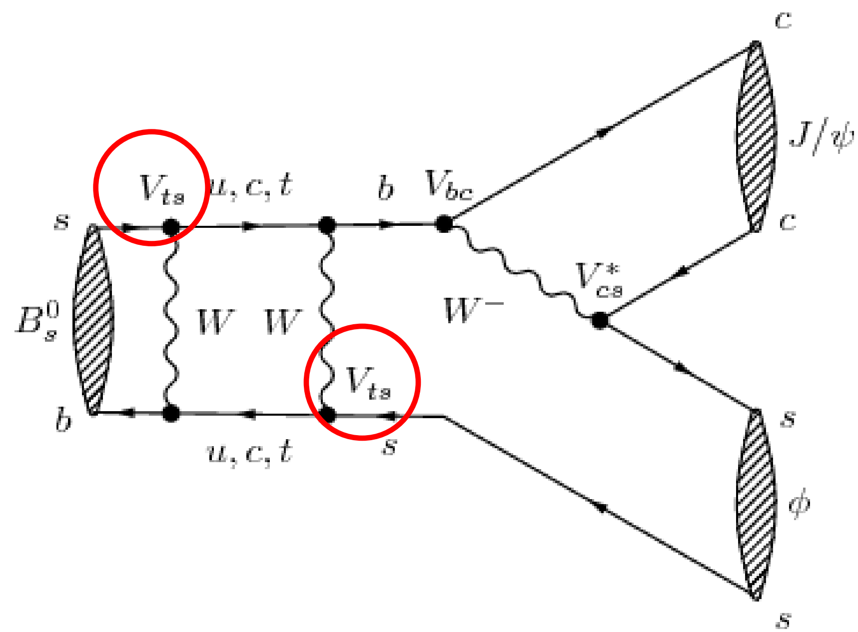
β_s: $B_s^0 \to J/\psi\phi$: B_s^0 analogue of $B^0 \to J/\psi K^0_S$



- Replace spectator quark d → s

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





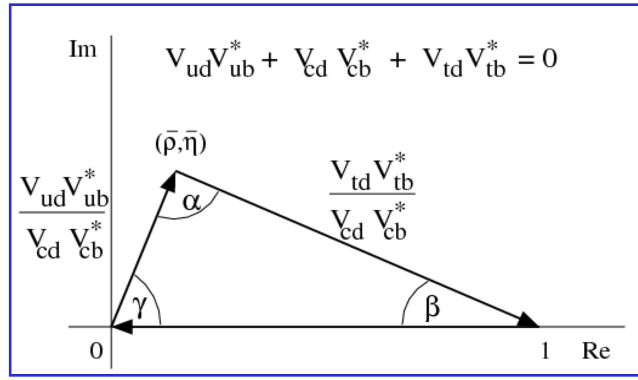
$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

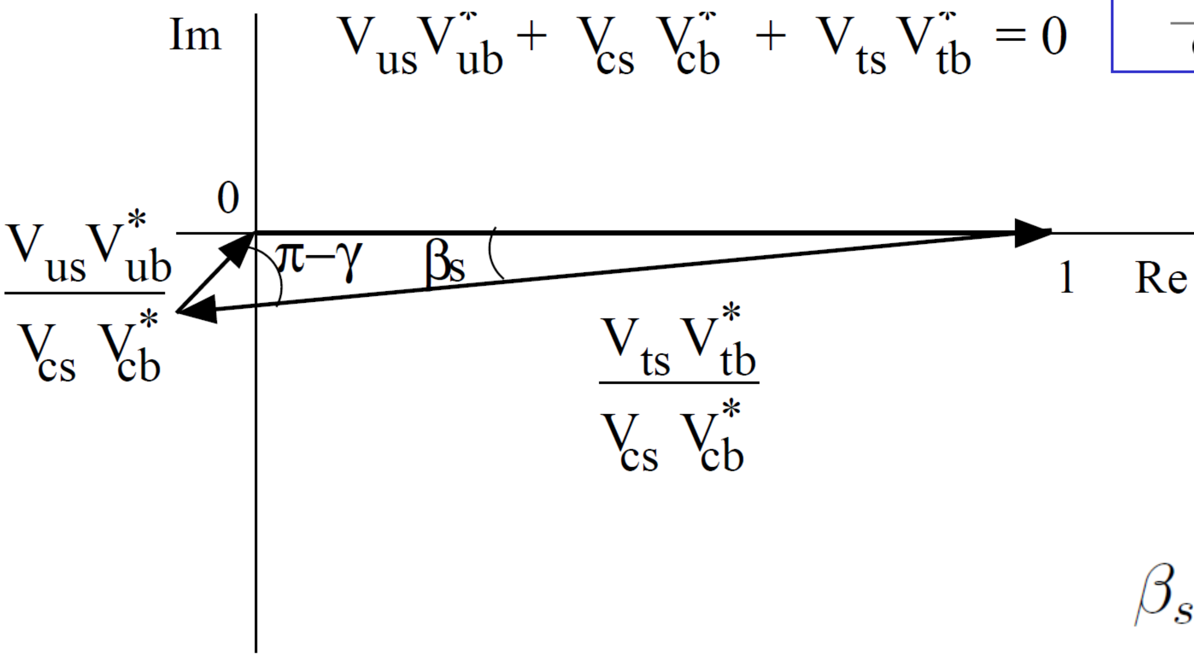
$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

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

Remember: The "B_s-triangle": β_s

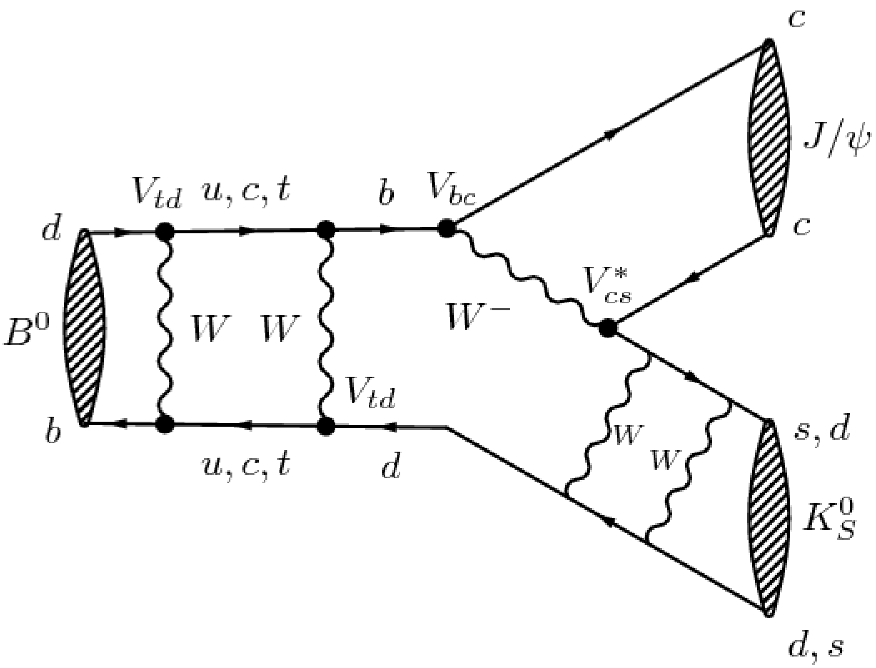
- Replace *d* by *s*:

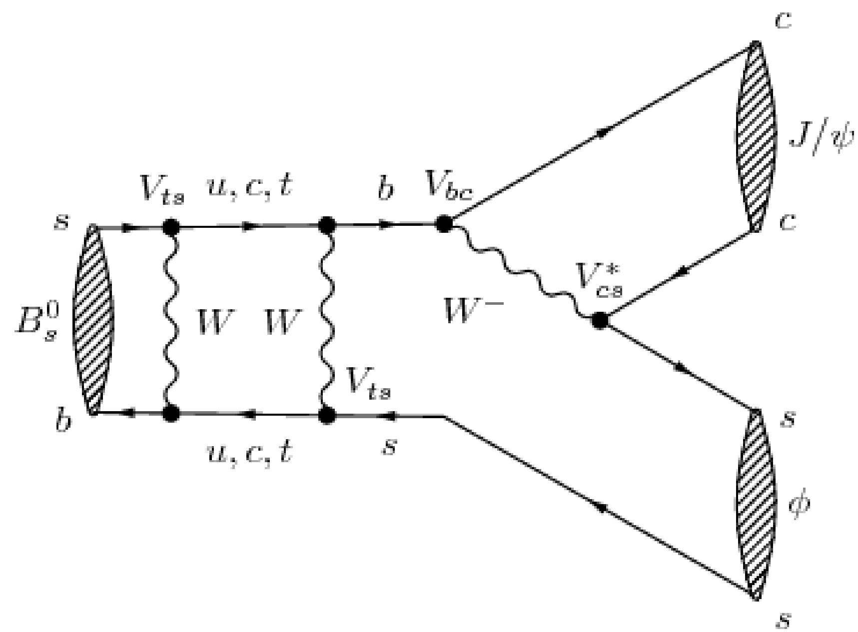




$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

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





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: $B_s^0 \rightarrow J/\psi\varphi$

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

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

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

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

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

3 amplitudes

	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	-

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

"Recent" excitement (5 March 2008)

FIRST EVIDENCE OF NEW PHYSICS IN b ↔ s TRANSITIONS

(UT*fit* Collaboration)

