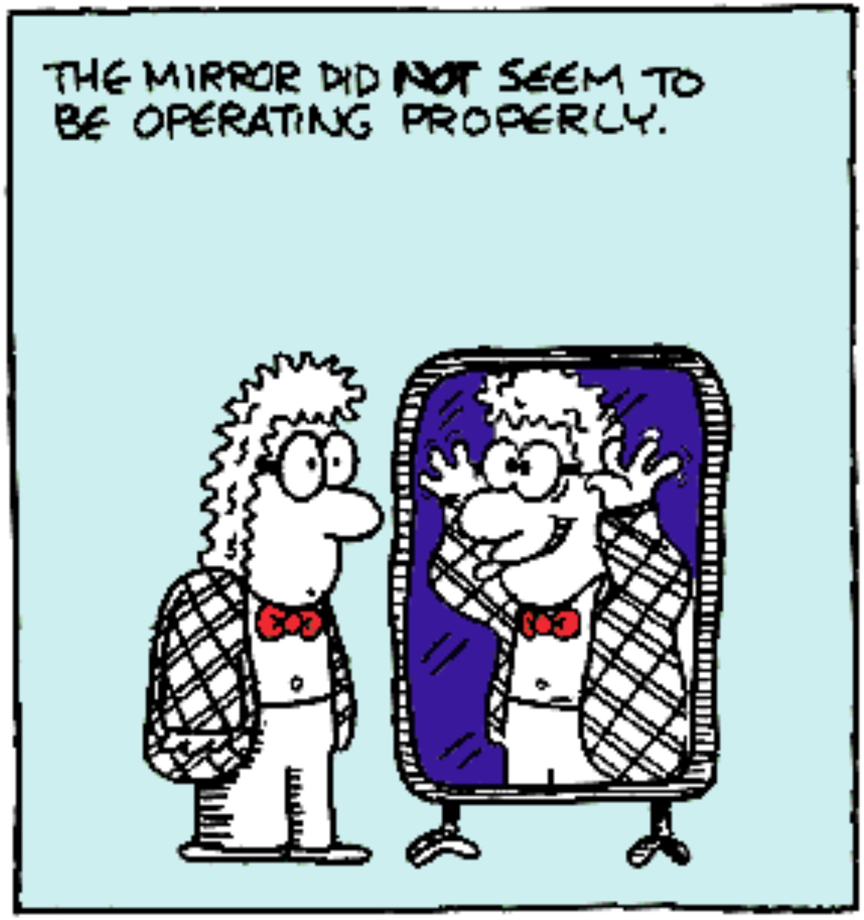
Recent CP violation measurements



Recap of last week

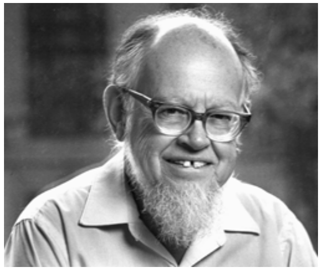
What we have learned last week:

- Indirect searches (CP violation and rare decays) are good places to search for effects from new, unknown particles.
    - Example from past: GIM mechanism
- Symmetries are a very important concept in physics
    - Lead to conservation laws, new theories, etc.
- P (parity) and C (charge conjugation) are completely broken in weak interactions
    - CPT is still an exact symmetry (required by field theory).
- Weak interaction shows a small CP violation.
    - Not enough to explain baryon asymmetry in the Universe.
- Fermion masses and the CKM matrix originate from the Yukawa couplings with the Higgs.
    - V_{CKM} relates the quarks in the mass eigenbase with the weak eigenbase.
- V_{CKM} has one complex phase which is responsible for CP violation.
    - All current CP-violating measurements are consistent with this single phase.

Wolfenstein Parametrization (recap)

Makes use of the fact that the off-diagonal elements are small compared to the diagonal elements.
→ Expansion in $\lambda = V_{us}$, $A = V_{cb}/\lambda^2$ and ρ, η.

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



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

$\lambda \sim 0.22$ (sinus of Cabibbo angle)
$A \sim 1$ (actually 0.80)
$\rho \sim 0.14$
$\eta \sim 0.34$

CKM angles and unitarity triangle

Writing the complex elements explicitly:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \sim \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \sim \lambda^3 e^{-i\beta} & \sim -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix} + O(\lambda^4)$$

Definition of the angles:

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

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

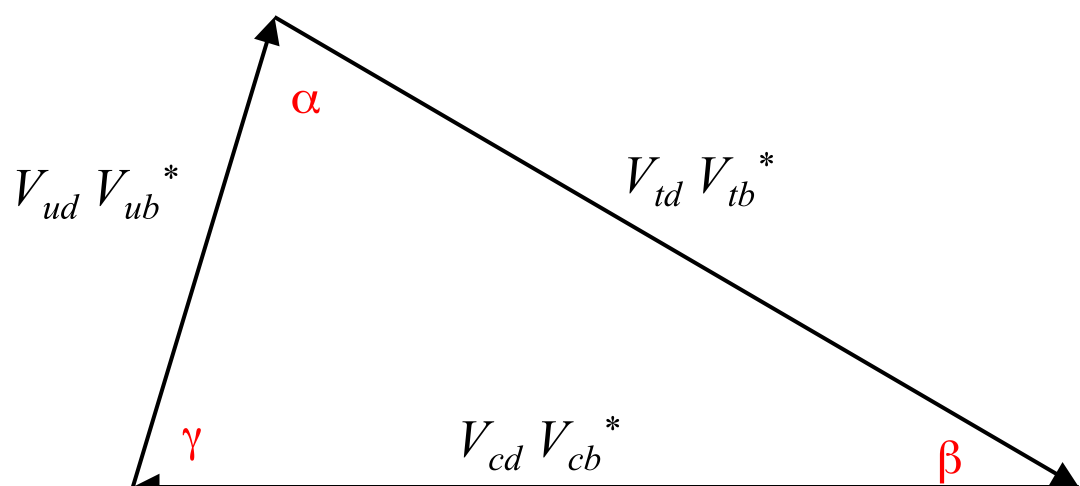
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{tb}^*}{V_{cd}V_{cb}^*}\right)$$

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

Using one of the 9 unitarity relations: $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = 1$

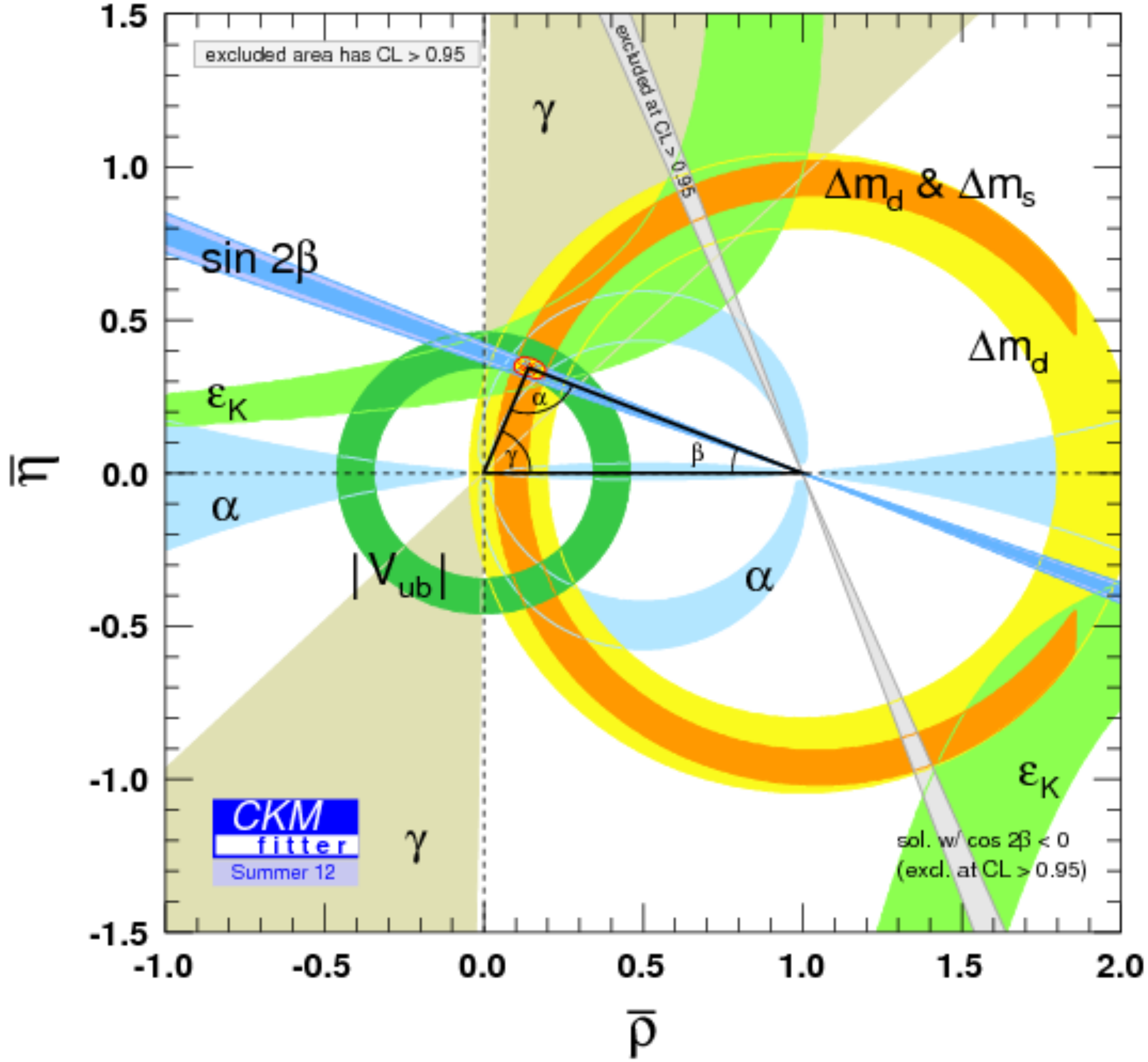
Multiply first “d” column with last “b” column:

