Latest results on CP violation in *B*-meson mixing

G.Borissov, Lancaster University, UK

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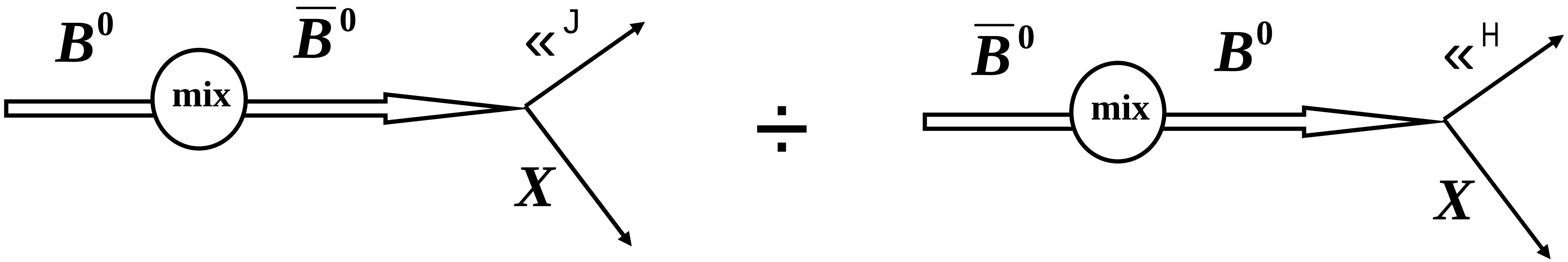
Introduction

- CP violation in mixing of neutral *B* mesons is a very active research direction
- Several new results are published recently
- Even more are expected
- SM predicts a very small value of CP violation compared to the current experimental sensitivity
- Uncertainties of the SM prediction are even less
- This opens an excellent possibility of searching for the new physics contribution by detecting a significant deviation of CP violation from zero
  - one of the "null tests" of the SM

CP violation in mixing



- – Can occur in any flavour-specific decay of neutral *B* mesons
- – Semileptonic decays provide the simplest way to measure it

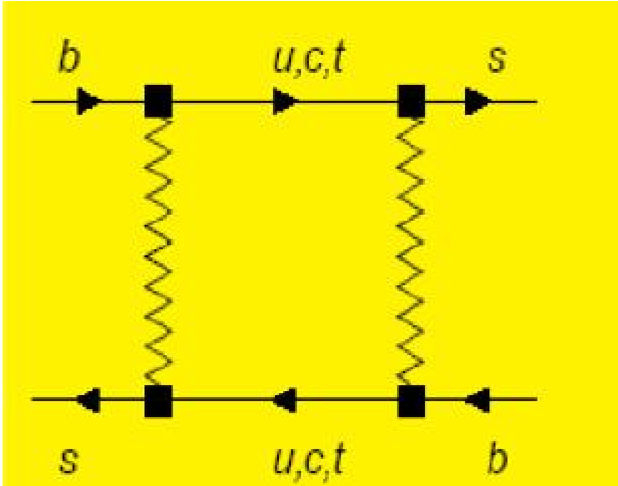
- Experimental observable of CP violation in mixing – semileptonic charge asymmetry of B_d and B_s mesons, or the asymmetry of the ``wrong-charge'' decay of *B* mesons:

$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \ell^+ X) - \Gamma(B_q^0 \to \ell^- X)}{\Gamma(\bar{B}_q^0 \to \ell^+ X) + \Gamma(B_q^0 \to \ell^- X)}; \quad q = d, s$$

Mass mixing matrix

- Semileptonic charge asymmetry is related to the parameters of mass matrix **(M-*i*Γ/2)** describing the propagation of $(B^0, \overline{B}^0)$ system:

$$a_{sl}^{q} = \frac{\Delta\Gamma_q}{\Delta m_q} \tan\phi_q^{12}$$



- Δm_q and $\Delta\Gamma_q$ are the mass and width difference of two physical states B_s^H (heavy) and B_s^L (light)
- m_q^{12} and Γ_q^{12} are non-diagonal elements of the **(M-*i*Γ/2)** matrix

$$\Delta m_q = m_{q,H} - m_{q,L} \approx 2\left|m_q^{12}\right|$$

$$\Delta\Gamma_q = \Gamma_{q,L} - \Gamma_{q,H} \approx 2\left|\Gamma_q^{12}\right| \cos\phi_q^{12}$$

$$\phi_q^{12} = \arg\left(-\frac{m_q^{12}}{\Gamma_q^{12}}\right)$$

CP violation in mixing in the standard model

- SM prediction of CP violation in mixing:

$$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$$
$$a_{sl}^{s} = (+1.9 \pm 0.3) \times 10^{-5}$$

