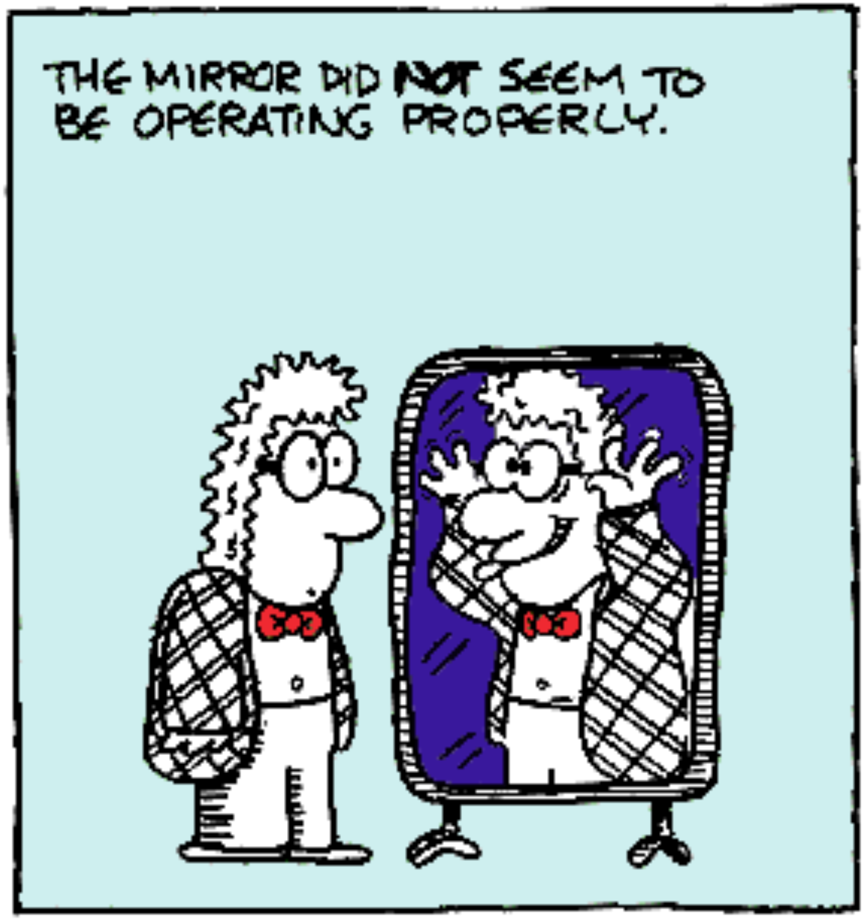
Recent CP violation measurements



Recap of last week

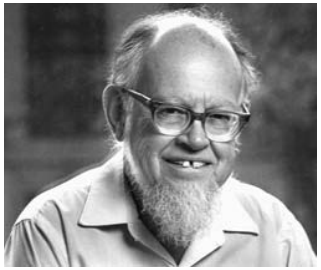
What we have learned last week:

- 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.

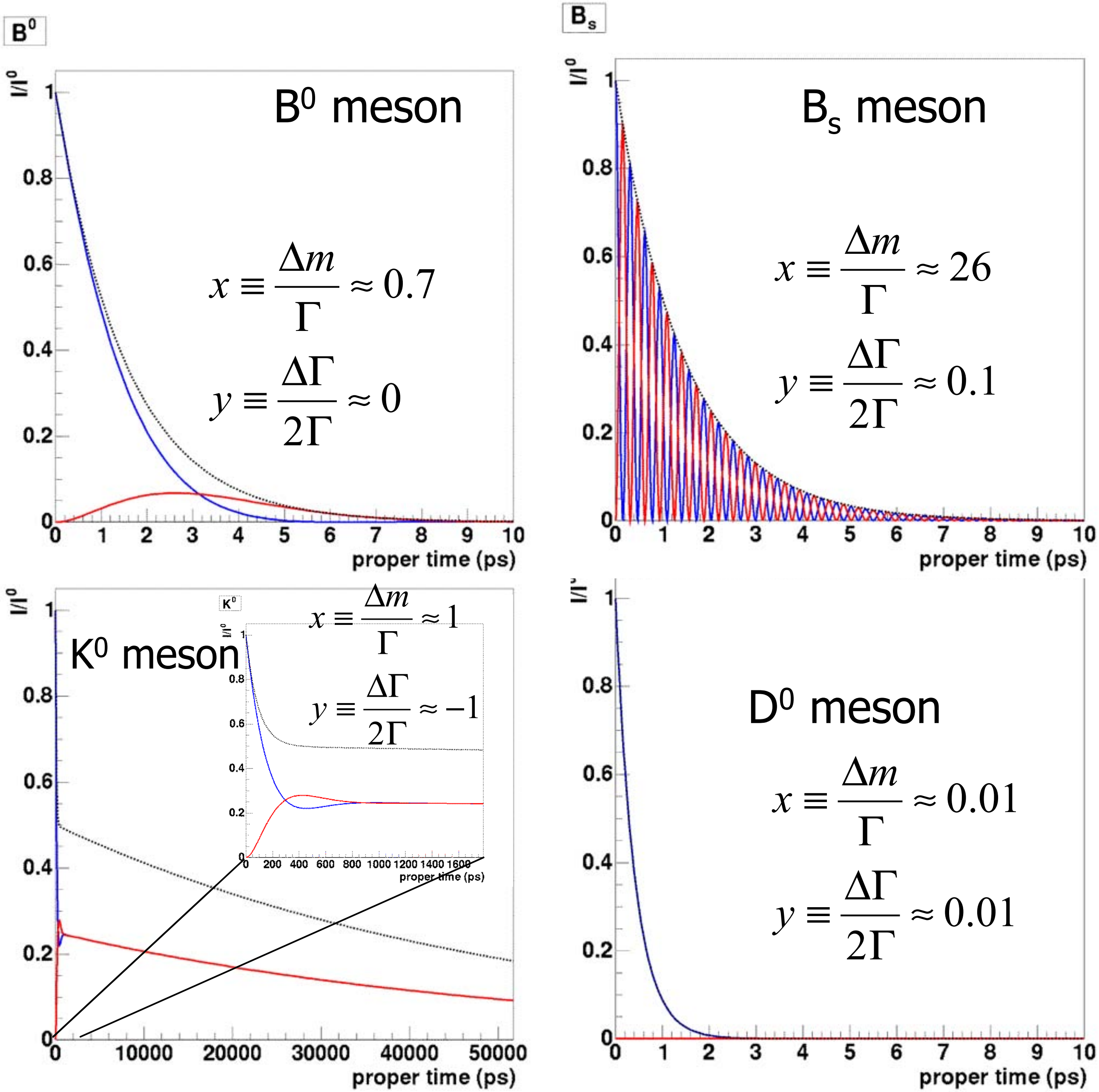
$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



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

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

Mixing of neutral mesons (recap)



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

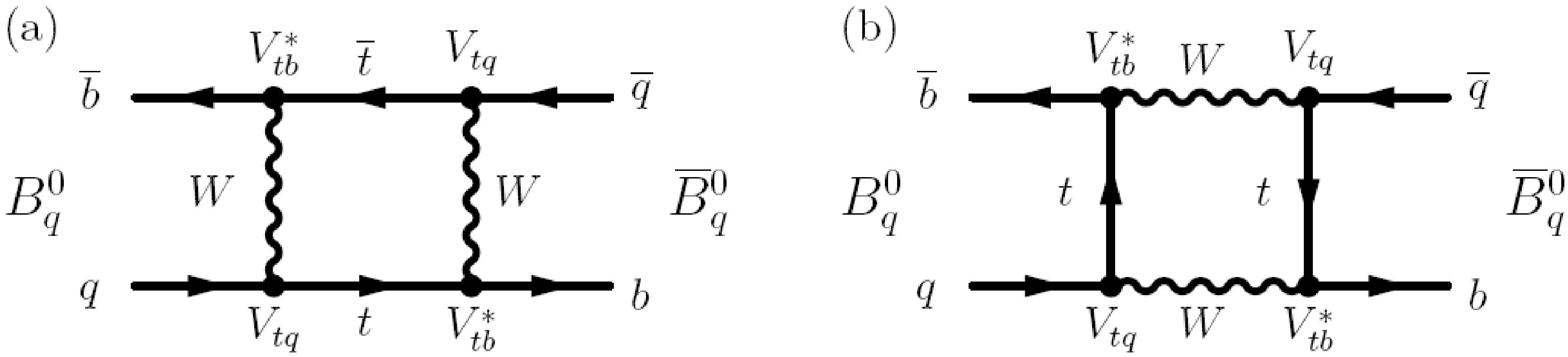
B_s system: very fast mixing

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).

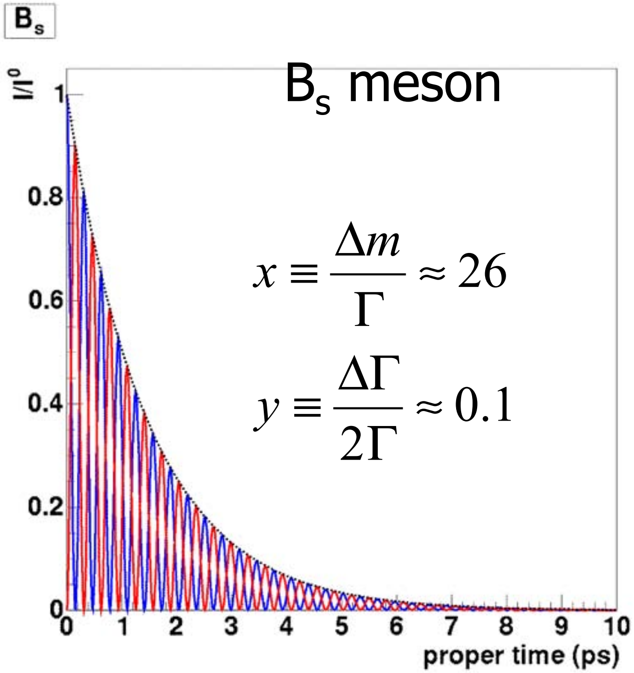
In the D system, the d,s,b quarks in internal loop (no top): small mixing.

Measurement of Δm_s

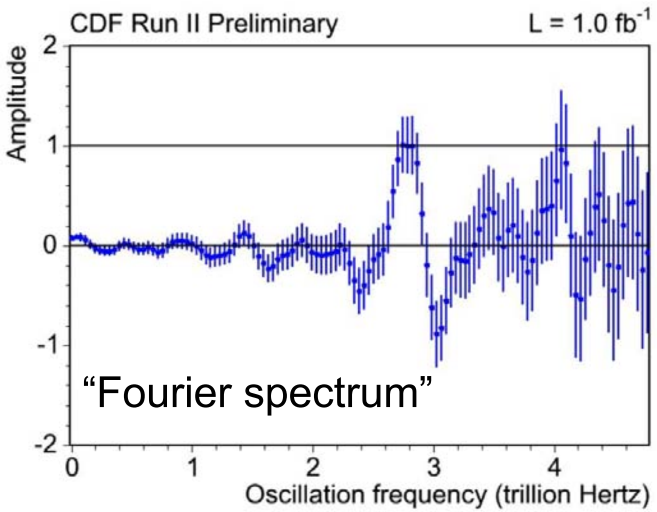
(B_s-$\overline{B}_s$ mixing frequency)

Beautiful example of oscillations.

