

Precision measurement of Δm_d using semi-leptonic decays at LHCb

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Outline

① LHCb

② Δm_d measurement at LHCb

③ Conclusion

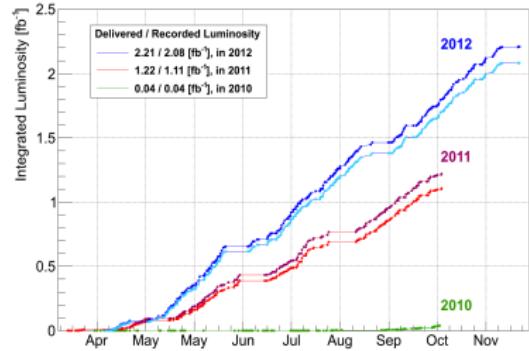
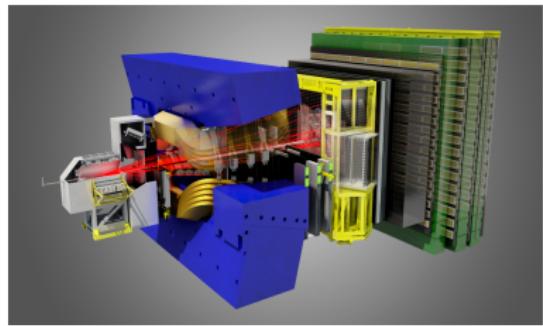
④ Backups

- LHCb experiment:
 - Single-arm forward spectrometer
 - Unique η coverage ($2 < \eta < 5$)
- LHCb physics:
 - Designed to search for New Physics in CP violation & Rare decays in Beauty & Charm
- LHCb luminosity:
 - Run I: 1 fb^{-1} (2011 @7 TeV), 2 fb^{-1} (2012 @8 TeV)
 - Run II: $\mathcal{O}(\text{pb}^{-1})$

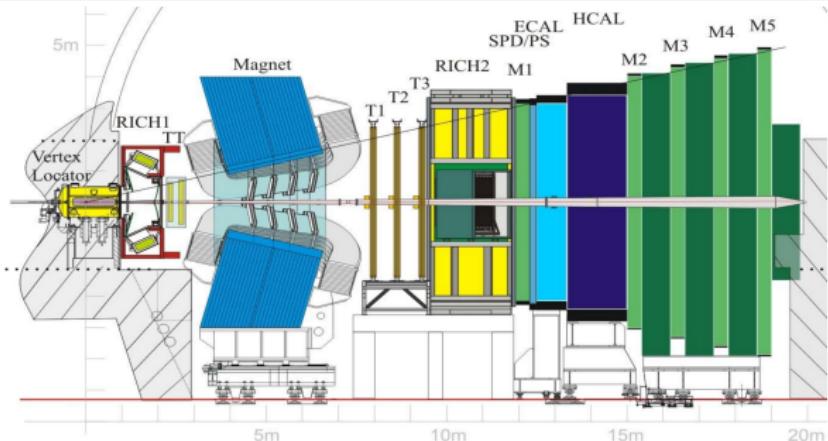
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LHCb detector



- VELO : $20\ \mu\text{m}$ for high p_{T} tracks
- Tracking system : $\delta(p)/p = (0.4 - 0.6)\%$, reversible magnet polarity
- RICH system : $\epsilon(\text{K}) \sim 95\%$, 5% $\pi \rightarrow \text{K}$ mis-id probability
- Calorimeter : Energy measurement, identify π^0, γ
- Muon detector : $\epsilon(\mu) \sim 97\%$, $(1 - 3)\%$, $\pi \rightarrow \mu$ mis-id probability
- Trigger : 40 MHz \rightarrow 5 kHz, efficiency(μ trigger) $\sim 90\%$

