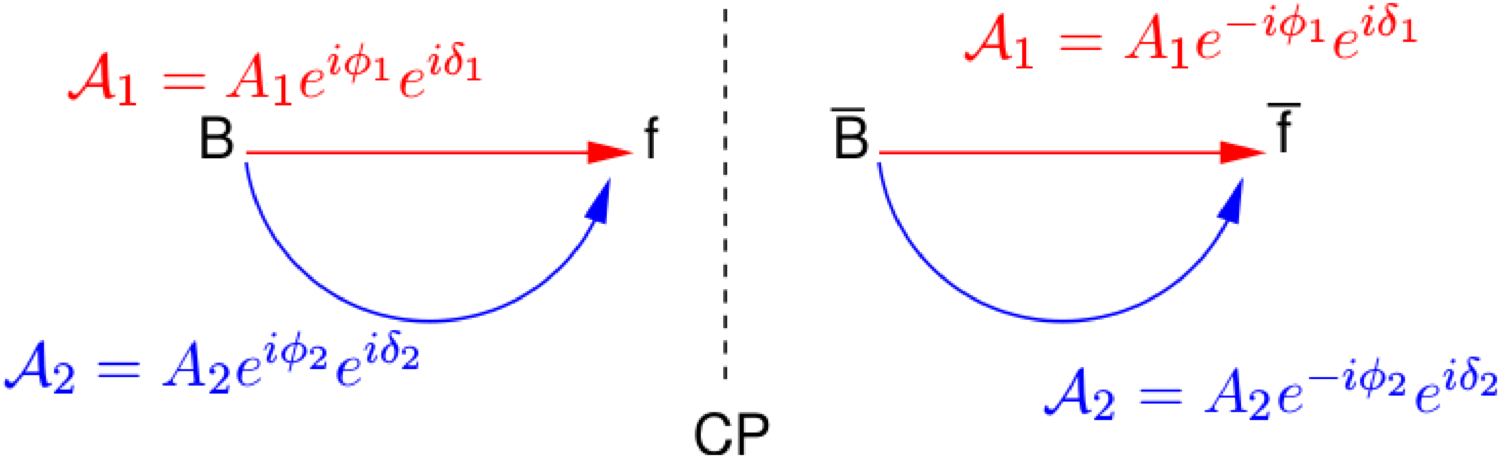
CP Violation



$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(-\Delta\phi + \Delta\delta)$$

$\mathcal{A}_1$ and $\mathcal{A}_2$ need to have different weak phases ϕ and different strong phases δ.

For sizable (measurable) effects both amplitudes should have about same size, and both phase differences have to be sizable.

To conclude on weak phases, strong phases need to be known/measured.

CP Violation in one Page

Mass eigenstates:

$B_L = p|B^0> +q|\overline{B^0}>$ w. m_L, Γ_L

$B_H = p|B^0> -q|\overline{B^0}>$ w. m_H, Γ_H

$|p^2| + |q^2| = 1,$ complex coefficients

Flavour eigenstates:

$B^0 = \frac{1}{2p}(|B_L> +|B_H>)$

$\overline{B^0} = \frac{1}{2q}(|B_L> -|B_H>)$

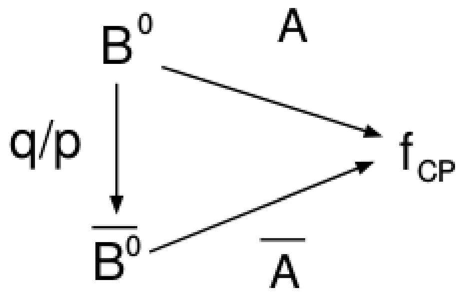
- CP Violation in mixing

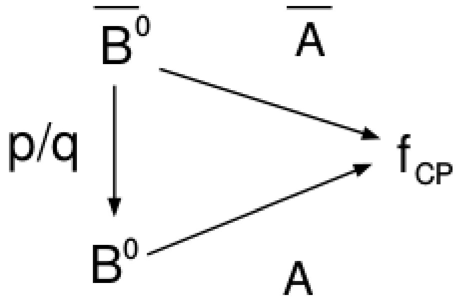
  If $|\frac{q}{p}| \neq 1$; mass eigenstates are no CP eigenstates;

  $\rightarrow P(B^0 \rightarrow \overline{B^0}) \neq P(\overline{B^0} \rightarrow B^0)$

- CP violation in decay $|A(B \rightarrow f)| \neq |\overline{A}(\overline{B} \rightarrow \overline{f})|$

- CP violation in interference of mixing and decay: $Im(\frac{q}{p}\frac{\overline{A}}{A}) \neq 0$



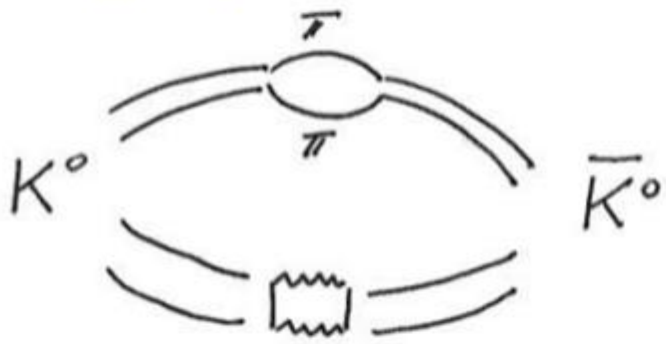


Definition valid for all meson systems not only for B system

CPV in Kaon System

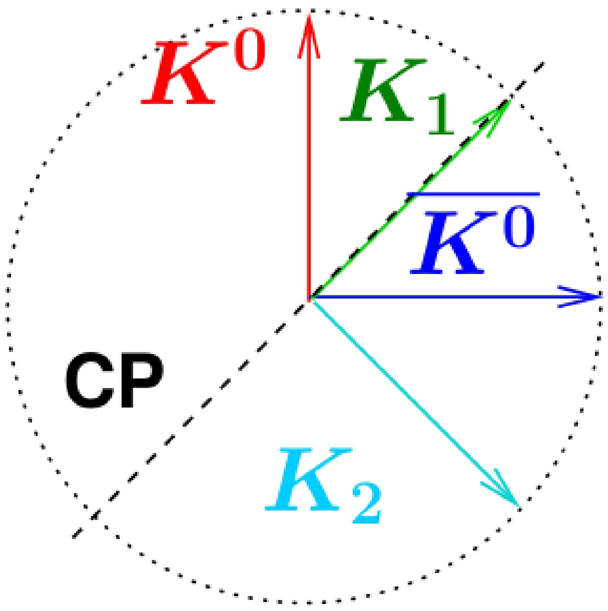
Interferring amplitudes which cause CPV in mixing:

long range contribution $\Delta\Gamma$



short range contribution Δm

Neutral Meson Mixing



$$CP(K^0) = \overline{K^0}$$
$$CP(\overline{K^0}) = K^0$$

$$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0})$$
$$CP(K_1) = +K_1$$

$$K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0})$$
$$CP(K_2) = -K_2$$

K^0, $\overline{K^0}$: flavour eigenstates; clear defined quark content ($K^0 = |d\bar{s}>$, $\overline{K^0} = |\bar{d}s>$)