  - using prediction of $a^d_{\rm sl}$ and $a^s_{\rm sl}$ from A. Lenz, U. Nierste, hep-ph/1102.4274
  - Very small values and even smaller uncertainties

Measurement of a^d_{sl} (DØ)

- charge asymmetry of reconstructed semileptonic B^0 decays:
  - $B^0 \to \mu^+ D^{*-} \nu$: ~545K events
  - $B^0 \to \mu^+ D^{-} \nu$: ~740K events
  - No initial flavour tagging: measure integrated asymmetry

$$A = \frac{N(B^0,\overline{B}^0 \to \mu^+ D^{(*)-}) - N(B^0,\overline{B}^0 \to \mu^- D^{(*)+})}{N(B^0,\overline{B}^0 \to \mu^+ D^{(*)-}) + N(B^0,\overline{B}^0 \to \mu^- D^{(*)+})}$$

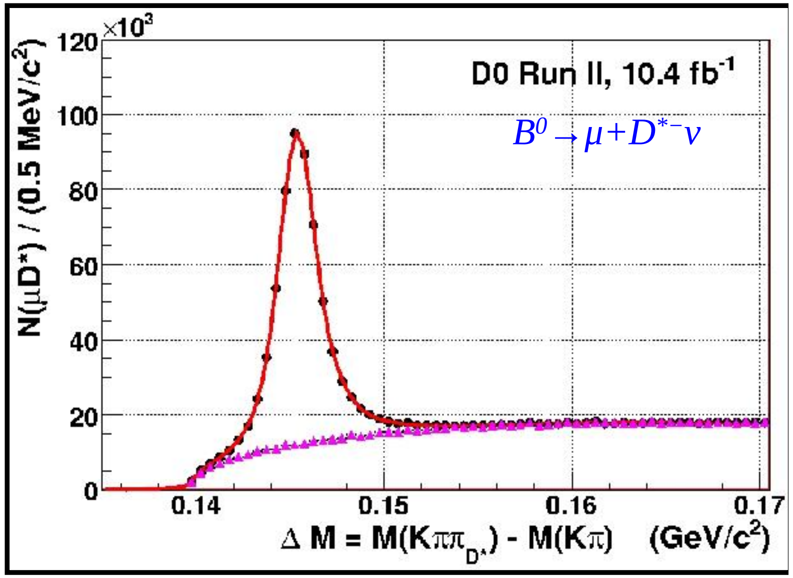
and translate it into a^d_{sl}

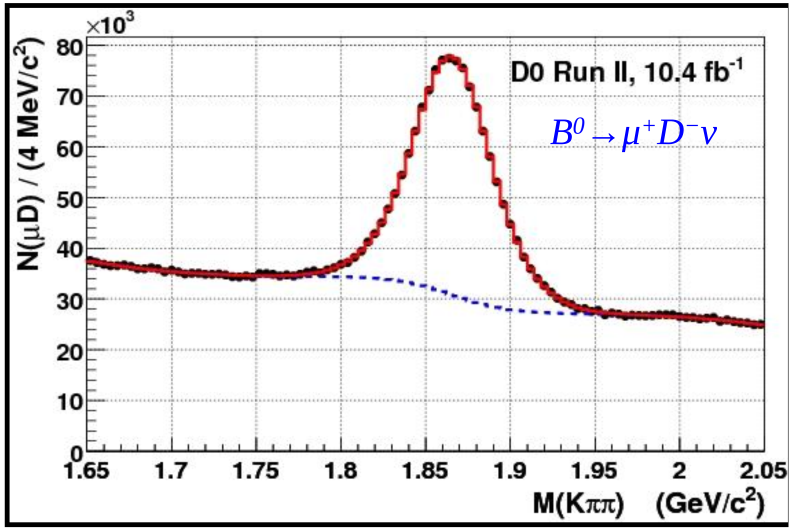
- resulting a^d_{sl} is reduced by factor $\chi_d \approx 0.186$