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

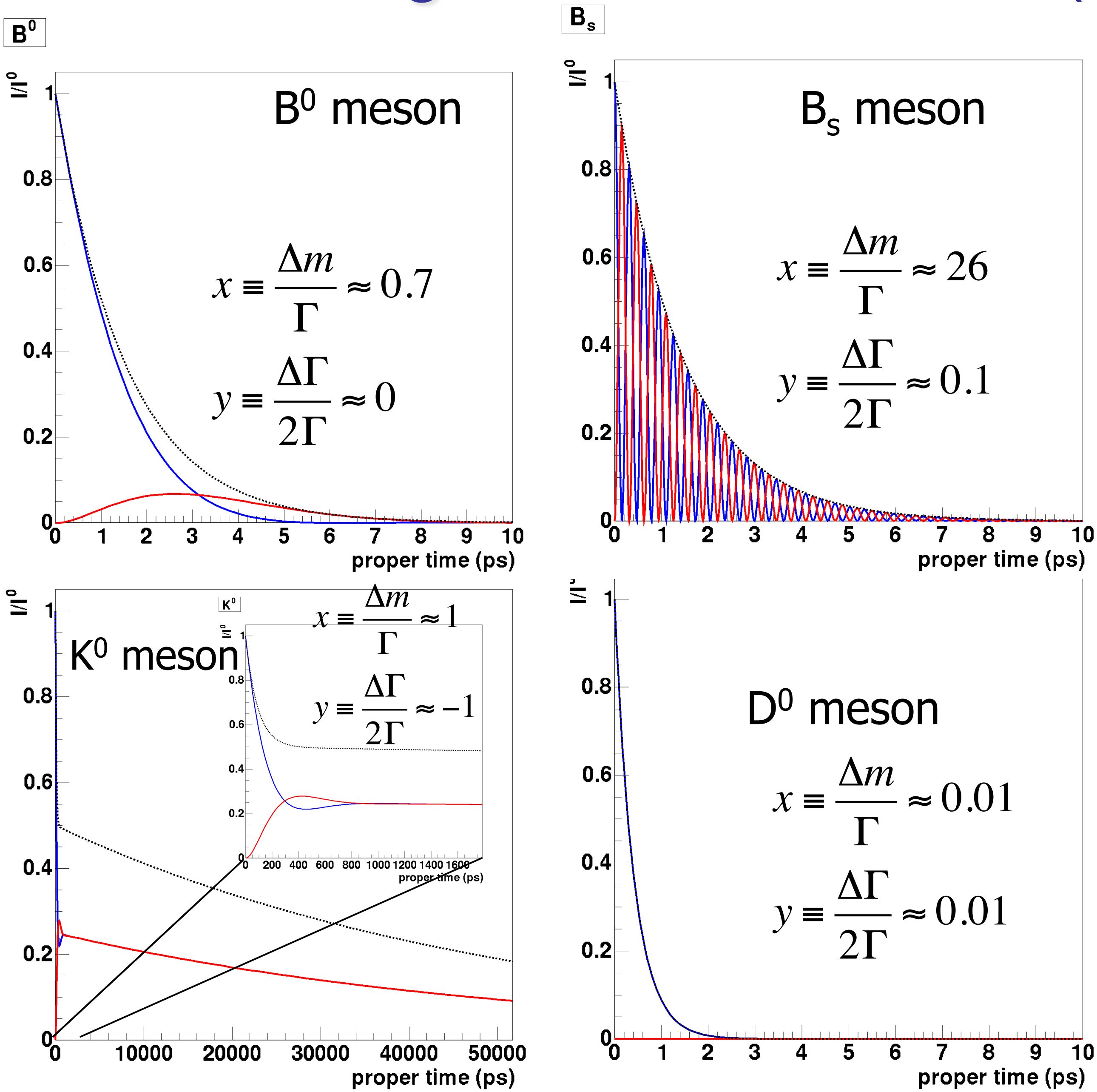


Progress in UT

2012



Mixing of neutral mesons (recap)



The 4 different neutral meson systems have very different mixing properties.

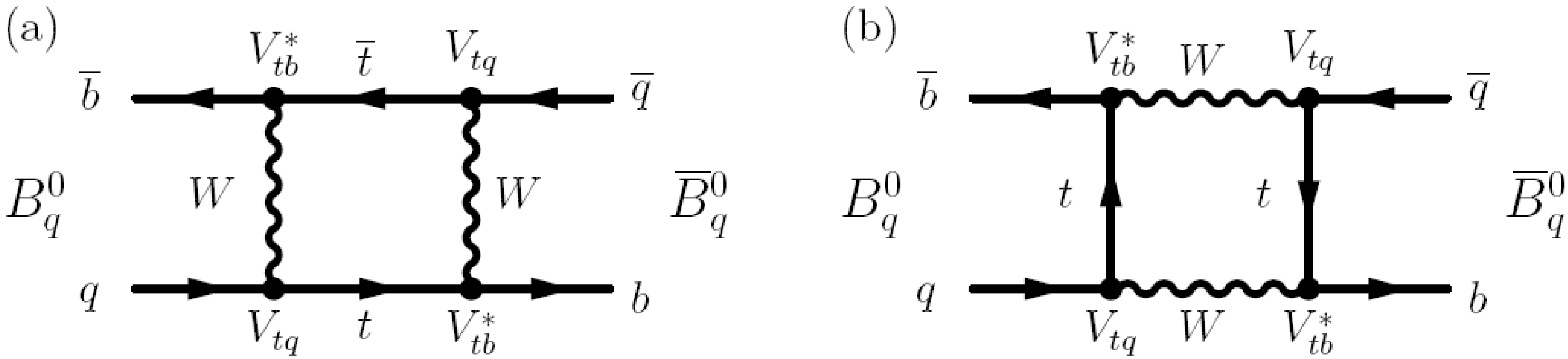
B_s system: very fast mixing

Kaon system: large decay time difference.

Charm system: very slow mixing

The weak box diagram

These two diagrams contribute to mixing in $B_{d,s}$ system:



The (heavy) top quark dominates the internal loop.
No GIM cancellation (if u,c,t would have the same mass these diagrams would cancel)

Why is are the oscillations in the B_s system so much faster than in B_d?
Why is the mixing in the D system so small?

Oscillations in B_d versus B_s system: V_{td} versus V_{ts}

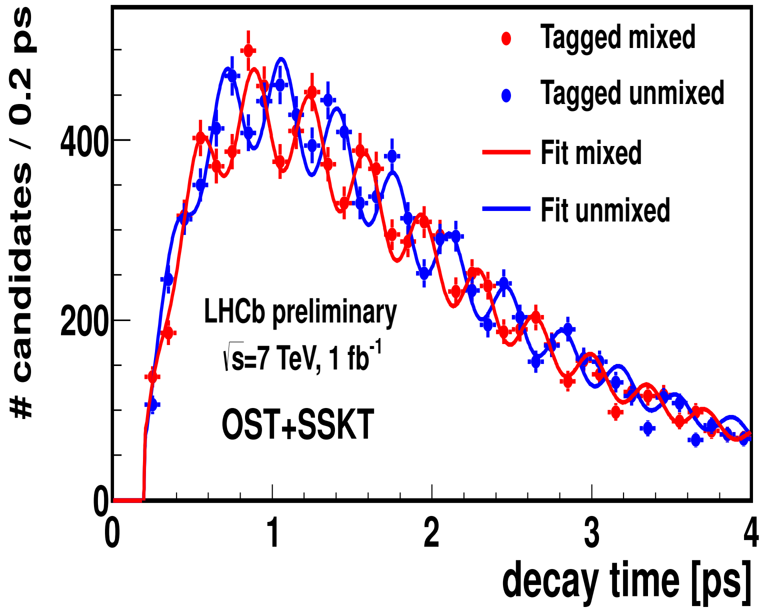
Order λ^3 Order λ^2

→ Much faster oscillation in B_s system (less Cabbibo suppression).

In the D system, the d,s,b quarks in internal loop (no top): small mixing.

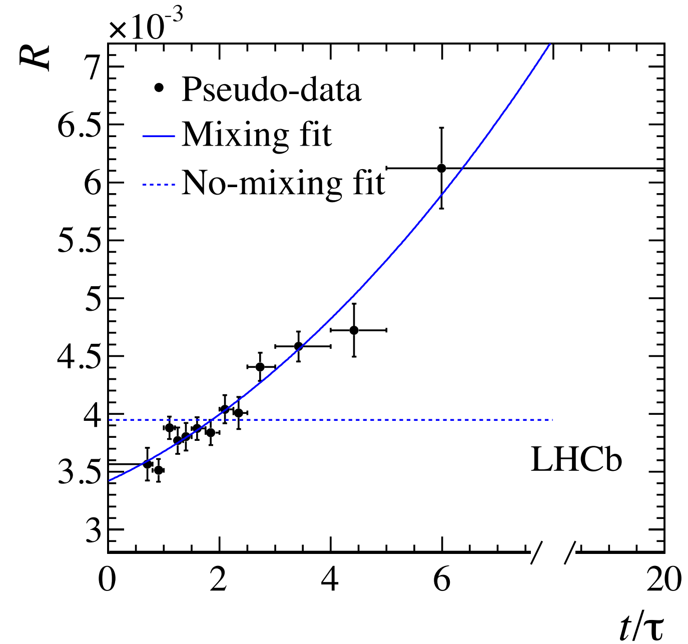
Recent measurements: two extremes

B_s mixing: very fast



Δm_s=17.725 ± 0.041(stat) ± 0.025 (sys) ps^{-1}

D^0 mixing: very slow



R_D	3.52 ± 0.15	x10^{-3}
y'	7.2 ± 2.4	
x'^2	-0.09 ± 0.13	

Both measurements very challenging

CP violation

So we just learned that neutral mesons mix, that we can actually measure the oscillations, but what has this to do with CP violation?

Types of CP violation

Phenomenologically, there are 3 types of CP violation:

Types of CP violation

Phenomenologically, there are 3 types of CP violation:

1. CPV in mixing
2. CPV in decay
3. CPV in the interference between mixing and decay

1. CP violation in mixing

We had already the probability that an initially pure B^0 or $\overline{B}^0$ oscillates into $\overline{B}^0$ or B^0:

$$
\begin{aligned}
|\langle B^0|B^0_{\rm phys}(t)\rangle|^2 &= |g_+(t)|^2 \quad , \\
|\langle \overline{B}^0|B^0_{\rm phys}(t)\rangle|^2 &= \left|\frac{q}{p}\right|^2 |g_-(t)|^2 \quad , \\
|\langle B^0|\overline{B}^0_{\rm phys}(t)\rangle|^2 &= \left|\frac{p}{q}\right|^2 |g_-(t)|^2 \quad , \\
|\langle \overline{B}^0|\overline{B}^0_{\rm phys}(t)\rangle|^2 &= |g_+(t)|^2 \quad ,
\end{aligned}
$$

Not the same if $|q/p| \neq 1$

One can see that in case $|q/p| \neq 1$ the oscillation probability $\mathcal{P}(B^0 \to \overline{B}^0)$ is different from the CP conjugate process $\mathcal{P}(\overline{B}^0 \to B^0)$.

