Results on b hadron properties in CMS: b hadron lifetime measurements at $\sqrt{s} = 8$ TeV

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on behalf of the CMS collaboration

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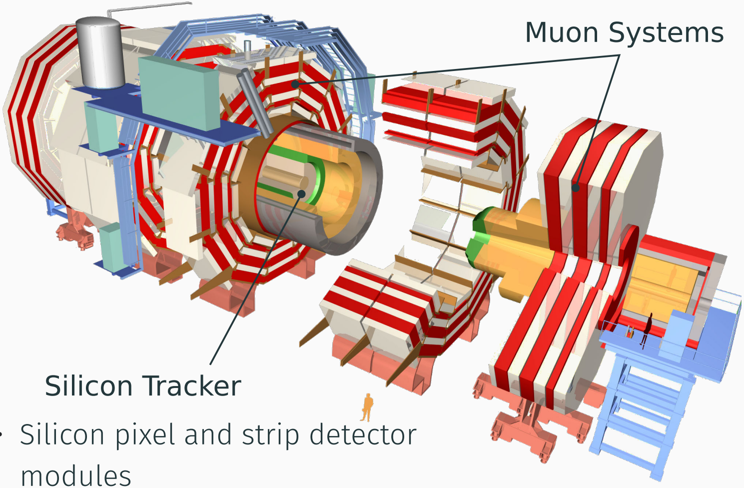
Lifetime measurements of b hadrons

- Precise lifetime measurements play important role in study of nonperturbative aspects of QCD
- Phenomenological description by Heavy Quark Expansion (HQE) model
  - Based on perturbative expansion of interaction of a single heavy quark with light quarks
  - Provides accurate estimates of the ratio of lifetimes for hadrons containing a heavy quark
- Some discrepancies in experimental measurements in $\tau_{B_c^+}$

CMS Detector



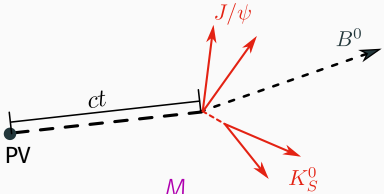
- Drift tubes, cathode strip chambers and resistive-plate chambers
- Used in first-level, hardware based trigger
- Segments are matched to charged tracks to identify muons
- High-level trigger has access to full event information

- Silicon pixel and strip detector modules
- Measurement of charged particles without particle identification
- Transverse impact parameter resolution $\sim 25 - 90\ \mu m$

Reconstruction of b hadrons

CMS PAS-BPH-13-008

- Using final states with a J/ψ
  - J/ψ candidates reconstructed by combining oppositely charged muons
- Neutral particle candidates reconstructed by combining oppositely charged tracks with appropriate mass assignments
- Candidate b hadrons reconstructed by combining a J/ψ candidate with tracks or reconstructed neutral particles
  - Fit to a common vertex
  - Reconstructed muons and charged tracks have to satisfy quality requirements



$$ct = cL_{xy}\frac{M}{p_T}$$

- Production vertex (PV) determined from fitting of reconstructed tracks
- Distance between PV and decay vertex is proper decay length ct

Lifetime measurements of b hadrons at $\sqrt{s} = 8$ TeV

Reconstructed in final states with a J/ψ

CMS PAS-BPH-13-008

$$B^0 \to J/\psi K^*(892)^0 \quad \text{with } K^*(892)^0 \to K^\pm \pi^\mp$$
$$B^0 \to J/\psi K^0_S \quad \text{with } K^0_S \to \pi^+\pi^-$$
$$B^0_s \to J/\psi \pi^+\pi^-$$
$$B^0_s \to J/\psi \phi(1020) \quad \text{with } \phi(1020) \to K^+K^-$$
$$\Lambda^0_b \to J/\psi \Lambda^0 \quad \text{with } \Lambda^0 \to p\pi^-$$
$$B^+_c \to J/\psi \pi^+$$

- Using 19.7 fb^{-1} of data collected in 2012 from pp collisions at $\sqrt{s} = 8$ TeV