  - Reversal of magnet polarities significantly reduces systematics

- Result:

$$a^d_{sl} = (+0.68 \pm 0.45 \pm 0.14)\% \ \ \text{(D0)}$$





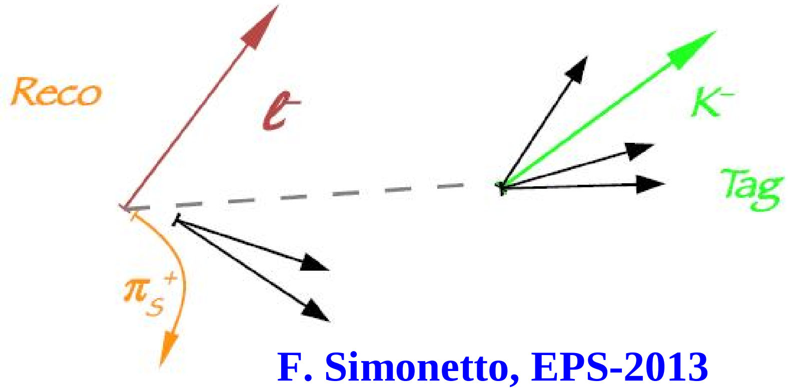
Measurement of a^d_{sl} (BaBar)

- Original method to measure a^d_{sl}
- Semi-inclusive selection of semileptonic $B^0 \to l^+ D^{*-} \nu$ decays
- Tag initial state of B^0 by the charge of additional kaon from the second B^0 meson:

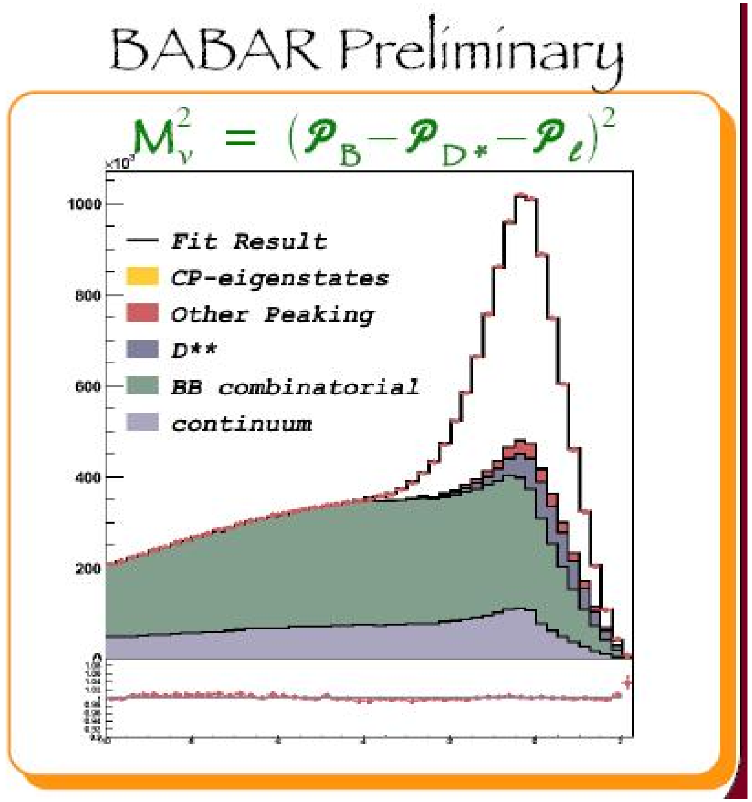
$$A_{ll} = \frac{N(l^+K^+) - N(l^-K^-)}{N(l^+K^+) + N(l^-K^-)}$$

- ~5.4 M partially reconstructed decays $B^0 \to l^+ D^{*-} \nu$ selected
- The most precise value of a^d_{sl} obtained:

$$a^d_{sl} = (+0.06 \pm 0.16^{+0.36}_{-0.32})\% \text{ (BaBar)}$$



F. Simonetto, EPS-2013



Measurements of a^{d}_{sl}

- Combination of all available results

$$a_{sl}^{d} = (-0.05 \pm 0.56)\% \quad \text{(BaBar, Belle)}$$
$$a_{sl}^{d} = (+0.68 \pm 0.45 \pm 0.14)\% \quad \text{(D0)}$$
$$a_{sl}^{d} = (+0.06 \pm 0.16^{+0.36}_{-0.32})\% \quad \text{(BaBar new)}$$

