Measurement of CP Violation in B^0-$\overline{B^0}$ mixing @ LHCb

1) What do we want to measure?

<u>Reminder</u> from the previous lectures

(a) Neutral meson mixing

$$i \frac{d}{dt} \begin{pmatrix} |B^0\rangle \\ |\overline{B^0}\rangle \end{pmatrix} = \left(M - i\frac{\Gamma}{2} \right) \begin{pmatrix} |B^0\rangle \\ |\overline{B^0}\rangle \end{pmatrix}$$

$$|B_L\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$$

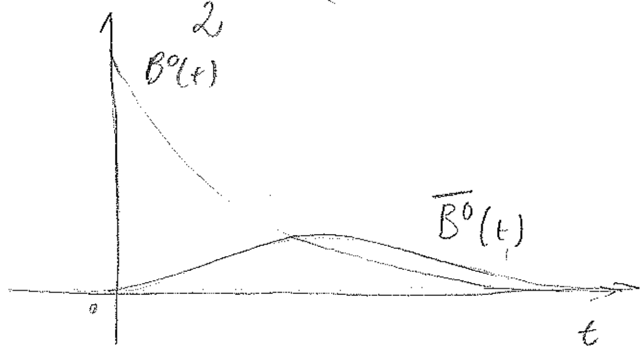
(b) we can define the mixing observables:

$\Delta m = m_H - m_L$ mixing frequency

$\Delta\Gamma = \Gamma_L - \Gamma_H$ decay width difference

we can calculate the probability:

$$|\langle \overline{B^0} | B^0(t) \rangle|^2 = \frac{e^{-\Gamma t}}{2} \left(1 - \cos(\Delta m_d t)\right) \left|\frac{q}{p}\right|^2$$



(c) CP violation in mixing:

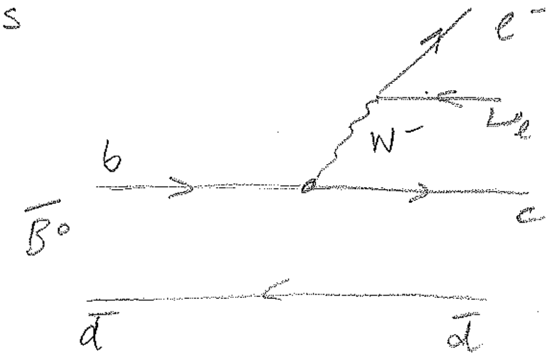
$$\text{Prob}(B^0 \to \overline{B^0}) \overset{?}{=} \text{Prob}(\overline{B^0} \to B^0)$$

Given a $\overset{(-)}{B^0}$ sample, we are therefore interested in measure the asymmetry:

$$a = \frac{N(\overline{B^0} \to B^0) - N(B^0 \to \overline{B^0})}{N(\overline{B^0} \to B^0) + N(B^0 \to \overline{B^0})}$$

<u>2 Problems</u>: Flavor of the B^0 meson at the Production and flavor of the B^0 meson at the decay

2) Flavor of the B^0 meson at the decay: Semileptonic decays



Relevant Feature: They are flavor specific

$B \longrightarrow f$

$\bar{B} \not\longrightarrow f$

$\to B$

with f final state.

We can than write the asymmetry we are interested in:

$$a_{sl}^d = \frac{\Gamma(\bar{B}^0 \to B^0 \to f) - \Gamma(B^0 \to \bar{B}^0 \to f)}{\Gamma(\bar{B}^0 \to B^0 \to f) + \Gamma(B^0 \to \bar{B}^0 \to f)}$$

The lower index "sl" refers to the semileptonic nature of the decays. (sometimes we refer to the same asymmetry with the "fs" index, standing for "flavor specific".