Remember that:

$$\frac{q}{p} = -\sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$$

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

In the B_d and B_s systems Γ_{12} is small ➔ Small CP violation in mixing.
(do you remember why Γ_{12} is small?)

1. CP violation in mixing

Remember that:

$$\frac{q}{p} = -\sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$$

Requirements for CP violation in mixing, i.e. $|q/p| \neq 1$
- M_{12} and Γ_{12} must be non-negligible.
- M_{12} and Γ_{12} must have a phase difference.

→ CP violation in mixing is due to the interference between the amplitudes M_{12} and Γ_{12}.
(between off-shell and on-shell mixing amplitudes)

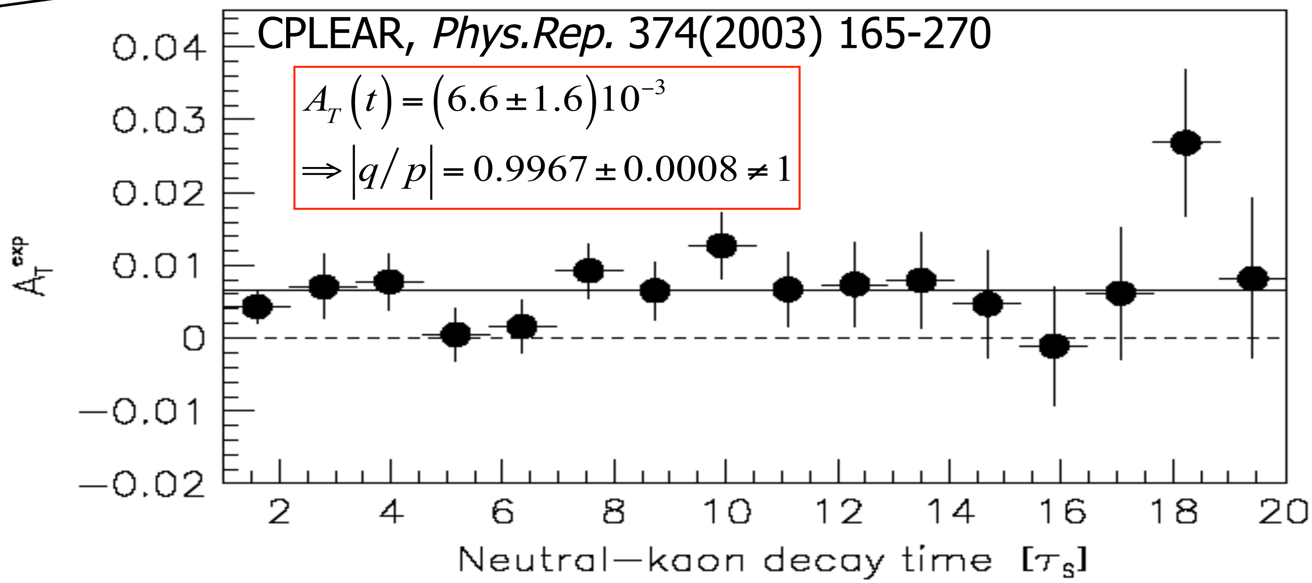
Example of CPV in mixing: kaon system

$$A_{+-} \equiv \frac{R\left(K_L^0 \to e^+\pi^-\nu_e\right) - R\left(K_L^0 \to e^-\pi^+\bar{\nu}_e\right)}{R\left(K_L^0 \to e^+\pi^-\nu_e\right) + R\left(K_L^0 \to e^-\pi^+\bar{\nu}_e\right)} = \frac{1-|q/p|^4}{1+|q/p|^4} = 4\Re\varepsilon$$

Flavour-specific final state:

$$K^0 \to e^+\pi^-\nu_e$$

$$\bar{K}^0 \to e^-\pi^+\bar{\nu}_e$$



CP violation in mixing small in SM:

K^0 system:	Order 1%	
D^0 system:	Order 10^{-5}	Not yet observed
B_d system:	Order 5×10^{-4}	Not yet observed
B_s system:	Order 10^{-5}	Not yet observed

Searches for mixing CPV in $B_{d,s}$

Asymmetry for B_d:

$$a_{sl}^{d}=\frac{\Gamma(\overline{B}^{0}\rightarrow D^{-}\mu^{+})-\Gamma(B^{0}\rightarrow D^{+}\mu^{-})}{\Gamma(\overline{B}^{0}\rightarrow D^{-}\mu^{+})+\Gamma(B^{0}\rightarrow D^{+}\mu^{-})}=\frac{1-(q/p)^{4}}{1+(q/p)^{4}}$$

Asymmetry for B_s: (substitute d→s)

$$a_{sl}^{s}=\frac{\Gamma(\overline{B_{s}^{0}}\rightarrow D_{s}^{-}\mu^{+})-\Gamma(B_{s}^{0}\rightarrow D_{s}^{+}\mu^{-})}{\Gamma(\overline{B_{s}^{0}}\rightarrow D_{s}^{-}\mu^{+})+\Gamma(B_{s}^{0}\rightarrow D_{s}^{+}\mu^{-})}=\frac{1-(q/p)^{4}}{1+(q/p)^{4}}$$

Standard Model for B

$$a_{sl}^{s}=(1.9\pm0.3)\times10^{-5}$$

$$a_{sl}^{d}=(-4.1\pm0.6)\times10^{-4}$$

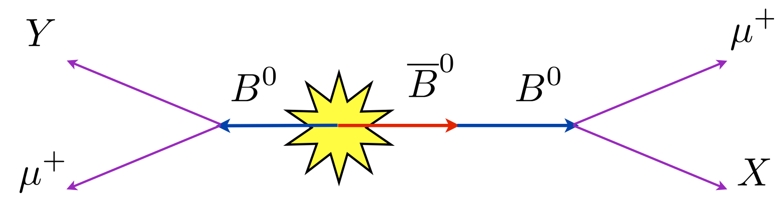
Very similar to kaon system

Searches for mixing CPV in $B_{d,s}$

Possible measurements

Dimuon analysis:

$$A_{sl}^{b} = \frac{\Gamma(\mu^{+}\mu^{+}) - \Gamma(\mu^{-}\mu^{-})}{\Gamma(\mu^{+}\mu^{+}) + \Gamma(\mu^{-}\mu^{-})} = C_{d} a_{sl}^{d} + C_{s} a_{sl}^{s}$$



Consider that muons from two B decays can be like-sign:
one mixes and the other not.
→ contains contribution from both B_d and B_s

Untagged analysis:

$$\frac{\Gamma(D_{(s)}^{-}\mu^{+}) - \Gamma(D_{(s)}^{+}\mu^{-})}{\Gamma(D_{(s)}^{-}\mu^{+}) + \Gamma(D_{(s)}^{+}\mu^{-})} \approx \frac{a_{sl}}{2}$$

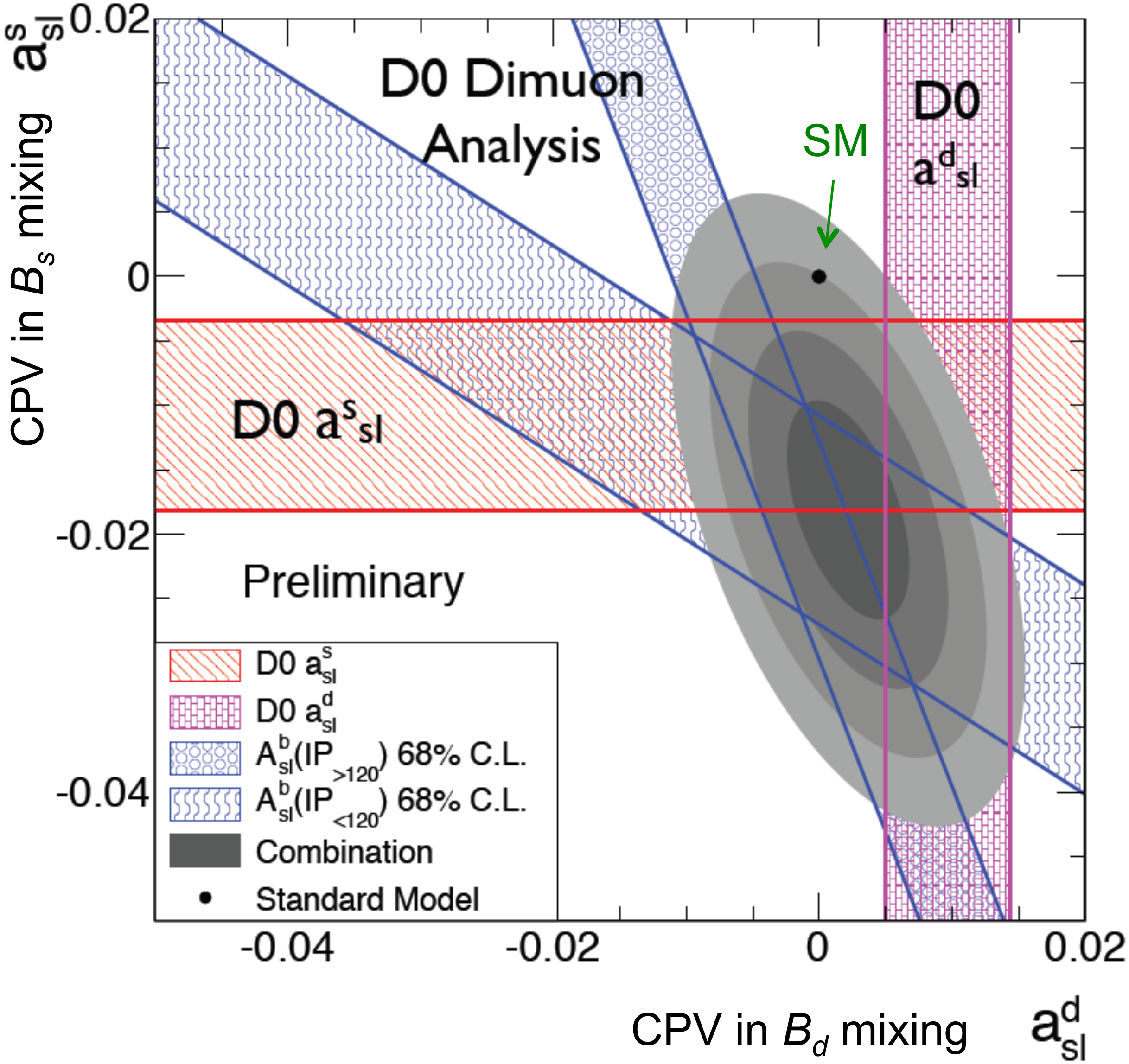
Dilutes sensitivity by 50% (compared to 3% from flavour tagging)
→ need to measure production asymmetry and detection asymmetry

a_{sl} according to D0

$$a_{sl}^{s} = (-1.81 \pm 0.56)\,\%$$
$$a_{sl}^{d} = (0.22 \pm 0.30)\,\%$$
$$\rho = -0.50$$

3σ from SM

Discrepancy of central value even too large for New Physics.