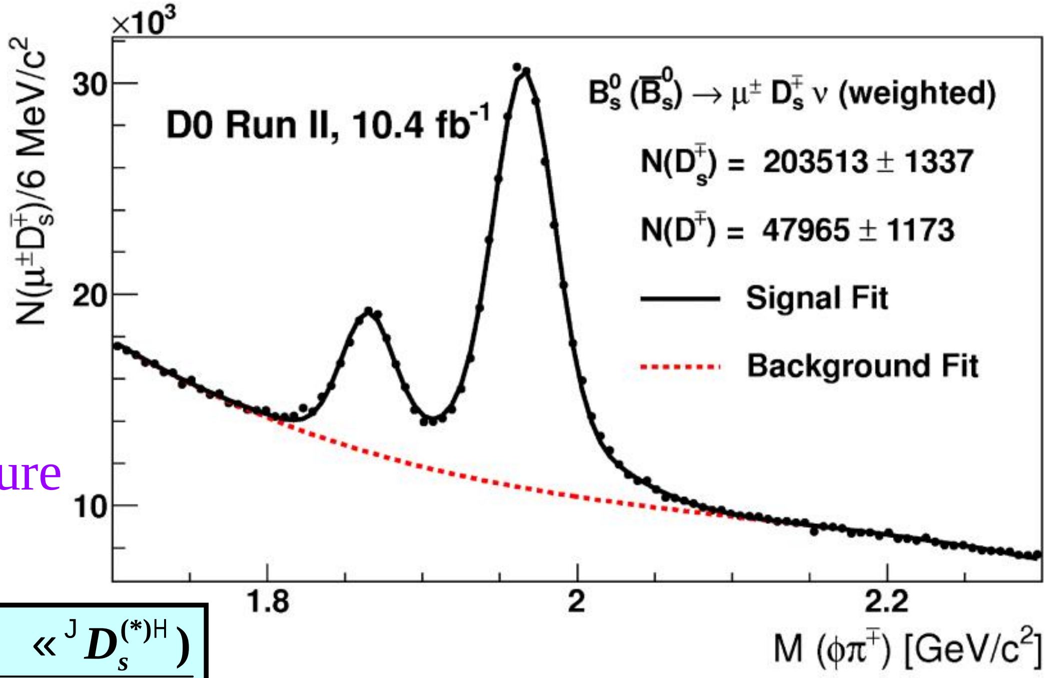
- Mean value of these measurements (my average):

$$a_{sl}^{d} = (+0.23 \pm 0.26)\%$$

- Consistent with the SM prediction

Measurement of a^s_{sl} (DØ)

- Charge asymmetry of reconstructed semileptonic B^0_s decays:
  - $B^0_s \to \mu^+ D^{(*)-}_s \nu$: ~204K events
  - $D_s \to \varphi\pi$ decay used
  - No initial flavour tagging: measure integrated asymmetry



$$A = \frac{N(B^0_s,\bar{B}^0_s \to \mu^+ D^{(*)-}_s) - N(B^0_s,\bar{B}^0_s \to \mu^- D^{(*)+}_s)}{N(B^0_s,\bar{B}^0_s \to \mu^+ D^{(*)-}_s) + N(B^0_s,\bar{B}^0_s \to \mu^- D^{(*)+}_s)}$$

