Measurement of the B_s^0 oscillation frequency Δm_s at the LHCb experiment

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Overview

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  - Motivation
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  - Results
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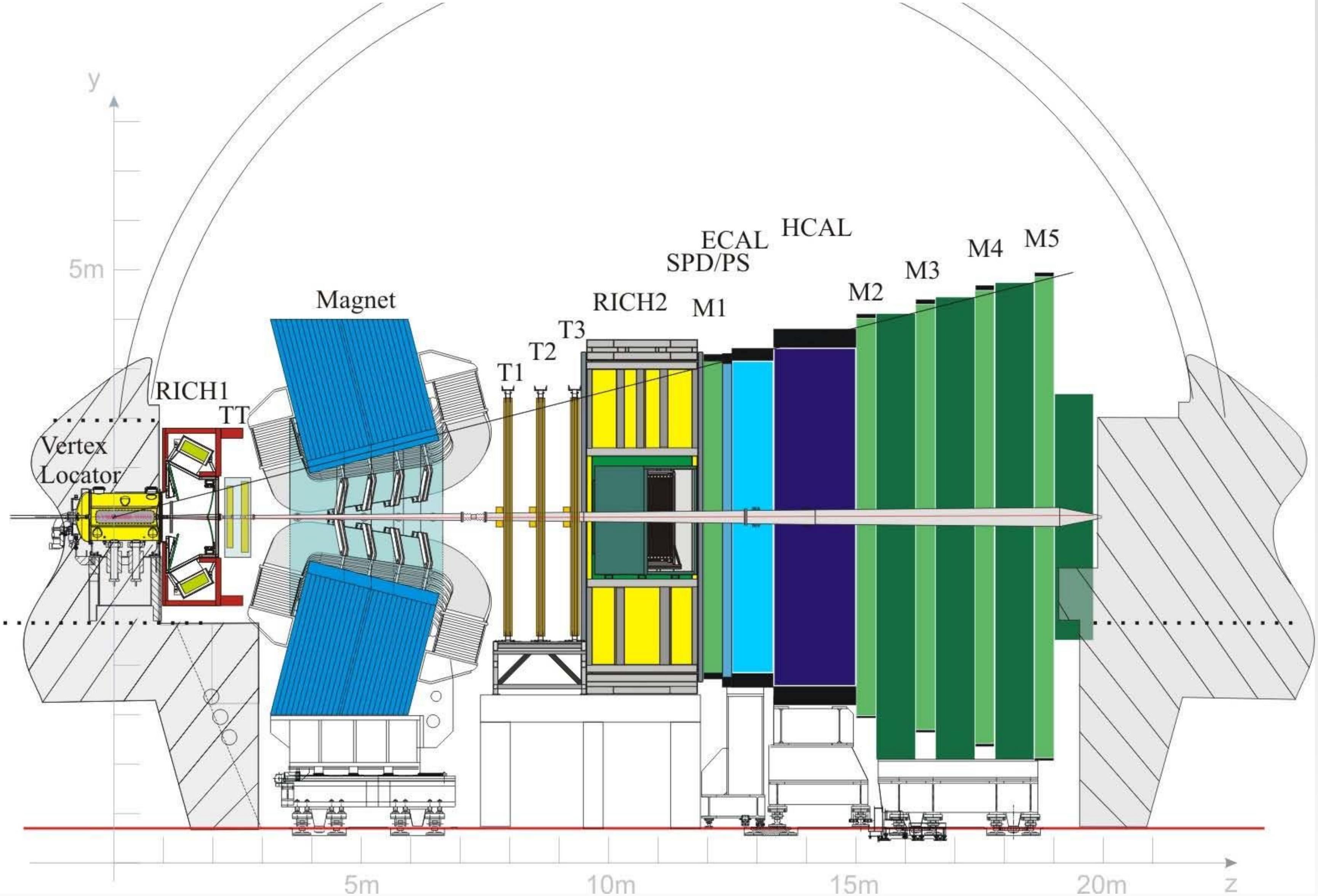
- Summary