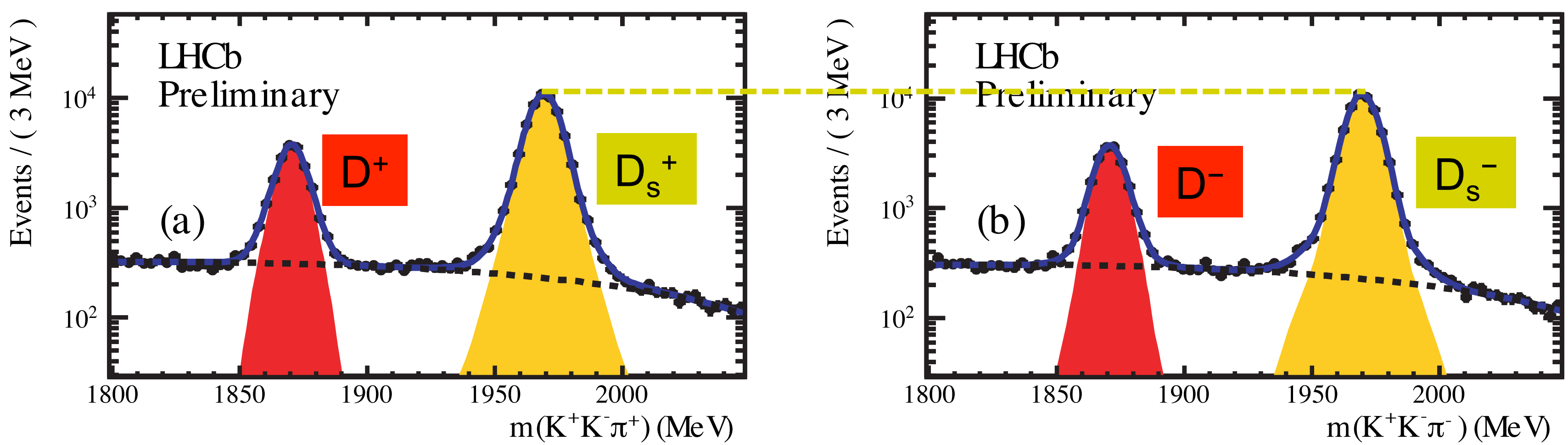


LHCb's measurement of a_{sl}^{s}

$$B_s^0 \rightarrow D_s^+(\rightarrow \phi\pi^+)\mu^-$$

- Effect of B_s production asymmetry is reduced to negligible level by rapid mixing oscillations
- Calibration samples (J/ψ, D^{*+}) used to measure detector trigger, track & muon ID biases

Magnet down:



	Magnet UP	Magnet Down
$D_s^- \mu^+$	40,945±285	55,755±278
$D_s^+ \mu^-$	39,849±239	56,447±294

a_{sl} according to rest of world

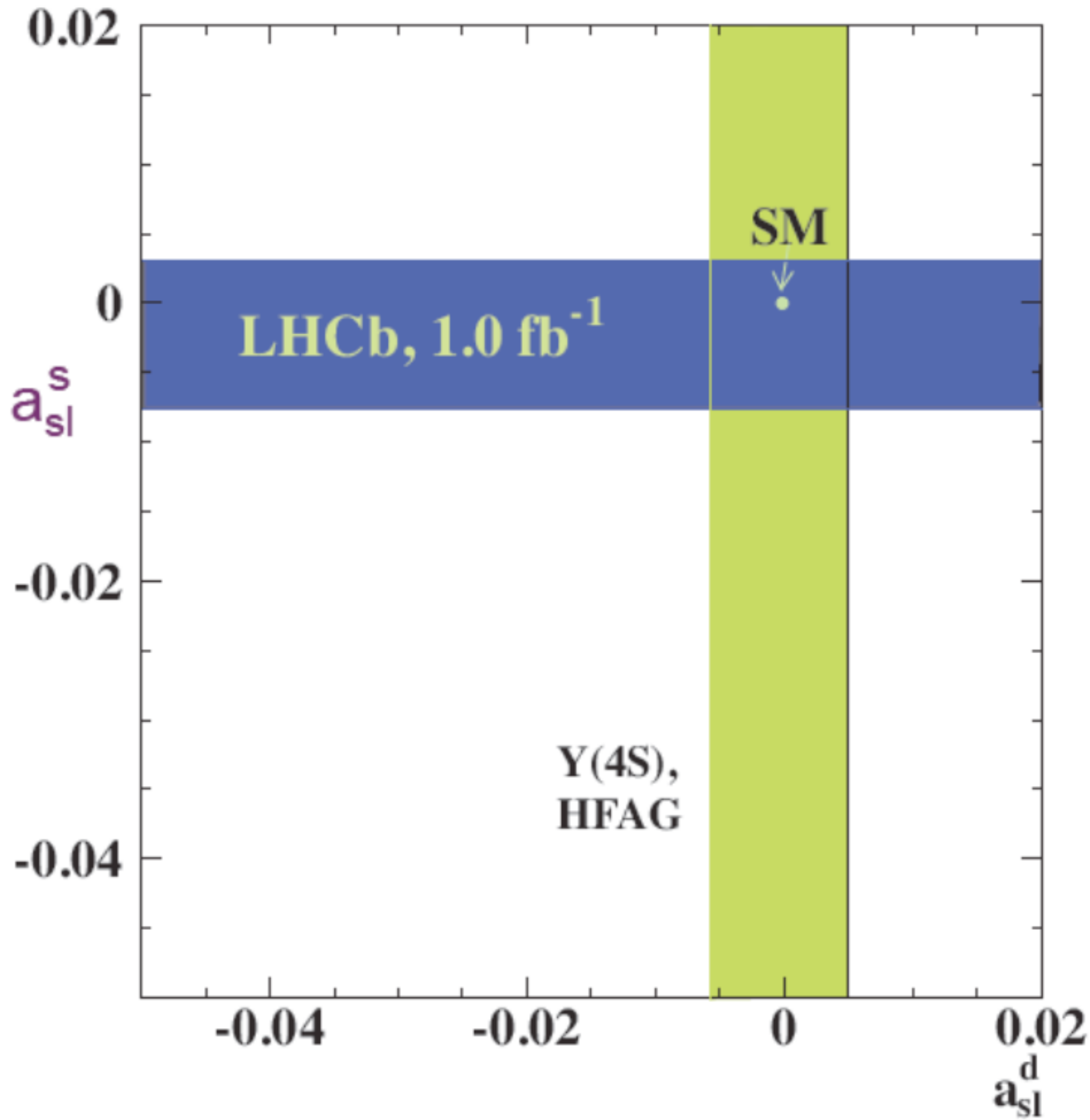
- LHCb finds

$$a_{sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%$$

- B-factory

$$a_{sl}^{d} = (-0.05 \pm 0.56)\%$$

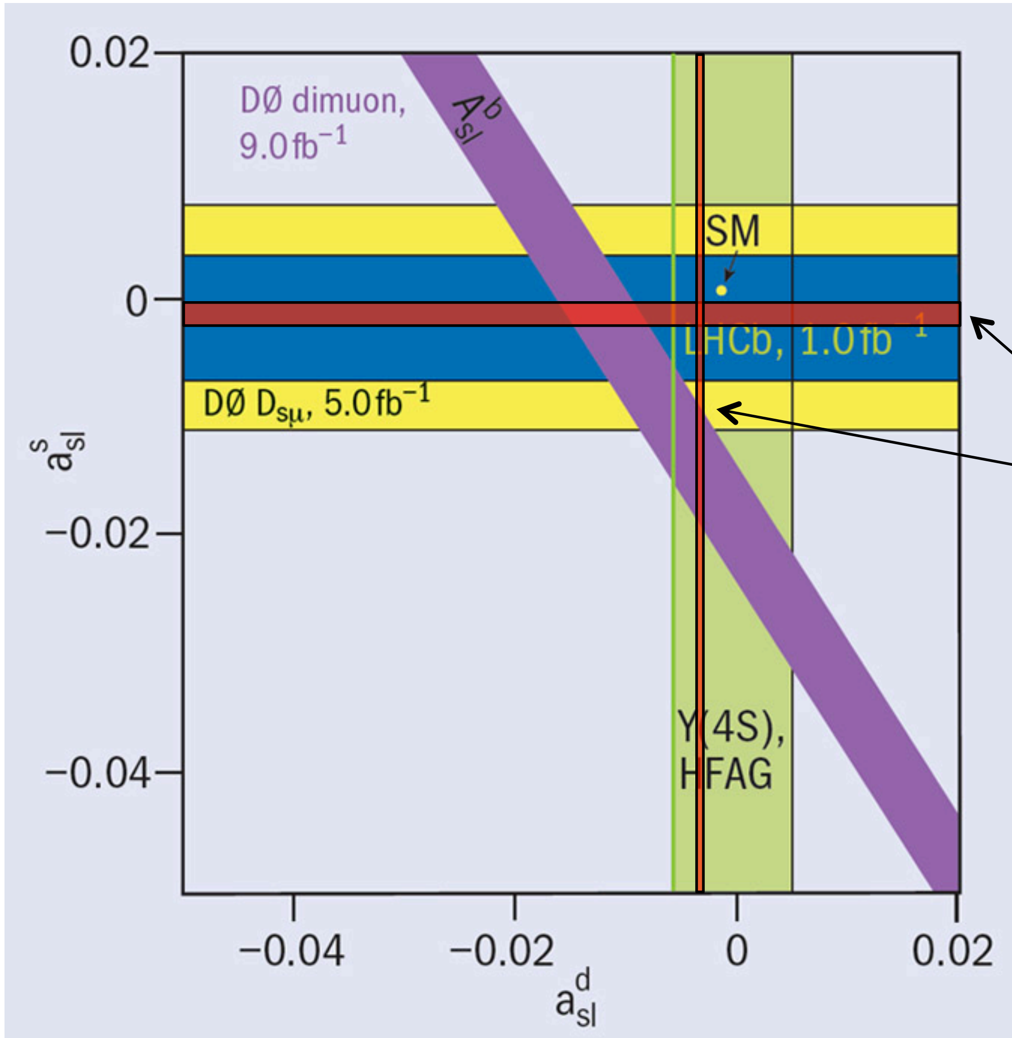
Consistent with SM



Outlook

Semileptonic measurement of CPV in *B* mixing

CPV in B_s mixing



CPV in B_d mixing

Sensitivity LHCb in 2017

LHCb will pin this discrepancy down.