B_s^0 measurement

- Decay rate of neutral B_q^0 mesons characterized by

$$\Gamma_q = (\Gamma_L^q + \Gamma_H^q)/2 \quad \text{and} \quad \Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q$$

- B^0 system: $\frac{\Delta\Gamma_d}{\Gamma_d} = (-0.3 \pm 1.5)\%$
- B_s^0 system: $\frac{\Delta\Gamma_s}{\Gamma_s} = (12.4 \pm 1.1)\%$

$B_s^0 \to J/\psi\pi^+\pi^-$:

- $0.9240 < M(\pi^+\pi^-) < 1.0204\,\text{GeV}$
  $\to$ dominated by $f_0(980)$
  $\to$ CP-odd final state

$\to$ $c\tau_{B_s^0}^{\text{CP-odd}} \approx 1/\Gamma_H$

$B_s^0 \to J/\psi\phi(1020)$:

- Admixture of one CP-odd and two CP-even states

$\to$ Measurement of effective lifetime $c\tau_{\text{eff}}$

- Complementary to weak mixing phase analysis

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Event selection

b hadron requirements:

- $p_T > 13$ GeV (except for B^0_s)
- $ct > 0.02$ cm

J/ψ requirements:

- $p_T > 7.9$ GeV
- $M^{\mu\mu}$ within 0.15 GeV of world average
- Vertex χ^2 probability > 0.5 %

Track and muon requirements:

- Track $p_T > 0.5$ GeV
- $|\eta(\mu)| < 2.2$

Mass windows for neutral states:

state	min/GeV	max/GeV
$K^*(892)^0$	0.7960	0.9880
K^0_S	0.4876	0.5076
$\pi^+\pi^-$	0.9240	1.0204
$\phi(1020)$	1.0095	1.0295
Λ^0	1.1096	1.1216

Data modelling and fitting

- Signal decay length distribution

$$T(ct, \sigma_{ct}|\tau_B) = \left[E(ct|\tau_B) \otimes R(ct, \sigma_{ct})\right] \cdot \mathcal{E}(ct)$$

$E(ct|\tau_B)$ – Decay distribution
$R(ct, \sigma_{ct})$ – Detector resolution
$\mathcal{E}(ct)$ – Efficiency

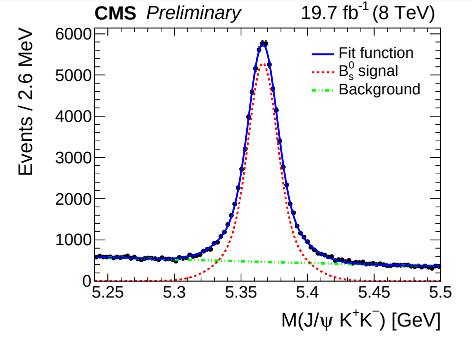
- Signal decay length distribution parameters obtained from three dimensional fit using
  - b hadron mass
  - ct
  - per event ct uncertainty σ_{ct}

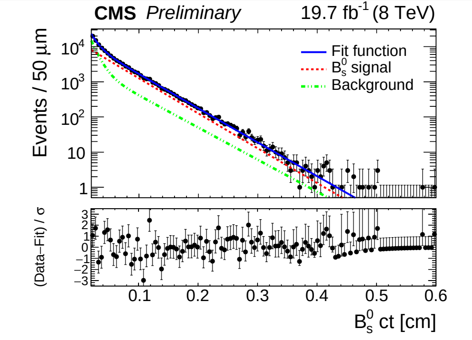
- Efficiency correction obtained from fully simulated MC samples as function of ct

$$\frac{\text{Generated distribution of selected events after reconstruction}}{\text{Exponential distribution with lifetime used in generation}^{\dagger}}$$

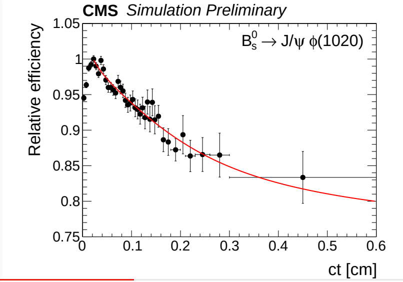
†sum of two exponentials for $B_s^0 \to J/\psi\phi(1020)$

