B_s^0 lifetime measurement using semileptonic decays at the LHCb experiment

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Motivation

- Measurement of b-hadron lifetimes provide stringent test and tuning of effective models of QCD at low-energy transfer (e.g. HQET).
- Effectiveness of such QCD models can limit the prediction power in many indirect searches for physics beyond the SM.
- More accurate lifetime measurements help to reduce QCD-related uncertainties, which sharpen our probes into new physics.
- Thanks to large statistics, semileptonic decays offer the highest potential for the ultimate lifetime precisions.

Goal: effective lifetime

- Goal: Probe the difference between two lifetimes

$$\Delta = \Gamma(B_s^0) - \Gamma(B^0)$$

  by using the decays **$B_s^0 \to D_s^-(\to K^+K^-\pi^-)\mu^+\nu$ and $B^0 \to D^-(\to K^+K^-\pi^-)\mu^+\nu$ as a reference**.

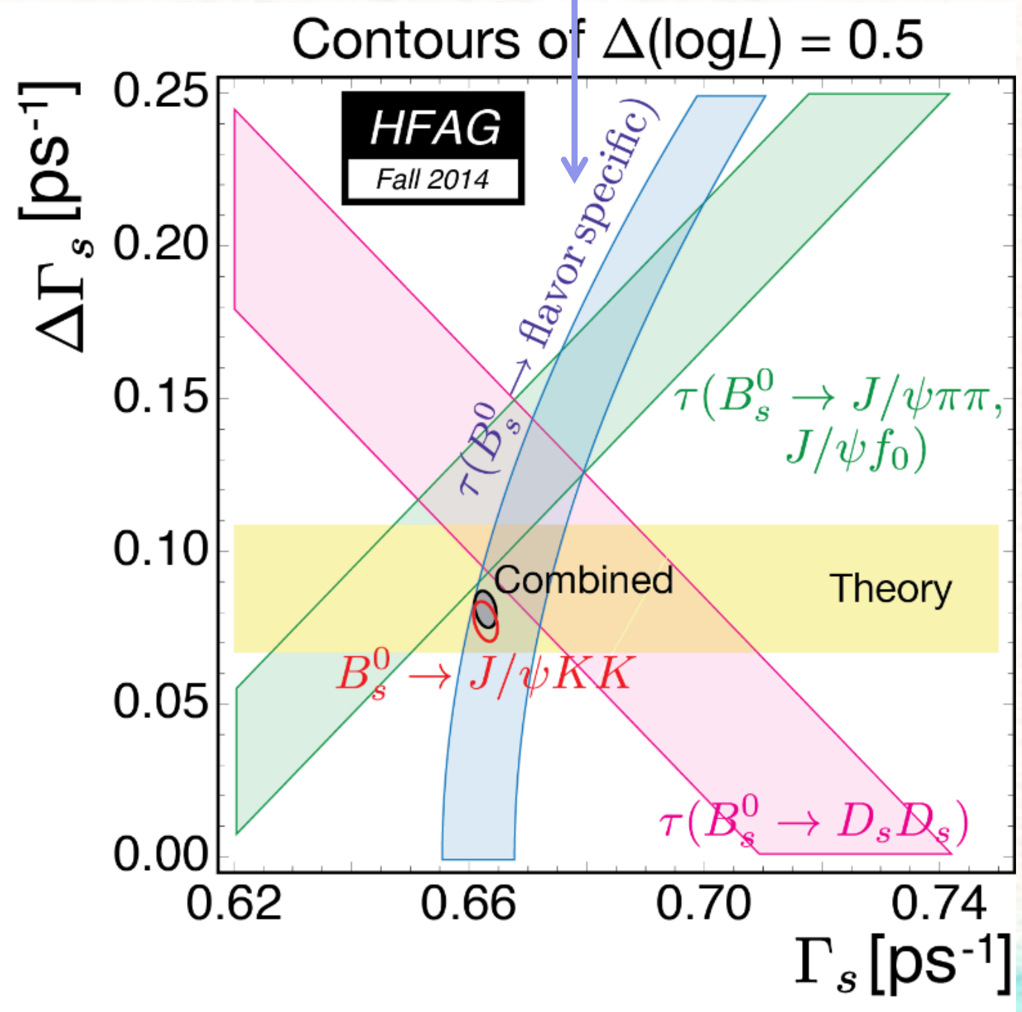
- For neutral B mesons, we distinguish two kinds of eigenstates:
  - Flavour eigenstates: B and $\overline{B}$
  - Mass and lifetime eigenstates: B_H and B_L
- These are flavour-specific decays: $B \to f$, $\overline{B} \to \overline{f}$
  - On average, we expect equal fraction of B_H and B_L at production.
  - For flavour-specific decays, it is common in this case to fit the decay time distribution with a single exponential
- Effective B^0_s lifetime, defined as: $\frac{1}{\Gamma^s_{\mathrm{FS}}} = \frac{1}{\Gamma_s}\left[\frac{\left(1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2\right)}{\left(1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2\right)}\right]$, where $\Gamma_s = (\Gamma_L + \Gamma_H)/2,\ \Delta\Gamma = \Gamma_L - \Gamma_H$

Status and method

- WA value: 1.511 ± 0.014 ps

Method: Fit the ratio of the decay time distributions to probe $\mathbf{\Delta = \Gamma(B_s^0) - \Gamma(B^0)}$.

- With B^0 lifetime as input (well-known), obtain the B_s^0 lifetime and the ratio between B_s^0 and B^0 lifetimes.
- Use of **same final states and similar kinematic properties** allows for a significant simplification in dealing with systematic uncertainties (mainly for the decay-time acceptances).
- Potential for competitive result if manage to control the systematic uncertainty.



Today: null-test

Perform the full analysis using

"signal" $B^0 \to D^-(\to K^+\pi^-\pi^-)\mu^+\nu$
"reference" $B^0 \to D^-(\to K^+K^-\pi^-)\mu^+\nu$

and measure

$$\Delta = \Gamma(B^0) - \Gamma(B^0) = 0$$

to validate the method with same precision of the target measurement (limited by the reference statistics).

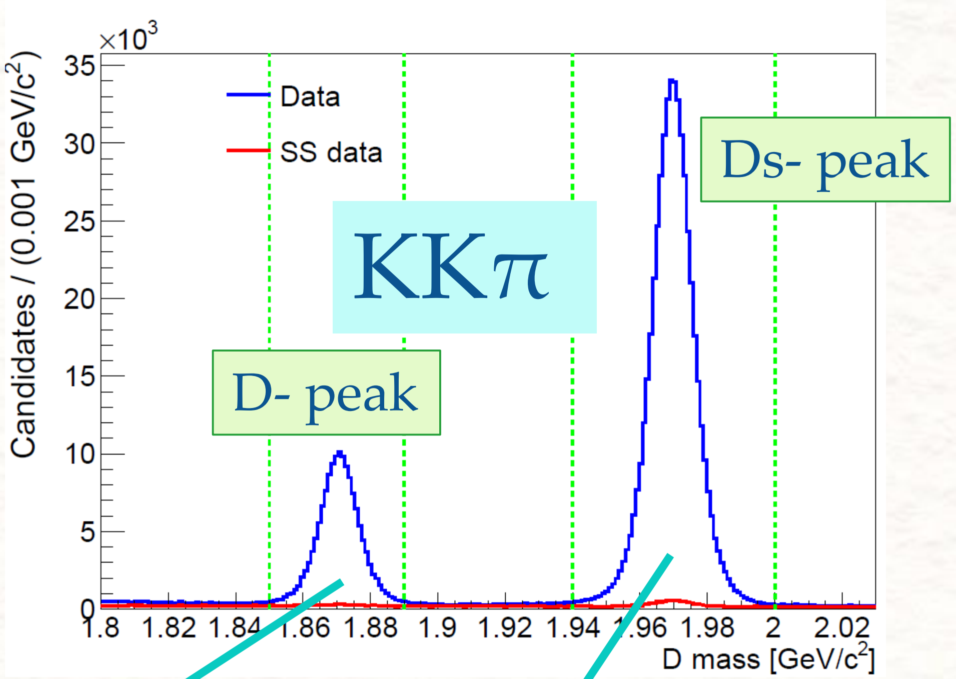
Will sketch the status of the B_s^0 signal in each step of the analysis.

