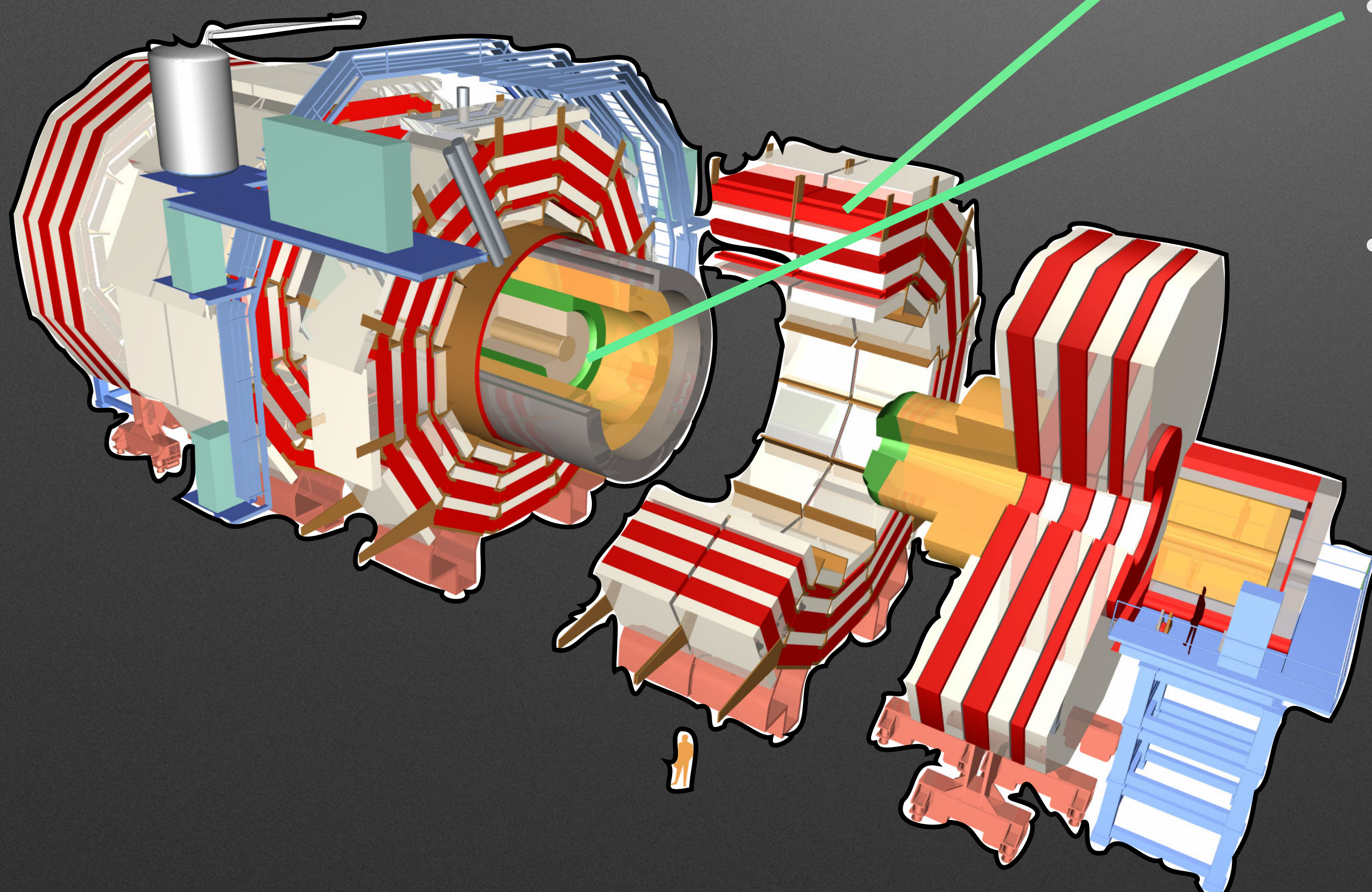
Measurements of heavy flavor properties at CMS

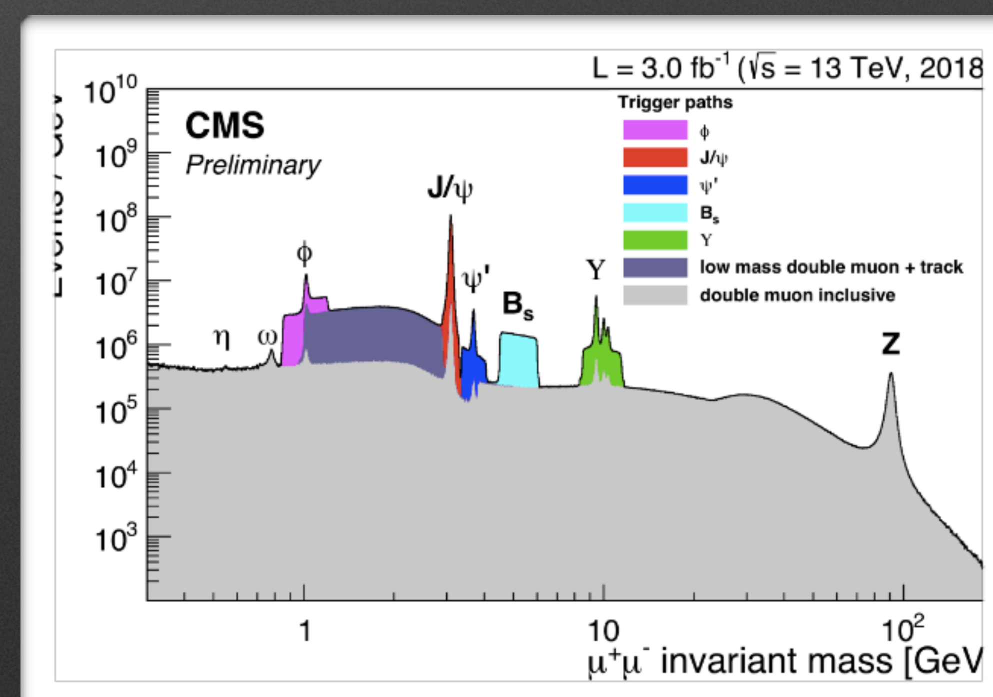
Po-Hsun Chen(NTU, Taipei)
on behalf of **the CMS Collaboration**

ICHEP2018 @ Seoul

CMS in heavy-flavor studies



- Muon tracking system consists of muon chamber and silicon tracker covers **wide rapidity and p_T regions**.
- Thanks to the **highly sensitive tracker**, even low energy photons can be measured accurately using conversions.
- **Flexible trigger strategy** provides a wide variety of study scopes including Higgs, SUSY, and even b-physics.