INTRODUCTION

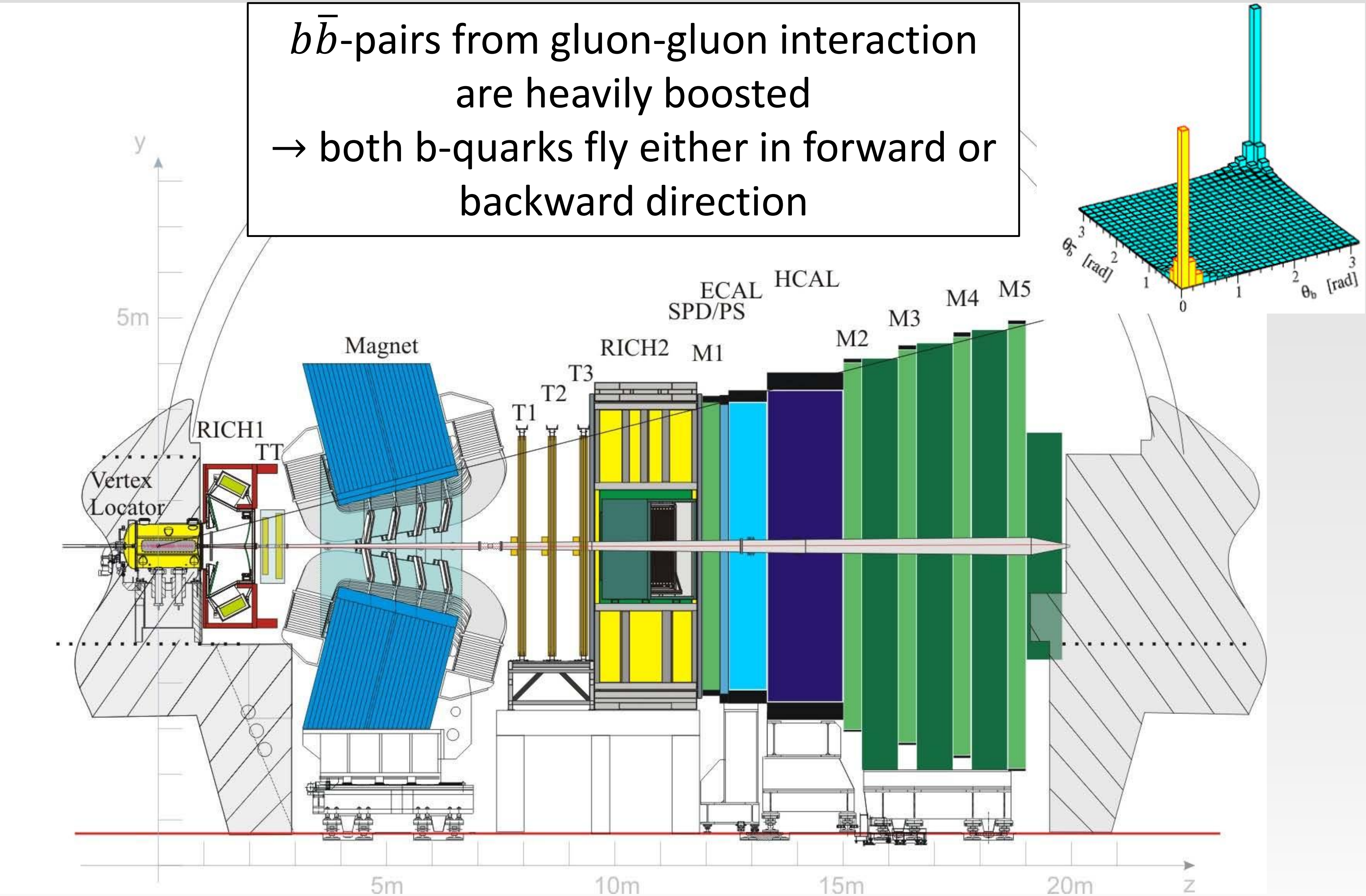
The LHCb experiment

Forward spectrometer



The LHCb experiment

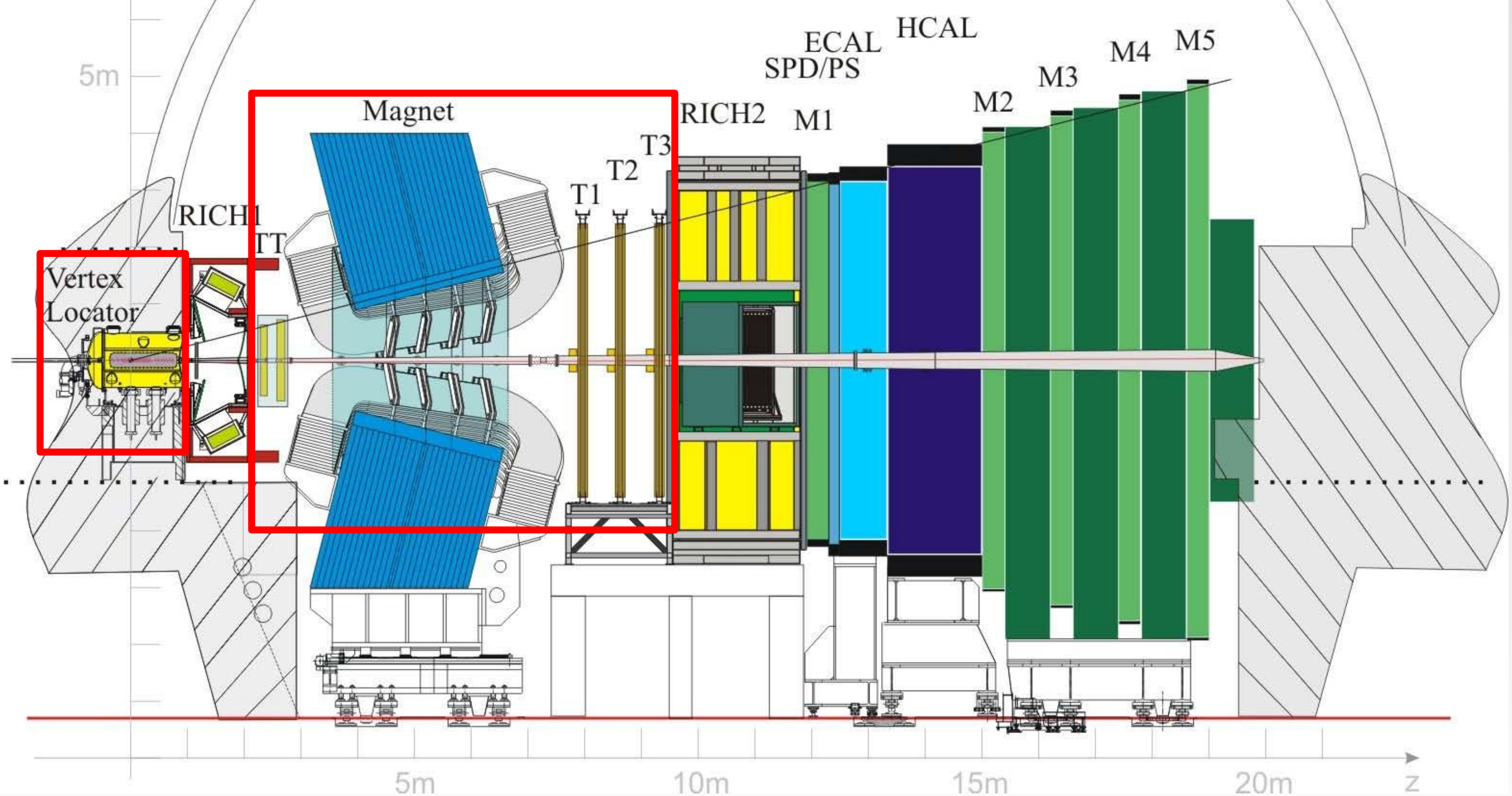
$b\bar{b}$-pairs from gluon-gluon interaction are heavily boosted
→ both b-quarks fly either in forward or backward direction