K_1, K_2: CP eigenstates

K_S, K_L: mass eigenstates

(with clear defined mass and lifetime, $\psi_{S/L}(t) = e^{-im_{S/L}t}e^{-\Gamma_{S/L}t/2}$)

in absence of CPV: $K_S = K_1, K_L = K_2$

Kaon Mixing

$$P(\mathbf{K^0} \rightarrow \overline{\mathbf{K^0}}) = <\mathbf{K^0}(\mathbf{t})|\overline{\mathbf{K^0}}> =$$
$$\frac{1}{4}|\frac{q}{p}|^2 \left(e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right)$$

$$P(\overline{\mathbf{K^0}} \rightarrow \mathbf{K^0}) = <\overline{\mathbf{K^0}}(\mathbf{t})|\mathbf{K^0}> =$$
$$\frac{1}{4}|\frac{p}{q}|^2 \left(e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right)$$

CP conserved: $P(\mathbf{K^0} \rightarrow \overline{\mathbf{K^0}}) = P(\overline{\mathbf{K^0}} \rightarrow \mathbf{K^0})$

$$\Leftrightarrow$$

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

(+ normalisation $q^2 + p^2 = 1$)

$$\Leftrightarrow$$

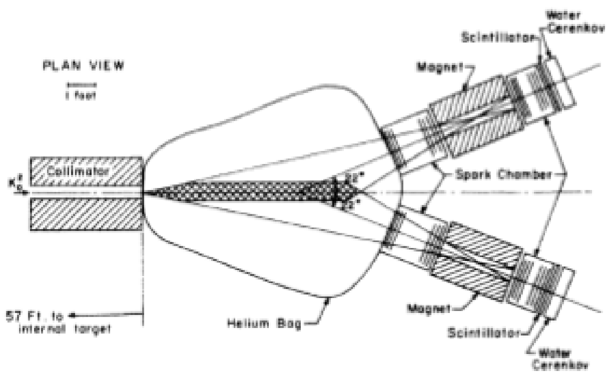
$$q = p = \frac{1}{\sqrt{2}}$$

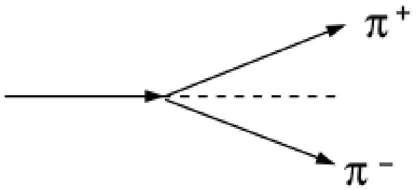
$$\Leftrightarrow$$

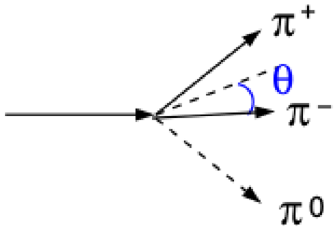
$$\boldsymbol{K_S = K_1, K_L = K_2}$$

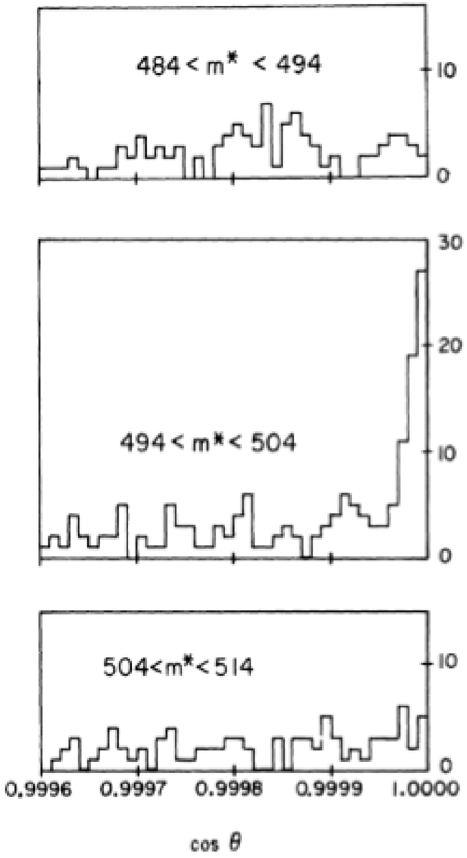
1964: Discovery of CPV

- produce K^0, wait long enough for K_S component to decay away $\rightarrow$ pure K_L beam
- search for CP violation: $K_L \rightarrow \pi^+\pi^-$
  $\rightarrow$ excess of 56 events: BR($K_L \rightarrow \pi^+\pi^-$) $\sim 2 \times 10^{-3}$









mass eigenstates $\neq$ CP eigenstates: $|\mathbf{K_L}>= \frac{1}{\sqrt{1+|\epsilon^2|}}(|\mathbf{K_2}> +\epsilon|\mathbf{K_1}>)$

CP=-1 CP=+1

Nobel prize for Cronin and Fitch in 1980

New physics in B_s mixing?

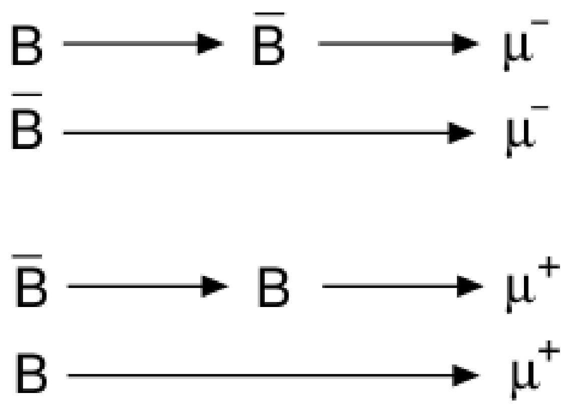
▶ $P(B \to \overline{B}) \neq P(\overline{B} \to B)$

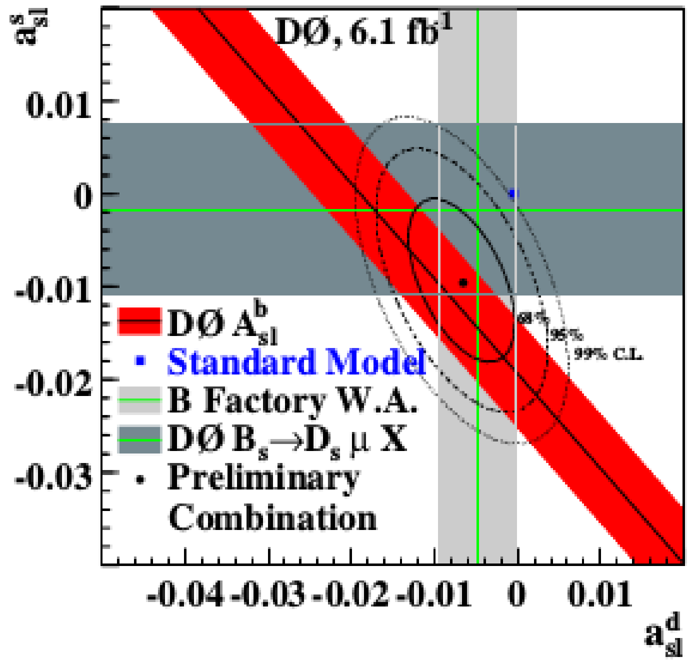
SM: A^b_{sl} = (-0.20 $\pm$ 0.03) $\times$ 10^{-3}