and translate it into a^s_{sl}

- Reduction factor is $\chi_s \approx 0.5$

  - Reversal of magnet polarities significantly reduces systematics

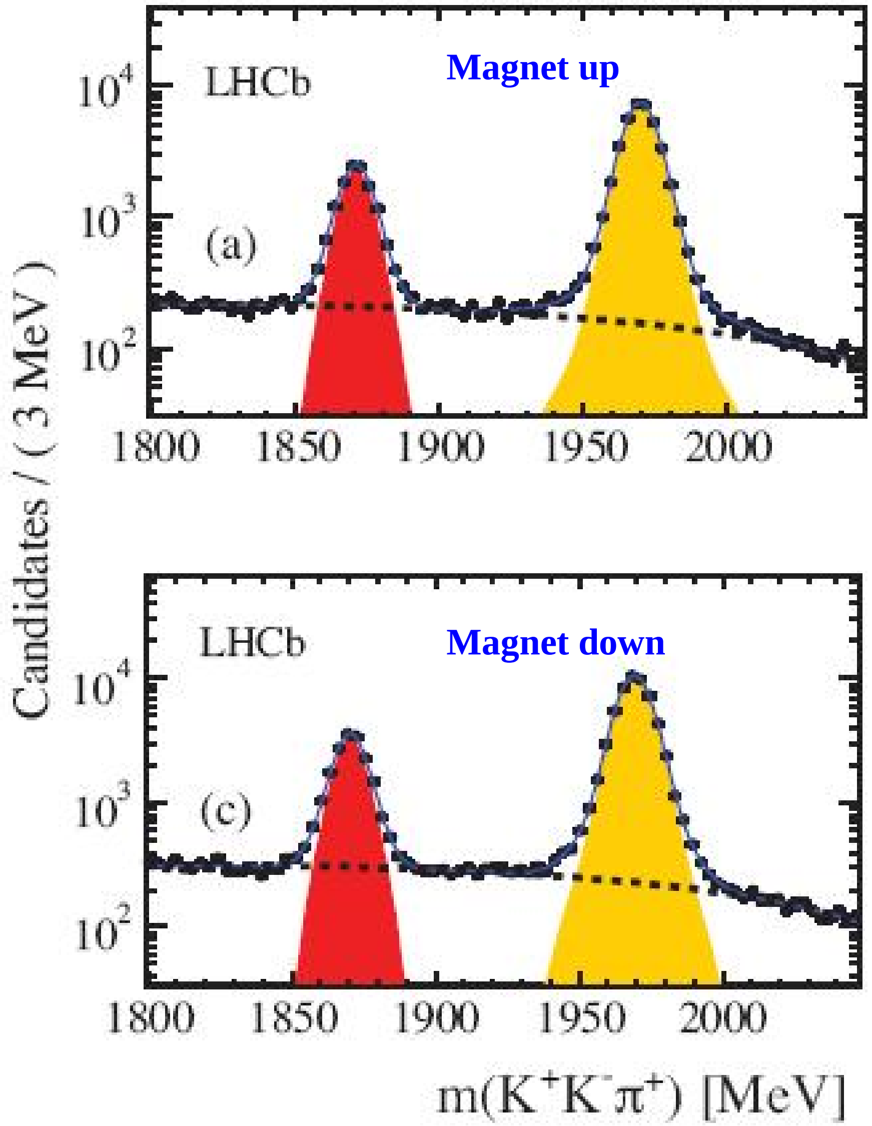
- Result: $a^s_{sl} = (-1.12 \pm 0.74 \pm 0.17)\%$ **(D0)**

Measurement of a^s_{sl} (LHCb)

- Charge asymmetry of reconstructed semileptonic B^0_s decays:
  - $B^0_s \to \mu^+ D^{(*)-}_s \nu$: ~185K events
  - Clean signal selection with low background
  - No initial flavour tagging
    - Reduction factor is $\chi_s \approx 0.5$
  - Production asymmetry is suppressed due to high oscillation frequency of B_s
  - Reversal of magnet polarities significantly reduces systematics
- Result:

a^s_{sl} Z (J0.06 ï 0.50 ï 0.36)% (LHCb)

  - arXiv: 1308.1048 [hep-exp]



Measurements of a^s_{sl}

- Combination of all available results

$$a_{sl}^{s} = (-1.12 \pm 0.74 \pm 0.17)\% \quad \text{(D0)}$$
$$a_{sl}^{s} = (-0.06 \pm 0.50 \pm 0.36)\% \quad \text{(LHCb)}$$

- Mean value of these measurements (my average):

$$a_{sl}^{s} = (-0.48 \pm 0.48)\%$$

- Consistent with the SM prediction

Dimuon charge asymmetry (DØ)

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$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- N^{++}, N^{--} − number of events with two muons of the same charge
- Measured in $p\bar{p}$ collisions so far

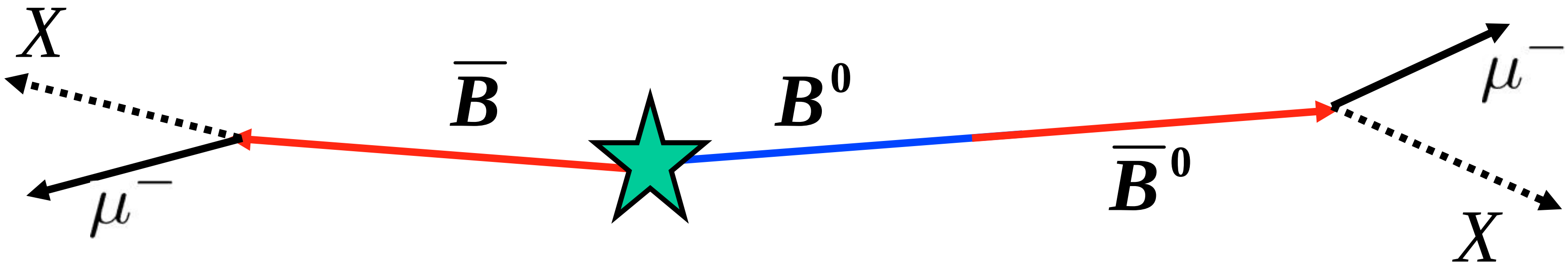
- After subtracting all possible background sources (not related to CP violation) the residual asymmetry reflects the contribution of CP-violating processes:

$$A_{CP} = A - A_{bkg}$$

- ~3.9σ deviation from the SM expectation (PRD, 84, 052007, 2011)