Keep in mind this very fast oscillation in the B_s system:



This oscillation was first observed at the Tevatron in 2006 at the Tevatron:

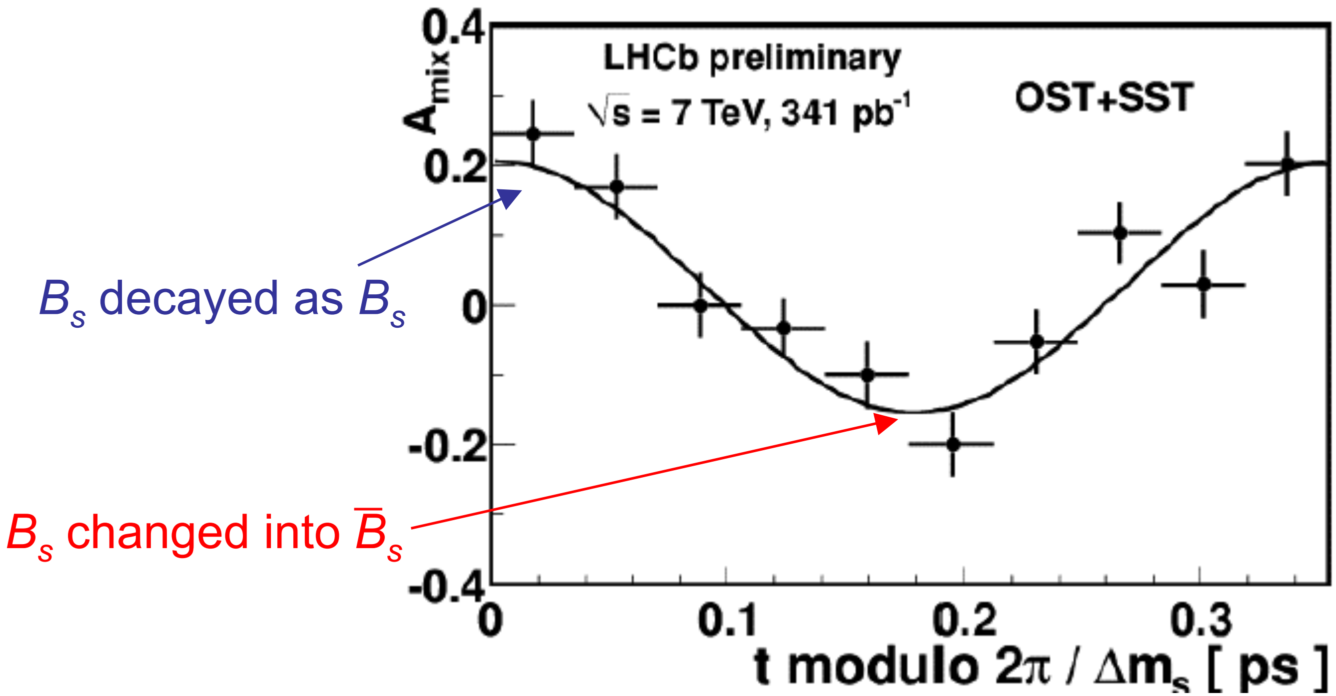


Δm_s=17.77 ± 0.10(stat) ± 0.07 (sys) ps^{-1}

Measurement of Δm_s

(B_s-$\overline{B}_s$ mixing frequency)

Now this measurement has been repeated with much better precision by LHCb:



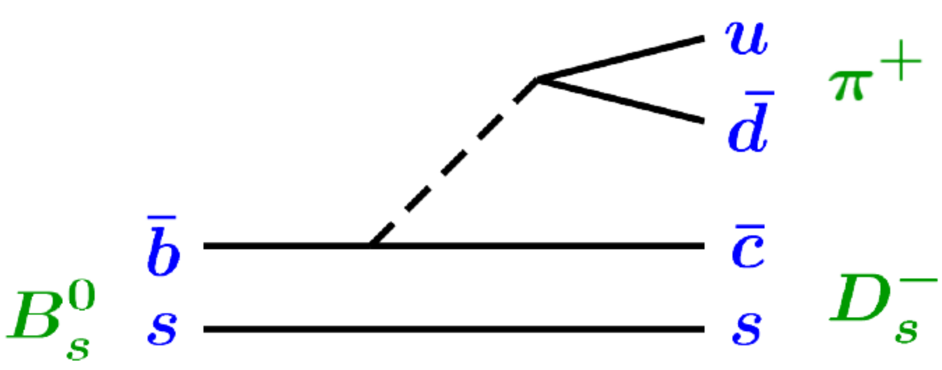
Measurement of Δm_s

(B_s-$\overline{B}_s$ mixing frequency)

What is needed to measure Δm_s ?

Main ingredients for measuring Δm_s:

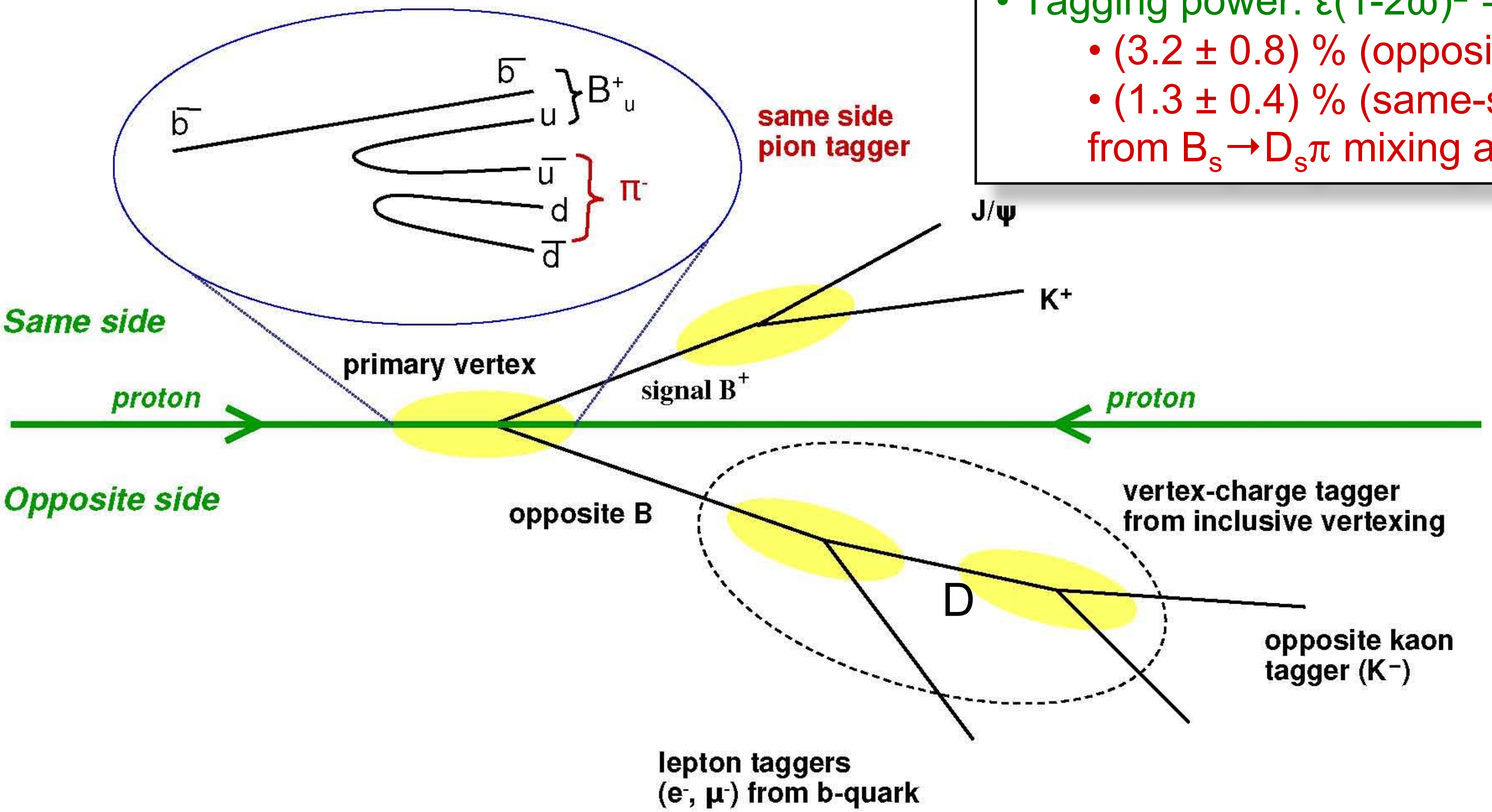
- Resolve the fast B_s oscillations.
  - Average decay time resolution ~45 fs
- Decays into flavour specific final state: $B_s \rightarrow D_s \pi$
  - High branching ratio (~0.3%)
- Tag the B_s flavour at production.
  - High efficiency and low mistag rate.
  - Tagging power: ~5%.



Flavour tagging

- Tagging of production flavour (B or $\overline{B}$)
- Important for mixing & CP analyses.
- Performance calibrated using control channels such as $B^+ \rightarrow J/\psi\, K^+$
- Tagging power: $\varepsilon(1-2\omega)^2$ =
  - (3.2 ± 0.8) % (opposite-side tag)
  - (1.3 ± 0.4) % (same-side tag)

  from $B_s \rightarrow D_s\pi$ mixing analysis.



In a perfect detector, why is the OS mistag rate not 0% ?