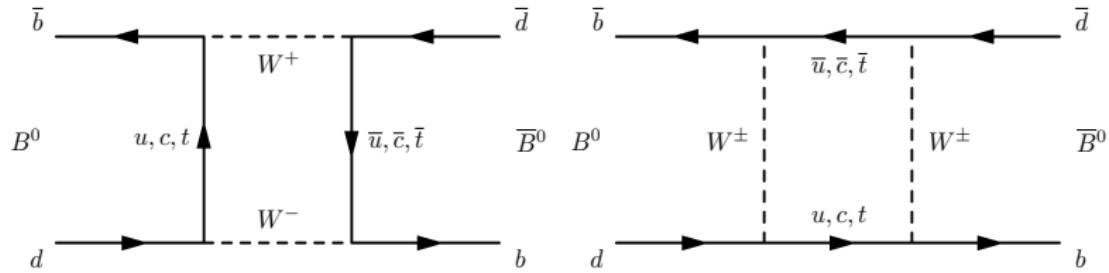
Δm_d measurement at LHCb

A precise measurement of the B^0 meson oscillation frequency,
LHCb-CONF-2015-003¹

¹Paper is in preparation

Introduction

- Flavour oscillation through electroweak interaction in neutral B mesons



$$N_{\pm}(t) \propto e^{\frac{-t}{\tau}} (1 + q_{\text{mixing}} \cos(\Delta m_d t))$$

- Tagged time-dependent analysis:

- $N_-(t)$: mixed ($B^0(\bar{B}^0) \rightarrow \bar{B}^0(B^0)$), $N_+(t)$: unmixed
- Mixing state ($q_{\text{mixing}} = \pm 1$) of B^0 : flavour at decay \times flavour at production
- Decay time of B^0 (t)

Analysis strategy

- Analysis in two channels $B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu$ using Run I data (3 fb^{-1})
 - $B^0 \rightarrow D^- \mu^+ \nu_\mu$ ($D^- \rightarrow K^+ \pi^- \pi^-$)
 - $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ ($D^{*-} \rightarrow \bar{D}^0 (\rightarrow K^+ \pi^-) \pi^-$)
- Flavour Tagging (q_{mixing})
- Decay time estimation (t)
- Background rejection
- Extraction of Δm_d from tagged time-dependent fit
- Evaluation of systematic uncertainties

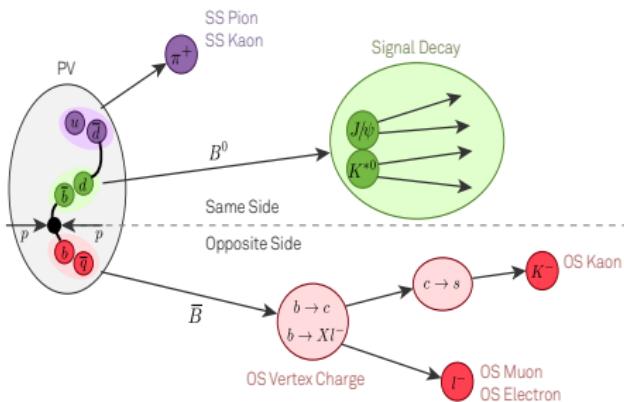
Flavour tagging: q_{mixing}

- Mixing state q_{mixing} : flavour at decay \times flavour at production $= \pm 1$
- Determine the flavour of B^0 at production in LHCb

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- Use Opposite B and Fragmentation products
- Flavour at production ($q_i : \pm 1, 0$)
- ... With Mistag probability



- Flavour at decay in $B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu$ is determined by μ charge

$$N_{\pm}(t) \propto e^{\frac{-t}{\tau}} (1 + q_{\text{mixing}}(1 - 2\omega) \cos(\Delta m_d t))$$

- Events are Grouped in 4 categories in increasing mistag probability
 - a $\in [0, 0.25]$, b $\in [0.25, 0.33]$, c $\in [0.33, 0.41]$, d $\in [0.41, 0.47]$