2. CP violation in decay

We define the decay amplitudes as:

$$A_f = \langle f|T|B^0\rangle \quad , \quad \bar{A}_f = \langle f|T|\overline{B}^0\rangle$$

$$A_{\bar{f}} = \langle \bar{f}|T|B^0\rangle \quad , \quad \bar{A}_{\bar{f}} = \langle \bar{f}|T|\overline{B}^0\rangle$$

CP violation in decay means: $|A_f| \neq |\bar{A}_{\bar{f}}|$

In other words: $\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$

This only occurs when there are different decay amplitudes (Feynman diagrams) to the same final state with different weak phases and different strong phases:

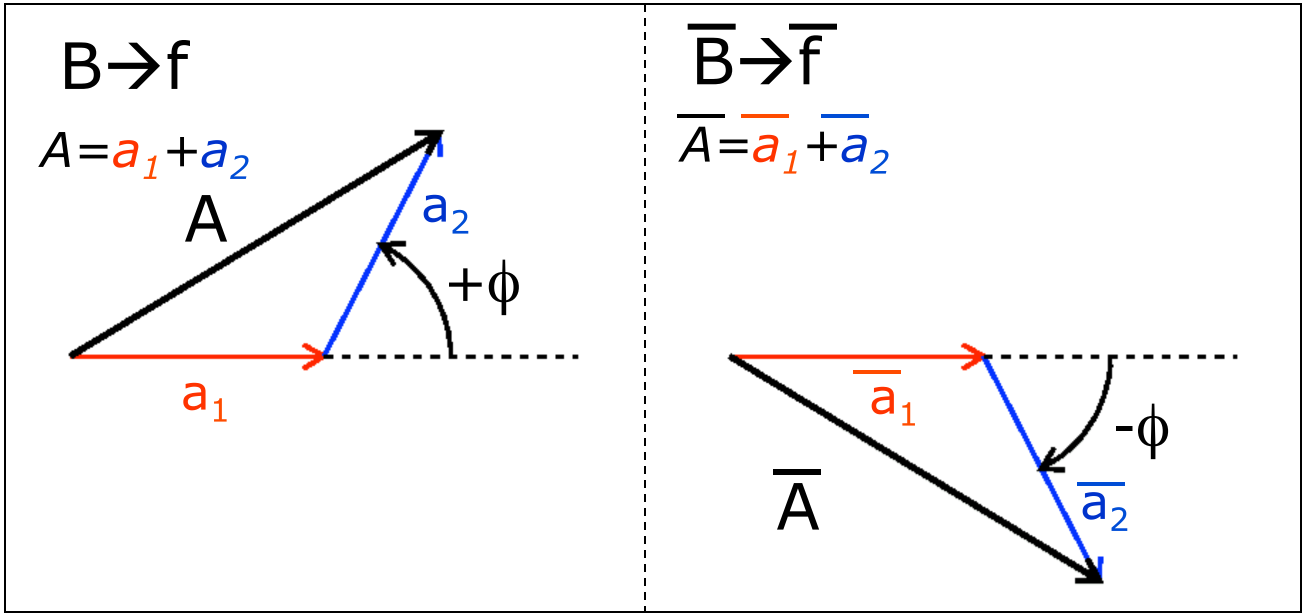
Weak phase changes sign under CP transformation

$$A_f = \sum_k A_k e^{i\delta_k} e^{i\phi_k} \quad , \quad \bar{A}_{\bar{f}} = \sum_k A_k e^{i\delta_k} e^{-i\phi_k}$$

Strong phase invariant under CP transformation

CP violation in decay is also called direct CP violation

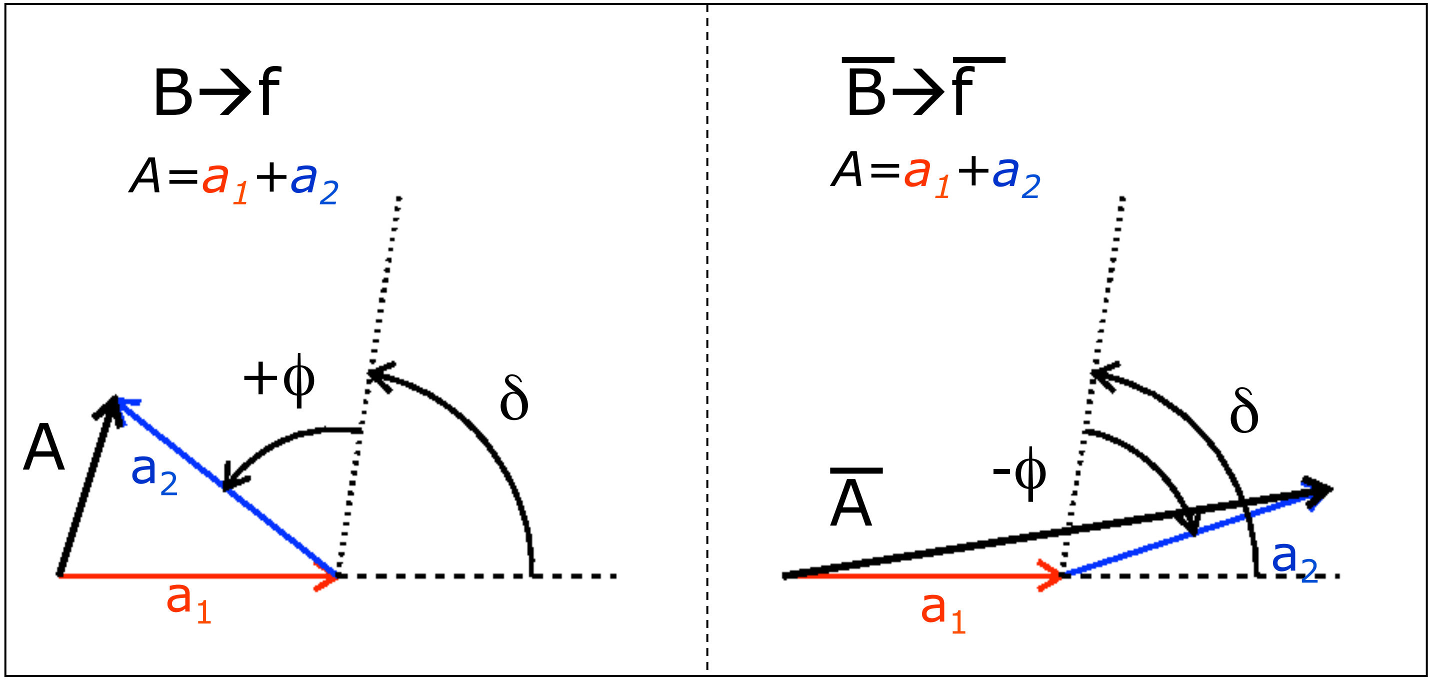
2. CP violation in decay



No strong phase difference ➔ $|A_f| = |\bar{A}_{\bar{f}}|$

No CP violation

2. CP violation in decay



Strong phase difference (δ not zero) ➔ $|A_f| \neq |\bar{A}_{\bar{f}}|$

CP violation in decay due to interference between strong and weak phase difference.

CP violation in decay does not require mixing: can also occur in charged hadrons decays

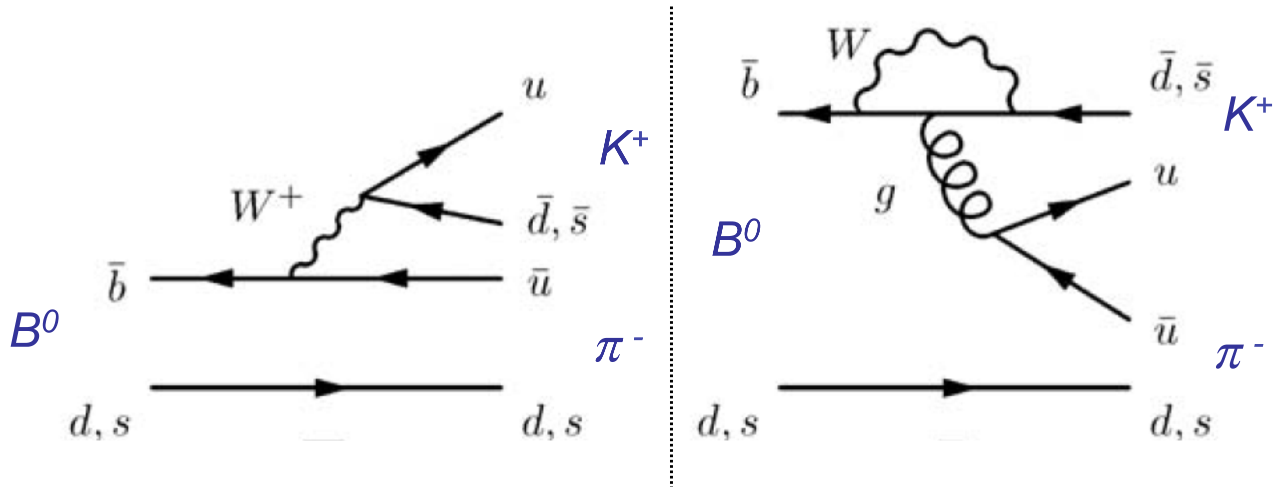
Problem: strong phases unknown, so difficult to extract the weak phase.