The LHCb experiment

Time-dependent analysis:
proper decay time $t = \frac{L*m}{p}$

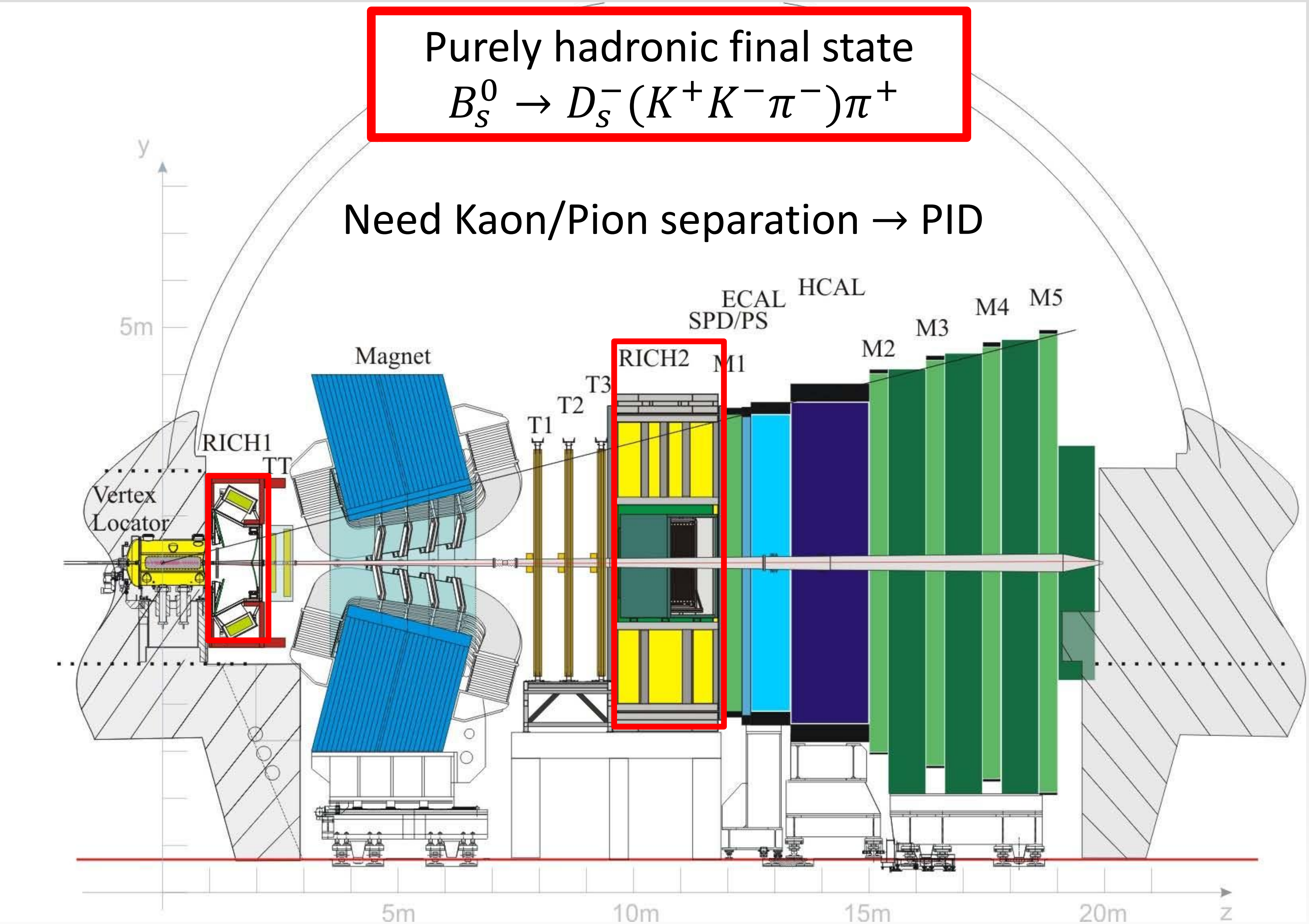
excellent vertex & momentum resolution



The LHCb experiment

Purely hadronic final state
$B_s^0 \rightarrow D_s^-(K^+K^-\pi^-)\pi^+$

Need Kaon/Pion separation → PID



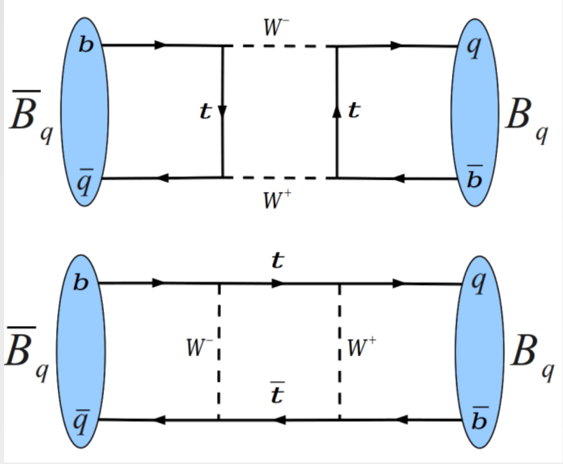
B-oscillation

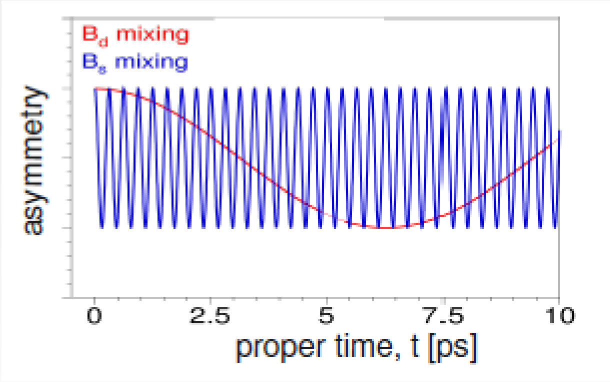
Neutral B-mesons oscillate into their anti particles

$$|B_L\rangle = k|B_q\rangle + l|\overline{B_q}\rangle$$
$$|B_H\rangle = k|B_q\rangle - l|\overline{B_q}\rangle$$

Mass eigenstates ≠ flavour eigenstates

Dominant Feynman diagrams (Standardmodel)





Oscillation frequency corresponds to mass difference Δm_q of B_L and B_H

Frequency in the B_s^0-system much larger than in B_d^0-system

→ need precise decay time resolution

MEASUREMENT OF $\Delta \mathrm{m_s}$
IN THE DECAY $B_s^0 \rightarrow D_s^-(K^+K^-\pi^-)\pi^+$

