Measurements of *b*-flavoured hadron lifetimes at LHCb

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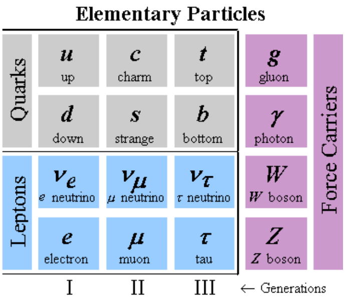
IMPRS-PTFS seminar - May, 08th 2014

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

What is a *b*-flavoured hadron?



We want to measure the lifetime of several hadrons that contains one *b* quark.

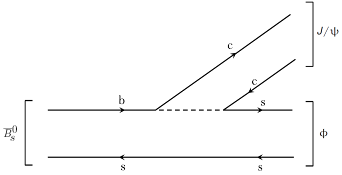
Three mesons (quark-antiquark):

- $B^+ = u\overline{b}$ and $B^- = \overline{u}b$
- $B^0 = d\overline{b}$ and $\overline{B}^0 = \overline{d}b$
- $B_s^0 = s\overline{b}$ and $\overline{B}_s^0 = \overline{s}b$

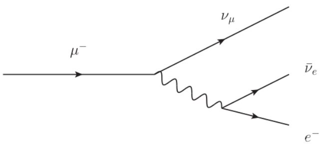
One baryon (three quarks):

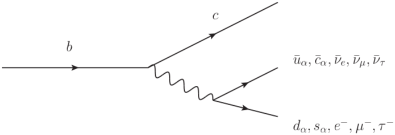
- $\Lambda_b^0 = udb$ and $\overline{\Lambda}_b^0 = \overline{udb}$

Theoretical status of *b*-flavoured hadron lifetimes



Lifetimes of heavy hadrons are dominated by the weak decay of the *b*-quark: **spectator model**.





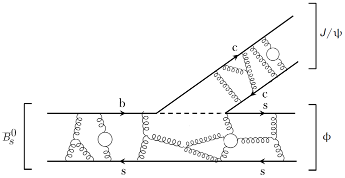
The calculations for the Feynman diagram for the B meson width and the muon width are very similar.

- μ mass $\Longrightarrow$ *b* quark mass;
- different coupling μ - ν $\Longrightarrow$ *b* - *c*
- Phase space $\Longrightarrow$ 9 times bigger for *b* quarks.

The lifetime of the *b*-hadron can be predicted from the muon lifetime: $1.3 < \tau_B[\mathrm{ps}] < 1.6$.

Theoretical status of *b*-flavoured hadron lifetimes

Different B species have distinct lifetimes $\Longrightarrow$ light quarks cannot be ignored.



Predictions made from series expansion (convergence due to $m_b > \Lambda_{QCD}$)

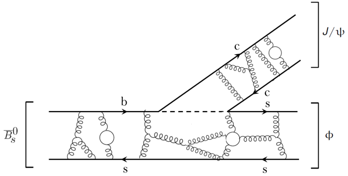
$\hookrightarrow$ **Heavy Quark Expansion (HQE)**

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \ldots$$

- decay of a free heavy b-quark: $\tau_{B_d^0} \sim \tau_{B^+} \sim \tau_{B_s^0} \sim \tau_{\Lambda_b^0}$
- separation between mesons and baryons: $\tau_{B^+} \sim \tau_{B_d^0} \sim \tau_{B_s^0} > \tau_{\Lambda_b^0}$
- spectator quark/s involved: $\tau_{B^+} > \tau_{B_d^0} \sim \tau_{B_s^0} > \tau_{\Lambda_b^0}$

Theoretical status of *b*-flavoured hadron lifetimes

- The study of the b-hadron lifetimes is a good probe of QCD predictions.



Most precise predictions in lifetime ratios:

$$\frac{\tau_1}{\tau_2} = 1 + \frac{\Lambda^2}{m_b^2}\Gamma_2' + \frac{\Lambda^3}{m_b^3}\Gamma_3' + \ldots$$

Numerical values

$$\frac{\tau_{B^+}}{\tau_{B_d^0}} = 1.063 \pm 0.027 \qquad \frac{\tau_{B_s^0}}{\tau_{B_d^0}} = 1.00 \pm 0.01 \qquad \frac{\tau_{\Lambda_b^0}}{\tau_{B_d^0}} = 0.88 \pm 0.05$$

[A. Lenz, Nucl.Phys.Proc.Suppl.**177-178:81-86,2008**]