Exemplary fit results and efficiency





$$B_s^0 \to J/\psi\phi(1020)$$



Results

	channel	This results / µm			PDG* / µm	
$c\tau_{B^0}$	$J/\psi K^*(892)^0$	453.0	±1.6	±1.5	455.7	±1.2
	$J/\psi K^0_S$	457.8	±2.7	±2.7		
$c\tau_{B^0_s}$	$J/\psi\pi^+\pi^-$	504.3	±10.5	±3.7	497.1	$\pm9.6^\dagger$
	$J/\psi\phi(1020)$	443.9	±2.0	±1.2	443.4	$\pm3.6^\dagger$
$c\tau_{\Lambda^0_b}$	$J/\psi\Lambda$	443.1	±8.2	±2.7	440.7	±3.0
			stat	syst		

All results in good agreement with current world average values

*Chin. Phys. C, **40**, 100001 (2016)

†Taken from HFLAV: arXiv:1612.07233 [hep-ex]

B_c^+ lifetime

- B_c^+ weak decay
  - b quark decays with c quark as spectator or vice versa
  - Annihilation process predicted to contribute up to 10 % of decay width
- LHCb measures longer lifetimes than D0 and CDF

	channel	decay length/µm		
LHCb:	$B_c^+ \to J/\psi\pi^+$	154.4	± 3.7	PLB **742** (2015) 29
LHCb:	$B_c^+ \to J/\psi\mu^+\nu_\mu X$	152.6	± 4.3	JHEP **74** (2014) 2839
CDF:	$B_c^+ \to J/\psi e^+\nu_e$	138.8	± 24.3	PRL **97**, 012002
CDF:	$B_c^- \to J/\psi\pi^-$	135.5	± 16.5	PRD **87**, 011101(R)
D0:	$B_c^\pm \to J/\psi\pi^\pm$	134.3	± 14.9	PRL **102**, 092001

B_c^+ lifetime measurement

- Use precise knowledge of B^+ lifetime to measure B_c^+ lifetime

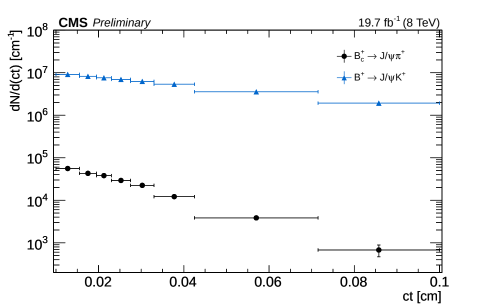
$$\frac{N_{B_c^+}(t)}{N_{B^+}(t)} = \mathcal{R}(t) = \frac{\left[E(t|\tau_{B_c^+}) \otimes R(t)\right]\mathcal{E}(t)}{\left[E(t|\tau_{B^+}) \otimes R(t)\right]\mathcal{E}(t)}$$

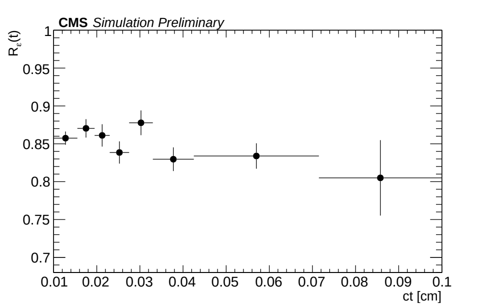
- Ratio not significantly affected by resolution

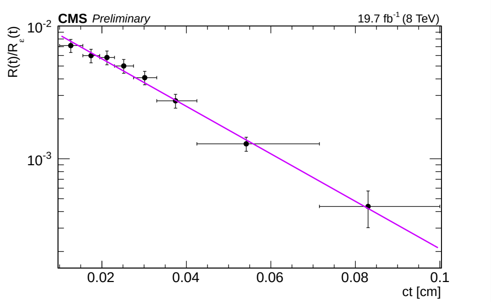
$$\rightarrow \mathcal{R}(t) = R_\varepsilon(t)\exp\left(-\Delta\Gamma t\right) \qquad \text{with} \qquad \Delta\Gamma = \Gamma_{B_c^+} - \Gamma_{B^+} = \frac{1}{\tau_{B_c^+}} - \frac{1}{\tau_{B^+}}$$