Example: CP violation in decay

Charmless charged two-body *B* decays

Tree

“a_1”



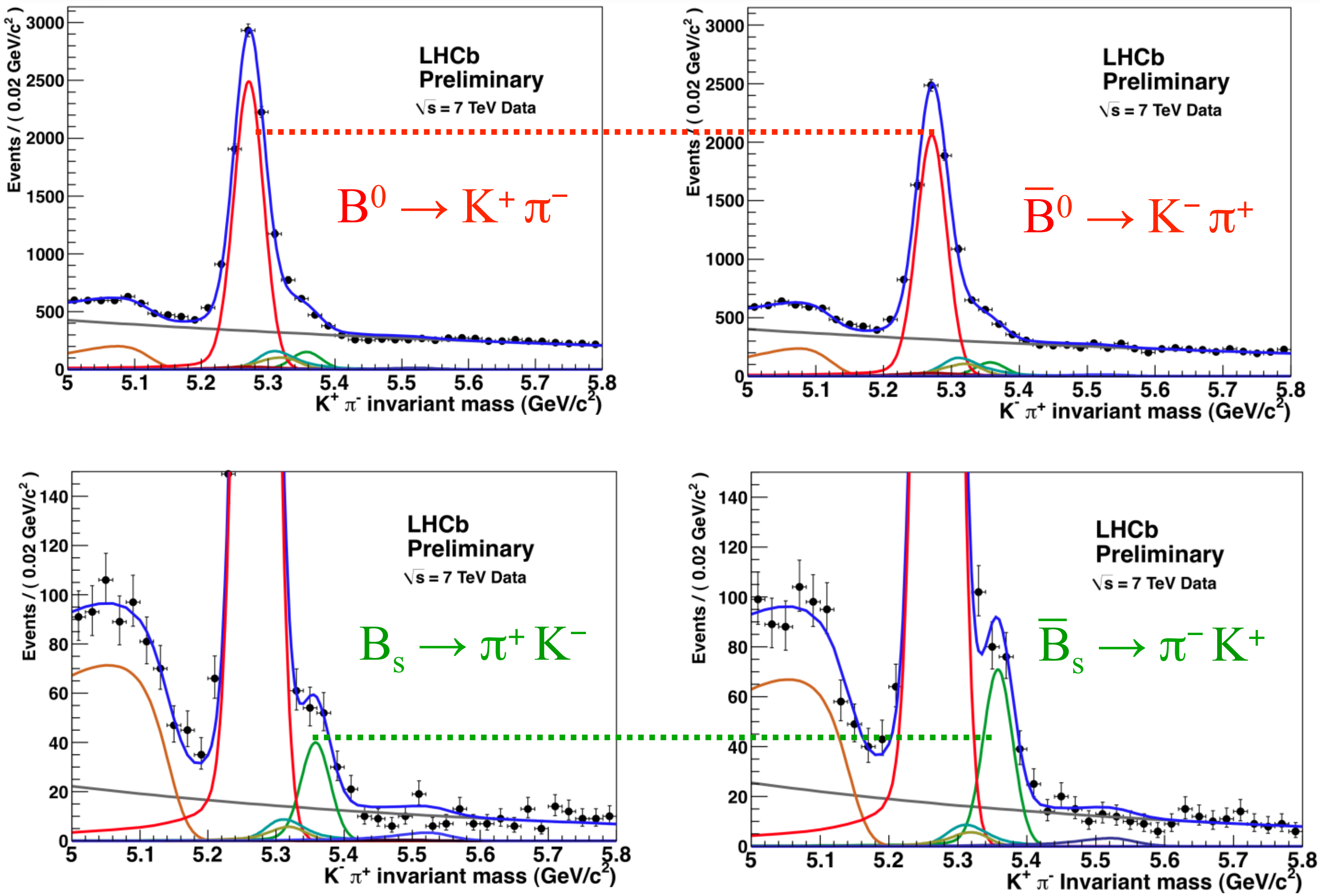
Penguin

“a_2”

Direct CP violation possible due to tree-penguin interference in $B_{d,s} \rightarrow K\pi$ decays.

Example: CP violation in decay

$B_{d,s} \to K^+\pi^-$: Clear asymmetry in raw distributions



[LHCb-CONF-2011-042]

Nice example of CPV in decay, but
strong phases unknown, so difficult to extract the weak phase.

Another Example: CP violation in decay

ΔA_{CP} in $D^0 \to h^+h^-$ (CPV in decay)

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = \Delta a_{CP}^{\text{dir}} - 0.1 a_{CP}^{\text{ind}}$$

Theory predictions: ~0.1%

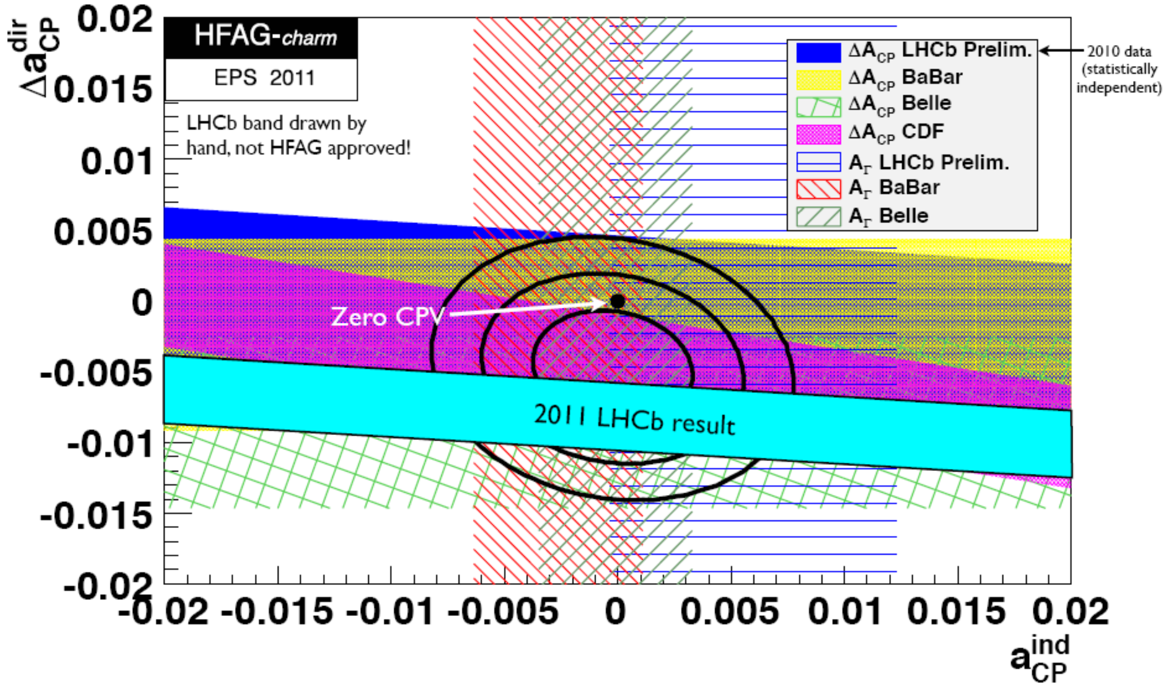
LHCb measurement (2011 only; 0.6 fb^{-1}):

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})]\,\%$$

Signifance 3.5σ

[LHCb-PAPER-2011-023]

First evidence of CP violation in charm sector!

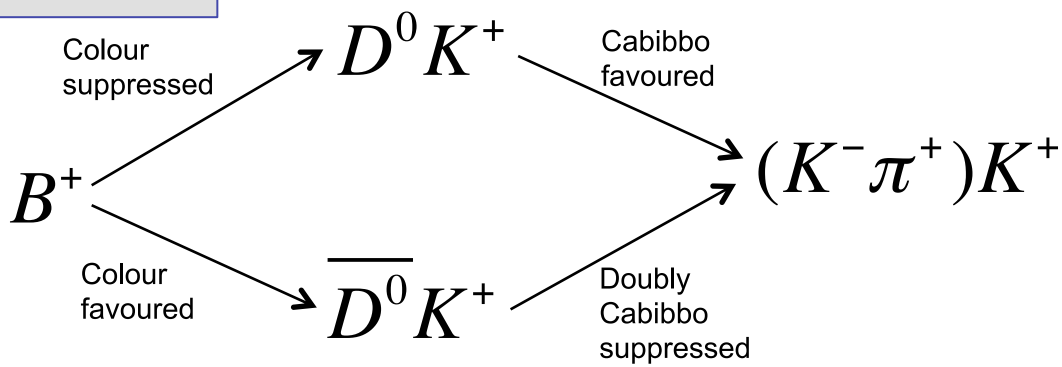


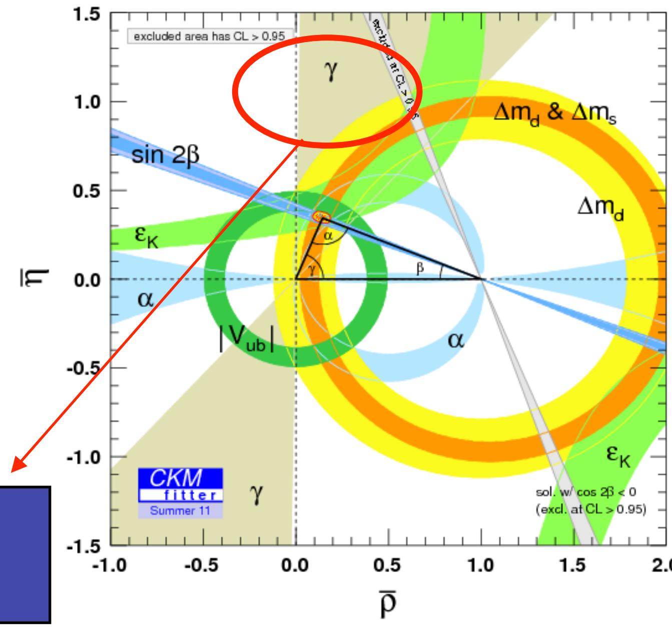
News flash:
Updates with more data push result much closer to zero.

Another example: measurement of γ

Direct CP violation in interference between two subsequent weak decays.

ADS method

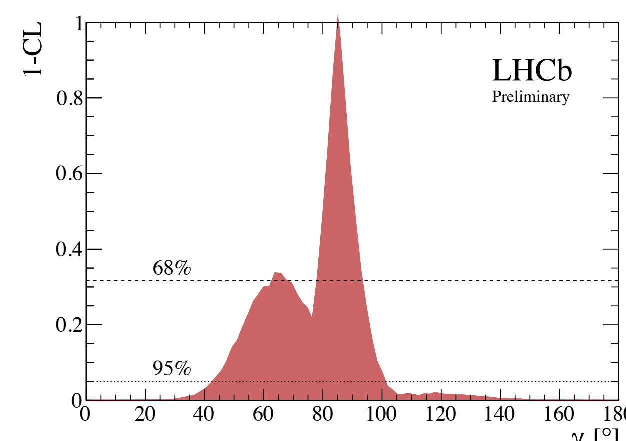




- Diagrams with $b \rightarrow c$ and $b \rightarrow u$ transitions are sensitive to γ.
- Clean extraction of γ : strong phases can be measured.

First measurement of CKM angle γ from LHCb
(including ADS, GLW, GGSZ methods)

$$\gamma = (71.1\,^{+16.6}_{-15.7})^\circ$$



[LHCb-CONF-2012-032]

Is becoming competitive with B factories.