A. Lenz, U. Nierste, (2006/2011)

semileptonic asymmetry

$(B^0 + B_s)$





$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

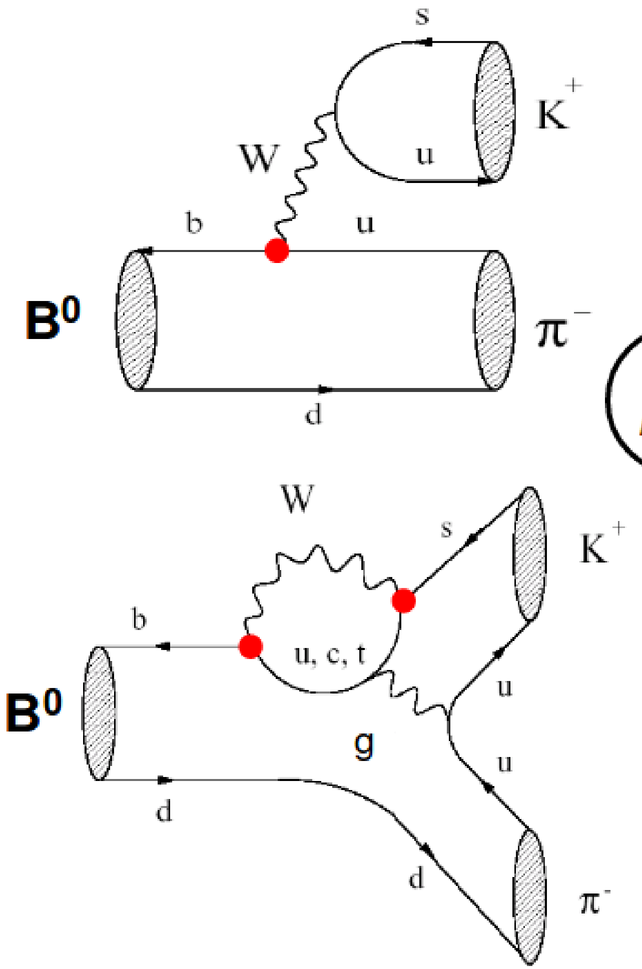
$$a = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$$

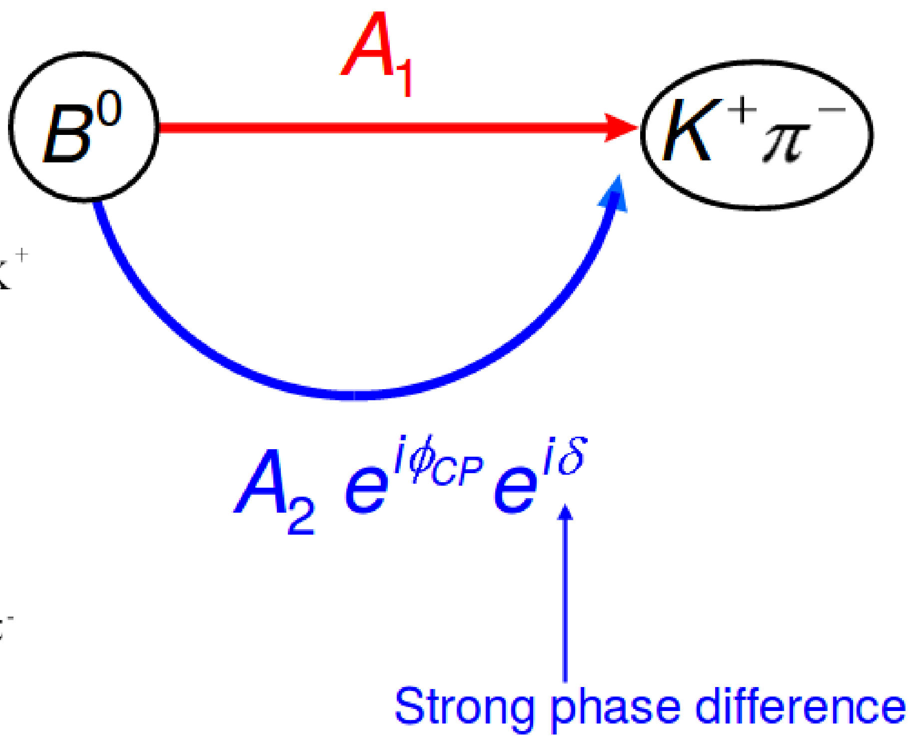
A^b_{sl} = -0.957 $\pm$ 0.251 (stat) $\pm$ 0.14 (syst) %

(Phys. Rev. Lett 105, 081802 (2010))

$\to$ 3.2σ deviation from SM

Direct CP Violation





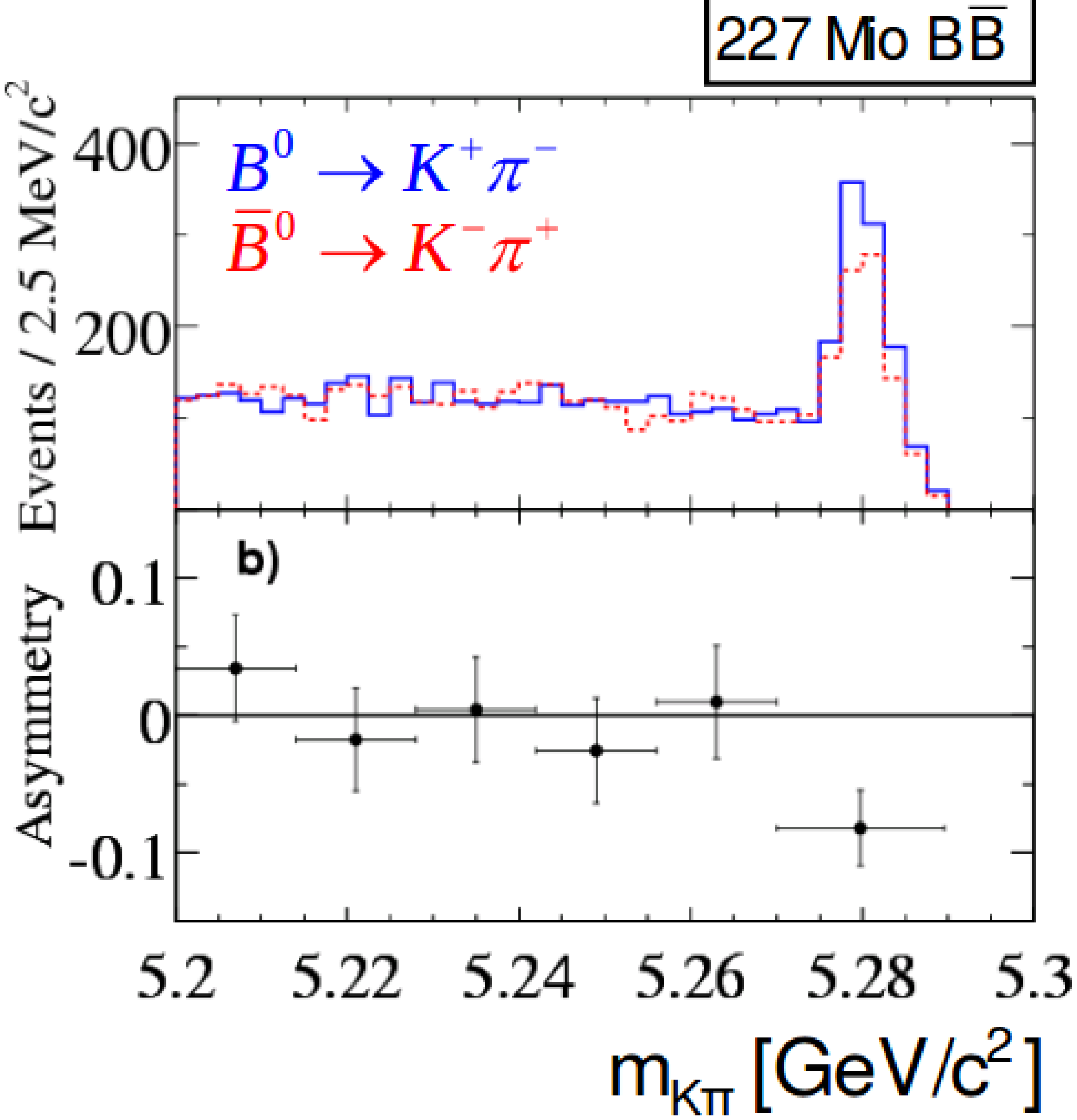
CP Asymmetrie $$|\bar{A}|^2 - |A|^2 = 4|A_1||A_2|\sin\varphi \sin\delta$$