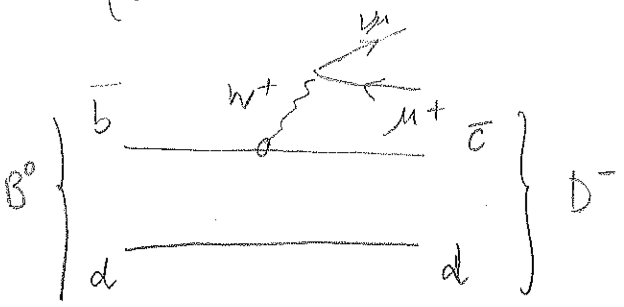
Experimentally it is very convenient to use semileptonic decays, given the high statistics of the samples. The Standard Model predictions for a_{sl}^d are indeed very small:

$$a_{sl}^d = (-4.1 \pm 0.6) \cdot 10^{-4}$$

To introduce an example of decays suitable for this measurement: $B^0 \to D^- \mu^+ \nu_\mu$

(a second example: $B^0 \to D^{*-} \mu^+ \nu_\mu$)

$$\left[\begin{array}{l} D^- = d\bar{c} \\ D^+ = \bar{d}c \\ D^0 = c\bar{u} \\ \bar{D}^0 = \bar{c}u \end{array}\right]$$



3) Flavor of the B^0 meson at the decay: (A) Method used at LHCb

It is possible to identify the flavor of the B^0 meson at the production (we have seen an example of "flavor tagging" in the second lecture: it can be inferred from the particles produced in association to the decay of interest, or, given the $b\bar{b}$ quarks produced always in pairs, from the decay products of a B meson, the flavor of the other B meson can be understood)

But the flavor tagging is non very efficient at hadron colliders. It is preferred to use the so called "untagged" decay rates:

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

The final state charge asymmetry will be:

$$A_{meas}(t) = \frac{\Gamma(\overbrace{D^-\mu^+}^{f}, t) - \Gamma(\overbrace{D^+\mu^-}^{\bar{f}}, t)}{\Gamma(D^-\mu^+, t) + \Gamma(D^+\mu^-, t)} = \frac{a_{sl}^d}{2} - \frac{a_{sl}^d}{2}\cos(\Delta m t)$$

Using already $f = D^-\mu^+$ and $\bar{f} = D^+\mu^-$ as in the example.

The rigorous derivation of this relation should be carried out by explicitely writing the decay rates (see U. Nierste arXiv:0904.1869v1) but it is possible to get an idea about why this behavior is expected:

$$A_{meas}(t) = \frac{\Gamma(\bar{B} \to f)(t) + \Gamma(B \to f)(t) - \Gamma(\bar{B} \to \bar{f})(t) - \Gamma(B \to \bar{f})(t)}{\Gamma_{all}(t)}$$

$$= \frac{\boxed{\Gamma(\bar{B} \to f)(t) - \Gamma(B \to \bar{f})(t)} + \underbrace{\boxed{\Gamma(B \to f)(t) - \Gamma(\bar{B} \to \bar{f})(t)}}_{=0 \text{ because NO CPV in decay}}}{\Gamma_{all}(t)}$$

$\to$ using the definition of a_{sl}: $\Gamma(\bar{B} \to f) - \Gamma(B \to \bar{f}) = a_{sl}\,\Gamma_{mixed}$

Here we indicate with Γ_{mixed} the decays where $B \to \bar{B}$ or $\bar{B} \to B$ oscillation had occurred

$$A_{meas}(t) = \frac{a_{sl} \cdot \Gamma_{mixed}(t)}{\Gamma_{all}(t)}$$

From neutral meson oscillation:

$$\frac{\Gamma_{unmixed}(t) - \Gamma_{mixed}(t)}{\Gamma_{all}(t)} = \cos(\Delta m t)$$

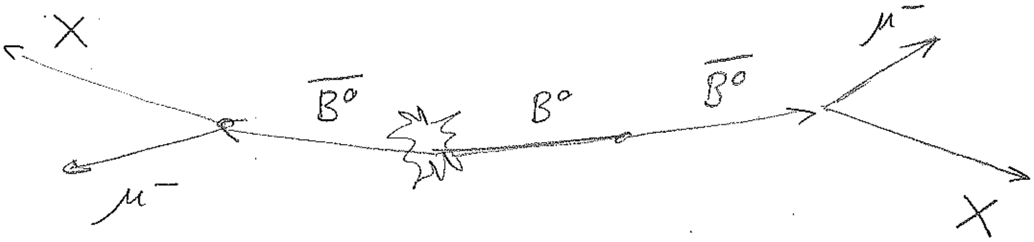
$$\frac{\Gamma_{mixed}(t)}{\Gamma_{all}(t)} = \frac{1}{2} - \frac{1}{2}\cos(\Delta m t)$$