M. Bona,[1] M. Ciuchini,[2] E. Franco,[3] V. Lubicz,[2,4] G. Martinelli,[3,5] F. Parodi,[6] M. Pierini,[1] P. Roudeau,[7] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

In the Standard Model (SM), all flavour and CP violating phenomena in weak decays are described in terms of quark masses and the four independent parameters in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. In particular, there is only one source of CP violation, which is connected to the area of the Unitarity Triangle (UT). A peculiar prediction of the SM, due to the hierarchy among CKM matrix elements, is that CP violation in B_s mixing should be tiny. This property is also valid in models of Minimal Flavour Violation (MFV) [2], where flavour and CP violation are still governed by the CKM matrix. Therefore, the experimental observation of sizable CP violation in B_s mixing is a clear (and clean) signal of New Physics (NP) and a violation of the MFV paradigm. In the past decade, B factories have collected an impressive amount of data on B_d flavour- and CP-violating processes. The CKM paradigm has passed unscathed all the tests performed at the B factories down to an accuracy just below 10% [3, 4]. This has been often considered as an indication pointing to the MFV hypothesis, which has received considerable attention in recent years. The only possible hint of non-MFV NP is found in the penguin-dominated $b \to s$ non-leptonic decays. Indeed, in the SM, the $S_{q\bar{q}s}$ coefficient of the time-dependent CP asymmetry in these channels is equal to the $S_{c\bar{c}s}$ measured with $b \to c\bar{c}s$ decays, up to hadronic uncertainties related to subleading terms in the decay amplitudes. Present data show a systematic, although not statistically significant, downward shift of $S_{q\bar{q}s}$ with respect to $S_{c\bar{c}s}$ [5], while hadronic models predict a shift in the opposite direction in many cases [6, 7].

From the theoretical point of view, the hierarchical structure of quark masses and mixing angles of the SM calls for an explanation in terms of flavour symmetries or of other dynamical mechanisms, such as, for example, fermion localization in models with extra dimensions. All such explanations depart from the MFV paradigm, and generically cause deviations from the SM in flavour violating processes. Models with localized fermions [8], and more generally models of Next-to-Minimal Flavour Violation [9], tend to produce too large effects in ε_K [10, 11]. On the contrary, flavour models based on nonabelian flavour symmetries, such as $U(2)$ or $SU(3)$, typically suppress NP contributions to $s \leftrightarrow d$ and possibly also to $b \leftrightarrow d$ transitions, but easily produce large NP contributions to $b \leftrightarrow s$ processes. This is due to the large flavour symmetry breaking caused by the top quark Yukawa coupling. Thus, if (nonabelian) flavour symmetry models are relevant for the solution of the SM flavour problem, one expects on general grounds NP contributions to $b \leftrightarrow s$ transitions. On the other hand, in the context of Grand Unified Theories (GUTs), there is a connection between leptonic and hadronic flavour violation. In particular, in a broad class of GUTs, the large mixing angle observed in neutrino oscillations corresponds to large NP contributions to $b \leftrightarrow s$ transitions [12].

In this Letter, we show that present data give evidence of a B_s mixing phase much larger than expected in the SM, with a significance of more than 3σ. This result is obtained by combining all available experimental information with the method used by our collaboration for UT analyses and described in Ref. [13].

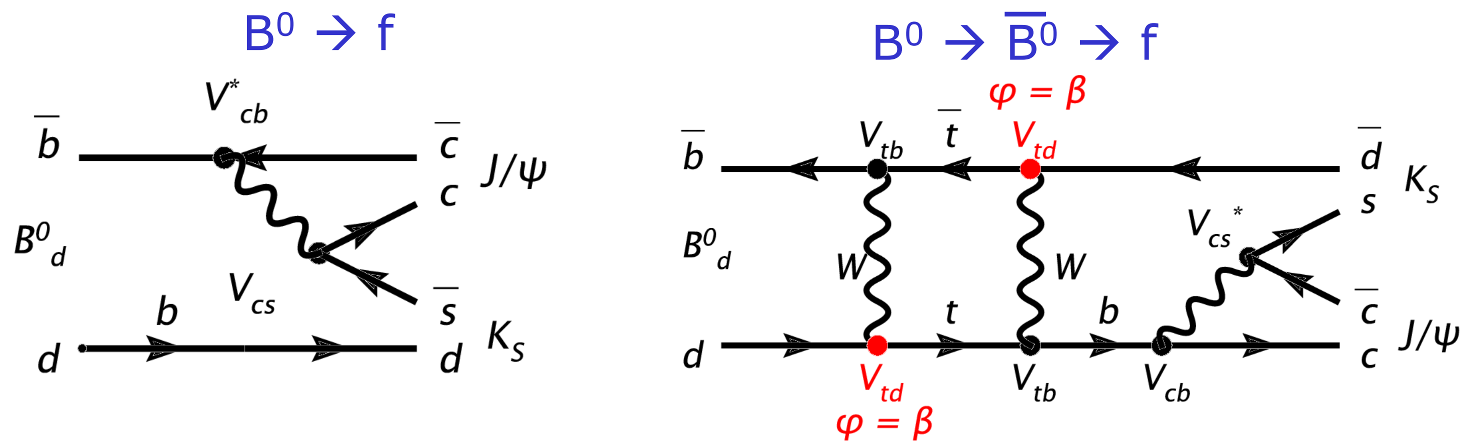
We perform a model-independent analysis of NP contributions to B_s mixing using the following parametrization [14]:

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP}-\beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}} = \frac{\langle B_s | H_{\rm eff}^{\rm full} | \bar{B}_s \rangle}{\langle B_s | H_{\rm eff}^{\rm SM} | \bar{B}_s \rangle}, \quad (1)$$

where $H_{\rm eff}^{\rm full}$ is the effective Hamiltonian generated

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

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



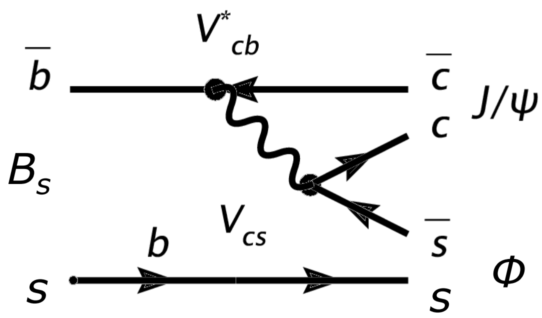
Wolfenstein parametrization to O(λ^5):

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

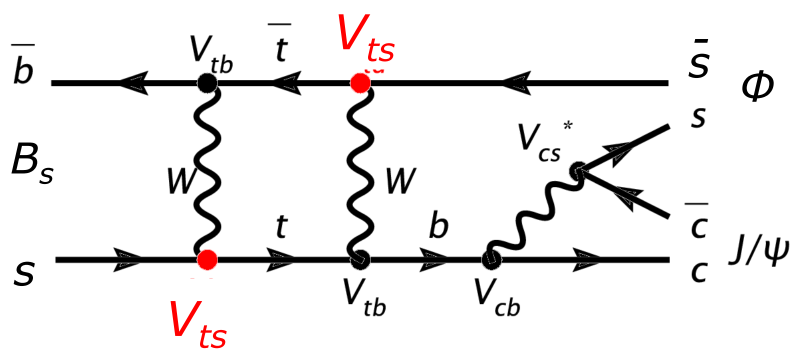
$B_s \to J/\psi\Phi$: B_s equivalent of $B \to J/\psi K_s$!

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

$B^0 \to f$



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



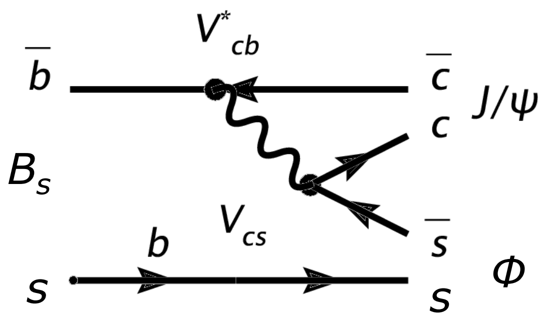
Wolfenstein parametrization to O(λ^5):

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

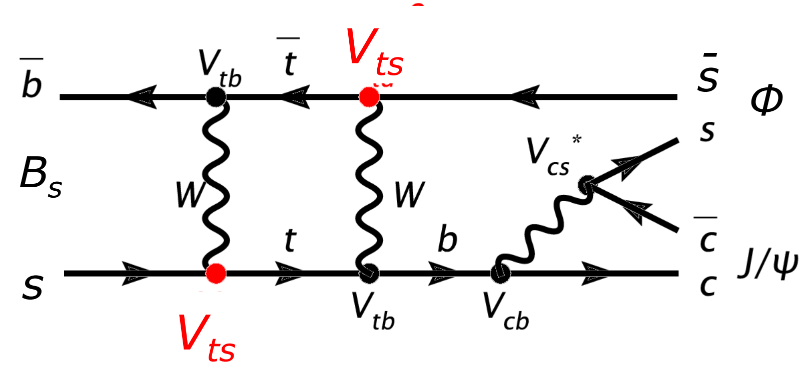
$B_s \to J/\psi\Phi$: B_s equivalent of $B \to J/\psi K_s$!