3. CPV in interference mixing&decay

Now you have seen two examples of CP violation:

1. CPV in mixing (interference between M_{12} and Γ_{12})
2. CPV in decay (interference between strong and weak phases)

And both are due to interference.
Now the obvious third type of CP violation (and most beautiful) is:

3. CPV in the interference between mixing and decay

3. CPV in interference mixing&decay

We have seen already the time-dependence of flavour of a initially pure B^0 or $\overline{B}^0$:

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

with

$$g_\pm(t) = \frac{1}{2}(e^{-(im_L+\Gamma_L/2)t} \pm e^{-(im_H+\Gamma_H/2)t})$$

But what we are actually interested in is the decay rate of a B into a final state f

$$\Gamma_{B\to f}(t) = |\langle f|T|B^0_{\rm phys}(t)\rangle|^2$$

So, we define the decay amplitudes as:

$$A_f = \langle f|T|B^0\rangle \quad , \quad \bar{A}_f = \langle f|T|\overline{B}^0\rangle$$
$$A_{\bar{f}} = \langle \bar{f}|T|B^0\rangle \quad , \quad \bar{A}_{\bar{f}} = \langle \bar{f}|T|\overline{B}^0\rangle$$

3. CPV in interference mixing&decay

Now let's just write down the full time-dependent decay rate:

$$\Gamma_{B\to f}(t) = |A_f|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\cdot \left(\cosh\frac{\Delta\Gamma t}{2} + \boxed{D_f \sinh\frac{\Delta\Gamma t}{2}} + C_f\cos\Delta m t - \boxed{S_f \sin\Delta m t}\right)$$

$$\Gamma_{\overline{B}\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\cdot \left(\cosh\frac{\Delta\Gamma t}{2} + \boxed{D_f \sinh\frac{\Delta\Gamma t}{2}} - C_f\cos\Delta m t + \boxed{S_f \sin\Delta m t}\right)$$

Compared to plain mixing:
Two new interference terms

where:

$$D_f = \frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2} \quad , \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \quad , \quad S_f = \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}$$

and:

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \quad , \quad \lambda_{\bar{f}} = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}$$

3. CPV in interference mixing&decay

This beast simplifies a lot when assuming no CPV in decay, no CPV in mixing and f is CP eigenstate:

$$|q/p| = 1$$
$$|A_f/\bar{A}_f| = 1$$

Then defining the CP asymmetry as:

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{\overline{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\overline{B}\to f}(t) + \Gamma_{B\to f}(t)} = \mathrm{Im}\lambda_f \sin \Delta m t$$

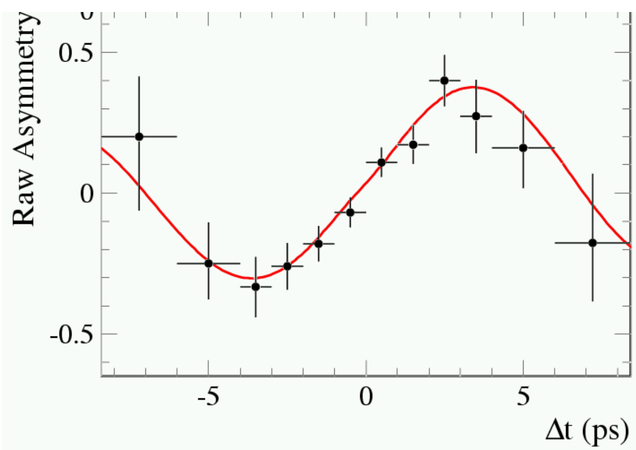
If amplitude non-zero: CP

The asymmetry is oscillating with Δm and amplitude Im(λ).
Experimentally, you simply need to measure this amplitude to access directly the phases of the CKM matrix (time-dependent + flavour tagging)

For example, for the "golden" decay $B^0 \to J/\psi\, K^0_S$ this amplitude equals:

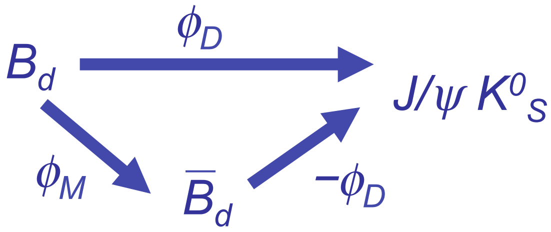
$$\mathrm{Im}\lambda_{J/\psi\, K^0_S} = \sin 2\beta$$

CKM phase β directly observable!



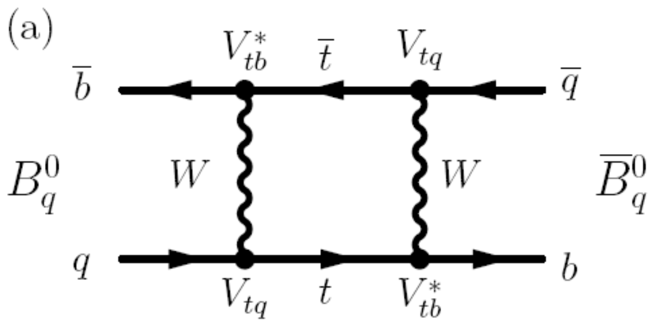
Example: Measurement of sin2β

The "golden" decay $B^0 \rightarrow J/\psi\, K^0{}_S$ (final state is CP eigenstate)



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \sim\lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \sim\lambda^3 e^{-i\beta} & \sim-\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix}$$

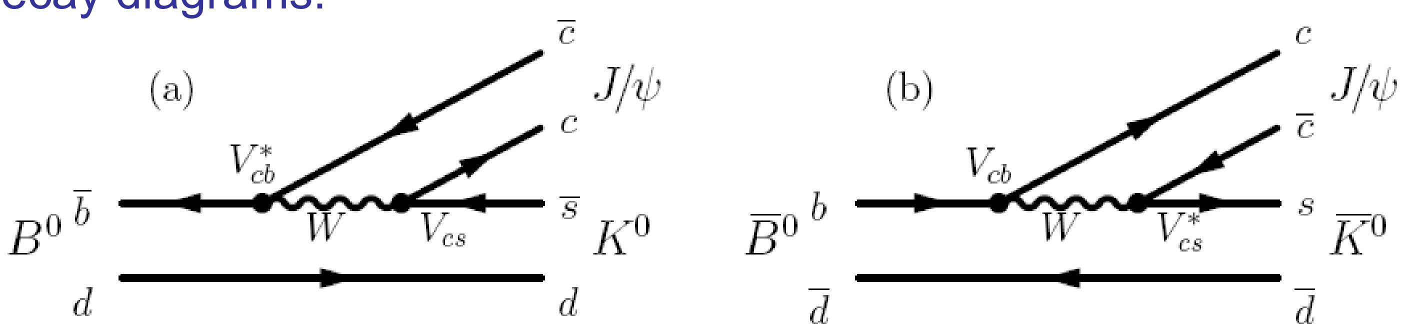
Mixing (box) diagram:



$$\lambda_{J/\psi K_S^0} = \left(\frac{q}{p}\right)_{B_d} \frac{\bar{A}_{J/\psi K_S^0}}{A_{J/\psi K_S^0}} = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)$$

$$\mathrm{Im}\lambda_{J/\psi K_S^0} = \sin 2\beta$$

Decay diagrams:



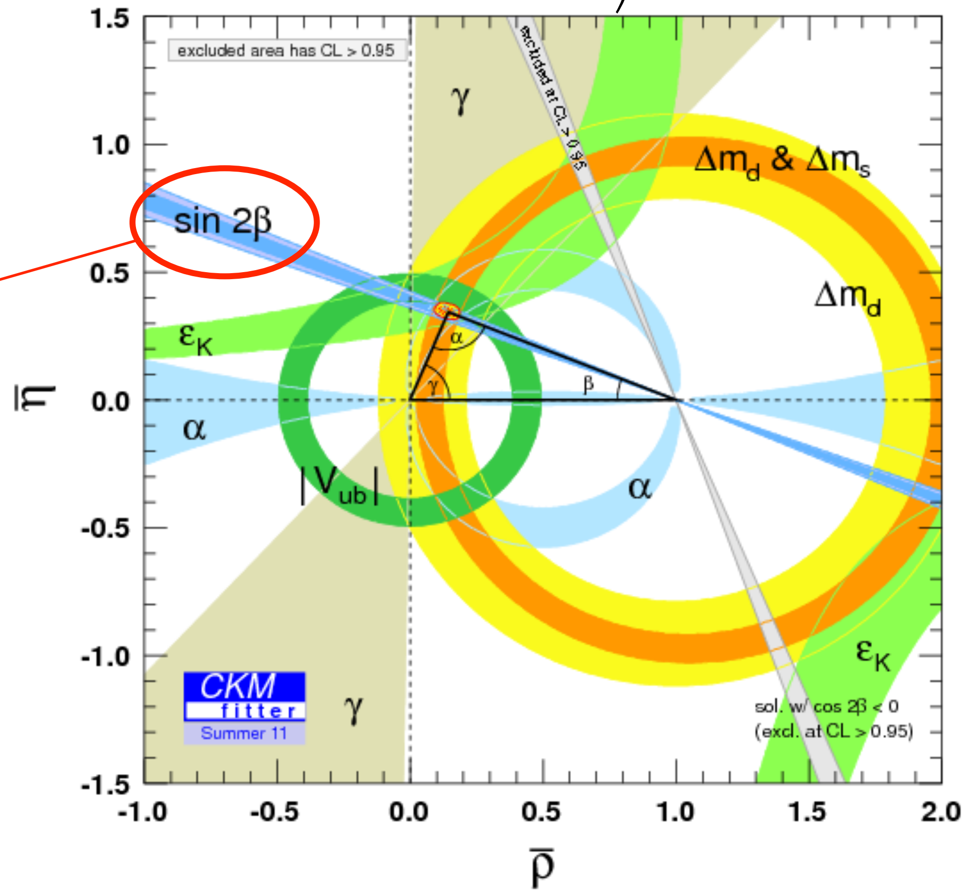
Example: Measurement of sin2β

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \sim \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \sim \lambda^3 e^{-i\beta} & \sim -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix}$$

sin2β well determined by B-factories (BaBar and Belle) using the "golden" decay $B^0 \to J/\psi\, K^0_S$:

$$\sin 2\beta = 0.679 \pm 0.020$$

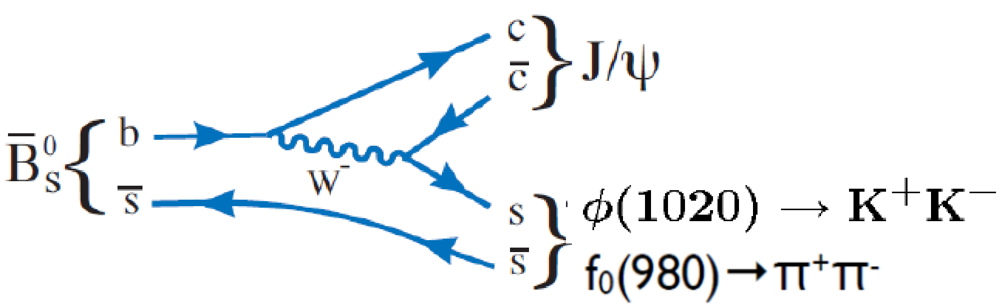
Recent measurement from LHCb:
sin2β = 0.73±0.07(stat)±0.04(syst)