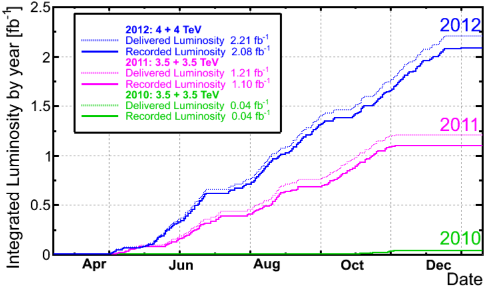
Data used for the analysis

This analysis is based on data collected by the LHCb detector in 2011, corresponding to $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

This means:

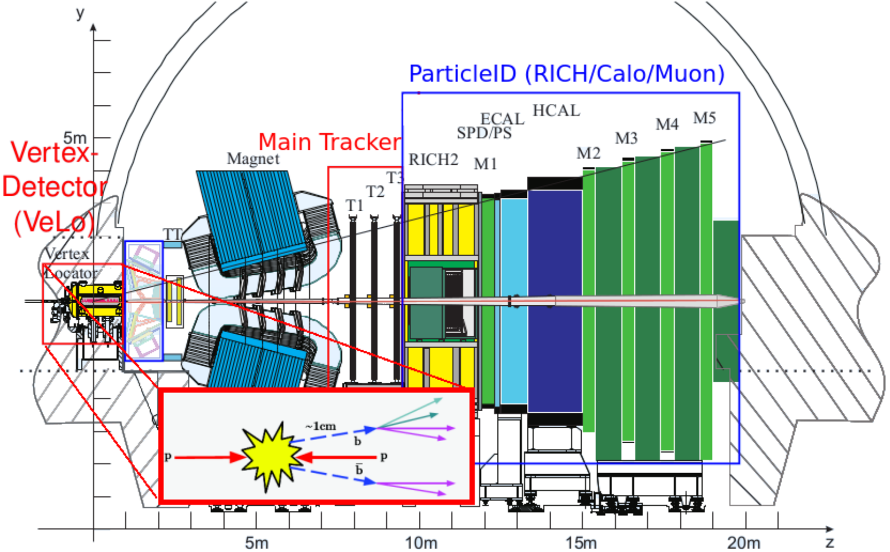
- $\sim 230000\ B^+ \to J/\psi K^+$
- $\sim 70000\ B^0 \to J/\psi K^*(892)^0$
- $\sim 17000\ B^0 \to J/\psi K^0_S$
- $\sim 19000\ B^0_s \to J/\psi \phi$
- $\sim 4000\ \Lambda_b \to J/\psi \Lambda$

reconstructed signal candidates.

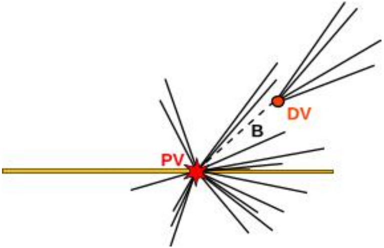


We use: $J/\psi \to \mu^\pm\mu^\mp$, $K^*(892)^0 \to K^\pm\pi^\mp$, $K^0_S \to \pi^\pm\pi^\mp$, $\phi \to K^\pm K^\mp$ and $\Lambda \to \pi^\pm p^\mp$.

The LHCb detector

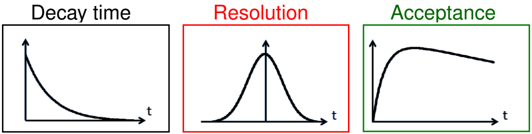


How to experimentally measure lifetimes



$$t = \frac{(\mathrm{DV}-\mathrm{PV})}{\beta\gamma} = \frac{(\mathrm{DV}-\mathrm{PV})\cdot Mass_{B/\Lambda_b}}{p}$$

In principle very easy to measure:



$$\text{Measured distribution} = \left[e^{\frac{-t}{\tau}} \otimes \mathrm{Res}(t, t')\right] \cdot \mathrm{Acc}(t')$$

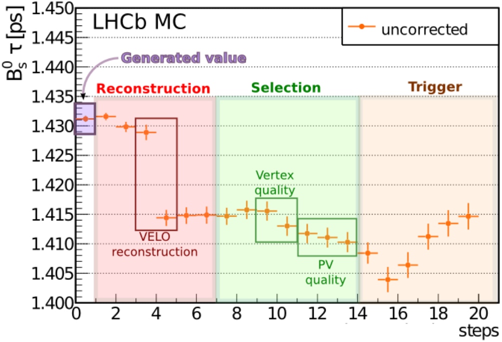
But... given the statistical precision of few fs:

- time-dependent acceptance must be controlled to a very accurate level;
- we cannot rely on simulations to keep small systematic uncertainties.