This brings to:

$$A_{meas}(t) \simeq \frac{a_{sl}}{2} - \frac{a_{sl}}{2}\cos(\Delta m t)$$

In summary: by measuring the charge asymmetry of the final state particles, we should be able to determine the a_{sl}^{d} parameter. This is the method used @ LHCb. other methods? (B)

Yes: For example the inclusive like-sign dilepton asymmetry:



$$A_{ee} = \frac{N(e^+e^+) - N(e^-e^-)}{N(e^+e^+) + N(e^-e^-)} = a_{sl}$$

Experimental results obtained before LHCb?

Experimental Status at 2010

"Evidence for an Anomalous Like-Sign Dimuon Charge asymmetry" DØ Collaboration (PRL 105, 081801)

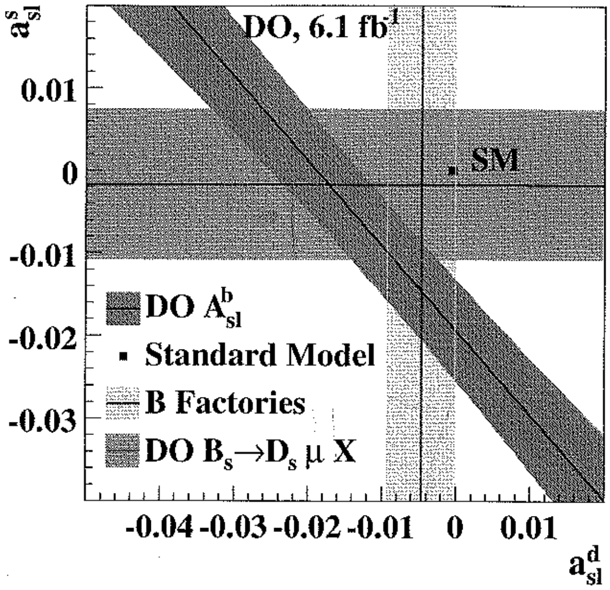
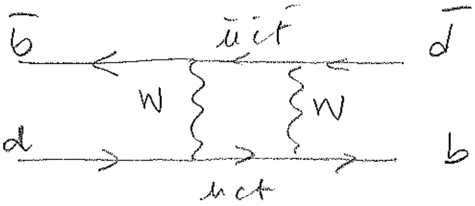


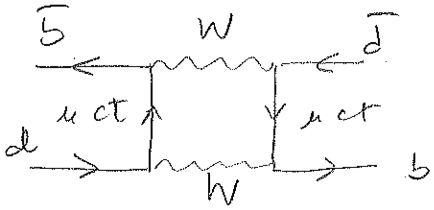
FIG. 3 (color online). Comparison of A^b_{sl} in data with the SM prediction for a^d_{sl} and a^s_{sl}. Also shown are other measurements of $a^d_{sl} = -0.0047 \pm 0.0046$ [16–18] and $a^s_{sl} = -0.0017 \pm 0.0091$ [19]. The bands represent the ± 1 standard deviation uncertainties on each measurement.

The value of A^b_{sl} was measured to be at 3.2σ from the SM prediction –

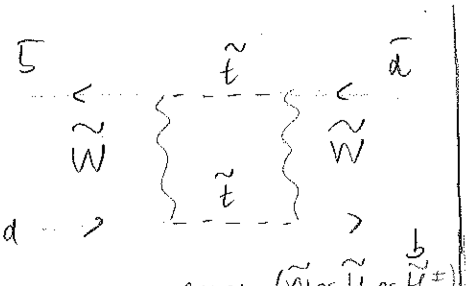
New Physics ?