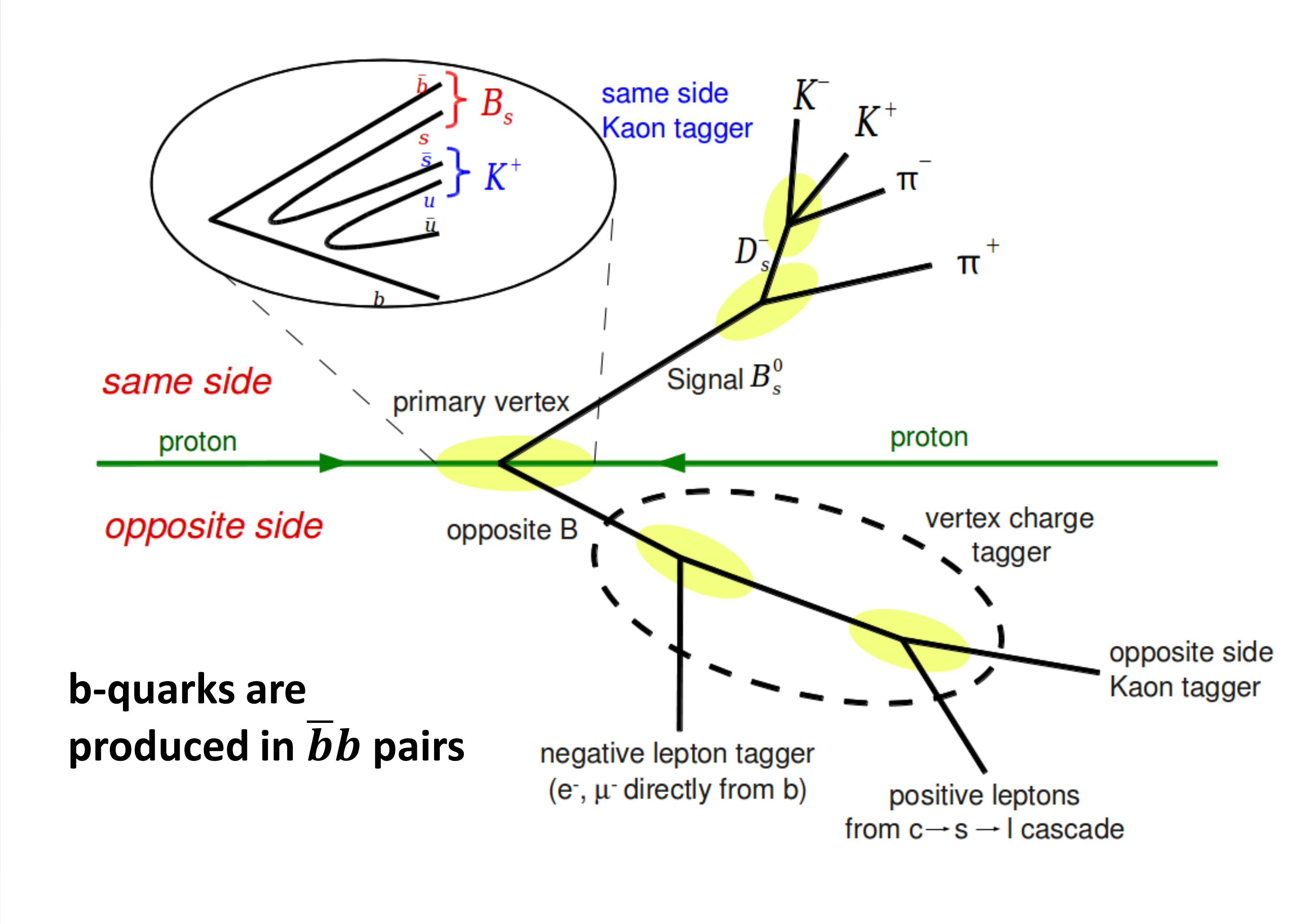
Idea of the analysis

- Distinguish between oscillated ($B_s^0 \rightarrow \overline{B_s^0} \rightarrow D_s^+\pi^-$) and not oscillated ($B_s^0 \rightarrow D_s^-\pi^+$) B-mesons
  - Decay flavour determined by charge of D_s^-
  - Production flavour → Flavour tagging algorithms
- Time-dependent measurement of oscillation asymmetry A_{osc}

Proper decay time: $t = \frac{L*m}{p}$

$$A_{osc}(t) = \frac{N_{not\ osc.}(t) - N_{osc.}(t)}{N_{not\ osc.}(t) + N_{osc.}(t)} \propto \cos(\Delta m_s t)$$

Flavour tagging algorithms



2 possibilities to determine the production flavour

- Tag the signal b-quark directly (same side) → used for the first time at LHCb in this analysis
- Tag the „other" b-quark (opposite side) → calibrated in reference channels

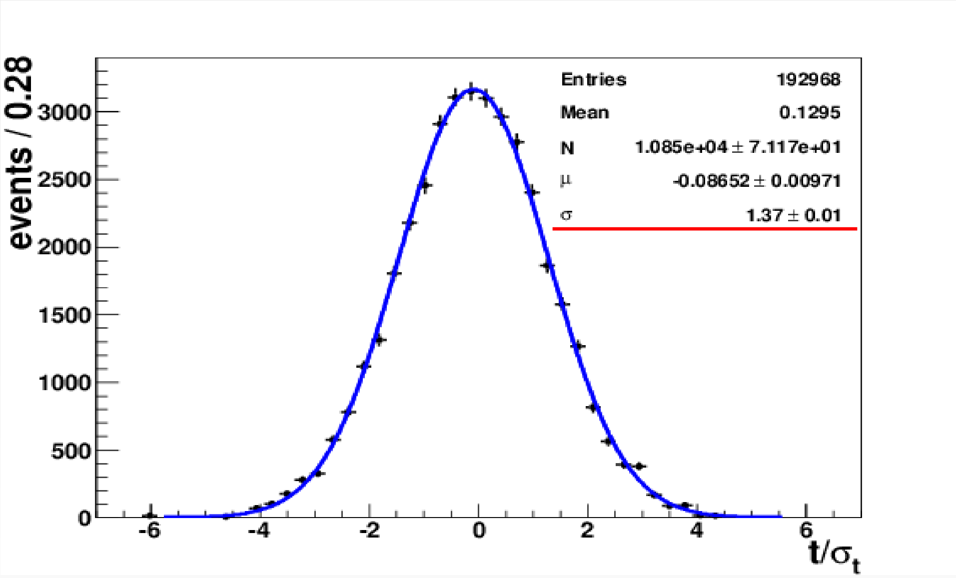
Flavourtagging algorithms

- Don't work perfectly
  - Efficiency that tagger gives a decision at all $\boldsymbol{\varepsilon_{tag}}$
  - probability for wrong decision $\boldsymbol{\omega}$
    - „other" b-meson oscillates → wrong decision
    - wrong lepton/kaon chosen → 50% wrong decision
    - charged particle missed in vertex charge tagger → wrong decision
- Combined to figure of merit $\varepsilon_{eff} = \varepsilon_{tag} D^2$ (with $D = 1 - 2\omega$)
- Typical value for $\varepsilon_{eff} = 2 - 4\%$
- Dilution factor D corresponds to amplitude of oscillation

Decay time resolution

- Fast oscillation of B_s^0 → require very good resolution (≈45fs)
- Completely dominated by resolution of secondary vertex
- Use per-event error estimate σ_t by the fit
- Calibrated on data
  - Take D-meson from primary interaction
  - Combine with π from primary vertex
  - Fake B-meson has by construction decay time t=0
  - Width of pull-distribution t/σ_t → correction factor S_{σ_t} for σ_t
  - Uncertainty of $S_{\sigma_t} \approx 10\%$ (→systematic studies)

$$\boxed{t = \frac{L * p}{m}}$$



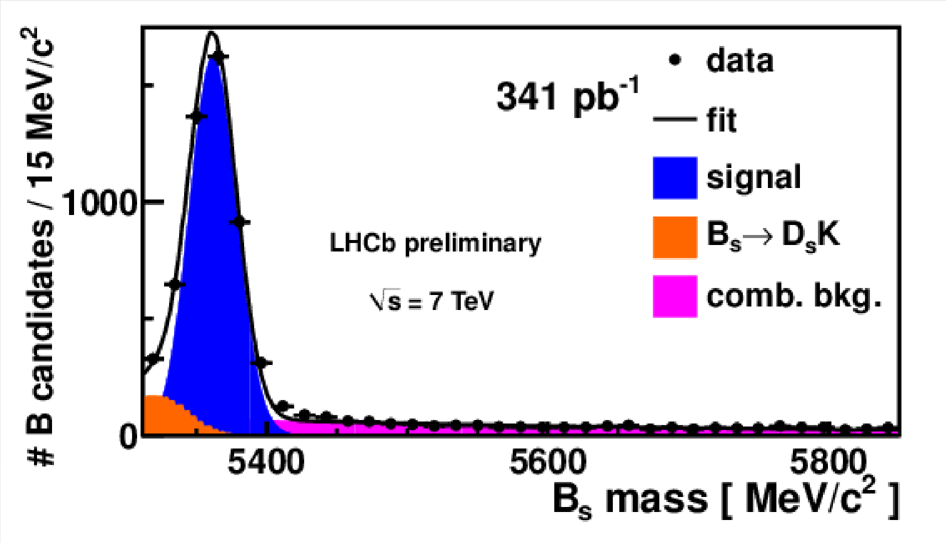
Details of the analysis

- Data-set: 341 pb^{-1} taken 2011
- Divide in 3 subsample → profit from resonant D_s^- decays
  - $B_s^0 \to D_s^-(\boldsymbol{\phi}(K^+K^-)\pi^-)\pi^+$
  - $B_s^0 \to D_s^-(\boldsymbol{K}^*(K^+\pi^-)K^-)\pi^+$
  - $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$

