# Semileptonic B hadron decays

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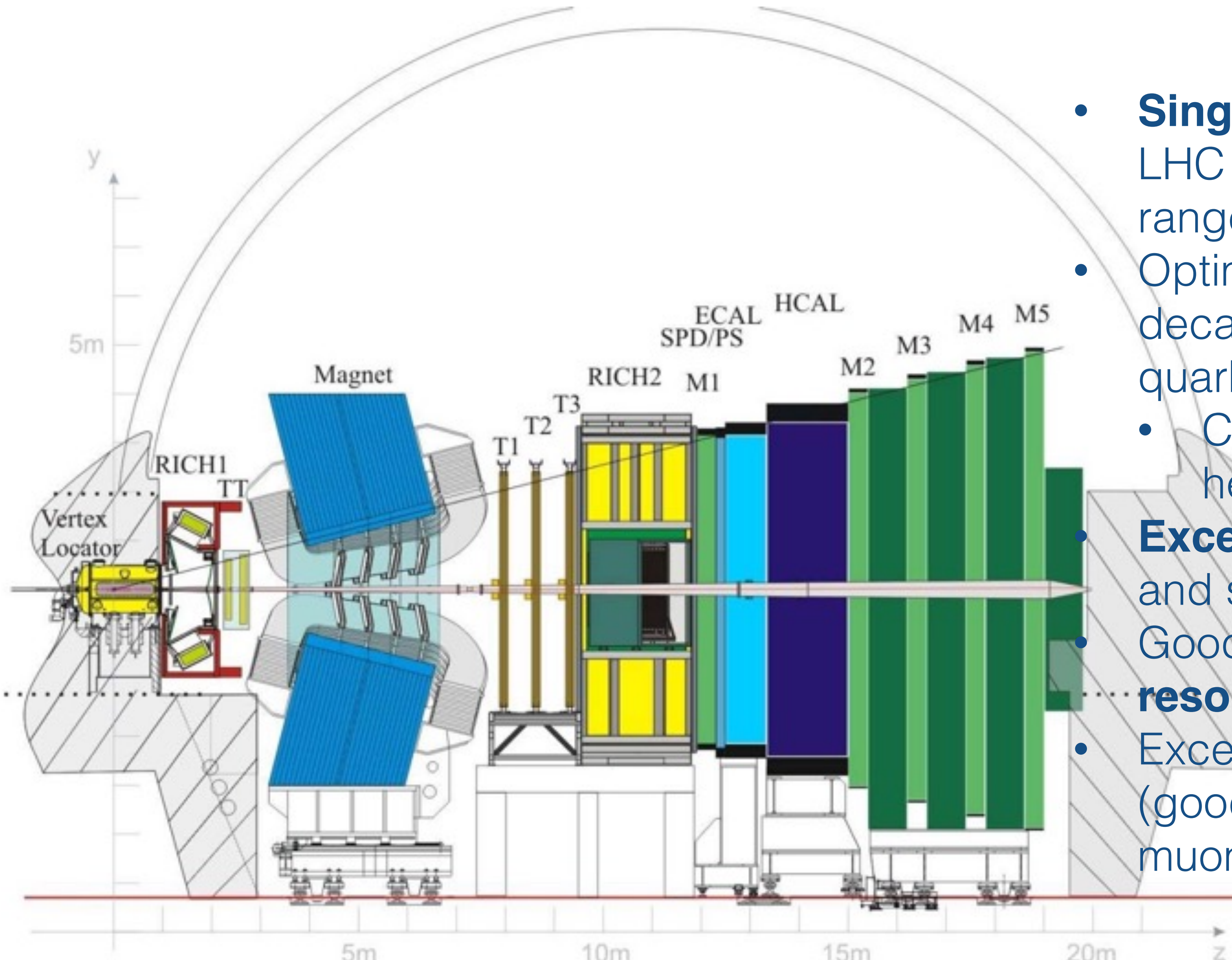
# Outline

- LHCb Detector
- Semitauonic decays of b hadrons:
  - $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$ with $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
  - Prospects for other final states
- $B^0$ oscillation frequency

# The LHCb Detector

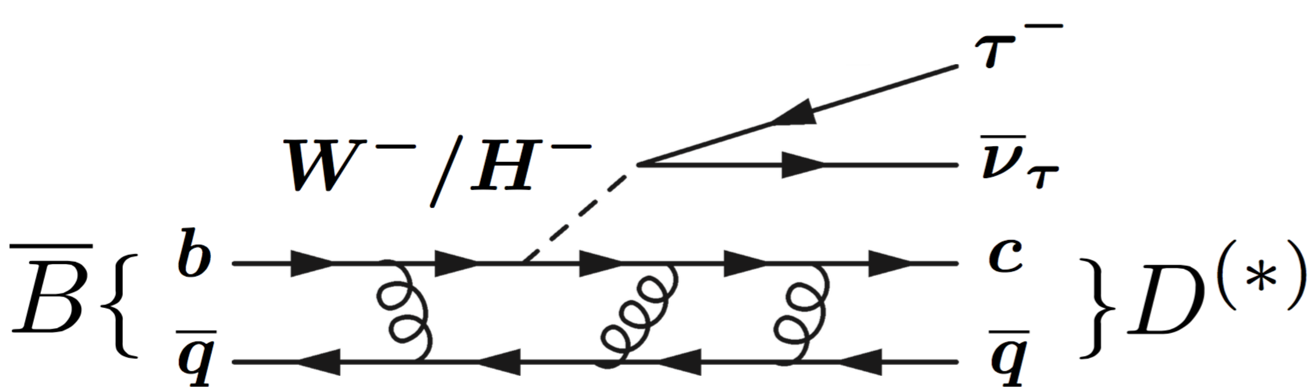



- **Single arm spectrometer** at LHC in the pseudorapidity range $2<\eta<5$;
- Optimized to study hadron decays containing **b** and **c** quarks:
  - CP violation, rare decays, heavy flavor production;
- **Excellent vertex resolution** and separation of B vertices;
- Good **momentum and mass resolution**;
- Excellent **PID** capabilities (good separation **K**-**π** and muon identification);

- Run 1: collected 1.0 $fb^{-1}$ @ $\sqrt{s}$ = 7 TeV in 2011 and 2.0 $fb^{-1}$ @ $\sqrt{s}$ = 8 TeV in 2012
- Run 2: collected about 320 $pb^{-1}$ @ $\sqrt{s}$ = 13 TeV in 2015

# B hadron semileptonic decays in tau lepton final states

- *Lepton universality*, described in the Standard Model, predicts equal coupling between gauge bosons and the three lepton families.
- SM extensions bring in additional interactions, implying in some cases a stronger coupling with the third generation of leptons.
- Semileptonic decays of b hadrons provide a *sensitive probe to such New Physics effects*.
- *Presence of additional charged Higgs bosons*, required by such SM extensions, can have significant effect on the semi-tauonic decay rate for example in $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$




$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

# B hadron semileptonic decays in tau leptons final states

- These decays are successfully studied in B factories with high purity and high statistics $D^{(*)}\tau\nu$ samples
- Despite the hadronic environment LHCb is also able to study such kind of decays and extend to other b hadrons thanks to the high boost of the b hadrons and excellent vertexing