Determination of the sample composition

Data samples

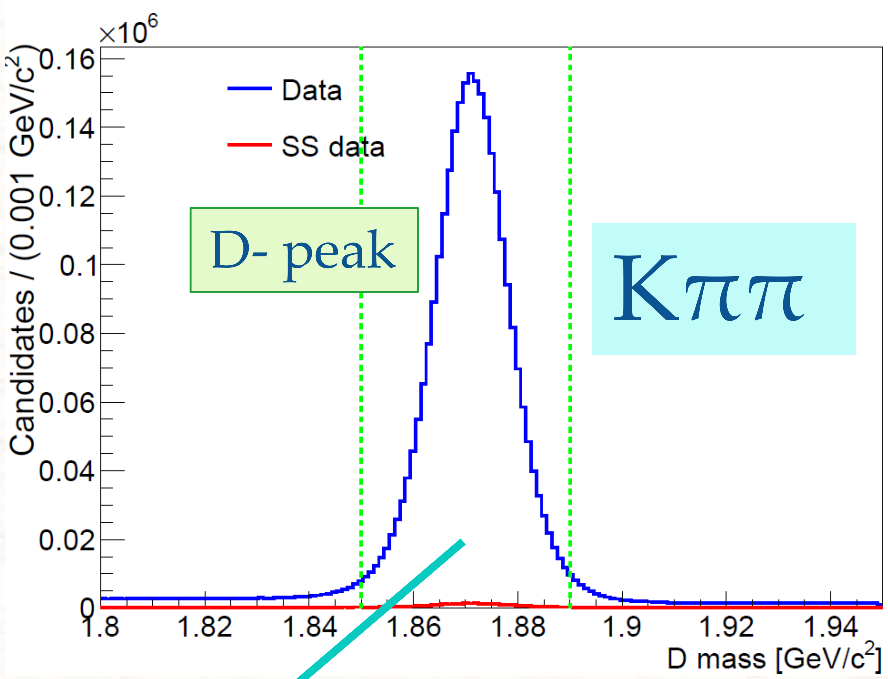
D mass
After selection

SS data:
$D_{(s)}+\mu+$,
$D_{(s)}+\mu+$ pairs

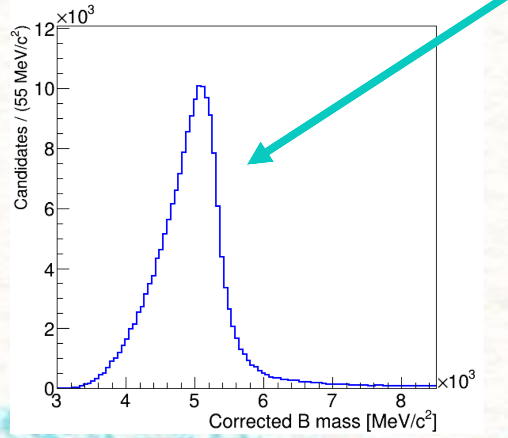


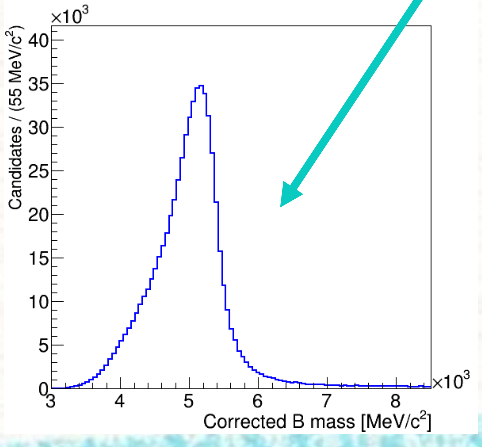
150k

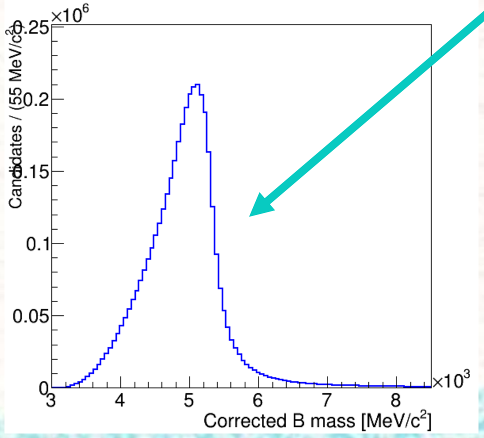
530k



2.8M







Corrected B mass
After selection

$$M_{cor}(B^0) = \sqrt{M_{vis}^2 + p_\perp^2} + p_\perp$$

$$p_\perp = |\mathbf{p_{vis}} - (\mathbf{p_{vis}} \cdot \hat{\mathbf{f}})\hat{\mathbf{f}}|$$

Corrected B mass fit: purpose

Fit the corrected B mass w/o considering decay time information to:

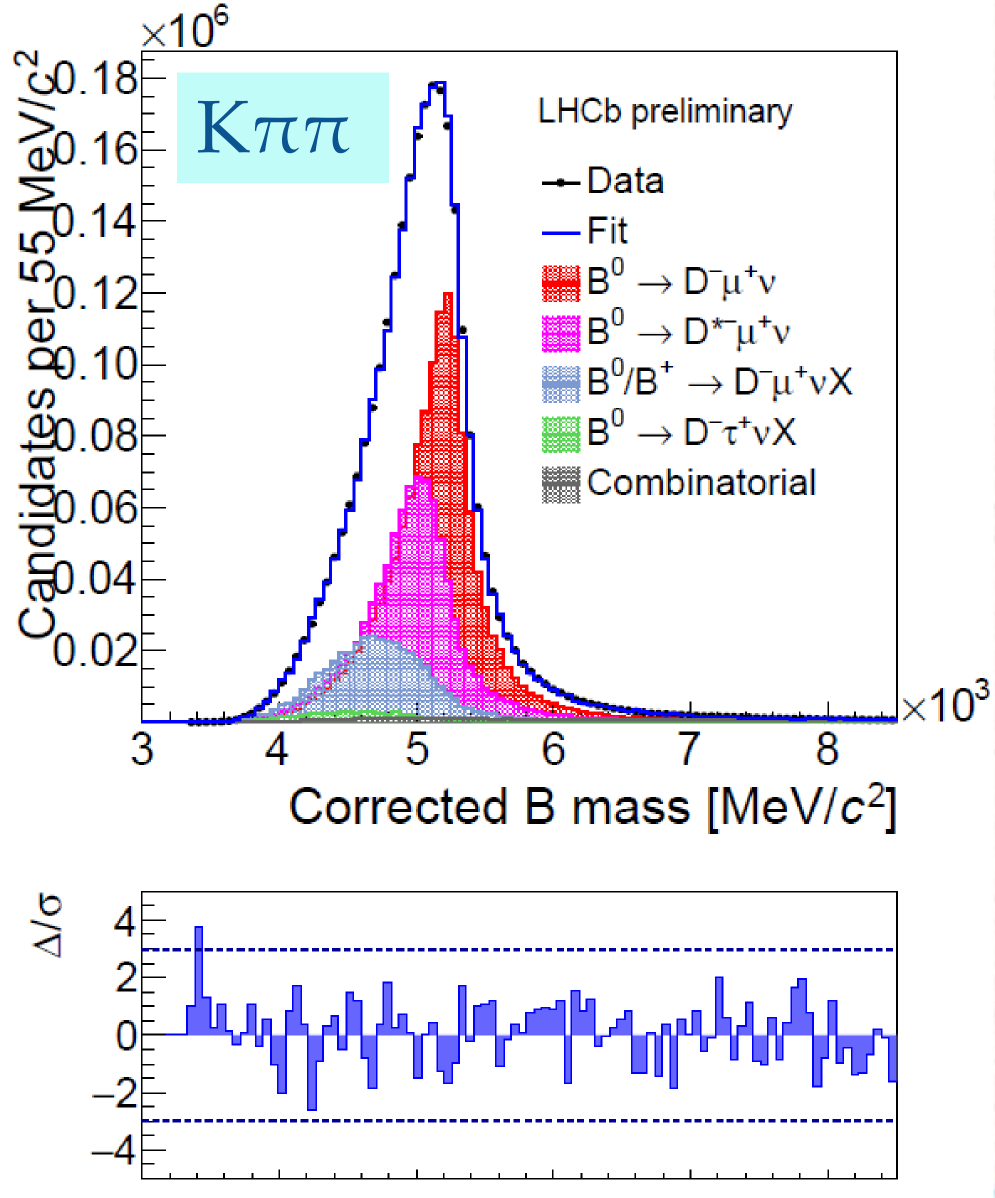
- Determine the background decays surviving the selection.
- Determine the signal composition
  - $B_{(s)}^0 \rightarrow D_{(s)}$-μν
  - $B_{(s)}^0 \rightarrow D_{(s)}^*$-μν
  - $B_{(s)}^0 \rightarrow D_{(s)}$-μνX
  - $B_{(s)}^0 \rightarrow D_{(s)}$-τνX
  - …

  Well-known for B^0, but limited knowledge for B_s^0.