Example: Measurement of $\sin 2\beta_s$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \sim \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \sim \lambda^3 e^{-i\beta} & \sim -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix}$$

- Measure CP asymmetry in $B_s \to J/\psi\ \phi$
  - B_s counterpart of $B_d \to J/\psi\ K^0$.
  - Can simultaneously extract $\Delta\Gamma_s$
- Small SM prediction: $2\beta_s = 0.036 \pm 0.002$



☺ Narrow ϕ resonance (clean)
☹ Vector-vector final state (requires angular analysis)

☺ CP odd final state (no angular analysis)
☹ BR about 20% of $B_s \to J/\psi\ \phi$

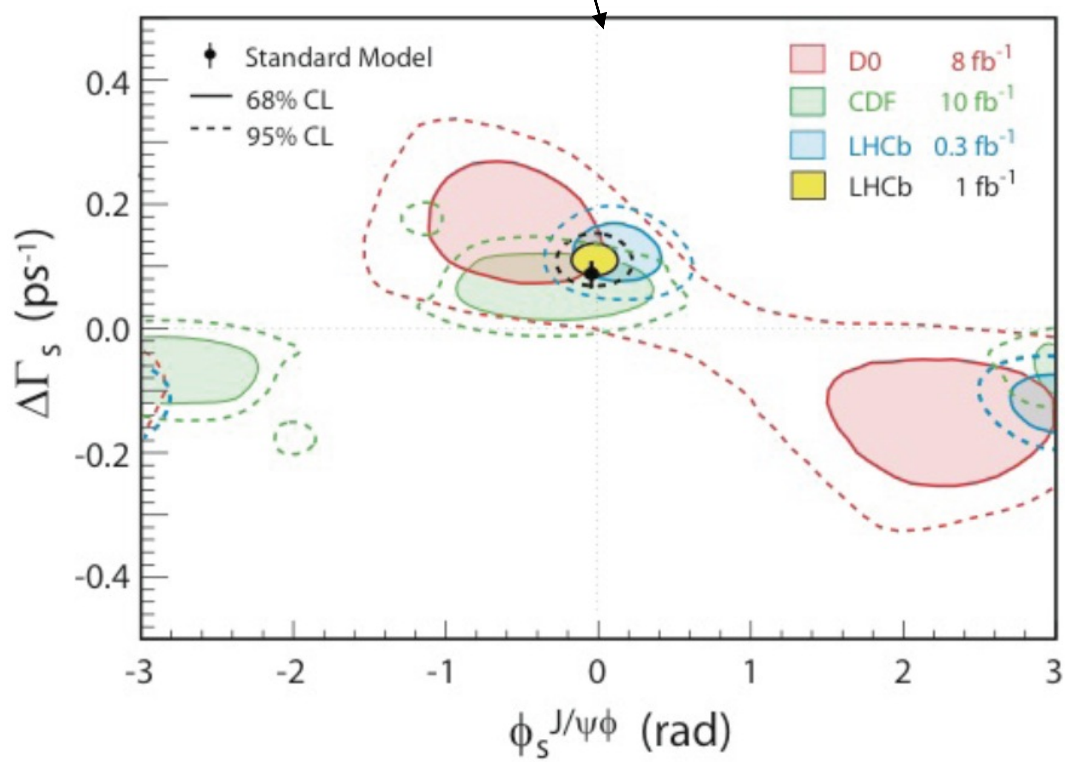
Example: Measurement of $\sin 2\beta_s$

$B_s \to J/\psi\, \phi$ and $B_s \to J/\psi\, \pi\pi$ time-dependent analysis

Using 1.0 fb^{-1}
[LHCb-CONF-2012-002]
[Phys. Lett. B 713 (2012) 378-386]

Γ_s = 0.6580 ± 0.0054(stat.) ± 0.0066(syst.)
$\Delta\Gamma_s$ = 0.116 ± 0.018(stat.) ± 0.006(syst.)
ϕ_s = -0.002 ± 0.083(stat.) ± 0.027(syst.)

Definition: $\phi_s = -2\beta_s$

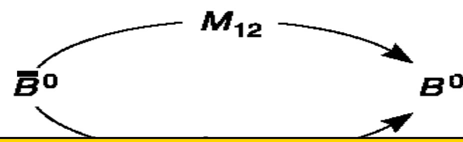


In good agreement with Standard Model

Overview: Types of CP violation

- Three types of CP violation (always two amplitudes!):

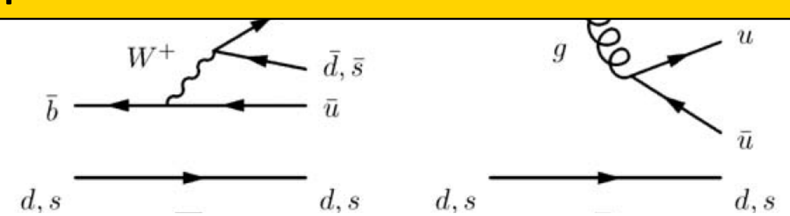
1. CP violation in mixing ("indirect" CP violation): $\left|\frac{q}{p}\right| \neq 1$



2. CP vi … $_f| \neq |\overline{A}_{\overline{f}}|$

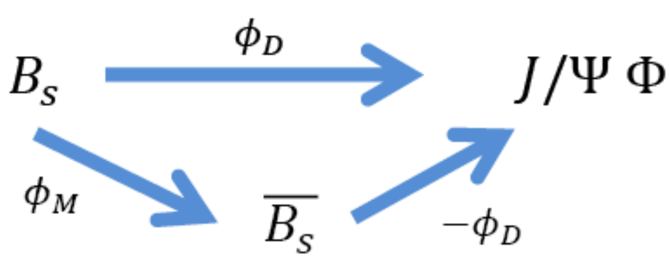
Note that in the SM all these effects are caused by a single complex parameter δ in the CKM matrix!

Tree



Penguin

3. CP violation in the interference: $\arg\lambda_f + \arg\lambda_{\bar{f}} \neq 0$



CPT violation?

- Question 1:

The mass difference between K_L and K_S: $\Delta m = 3.5 \times 10^{-6}$ eV => CPT violation?

- Question 2:

How come the lifetime of K_S = 0.089 ns while the lifetime of the K_L = 51.7 ns?

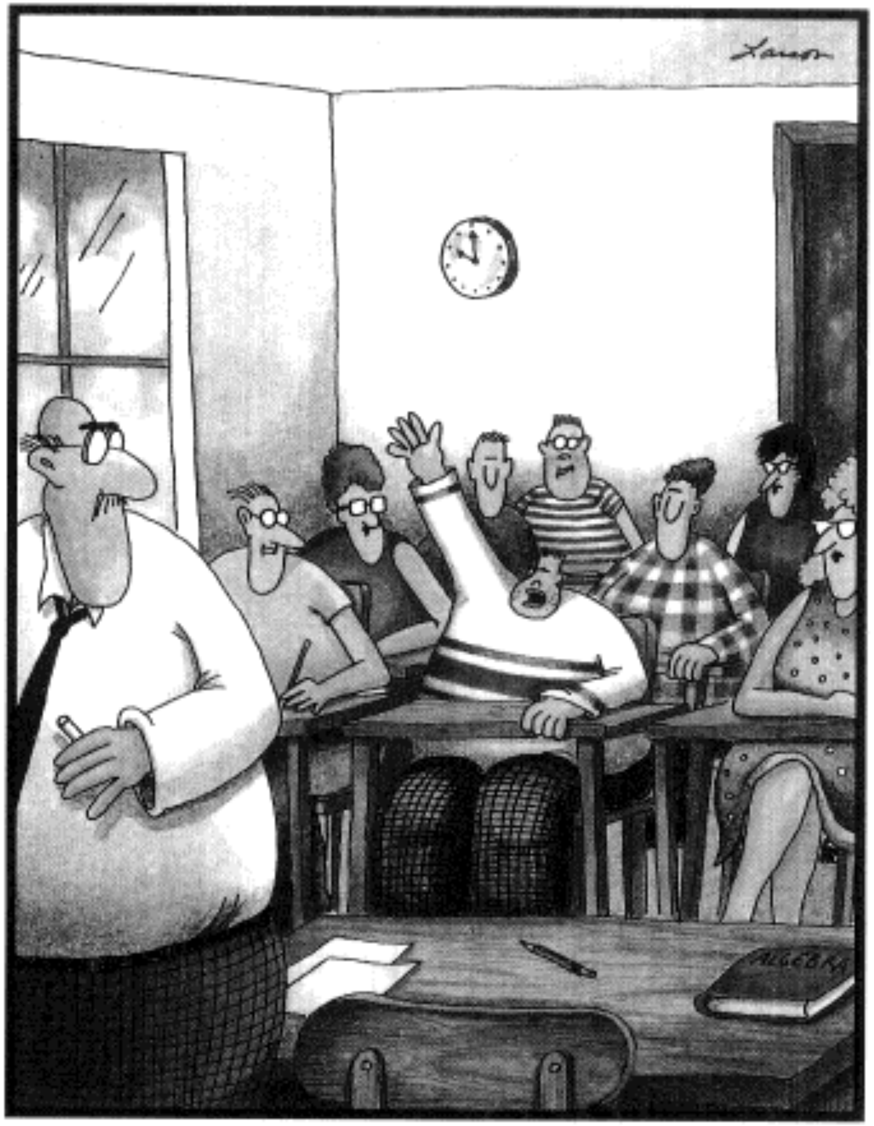
Answer 1 + 2: A $K_L \neq$ an anti-K_S particle!

- Question 3:

BaBar measures decay rate **B→J/ψ K$_S$** and **$\overline{\text{B}}$→J/ψ K$_S$**. Clearly not the same: how can it be?

Answer 3:

Partial decay rate ≠ total decay rate! However, the sum over all partial rates (>200 or so) is the same for **B** and **$\overline{\text{B}}$**. (Amazing! – at least to me)



"Mr. Osborne, may I be excused?
My brain is full."