Where does the time-dependent acceptance come from?

From now on I will mainly take $B_s^0 \to J/\psi\phi$ as a prototype.

MC lifetime for various reconstruction and selection requirements.



The **major sources** are:

- VELO reconstruction (step 4);
- Selection on the quality of the ϕ vertex (step 10);
- *PV* reconstruction (steps 11-13);
- Trigger (steps 14-19).

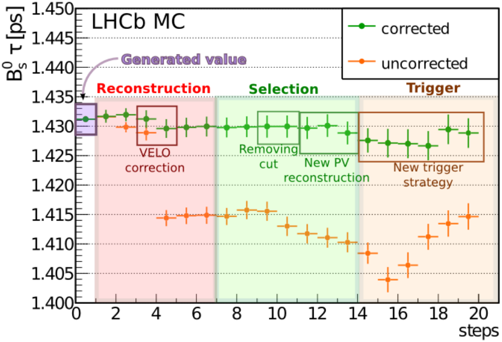
This corresponds to $\Delta\tau \sim 20$ fs

Strategy: remove bias in simulation and use same method on data.

Overview of the corrections done

- Remaining bias no longer statistically significant.
- The same strategy can be applied on data without using simulated data.

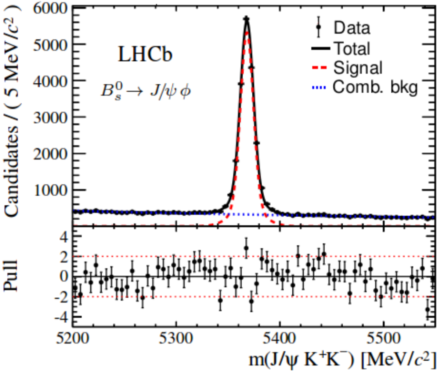
MC lifetime for various reconstruction and selection requirements.



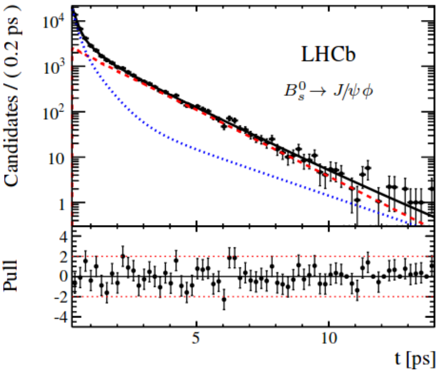
Fit projections for the B_s^0 lifetime

The lifetime is extracted by mean of an unbinned Maximum Likelihood fit in 2D:

b-hadron mass



b-hadron decay time



Lifetime results

Results for the B^+, B^0, B_s^0 mesons and Λ_b^0 baryon lifetimes and lifetime ratios.