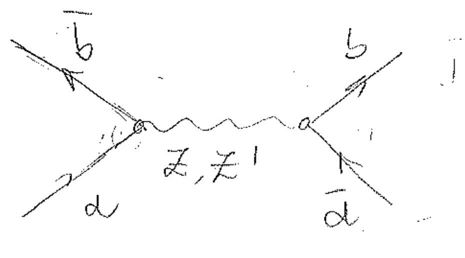
Of the SM diagrams look like :

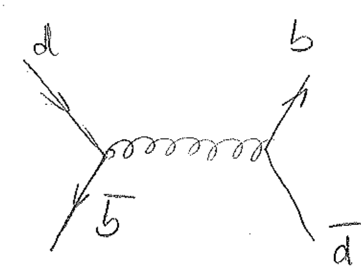




In super symmetry scenarios we could have different particles in the box diagram. Or we can imagine extra-dimension scenarios, where the transition could be also at tree level :







susy ($\tilde{W}$ or $\tilde{H}$, or $\tilde{H}^\pm$) summarized in arXiv:1402.6677

Tree level gauge boson exchange (arXiv:1306.3775)

Extra dimensions arXiv:0809.1073, 0912.1625

Other models: arXiv:1111.5014, arXiv:0605214

Now, more precise measurements are needed, also of the individual asymmetries a^s_{sl} ($B^0_s - \bar{B}^0_s$ mixing) and a^d_{sl} (B^0 system)

Current experimental status: the DØ ~3σ discrepancy is still there. New measurements contribute to the picture.

Recent review of the theory status: A. Lenz, CKM Proceeding (arXiv:1409.6963)

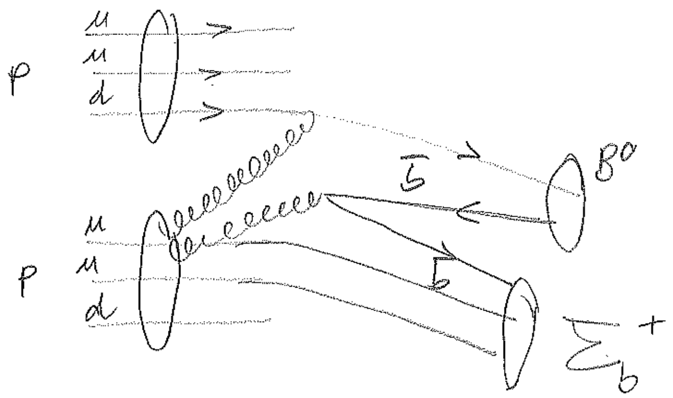
Coming back to LHCb :

$$A_{meas}(t) = \frac{a_{sl}^d}{2} - \frac{a_{sl}^d}{2}\cos(\Delta m t)$$

But the equation above does not account for the two major issues of this measurement : the $B^0-\overline{B^0}$ meson production asymmetry and the detection asymmetry of the final state particles.

4) $B^0-\overline{B^0}$ production asymmetry

Problem : the $b\overline{b}$ production is always symmetric, but the $B^0\overline{B^0}$ production is not at LHCb.



The hadronization of b and $\overline{b}$ is different. Example mechanism

We define $$A_P \equiv \frac{\sigma(\overline{B^0}) - \sigma(B^0)}{\sigma(\overline{B^0}) + \sigma(B^0)}$$, representing the B^0 production asymmetry in the selected kinematic region. The measured charge asymmetry becomes:

$$A_{meas}(t) = \frac{a_{sl}^d}{2} - \left(A_P + \frac{a_{sl}^d}{2}\right)\cos(\Delta m_d t)$$

A_P enters in the amplitude of the oscillating term, since it affects the initial state $(B^0\overline{B^0})$. Correcting the not rigorous calculation made before:

$$A_{meas}(t) = \frac{\underbrace{\boxed{\Gamma(\bar{B}\to f)(t) - \Gamma(B\to \bar{f})(t)}}_{= a_{sl}\cdot\Gamma_{mixed}(t) + A_P\,\Gamma_{mixed}(t)} + \underbrace{\boxed{\Gamma(B\to f)(t) - \Gamma(\bar{B}\to \bar{f})(t)}}_{= -A_P\cdot\Gamma_{unmix}(t)}}{\Gamma_{all}(t)}$$