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

$B^0 \to f$



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

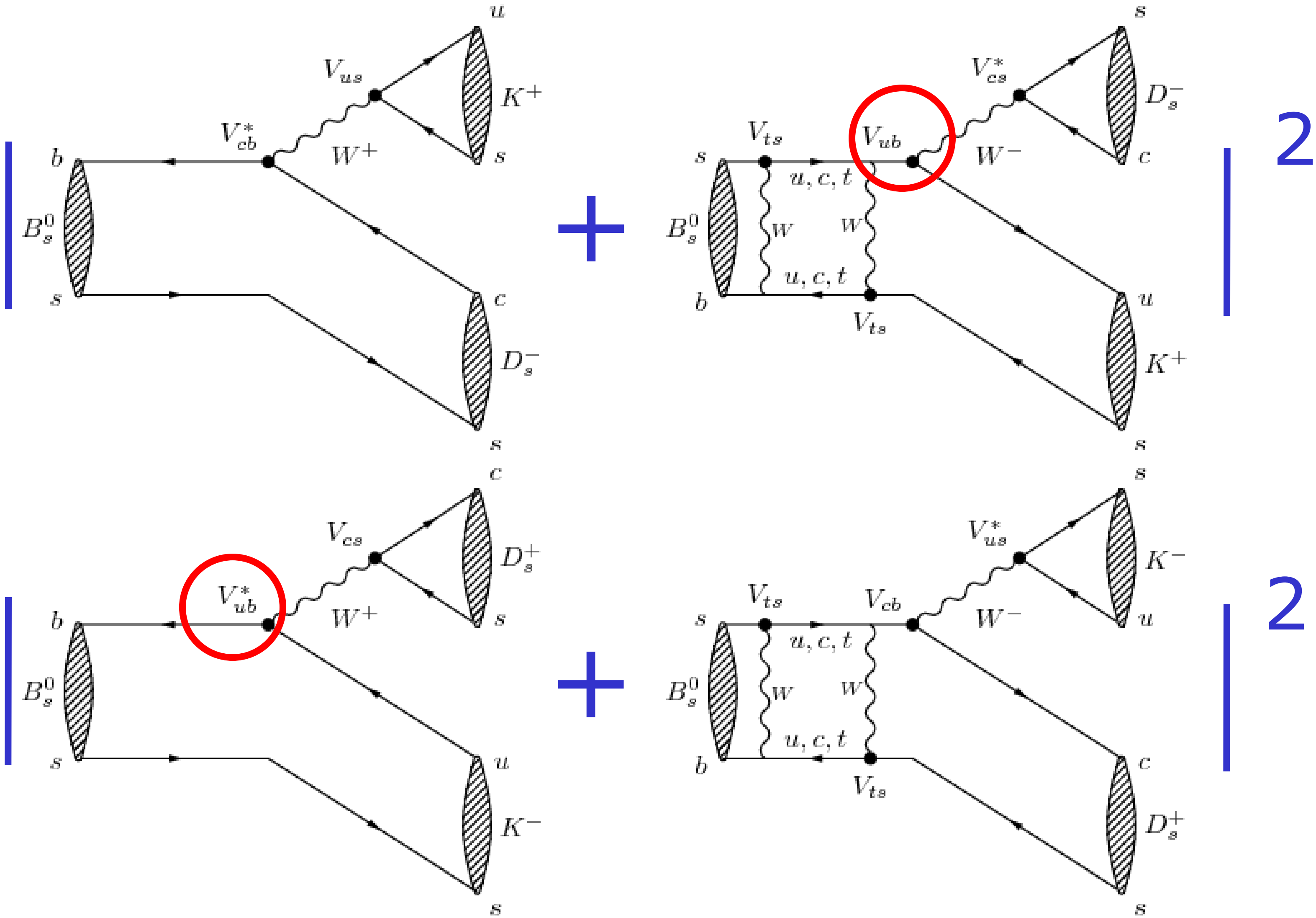


$$V_{CKM,\mathrm{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

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

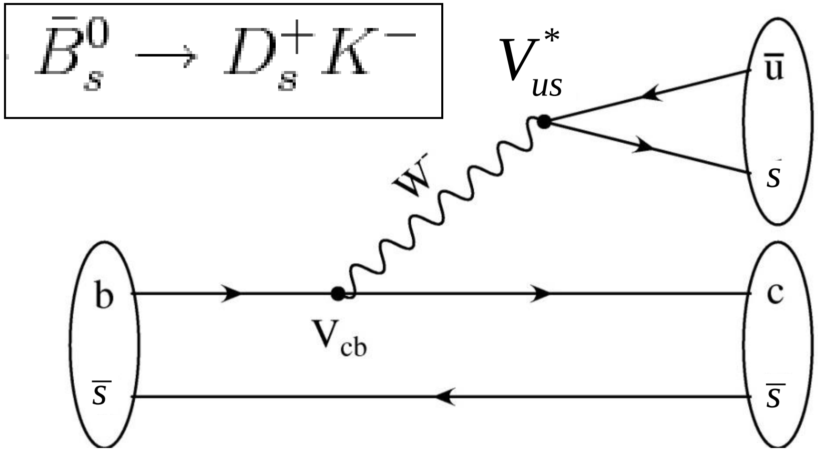
$\Gamma(B\to f)=$

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

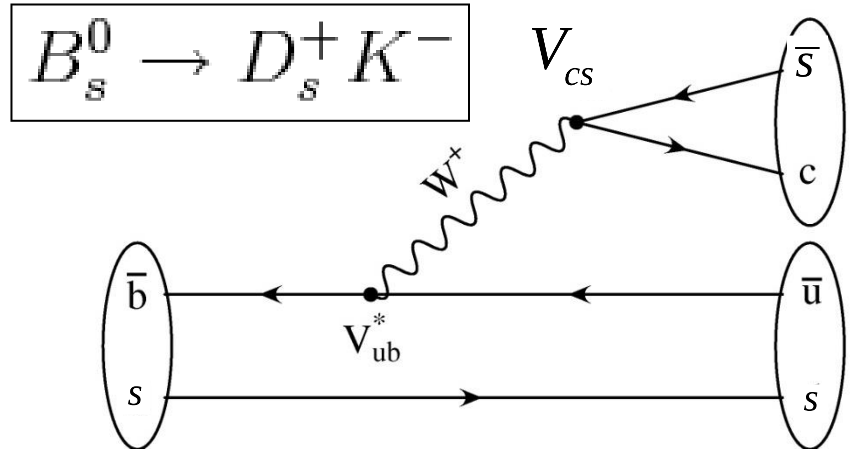


NB: In addition $\bar{B}_s \to D_s^{\pm}K^{-/+}$: both $\bar{\lambda}_f$ and $\bar{\lambda}_{\bar{f}}$

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



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



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

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

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

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

- 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

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End

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

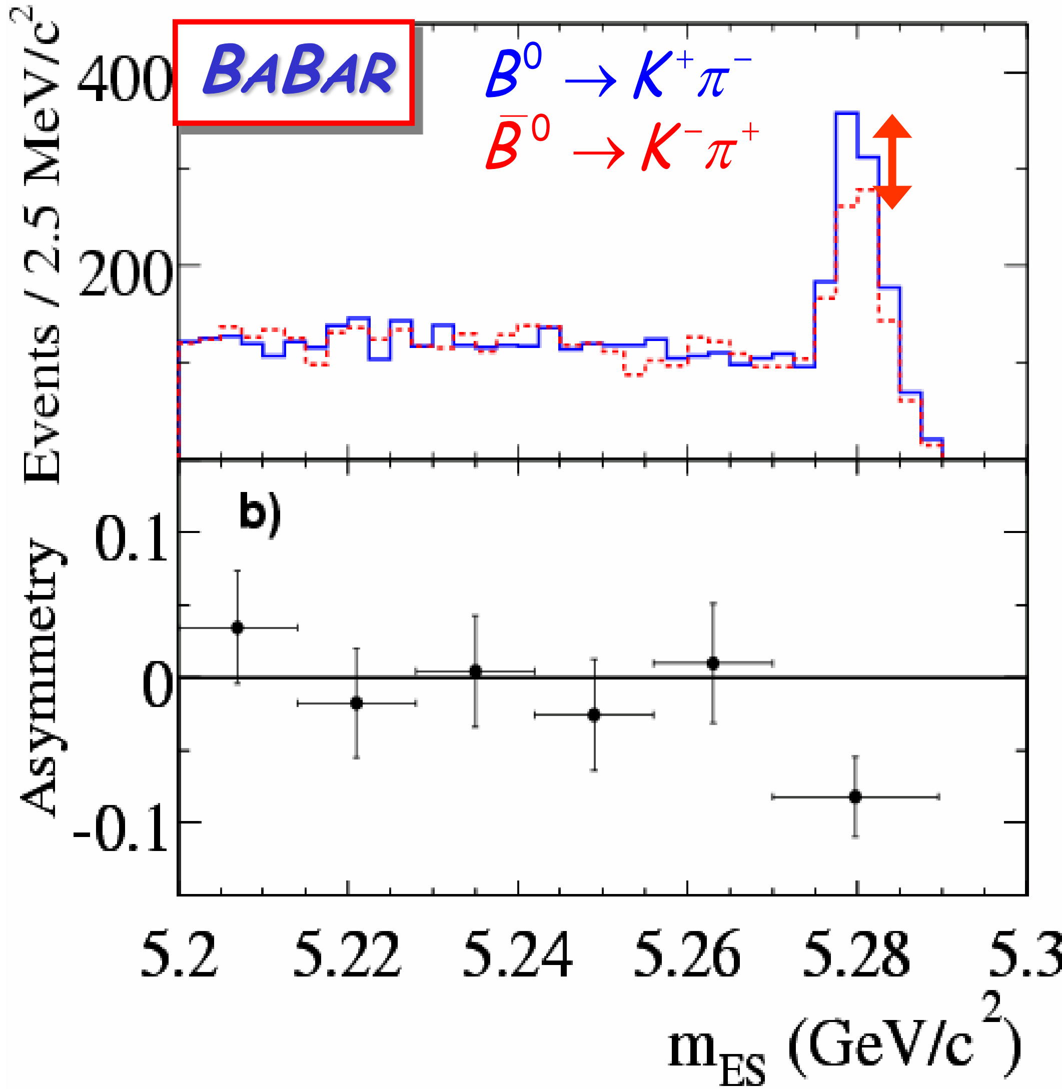
$$\Gamma(P^0{}_{(\leadsto \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\leadsto P^0)} \to f)(t)$$