Outline

New

Observation of $B_{s2}^{*}(5840)^0 \rightarrow B^0 K_S$ decay
and studies of excited B_s meson
[CMS Preliminary result]

Λ_b polarization and angular parameters
in $\Lambda_b \rightarrow J/\psi \Lambda$ decays.
[Phys. Rev. D 97 (2018) 072010]

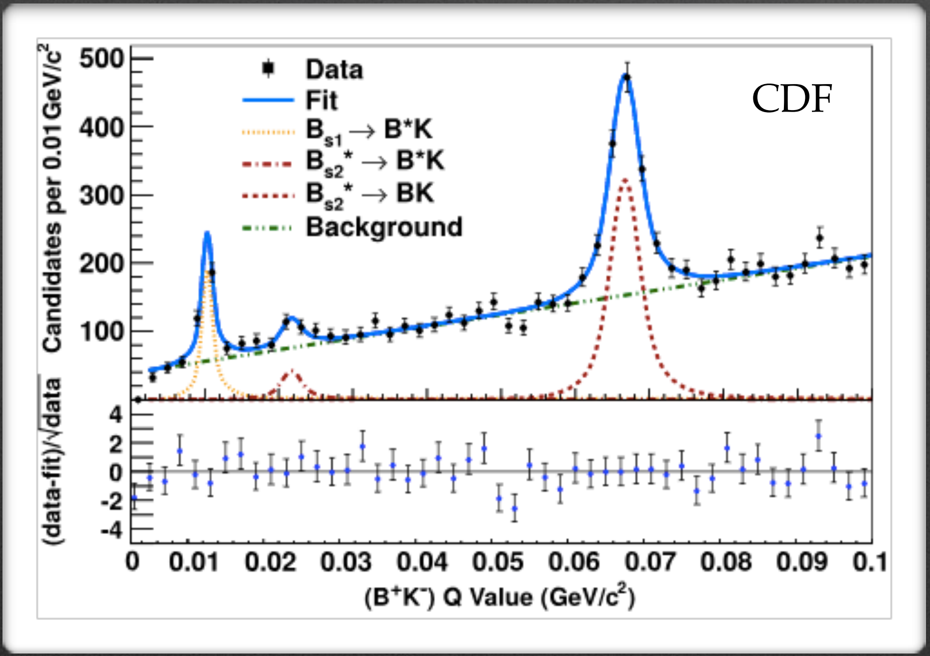
Lifetime measurements of b hadrons
reconstructed in final states with a J/ψ meson.
[Eur. Phys. J. C 78 (2018) 457]

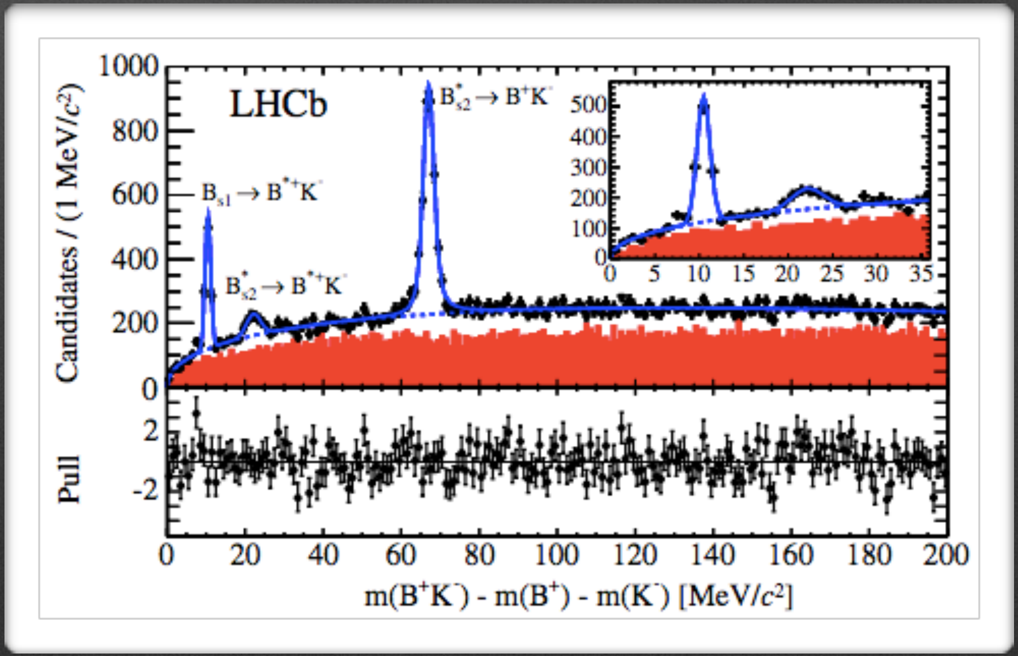
Introduction to P-wave B_s^0 states

- Since b quark is considerably heavier than s quark, heavy quark effective theory(HQET) can be used to describe the b-s system with orbital momentum L and the light quark spin.

  The observed P-wave(L=1) states are $B_{s2}^*(5840)^0$ ($J^P=2^+$) and $B_{s1}(5830)^0$, ($J^P=1^+$)

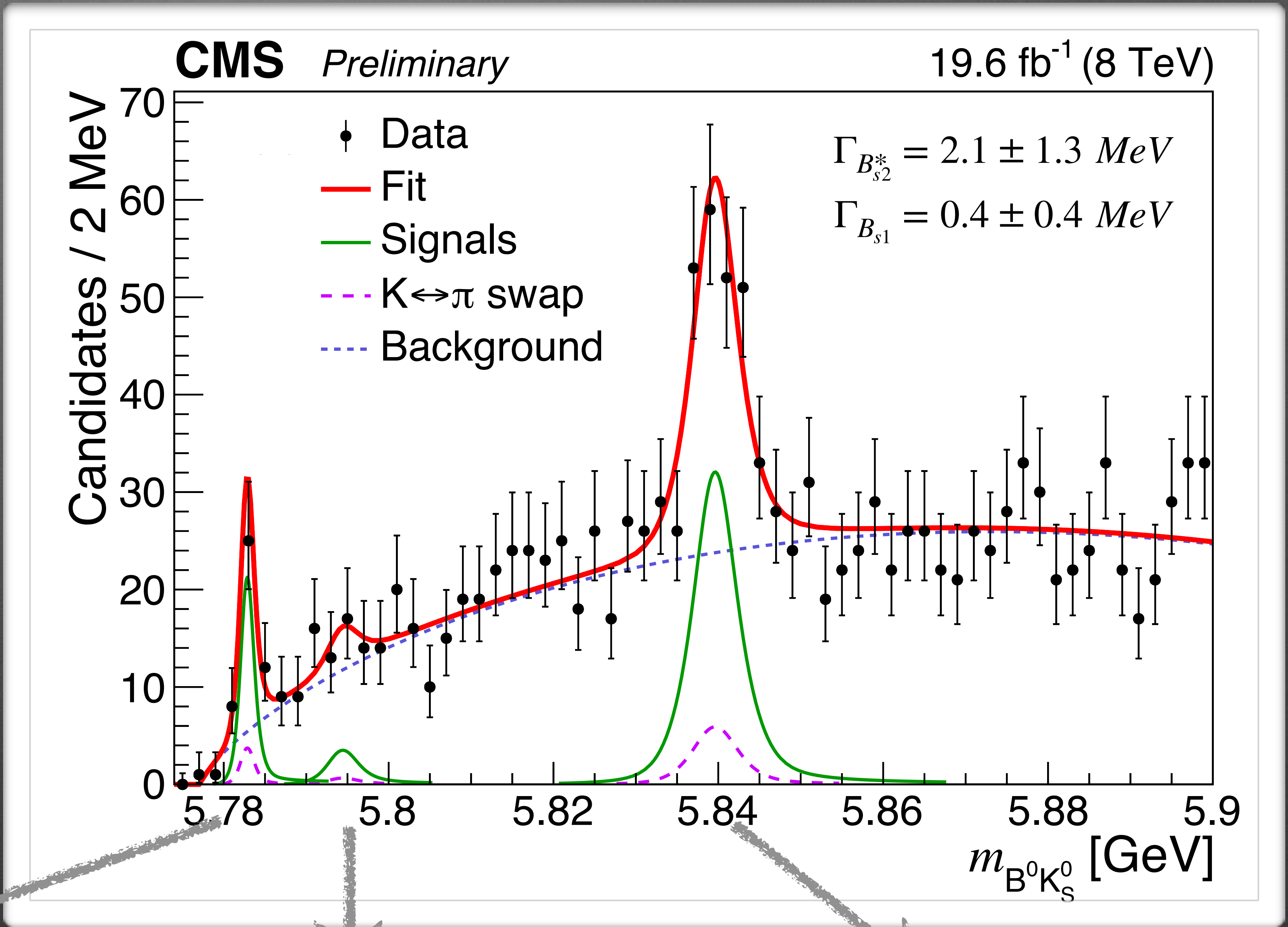
- Orbital excited B_s states were seen by CDF, D0, and LHCb through $B^{(*)+}K^-$ channels through a D-wave. According to HQET, it's allowed to replace $B^{(*)+}K^-$ with $B^{(*)0}K_s$ in these decays as long as J^P is kept conserved.