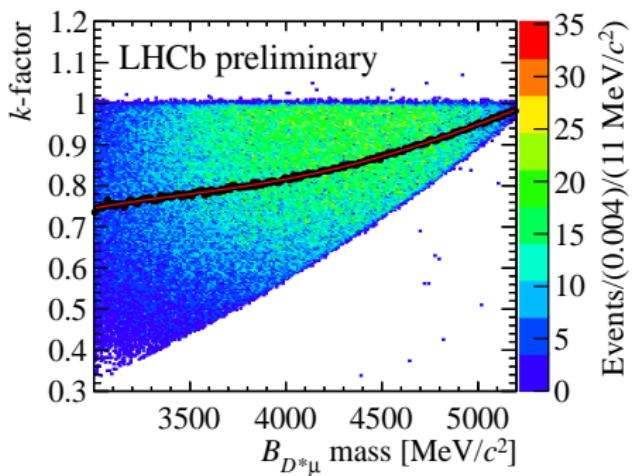
Determination of B decay time

- Wrong B momentum due to missing neutrino → wrong t
- Use k-factor method to correct t
 - $k(m_{D\mu})$: $p_{D\mu}^{\text{rec}}/p^{\text{true}}$ as a function of B mass (simulation)
 - Apply correction function on data

$$t_{\text{corr}} = \frac{L_B M_{B^0 \text{PDG}}}{p_{D\mu}^{\text{rec}}} \times k(m_{D\mu})$$

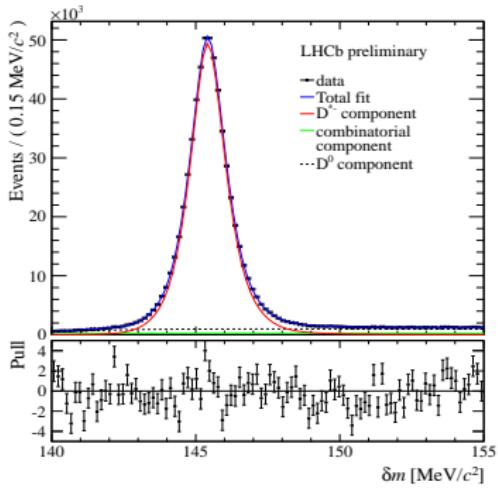
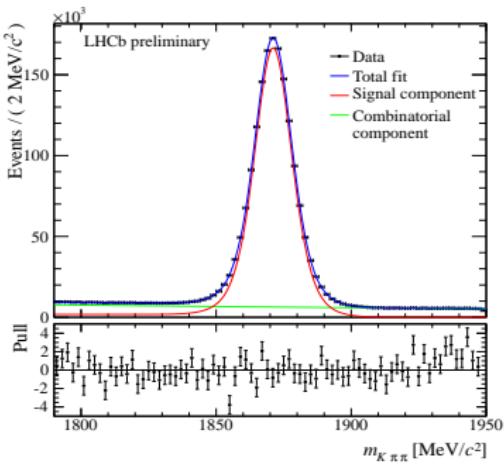
- $k(m_{D\mu})$: average correction → additional resolution function $F(k)$

$$N_{\pm}(t) \propto e^{-\frac{t}{\tau}} (1 + q_{\text{mixing}}(1 - 2\omega) \cos(\Delta m_d t)) \otimes R(t) \otimes F(k)$$