- $R_\varepsilon(t)$ - ratio of efficiency functions evaluated from MC simulation absorbing residual resolution effects
- N_{B^+} and $N_{B_c^+}$ obtained from fits to data in different ct bins

Results







$$\Delta\Gamma = 4.12 \pm 0.30 \pm 0.16 \text{ mm}^{-1}c$$
$$c\tau_{B_c^+} = 162.3 \pm 8.2 \pm 4.7 \pm 0.1\,(\tau_{B^+})\ \mu\text{m}$$

Results in agreement with LHCb measurement

Summary

- Lifetime measurements of
  - $B^0 \to J/\psi K^*(892)^0$
  - $B^0 \to J/\psi K^0_S$
  - $B^0_s \to J/\psi \pi^+\pi^-$
  - $B^0_s \to J/\psi \phi(1020)$
  - $\Lambda^0_b \to J/\psi \Lambda^0$
  - $B^+_c \to J/\psi \pi^+$

  at CMS at $\sqrt{s} = 8\,\text{TeV}$ have been presented
- All measurements are in good agreement with current world average values
- Some measurements are already at the precision level of the current world average
- Measurement of B^+_c lifetime is in agreement with recent LHCb measurements

Supplementary Material

Systematic uncertainties for neutral b hadrons

Common uncertainties:

- Production vertex (PV) selection
- Detector alignment
- ct resolution
- MC finite size
- Efficiency modeling
- Absolute ct accuracy
- Mass modelling
- ct modelling

Channel specific uncertainties:

- $B_s^0 \to J/\psi\pi^+\pi^-$
  - B^+ contamination
  - Invariant $\pi^+\pi^-$ mass window
- $B^0 \to J/\psi K^*(892)^0$
  - $K^\pm\pi^\mp$ mass assumption for $K^*(892)^0$
- $B_s^0 \to J/\psi\phi(1020)$
  - ct range
  - S-wave contamination

Combined systematic uncertainty between 1.2 - 3.7 µm for all channels

Detailed systematic uncertainties for neutral b hadrons

Source	Decay channel				
	$B^0 \to J/\psi K^{*0}$	$B^0 \to J/\psi K^0_S$	$B^0_s \to J/\psi \pi^+\pi^-$	$\Lambda^0_b \to J/\psi \Lambda^0$	$B^0_s \to J/\psi \phi$
PV selection	0.7	0.7	0.7	0.7	0.7
Detector alignment	0.3	0.7	0.3	0.7	0.3
ct resolution	0.0	0.1	0.1	0.2	0.1
MC finite size	1.1	2.4	2.0	2.3	0.6
Efficiency modelling	0.3	0.5	0.6	0.6	0.2
Absolute ct accuracy	0.2	0.2	0.2	0.2	0.2
Mass modelling	0.3	0.4	0.5	0.9	0.0
ct modelling	0.1	0.1	0.4	0.1	0.4
B^+ contamination	–	–	2.4	–	–
Mass window of the $\pi^+\pi^-$	–	–	1.5	–	–
$K^\pm\pi^\mp$ mass assumption	0.3	–	–	–	–
ct range	–	–	–	–	0.1
S-wave contamination	–	–	–	–	0.4
Total	1.5	2.7	3.7	2.7	1.2

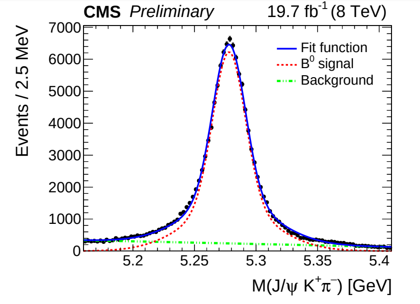
systematic uncertainties in μm

Systematic uncertainties for B_c^+

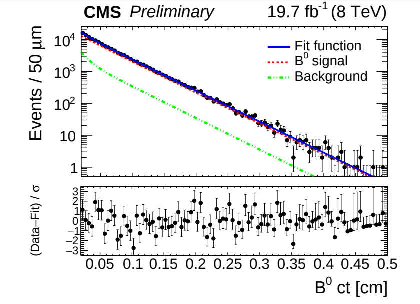
- Production vertex (PV) selection
- Fit model
- Binning definition
- Simulated sample sizes
- Detector alignment