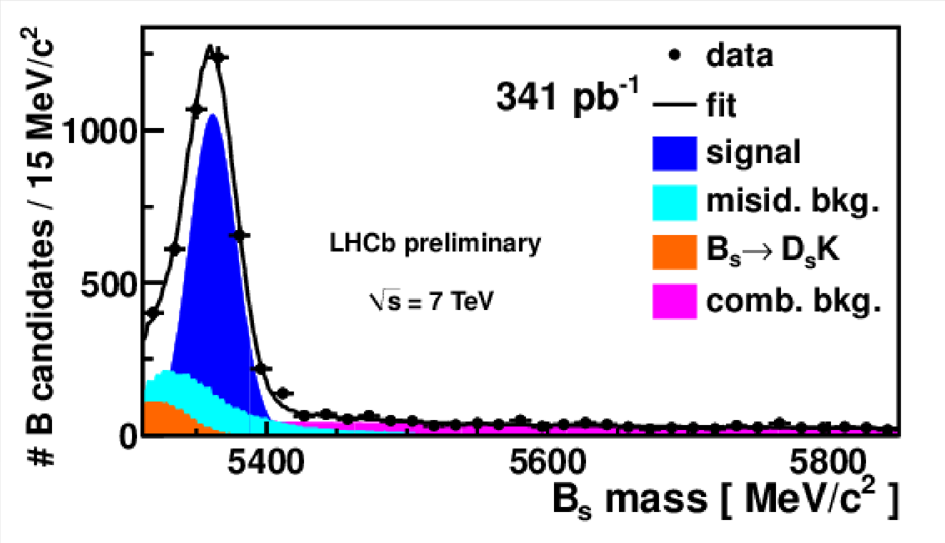
  Fitted simultaneously with physical parameters common
- Background
  - $B_s^0 \to D_s^-(K^+K^-\pi^-)K^+$ (Treated as signal)
  - $B_d^0 \to D^-(K^+\pi^-\pi^-)\pi^+$
  - $\Lambda_b \to \Lambda_c^-(\bar{p}K^+\pi^-)\pi^+$
  - Combinatorial background
- 2 dim. Unbinned Fit in mass + decay time

Projection on mass-dimension

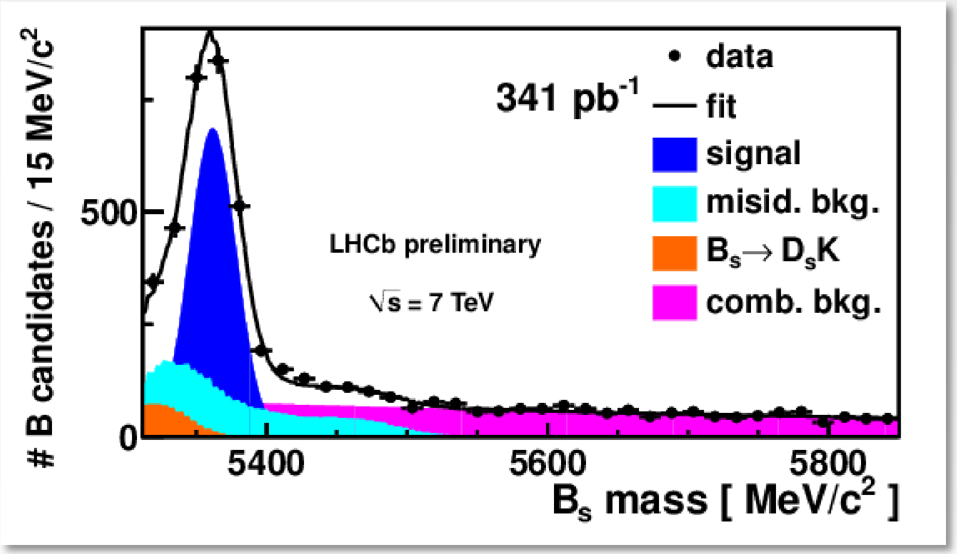
$D_s^- \to \phi\pi^-$



$D_s^- \to K^*K^-$



$D_s^- \to K^-K^+\pi^-$

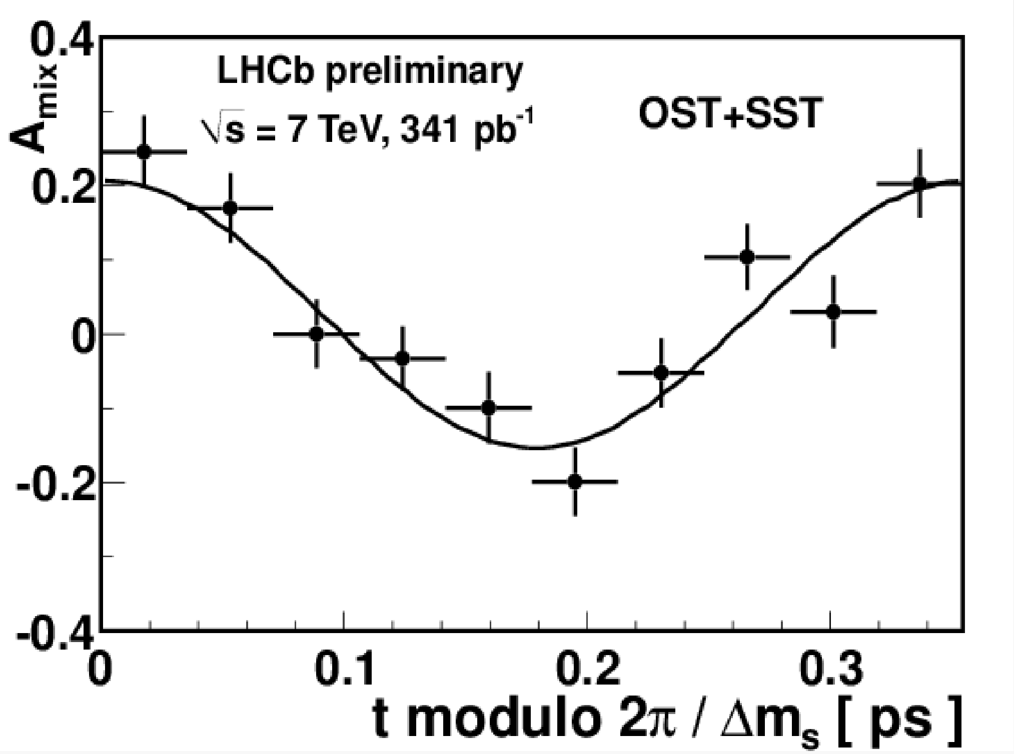


Decay channel	# Signal-candidates
$D_s^- \to \phi\pi^-$	4371±91
$D_s^- \to K^*K^-$	2910±89
$D_s^- \to K^-K^+\pi^-$	1908±74
Total	**9189±147**