Matching composition of the simulation with data is crucial to compute:

- the correction for missing momenta
- the decay time acceptances.

Mass fit results: B^0 case



Kππ: 2.8M candidates

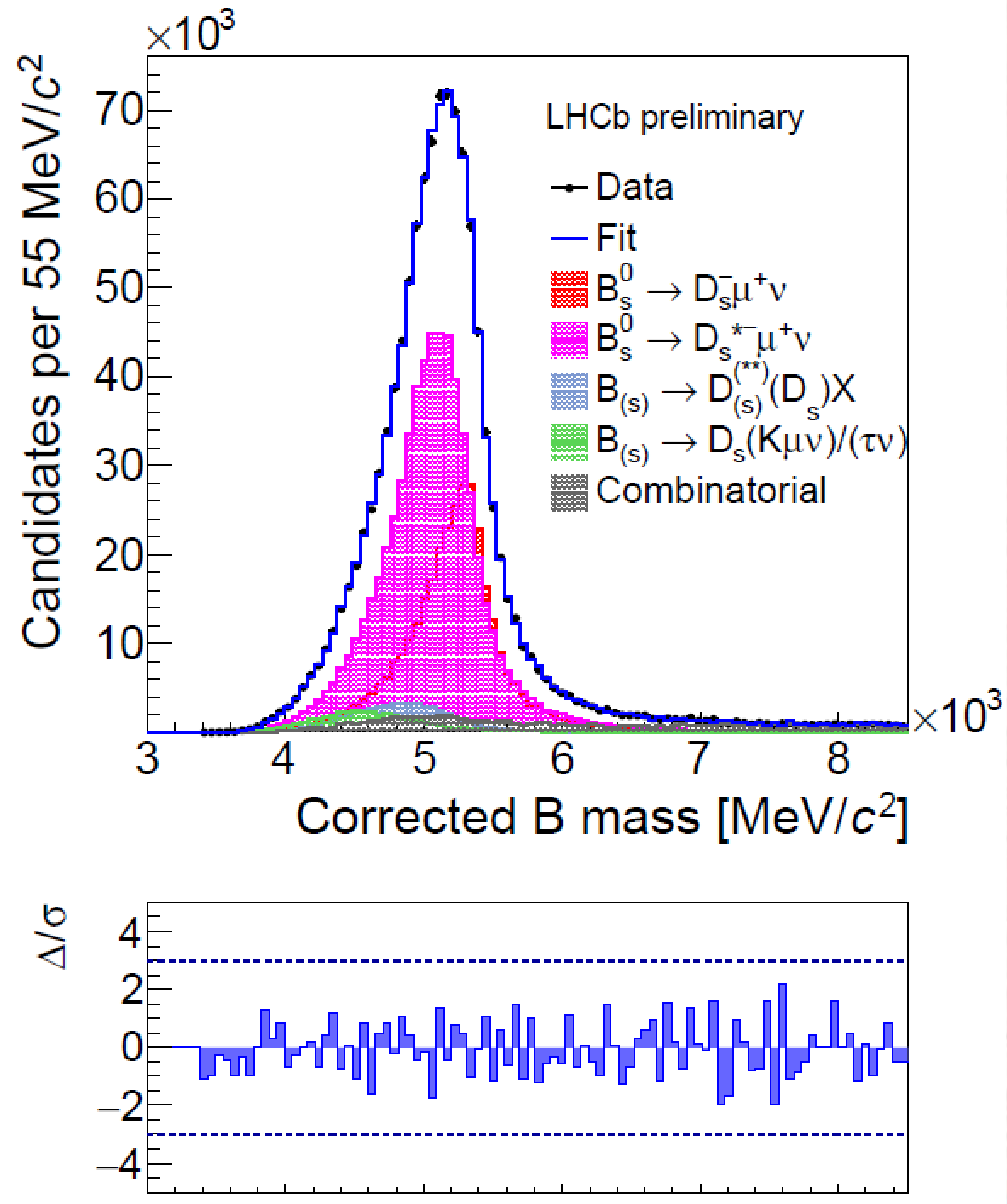
	Fit fraction [%]	Prediction [%]
$B^0 \to D^-\mu\nu$	49.0 ± 0.5	49.8 ± 2.7
$B^0 \to D^{*-}\mu\nu$	31.7 ± 0.9	32.7 ± 0.7
B^0 / B+ $\to D^-\mu\nu X$	14.8 ± 1.1	14.0 ± 1.6
$B^0 \to D^-\tau\nu X$	2.1 ± 0.7	1.2 ± 0.3
Combinatorial	2.4 ± 0.1	-

KKπ: 150k candidates

	Fit fraction [%]	Prediction [%]
$B^0 \to D^-\mu\nu$	45.2 ± 0.6	45.7 ± 2.5
$B^0 \to D^{*-}\mu\nu$	30.8 ± 0.9	30.9 ± 0.7
B^0 / B+ $\to D^-\mu\nu X$	13.6 ± 0.5	12.4 ± 1.5
Combinatorial	10.5 ± 0.3	-

- Good agreement of fit results compared to expectations.

Mass fit results: B_s^0 case



	Fit fraction [%]
$B_s^0 \to D_s\text{-}\mu\nu$	29.5 ± 0.7
$B_s^0 \to D_s^*\text{-}\mu\nu$	55.2 ± 1.2
$B_{(s)}^0 \to D_{(s)}(^{**})(Ds)X$	4.9 ± 0.9
$B_{(s)}^0 \to D_s\text{-}(K\mu\nu)/(\tau\nu)$	3.6 ± 0.3
Combinatorial	6.8 ± 0.2

- No measurement available to date on the BR of the B_s^0 components
  - Predictions not easily made, from B^0 measurement and flavour symmetries.