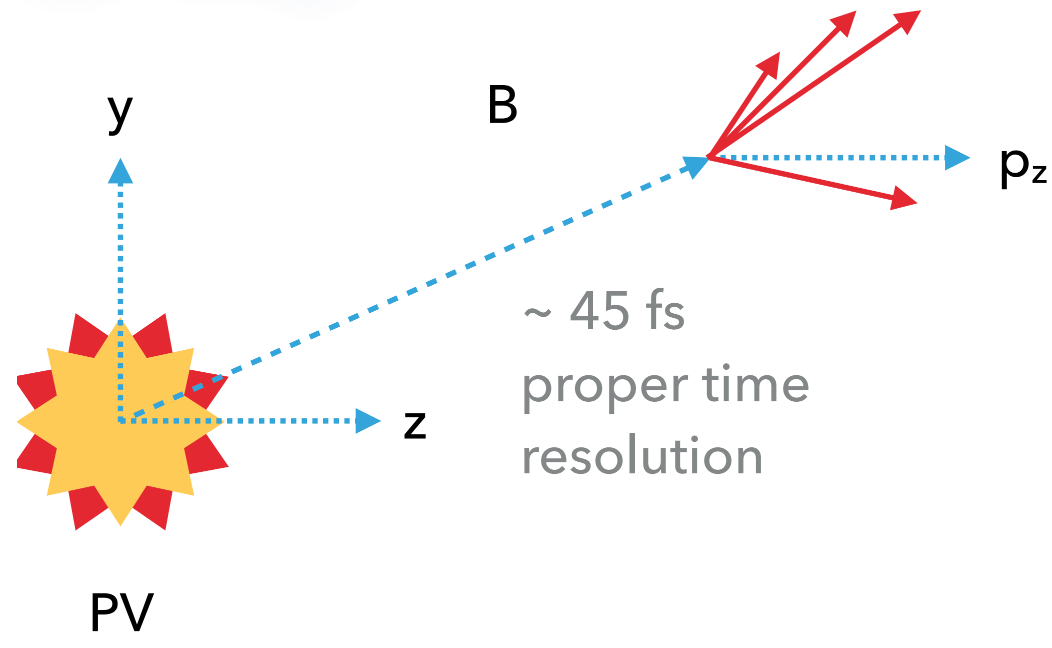
## Analysis Challenges

- Finding kinematic variables that distinguish signal from background
- Suppressing background with additional charged/neutral particles
- Normalization channel

- These challenges have different levels of importance and difficulty, and different solutions between analyses
  - Especially between analyses of muonic and hadronic $\tau$ decays

# $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$

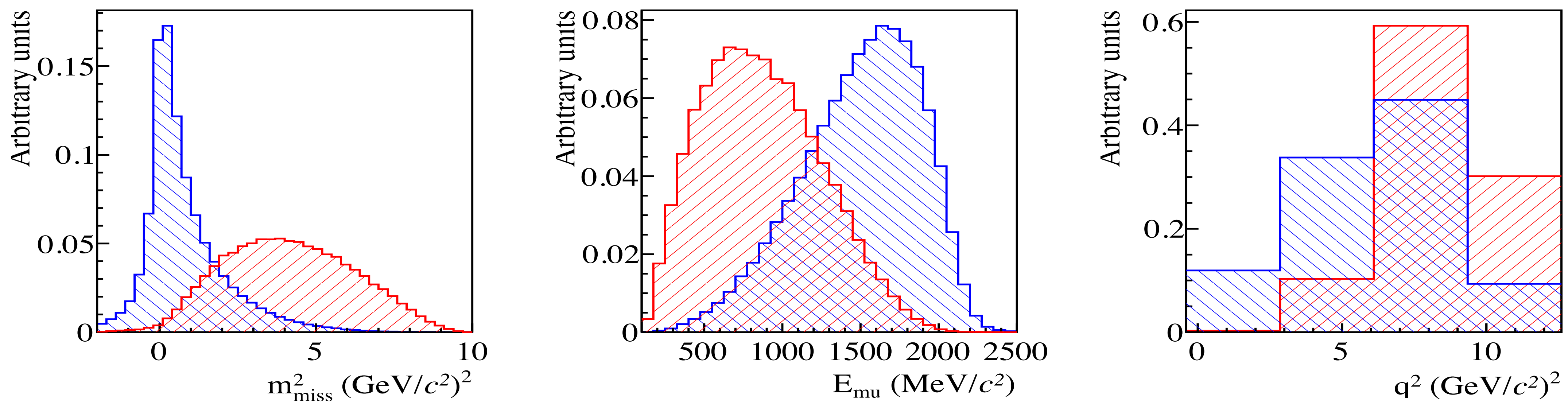
[PhysRevLett.115.111803]




- In Signal B→D*τν (τ→μνν) there are 3 missing neutrinos;
- B flight direction is well known;
- Approximate B momentum $p^z_{\bar{B}} = \frac{m_B}{m_{D^*\mu}} p^z_{D^*\mu}$

$$m^2_{\mathrm{miss}} = (p_B - p_{D^{*-}} - p_\mu)^2, q^2 = (p_B - p_{D^{*-}})^2 \text{ and } \mu \text{ energy}$$

- Broad shapes in the reconstructed distributions, but the discriminating power is preserved

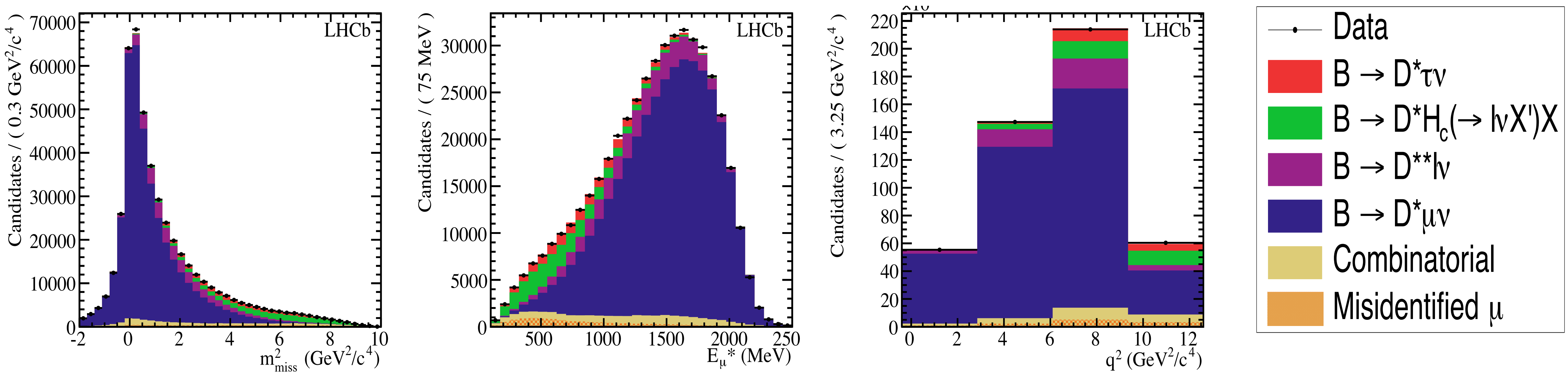



$B^0 \to D^{*-}\tau^+\nu_\tau$ MC (red) , $B^0 \to D^{*-}\mu^+\nu_\mu$ MC (blue)

# $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$

[PhysRevLett.115.111803]

- Binned Likelihood fit using 3D templates ($m^2_{miss}$, $q^2$, $E_\mu$)
  - Templates for signal and normalization are extracted from Monte Carlo simulation
  - Templates for backgrounds are validated using control samples in data
  - Form Factors (from HQET) included as external constraints.