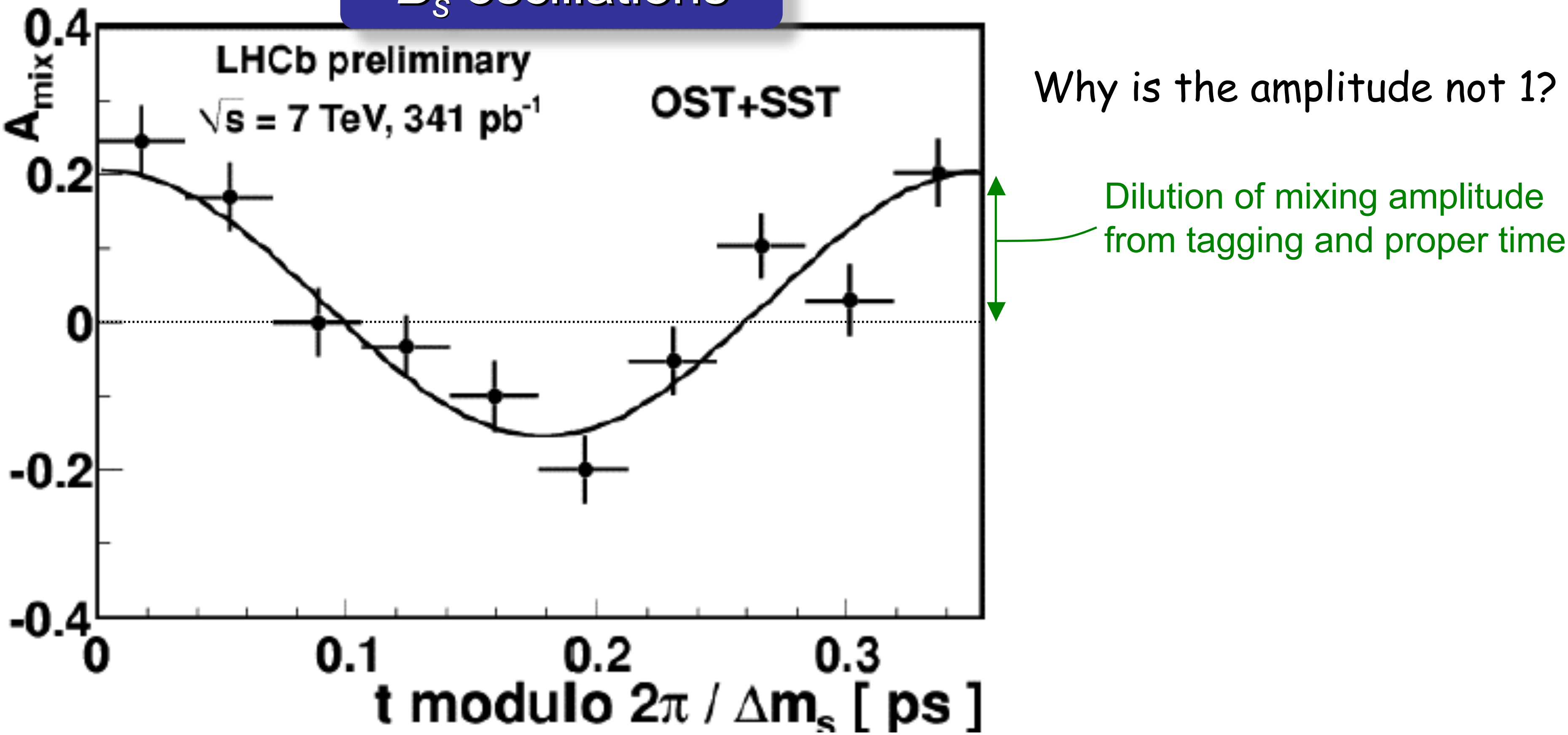
Measurement of Δm_s

[LHCb-CONF-2011-50]

Define "mixing asymmetry":

$$A_{\text{mix}}(t) = \frac{N(B_s^0 \to D_s^- \pi^+) - N(B_s^0 \to D_s^+ \pi^-)}{N(B_s^0 \to D_s^- \pi^+) + N(B_s^0 \to D_s^+ \pi^-)}$$

B_s oscillations



Why is the amplitude not 1?

Measurement of Δm_s

[LHCb-CONF-2011-50]

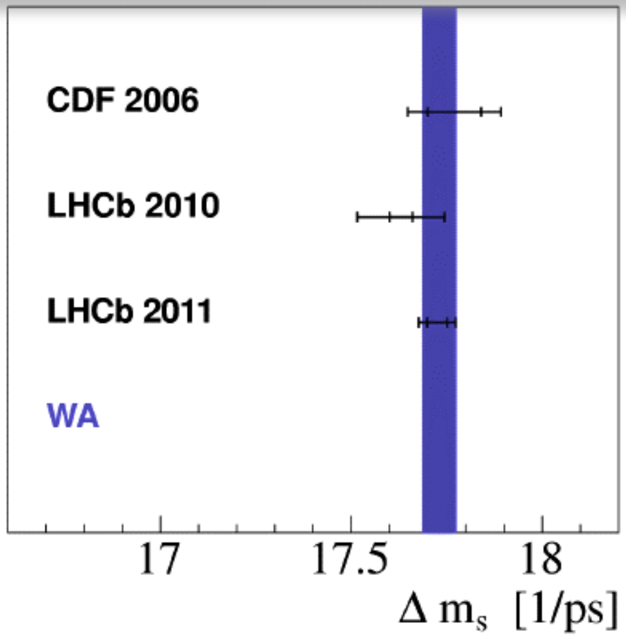
- Δm_s extracted from unbinned ML fit to $B_s \to D_s \pi$ candidates
  - Uses mass, decay time and flavour tagging
  - Method includes now same side tagging (cf 2010 fit)

Preliminary

$\Delta m_s = 17.725 \pm 0.041(\text{stat}) \pm 0.025\ (\text{sys})\ \text{ps}^{-1}$

Dominant systematics uncertainty: z-scale and momentum scale

Most precise measurement of Δm_s



Analysis done with 341 pb^{-1}.
(3x more data now available)

SM: $\Delta m_s = 17.3 \pm 2.6\ \text{ps}^{-1}$

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 P($B^0 \to \overline{B}^0$) is different from the CP conjugate process P($\overline{B}^0 \to B^0$).

Remember that:

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

In the B_d and B_s systems Γ_{12} is small ➔ Small CP violation in mixing.

1. CP violation in mixing

Remember that:

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

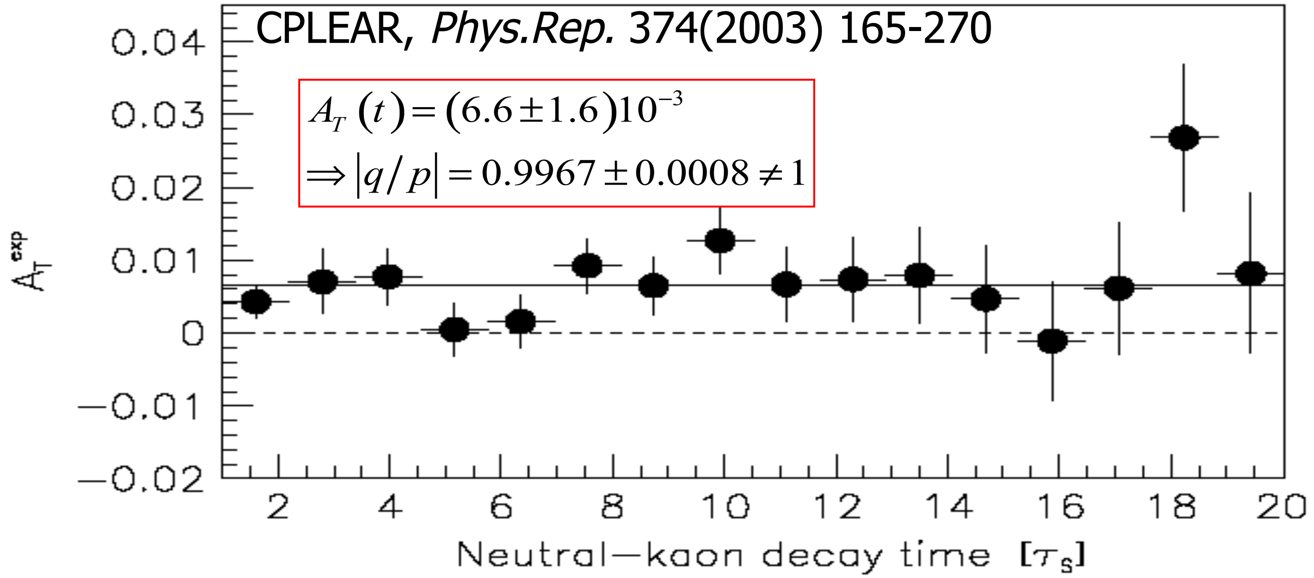
Requirements for CP violation in mixing, i.e. $|q/p| \neq 1$

- 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

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

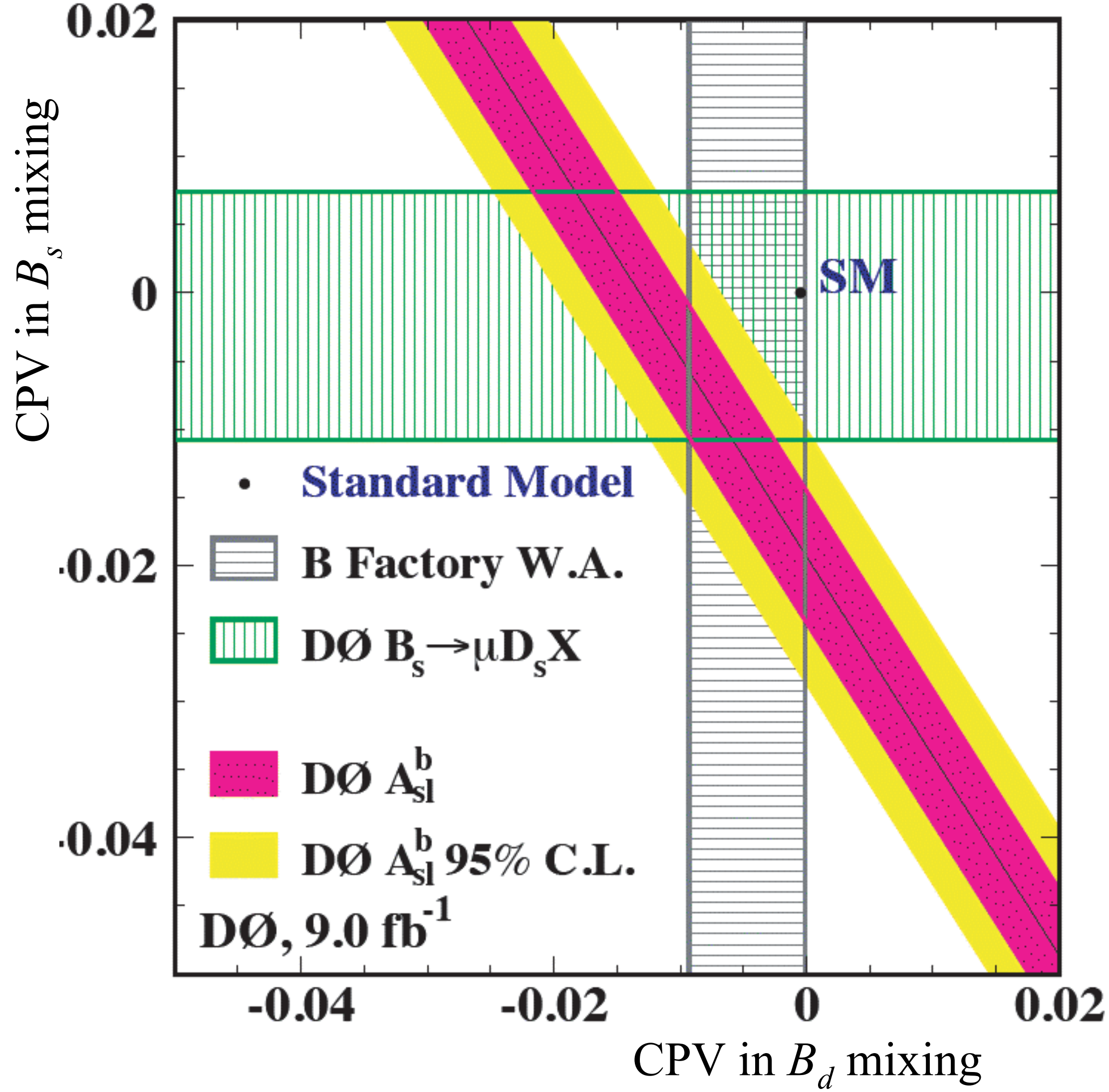


CP violation in mixing small in SM: (due to cancellations)

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

Hints for New Physics?