Observation of $B_{s2}^*(5840)^0 \to B^0K_S$ decay
and evidence of $B_{s1}(5830)^0 \to B^{*0}K_S$ decay

- 8 TeV pp parked dataset of 19.8/fb
- $K \leftrightarrow \pi$ swap in $B^0 \to J/\psi K^+\pi^-$ makes a wider peak.
- Peaks modeled by relativistic Breit-Wigner function (RBW) convolved with detector resolution. Natural widths and masses are free to float.
- Background modeled by a threshold function.



$B_{s1}(5830)^0 \to B^{*0}K_S$
34.5±8.3 events, **3.9σ**

$B_{s2}^*(5840)^0 \to B^{*0}K_S$
12±11 events

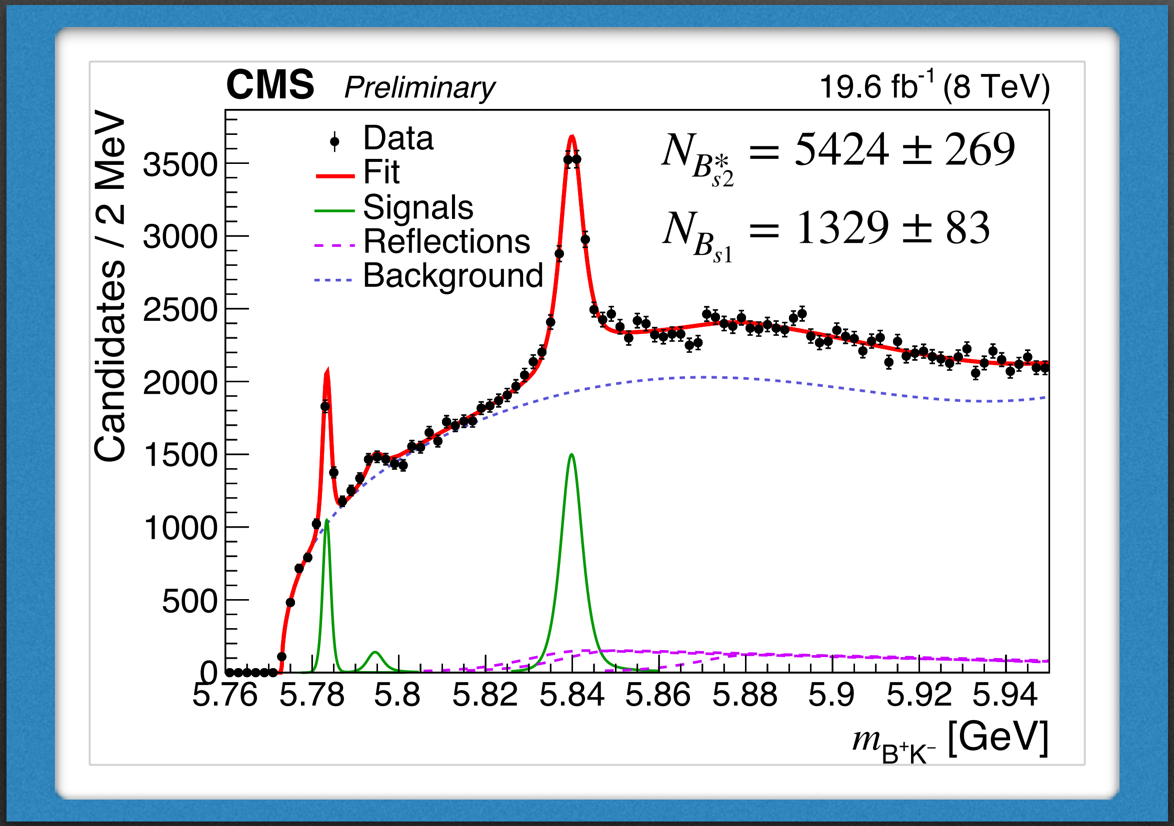
$B_{s2}^*(5840)^0 \to B^0K_S$
128±22 events, **6.3σ**

Relative branching ratios

From data / From MC

$$R_2^{0\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^0 K_s^0)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)} = \frac{N(B_{s2}^* \to B^0 K_s^0)}{N(B_{s2}^* \to B^+ K^-)} \times \frac{\varepsilon(B_{s2}^* \to B^+ K^-)}{\varepsilon(B_{s2}^* \to B^0 K_s^0)} \times \frac{\mathcal{B}(B^+ \to J/\psi K^+)}{\mathcal{B}(B^0 \to J/\psi K^{*0})\mathcal{B}(K^{*0} \to K^+\pi^-)\mathcal{B}(K_s \to \pi^+\pi^-)}$$

From PDG values



$R_{s2}^{0\pm} = 0.432$

$\pm 0.077(\text{stat.}) \pm 0.075(\text{syst.}) \pm 0.021(\text{PDG})$

$R_{s1}^{0\pm} = 0.492$

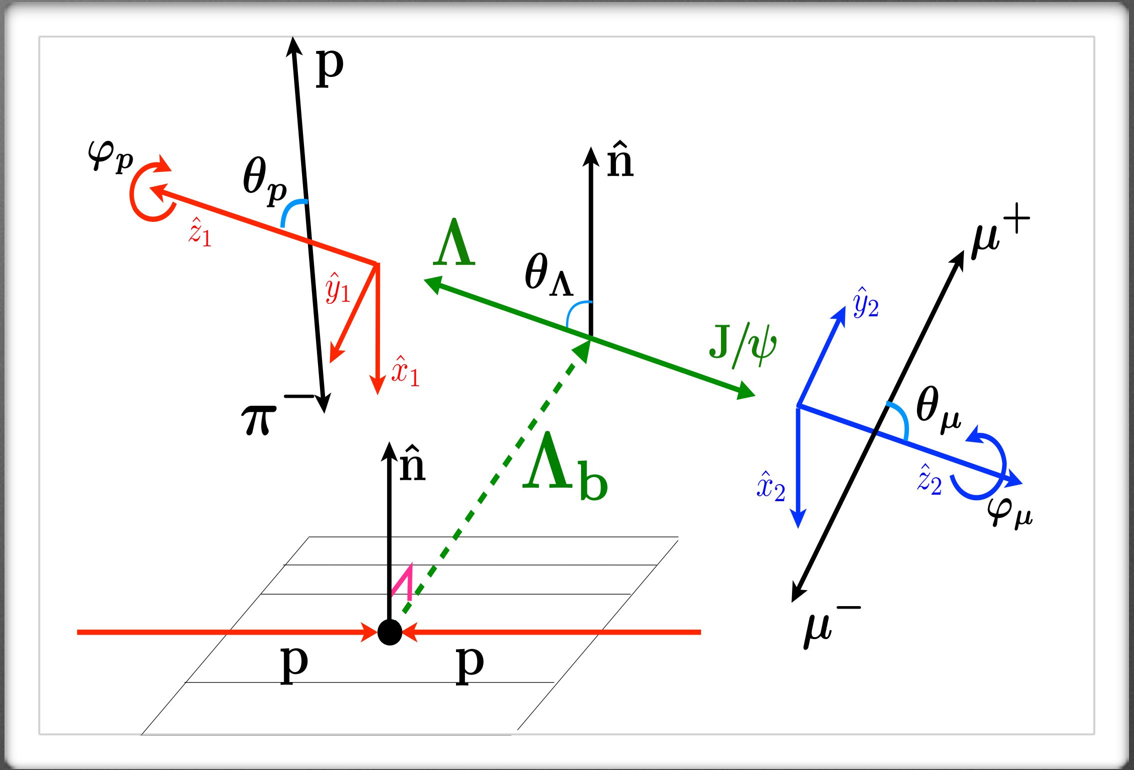
$\pm 0.122(\text{stat.}) \pm 0.068(\text{syst.}) \pm 0.024(\text{PDG})$