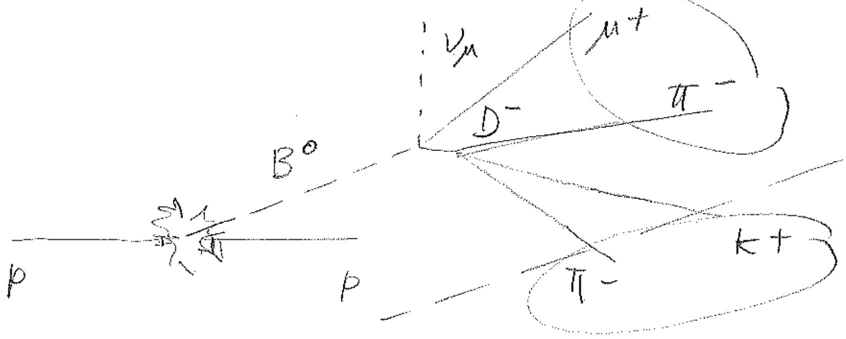
$$= \frac{a_{sl}\cdot\Gamma_{mixed}(t)}{\Gamma_{all}(t)} + \frac{A_P\,\Gamma_{mixed}(t)}{\Gamma_{all}(t)} - \frac{A_P\,(\Gamma_{all}(t) - \Gamma_{mixed}(t))}{\Gamma_{all}(t)}$$

$$= (a_{sl} + 2A_P)\left(\frac{1}{2} - \frac{1}{2}\cos(\Delta m t)\right) - A_P$$

$$= \frac{a_{sl}}{2} - \left(A_P + \frac{a_{sl}}{2}\right)\cos(\Delta m t)$$

Solution: A_P is another parameter determined in this analysis, together with a_{sl}^d by means of the same Maximum Likelihood fit.

5) Detection asymmetries



decays used in this measurement.

Cabibbo favored $D^-\to k^+\pi^-\pi^-$ decays, direct (in decay) CPV assumed to be negligible

Problem: The origin of different detection efficiencies between positively and negatively charged particles can be ascribed to the different interaction of the particles with the detector material and to inefficiencies of the detector itself. We define:

$$A_D = \frac{\varepsilon(\mu^+\pi^-k^+\pi^-) - \varepsilon(\mu^-\pi^+k^-\pi^+)}{\varepsilon(\mu^+\pi^-k^+\pi^-) + \varepsilon(\mu^-\pi^+k^-\pi^+)}$$

Solution: A_D has to be determined independently from the determination of a_{sl}^d and data-driven techniques need to be used.

For convenience we split the final state in two parts: $k\pi$ and $\mu\pi$

$$A_D = \underbrace{A_{\mu\pi}}_{\text{small}} + \underbrace{A_{K\pi}}_{\sim 1\%} \text{ (mainly due to the } K^+ \text{ nuclear interaction)}$$

Let's discuss about the $A_{K\pi}$: To evaluate it we use two control samples :

$$
\begin{aligned}
A(K^+\pi^-) = {} & A\,(D^- \to K^+\pi^-\pi^-) \\
& - A\,(D^- \to \overline{K}^0 \pi^-) \\
& - A\,(\overline{K}^0)
\end{aligned}
$$

arXiv:1405.2797

The charge asymmetry of the first control sample contains the detection asymmetry of the desired $K\pi$ pair, but it has to be corrected for the D meson production asymmetry and the detection asymmetry of the additional pion. The asymmetry of the second sample ($D^- \to \overline{K}^0\pi^-$), together with the asymmetry due to the neutral kaon interaction $A(\overline{K}^0)$ is the correction needed.

A kinematic re-weighting procedure is needed, in order to match the $K\pi$ pair of the control sample to the $K\pi$ pair kinematics of the signal sample.