$$N(B^0/\bar{B}^0 \rightarrow K^{\pm}\pi^{\mp}) = 1606 \pm 51$$

$$A_{CP} = \frac{N(\bar{B}^0 \rightarrow K^{+}\pi^{-}) - N(B^0 \rightarrow K^{-}\pi^{+})}{N(\bar{B}^0 \rightarrow K^{+}\pi^{-}) + N(B^0 \rightarrow K^{-}\pi^{+})}$$

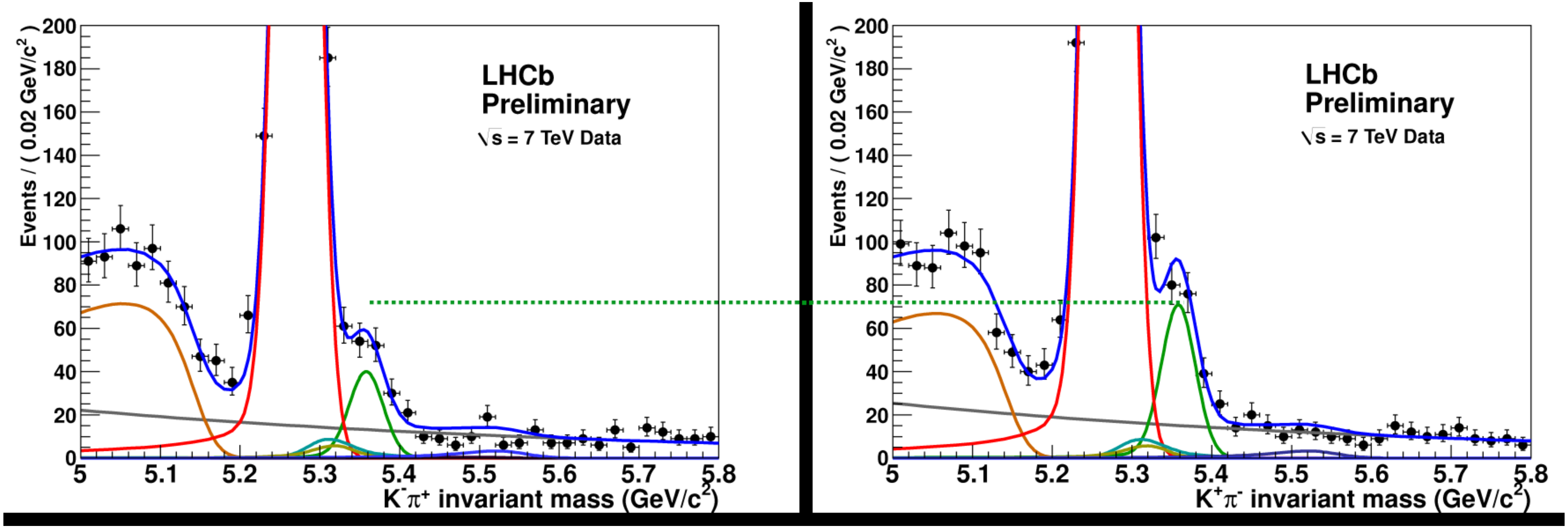
$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

4.2σ

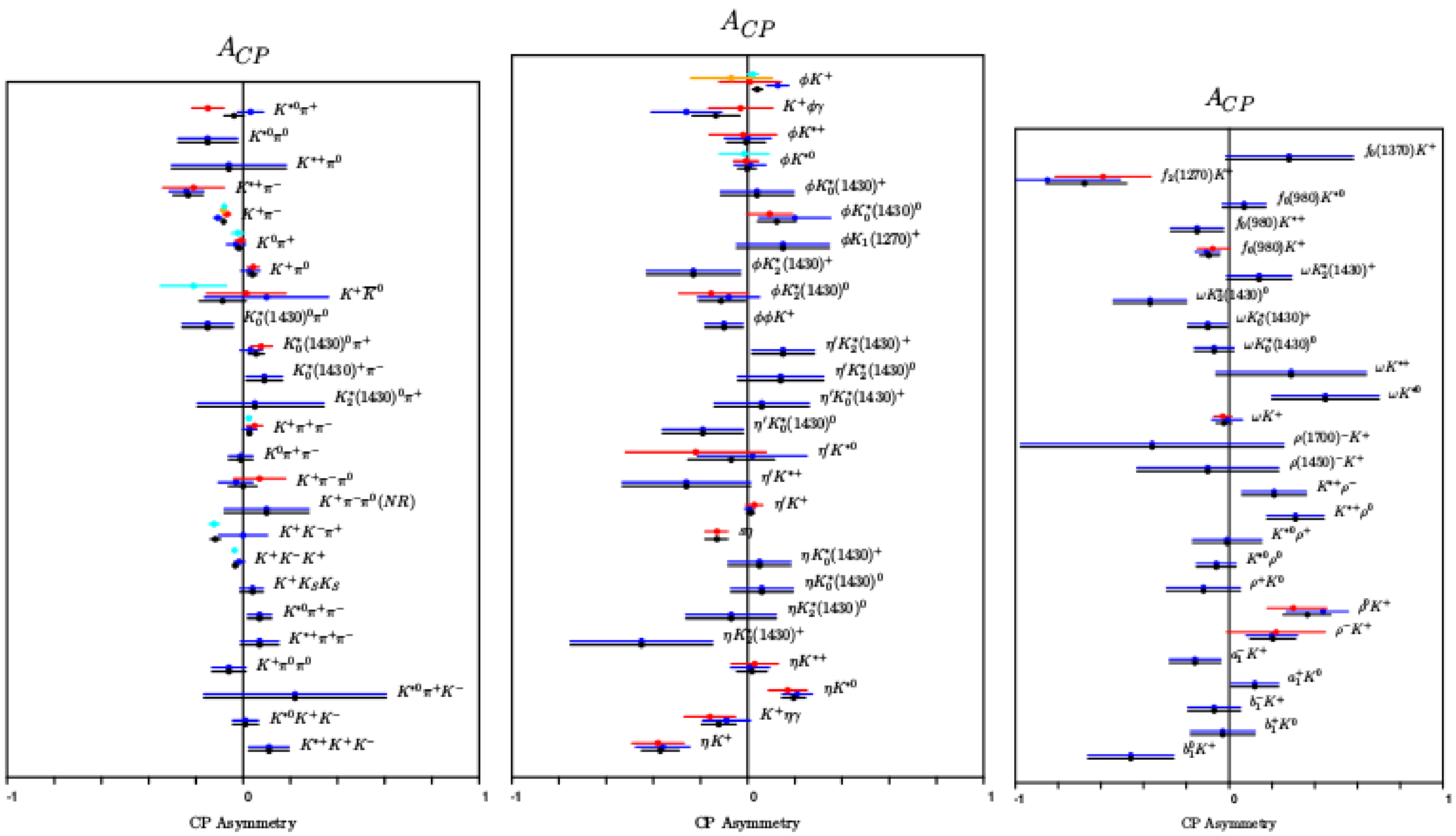


PRL93(2004) 131801.