Λ_b polarization and angular parameters

- LHCb measures transverse polarization at the order of 10%. However, the reference predictions range up to 20%, which is at level of **2.7σ**.

- Parity asymmetry parameter has been calculated to lie in **-21~ -10 %** in most publications. However, the HQET obtains a large positive value of **78%**. [Physics Letters B 724 (2013) 27]

- **$\Lambda_b \to \Lambda(\to p\pi^-) J/\psi(\to \mu^+\mu^-)$**
  from 7 TeV data of 5.2/fb and 8 TeV data of 19.8/fb.



- Assuming uniform detector acceptance over the azimuthal angles φ_p and φ_μ, angular distribution of the decay daughters can be described by 5 angular parameters. [Nucl. Phys. Proc. Suppl. 50 (1996) 125]

  - **P** : Λ_b transverse polarization.
    α_1 : Λ_b parity-violating asymmetry parameter.
    α_2 : Λ longitudinal polarization.
    α_Λ: Asymmetry parameter in $\Lambda \to p\pi$ decay. Fix to world-average 0.642 ± 0.013.
    γ_0 : A linear combination of complex helicity amplitudes.

Analysis strategy - fit PDF

$$L = exp(-N_{sig} - N_{bkg})$$

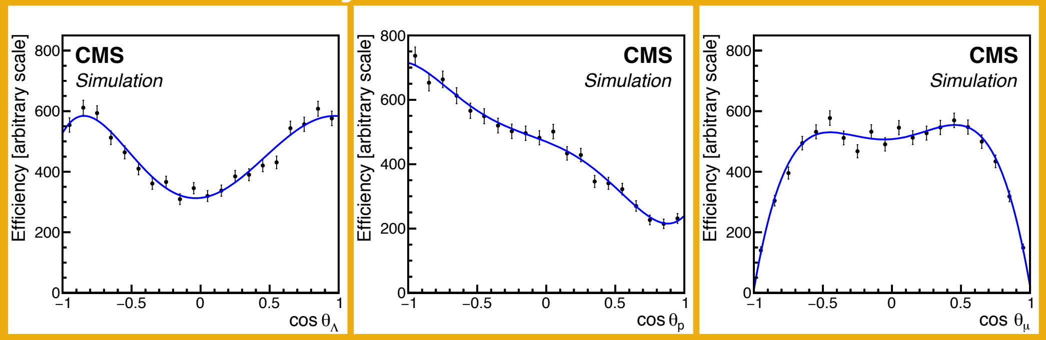
$$\times \prod^{N} [N_{sig} F_{sig}(\vec{\theta}; P, \alpha_1, \alpha_2, \alpha_\Lambda, \gamma_0) \cdot \varepsilon(\vec{\theta}) \cdot G(m_{J/\Psi\Lambda}) + N_{bkg} F_{bkg}(\vec{\theta}) \cdot P(m_{J/\Psi\Lambda})]$$

$$F_{sig} = \frac{d^3\Gamma}{dcos\theta_\Lambda dcos\theta_p dcos\theta_\mu}(\theta_\Lambda, \theta_p, \theta_\mu)$$

$$\sim \sum_{0}^{8} u_i(P, \alpha_1, \alpha_2, \gamma_0) \cdot v_i(P, \alpha_\Lambda) \cdot w_i(\theta_\Lambda, \theta_p, \theta_\mu)$$

i	u_i	v_i	w_i
1	1	1	1
2	α_2	α_Λ	$\cos\theta_p$
3	$-\alpha_1$	P	$\cos\theta_\Lambda$
4	$-(1+2\gamma_0)/3$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p$
5	$\gamma_0/2$	1	$(3\cos^2\theta_\mu - 1)/2$
6	$(3\alpha_1 - \alpha_2)/4$	α_Λ	$\cos\theta_p (3\cos^2\theta_\mu - 1)/2$
7	$(\alpha_1 - 3\alpha_2)/4$	P	$\cos\theta_\Lambda (3\cos^2\theta_\mu - 1)/2$
8	$(\gamma_0 - 4)/6$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p (3\cos^2\theta_\mu - 1)/2$