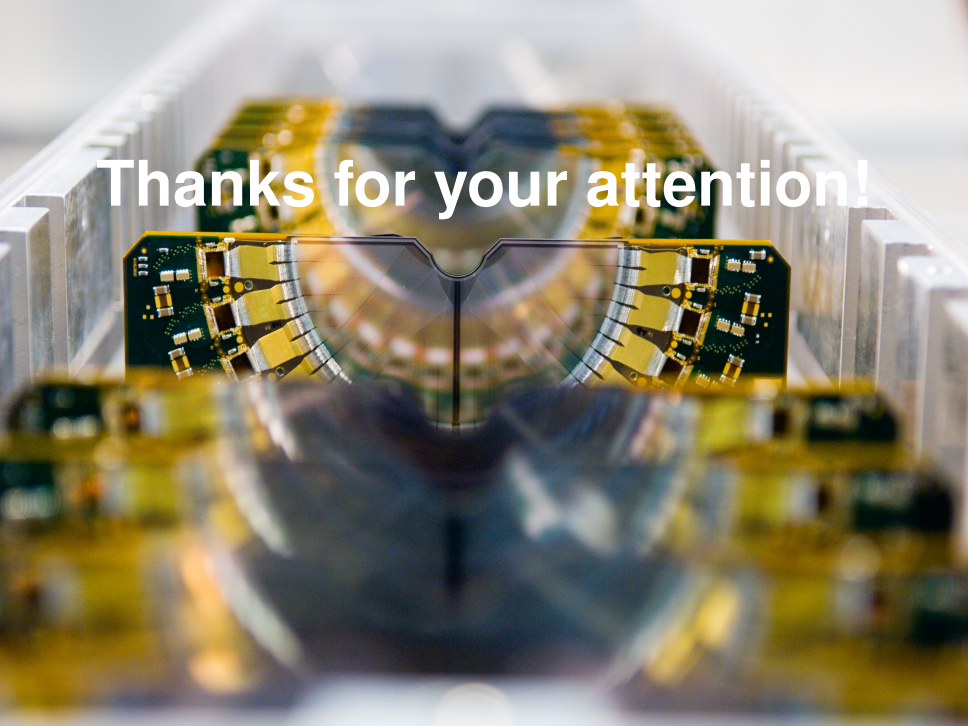
Lifetime	Value [ps]	World average 2013 [ps]
$\tau_{B^+ \to J/\psi K^+}$	$1.637 \pm 0.004 \pm 0.003$	1.641 ± 0.008
$\tau_{B^0 \to J/\psi K^*(892)^0}$	$1.524 \pm 0.006 \pm 0.004$	1.519 ± 0.007
$\tau_{B^0 \to J/\psi K_S^0}$	$1.499 \pm 0.013 \pm 0.005$	1.519 ± 0.007
$\tau_{\Lambda_b^0 \to J/\psi \Lambda}$	$1.415 \pm 0.027 \pm 0.006$	1.429 ± 0.024
$\tau_{B_s^0 \to J/\psi \phi}$	$1.480 \pm 0.011 \pm 0.005$	1.429 ± 0.088

- From a theoretical point of view lifetime ratios are robust quantities $\Rightarrow$ **test of HQE**.
- Particle and antiparticle lifetimes ratio $\Rightarrow$ **test of CPT**

Ratio	Value
$\tau_{B^+} / \tau_{B^0 \to J/\psi K^{*0}}$	$1.074 \pm 0.005 \pm 0.003$
$\tau_{B_s^0 \to J/\psi \phi} / \tau_{B^0 \to J/\psi K^{*0}}$	$0.971 \pm 0.008 \pm 0.004$
$\tau_{\Lambda_b^0} / \tau_{B^0 \to J/\psi K^{*0}}$	$0.929 \pm 0.018 \pm 0.004$
τ_{B^+} / τ_{B^-}	$1.002 \pm 0.004 \pm 0.002$
$\tau_{\Lambda_b^0} / \tau_{\overline{\Lambda}_b^0}$	$0.940 \pm 0.035 \pm 0.005$
$\tau_{B^0 \to J/\psi K^{*0}} / \tau_{\overline{B}^0 \to J/\psi \overline{K}^{*0}}$	$1.000 \pm 0.008 \pm 0.003$

Conclusions

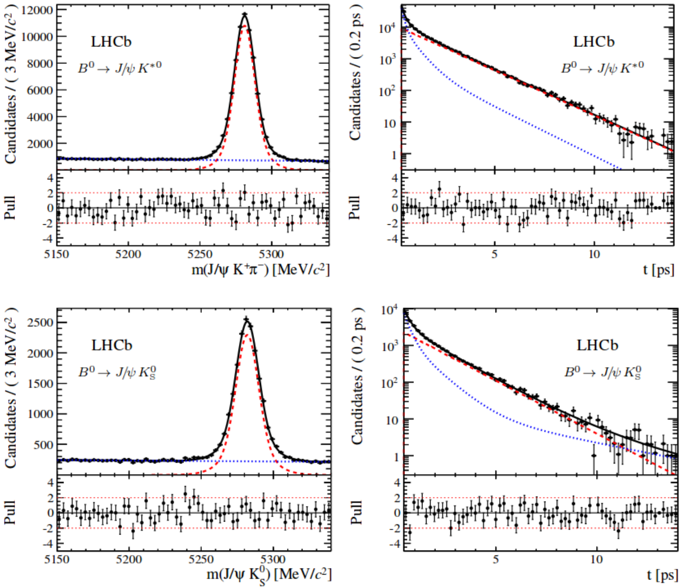
- All the results have been published recently: JHEP, **04-114**(2014)
- Level of precision achieved shows a very good understanding of the LHCb detector.
- Absolute lifetime measurements performed for B^+, B^0, B_s^0 mesons and Λ_b baryon:
  - all results are compatible with existing world averages;
  - with the Λ_b lifetime measurement: $\tau_{\Lambda_b} = 1.479 \pm 0.009 \pm 0.010$ ps [arXiv:1402.6242]
    LHCb performed the **most precise measurements** of *b*-hadron lifetimes.
- Several ratios have been computed to test HQE predictions and CPT conservation:
  - all results are consistent with theory predictions and previous measurements.
- A factor of 2 more data available to be analysed!