Mass resolution:
$\sigma_m = 16.7 \pm 0.2\ MeV$
Fitted B_s^0 mass:
$m_{B_s^0} = 5361.9 \pm 0.3\ MeV$

Results (only stat. uncertainty)

- Fit using same + opposite side tagger
  - $\Delta m_s = (17.725 \pm 0.041)\ ps^{-1}$
  - $\varepsilon_{eff,SST} = (1.2 \pm 0.4)\%$
  - $\varepsilon_{eff,OST} = (3.1 \pm 0.8)\%$



Systematic studies

Systematic	Effect on Δm_s $[ps^{-1}]$
Decay time acceptance	0.000
Decay time resolution ($\pm 10\%$)	0.001
Decay time resolution model	0.001
z-scale	0.018
Momentum scale	0.018
σ_t PDF	0.000
$\Delta\Gamma_s$	0.002
Mass model	0.003
total	**0.025**

Summary

- 341 pb^{-1} of data taken by the LHCb experiment (9189 signal candidates) were analyzed
- Using same side and opposite side taggers we obtain

$$\boxed{\boldsymbol{\Delta m_s = 17.725 \pm 0.041(stat) \pm 0.025(syst)\; ps^{-1}}}$$

compare: $\boldsymbol{\Delta m_s = 17.77 \pm 0.1(stat) \pm 0.07(syst)\; ps^{-1}}$ **(CDF 2006)**

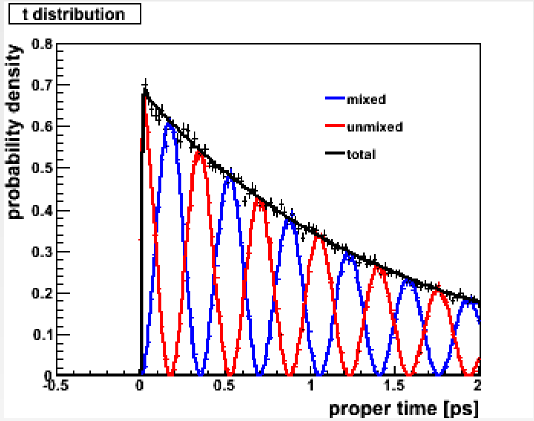
BACKUP

Decay time resolution/Flavourtagging

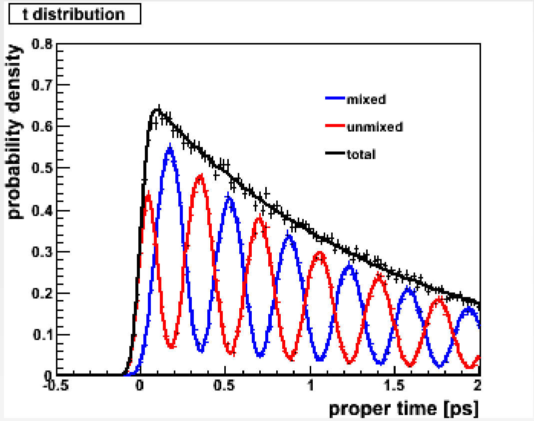
Both flavourtagging and decay time resolution directly influence the amplitude of the oscillation
→ can only measure combination of both

To measure the tagging power, the resolution has to be known as precisely as possible and fixed in the fit