CP Violation in $B_s^0 \to K^+\pi^-$



Lot's of direct CPV ...



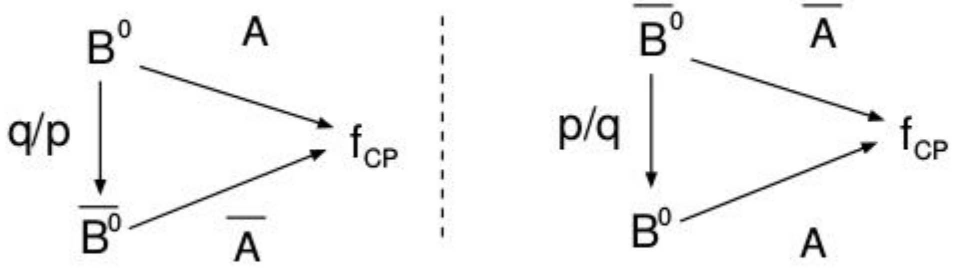
Due to unknown strong phases, hard to relate CPV directly to CKM parameters :-(.

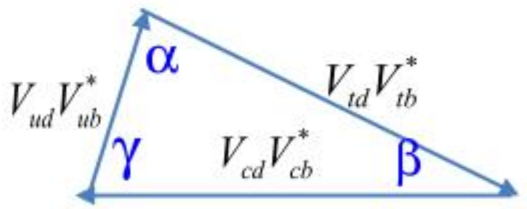
"The strong interaction can be seen either as the unsung hero or the villain in the story of quark flavour physics"; I. Bigi.

CPV in interference of mixing and decay

Measurement of $\sin(2\beta)$: golden channel $B_d \to J/\psi K_s$

"Golden": large statistics, easy to detect, (almost) no CPV in decay





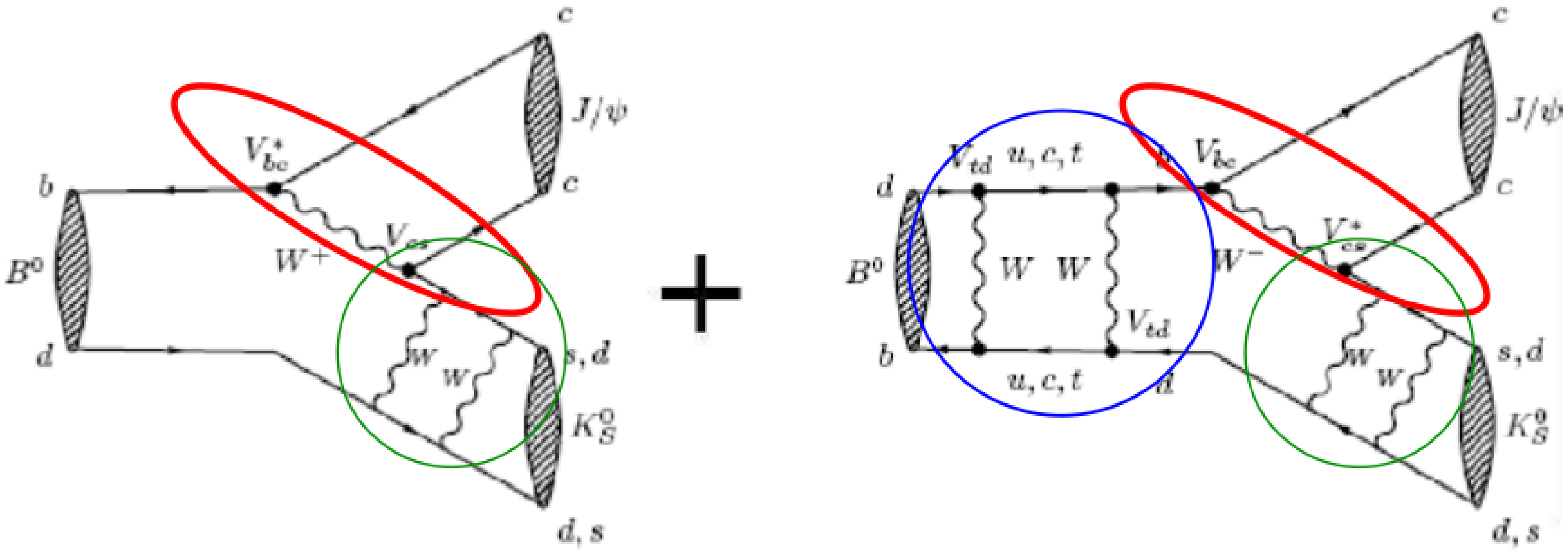
Weak phase: $Im(\frac{q}{p}\frac{\overline{A}}{A})$

$$\beta = \arg \frac{V_{cb}V_{cd}^*}{V_{tb}V_{td}^*}$$

$B_d \to J/\Psi K^0$

Reach same final state through decay & mixing + decay

(assume no CPV in mixing and no CPV in decay)



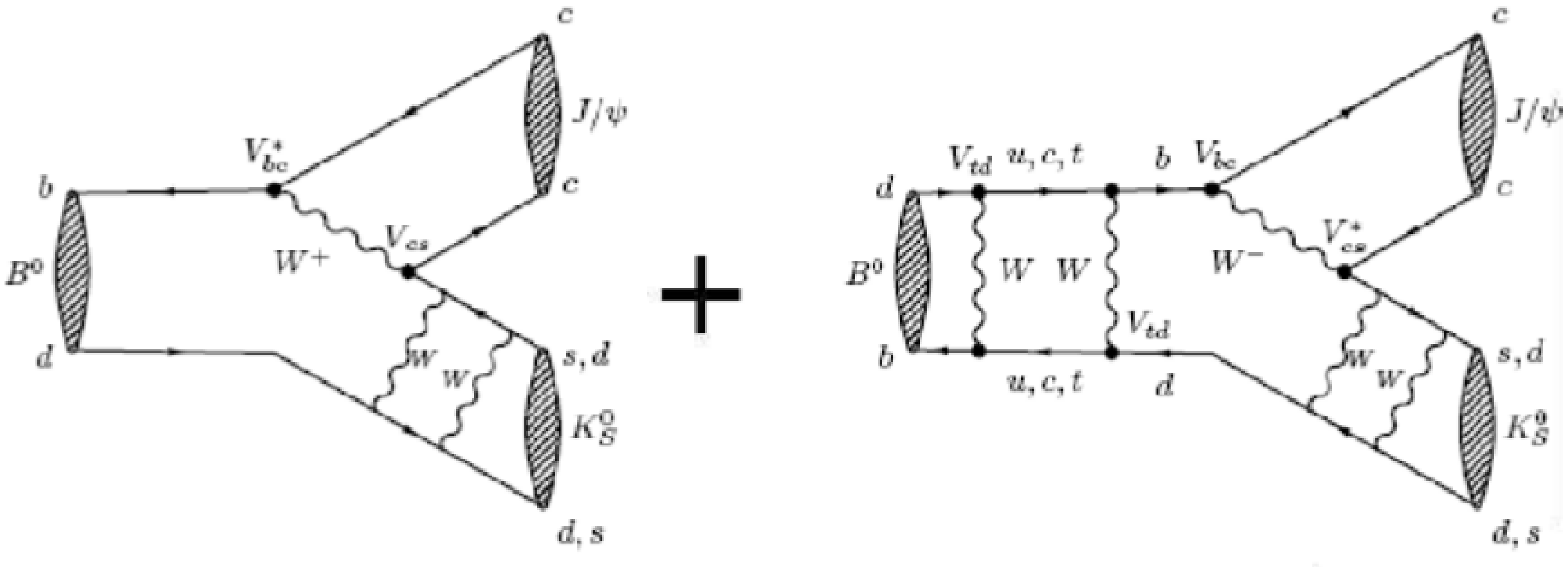
$$\mathcal{A}_1 = \mathcal{A}_{mix}(B^0 \to B^0) * \mathcal{A}_{decay}(B^0 \to J/\Psi K^0) = \cos(\frac{\Delta m t}{2}) * A * e^{i\omega}$$