Thanks for your attention!

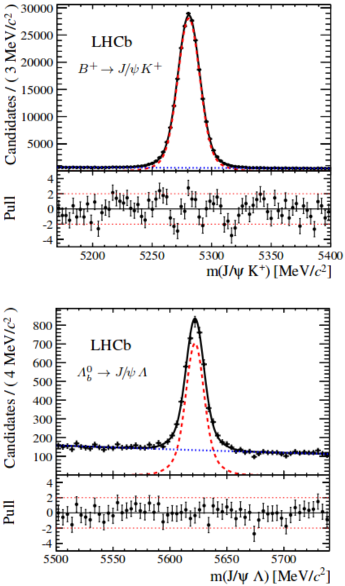
Backup Slides

Backup Slides

Fit projections for the B^0 effective lifetime



Fit projections for the B^+ and Λ_b^0 lifetime



Systematic uncertainties

Statistical and systematic uncertainties (in femtoseconds) for the values of the *b*-hadron lifetimes.

Dominant contributions:

1. VELO reconstruction efficiency: vary the parameterisation by $\pm 1\sigma$;
2. MC size: the statistical uncertainty on the simulated fitted lifetime is taken as a systematic;
3. Mass-time correlation: check by repeating the fit using mass parameters from fits to mass in bins of decay time.

Source	$\tau_{B^+\to J/\psi K^+}$	$\tau_{B^0\to J/\psi K^{*0}}$	$\tau_{B^0\to J/\psi K^0_S}$	$\tau_{\Lambda^0_b\to J/\psi \Lambda}$	$\tau_{B^0_s\to J/\psi \phi}$
Statistical uncertainty	3.5	6.1	12.8	26.5	11.4
VELO reconstruction	2.0	2.3	0.9	0.5	2.3
Simulation sample size	1.7	2.3	2.9	3.7	2.4
Mass-time correlation	1.4	1.8	2.1	3.0	0.7
Trigger and selection eff.	1.1	1.2	2.0	2.0	2.5
Background modelling	0.1	0.2	2.2	2.1	0.4
Mass modelling	0.1	0.2	0.4	0.2	0.5
Peaking background	–	–	0.3	1.1	0.4
Effective lifetime bias	–	–	–	–	1.6
B^0 production asym.	–	–	1.1	–	–
LHCb length scale	0.4	0.3	0.3	0.3	0.3
Total systematic	3.2	3.9	4.9	5.7	4.6

Systematic uncertainties

Statistical and systematic uncertainties (in units of 10^{-3}) for the lifetime ratios and $\Delta\Gamma_d/\Gamma_d$. Many systematics cancel in the ratio.

Dominant contributions:

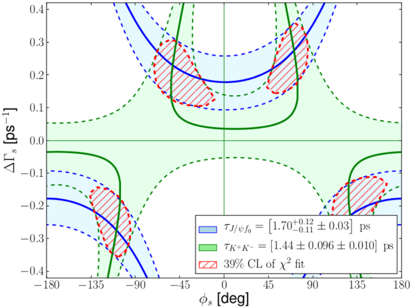
1. MC size: the statistical uncertainty on the simulated fitted lifetime is taken as a systematic;
2. Mass-time correlation: check by repeating the fit using mass parameters from fits to mass in bins of decay time;
3. B^0 production asymmetry.