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

CP violation in 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

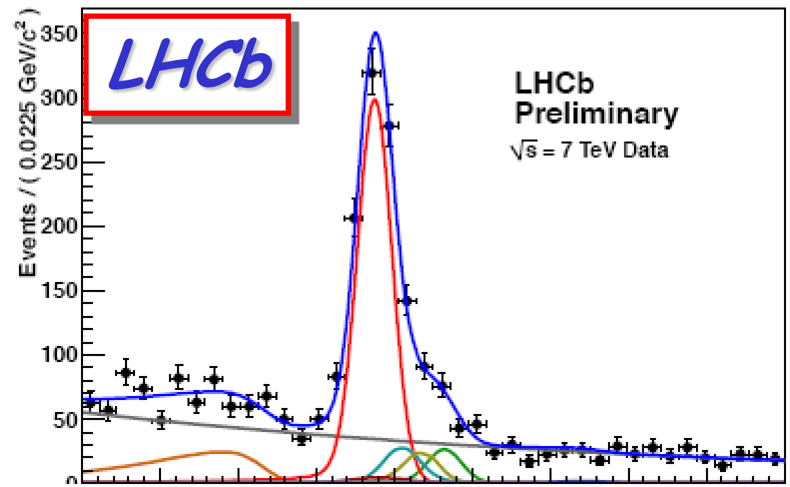
HFAG:

A_{CP} = -0.098 ± 0.012

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

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

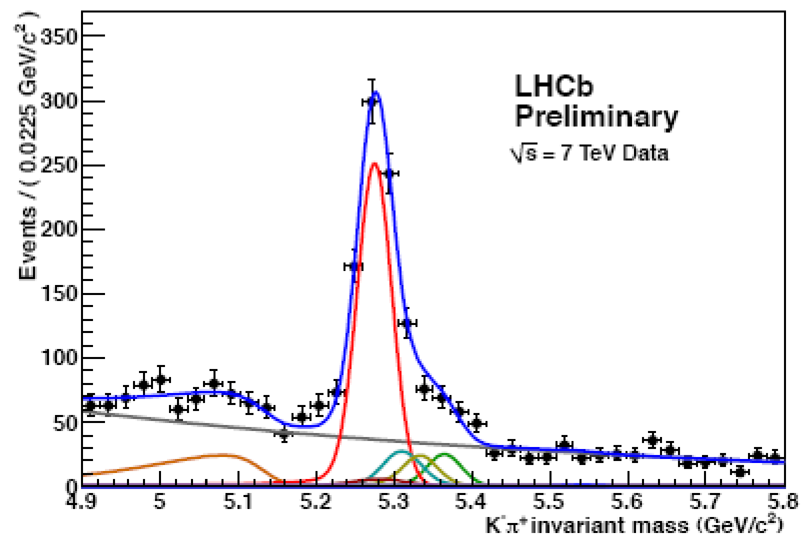
$$A_{CP} = \frac{\Gamma_{\bar{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\bar{B}\to\bar{f}} + \Gamma_{B\to f}}$$



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)

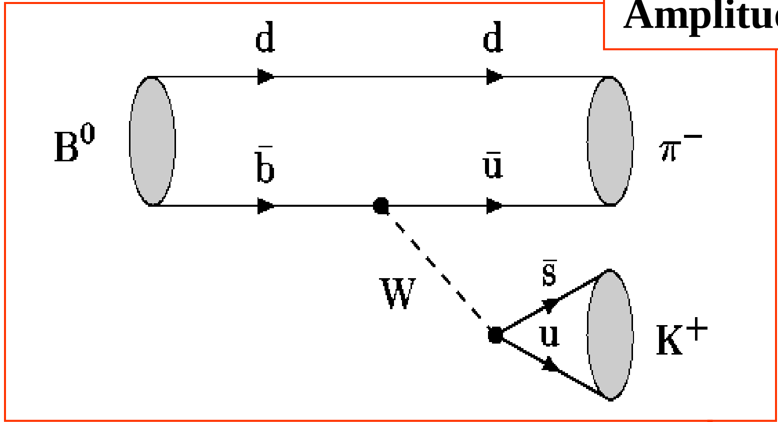
2 amplitudes
2 phases

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

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

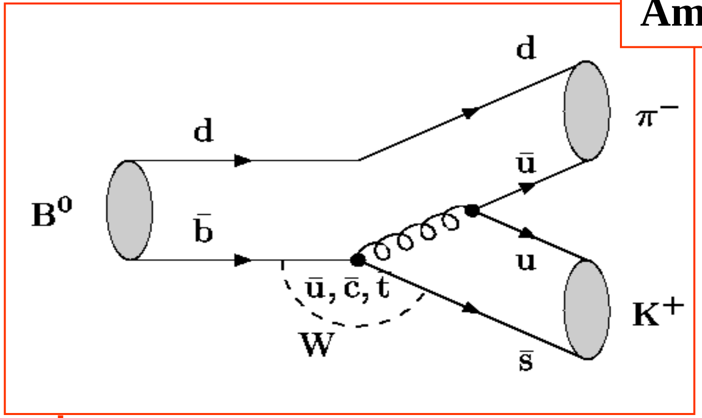
But: need 2 amplitudes → interference

Amplitude 1



+

Amplitude 2



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

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

Only different if both δ and γ are ≠0 !

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

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

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

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

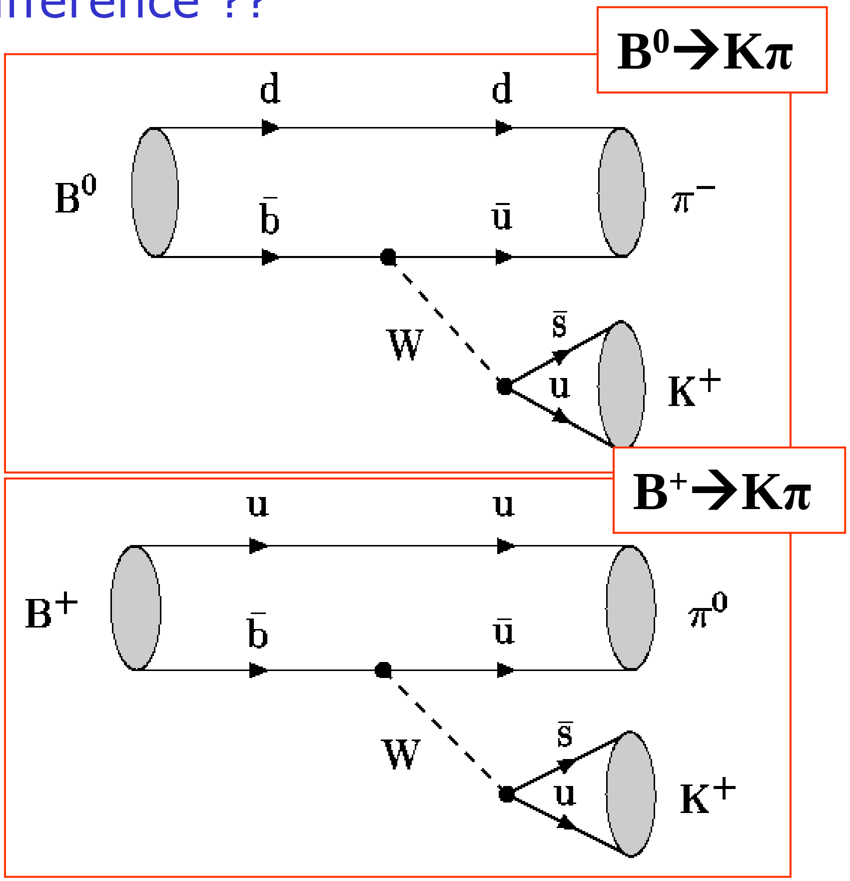
$B^0 \to K^+\pi^-$

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

3.6σ ?