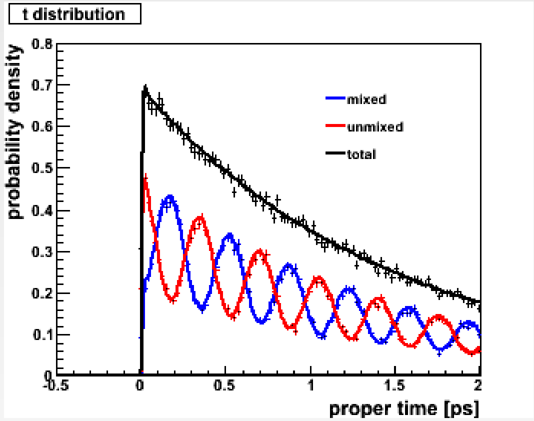
Perfect tagging
Perfect resolution



Perfect tagging
Realistic resolution

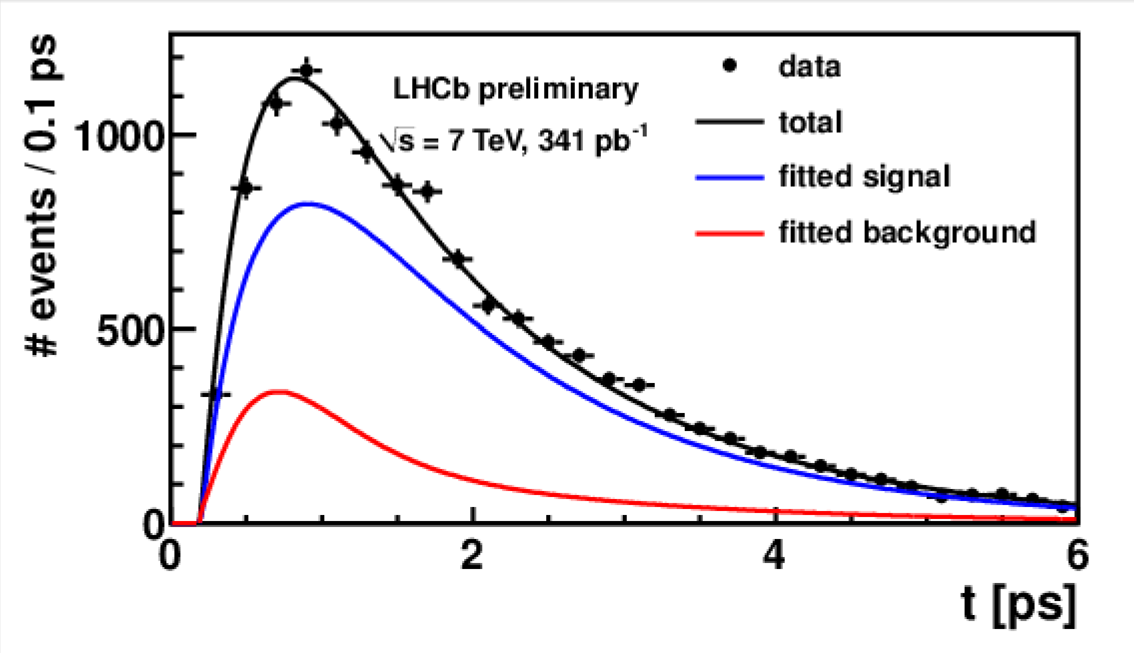


Realistic tagging
Perfect resolution



Projection on decay-time-dimension

Sum of the 3 decay modes

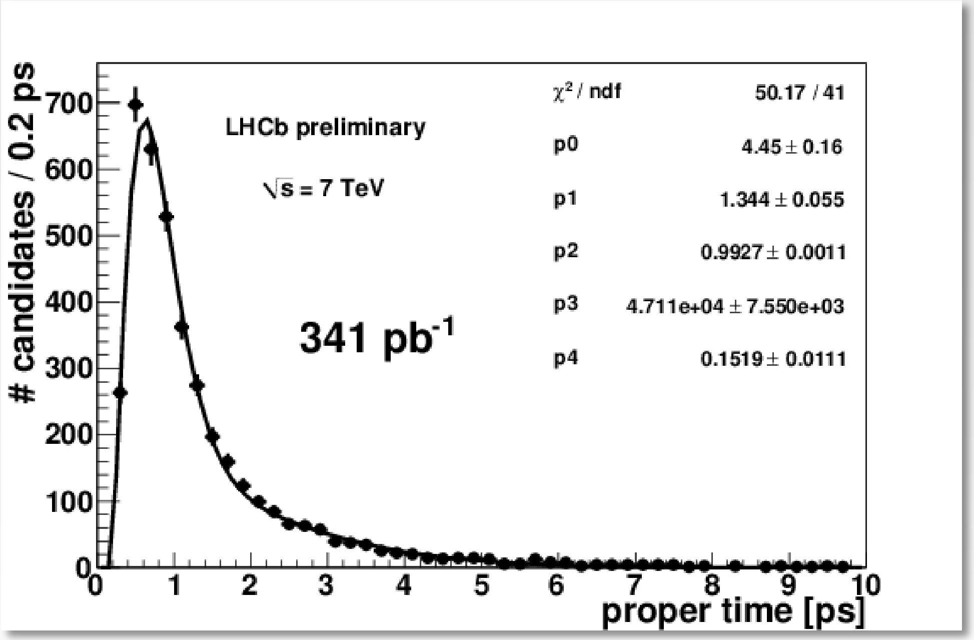


- decay time biasing selection (impact parameter of B-daughters) → need acceptance function
- Determined on Monte Carlo simulated data
- Essential for a lifetime measurement; however cancels to first order in oscillation asymmetry A_{osc}

Combinatorial bkg

- Shape motivated by fit to high mass sidebands (sum of 3 modes, left plot)
- Distribution similar for the three modes (right plot)
- α, β, f and a are floating parameters in the lifetime fit (shared)

$$P_{combbkg}(t) = (t-a)^2\left(fe^{-\alpha t} + (1-f)e^{-\beta t}\right)$$



Signal proper time pdf

$\Delta\Gamma_s$ is fixed to 0.1* Γ_s, systematics in range [0,0.2* Γ_s]

$$P_t = \left[e^{-\Gamma_s t} \cdot \left(\cosh\left(\frac{\Delta\Gamma_s}{2} \cdot t \right) \pm (1 - 2 \cdot \omega)\cos(\Delta m_s \cdot t) \right) \right] \otimes Gauss(0{,}1.37 \cdot \sigma_t) \cdot f_{acc}(t)$$

❖ OST only fit

- use per-event ω_{pred} from independent calibration
- $\omega_{true} = a * (\omega_{pred} - <\omega>) + b$
- Cross check: fit for a and b ($a = 1.28 \pm 0.20$, $b = 0.382 \pm 0.018$)
- Compatible with a and b from calibration

❖ SST only fit

- Fit for average ω

❖ OST+SST combination

- In case both give a decision pick the one with smaller ω
  - $\omega_{OST} = \omega_{pred}, \omega_{SST} = 0.35$
- Use event-by-event ω for OST, average ω for SST

Background proper time pdf

- Detailed description of the background PDFs are in the note

Combinatorial background:

- Average tagging asymmetry included (free parameter, shared among 3 modes)

B_d^0 reflection background:

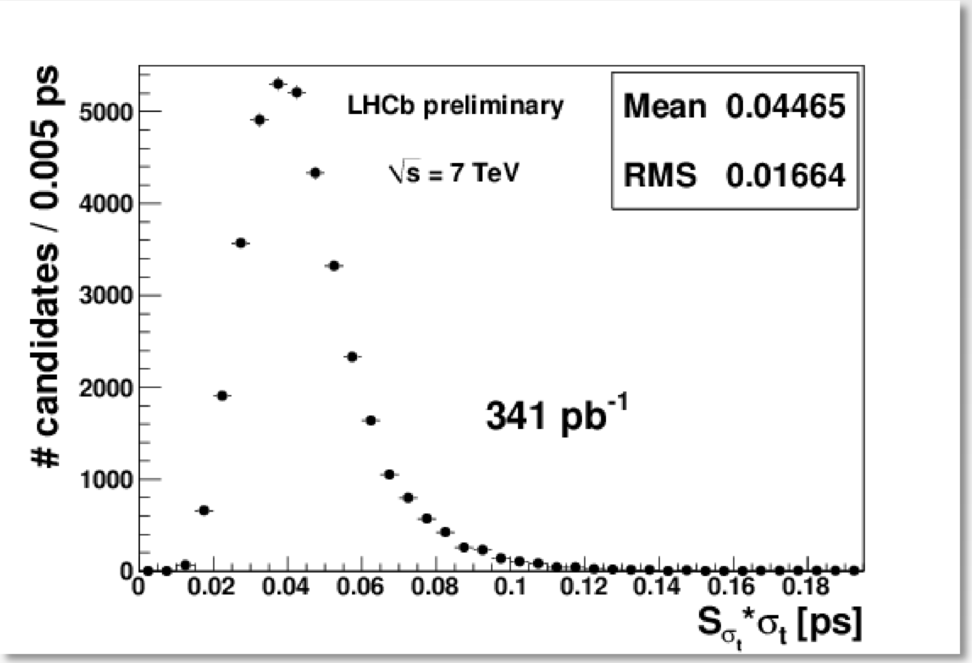
- Same pdf as signal ($\Delta\Gamma_s = 0$, slow oscillation, B_d lifetime)
- OST behaviour like signal
- SST average tagging asymmetry (free parameter, shared among 3 modes)