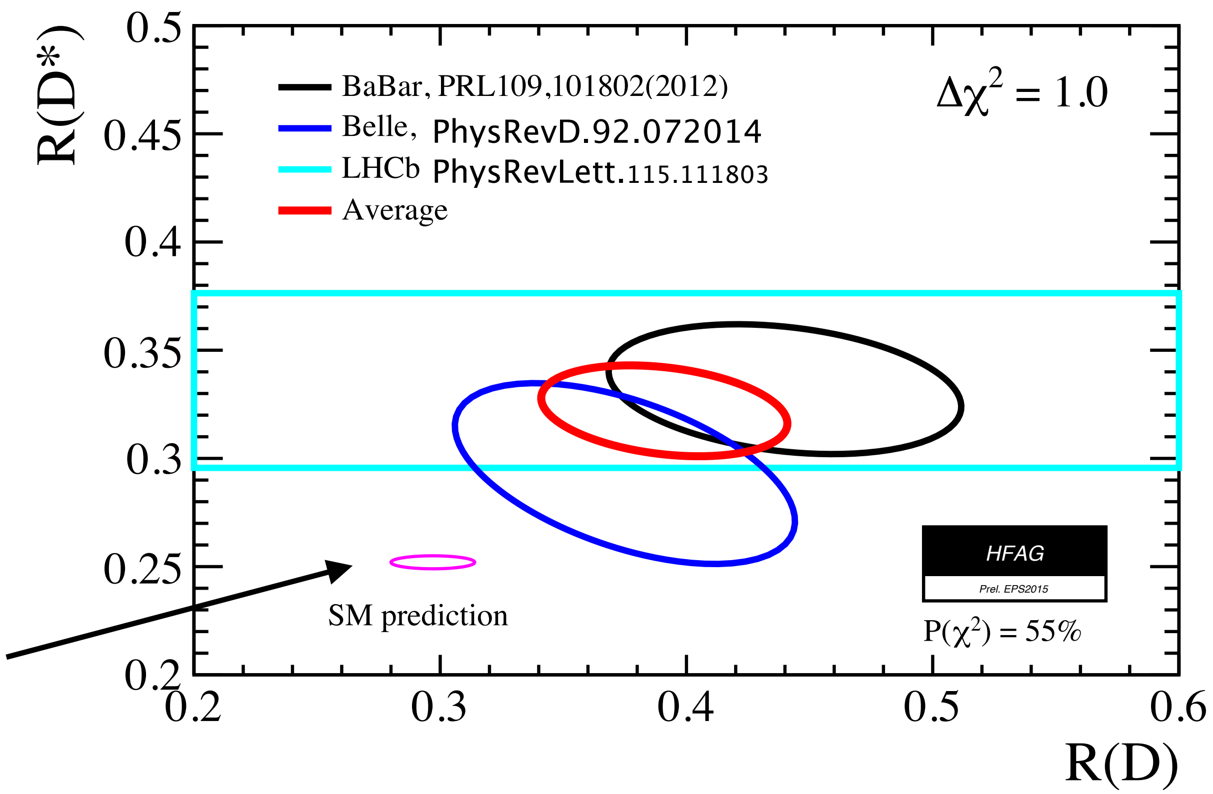



$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = 0.336 \pm\ 0.027(stat) \pm 0.030(syst)$$

- Systematics uncertainties dominated by:
  - Monte Carlo statistics;
  - misID muon background

# B hadron semileptonic decays in tau leptons final states

| Experiment | | $R_D^*$ | $R_D$ |
|---|---|---|---|
| BABAR | 2012 | $0.332 \pm 0.024 \pm 0.018$ | $0.440 \pm 0.058 \pm 0.042$ |
| Belle | 2015 | $0.293 \pm 0.038 \pm 0.015$ | $0.375 \pm 0.064 \pm 0.026$ |
| LHCb | 2015 | $0.336 \pm 0.027 \pm 0.030$ | – |
| Average | | $0.322 \pm 0.018 \pm 0.012$ | $0.391 \pm 0.041 \pm 0.028$ |
| SM | | $0.252 \pm 0.003$ | $0.297 \pm 0.017$ |




SM precision = 1.19%

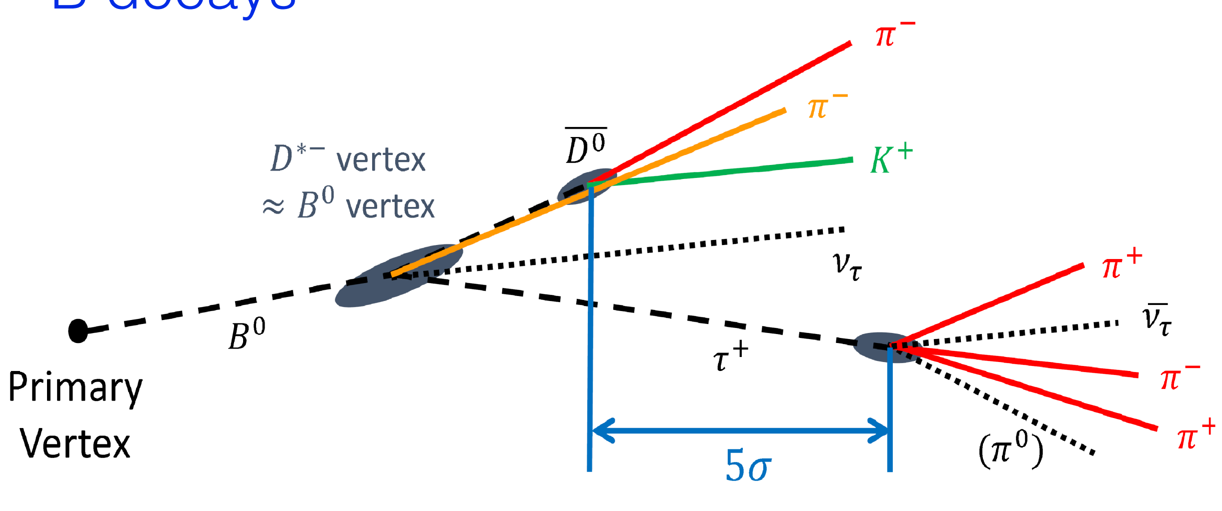
Combination is 3.9$\sigma$ away from the SM value

# Prospects for other final states

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

Good precision in **τ decay vertex** reconstruction

discriminate between signal and the most abundant **background** source due to hadronic B decays




Background coming from B→D*3**π**X can be suppressed by a factor $10^4$.

Remaining background is due to:

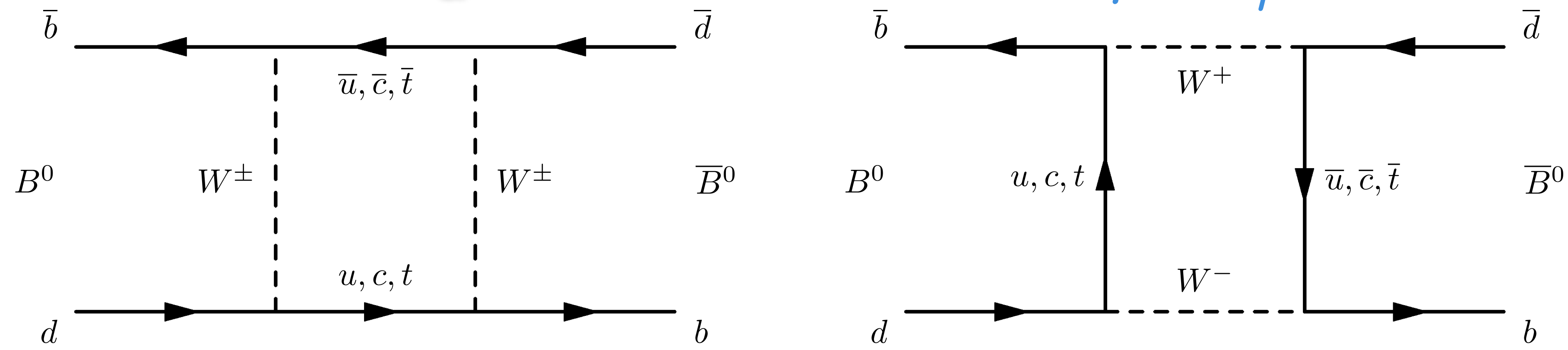
$B \to D^*(D_{(s)} \to 3\pi)X$

suppressed using isolation tools

- **LHCb can potentially measure semitauonic decays of all b hadrons e.g.:**
  - $B_c \to J/\psi\tau\nu$
  - $B_s \to D_s\tau\nu$
  - $\Lambda_b \to \Lambda_c^{(*)}\tau\nu$
  - $B^0 \to D^+\tau\nu$
- **Targeting both muonic and hadronic τ modes**
- **R(D) (simultaneous measurement with R(D*)) on $D^{*+}$ and $D^0$ τν final states**