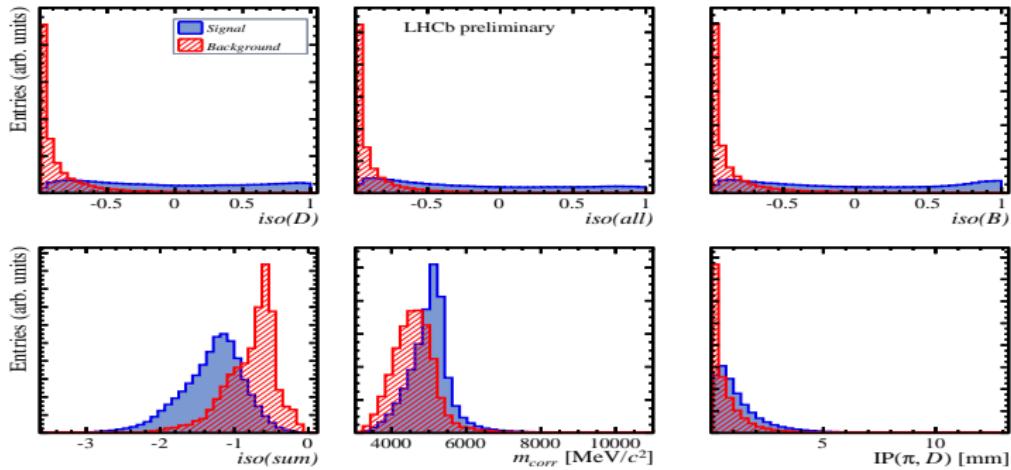
Background rejection I

- First type of backgrounds: Combinatorics, D^0 from B decays
 - Not sharing $D^{(*)-}$ with the signal in their final state
- Apply **sPlot** technique to subtract those backgrounds (Nucl. Instrum. Meth. A555 (2005) 356)
 - $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$: $m_{D^0}, \delta m (= m_{D^{*-}} - m_{D^0})$ distributions
 - $B^0 \rightarrow D^- \mu^+ \nu_\mu$: m_{D^-} distribution



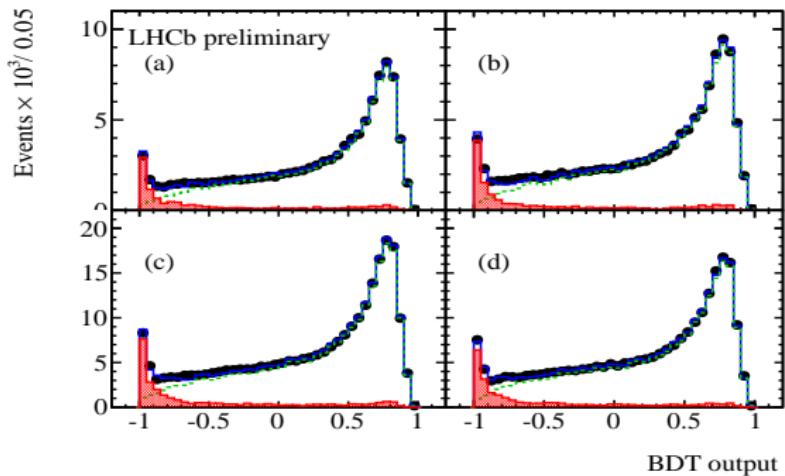
Background rejection II

- Second type of backgrounds: $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ decays
 - Sharing $D^{(*)-}$ with signal in their final state
- Exploit topological differences between signal and $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$
 - Additional π in $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ decays w.r.t signal
 - Kinematic & geometric variables combined in a MVA classifier (BDT)



Background rejection II

- Use the BDT classifier to estimate the contribution of $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ in data
 - Fit to BDT distributions in data ²



- Apply a cut on the BDT classifier \rightarrow retain 90% of signal & reduce $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ by 70%
 - Determine the fraction of **remaining** $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ by extrapolation

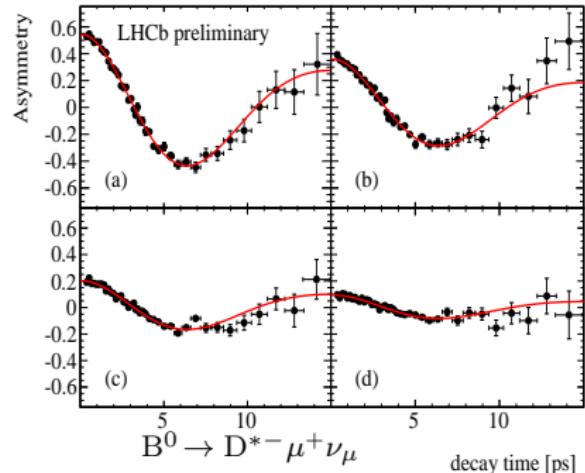
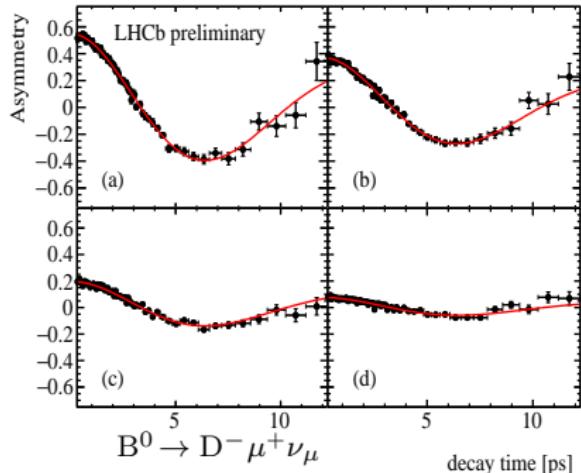
²Weights from sPlot technique are applied