Also the $A_{\mu\pi}$ contribution to A_D is determined by means of data-driven techniques (refer to the paper: arXiv:1409.8586)

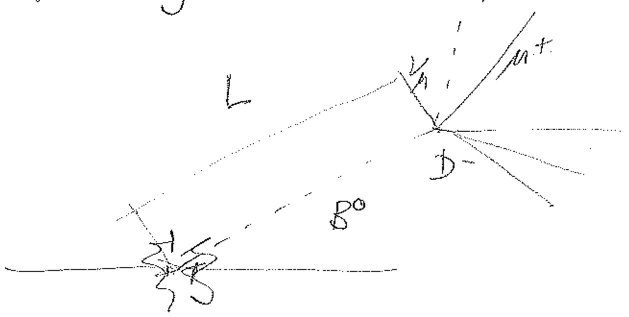
A_D is used as input for the determination of a_{sl}^d and A_P:

$$A_{meas}(t) = \frac{a_{sl}}{2} + A_D - \left(A_P + \frac{a_{sl}^d}{2}\right)\cos(\Delta m_d t)$$

The uncertainty on A_D represents the leading systematic uncertainty on a_{sl}^d.

Last set of challenges: we are performing a time dependent analysis with partially reconstructed decays (we miss at least the ν_μ). Main challenges due to the partial reconstruction are to correctly describe the decay time distributions and to separate signal from background decays

6) Decay time description:



$$t = \frac{L\gamma}{\beta} = \frac{L \cdot M}{|\vec{p}|}$$

it will be wrong because of the partial reconstruction

use M_{PDG}

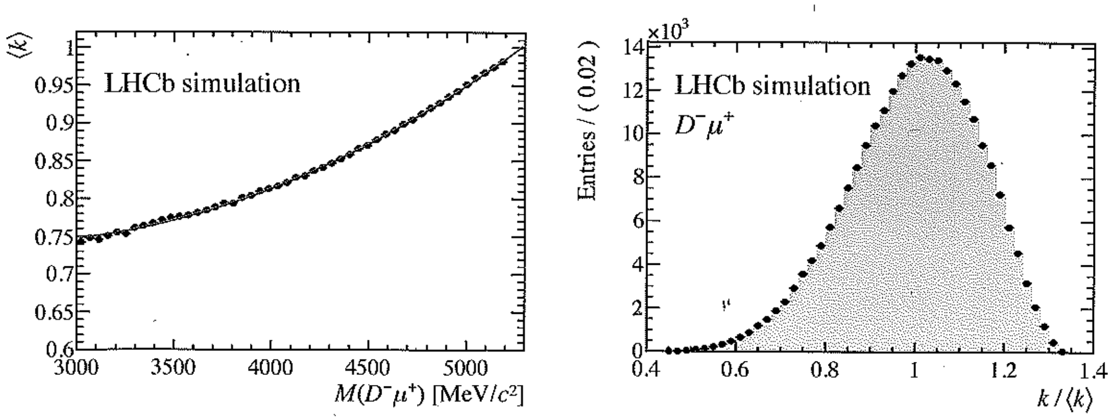
Need to rely on Monte Carlo

* we define $k = \frac{|P_{reco}|}{|P_{true}|}$

* we use an average k-Factor in function of the visible mass (reconstructed B^0 mass) to correct the B^0 decay time

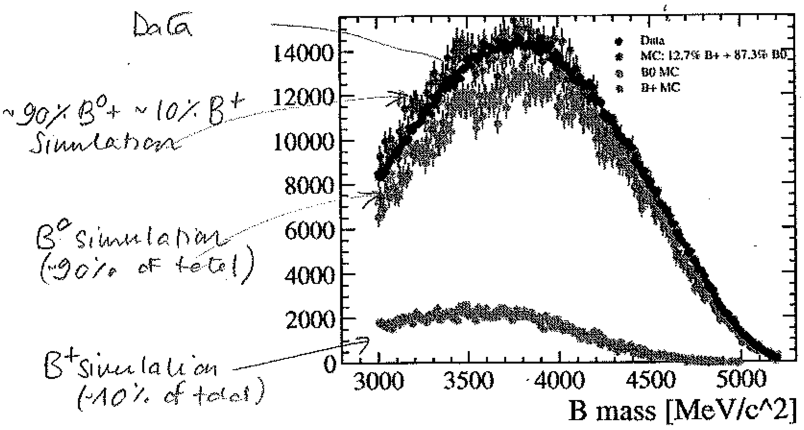
$$t = \frac{L \cdot M}{|\vec{p}|} \langle k \rangle$$