$$\mathcal{A}_2 = \mathcal{A}_{mix}(B^0 \to \overline{B^0}) * \mathcal{A}_{decay}(\overline{B^0} \to J/\Psi K^0) = i \sin(\frac{\Delta m t}{2}) * e^{+i\phi} * A * e^{-i\omega} A_K * e^{+i\xi}$$

weak phase difference $\mathcal{A}_2 - \mathcal{A}_1$: $\Delta\phi = \phi - 2\omega + \xi = 2\beta$

strong phase difference $\Delta\delta = \pi/2 \Leftarrow$ mixing introduces second phase difference

$B_d \to J/\Psi K^0$



$$\Delta\phi = \phi - 2\omega + \xi = arg[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}]$$

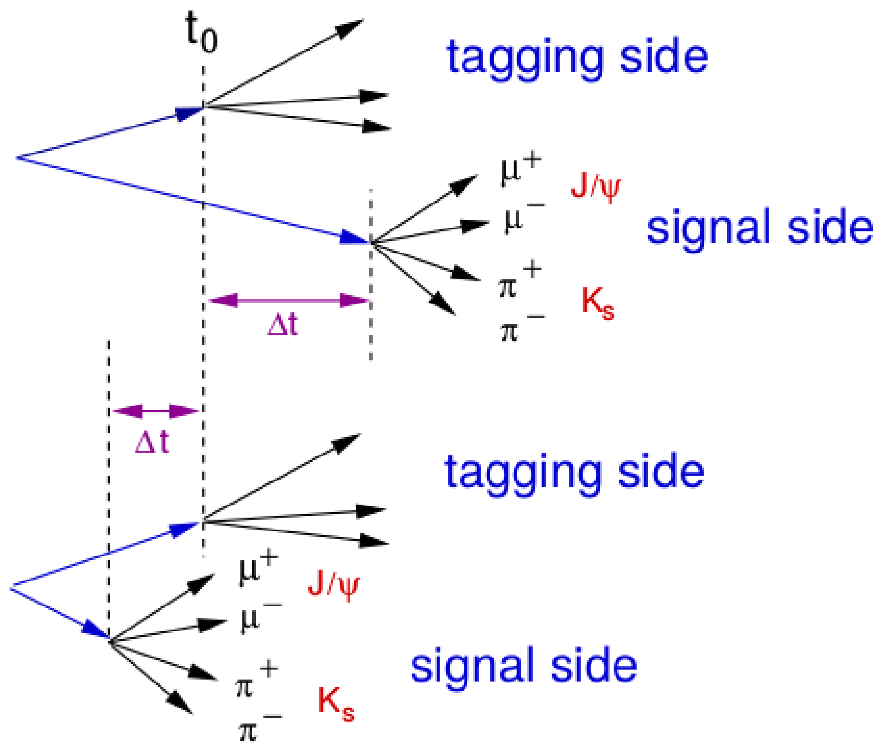
$$= arg[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}] = 2arg[\frac{V_{cb} V_{cd}^*}{V_{tb} V_{td}^*}] = 2\beta$$

c quark dominates mixing box diagram

Correlated B Production

$$A(t) = \frac{N(\overline{B}\to J/\psi K_s)(t) - N(B\to J/\psi K_s)(t)}{N(\overline{B}\to J/\psi K_s)(t) + N(B\to J/\psi K_s)(t)} = \eta_{CP}\sin(2\beta)\sin\Delta m_d t$$

(for K_s η_{CP} = -1, for K_L η_{CP} = +1 ... neglecting CP in kaon mixing)

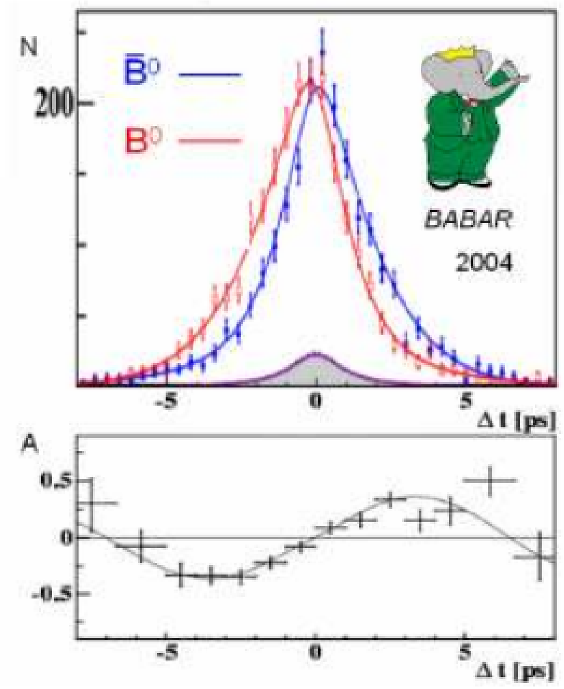


This is how it works at e^+e^- B factories

$B - \overline{B}$ pair produced on Y(4S) resonance with well defined quantum numbers.

$\to$ Correlated $B - \overline{B}$ state till the time of the decay of the first B.