Contributions to dimuon charge asymmetry

- Mixing of B mesons is a natural source of dimuon pairs at $p\bar{p}$ collider → CP violation in mixing contributes to the like-sign dimuon charge asymmetry



- Considered so far as the only contribution to the like-sign dimuon charge asymmetry:

$$A_{CP} = A_{CP}^{mix}$$
$$A_{CP}^{mix} = K_d a_{sl}^d + K_s a_{sl}^s$$

  - Linear contribution from both a^d_{sl} and a^s_{sl}
  - K_d and K_s – determined by the production and decay properties of B_d and B_s

Comparison with dimuon asymmetry

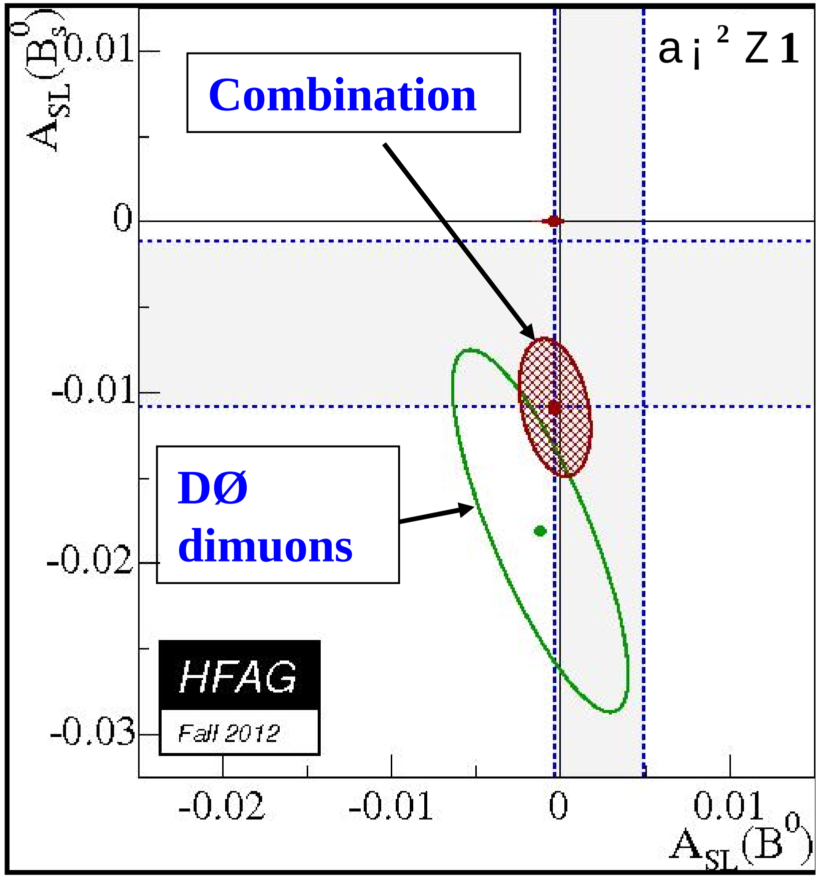
- Using only direct measurements of a^d_{sl} and a^s_{sl} we get:

A_{CP} Z (J0.024 ï 0.094)% (from a^d_{sl}, a^s_{sl})

  – to be compared with the dimuon result:

A_{CP} Z (J0.272 ï 0.092)% (from « ï « ï)

- There is some tension between these results, at about 2σ



This comparison is obsolete because a new source of the like-sign dimuon asymmetry is identified recently