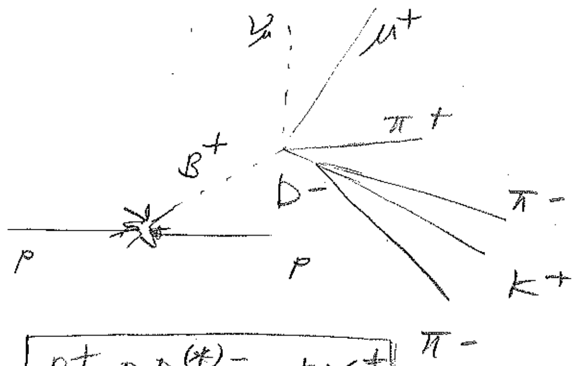
* the k-factor distribution (corrected by $\langle k \rangle$) is used as resolution function, in addition to the resolution on the flight distance, in the time depedent fit



7) "Peaking" background

Due to the partial reconstruction, the B meson mass is not a good variable to distinguish signal decays wrt background decays. In particular decays like:





$\boxed{B^+ \to D^{(*)-} \mu^+ X^+}$

(where the additional π^+ is not reconstructed), look very much like the signal decays. This background is about 10% of the data sample. In the published analysis shapes and fraction are taken from Monte Carlo. The production asymmetry assumed for the B^+ meson is:

$A_P(B^+) = (-0.6 \pm 0.6)\%$ taken from the asymmetry observed in $B^+ \to J/\psi K^+$ decays (arXiv: 1408.0978), corrected by the CP asymmetry (PDG, Chin Phys. C38 (2014) 090001)

This background is the second largest systematic, the leading systematic is due to the detection asymmetries uncertainty (statistical and systematic).

Systematics related to the decay time description give a smaller contribution.

TABLE I. Systematic uncertainties (in %) on a^d_{sl} and A_P for 7 and 8 TeV pp centre-of-mass energies. Entries marked with – are found to be negligible.

Source of uncertainty	a^d_{sl}	A_P(7 TeV)	A_P(8 TeV)
Detection asymmetry	0.26	0.20	0.14
B^+ background	0.13	0.06	0.06
Λ^0_b background	0.07	0.03	0.03
B^0_s background	0.03	0.01	0.01
Combinatorial D background	0.03	–	–
k-factor distribution	0.03	0.01	0.01
Decay-time acceptance	0.03	0.07	0.07
Knowledge of Δm_d	0.02	0.01	0.01
Quadratic sum	0.30	0.22	0.17

8) Results:

The values of a_{sl}^d and A_P are extracted by means of a maximum likelihood fit to the D^- (or $\bar{D}^0$) mass, B decay time and final state

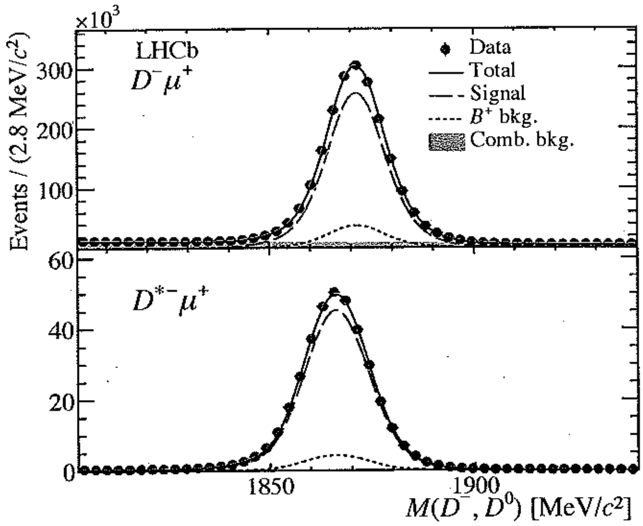


FIG. 1. Mass distributions after weighting of (top) D^- candidates in the $D^-\mu^+$ sample and of (bottom) D^{*-} candidates in the $D^{*-}\mu^+$ sample, with fit results overlaid.