Source	$\sigma_{\Delta\Gamma}$ [c/mm]	$\sigma_{c\tau_{B_c}}$ [μm]
PV choice	0.07	2.0
Fit model	0.12	3.7
ct binning	0.06	1.6
Simulation size	0.04	1.3
Misalignment	0.03	0.6
Total uncertainty	0.16	4.7

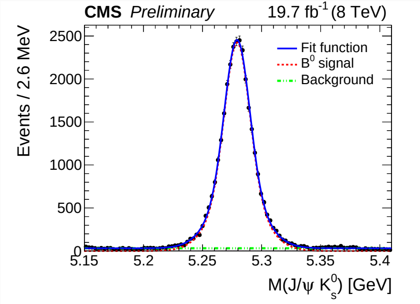
Fit results



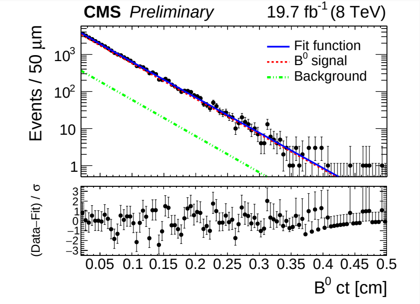
CMS Preliminary
19.7 fb-1 (8 TeV)
Events / 2.5 MeV
Fit function
B0 signal
Background
7000
6000
5000
4000
3000
2000
1000
0
5.2
5.25
5.3
5.35
5.4
M(J/ψ K+π−) [GeV]



CMS Preliminary
19.7 fb-1 (8 TeV)
Events / 50 µm
Fit function
B0 signal
Background
104
103
102
10
1
(Data−Fit) / σ
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
B0 ct [cm]

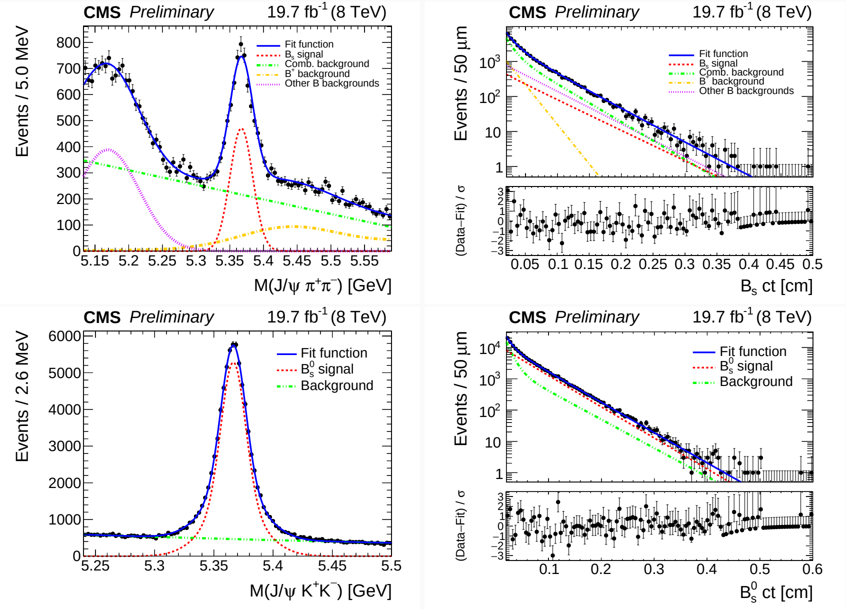


CMS Preliminary
19.7 fb-1 (8 TeV)
Events / 2.6 MeV
Fit function
B0 signal
Background
2500
2000
1500
1000
500
0
5.15
5.2
5.25
5.3
5.35
5.4
M(J/ψ K0S) [GeV]