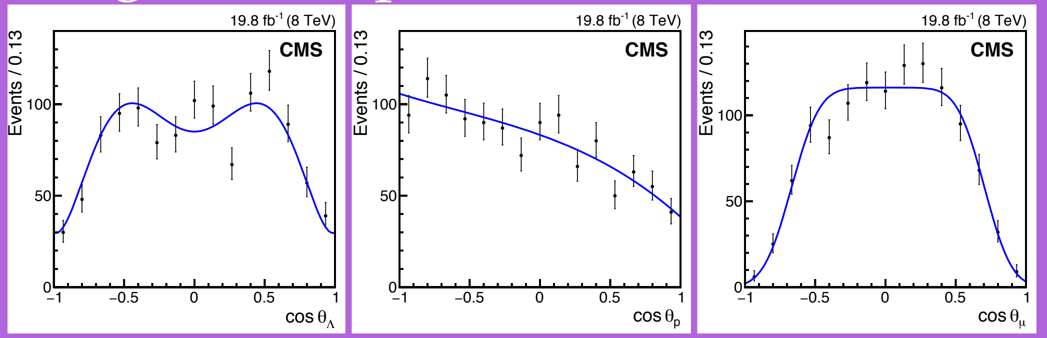
Efficiency correction from MC



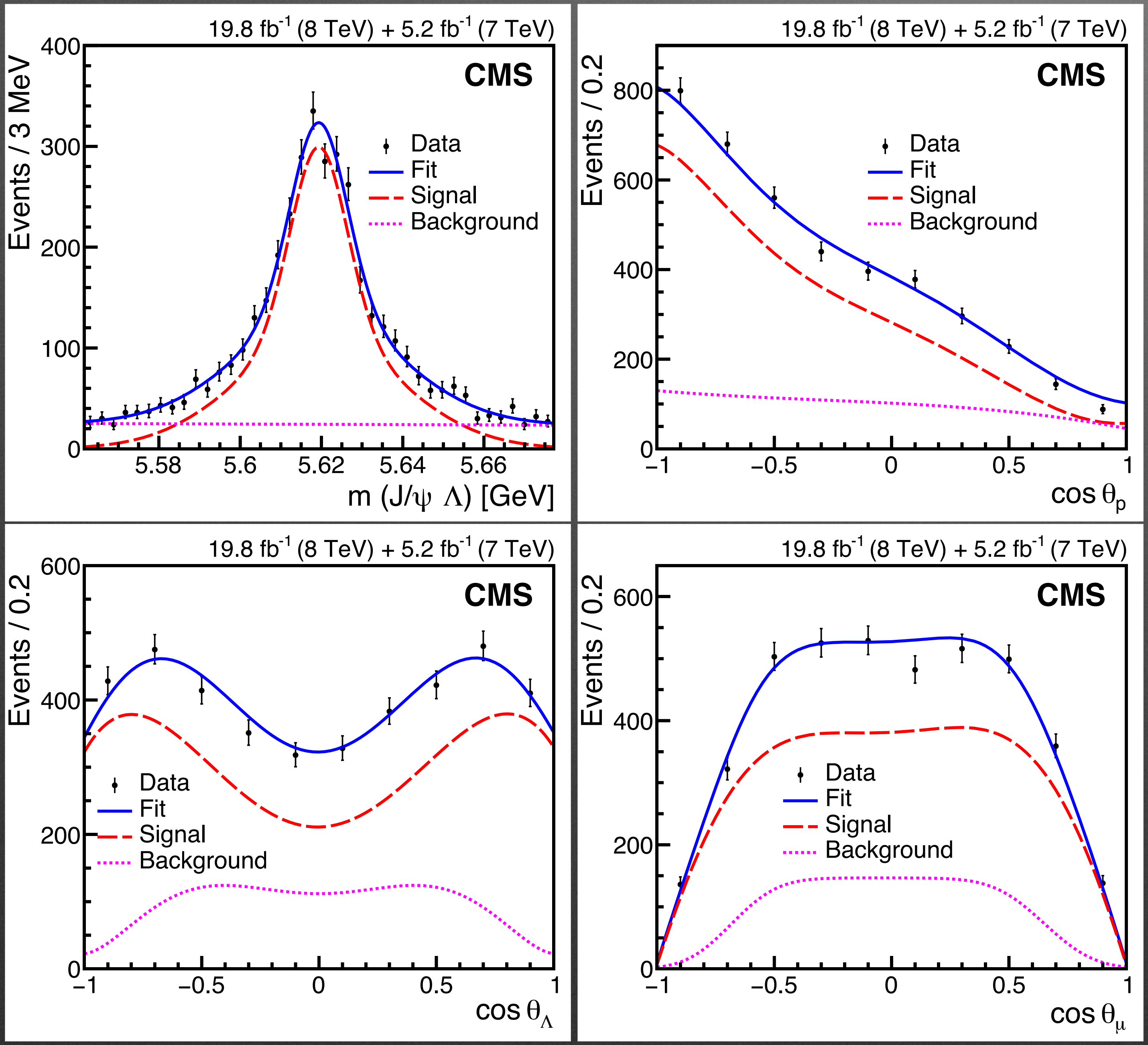
G : Double Gaussian

P : Linear function

Angular shape from data sideband



Results



- ~6000 signal yields from both $J/\psi\Lambda$ and $J/\psi\overline{\Lambda}$.

- $P = 0.00 \pm 0.06 \pm 0.06$
  $\alpha_1 = 0.14 \pm 0.14 \pm 0.10$
  $\alpha_2 = -1.11 \pm 0.04 \pm 0.05$
  $\gamma_0 = -0.27 \pm 0.08 \pm 0.11$

- Measured P is consistent with LHCb result.

- Measured α_1 is consistent with LHCb(0.05±0.17±0.07) and ATLAS(0.30±0.16±0.06) results.

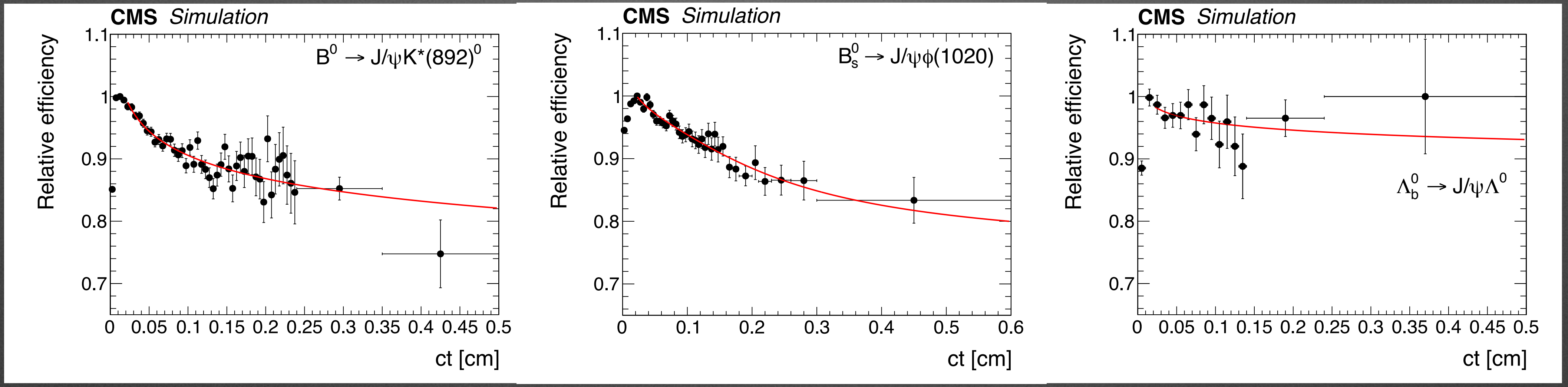
- Measured α_2 is compatible with -1, which implies Λ of positive-helicity state from Λ_b is suppressed.

b lifetime measurement

- Precise lifetime measurement tells the story about underlying non-perturbative QCD.
- Some discrepancy of B_c^+ lifetime measured by LHCb (~500 fs) and CDF, D0 (~450 fs). An independent measurement helps resolving this disagreement.
- 19.8/fb data of pp collision at 8 TeV (2012)
- Decay channels (all triggered by $J/\psi \to \mu^+\mu^-$)
  - $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi Ks$
  - $\Lambda_b \to J/\psi \Lambda^0$
  - $B_s^0 \to J/\psi \pi^+\pi^-$, $B_s^0 \to J/\psi \phi(1020)$
  - $B_c^+ \to J/\psi \pi^+$

Analysis strategy

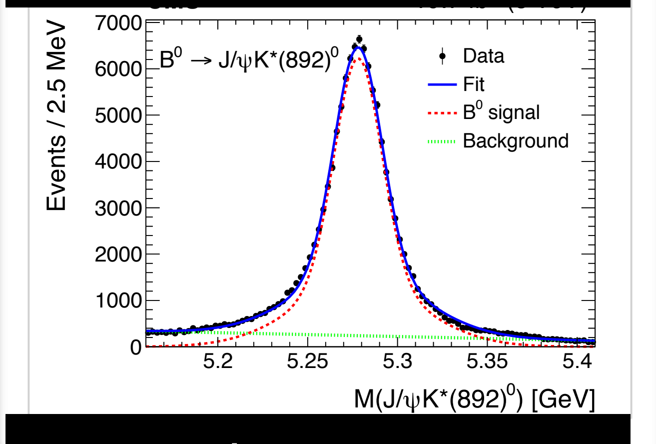
- B^0, B_s, Λ_b lifetime (ct) measurement
  - Unbinned ML fit to **mass**, **ct** (=c L_{xy}*m/p_T), **σ_{ct}**.
  - **Lifetime-dependent efficiency correction** is taken into account.