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

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

J. Zupan Hadronic decays... 8 Beauty 2011, Amsterdam, Apr. 7, 2011

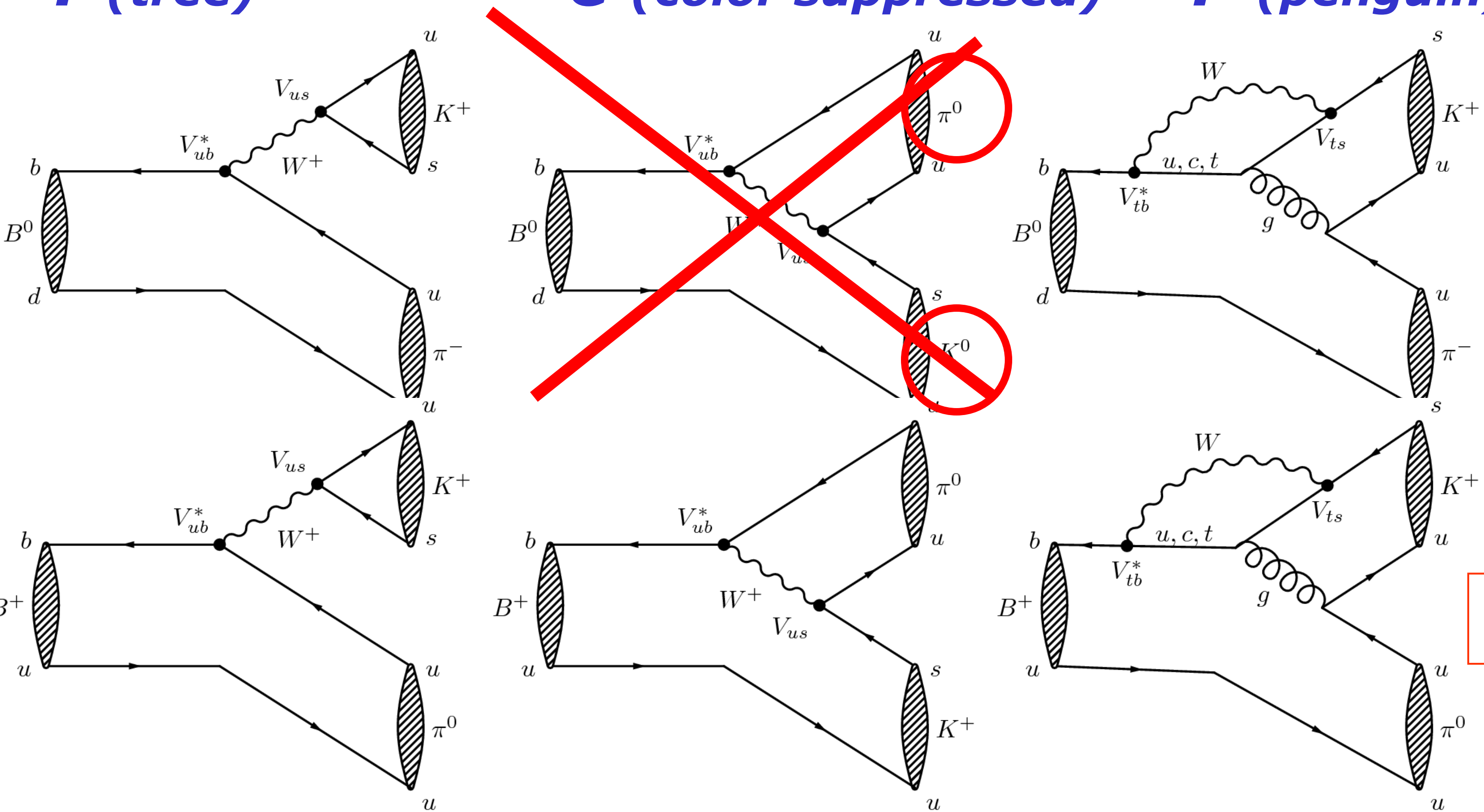
Hint for new physics? $B^0 \to K\pi$ and $B^\pm \to K^\pm\pi^0$

- 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

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

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

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

3. CP violation in interference

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

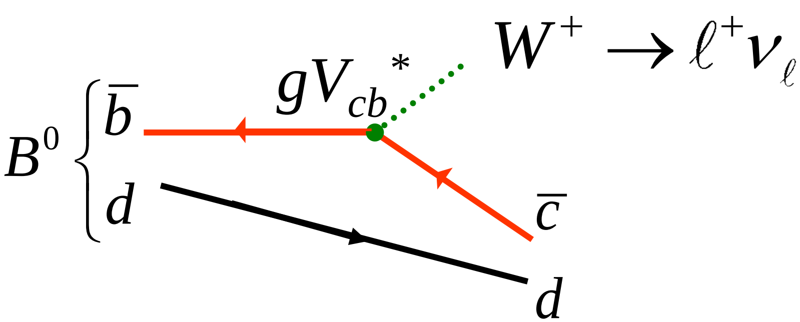
$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

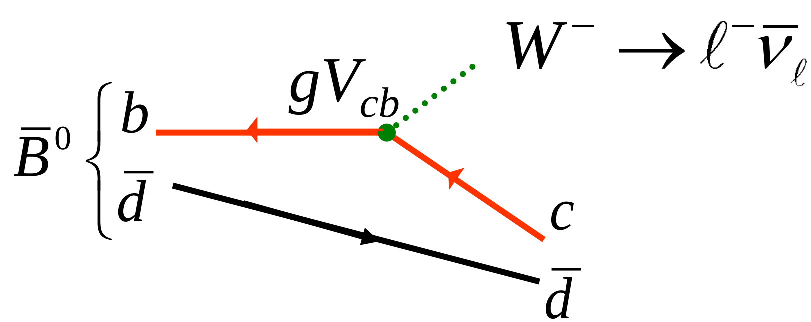
CP violation in Mixing? *(also known as: "indirect CPV": ε≠0 in K-system)*

$$P\left(B^0 \to \bar{B}^0\right) \stackrel{?}{=} P\left(\bar{B}^0 \to B^0\right)$$

Look for like-sign lepton pairs:

t=0	t	Decay	
$B^0\bar{B}^0$	$B^0\bar{B}^0$	$\to \ell^+\ell^- X$	
	$B^0 B^0$	$\to \ell^+\ell^+ X$	$\propto P\left(\bar{B}^0 \to B^0\right)$
	$\bar{B}^0\bar{B}^0$	$\to \ell^-\ell^- X$	$\propto P\left(B^0 \to \bar{B}^0\right)$
	$\bar{B}^0 B^0$	$\to \ell^-\ell^+ X$	





(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

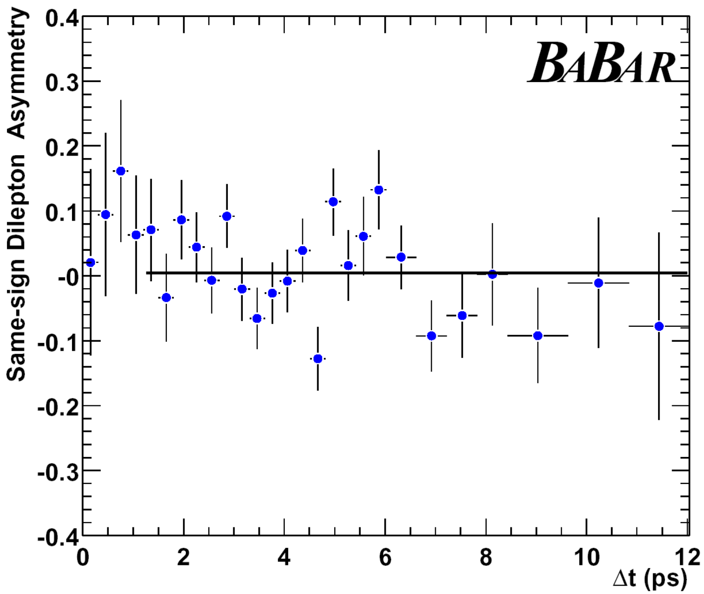


FIG. 3: Corrected same-sign dilepton asymmetry as a function of Δt. The line shows the result of the fit for the dileptons with $\Delta z > 200\,\mu$m.

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

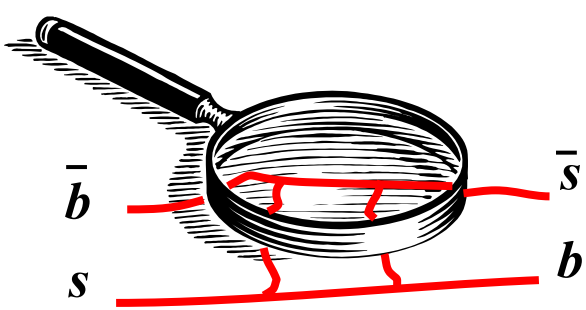
Fermilab-Pub-10/114-E

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]

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

"Box" diagram: ΔB=2



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

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

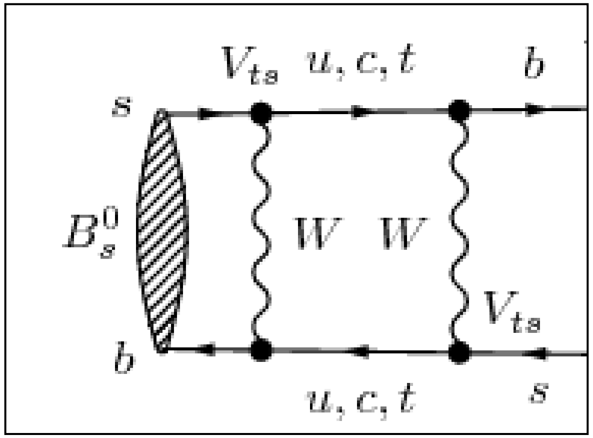
$$\phi = \phi_M - \arg(-\Gamma_{12})$$

$\varphi_s^{SM} \sim 0.004$
$\varphi_s^{SM}{}_M \sim 0.04$

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

?