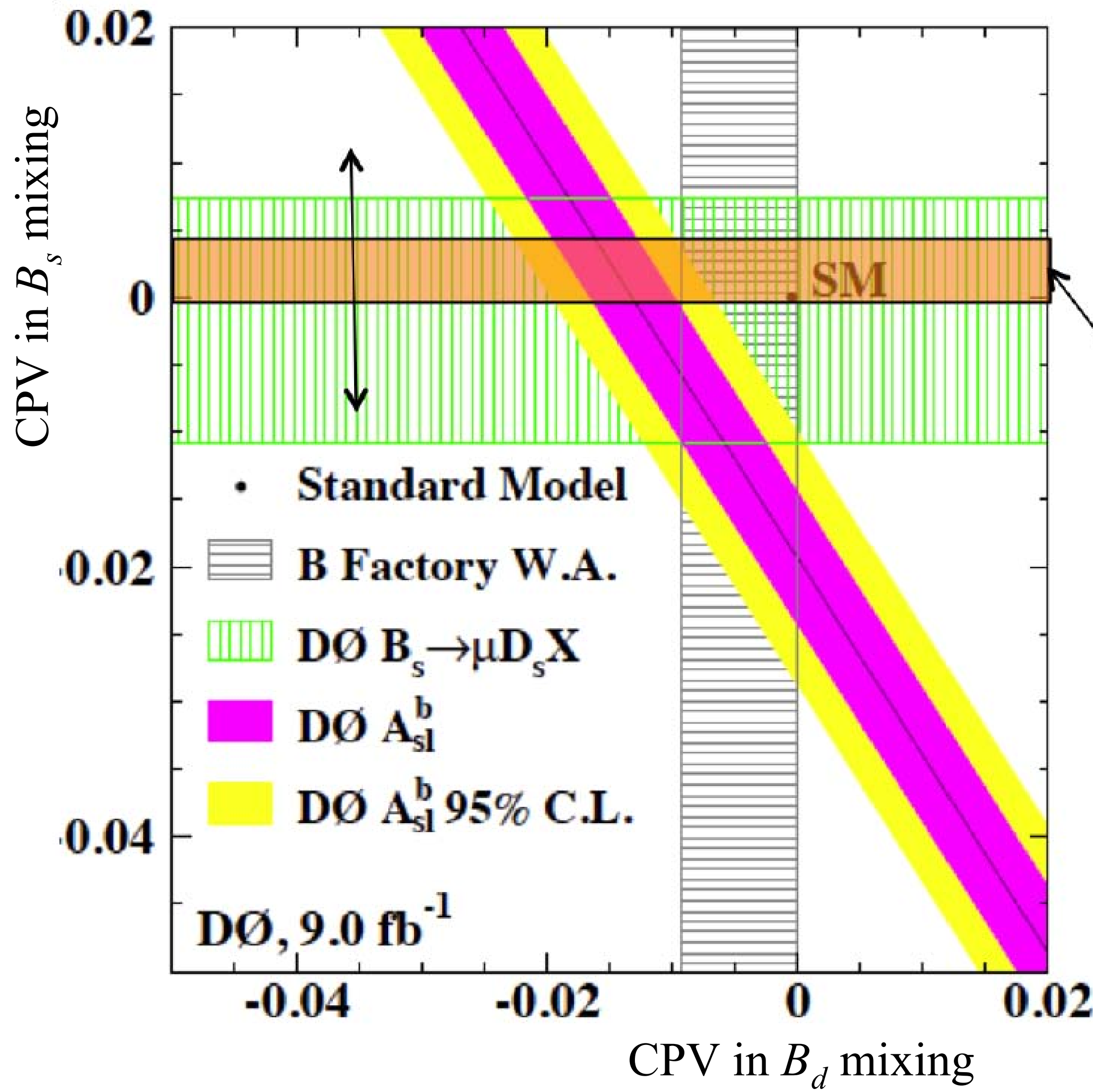
Semileptonic measurement of CPV in *B* mixing from D0 (Tevatron)



Discrepancy of central value too large for New Physics.

Hints for New Physics?

Semileptonic measurement of CPV in *B* mixing from D0 (Tevatron)



High on agenda LHCb:

Estimated uncertainty for measurement from LHCb (expected this Winter)

Stay tuned…

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

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

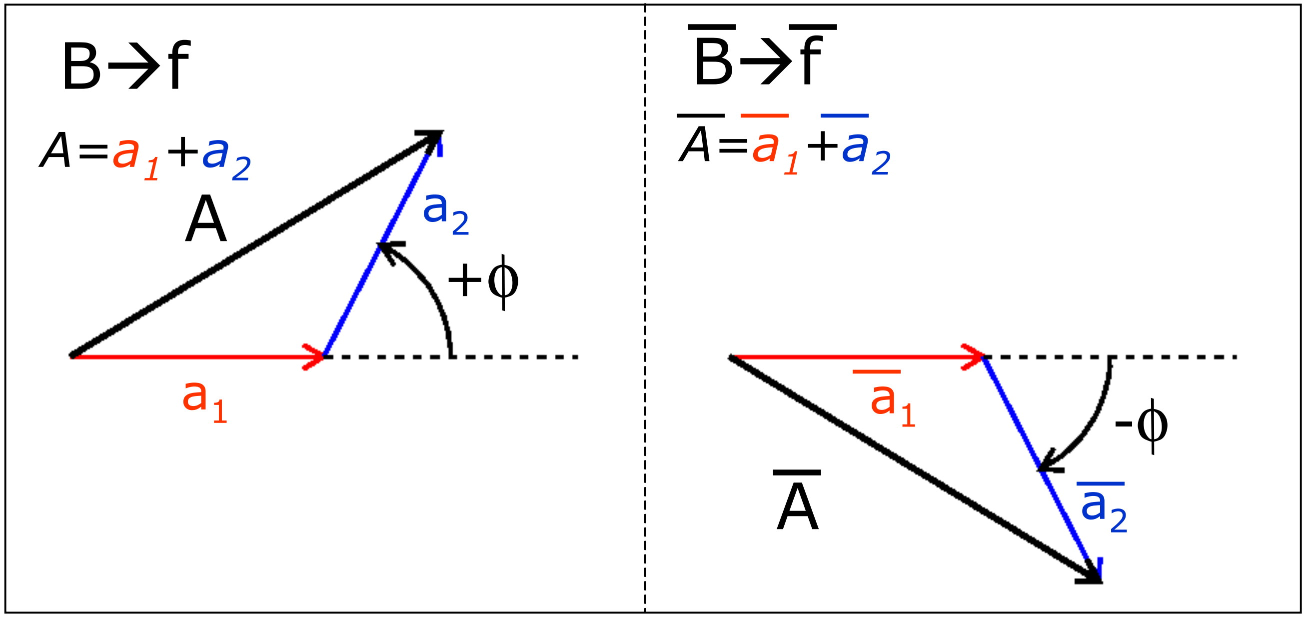
Weak phase changes sign under CP transformation

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

Strong phase invariant under CP transformation

CP violation in decay is also called direct CP violation

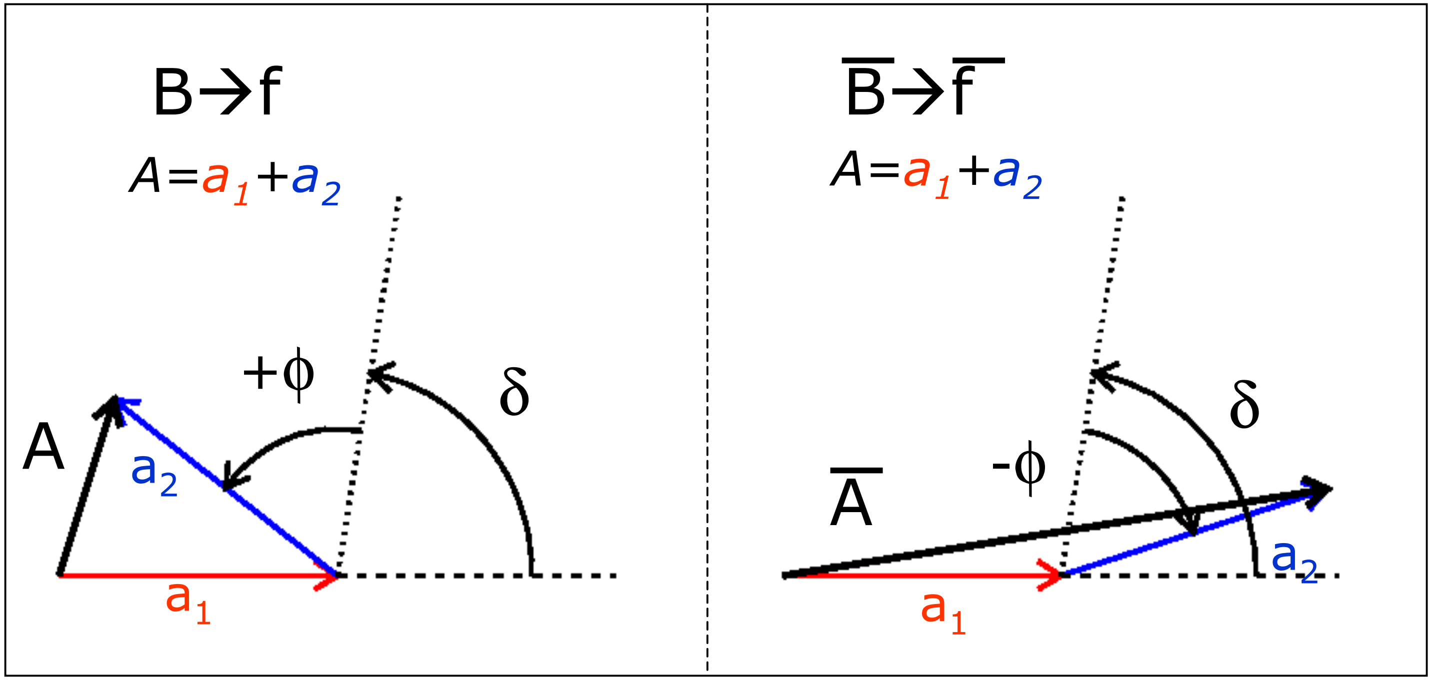
2. CP violation in decay



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

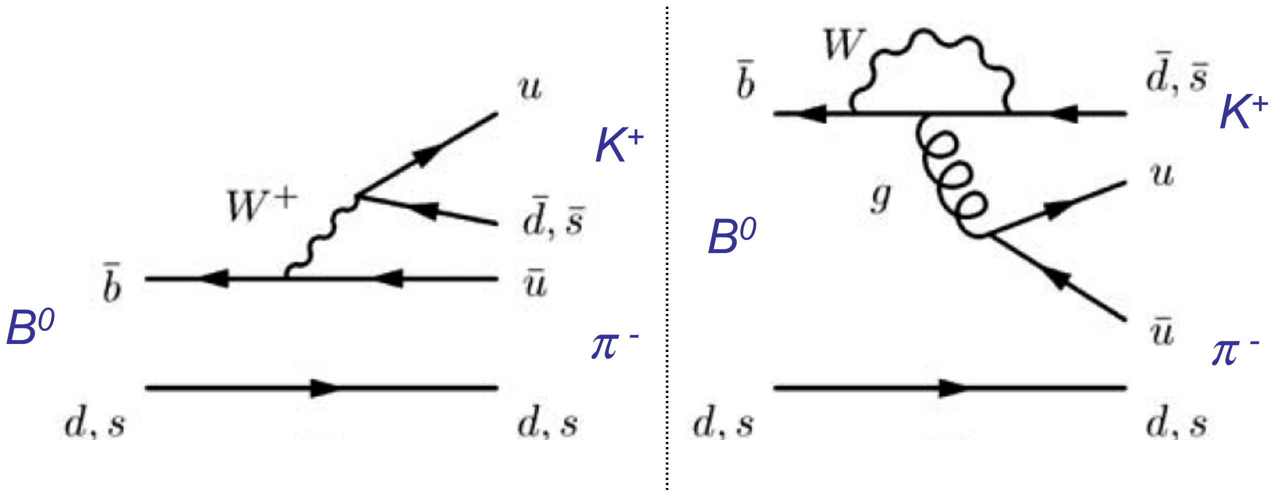
Problem: strong phases unknown, so difficult to extract the weak phase.