530k candidates

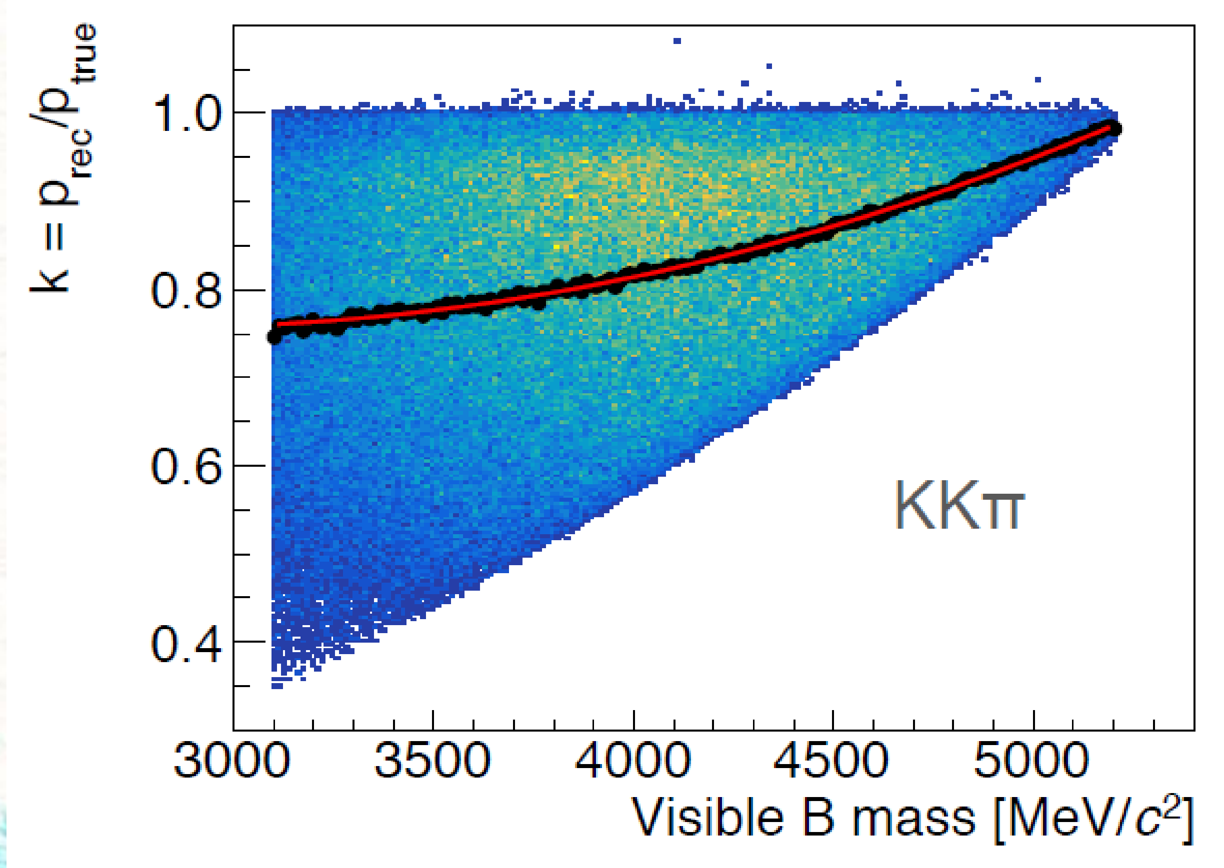
Measuring the yields in decay time bins

Missing momentum correction

K-factor: standard method to correct for the missing momentum in partially reconstructed decays.

Correction factor computed using **simulation only** (signal components only).

$$t = \frac{M_B \vec{d_B} \cdot \vec{p_B}}{|\vec{p_B}|^2}$$



- Compute $k = p_{rec}(D\mu) / p_{true}(B)$.
- Fit the k-factor k(m) as a function of the visible B mass, m(Dμ).
- Correct the decay time event by event:

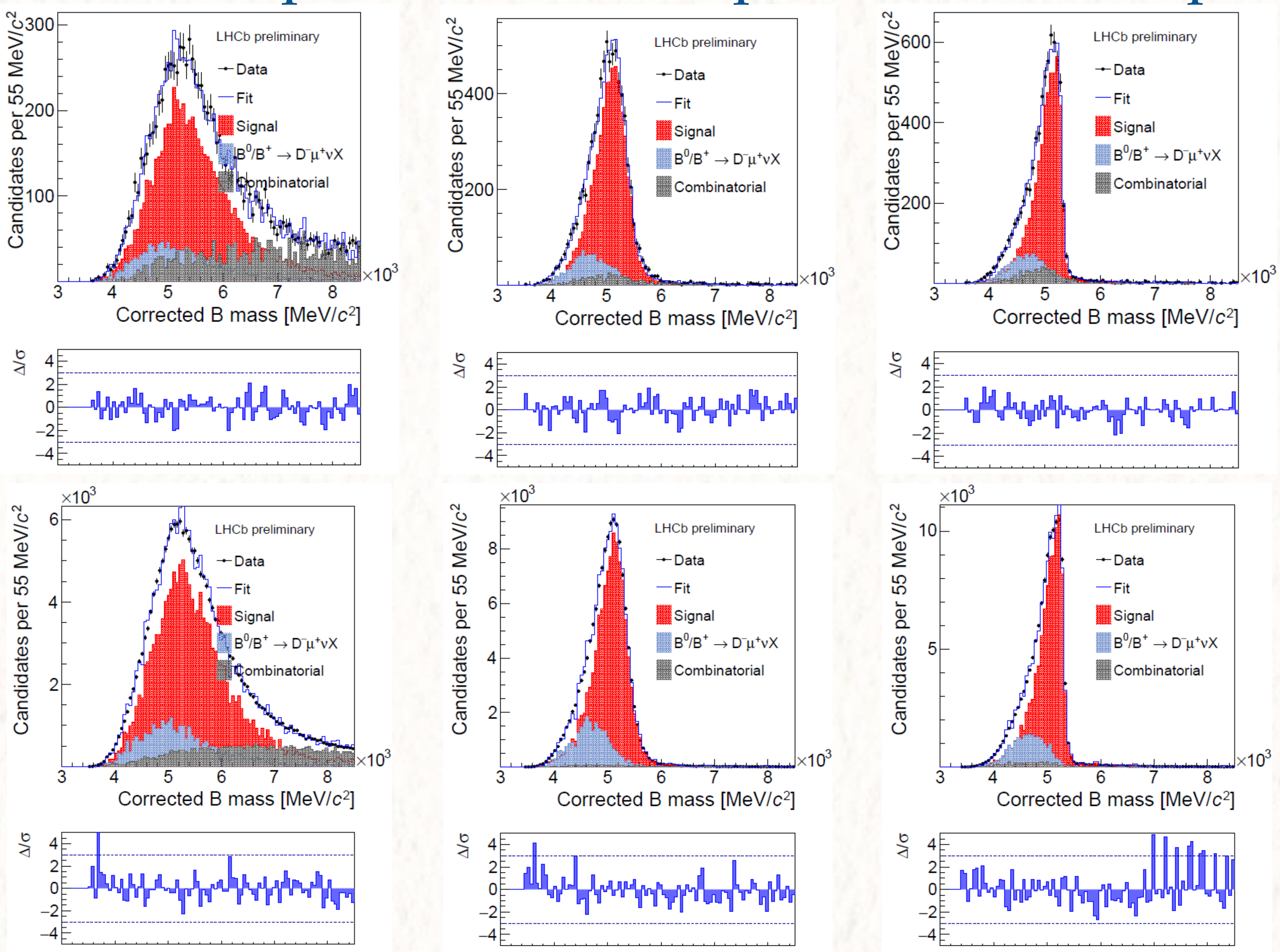
$$t_{corr} = t_{rec} \times k(m)$$

Examples of mass fits for the two B^0 samples

0.00-0.47 ps | 1.57-1.73 ps | 5.25-12.00 ps

$KK\pi$

$K\pi\pi$



Fit of the ratio of yields

Description of the fit

- Fit ratios of signal yields in bins of t_{corr} by minimizing

$$\chi^2 = \sum_{i}^{N_{\text{bins}}} \frac{(N_i - R_i D_i)^2}{\sigma_{N_i}^2 + R_i^2 \sigma_{D_i}^2}$$

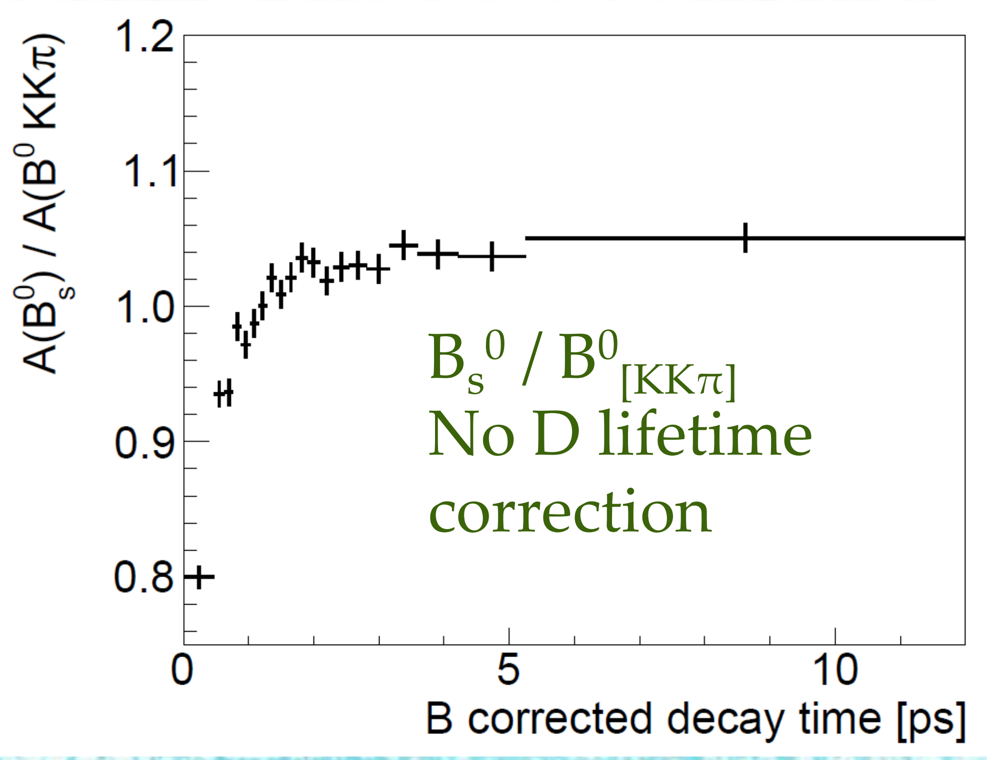
where N_i (D_i) is the yield of the numerator (denominator) in the bin i and R_i is the fitted time-dependent ratio containing the lifetimes and several experimental effects:

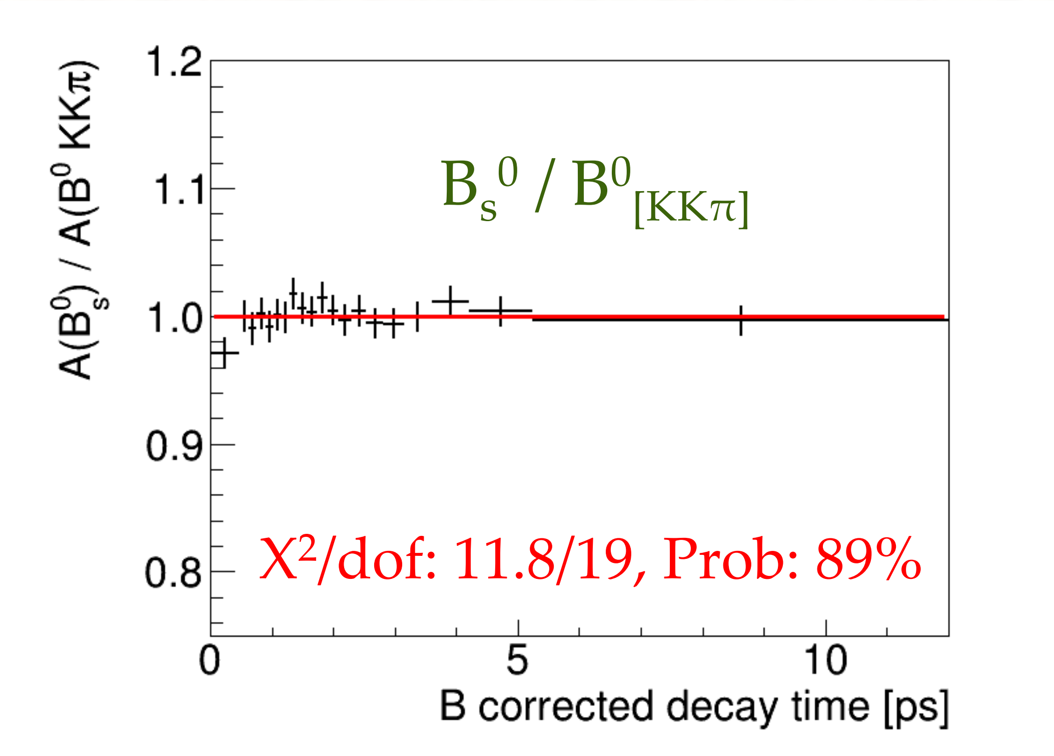
- The acceptances ratio, assumed constant in a decay-time bin
- Momentum resolution
- Flight-distance resolution ~70 fs (negligible)

Denominator: fix Γ to PDG value of $\Gamma(B^0)$
Numerator: fit $\Gamma = \Gamma(B^0) + \boldsymbol{\Delta}$

Acceptances ratio: B_s^0/B^0

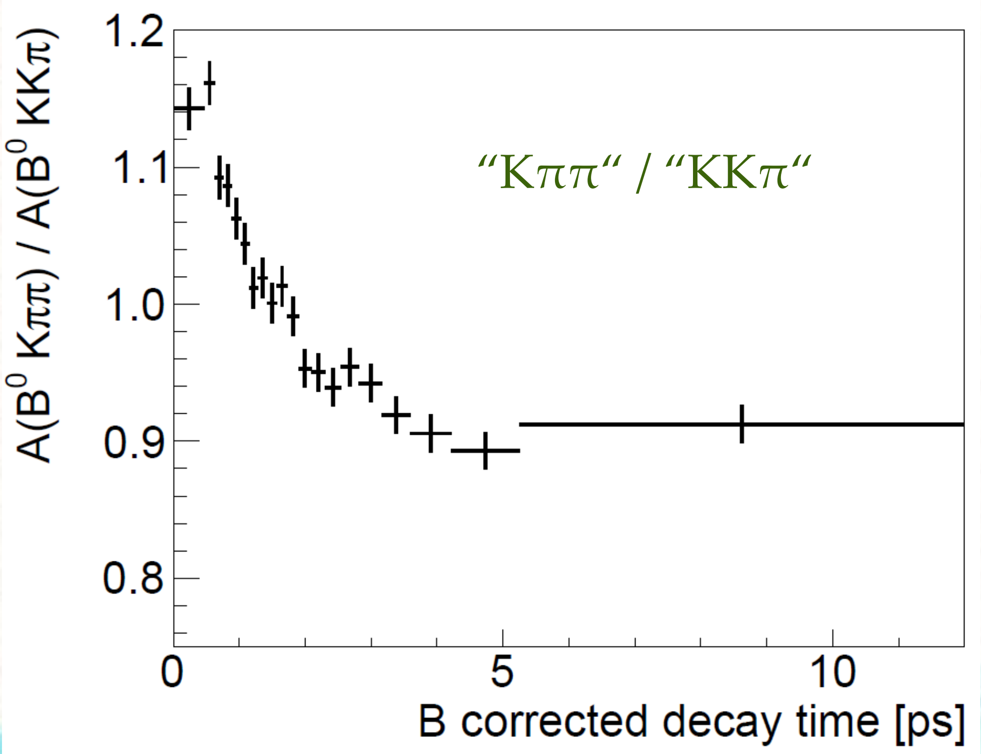
- Selection favours decays with close B and D vertexes (small D decay time).
- D- and D_s- have a different lifetime => different acceptances.
- Equalize acceptances by reweighing for the difference of D- and D_s- lifetimes.