# $\Delta m_d$ with $B^0 \to D^{(*)-}\mu^+\nu_\mu$

[LHCB-CONF-2015-003]




$\Delta m_d$ → (related to) **CKM matrix elements $V_{tb}$ and $V^*_{td}$** → (probes of) **CP violation**

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

- **High branching fraction**
- **LHCb high efficient lepton identification**
- **LHCb flavor tagging capabilities**

→ **High statistics samples**

# Δm$_d$ with $B^0 \to D^{(*)-}\mu^+\nu_\mu$

[LHCB-CONF-2015-003]

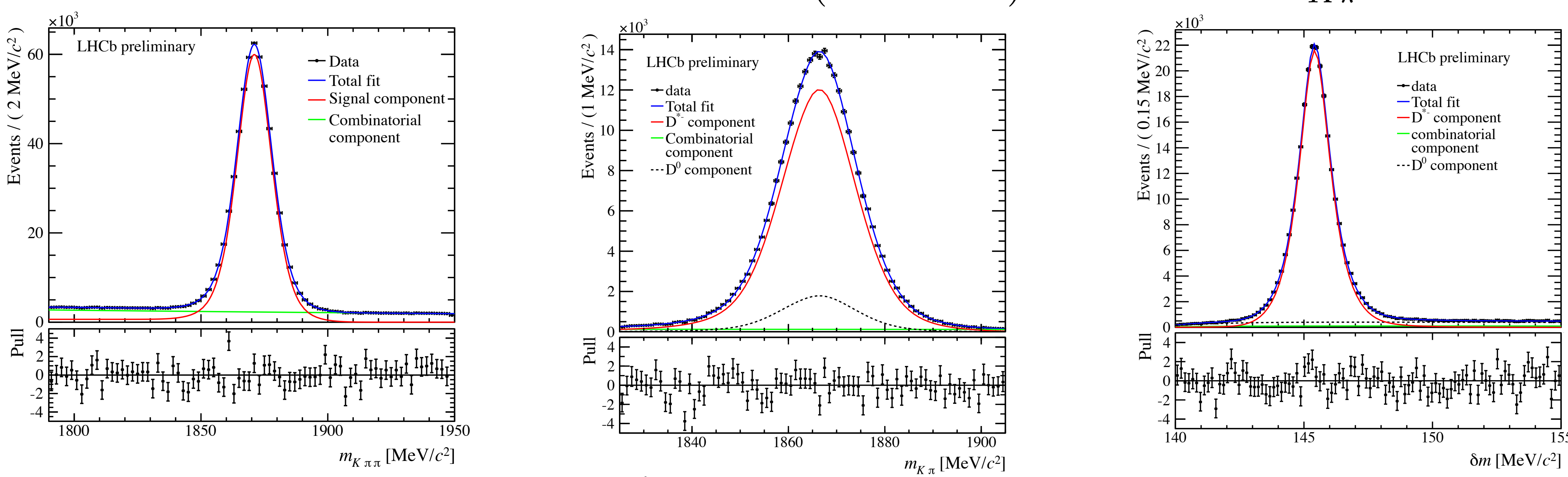
- Time dependent flavor asymmetry $A(t) = \frac{N^{\rm Unmix}(t) - N^{\rm mix}(t)}{N^{\rm Unmix}(t) + N^{\rm mix}} = cos(\Delta m_d t)$

$N^{\rm Unmix}(t) = N(B^0 \to D^{(*)-}\mu^+\nu_\mu X)(t) \propto e^{-\Gamma_d t}[1 + cos(\Delta m_d t)]$ **B$^0$ the same at production and at decay time**

$N^{\rm Mix}(t) = N(B^0 \to \bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu X)(t) \propto e^{-\Gamma_d t}[1 - cos(\Delta m_d t)]$ **opposite B$^0$ at production and at decay time**

- Flavour tagging: the events are grouped into 4 categories of increasing mistag in order to increase the statistical precision.

$D^- \to K\pi\pi$ $\quad$ $D^{*-} \to D^0(\to K^-\pi^+)\pi^-$ 2D fit in $m_{K\pi}$ and $\delta m = m_{D^*} - m_{D^0}$




yields (2011 data) for $D^-(5.73 \pm 0.02) \times 10^5$ for $D^*(2.447 \pm 0.007) \times 10^5$
yields (2012 data) for $D^-(1.598 \pm 0.003) \times 10^6$ for $D^*(5.758 \pm 0.010) \times 10^5$

L = 3fb$^{-1}$

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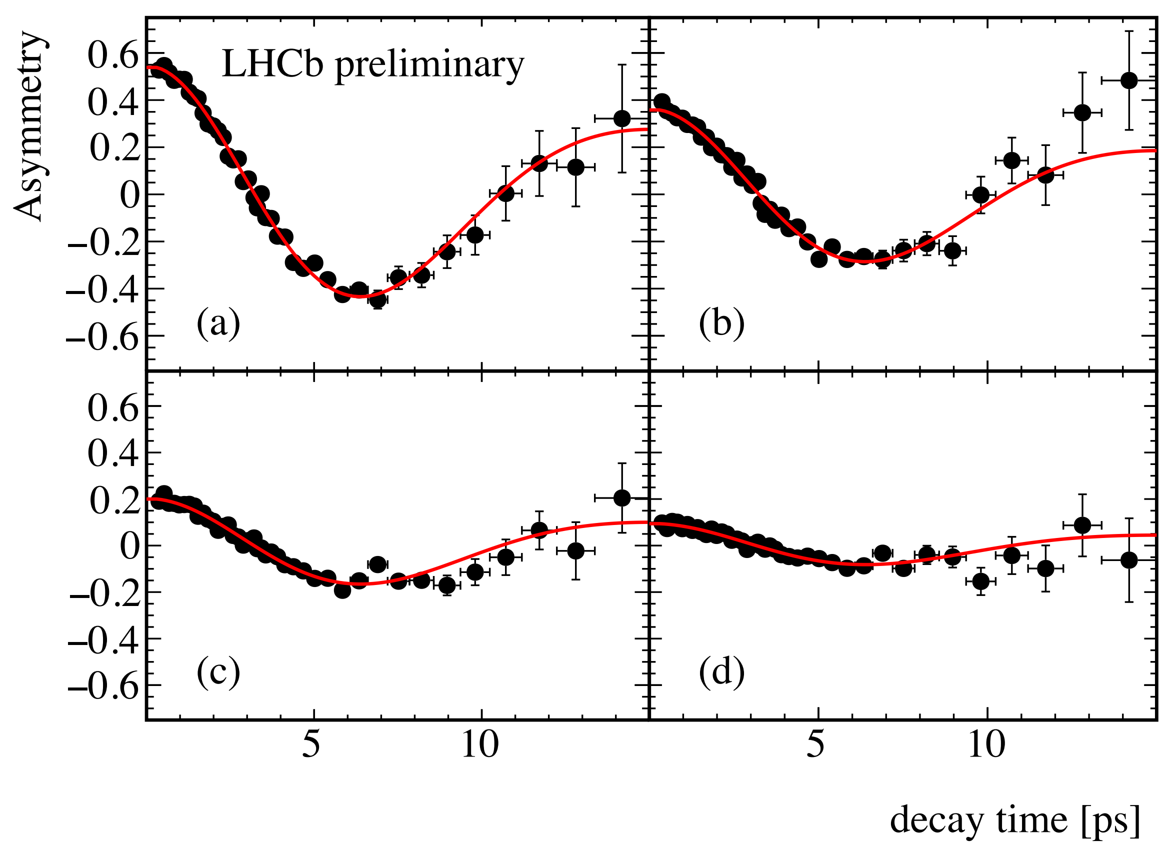
# $\Delta m_d$ with $B^0 \to D^{(*)-}\mu^+\nu_\mu$