Example: CP violation in decay

Charmless charged two-body *B* decays

Tree

"a_1"



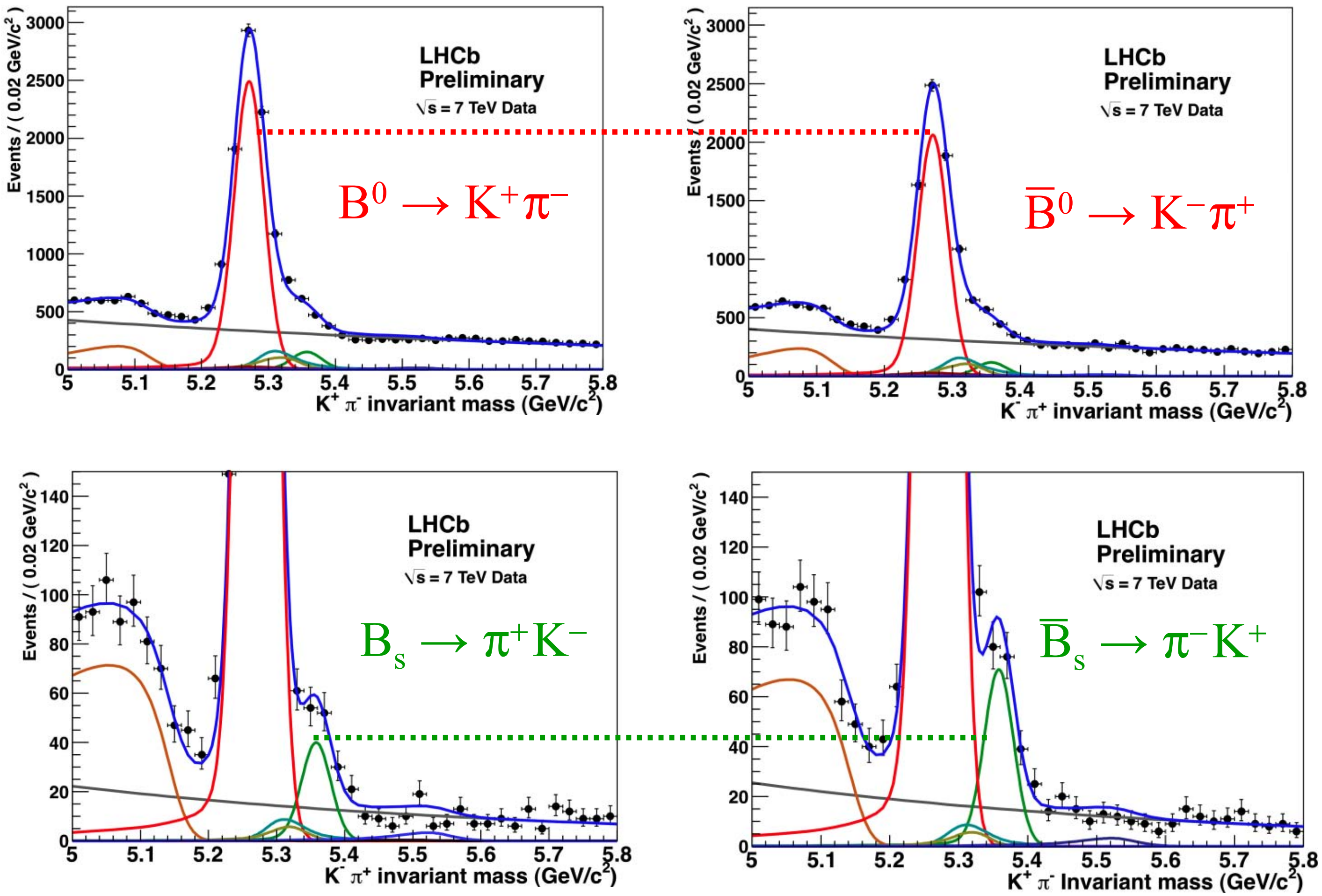
Penguin

"a_2"

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

Example: CP violation in decay

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



[LHCb-CONF-2011-042]

Example: CP violation in decay

Definition of asymmetry (time-integrated):

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

$$A_{CP}(B_s^0 \to \pi K) = \frac{\Gamma(\bar{B}_s^0 \to \pi^- K^+) - \Gamma(B_s^0 \to \pi^+ K^-)}{\Gamma(\bar{B}_s^0 \to \pi^- K^+) + \Gamma(B_s^0 \to \pi^+ K^-)}$$

Note that this does not require flavour tagging: we want to know flavour at decay.

LHCb's measurement for A_{CP}

Preliminary [LHCb-CONF-2011-042]

$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011 \pm 0.008$$

WA: $-0.098^{+0.012}_{-0.011}$

→ Most precise, and first 5σ observation of CP violation in hadronic machine.

$$A_{CP}(B_s \to \pi K) = 0.27 \pm 0.08 \pm 0.02$$

→ first 3σ evidence of CP violation in $B_s^0 \to \pi K$

Caveat: strong phases and T/P 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)

Preliminary
[LHCb-CONF-2011-061]

New result!
Only presented 3 weeks ago at HCP

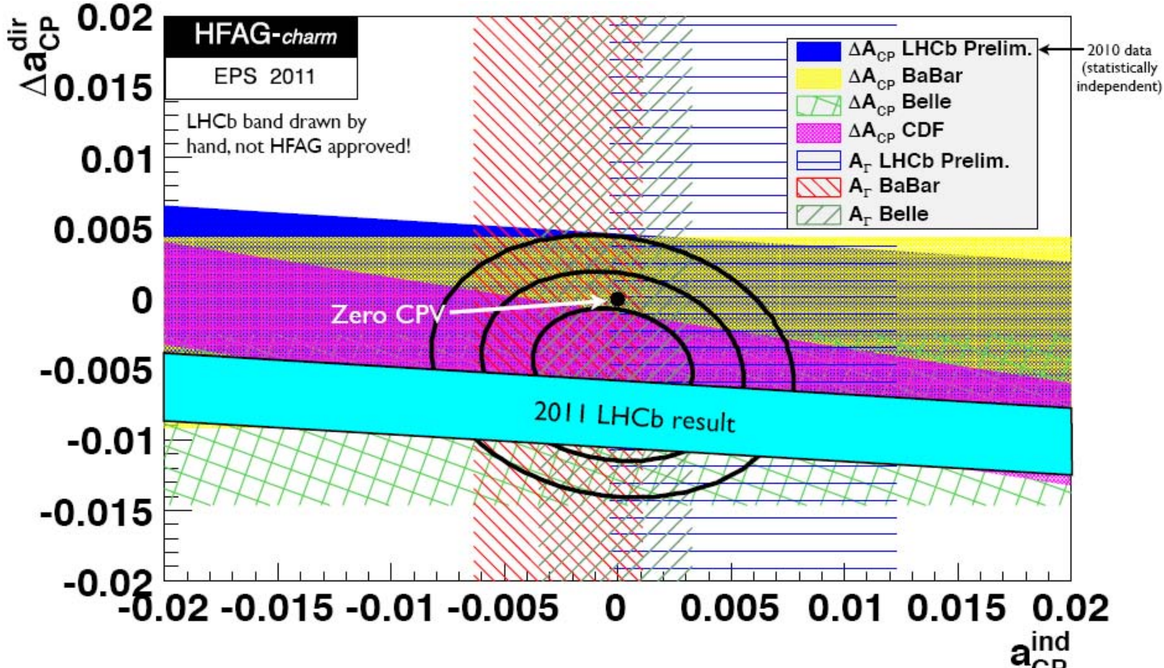
$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = \Delta a_{CP}^{\text{dir}} - 0.1 a_{CP}^{\text{ind}}$$

Measurement (2011 only; 580 pb^{-1}):

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

Signifance 3.5σ

First evidence of CP violation in charm sector!



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 $\overline{B}^0$ or B^0:

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

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:

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

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

Compared to plain *B* 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 and no CPV in mixing:

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

Then defining the CP asymmetry as:

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

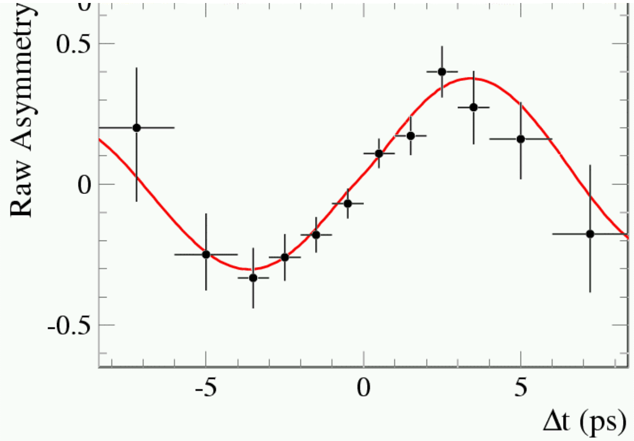
If amplitude non-zero: CP

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:

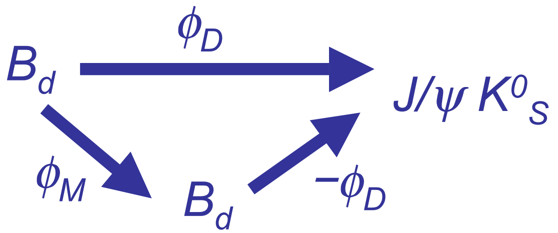
$$\mathrm{Im}\lambda_{J/\psi K^0_S} = \sin 2\beta$$

CKM phase β directly observable!