- $b \rightarrow X\mu^- \nu$, $b \rightarrow X\mu^+ \nu$
- $\bar{b} \rightarrow b \rightarrow X\mu^+ \nu$, $b \rightarrow \bar{b} \rightarrow X\mu^- \nu$
- Compare events with like-sign $\mu\mu$
- Two methods:
  - Measure asymmetry of events with 1 muon

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

  - Measure asymmetry of events with 2 muons

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

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

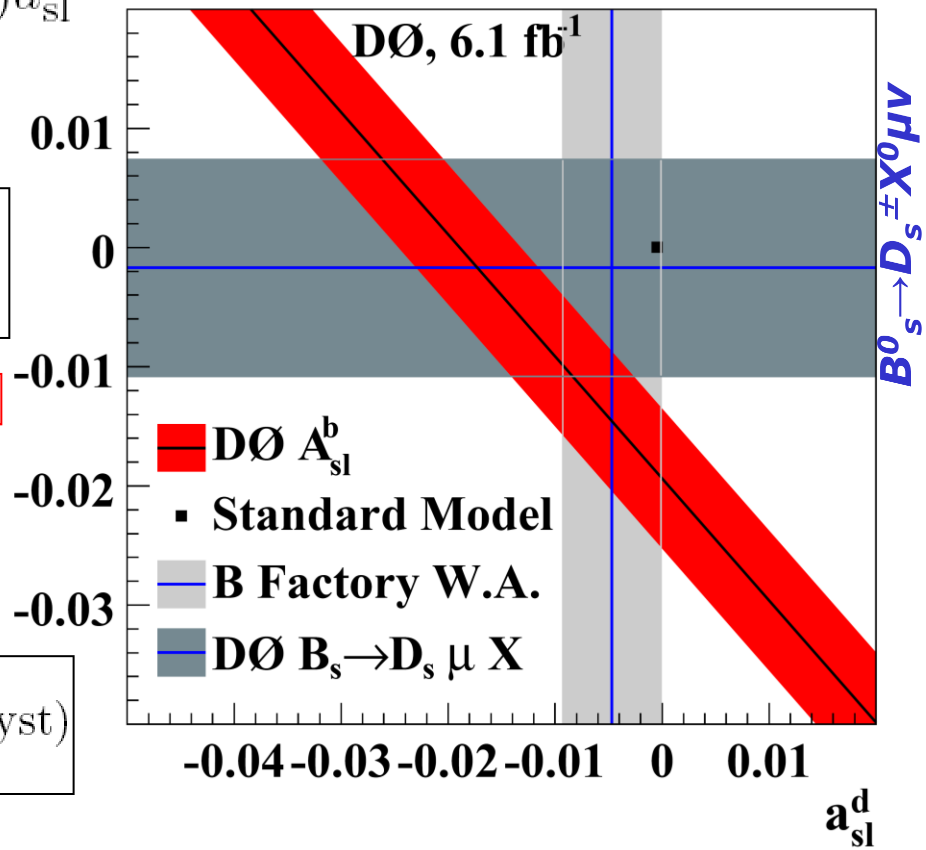
?

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

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: $A^b_{\rm sl} = -0.00957 \pm 0.00251\,({\rm stat}) \pm 0.00146\,({\rm sys})$. It differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$, and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

3.2 standard deviations from the standard model

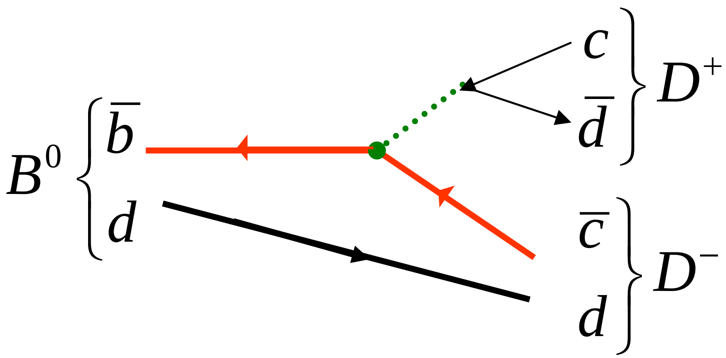
$$A^b_{\rm sl} = -0.00957 \pm 0.00251\ ({\rm stat}) \pm 0.00146\ ({\rm syst})$$



More β…

Other ways of measuring sin2β

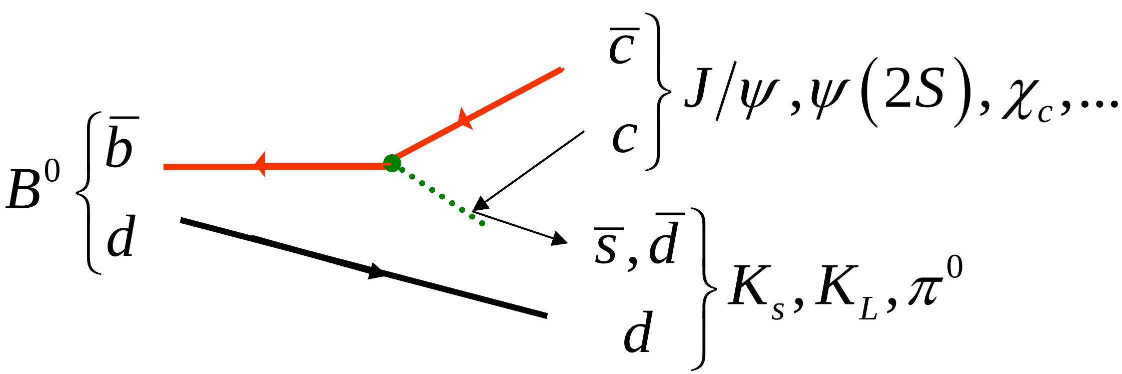
- Need interference of b→c transition and $B^0 - \overline{B}^0$ mixing
- Let's look at other b→c decays to CP eigenstates:



All these decay amplitudes have the same phase

(in the Wolfenstein parameterization)

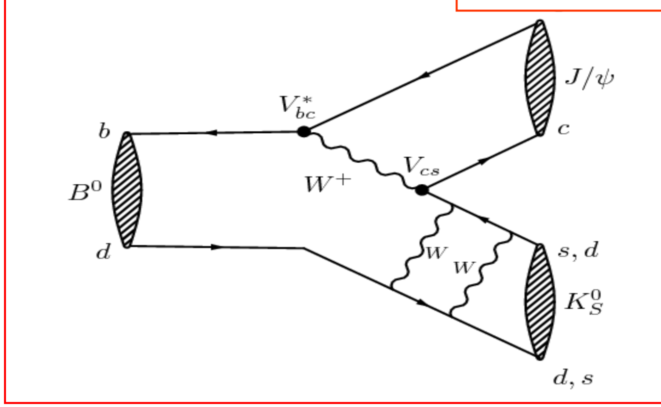
so they (should) measure the same CP violation



CP in interference with $B \rightarrow \varphi K_s$

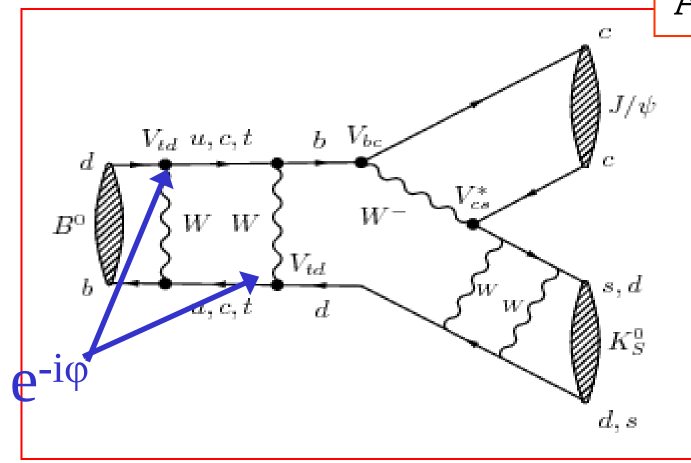
- Same as $B^0 \rightarrow J/\psi K_s$:
- Interference between $B^0 \rightarrow f_{CP}$ and $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$
  - For example: $B^0 \rightarrow J/\Psi K_s$ and $B^0 \rightarrow \bar{B}^0 \rightarrow J/\Psi K_s$
  - For example: $B^0 \rightarrow \varphi K_s$ and $B^0 \rightarrow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

Amplitude 1



+

Amplitude 2



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

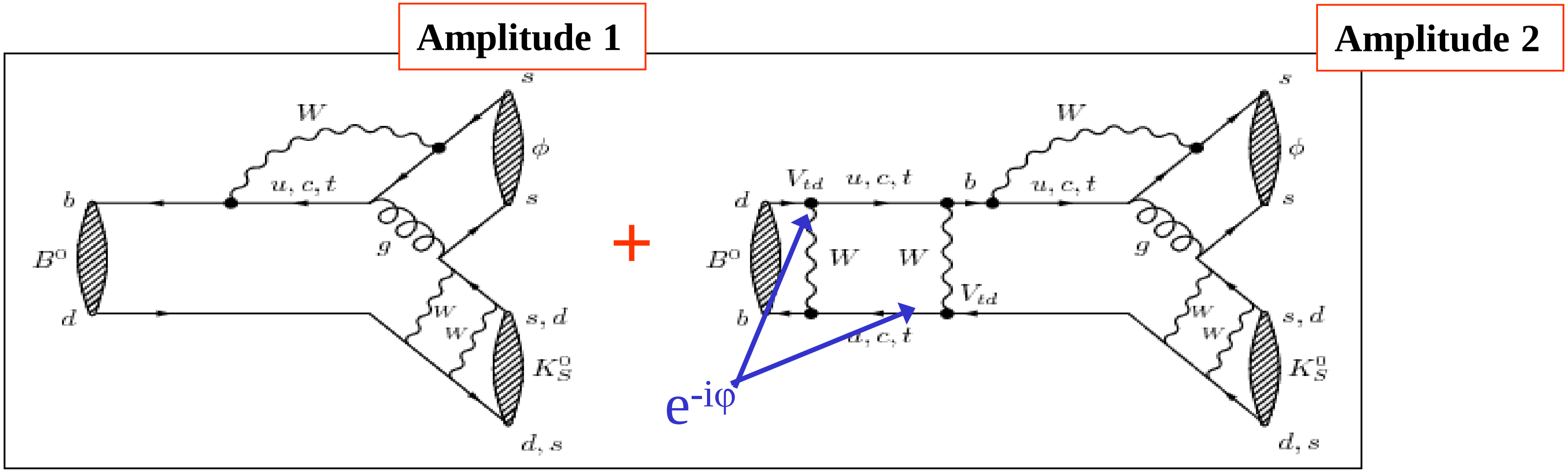
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\rightarrow f}(t) - \Gamma_{B\rightarrow f}(t)}{\Gamma_{\bar{B}\rightarrow f}(t) + \Gamma_{B\rightarrow f}(t)} = \mathrm{Im}(\lambda_f) \sin \Delta m t$$

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

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

CP in interference with $B \rightarrow \varphi K_s$: what is different??