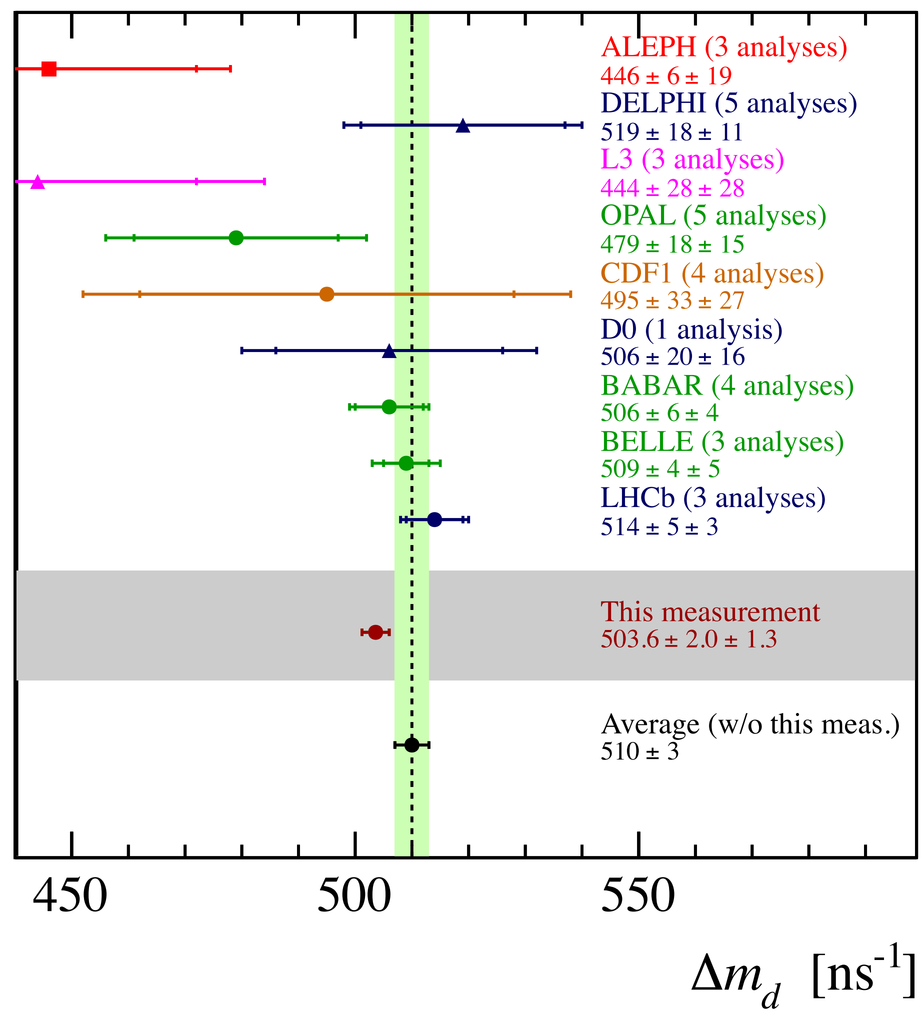
[LHCB-CONF-2015-003]

- **Dominant background** is due to $B^+ \to D^-\mu^+\nu_\mu X$ and $B^+ \to D^{*-}\mu^+\nu_\mu X$ decays, reduced with a Boosted Decision Tree that exploits topological differences between signal and background; combinatorial background is studied from $D^{(*)}$ mass sidebands
- Combination of the two signal channels results using the full dataset gives:

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

- World average **[HFAG]**
- $\Delta m_d = (510 \pm 3)ns^{-1}$ (without this measurement)
  $\Delta m_d = (505.5 \pm 2.0)ns^{-1}$ (with this measurement)



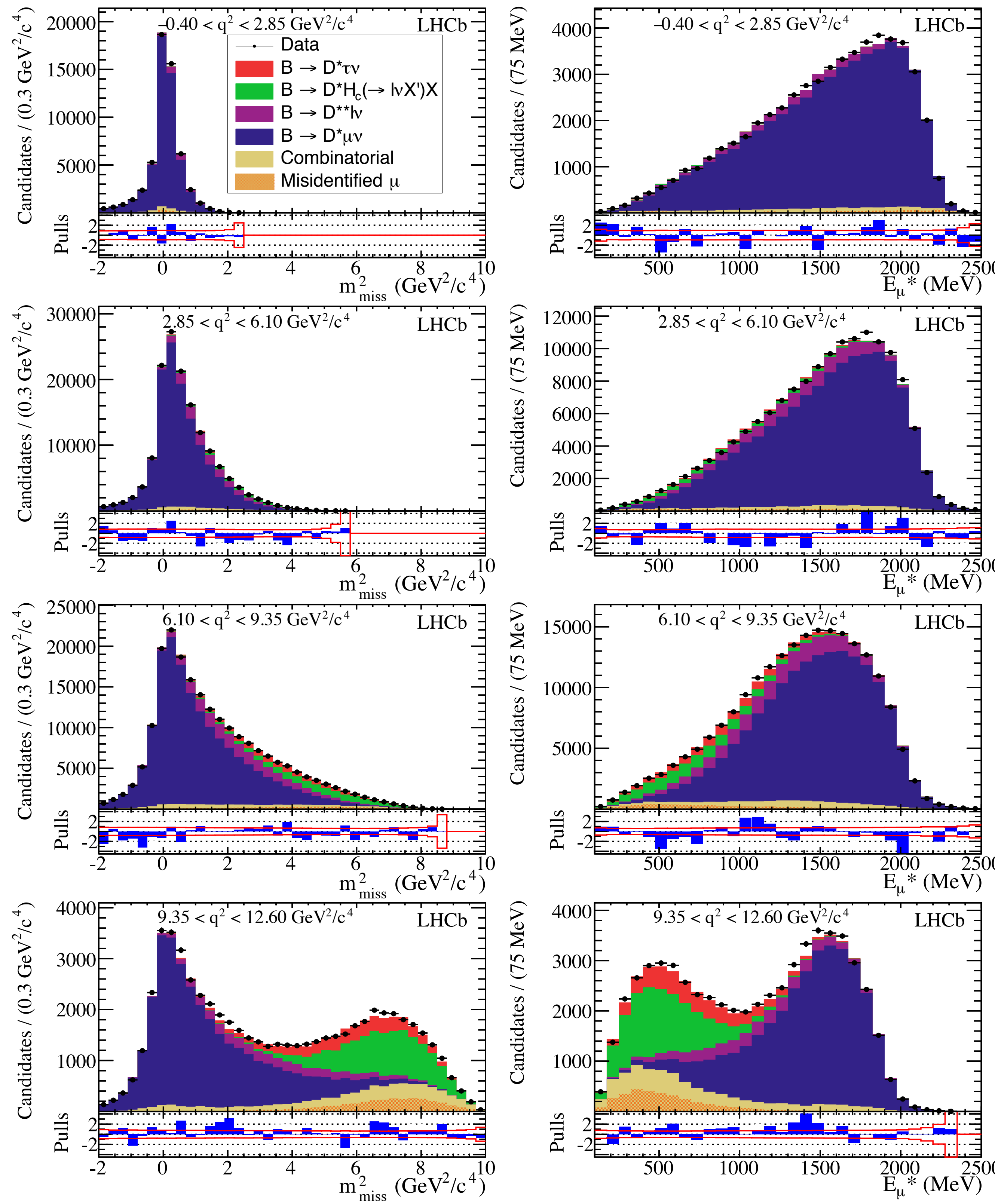
# Conclusions

- LHCb provides many interesting results in the semileptonic b decays
- LHCb performed the measurement of $R(D^*)$ in muonic tau decays:
  - Combination of $R(D^*)$ and $R(D)$ from Belle, BaBar and LHCb provide a $3.9\sigma$ deviation from the standard model values;
- A measurement in hadronic tau decay mode is ongoing:
  - advantages with respect to muonic channel thanks to 3 charged particles in final state;
- Most precise $\Delta m_d$ measurement

# Backup Slides

- The fit results in a uncorrelated ratio yield of the two decays $N(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = (4.54 \pm 0.46) \times 10^{-2}$