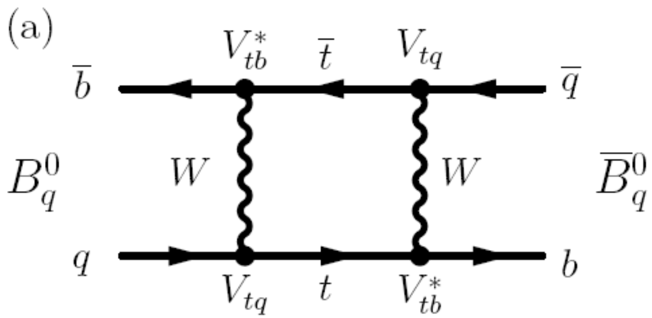
Example: Measurement of sin2β

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



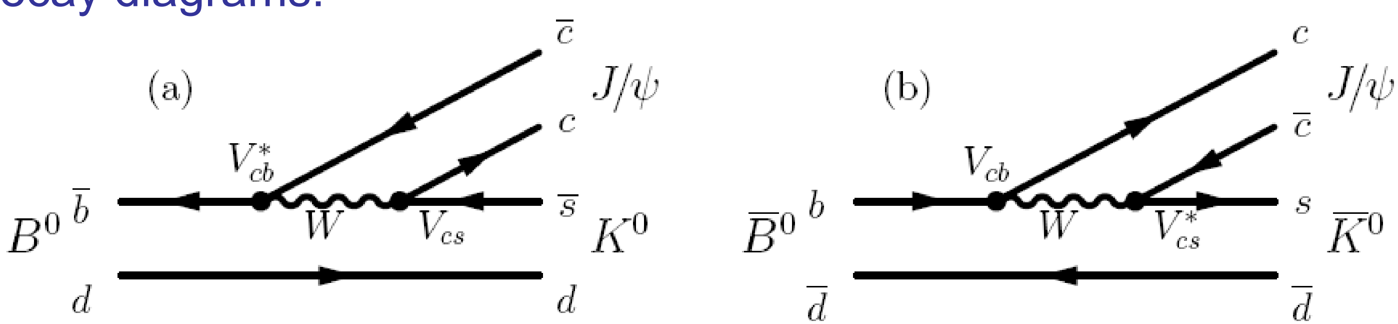
$$\lambda_{J/\psi K^0_S} = \left(\frac{q}{p}\right)_{B_d} \frac{\bar{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}} = -\left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\right)$$

Mixing (box) diagram:



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

Decay diagrams:

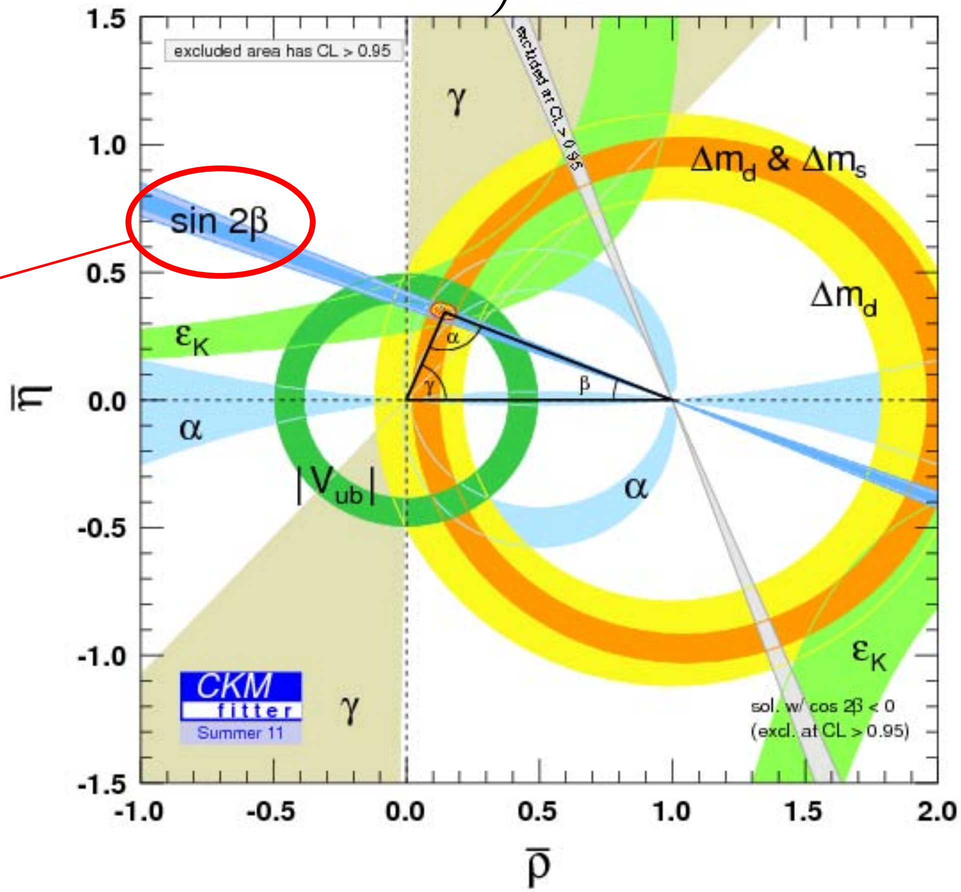


Example: Measurement of sin2β

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

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

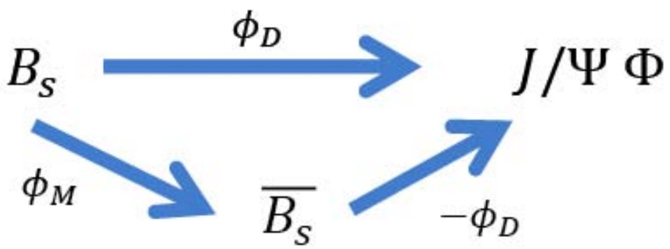
sin2β = 0.679±0.020



Example: Measurement of $\sin(2\beta_s)$

- 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: $2\beta_s = 0.036 \pm 0.002$

$2\beta_s$: interference phase between B_s mixing and $b \to c\bar{c}s$ decay:



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

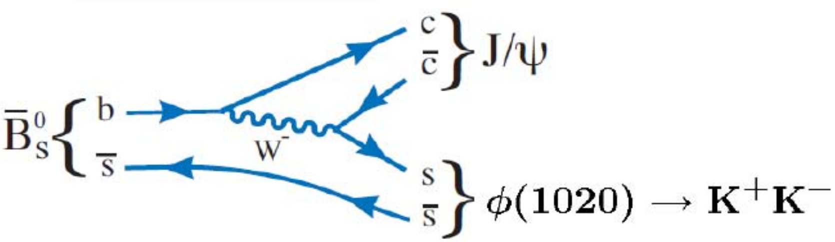
Definition: $\phi_s = -2\beta_s$

Example: Measurement of $\sin(2\beta_s)$

Two decay modes

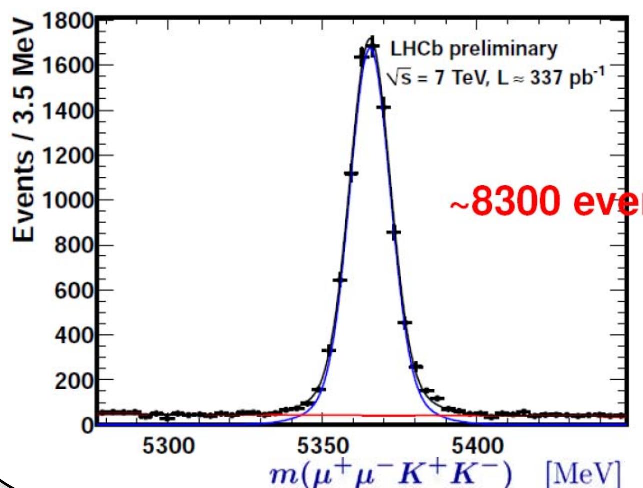
$B_s \rightarrow J/\psi\, \phi$

LHCb-CONF-049



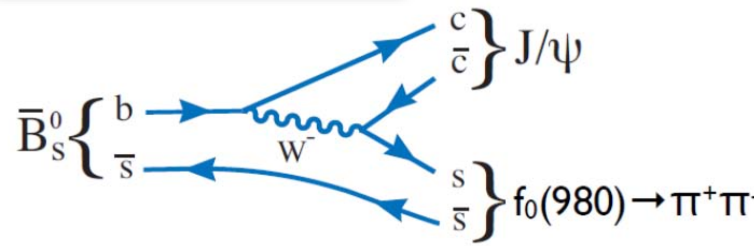
☺ Narrow ϕ resonance (clean)

☹ Vector-vector final state (requires angular analysis)



$B_s \rightarrow J/\psi\, f_0(980)$

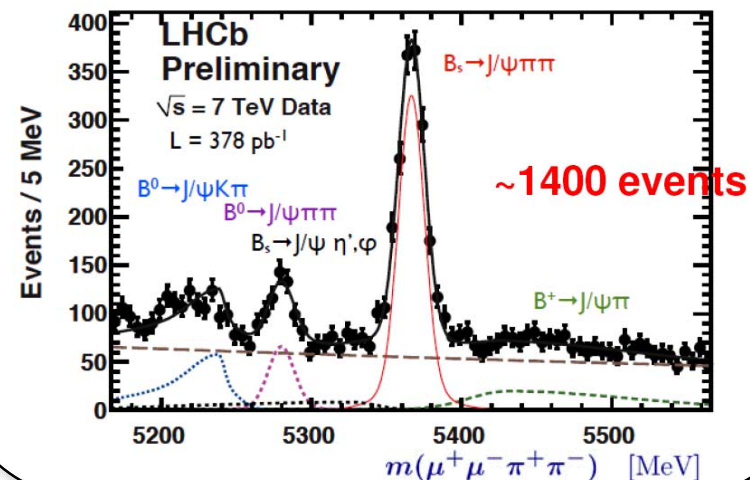
LHCb-CONF-051



→ First seen by LHCb last winter

☺ CP odd final state (no angular analysis)