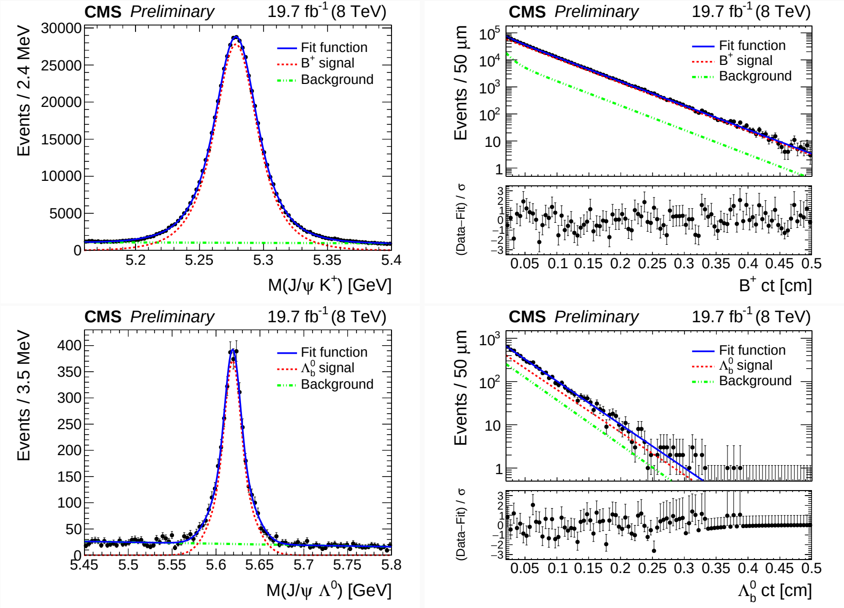
CMS Preliminary
19.7 fb-1 (8 TeV)
Events / 50 µm
Fit function
B0 signal
Background
103
102
10
1
(Data−Fit) / σ
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
B0 ct [cm]

Fit results



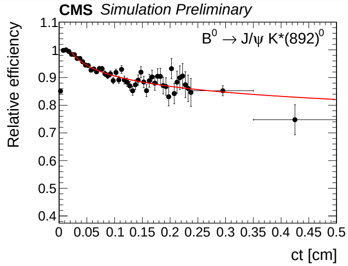
CMS Preliminary
19.7 fb^{-1} (8 TeV)
Events / 5.0 MeV
Fit function
B_s signal
Comb. background
B^+ background
Other B backgrounds
M(J/ψ π$^+$π$^-$) [GeV]
CMS Preliminary
19.7 fb^{-1} (8 TeV)
Events / 50 μm
Fit function
B_s signal
Comb. background
B^+ background
Other B backgrounds
(Data−Fit) / σ
B_s ct [cm]
CMS Preliminary
19.7 fb^{-1} (8 TeV)
Events / 2.6 MeV
Fit function
B_s^0 signal
Background
M(J/ψ K$^+$K$^-$) [GeV]
CMS Preliminary
19.7 fb^{-1} (8 TeV)
Events / 50 μm
Fit function
B_s^0 signal
Background
(Data−Fit) / σ
B_s^0 ct [cm]

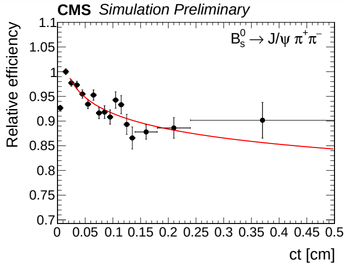
Fit results

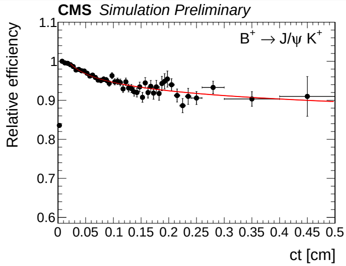


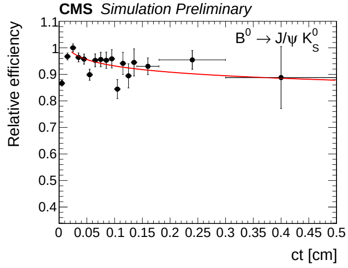
CMS Preliminary
19.7 fb-1 (8 TeV)
Events / 2.4 MeV
Fit function
B+ signal
Background
M(J/ψ K+) [GeV]
Events / 50 μm
(Data−Fit) / σ
B+ ct [cm]
Events / 3.5 MeV
Λb0 signal
M(J/ψ Λ0) [GeV]
Λb0 ct [cm]