$B_d \to J/\psi K_s$



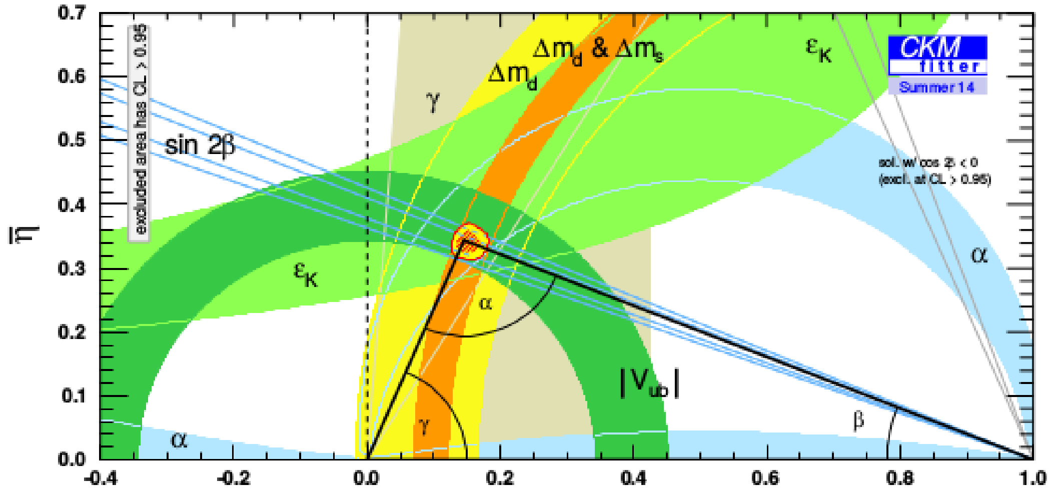
$$\mathcal{A}(t) = \frac{N(B^0)(t) - N(\overline{B^0})(t)}{N(B^0)(t) - N(\overline{B^0})(t)} = -\sin(2\beta)\sin(\Delta m_d t)$$

Babar:

$\sin(2\beta) = 0.722 \pm 0.040 \pm 0.023$

Belle:

$\sin(2\beta) = 0.652 \pm 0.039 \pm 0.020$



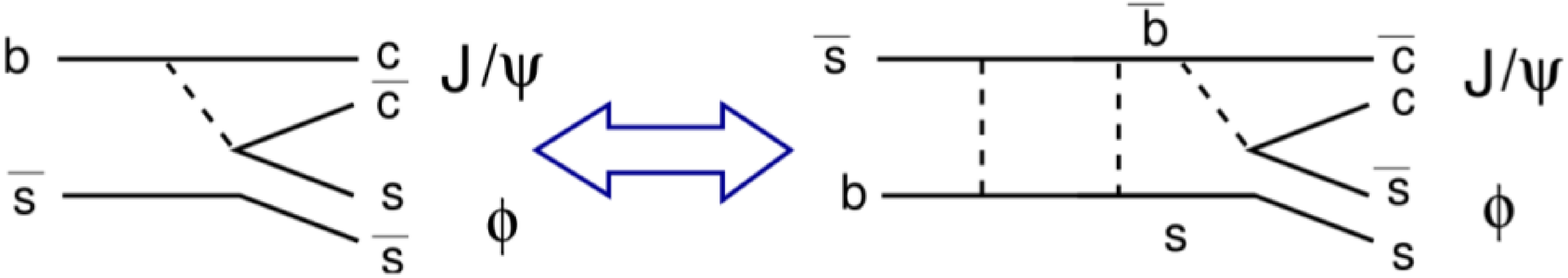
Nobel Prize 2008

Kobayashi & Maskawa:

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

$B_s \to J/\psi\phi$

Basic idea similar to measurement of $\sin(2\beta)$:

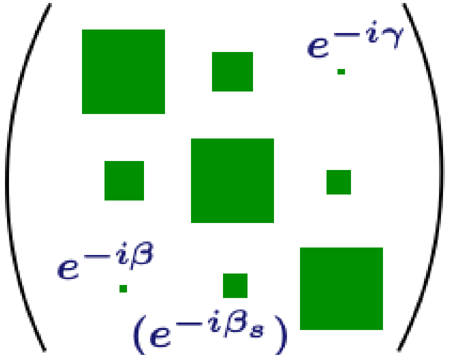


- No CP violation in mixing
- No CP violation in decay (watch out penguin pollution ..)

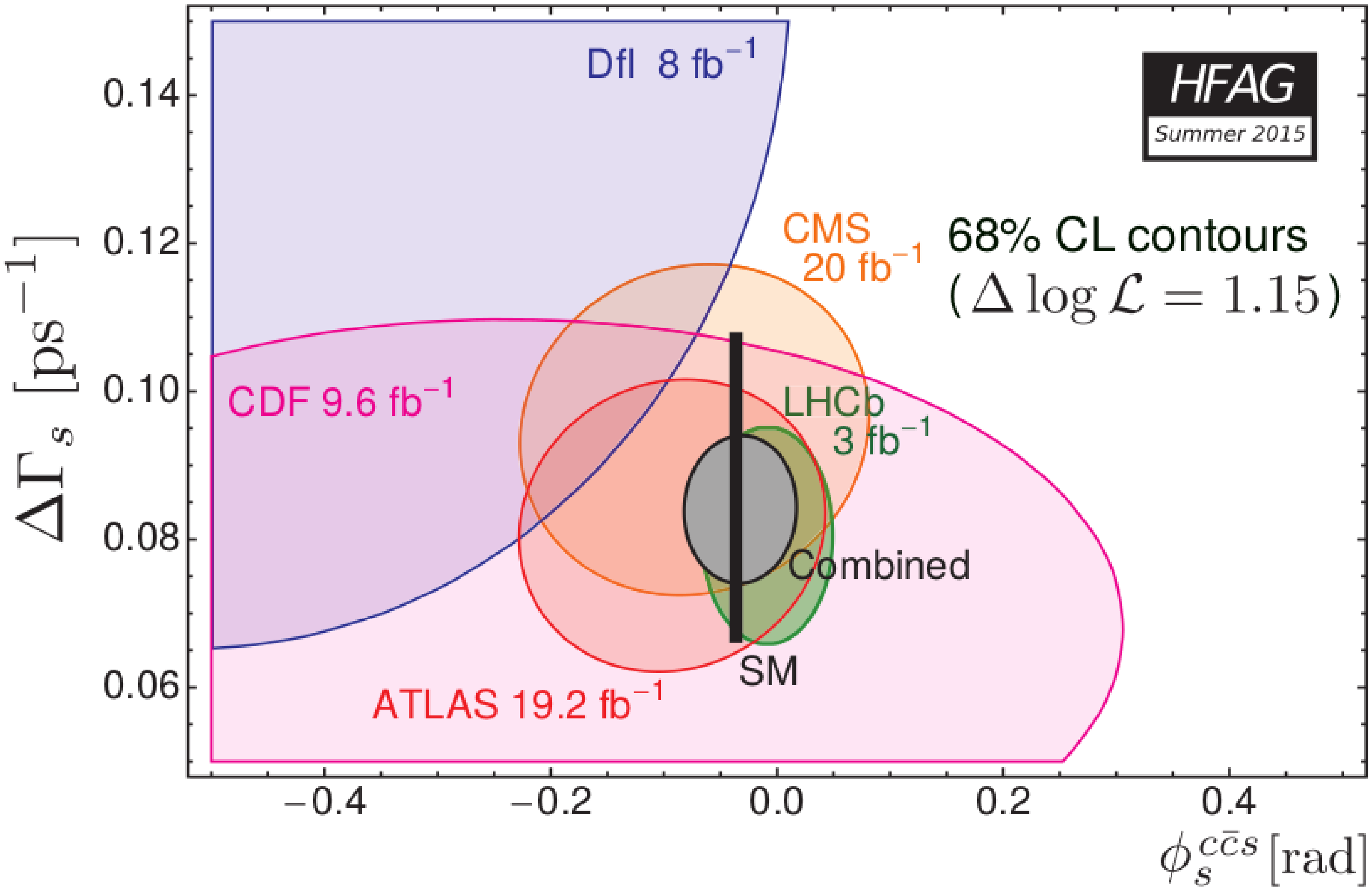
$\phi_{mix} = arg((V_{ts}V_{tb}^{*})^2) = -2\beta_s \approx 0.04(SM)$, (top quark dominates the box)