☹ BR about 20% of $B_s \rightarrow J/\psi\, \phi$



Example: Measurement of $\sin(2\beta_s)$

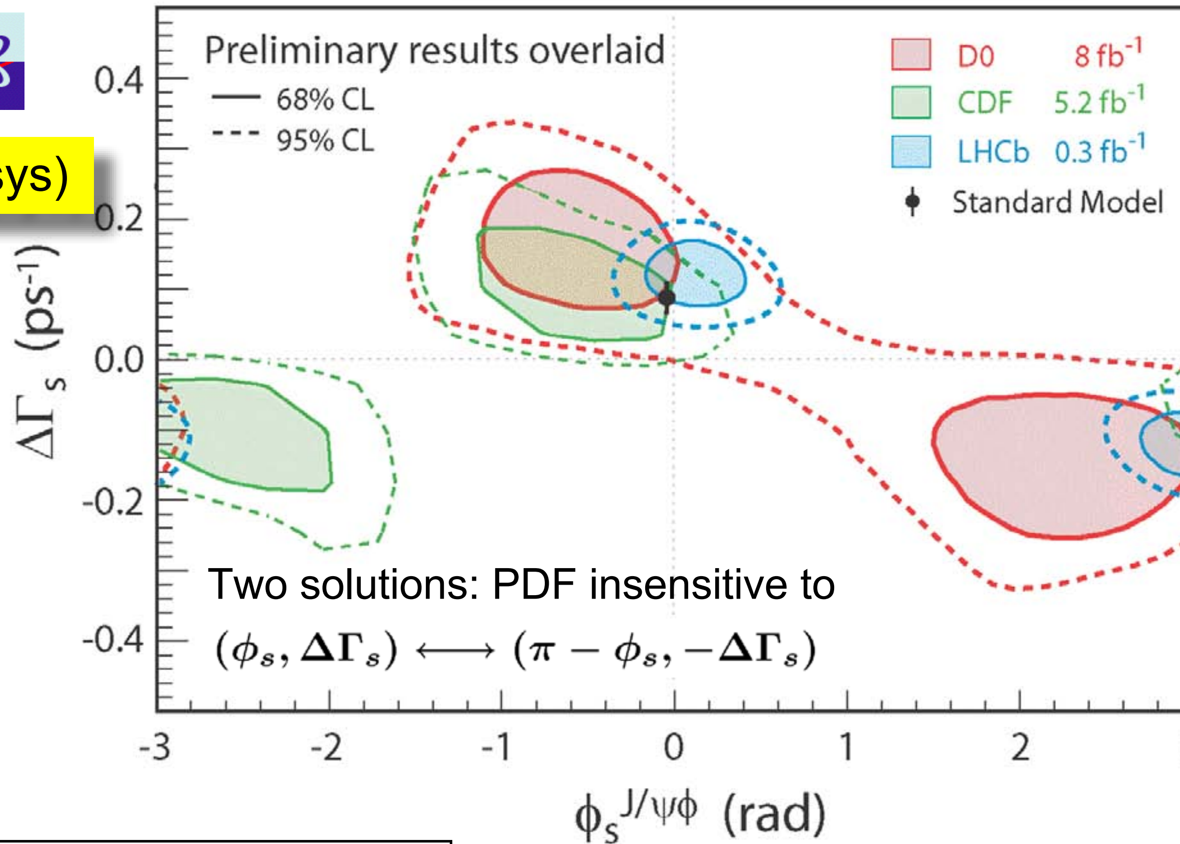
Combined fit

Preliminary
LHCb-CONF-2011-056

ϕ_s = -0.03 ± 0.16(stat) ± 0.07 (sys)

SM: ϕ_s = -0.036 ± 0.002

Comparison with Tevatron



Two solutions: PDF insensitive to

$$(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s)$$

Next steps:

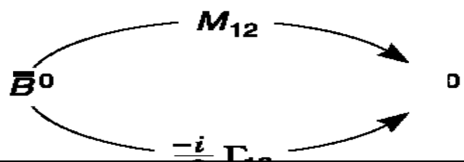
- Included more data (2.5 times more data recorded)
- Include same-side tagging (~1.5x more tagging power)

→ Expect ~2x smaller statistical error.

Overview: Types of CP violation

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

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

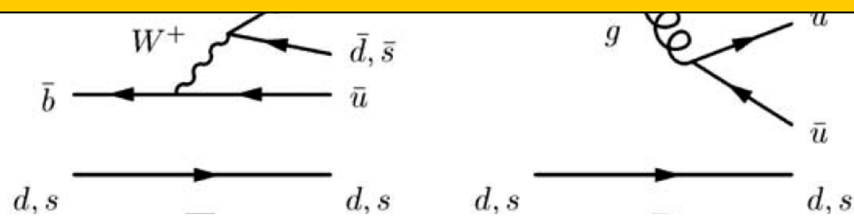


2. CP violat

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

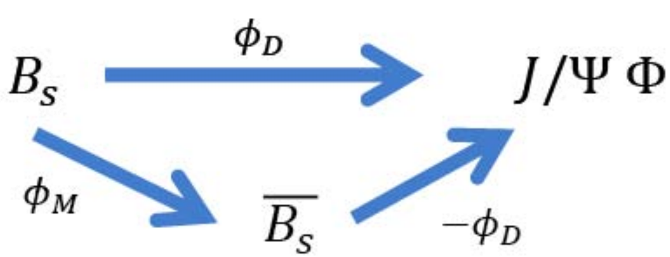
$\left|\overline{A}_{\overline{f}}\right|$

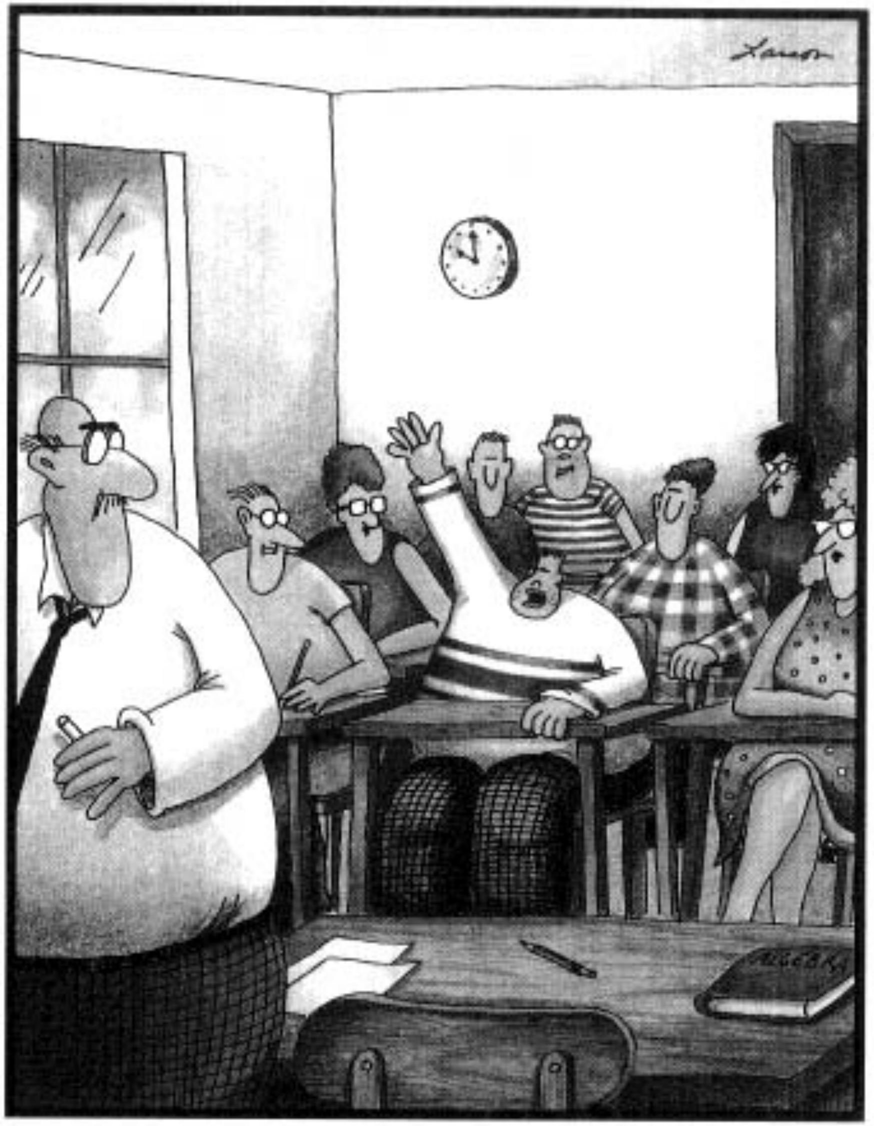
Tree



Penguin

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





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

Backup slides

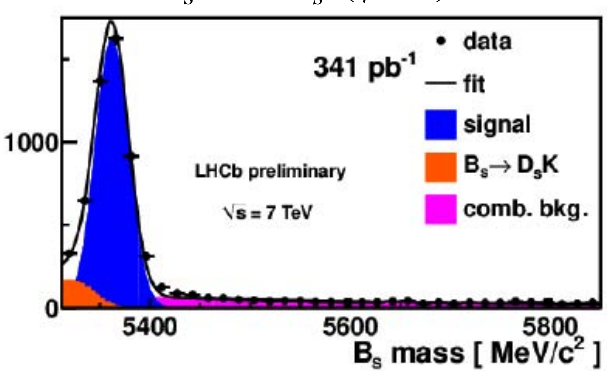
Measurement of Δm_s

- The D_s decays as $D_s \to K^+ K^- \pi^-$ (largest hadronic BR)
- Intermediate resonances used for this analysis:
  - $D_s \to \phi\, \pi^-$
  - $D_s \to K^* K^-$
  - $D_s \to K^+ K^- \pi^-$ (non-resonant)
- Event selection based on kaon ID, track IP and vertex χ^2

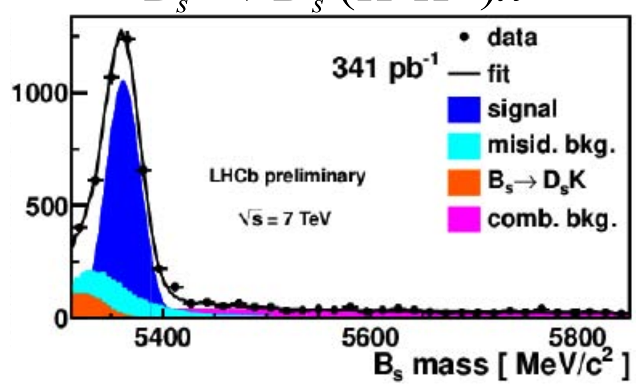
Event yield in 340 pb^{-1}

decay mode	signal yield
$B_s^0 \to D_s^-(\phi\pi^-)\pi^+$	4371 ± 91
$B_s^0 \to D_s^-(K^*K^-)\pi^+$	2910 ± 89
$B_s^0 \to D_s^-\pi^+$ non-resonant	1908 ± 74
total yield	9189 ± 147

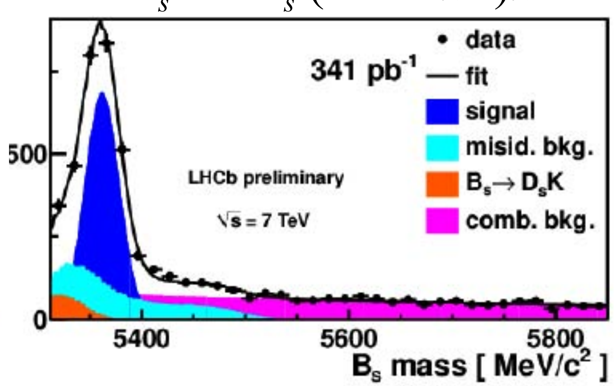
$B_s^0 \to D_s^-(\phi\pi^-)\pi^+$



$B_s^0 \to D_s^-(K^*K^-)\pi^+$



$B_s^0 \to D_s^-(K^-K^+\pi^-)\pi^+$



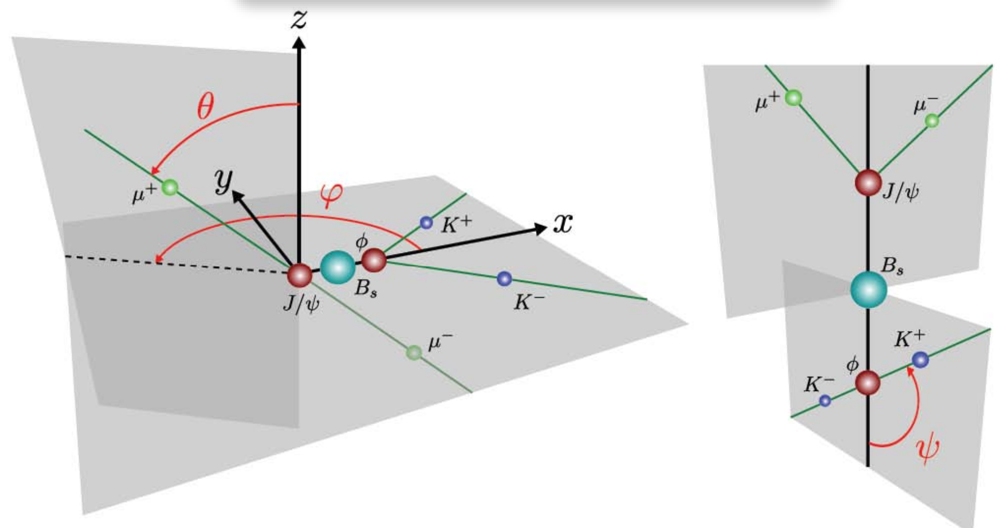
Example: measurement of ϕ_s

Angular analysis of $B_s \rightarrow J/\psi\ \phi$

$B_s \rightarrow J/\psi\ \phi$ has vector-vector final state:

- Mixture of CP-odd and CP-even decay amplitudes
- Even and odd amplitudes can be disentangled using decay angles.