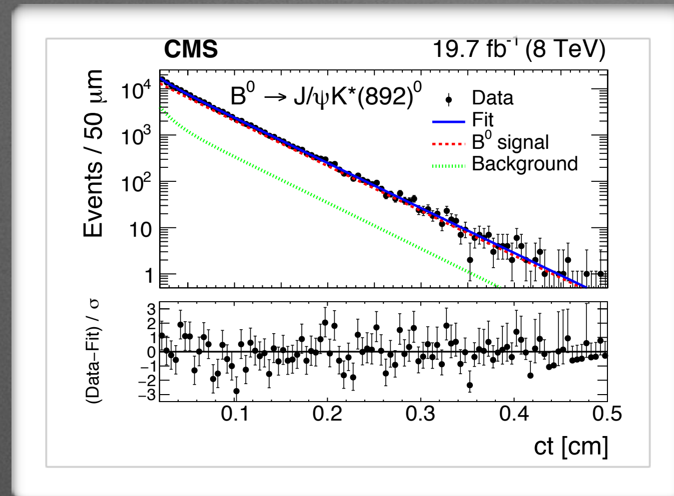


  - For B_s, run unbinned extended ML fit to cope with background contribution from B^+, B^0, etc..
- B_c lifetime measurement
  - Adopt the "**Reference method**" used by LHCb. [See also : PLB 742 (2015) 29]
    Based on precisely known B^+ lifetime, difference in total widths between B_c and B^+ is used to obtain B_c lifetime.
  - Systematic uncertainties shared by B^+ and B_c channels are cancelled by choosing the same selection criteria and fitting method.

Result : B^0, Λ_b

$B^0 \to J/\psi K^{*0}(\to K\pi)$

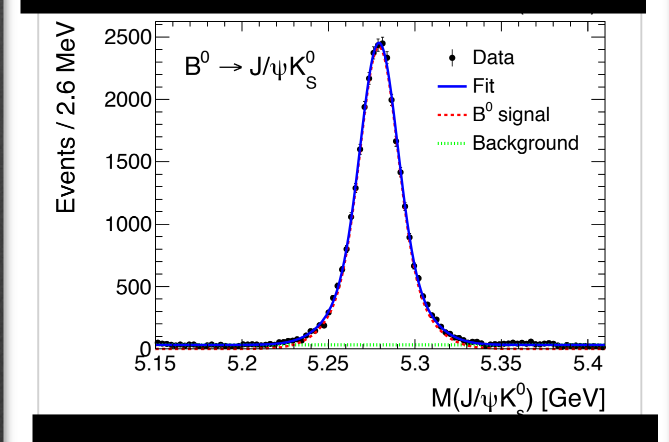


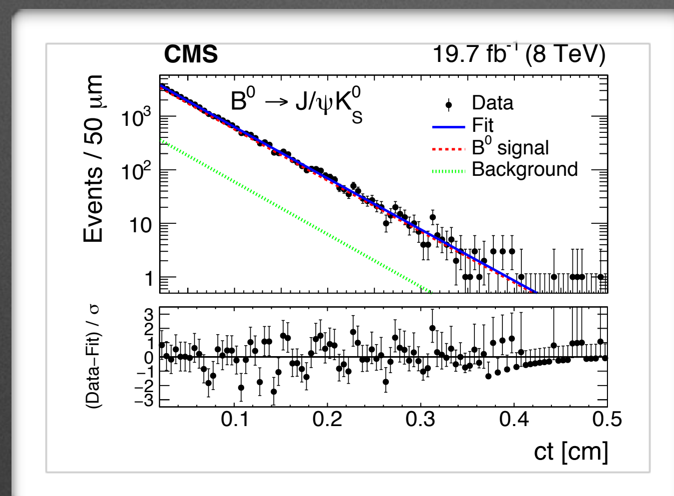


$c\tau = 453.0 \pm 1.6$ µm

Consistent with PDG value : 456.0 ± 1.2 µm

$B^0 \to J/\psi K_s(\to \pi^+\pi^-)$



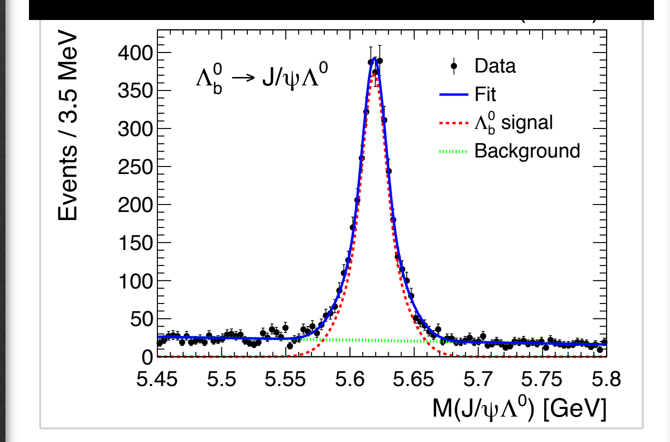


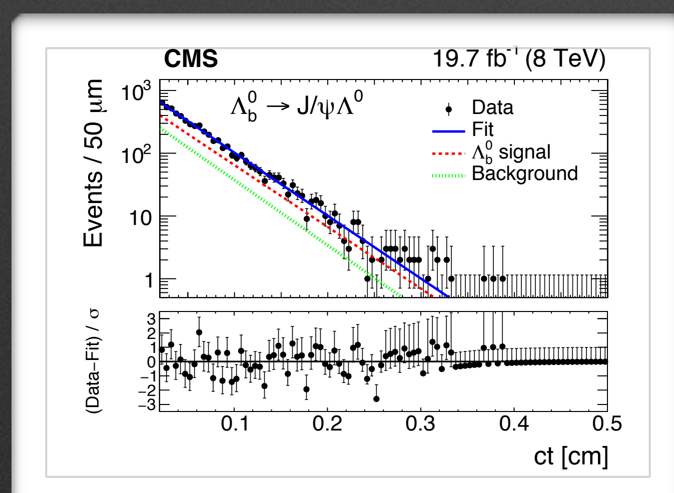
$c\tau = 457.8 \pm 2.7$ µm

Consistent with PDG value : 456.0 ± 1.2 µm

- K_s track $d_{xy}/\sigma > 2$
- K_s vertex $d_{xy}/\sigma > 15$

$\Lambda_b \to J/\psi \Lambda^0(\to p\pi)$





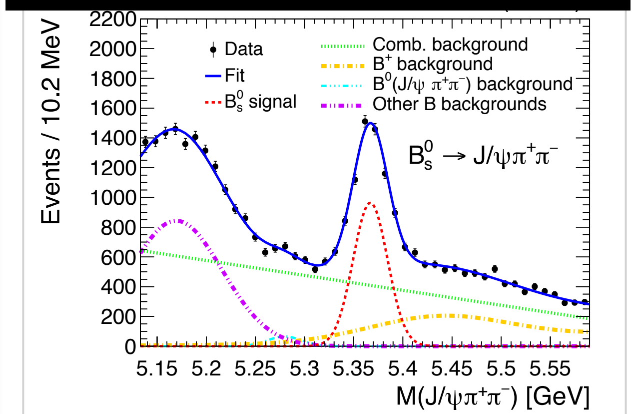
$c\tau = 432.9 \pm 8.2$ µm

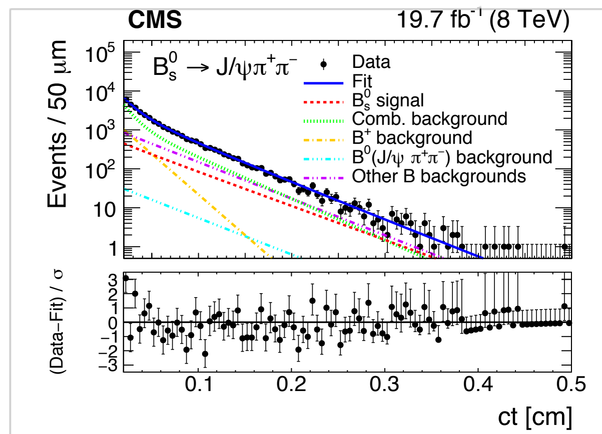
Consistent with PDG value : 441.0 ± 3.0 µm