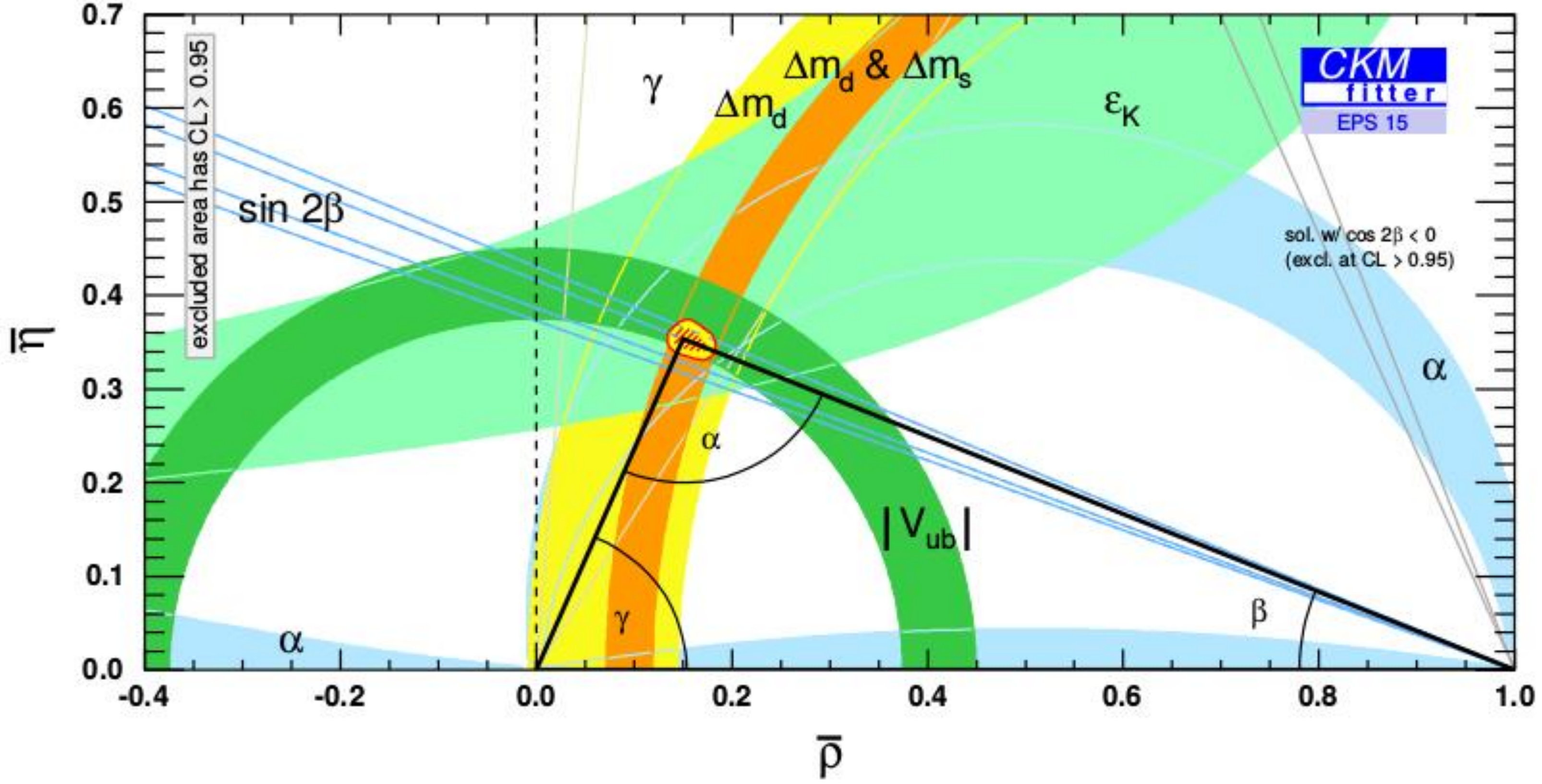
$\omega = arg((V_{cb}V_{cs}^{*})^2) = 0$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



$B_s^0 \to J/\Psi\phi$



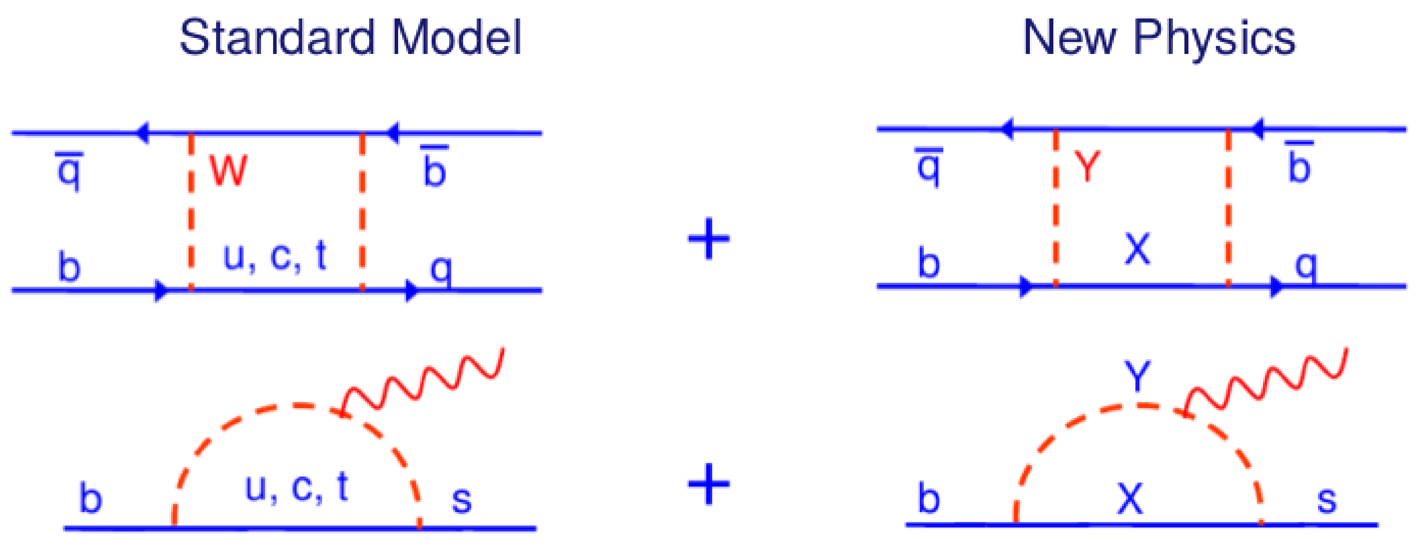


excluded area has CL > 0.95
γ
Δm_d & Δm_s
Δm_d
ε_K
CKM fitter
EPS 15
sin 2β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
|V_ub|
γ
β
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

What next?

New Physics in B decays

New Physics effects only appear as correction to leading SM terms.



$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{C_{SM}}{m_W^2} + \frac{C_{NP}}{\lambda_{NP}^2} \right); \quad (C_{SM} = \frac{g_W^2}{4\pi} \sim \frac{1}{30}, \lambda_{NP} \sim 1 \text{ TeV (?)})$$

Flavour physics approach to new physics:

- study processes which are sensitive to quantum corrections:
  e.g. very rare (SM suppressed) decays, CPV

New Physics in the Flavour Sector?

If couplings are of order $\mathcal{O}(1)$ ...