# Muonic R(D*)



# Δm$_d$ with $B^0 \to D^{(*)-}\mu^+\nu_\mu$

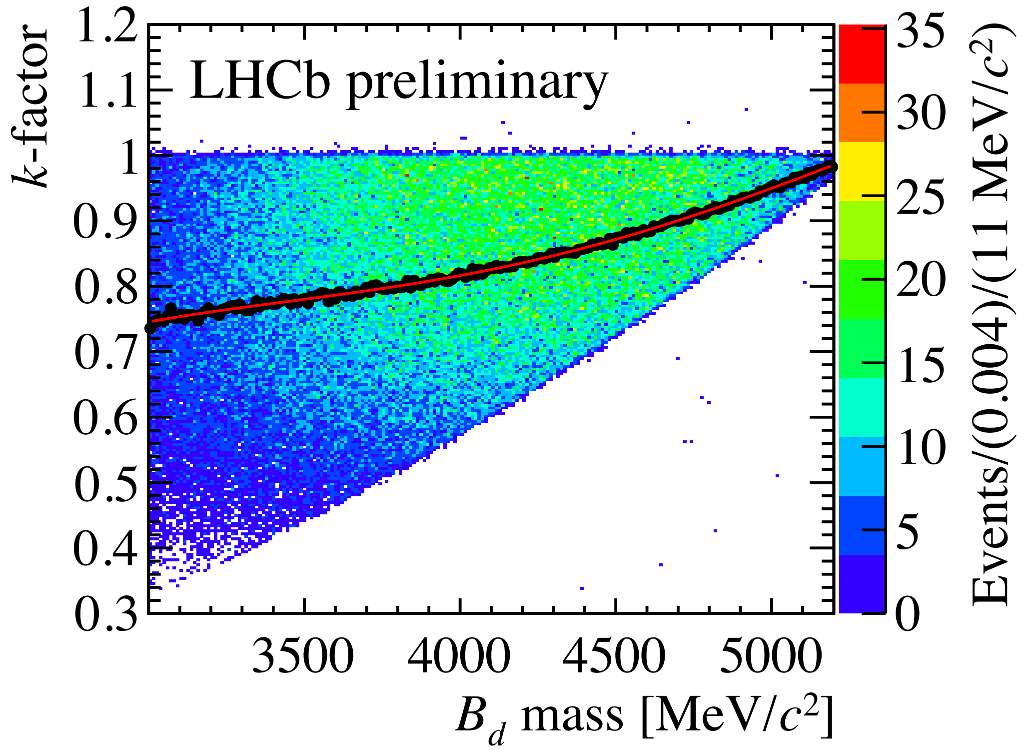
[LHCB-CONF-2015-003]

- Measured decay time requires a correction due to the missing neutrino in the final state as a function of the $D^{(*)}\mu$ invariant mass, determined from the simulation

$$k(m_{D^{(*)}\mu}) = p^{rec}_{D^{(*)}\mu}/p^{true}$$

- Apply correction on data $\quad t_{corr} = \frac{L_B M_{B^0_{PDG}}}{p^{rec}_{D^{(*)}\mu}} \times k(m_{D^{(*)}\mu})$