- Λ track $d_{xy}/\sigma > 2$
- Λ vertex $d_{xy}/\sigma > 15$

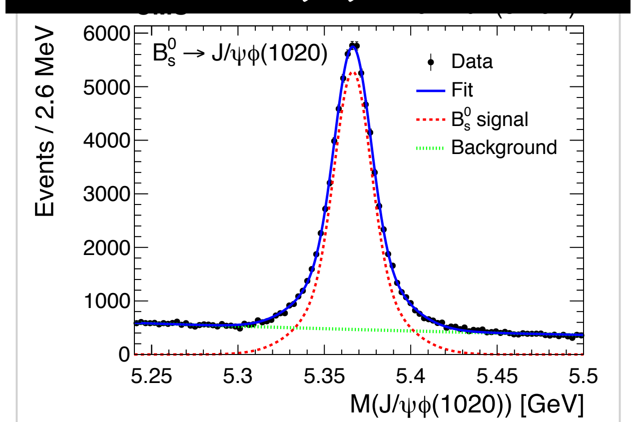
Result : B_s^0

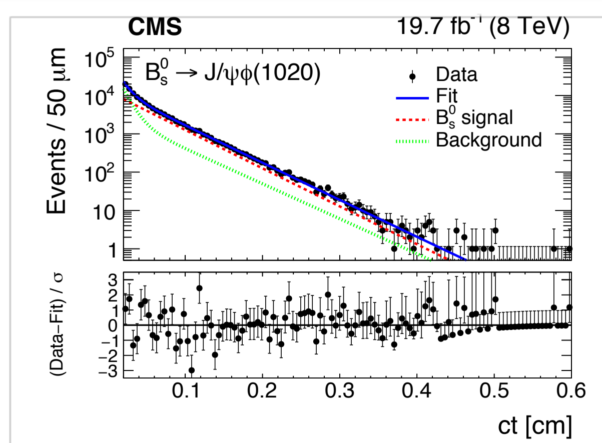
$B_s^0 \to J/\psi\pi^+\pi^-$





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





$c\tau = 502.7 \pm 10.2$ µm

Consistent with PDG value : 497.4 ± 9.6 µm

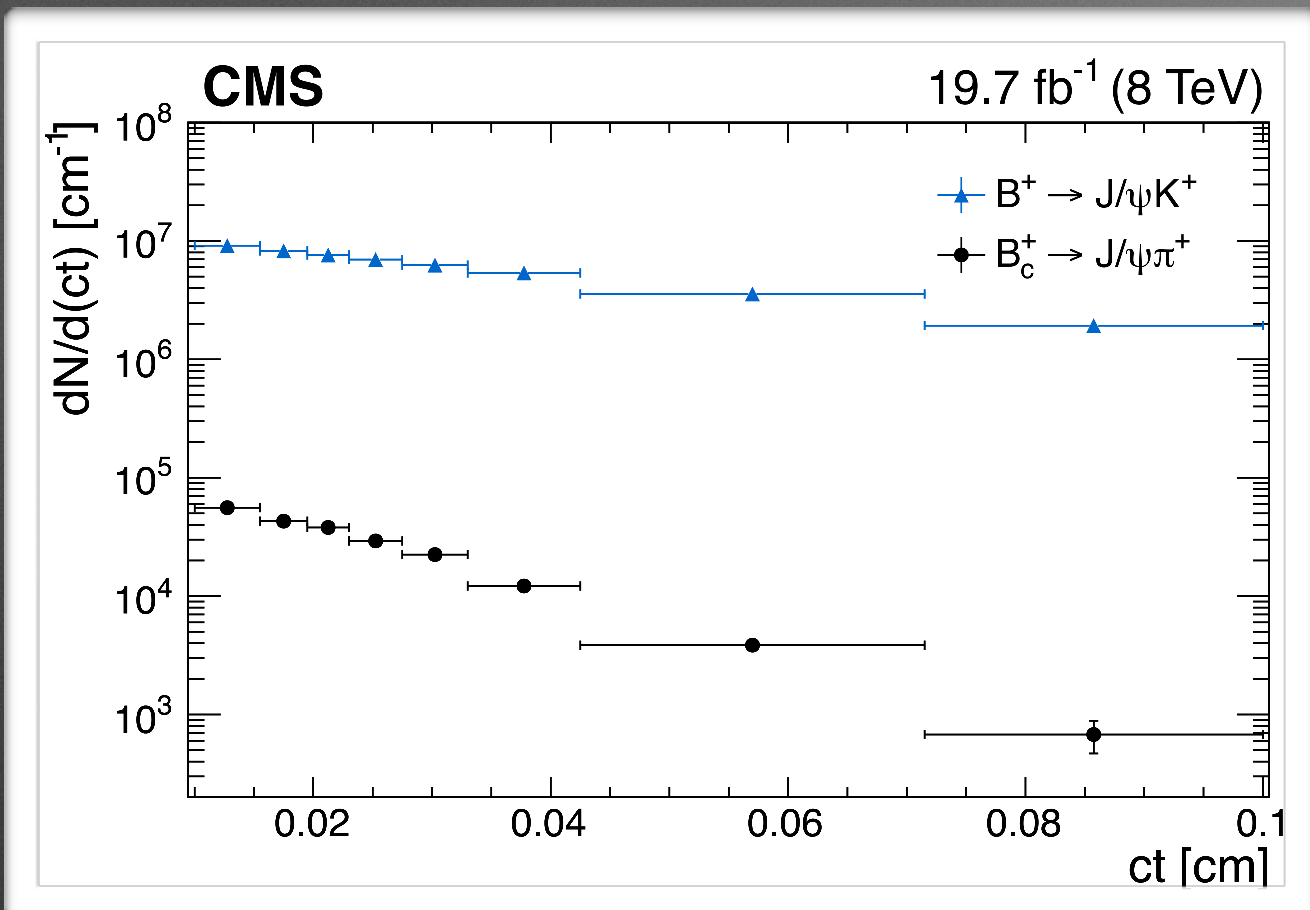
- Extended ML fit
- $1.02 > m_{\pi\pi} > 0.92$ GeV, CP-odd state