Contributions to dimuon charge asymmetry

- Recently one more contribution to the like-sign dimuon charge asymmetry is identified
  - G. Borissov, B. Hoeneisen, PRD 87, 074020(2013)
- It comes from CP violation in interference of decays with and without mixing

$$A_{CP} \; \mathrm{Z} \; A_{CP}^{mix} \; \mathrm{H} \; A_{CP}^{int}$$

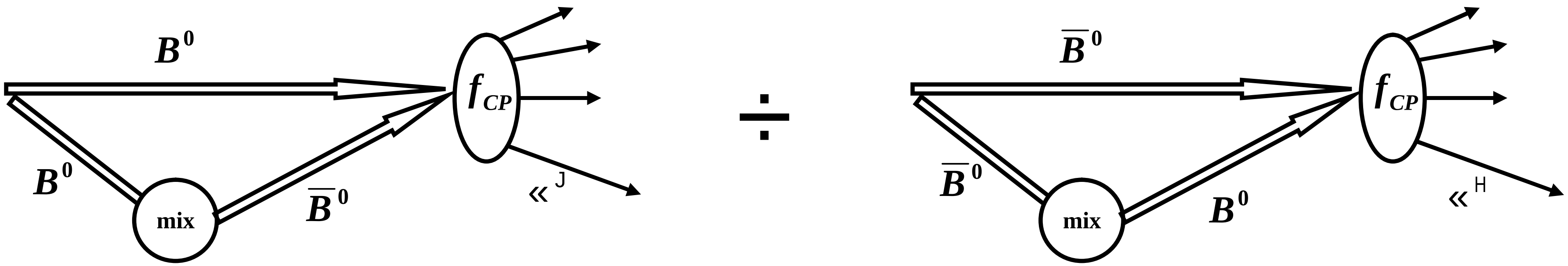
$$A_{CP}^{mix} \; \mathrm{Z} \; K_d a_{sl}^d \; \mathrm{H} \; K_s a_{sl}^s$$

$$A_{CP}^{int} \; \mathrm{Z} \; K_{\mathrm{d}} \frac{\mathrm{ad}_d}{\mathrm{d}_d}$$

  - This contribution is proportional to $\Delta\Gamma_d/\Gamma_d$
  - K_Γ – determined by the production and decay properties of B_d
  - It is much larger in magnitude than the contribution from CP violation in mixing considered so far

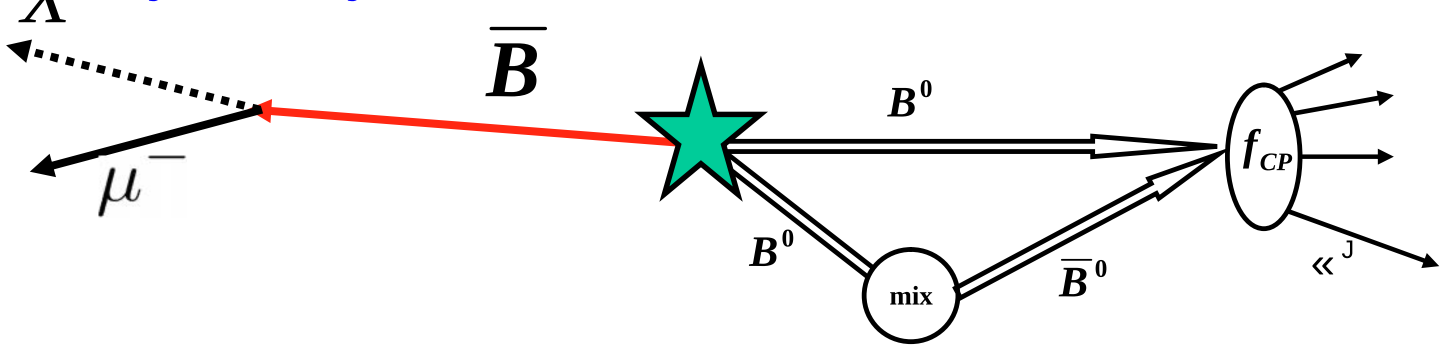
CP violation in interference

- CP violation in the interference of B^0 decay with and without mixing to the <u>same</u> CP-eigenstate final state f_{CP} which decays to muon



$$d\,(B^0 \text{ ì } f_{CP}) \div d\,(\bar{B}^0 \text{ ì } f_{CP})$$

- This type of CP violation also contributes to the dimuon asymmetry:



Example: $B^0 \to D^+D^-$

- Consider the process producing the positive like-sign dimuon pair:

$$
\begin{aligned}
&p\bar{p} \to b\bar{B}^0 X\\
&b \to \mu^+ X\\
&\bar{B}^0 \to D^+D^-; \quad D^+ \to \mu^+ X
\end{aligned}
$$

  - The state D^+D^- is CP-even and is accessible from both **B^0 and $\bar{B}^0$**
  - Both D^+ and D^- can decay to muon, but only $D^+ \to \mu^+ X$ contributes to the like-sign dimuon pair sample