Source	$\frac{\tau_{B^+}}{\tau_{B^0}}$	$\frac{\tau_{B_s^0}}{\tau_{B^0}}$	$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}}$	$\frac{\tau_{B^+}}{\tau_{B^-}}$	$\frac{\tau_{\Lambda_b^0}}{\tau_{\overline{\Lambda}_b}}$	$\frac{\tau_{B^0}}{\tau_{\overline{B}^0}}$	$\frac{\Delta\Gamma_d}{\Gamma_d}$
Stat uncertainty	5.0	8.5	18.0	4.0	35.0	8.0	25.0
VELO reco	1.6	1.7	1.1	–	–	–	4.1
Sim. sample size	2.0	2.2	2.8	2.1	5.3	3.0	6.3
Mass-time corr.	1.6	1.2	2.3	–	–	–	4.7
Trig. and sel eff.	1.1	1.8	1.5	–	–	–	4.0
Bkg. model	0.3	0.1	1.5	0.2	3.0	1.4	3.8
Mass model	0.2	0.4	0.2	0.1	0.2	0.2	0.8
Peaking bkg.	–	0.3	0.7	–	–	–	0.5
Eff. lifetime bias	–	1.0	–	–	–	–	–
B^0 prod. asym.	–	–	–	–	–	8.5	1.9
Total syst	3.2	3.7	4.4	2.1	6.1	9.1	10.7

Status at beginning of 2012

Fleischer, Kneijens [arXiv:1109.5115]

Using effective lifetime to constrain $\Delta\Gamma_s$ and ϕ_s



Using:

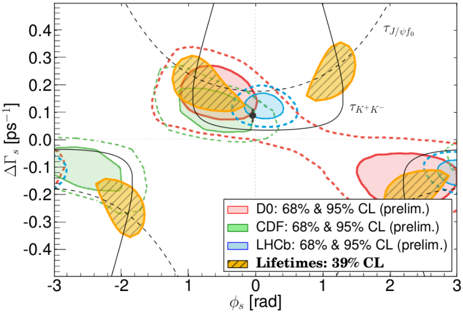
$\tau_{K^+K^-} = [1.44 \pm 0.096$ (stat) ± 0.010 (syst)$]$ ps

LHCb [PLB **707 (2012)**]

$\tau_{J/\Psi f_0(980)} = [1.70^{+0.12}_{-0.11}$ (stat) ± 0.03(syst) $]$ ps

CDF [**PRD84:052012,2011**]

Inluding direct measurement



Using:

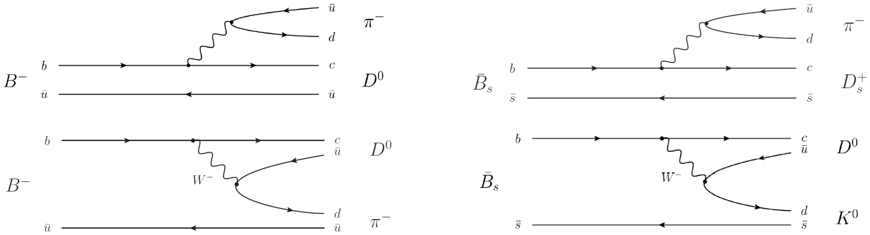
$\phi_s = 0.15 \pm 0.18$ (stat) ± 0.06 (syst) rad

$\Delta\Gamma_s = 0.123 \pm 0.029$ (stat) ± 0.011 (syst) ps^{-1}

[Phys.Rev. **L108, 10 (2012)**]

Theoretical status of *b*-flavoured hadron lifetimes

Why different *b*-hadron have different lifetimes? Spectator quarks are important!!



Pauli interference between the possible decays!

- The B^- has two decay paths to the same final state $\Rightarrow$ they interfere with each other destructively $\Rightarrow$ bigger lifetime!
- The B_s^0 has two unique final states $\Rightarrow$ no interference $\Rightarrow$ smaller lifetime!
- This argument also apply to the B^0.

We have the following hierarchy: $\tau_{B^+} > \tau_{B^0},\ \tau_{B_s^0}$

Effective lifetime in CP eigenstates

Fleischer, Kneijens [arXiv:1109.5115]

- In CP eigenstates the effective lifetime is sensitive to $\Delta\Gamma_s$ and ϕ_s (mixing induced $\not{CP}$ phase).

Considering a $B_s^0(\overline{B}_s^0) \to f$ transition the untagged decay time distribution is:

$$\Gamma(t) \propto (1 - \mathcal{A}_{\Delta\Gamma_s})e^{-(\Gamma_L t)} + (1 + \mathcal{A}_{\Delta\Gamma_s})e^{-(\Gamma_H t)}$$

with $\mathcal{A}_{\Delta\Gamma_s}$ is a function of ϕ_s.
If we assume no $\not{CP}$ then for the CP eigenstates $\mathcal{A}_{\Delta\Gamma_s} = \pm 1$:

CP even: e.g. $B_s^0 \to K^+K^- \Rightarrow \Gamma_L$

CP odd: e.g. $B_s^0 \to J/\Psi f_0(980) \Rightarrow \Gamma_H$

Effective lifetime is the lifetime measured by describing the untagged decay time distribution with a single exponential. Expanding in $y_s = \Delta\Gamma_s/2\Gamma_s$ and using $\tau_{B_s^0} = 2/(\Gamma_L + \Gamma_H) = \Gamma_s^{-1}$:

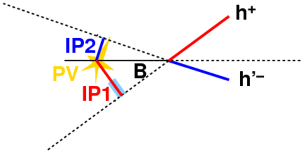
$$\frac{\tau_f}{\tau_{B_s^0}} = 1 + \mathcal{A}_{\Delta\Gamma_s} y_s + [2 - (\mathcal{A}_{\Delta\Gamma_s})^2]y_s^2 + \mathcal{O}(y_s^3)$$

Alternative way to extract ϕ_s and $\Delta\Gamma_s$:
- *complementary to e.g. $B_s^0 \to J/\Psi\phi$*
- *No flavour tagging needed*

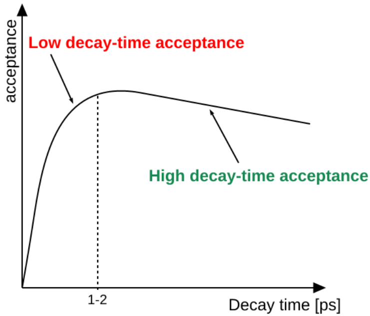
Decay-time acceptance

It can be divided into two contributions:

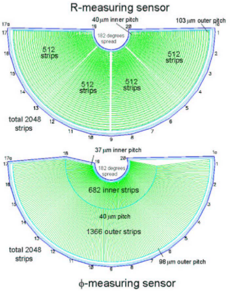
- **Low-decay time**: introduced by Impact Parameter requirement on the final state tracks. Trivial to correct making use of small data samples collected without this requirement.



- **High-decay time**: linear decrease as a function of the decay time
  $\Longrightarrow$ not so trivial to correct!!



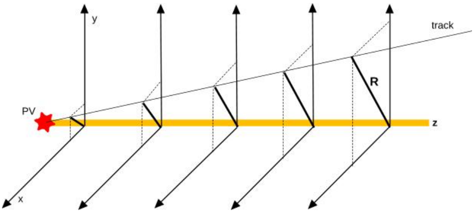
Origin of the VELO track reconstruction inefficiency II

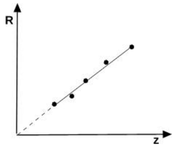


The first step in the VELO algorithm is to build a R-track, build out of hits from the R sensors.

Basics of RZ Tracking:

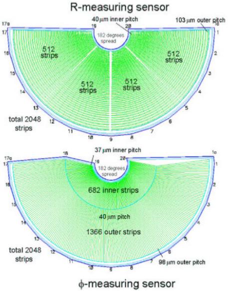
- Lay straight line through first and last hit.
- Search in between for hits near this line.





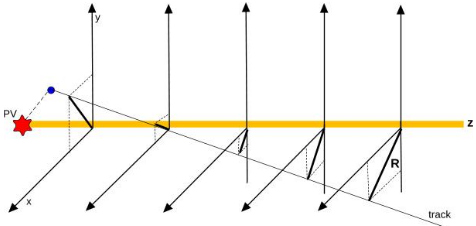
Origin of the VELO track reconstruction inefficiency II

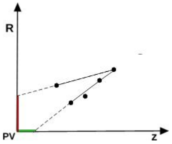
The first step in the VELO algorithm is to build a R-track, build out of hits from the R sensors.



Basics of RZ Tracking:

- Lay straight line through first and last hit pointing back to z.
- Search in between for hits near this line.
- For tracks with $\rho \neq 0$ it is not assured that these hits form a straight line in an R-z plot, which `FastVelo` is searching for.





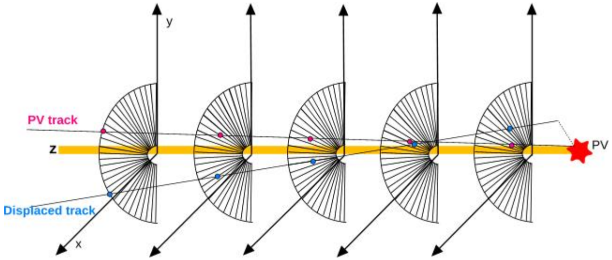
Origin of the VELO track reconstruction inefficiency III

The second step in the VELO algorithm is to build a space-track, selecting ϕ hits corresponding to an RZ-track.