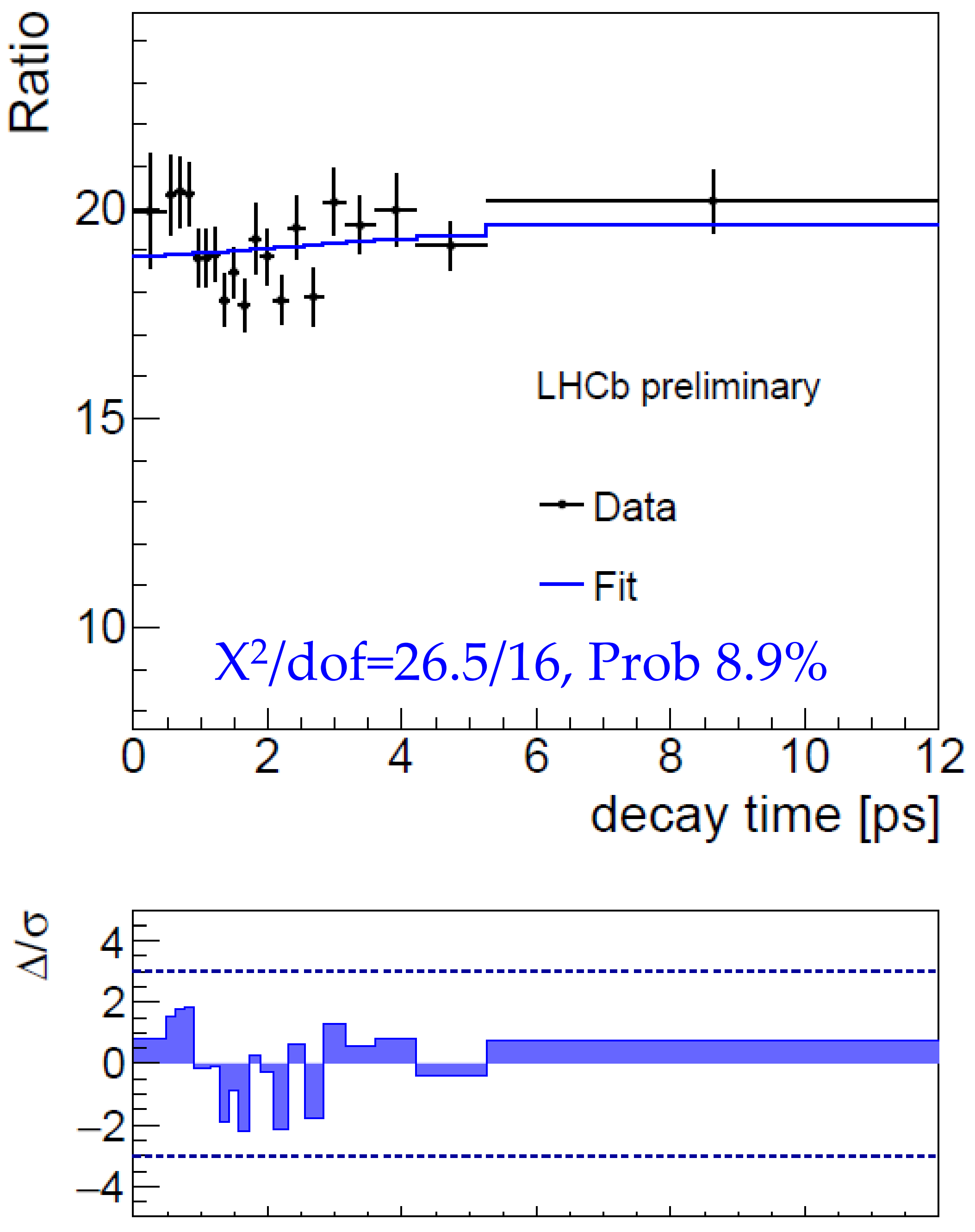




Acceptances ratio: $B^0(K\pi\pi)/B^0(KK\pi)$

- The acceptances ratio of the two B^0 acceptances varies by up to 20%, because of tighter requirements in the $K\pi\pi$ selection, leading to different momentum distributions.
- Plug the histogram in the fit (and propagate errors).
- A successful null-test proves a reliable MC description.





Null-test results

$$\mathbf{\Delta = (-5.7 \pm 5.9) \times 10^{-3}\ ps^{-1}},$$

which corresponds to

- Fitted $\tau(B^0) = 1.533 \pm 0.014$ ps
- PDG $\tau(B^0) = 1.520 \pm 0.004$ ps

Successful test despite the large 20% variation of the acceptances ratio, and a residual structure at low decay time

Conclusions and prospects

- Proposed and implemented a novel method for a measurement of the flavour-specific B_s^0 lifetime in semileptonic decays competitive with world best determinations.

- Null-test results are very encouraging and prove the reliability of the method.

- Now moving to complete the analysis of the B_s^0 decays.
  - Expected statistical uncertainty of 0.014 ps.
  - Expected systematic uncertainty ≤ 0.010 ps.
  - To be compared with current world-leading results
    - $1.479 \pm 0.010 \pm 0.021$ ps [PRL 114 (2015) 062001]
    - $1.535 \pm 0.015 \pm 0.014$ ps [PRL 113 (2014) 172001]

- Statistically limited: gives room for improvement in LHC Run II and beyond.

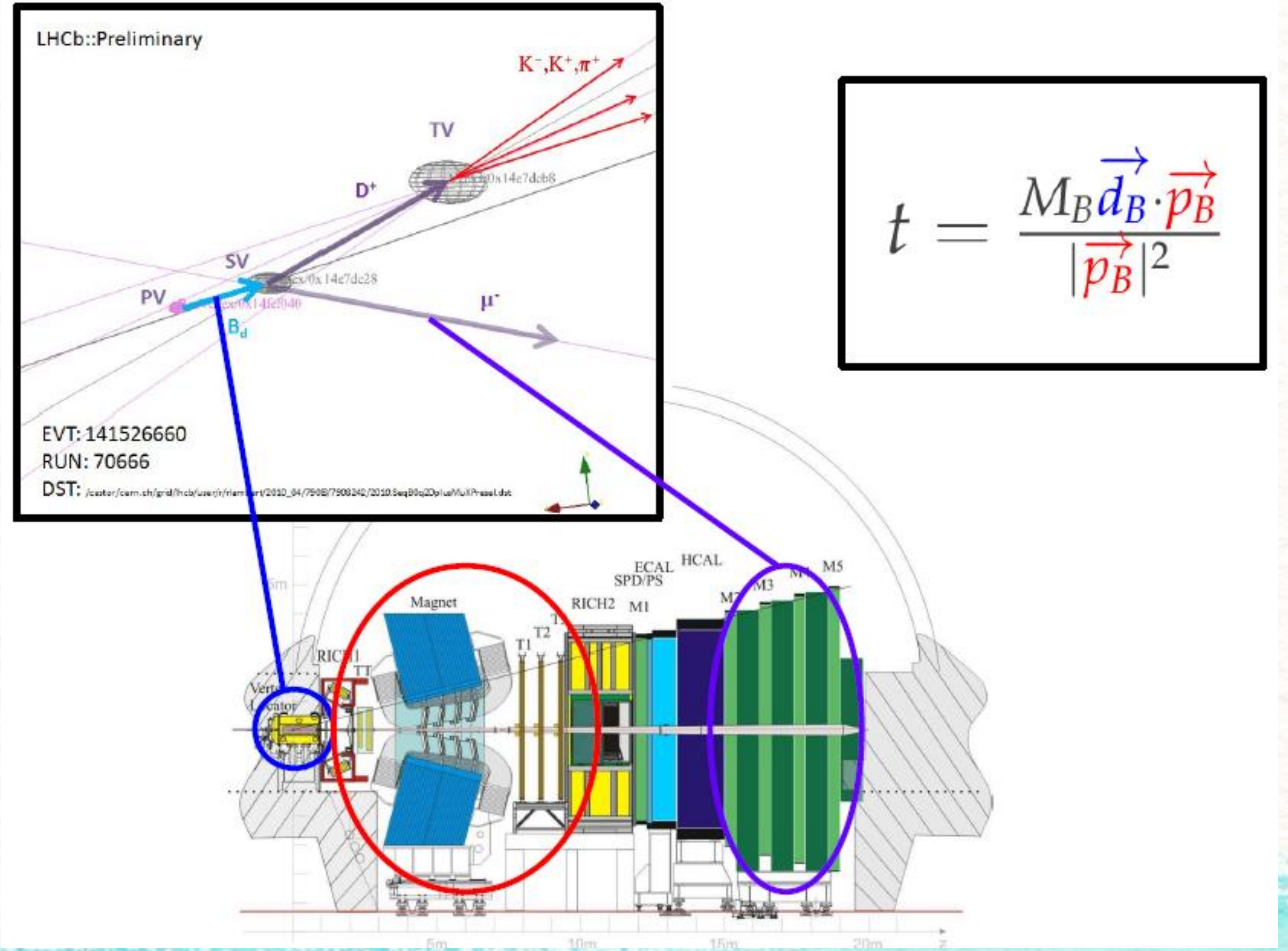
- Expect to converge by this fall.

BACKUP

Challenges of the measurement

- **Partial reconstruction** of an **inclusive final state**
  - Comprising the $B_s^0 \rightarrow D_s^- \mu^+ \nu$ signal, various signal-like decays ($B_s^0 \rightarrow D_s^{*-} \mu^+ \nu$, etc.), and other backgrounds.
- **No narrow B-mass discriminator** to disentangle the various contributions
  - Need an approximation of the invariant B mass.
- **Biased B decay times**
  - Missing the momenta of unreconstructed decay products.
  - Correct with simulations, after ensuring that it reproduces the signal composition.
- **Ensure same acceptances for B_s^0 and B^0**
  - Understand residual differences between the two samples (with simulations).
- **Cross-check with control data** the full method

Event selection and decay time determination



$$t = \frac{M_B \vec{d_B} \cdot \vec{p_B}}{|\vec{p_B}|^2}$$

Selection

- Select only TOS events of L0Muon, Hlt1 (TrackAllL0, TrackMuon, SingleMuonHighPT) and the «Mu» topological triggers at Hlt2 (Topo{2,3,4}MuNBody).
- Stripping v20r{0,1}
  p3: b2DsPhiPiMuXB2DMuNuX for $B_{(s)}^0 \to D_{(s)}^-(\to K^+K^-\pi^-)\mu^+\nu$
  p0: b2DpMuXB2DMuNuX for $B^0 \to D^-(\to K^+\pi^-\pi^-)\mu^+\nu$.
- Cut-based selection optimized to suppress background from misidentification for the $KK\pi$ sample.
- $K\pi\pi$ selection similar to $KK\pi$ but features tighter requirements, mainly at stripping level. Main source of differences between the $KK\pi$ and $K\pi\pi$ time acceptances.