Asymmetry fit

- Use binned likelihood sFit (arXiv:0905.0724) to extract Δm_d

$$\mathcal{P}(t, q_{\text{mixing}}) = (1 - f_{B^+})S(t, q_{\text{mixing}}) + f_{B^+}\mathcal{B}^+(t, q_{\text{mixing}})$$

- $S(t, q), \mathcal{B}^+(t, q)$: decay rates of signal & background
- f_{B^+} : fraction of the $B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ in the sample
- Time-dependent asymmetry



Results

- Several sources of systematic uncertainties
 - k-factor method, B^+ and other background sources & Other sources (time acceptance, detector resolution, momentum and length scale)
- Large number of parameterized simulation to evaluate systematic uncertainties
- Results per decay channel:

Mode	2011 sample	2012 sample	Total sample
	Δm_d [ns ⁻¹]	Δm_d [ns ⁻¹]	Δm_d [ns ⁻¹]
$B^0 \rightarrow D^- \mu^+ \nu_\mu$	$504.7 \pm 4.9_{\text{stat}}$	$503.2 \pm 2.9_{\text{stat}}$	$503.6 \pm 2.5_{\text{stat}} \pm 1.4_{\text{syst}}$
$B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$	$496.2 \pm 5.9_{\text{stat}}$	$506.9 \pm 3.9_{\text{stat}}$	$503.6 \pm 3.2_{\text{stat}} \pm 1.4_{\text{syst}}$

- Combination of Δm_d measurement across the two channels using Run I data:

$$\Delta m_d = 503.6 \pm 2.0 \text{ (stat)} \pm 1.3 \text{ (syst)} \text{ ns}^{-1}$$

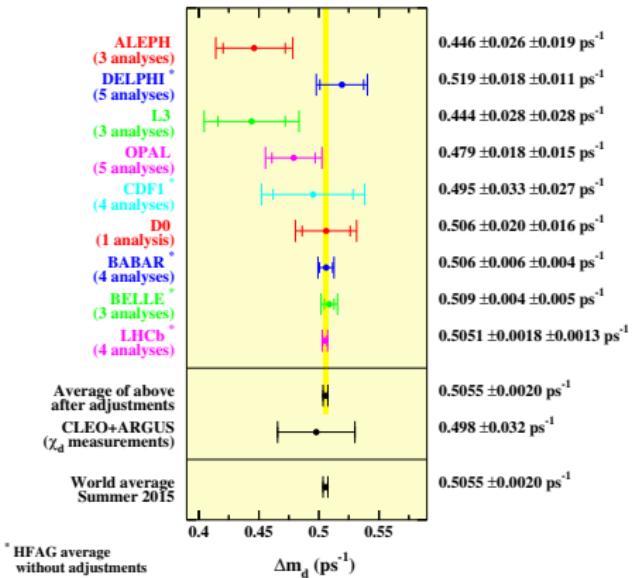
Conclusion

- LHCb measure Δm_d in $B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu$ channels using 3 fb^{-1}

$$\Delta m_d = 503.6 \pm 2.0 \text{ (stat)} \pm 1.3 \text{ (syst)} \text{ ns}^{-1}$$

- LHCb provides the most precise measurement of Δm_d
- Systematic uncertainties are under control
- New world average from HFAG including this measurement:

$$\Delta m_d(\text{world average 2015}) = 505.5 \pm 2.0 \text{ ns}^{-1}$$

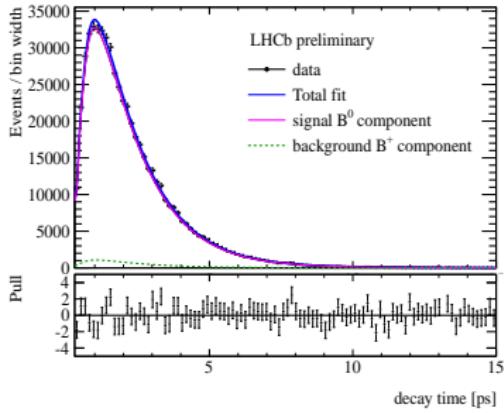
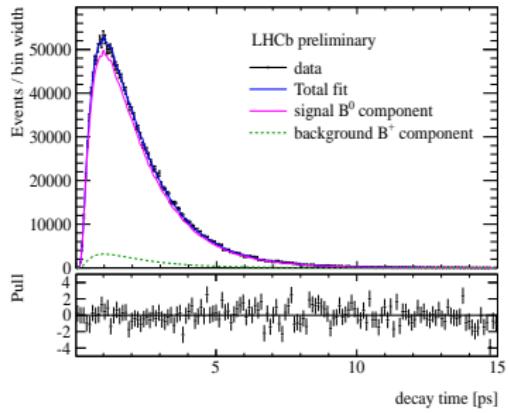


Backups

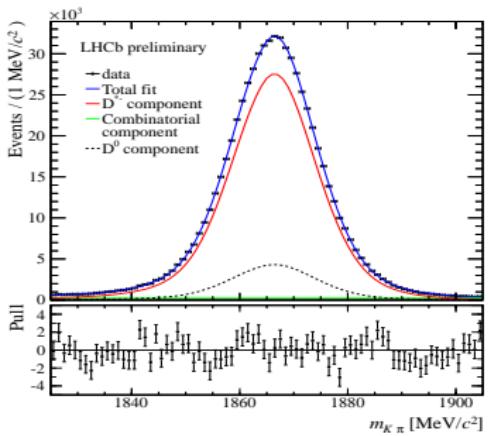
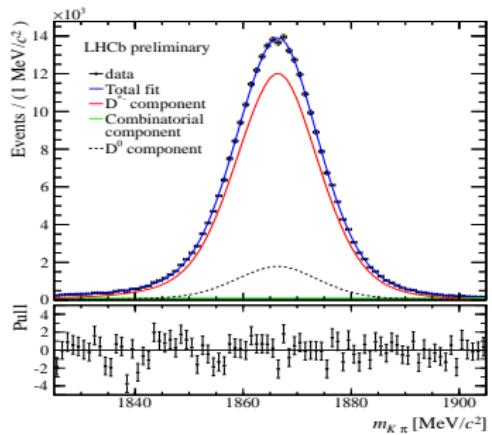
Systematic uncertainties

Source of uncertainty	$B^0 \rightarrow D^- \mu^+ \nu_\mu$ [ns ⁻¹]		$B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ [ns ⁻¹]	
	Uncorrelated	Correlated	Uncorrelated	Correlated
B^+ background	0.4	0.1	0.8	—
Other backgrounds	—	0.5	—	—
k -factor distribution	0.4	0.5	0.3	0.6
Other fit-related	0.6	0.9	0.2	0.9
Total	0.9	1.1	0.9	1.1

Time projections in 2012 data

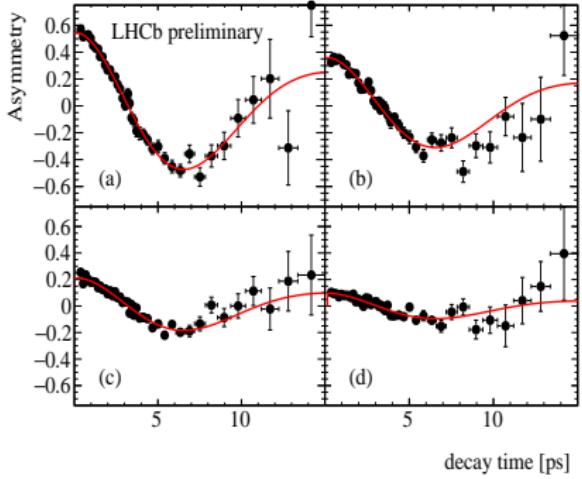
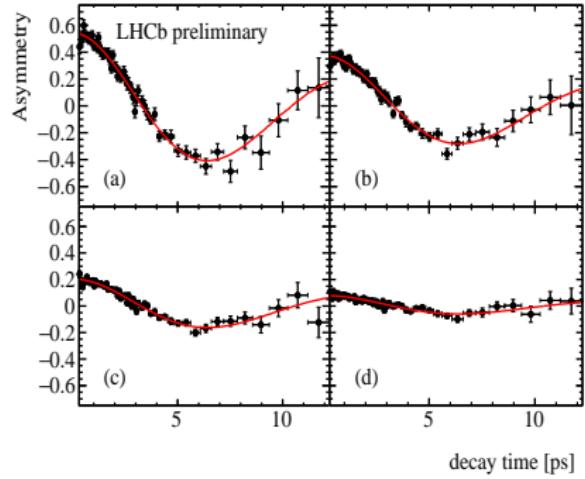