simulated $B^0 \to D^{*-}\mu^+\nu_\mu X$

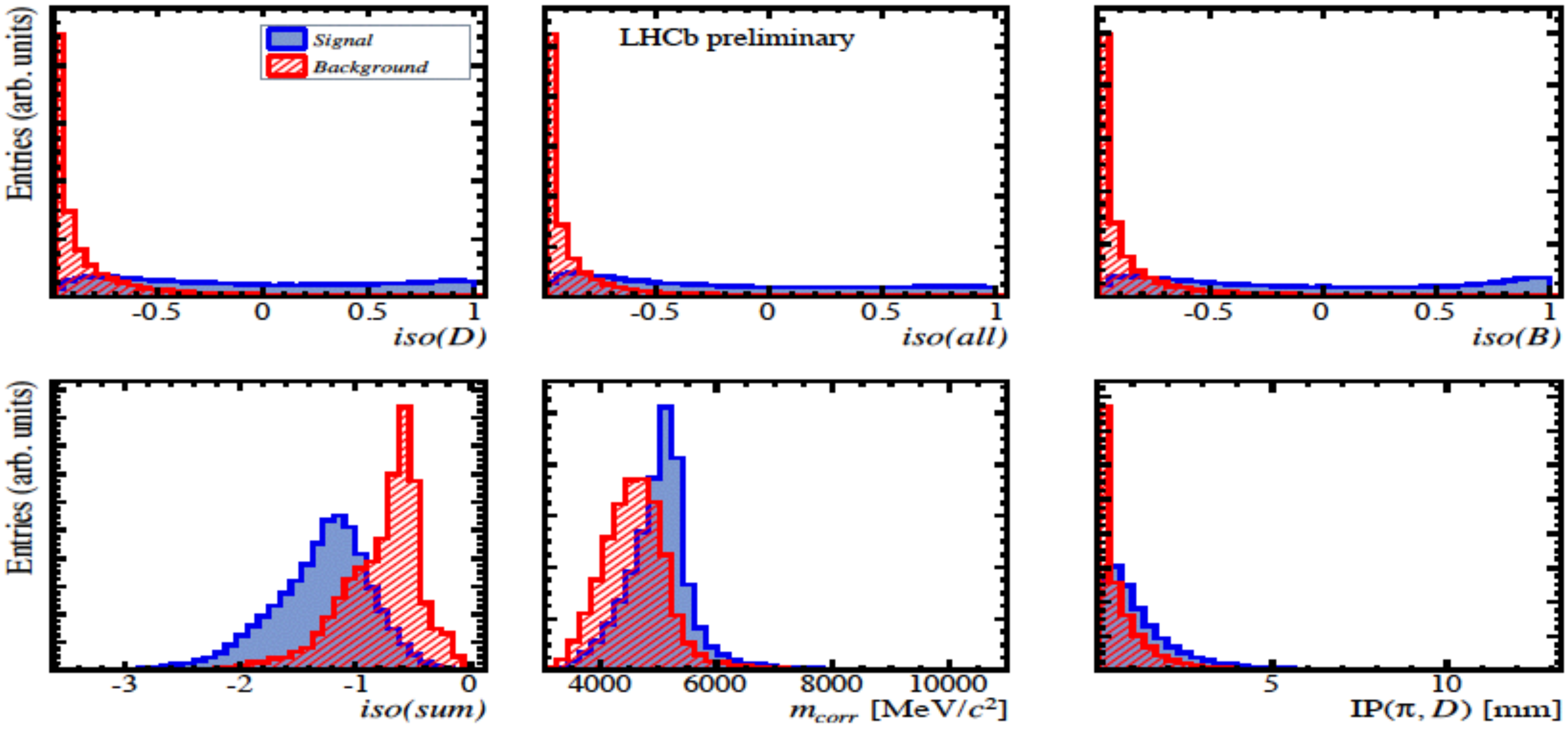


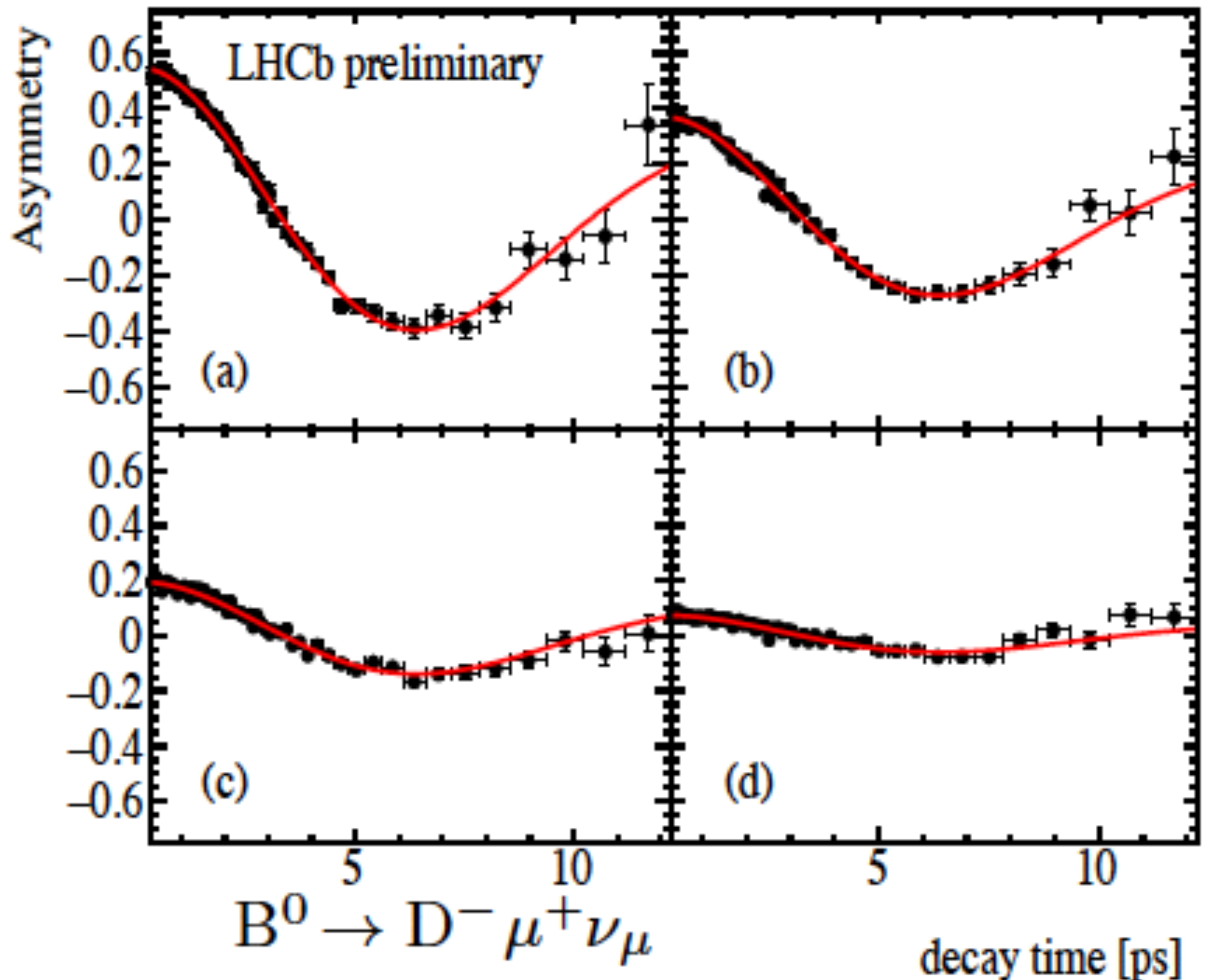

- k-factor depends on the decay kinematics, it is parametrized by a fourth order polynomial depending on the visible mass of the B candidate.
- This is an average correction that addition resolution function F(k), dominant above 1.5 ps

$$N^{(Un)mix}(t) \propto e^{-\Gamma_d t}(1 + q_{\text{mixing}}(1-2\omega)cos(\Delta m_d t)) \otimes R(t) \otimes F(k)$$

decay length resolution model ← $R(t)$

# Most discriminating variables for the isolation BDT in $\Delta m_d$ measurement






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

2012 data

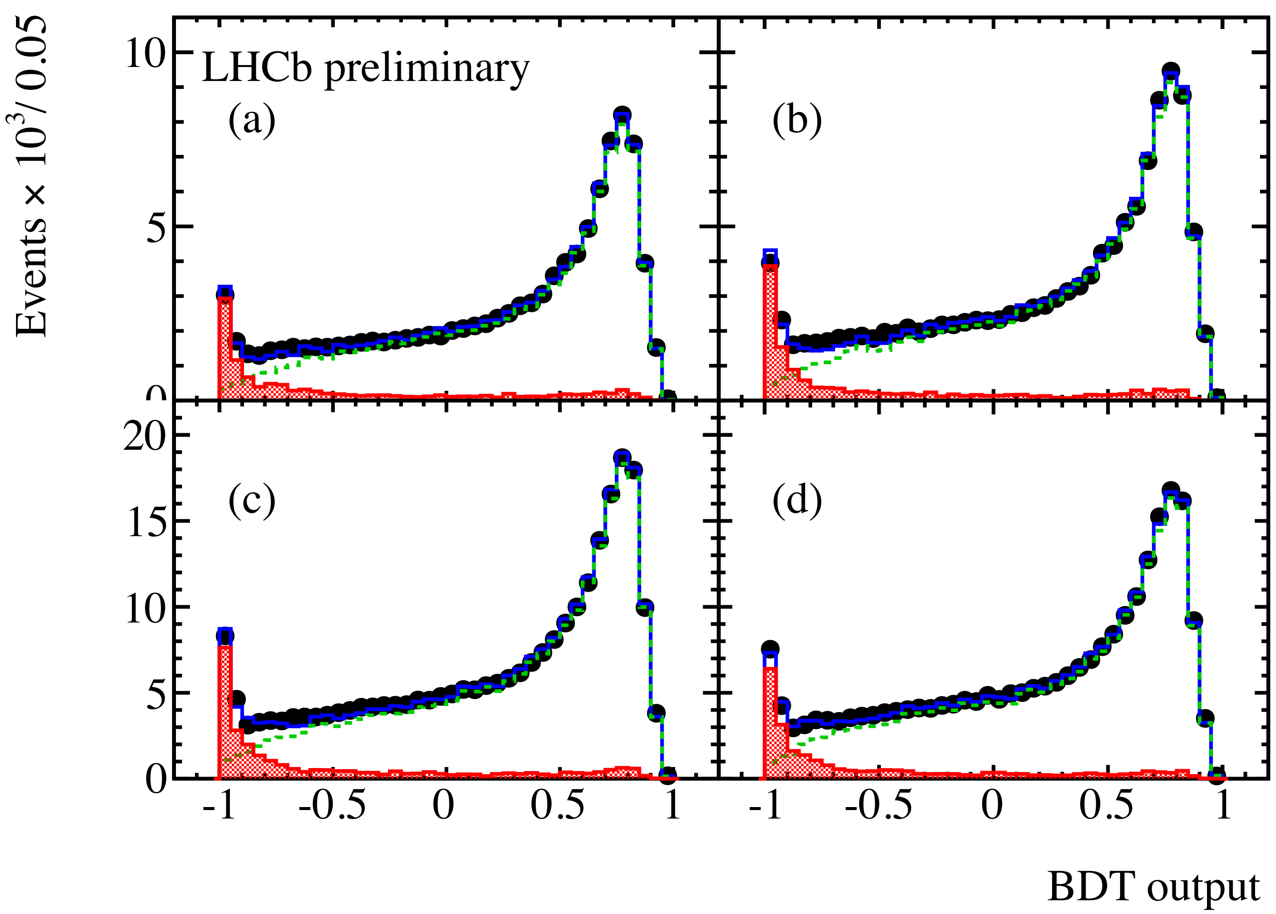
# Δm_d with $B^0 \to D^{(*)-}\mu^+\nu_\mu$

- **Dominant background** is due to $B^+ \to D^-\mu^+\nu_\mu X$ and $B^+ \to D^{*-}\mu^+\nu_\mu X$ decays, reduced with a Boosted Decision Tree that exploits topological differences between signal and background; combinatorial background is studied from $D^{(*)}$ mass sidebands

- Retained 90% of signal and reduced $B^+$ background by 70%, the remaining $B^+$ background fraction is determined from the fit to the BDT distribution.

- Fits to the output of the $B^+$ veto BDT for $B^+ \to D^{*-}\mu^+\nu_\mu X$ for each tagging category.