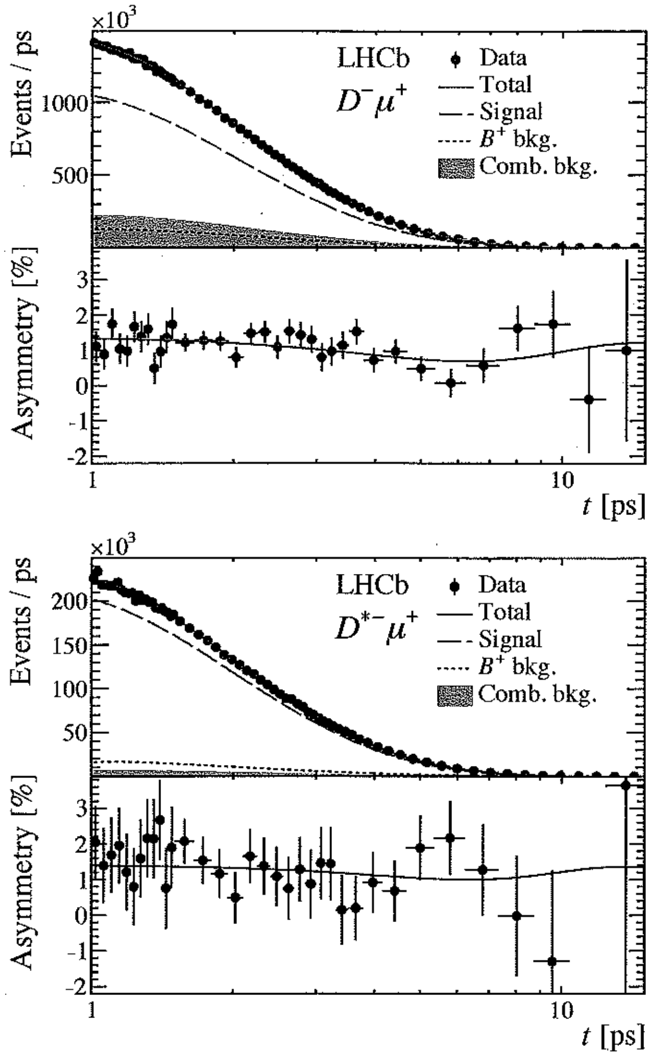


FIG. 2. Decay rate and charge asymmetry after weighting versus decay time for (top) the $D^-\mu^+$ sample and (bottom) the $D^{*-}\mu^+$ sample. The data from the two run periods and magnet polarities are combined and the fit results are overlaid. The number of bins in the asymmetry plots is reduced for clarity.

charge. You find here the projections of the fits, for the 2 decay modes used ($B^0 \to D^-\mu^+\nu_\mu$, which we have taken as example and gives most of the statistics, and $B^0 \to D^{*-}(\to \bar{D}^0\pi^-)\mu^+\nu_\mu$)

The analysis is performed separately for the 7 TeV and 8 TeV center of mass energies and for the two magnet polarities of LHCb (recall LHCb detector... JINST 3 (2008) S08005). The results for a_{sl}^d and A_P are than combined. We obtain: (arXiv: 1409.8586)

$$a_{sl}^d = (-0.02 \pm 0.19\,(\text{stat}) \pm 0.30\,(\text{syst}))\,\%$$

$$A_P\,(7\,\text{TeV}) = (-0.66 \pm 0.26\,(\text{stat}) \pm 0.22\,(\text{syst}))\,\%$$

$$A_P\,(8\,\text{TeV}) = (-0.48 \pm 0.15\,(\text{stat}) \pm 0.17\,(\text{syst}))\,\%$$

On the next page the current experimental picture

LHCb measurements of a_{sl}^d and a_{sl}^s are in agreement with the Standard Model predictions, and they are the current most precise measurements of these quantities from a single experiment.

The precision is not enough yet to exclude the DØ result.