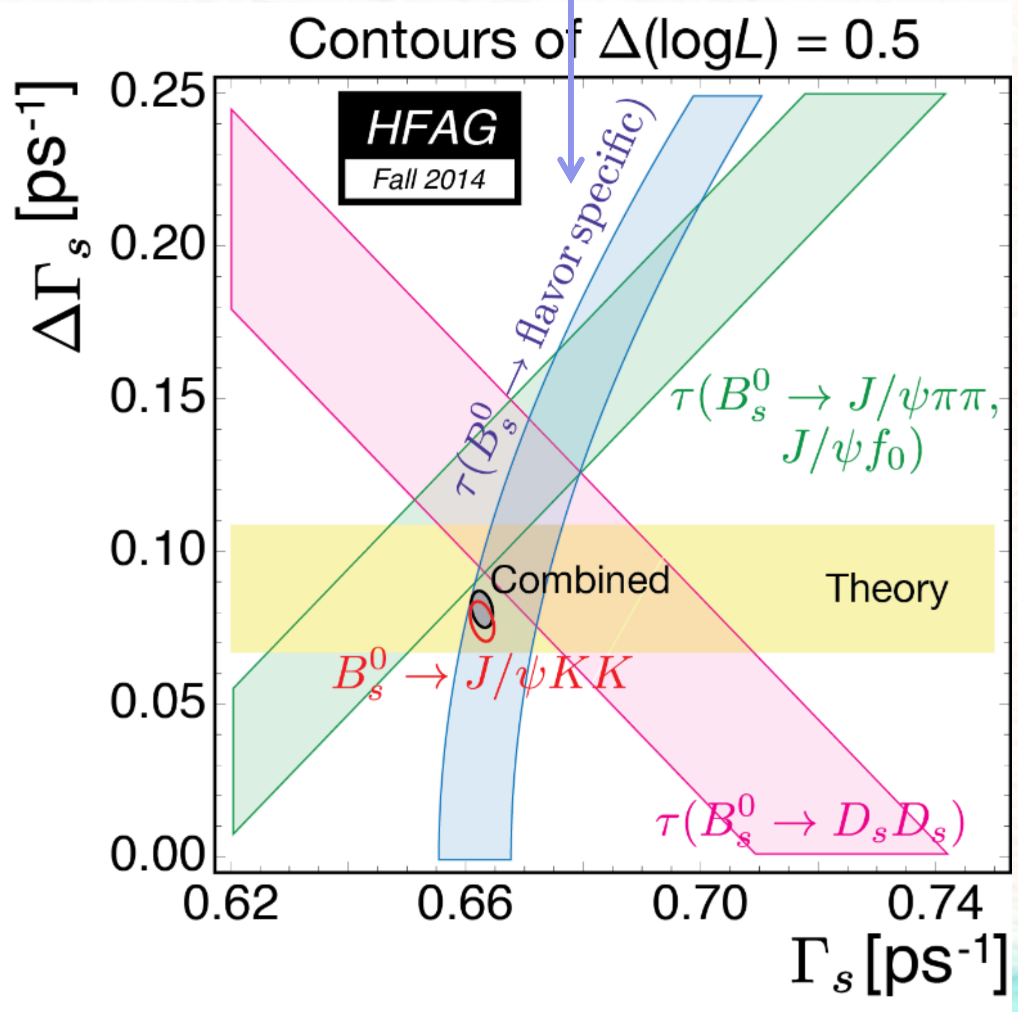
Experimental status

- WA value: 1.511 ± 0.014 ps

  – D0 with $B_s^0 \rightarrow D_s \mu\nu$ [PRL 114 (2015) 062001]
  1.479 ± 0.010 ± 0.021 ps.
  Major offender is combinatorial background.

  – LHCb with $B_s^0 \rightarrow D_s \pi$ [PRL 113 (2014) 172001]
  1.535 ± 0.015 ± 0.014 ps.
  Systematics dominated by acceptance description.

- Potential for competitive result if manage to control the systematic uncertainty.



Stripping cuts

Quantity	$K^+K^-\pi^-$ requirement (b2DsPhiPiMuXB2DMuNuX)	$K^+\pi^-\pi^-$ requirement (b2DpMuXB2DMuNuX)
ProbNNghost(μ, π, K)	< 0.5	< 0.5
Minimum IP$\chi^2(\mu, \pi, K)$	> 4.0	> 9.0
$p_T(\mu)$	> 600 MeV/c	> 800 MeV/c
$p(\mu)$	–	> 3.0 GeV/c
PIDmu(μ)	> 0.0	> 0.0
Track χ^2/ndf	-	< 4.0
$p_T(K)$, $p_T(\pi)$	> 150 MeV/c	> 300 MeV/c
$p(K)$, $p(\pi)$	> 1.5 GeV/c	> 2.0 GeV/c
PIDK(K)	> 0.0	> 4.0
PIDK(π)	< 20.0	< 10.0
D daughters' $\sum p_T$	–	> 1.8 GeV/c
D vertex χ^2/ndf	< 8.0	< 6.0
D χ^2/ndf separation from PV	> 20	> 100
D DIRA	> 0.99	> 0.99
$m(D^-_{(s)})$	$\in [1789.620, 2048.490]$ MeV/c^2	$\in [1789.620, 1949.620]$ MeV/c^2
$m(K^+K^-)$	$\in [979.455, 1059.455]$ MeV/c^2	–
B vertex χ^2/ndf	< 20.0	< 6.0
B DIRA	> 0.99	> 0.999
$m(D_{(s)}\mu)$	$\in [0.0, 1000.0]$ GeV/c^2	$\in [2.5, 6.0]$ GeV/c^2
$v_z(D) - v_z(B)$	> -0.3 mm	> 0.0 mm