Filled red histogram, dashed green line and blue line correspond to background, signal and total templates respectively

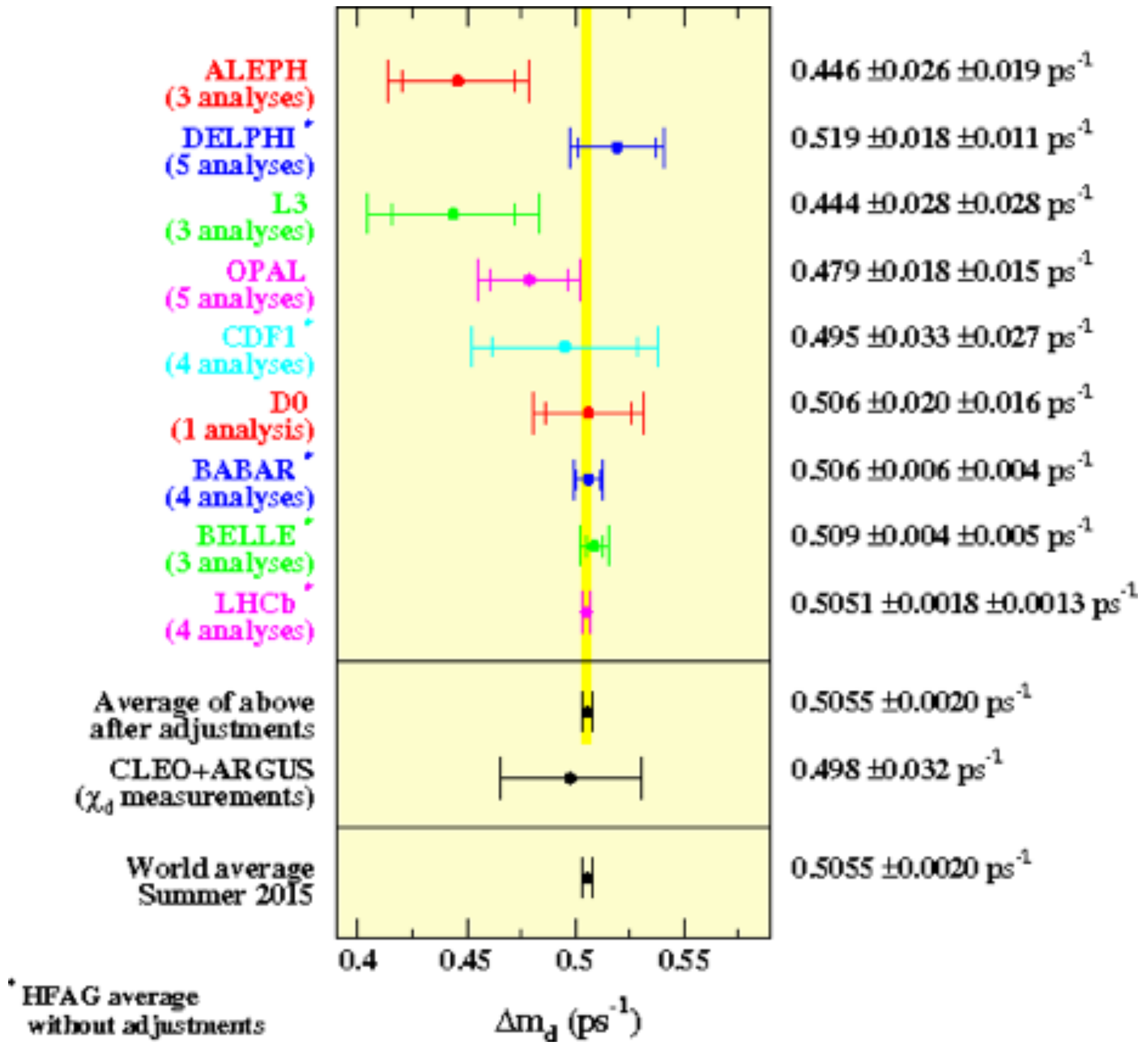


- Several sources of systematic uncertainties such as k-factor, B+ and other background fractions, time acceptance, etc, studied with parametrized simulation.

Table 2: Sources of systematic uncertainties on $\Delta m_d$, separated into those that are correlated and uncorrelated between the two decay channels $B^0 \to D^- \mu^+ \nu_\mu X$ and $B^0 \to D^{*-} \mu^+ \nu_\mu X$.

| Source of uncertainty | $B^0 \to D^- \mu^+ \nu_\mu X$ [ns$^{-1}$] | | $B^0 \to D^{*-} \mu^+ \nu_\mu X$ [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 |

# Updated $\Delta m_d$ world average after LHCb measurement

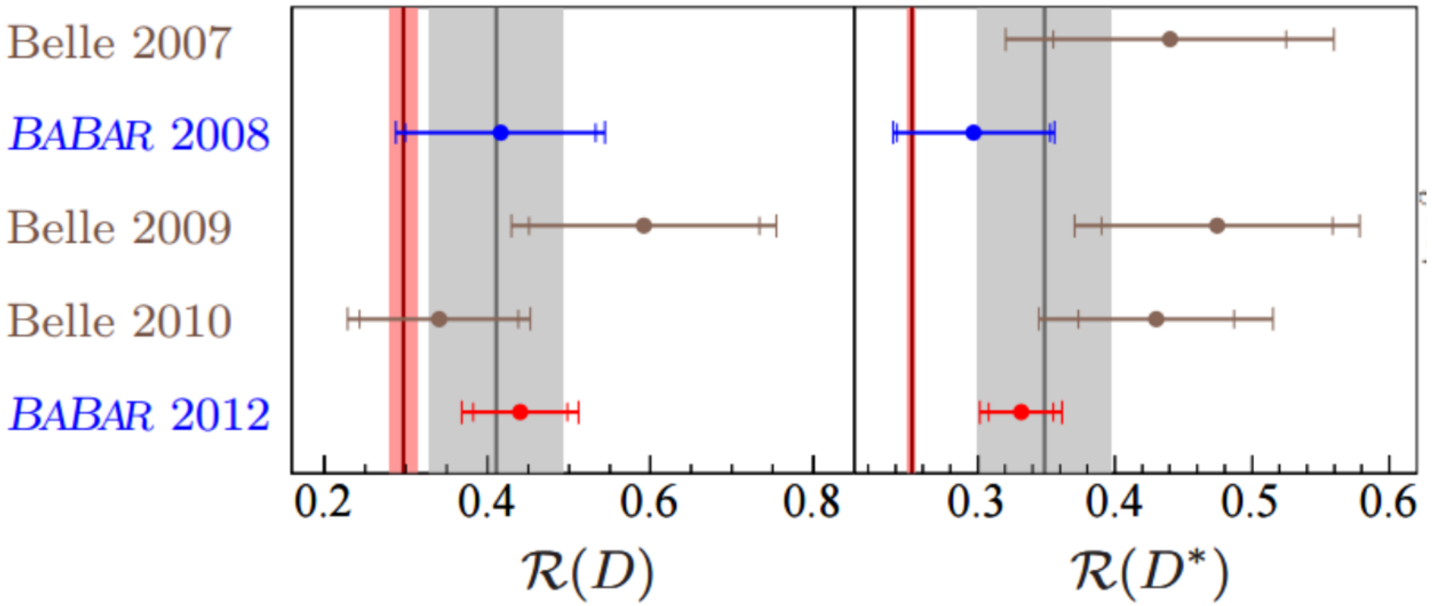


# B hadron semileptonic decays in tau leptons final states

$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\tau)} \qquad R(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^{+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{+}\mu^-\bar{\nu}_\tau)}$$

**Expected Standard Model values are:**

$$R(D^*) = 0.252 \pm 0.003 \qquad R(D) = 0.297 \pm 0.017$$




Experimental results at the beginning at 2015 are in tension with the Standard Model prevision [Fajfer et al., 2012], in particular, in 2012 *BaBar* experiment found a discrepancy of 2.7**$\sigma$** from the SM for R(D*)

[Lees et al., 2012]
[Bozek et al., 2010]