Transversity angles



Decay amplitudes used in fit:

A_0	even	P wave
$A_\perp$	even	P wave
$A_\parallel$	odd	P wave
A_s	odd	→ S wave (non resonant K^+K^-)

Example: measurement of ϕ_s

Angular analysis of $B_s \to J/\psi\, \phi$

PDF of unbinned ML fit described as:

$$\sum_{k=1}^{10} h_k(t;\phi_s,\Gamma_s,\Delta\Gamma_s)\, f_k(\theta,\psi,\phi)$$

k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_\parallel(t)\,A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. -\cos(\delta_\perp-\delta_\|)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m t)\right], \\
\Re(A_0(t)\,A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel-\delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_0(t)\,A_\perp(t)) &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. -\cos(\delta_\perp-\delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp-\delta_0)\cos(\Delta m t)\right], \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], \\
\Re(A_s^*(t)A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel-\delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel-\delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\parallel-\delta_s)\cos(\Delta m t)\right], \\
\Im(A_s^*(t)A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp-\delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], \\
\Re(A_s^*(t)A_0(t)) &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0-\delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. -\sin(\delta_0-\delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0-\delta_s)\cos(\Delta m t)\right].
\end{aligned}
$$

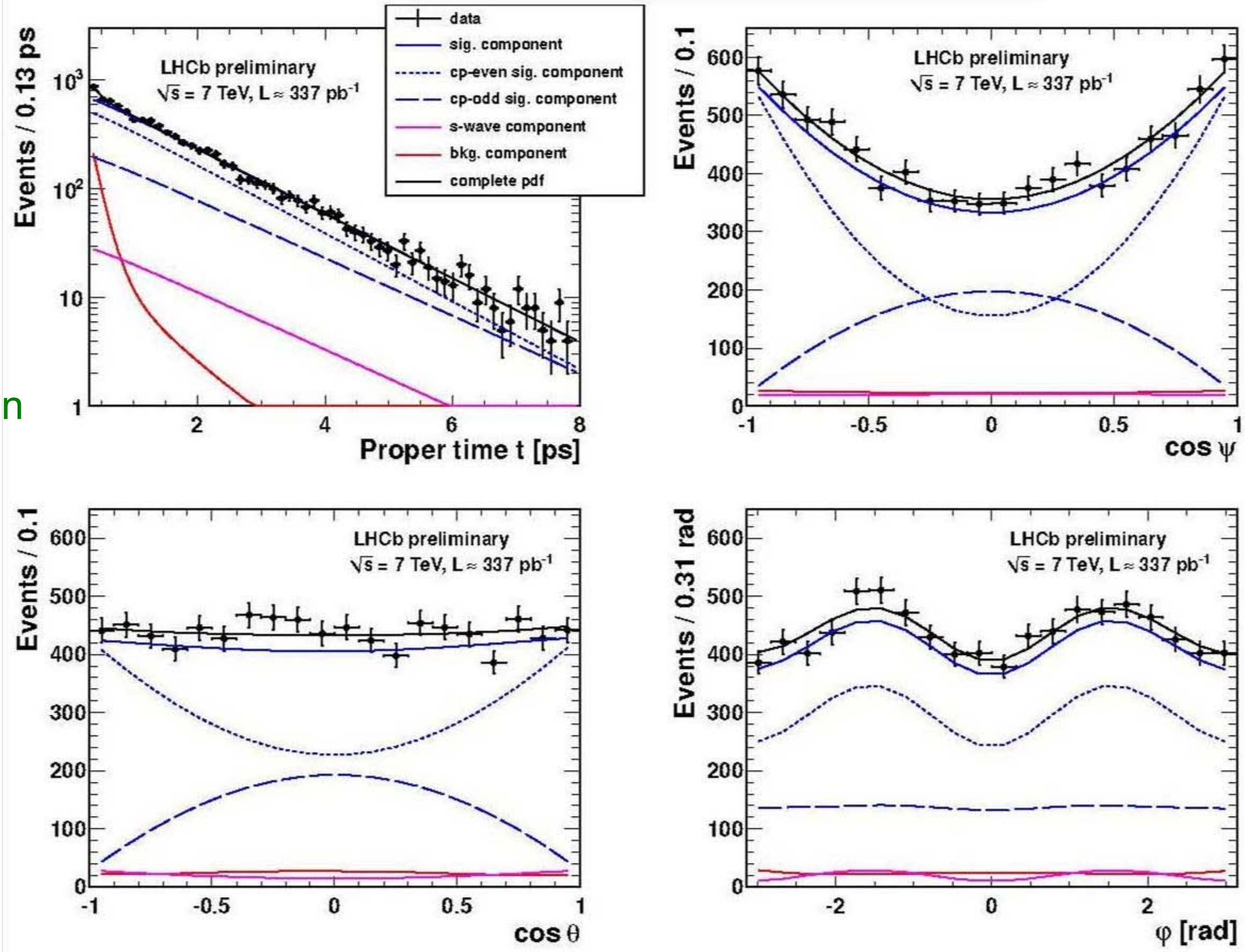
Complicated PDF: 3 independent implementations in LHCb

Example: measurement of ϕ_s

Angular analysis of $B_s \rightarrow J/\psi\, \phi$

Time and angular distributions

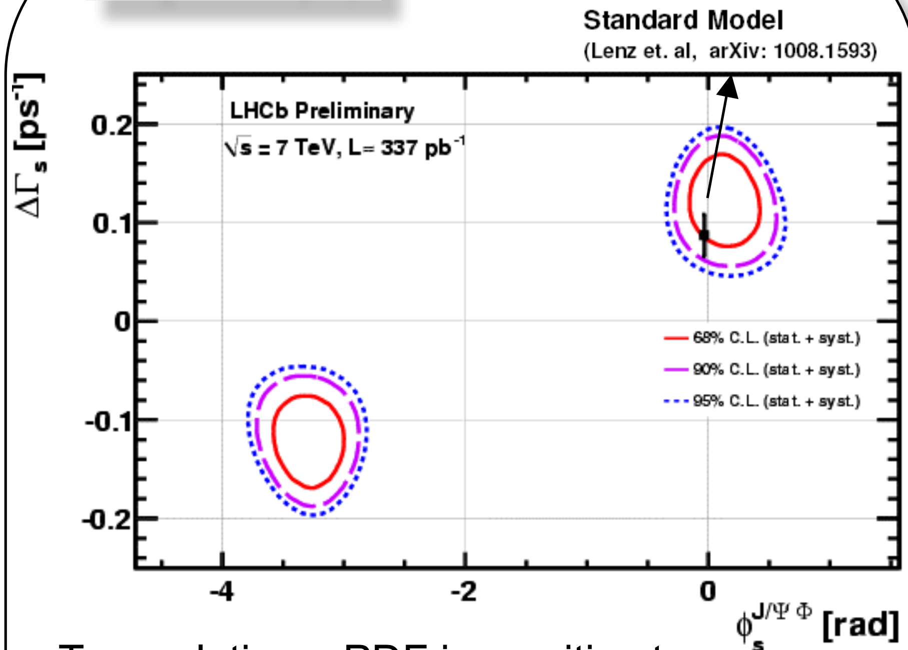
Main systematic errors from uncertainties in the description of angular and decay time acceptance and background angular distribution.



Example: Measurement of $\sin(2\beta_s)$

Result of the two fits

$B_s \to J/\psi\,\phi$

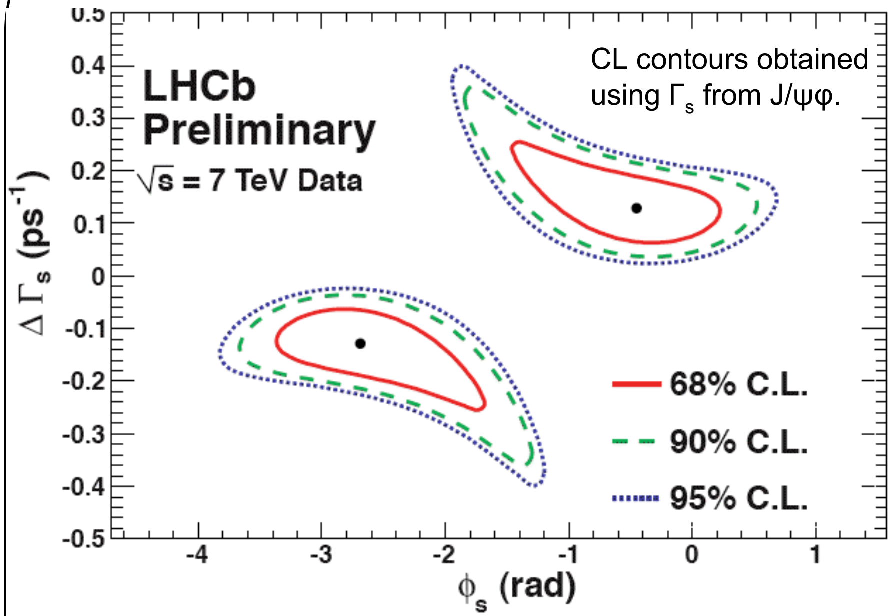


Two solutions: PDF insensitive to

$$(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s)$$

$$\begin{aligned}\phi_s^{J/\psi\phi} &= 0.13 \pm 0.18\ (\mathrm{stat}) \pm 0.07\ (\mathrm{sys})\ \mathrm{rad},\\ \Gamma_s &= 0.656 \pm 0.009\ (\mathrm{stat}) \pm 0.008\ (\mathrm{sys})\ \mathrm{ps}^{-1},\\ \Delta\Gamma_s &= 0.123 \pm 0.029\ (\mathrm{stat}) \pm 0.011\ (\mathrm{sys})\ \mathrm{ps}^{-1}.\end{aligned}$$

$B_s \to J/\psi\, f_0(980)$



CP-odd final state, cannot determine Γ_s and $\Delta\Gamma_s$ simultaneously. When using both Γ_s and $\Delta\Gamma_s$ from $B_s \to J/\psi\varphi$:

ϕ_s =-0.44±0.44(*stat*)±0.02(*syst*)