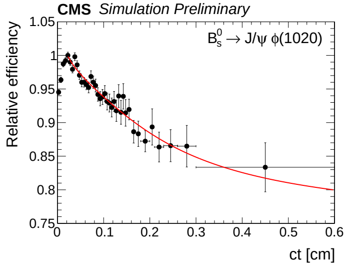
Efficiencies

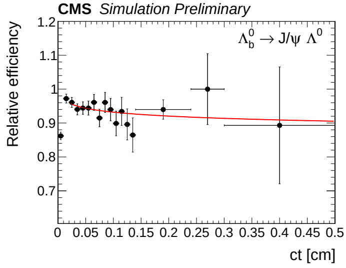




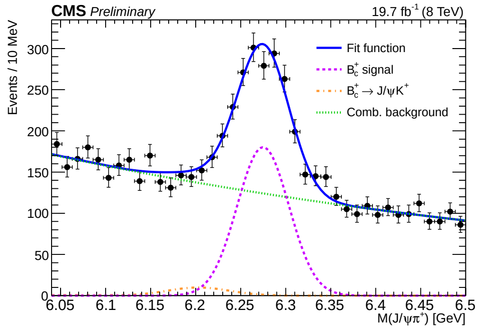


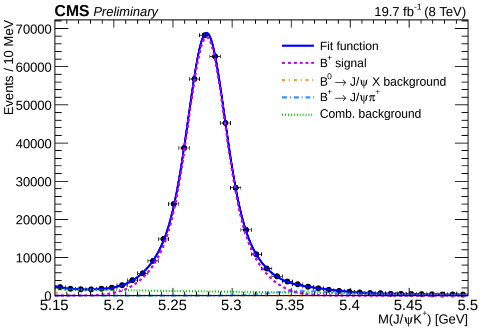






Mass fits for B^+ and B_c^+





Neutral B meson decay

- Decay rate of neutral B_q^0 mesons characterized by

$$\Gamma_q = (\Gamma_L^q + \Gamma_H^q)/2 \qquad \text{average decay width}$$

$$\Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q \qquad \text{decay width difference}$$

$\Gamma_{L,H}^q$ - widths of light (L) and heavy (H) mass eigenstates

- Decay rate into final state f

$$\Gamma_{B_q^0 \to f} = R_L^f e^{-\Gamma_L^q t} + R_H^f e^{-\Gamma_H^q t}$$

$R_{L,H}^f$ - amplitudes of light and heavy mass eigenstates

$\rightarrow$ ct distribution consists of two exponentials

- B^0 system: $\frac{\Delta\Gamma_d}{\Gamma_d} = (-0.3 \pm 1.5)\% \rightarrow$ ct distribution can be treated as one exponential
- B_s^0 system: $\frac{\Delta\Gamma_s}{\Gamma_s} = (12.4 \pm 1.1)\% \rightarrow$ sizeable deviations from exponential

B_s^0 measurements

- Measured in two final states: $J/\psi\phi(1020)$ and $J/\psi\pi^+\pi^-$
- $J/\psi\pi^+\pi^-$:
  - $0.9240 < M(\pi^+\pi^-) < 1.0204\,\text{GeV} \rightarrow$ dominated by $f_0(980) \rightarrow$ CP-odd final state

  $\rightarrow\ c\tau_{B_s^0}^{\text{CP-odd}} \approx 1/\Gamma_H$
- $J/\psi\phi(1020)$:
  - Admixture of one CP-odd and two CP-even states

  $\rightarrow\ c\tau_{\text{eff}} = f_H c\tau_H + (1 - f_H)c\tau_L$ $\qquad f_H = |A_\perp|^2 c\tau_H/(|A|^2 c\tau_L + |A_\perp|^2 c\tau_H)$
  - Complementary to weak mixing phase analysis

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