Basics of ϕ Tracking:

- Starting from the last R hit of an RZ track, loop over all ϕ hits.
- In the next ϕ station take each time the hit with the smallest radial distance ($\Delta\phi$) to the first hit.
- Make out of these two hits a space track.
- Search for further hits, . . .

Tracks coming from PV have the same ϕ position in all stations $\Longrightarrow$ but for displaced tracks this is not true!



Neutral meson mixing

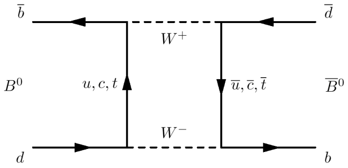
Time development of the mixing described by phenomenological Schroedinger equation:

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

Diagonalizing it in terms of mass eigenstates
$\Longrightarrow$ mass eigenstates $\neq$ flavour eigenstates:

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

B_d^0 mesons can oscillate into their antiparticle:



Phenomenological mixing parameters:

- **Lifetime difference**: $\Delta\Gamma_d = \Gamma_L - \Gamma_H$
- **Mass difference**: $\Delta m_d = m_H - m_L$

$\Delta\Gamma_d/\Gamma_d$ measurement

- $B^0 \to J/\psi K^*$ is a **flavour-specific** final state f decay:

$$B^0 \to f \quad \text{or} \quad \overline{B}^0 \to B^0 \to f$$
$$\overline{B}^0 \to \bar{f} \quad \text{or} \quad B^0 \to \overline{B}^0 \to \bar{f}$$

- while $B^0 \to J/\psi K^0_S$ is a **CP** final state eigenstate ($f = \bar{f}$).

$$B^0 \to f \quad \text{or} \quad \overline{B}^0 \to f$$

The decay rate of both B^0 and $\overline{B}^0$ can be written as:

$$\Gamma(B^0_d(\overline{B}^0_d) \to f)(t) \propto e^{-\Gamma_d t} \cdot \left[1 + A_f \frac{\Delta\Gamma_d}{2} t\right]$$

and we can use the fact that flavour-specific final states have $A_f = 0$, while $A_f \neq 0$ for $B^0 \to J/\psi K^0_S$.

$\Delta\Gamma_d/\Gamma_d$ measurement

With $\mathcal{R} = \tau_{B_d^0(\overline{B}_d^0)\to J/\psi K_S^0} / \tau_{B_d^0(\overline{B}_d^0)\to J/\psi K^{*0}}$:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = a_0(\mathcal{R}-1) + a_1(\mathcal{R}-1)^2 + \mathcal{O}((\mathcal{R}-1)^3)$$

Using this formula we can derive:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = -0.044 \pm 0.025\ (\mathrm{stat}) \pm 0.011\ (\mathrm{syst})$$

It can be compared to:

- SM: $\left|\frac{\Delta\Gamma_d}{\Gamma_d}\right| = 0.00409^{+0.00089}_{-0.00099}$;
  arXiv:0612167 [hep-ph]
- World average: $\left|\frac{\Delta\Gamma_d}{\Gamma_d}\right| = 0.015 \pm 0.018$ from Belle, BABAR and DELPHI.
  arXiv:1203.0930v2 [hep-ex] arXiv:0311037 [hep-ex]

Current world averages

As calculated by the HFAG:

b-hadron	World average [ps]
B^+	τ = 1.642 $\pm$ 0.008
B^0	τ = 1.519 $\pm$ 0.007
$B_s^0 \to J/\psi\phi$	τ^{eff} = 1.430 $\pm$ 0.050
Λ_b	τ = 1.426 $\pm$ 0.024

Also recent results:

CDF : $\tau^{\mathrm{eff}}_{B_s^0\to J/\psi\phi}$ = 1.528 $\pm$ 0.019(stat) $\pm$ 0.009(syst) ps - arXiv:1208.2967

ATLAS : τ_{Λ_b} = 1.449 $\pm$ 0.036(stat) $\pm$ 0.017(syst) ps - arXiv:1207.2284

LHCb : τ_{Λ_b} = 1.479 $\pm$ 0.018(stat) $\pm$ 0.012(syst) ps - LHCb-ANA-2013-037

CMS : τ_{Λ_b} = 1.503 $\pm$ 0.052(stat) $\pm$ 0.031(syst) ps - arXiv:1304.7495