- Numerically, the asymmetry is huge in magnitude and negative in sign:

$$
\frac{\Gamma(\bar{B}^0 \to D^+D^-) - \Gamma(B^0 \to D^+D^-)}{\Gamma(\bar{B}^0 \to D^+D^-) + \Gamma(B^0 \to D^+D^-)} = -\sin(2\beta)\frac{x_d}{1+x_d^2} \approx -0.328
$$

$$
x_d = \frac{\Delta m_d}{\Gamma_d}
$$

B_s meson contribution

- Contribution to the dimuon charge asymmetry:

$$A_{CP}^{int}(B^0) \approx -\sin(2\beta)\frac{x_d}{1+x_d^2}\frac{\Delta\Gamma_d}{\Gamma_d}; \quad x_d \equiv \frac{\Delta m_s}{\Gamma_d}$$

- Corresponding contribution from B_s meson is strongly suppressed:

$$A_{CP}^{int}(B_s) \approx -\sin(2\beta_s)\frac{x_s}{1+x_s^2}\frac{\Delta\Gamma_s}{\Gamma_s}; \quad x_s \equiv \frac{\Delta m_s}{\Gamma_s}$$

  – $\sin(2\beta_s) = 0.036$
  – $\Delta\Gamma_s/\Gamma_s = 0.15 \pm 0.02$
  – $x_s/(1+x_s^2) = 0.037$

Numerical values

- SM contribution to the like-sign dimuon asymmetry due to CP violation in interference of B^0 decay with and without mixing is

$$A_{CP}^{int}(SM) = (-0.035 \pm 0.008)\%$$

- To be compared with the SM contribution due to CP violation in mixing, considered so far:

$$A_{CP}^{mix}(SM) = (-0.008 \pm 0.001)\%$$

- and with the experimental value of the like-sign dimuon asymmetry:

$$A_{CP} = (-0.272 \pm 0.092)\% \quad \text{(experiment D0)}$$

Width difference of B^0

- Contribution A^{int}_{CP} is proportional to $\Delta\Gamma_d$
- Prediction of the width difference of B^0 in the SM:

$$\frac{ad_d}{d_d}(SM)\ Z\ \mathbf{0.0042}\ ï\ \mathbf{0.0008}$$

  - see A. Lenz, U. Nierste, arXiv: 1102.4274 [hep-ph]
- Experimental value is less precise:

$$\frac{ad_d}{d_d}(SM)\ Z\ \mathbf{0.015}\ ï\ \mathbf{0.018}$$

- Need a better experimental measurement of $\Delta\Gamma_d$
  - "Forgotten null test"
  - See T. Gershon, arXiv:1007.5135 [hep-ph]

Comparison of all measurements

- Dimuon charge asymmetry:

$$A_{CP} = (-0.272 \pm 0.092)\% \quad \textbf{(D0)}$$

- Using independent measurements:

$$A_{CP} = K_d a^d_{sl} + K_s a^s_{sl} + K_\Gamma \frac{\Delta\Gamma_d}{\Gamma_d}$$

  - a^d_{sl} = (0.23 ± 0.26)% (my average)
  - a^s_{sl} = (−0.48 ± 0.48)% (my average)
  - $\Delta\Gamma_d / \Gamma_d$ = (1.5 ± 1.8)% (World average, PDG-2013)

$$A_{CP} = (-0.147 \pm 0.175)\% \quad \textbf{(Independent measurements)}$$

  - Results are consistent within 1σ
  - Precision is determined by the width difference of $\Delta\Gamma_d / \Gamma_d$
  - Need to improve the precision of $\Delta\Gamma_d / \Gamma_d$

Final result on dimuon asymmetry (DØ)

- D0 collaboration prepares the final result on the dimuon asymmetry
  - Full statistics
  - Complete analysis of the dependence of asymmetry on muon impact parameter
  - Model-independent result on A_{CP}
  - Provides an independent measurement of a^d_{sl} , a^d_{sl} , $\Delta\Gamma_d / \Gamma_d$
  - Will be available soon (hopefully)

Conclusions

- Study of CP violation in mixing – a very active research area
- Several new results (D0, LHCb, BaBar) became available recently
- ~3.8σ deviation from the SM expectation in the dimuon charge asymmetry
- Independent measurements of a^d_{sl} , a^d_{sl} , $\Delta\Gamma_d / \Gamma_d$ are consistent with the dimuon asymmetry within 1σ
- This comparison depends on the value of $\Delta\Gamma_d / \Gamma_d$ which is known with poor precision
- New measurements of this "forgotten" parameter are required