- 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 $B^0 \rightarrow \bar{B}^0 \rightarrow \varphi K_s$



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

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

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

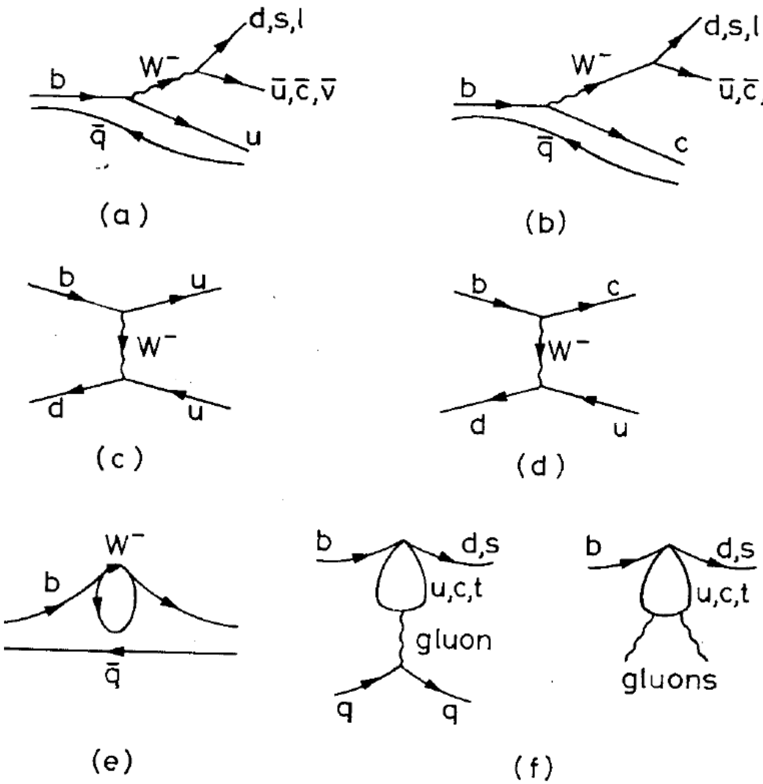
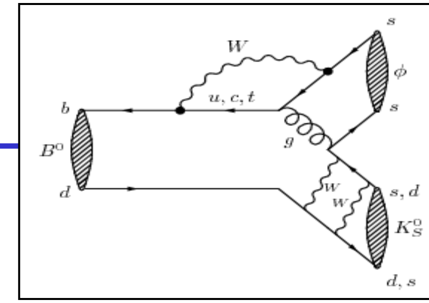


Fig. 2

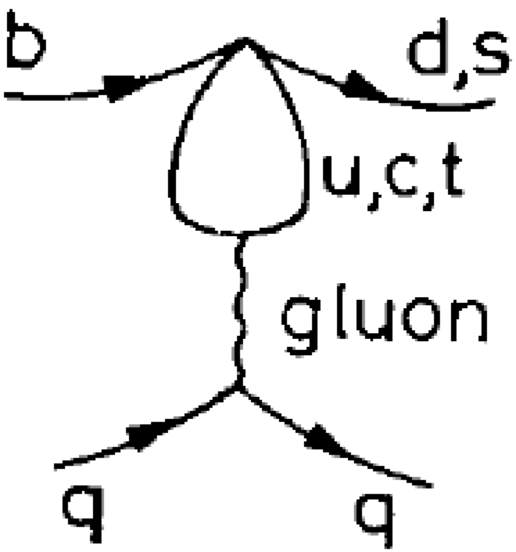
1.1 History of Penguins

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].

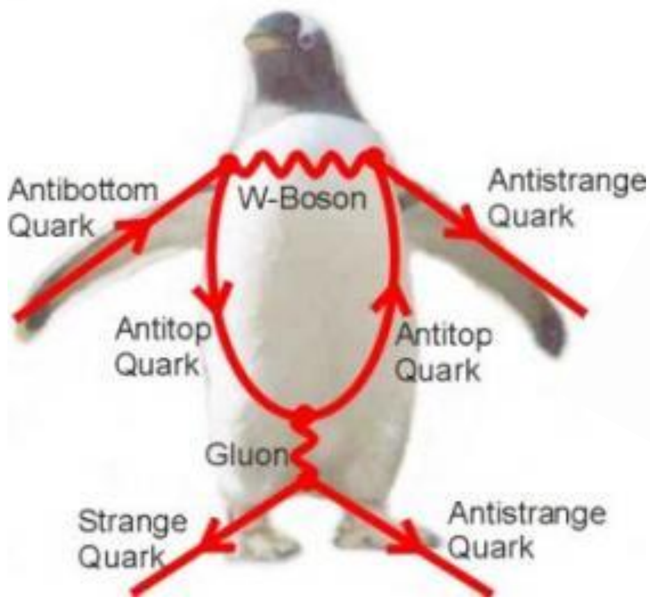
Penguins??



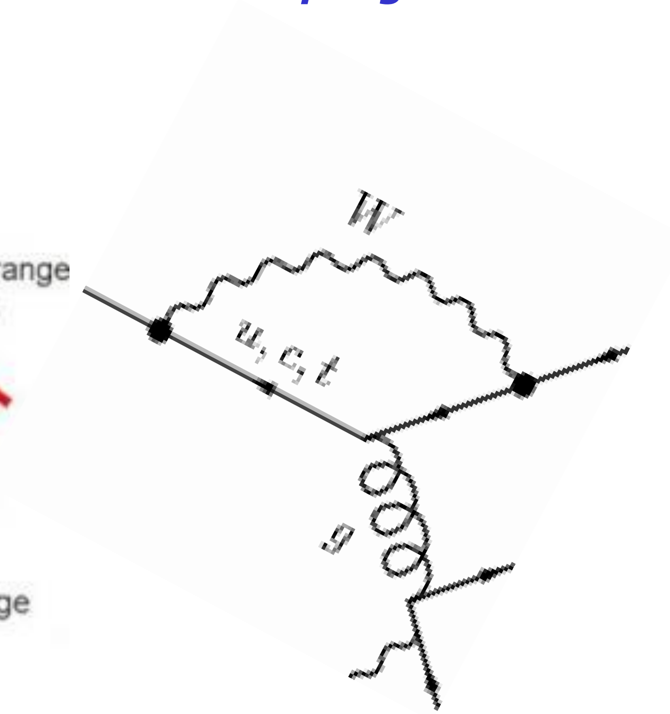
The original penguin:



A real penguin:



Our penguin:

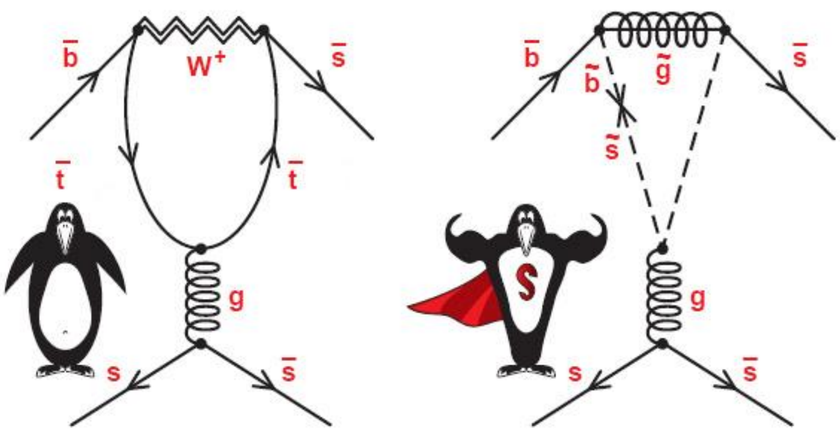


Funny

Flying Penguin

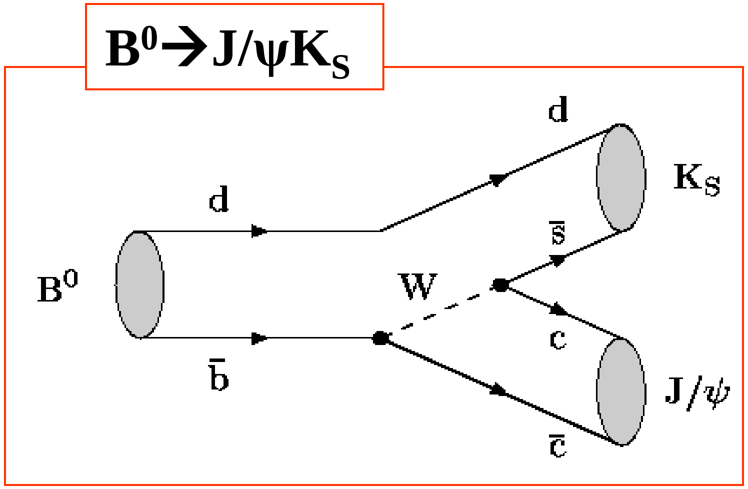
Dead Penguin

Super Penguin:



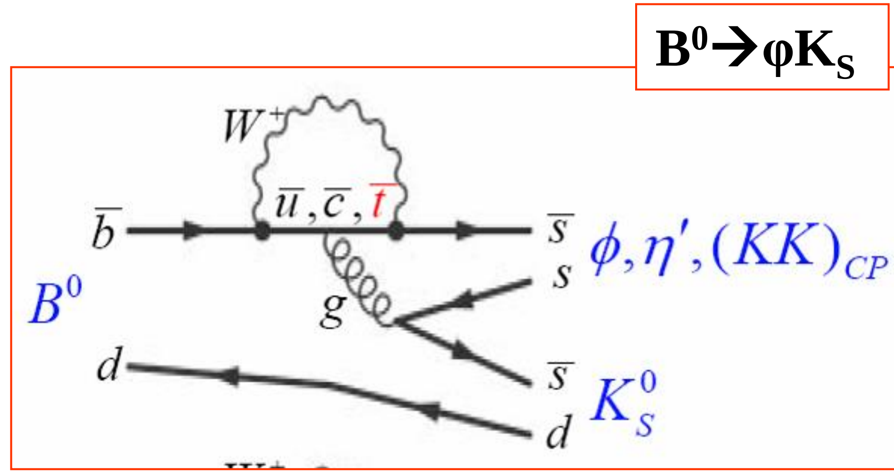
Penguin T-shirt:

The “b-s penguin”

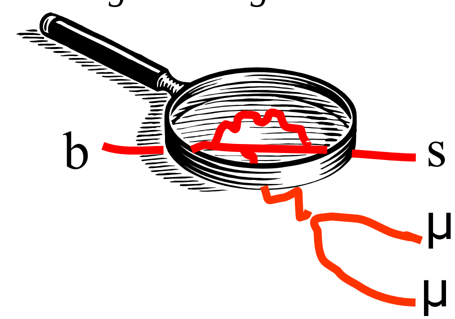


Asymmetry in SM

≈



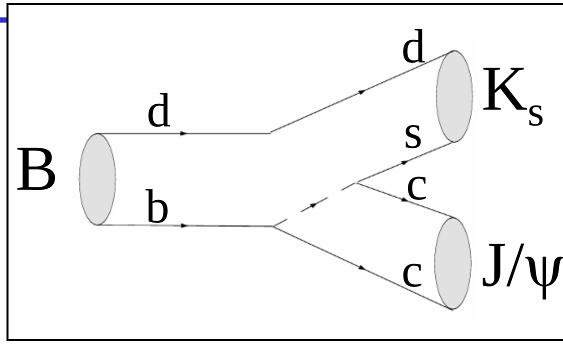
“Penguin” diagram: ΔB=1



… 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??



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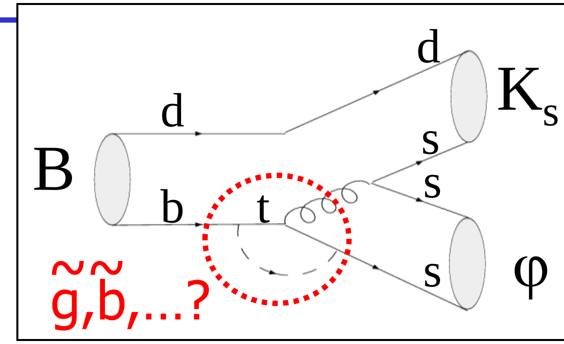
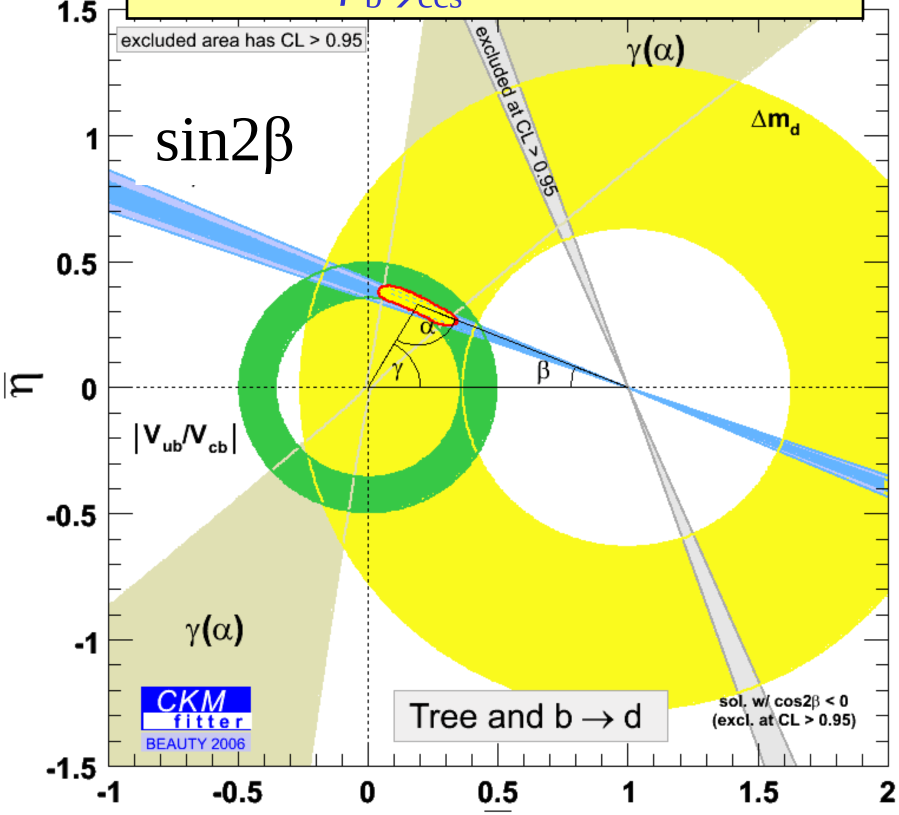
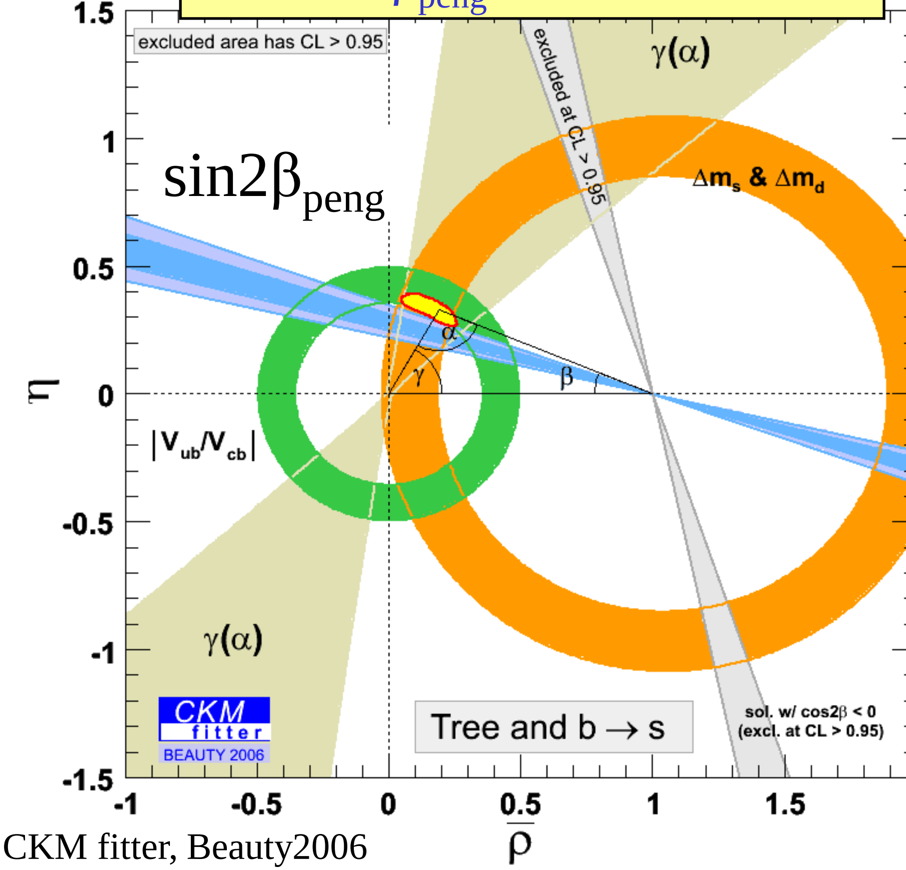


- $\sin 2\beta_{b\to ccs}$ = 0.68 ± 0.03



- $\sin 2\beta_{peng}$ = 0.52 ± 0.05



S.T' Jampens, CKM fitter, Beauty2006

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