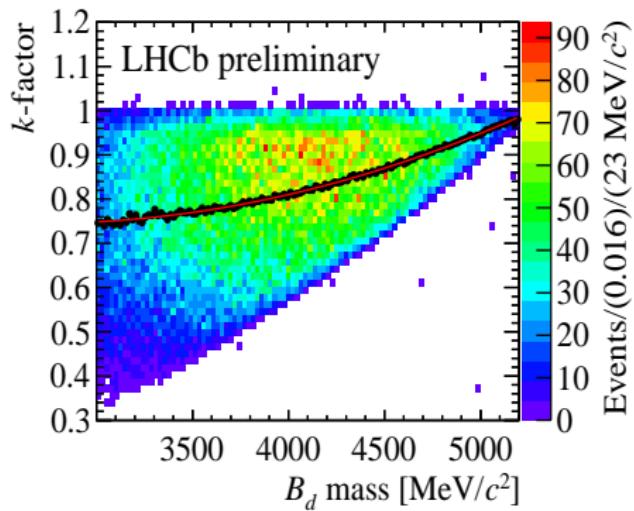
D⁰ mass distributions for 2012



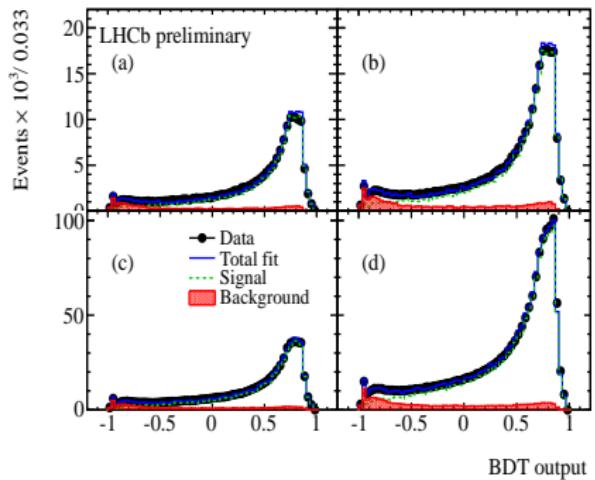
- D^0 mass fits in $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ decay
- Components with $D^{*-} D^0 \pi^-$ can be only distinguished using $\delta m (= m_{D^{*-}} - m_{D^0})$

Asymmetries in 2011

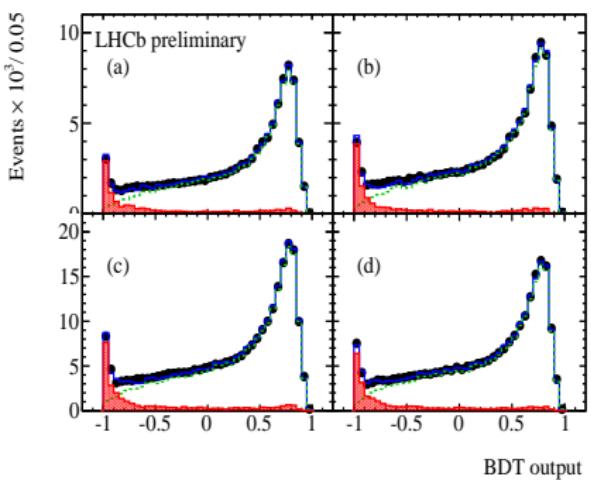


k-factor versus B mass in $B^0 \rightarrow D^- \mu^+ \nu_\mu$ (simulation)

BDT classifier



$$B^0 \rightarrow D^- \mu^+ \nu_\mu$$



$$B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$$