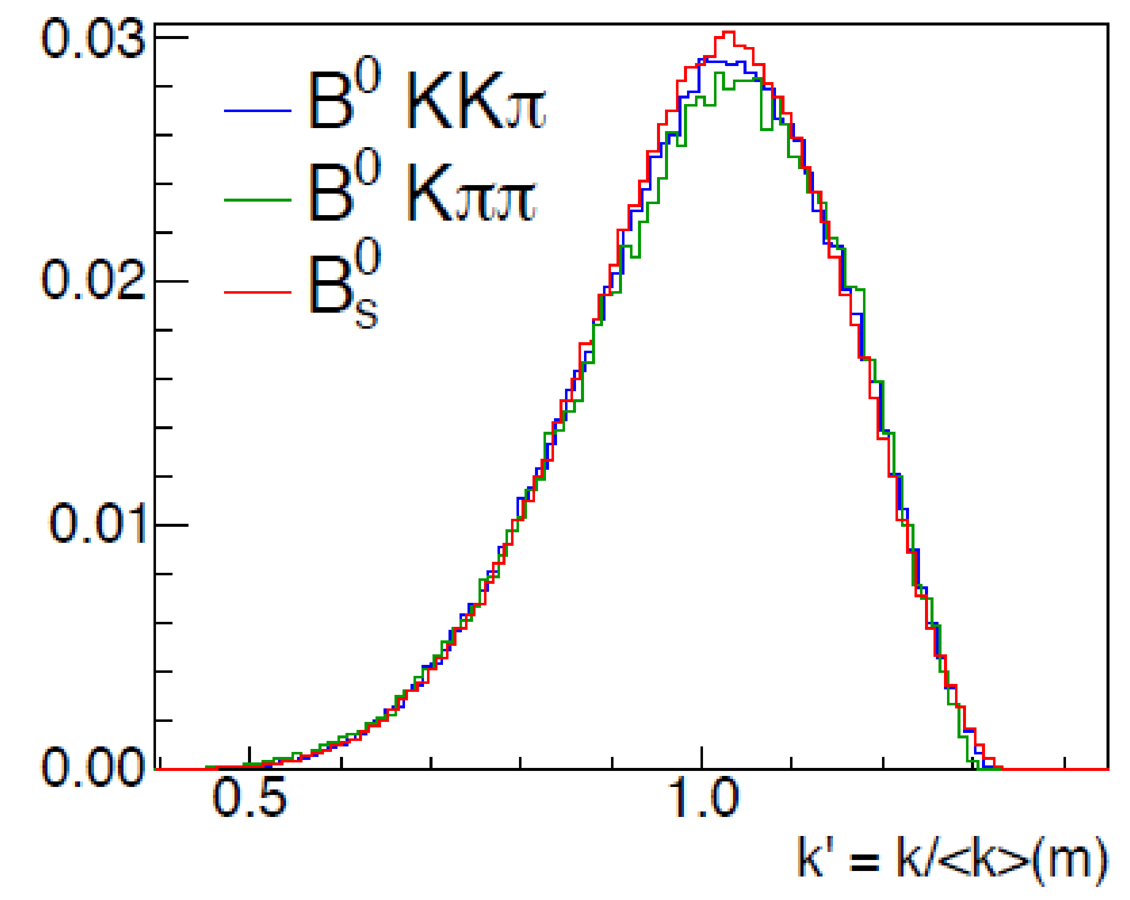
7

Selection cuts

Quantity	$K^+K^-\pi^-$ requirement	$K^+\pi^-\pi^-$ requirement
ProbNNk(K)	> 0.2	> 0.2
ProbNNpi(π)	> 0.2	> 0.5
ProbNNmu(μ)	> 0.2	> 0.2
$p(K)$	$> 2\,\text{GeV}/c$	$> 3\,\text{GeV}/c$
$p(\pi)$	$> 2\,\text{GeV}/c$	$> 5\,\text{GeV}$
$p_T(K),\ p_T(\pi)$	$> 300\,\text{MeV}/c$	$> 500\,\text{MeV}/c$
$D^-_{(s)}$ vertex χ^2/ndf	< 6.0	< 6.0
$v_z(D) - v_z(B)$	> 0.1 mm	> 0.1 mm
$m(K^+K^-)$	$\in [1.008, 1.032]\ \text{GeV}/c^2$	–
$m(D^-_{(s)}\mu^+)$	$> 3.1\,\text{GeV}/c^2$	$> 3.1\,\text{GeV}/c^2$
	$\notin [5.200, 5.400]\ \text{GeV}/c^2$	$\notin [5.200, 5.400]\ \text{GeV}/c^2$
$m(\mu^+\mu^-)$	$\notin [3.040, 3.160]\ \text{GeV}/c^2$	$\notin [3.040, 3.160]\ \text{GeV}/c^2$
	$\notin [3.635, 3.735]\ \text{GeV}/c^2$	$\notin [3.635, 3.735]\ \text{GeV}/c^2$
$m(Kp\pi)$	$\notin [2.260, 2.310]\ \text{GeV}/c^2$	$\notin [2.260, 2.310]\ \text{GeV}/c^2$

Missing momentum resolution

- K-factor correction leads to a degradation of the decay-time resolution.
- Taken into account with k′ factor.



Description of the fit

Fit ratios of signal yields in bins of t_{corr} by minimizing

$$\chi^2 = \sum_i^{N_{\rm bins}} \frac{(N_i - R_i D_i)^2}{\sigma_{N_i}^2 + R_i^2 \sigma_{D_i}^2}$$

where N_i (D_i) is the yield of the numerator (denominator) in the bin i and

$$R_i = \mathcal{N}\, A_i \frac{\int_{\Delta t_i} \mathrm{pdf}_{\rm num}(t)\, dt}{\int_{\Delta t_i} \mathrm{pdf}_{\rm den}(t)\, dt}$$

A_i: Acceptance ratio, assumed constant in the decay-time bin

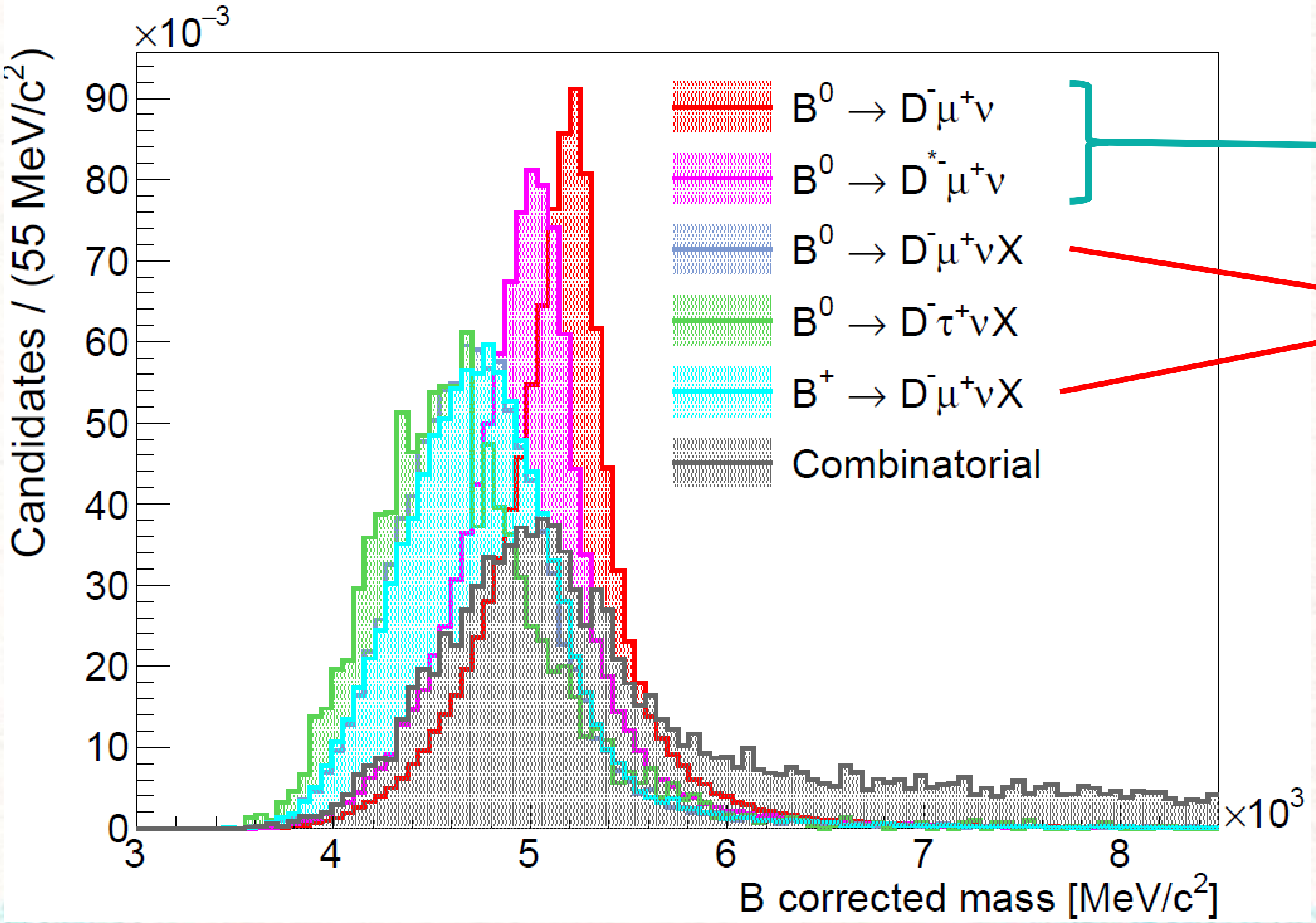
$$\mathrm{pdf_j}(t) = \int k' \left(\exp(-\Gamma_j k' t) \otimes \mathcal{R}_j^{\rm FD}\right) F_j(k') dk'$$

$\mathcal{R}_j^{\rm FD}$: Flight-distance resolution ~70 fs (negligible)

$F_j(k')$: Missing momentum resolution

Denominator: fix Γ_j to PDG value of $\Gamma(B^0)$
Numerator: fit $\Gamma_j = \Gamma(B^0) + \mathbf{\Delta}$

Fitting the B^0 sample



Signal components

Too similar to be separated by the mass fit
→ Merge components

All templates from MC simulations, but combinatorial (SS data)