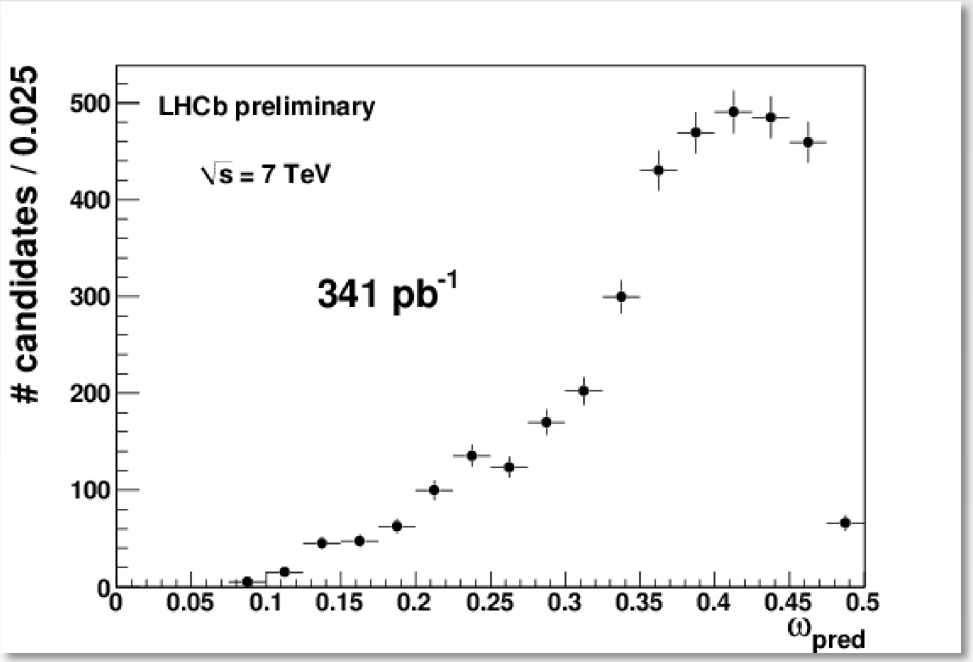
Λ_b background:

- Simple exponential with Λ_b lifetime, same acceptance as signal
- OST behaviour like signal
- SST average tagging asymmetry (free parameter, shared among 3 modes)

PDFs for event-by-event variables

- For the per-event variables σ_t and ω_{pred} a separate pdf for signal and background has to be included
- Take the σ_t (left) and ω_{pred} (right) distribution and normalize these histograms





Mixing fit results OST only

- Floating parameters (all shared among 3 modes)
  - Δm_s
  - Tagging efficiencies for signal & background
  - Tagging asymmetries for comb. background
  - Signal OST ω_{pred} calibration parameters (a, b) constraint from calibration
- Fit results:
  - $\Delta m_s = (17.775 \pm 0.046)\ \mathrm{ps}^{-1}$
  - $\varepsilon_{OST} = (32.5 \pm 0.5)\%$
  - This corresponds to $\varepsilon D^2 = (3.2 \pm 0.8)\%$

Mixing fit results SST only

- Floating parameters (all shared among 3 modes)
  - Δm_s
  - Tagging efficiencies for signal & backgrounds
  - Tagging asymmetries for comb., B_d and Λ_b background
  - Signal SST average $\overline{\omega}_{sig}$
- Fit results:
  - $\Delta m_s = (17.624 \pm 0.075)\ ps^{-1}$
  - $\overline{\omega}_{sig} = (34.4 \pm 2.7)\%$
  - $\varepsilon_{SST} = (13.4 \pm 0.4)\%$
  - This corresponds to $\varepsilon D^2 = (1.3 \pm 0.4)\%$

Mixing fit results overview

	OST only	SST only	OST + SST
$\varepsilon_{SST}[\%]$	---	13.4 ± 0.4	12.1 ± 0.4
$\overline{\omega}_{SST}[\%]$	---	$\boxed{34.4 \pm 2.7}$	34.4 ± 2.8
$(\varepsilon D^2)_{SST}[\%]$	---	1.3 ± 0.4	1.2 ± 0.4
$\varepsilon_{OST}[\%]$	32.5 ± 0.5	---	29.0 ± 0.5
$(\varepsilon D^2)_{OST}[\%]$	3.2 ± 0.8	---	3.1 ± 0.8
$\Delta m_s[\mathrm{ps}^{-1}]$	17.775 ± 0.046	17.624 ± 0.075	$\boxed{17.725 \pm 0.041}$

Results for Δm_s compatible within 1.7σ

We evaluated the systematics for these two results in these scenarios:

- $\overline{\omega}_{SST}$ for the SST only fit
- Δm_s for the OST + SST combination fit

Momentum scale systematic

Most of the systematics unchanged with respect to 2010 analysis

- Biggest change is larger mass shift → momentum scale bias ($s_p = 1.6‰$, from study on J/Psi mass peak)

$$t = \frac{L \cdot (1 + s_M) \cdot M_{B_s^0}}{\left(1 + s_p\right) \cdot p_{B_s^0}} \qquad \text{, with } s_M = \frac{s_p \cdot \left(M_{B_s^0} - 2M_K - 2M_\pi\right)}{M_{B_s^0}}$$

- Decay length L scaled by alignment → assigned 1‰ error on z-scale (unchanged with respect to 2010 analysis)
- Mass and momentum scaled, but bias cancels partially
- Total effect is $\frac{1+s_M}{1+s_p} = 0.9997 \rightarrow 0.3‰$, well within range of assigned 1‰
- As a cross check rescaling of 4-momenta on Ntuple, recalculated mass and proper time → $\Delta_{\Delta m_s} = 0.001$

Selection for $B_s^0 \to D_s^- \pi^+$

Stripping selection (Stripping12)

Cuts on B_s candidate	
$m(B_s)$	[4.80, 5.85] GeV
vtx χ^2	< 12
IP χ^2	< 25
cosDIRA	> 0.9998
lifetime	> 0.2 ps
Cuts on D_s candidate	
p	> 2 GeV
p_T	> 1.5 GeV
vtx χ^2	< 12
IP χ^2	> 9
cosDIRA	> 0.9
$\|m_{KK\pi} - m(D_s)_{PDG}\|$	< 110 MeV
$\|m(D_s) - m(D_s)_{PDG}\|$	< 100 MeV
Cuts on D_s daughters	
p	> 2 GeV
p_T	> 250 MeV
min(IP χ^2)	> 4
max(IP χ^2)	> 40
DOCA	< 1.5 mm
Track χ^2	< 5
Cuts on bachelor π	
p	> 5 GeV
p_T	> 500 MeV
IP χ^2	> 16
Track χ^2	< 5

Offline selection

Cuts on B_s candidate	
p	> 2 GeV
IP χ^2	< 16
cosDIRA	> 0.9999
primary vertex separation significance	> 64
Cuts on D_s candidate	
p_T	> 2 GeV
primary vertex separation significance	> 100
$\|m(D_s) - m(D_s)_{PDG}\|$	< 30 MeV
Cuts on D_s daughters	
p_T	> 300 MeV
min(IP χ^2)	> 9
DLL($K - \pi$) for kaons	> -10
DLL($K - \pi$) for pions	< 10
Cut on bachelor π	
DLL($K - \pi$) for pions	< 5
Cuts specific for $D_s \to \phi\pi$	
$\|m(\phi) - m(\phi)_{PDG}\|$	< 15 MeV
Cuts specific for $D_s \to K^*K$	
$\|m(K^*) - m(K^*)_{PDG}\|$	< 50 MeV
DLL($K - \pi$) for kaon with same charge as D_s	> 0
DLL($K - p$) for kaon with same charge as D_s	> -10
Helicity angle $\|\cos\psi\|$	> 0.4
Cuts specific for non-resonant $D_s \to K^+K^-\pi^-$	
DLL($K - \pi$) for pions	< 0
DLL($K - p$) for kaons	> 5
DLL($K - p$) for kaon with same charge as D_s	> -10