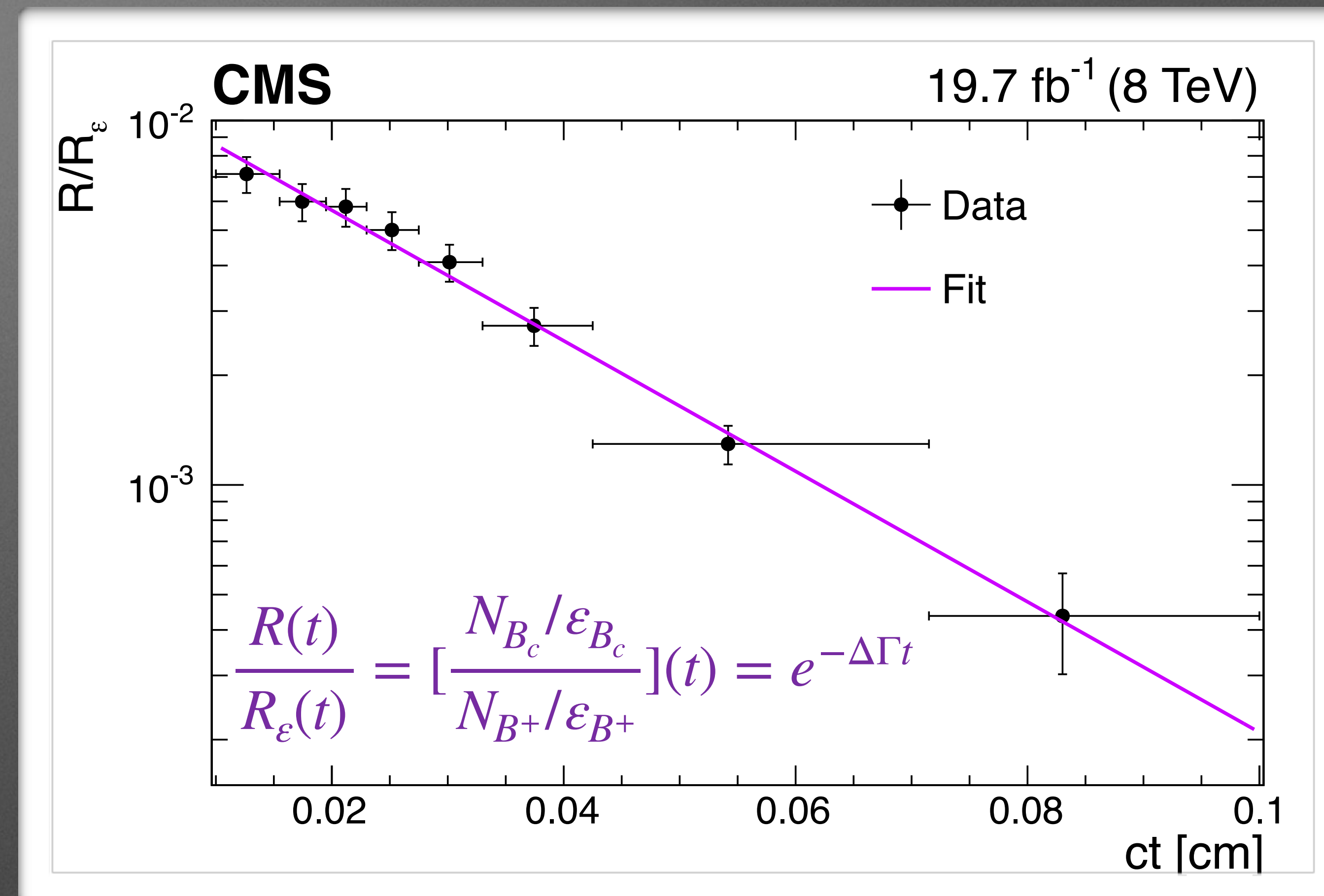
$c\tau = 443.9 \pm 2.0$ µm

Consistent with PDG value : 443.7 ± 3.6 µm

- $\phi(1020) \to KK$
- Mixture of B_{sH} and B_{sL}

Result : $B_c^+ \to J/\psi\pi^+$ wrt $B^+ \to J/\psi K^+$





- π or K $p_T > 3.3$ GeV
- B_c $p_T > 10$ GeV
- $|\eta_B| < 2.2$
- Same condition on B^+ reference to cancel systematics.

With referenced $c\tau(B^+) = 491.1 \pm 1.2$ μm

$c\tau = 162.3 \pm 7.8$ μm

Fitting result to efficiency-corrected ratio **in favors of LHCb result** (152.7 ± 2.7 μm)

Summary

- **Observation**(**6.3σ**) of $B_{s2}^{*}(5840)^0 \to B^0 K_S$ decay
  and **evidence**(**3.9σ**) of $B_{s1}(5830)^0 \to B^{*0} K_S$ decay
  - Branching ratios to $B^{(*)+}K^-$ channel and natural widths are also measured.

- Angular parameters of $\Lambda_b \to \Lambda J/\psi$ is measured.
  - Transverse polarization, **$0.00 \pm 0.06 \pm 0.06$**, is consistent with LHCb result.
  - Parity-asymmetry parameter, **$0.14 \pm 0.14 \pm 0.10$**, lies in range of most publications. However, the HQET prediction, 0.78, is disfavored.
  - Λ with positive helicity is suppressed in the decay.

- Measured lifetimes of b hadrons shows **nice match to world-average** with great precision.
  - **The LHCb result is favored** for B_c lifetime discrepancy.

Backup

More properties and by-products

	B^+K^-	$B^0K^0_S$
$N(B^*_{s2} \to BK)$	5424 ± 269	128 ± 22
$N(B^*_{s2} \to B^*K)$	455 ± 119	12 ± 11
$N(B_{s1} \to B^*K)$	1329 ± 83	34.5 ± 8.3
$\Gamma(B^*_{s2})$, MeV	1.52 ± 0.34	2.1 ± 1.3
$\Gamma(B_{s1})$, MeV	0.10 ± 0.15	0.4 ± 0.4
$M(B^*_{s2}) - M(B) - M(K)$, MeV	66.926 ± 0.093	62.42 ± 0.48
$M(B_{s1}) - M(B^*) - M(K)$, MeV	10.495 ± 0.089	5.65 ± 0.23

Relation between angular parameters and helicity amplitudes

$$1 = |T_{++}|^2 + |T_{+0}|^2 + |T_{-0}|^2 + |T_{--}|^2,$$
$$\alpha_1 = |T_{++}|^2 - |T_{+0}|^2 + |T_{-0}|^2 - |T_{--}|^2,$$
$$\alpha_2 = |T_{++}|^2 + |T_{+0}|^2 - |T_{-0}|^2 - |T_{--}|^2,$$
$$\gamma_0 = |T_{++}|^2 - 2|T_{+0}|^2 - 2|T_{-0}|^2 + |T_{--}|^2$$

$T_{\lambda 1,\lambda 2}$ are complex helicity amplitudes
$\lambda 1$: ±½ (Λ) and $\lambda 2$: ±1, 0 (J/ψ)

$$|T_{++}|^2 = 0.05 \pm 0.04\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$|T_{+0}|^2 = -0.10 \pm 0.04\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$|T_{-0}|^2 = 0.51 \pm 0.03\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$|T_{--}|^2 = 0.52 \pm 0.04\,(\text{stat}) \pm 0.04\,(\text{syst}).$$

Event selection for Λ_b decay

p, π

$p_{T,p} > 1\ GeV$

$p_{T,\pi} > 0.3\ GeV$

$p_{T,p\pi} > 8\ GeV$

$|m_{p\pi} - m_{\Lambda}| < 9\ MeV$

$|m_{p\pi} - m_{Ks}| > 20\ MeV$

μ

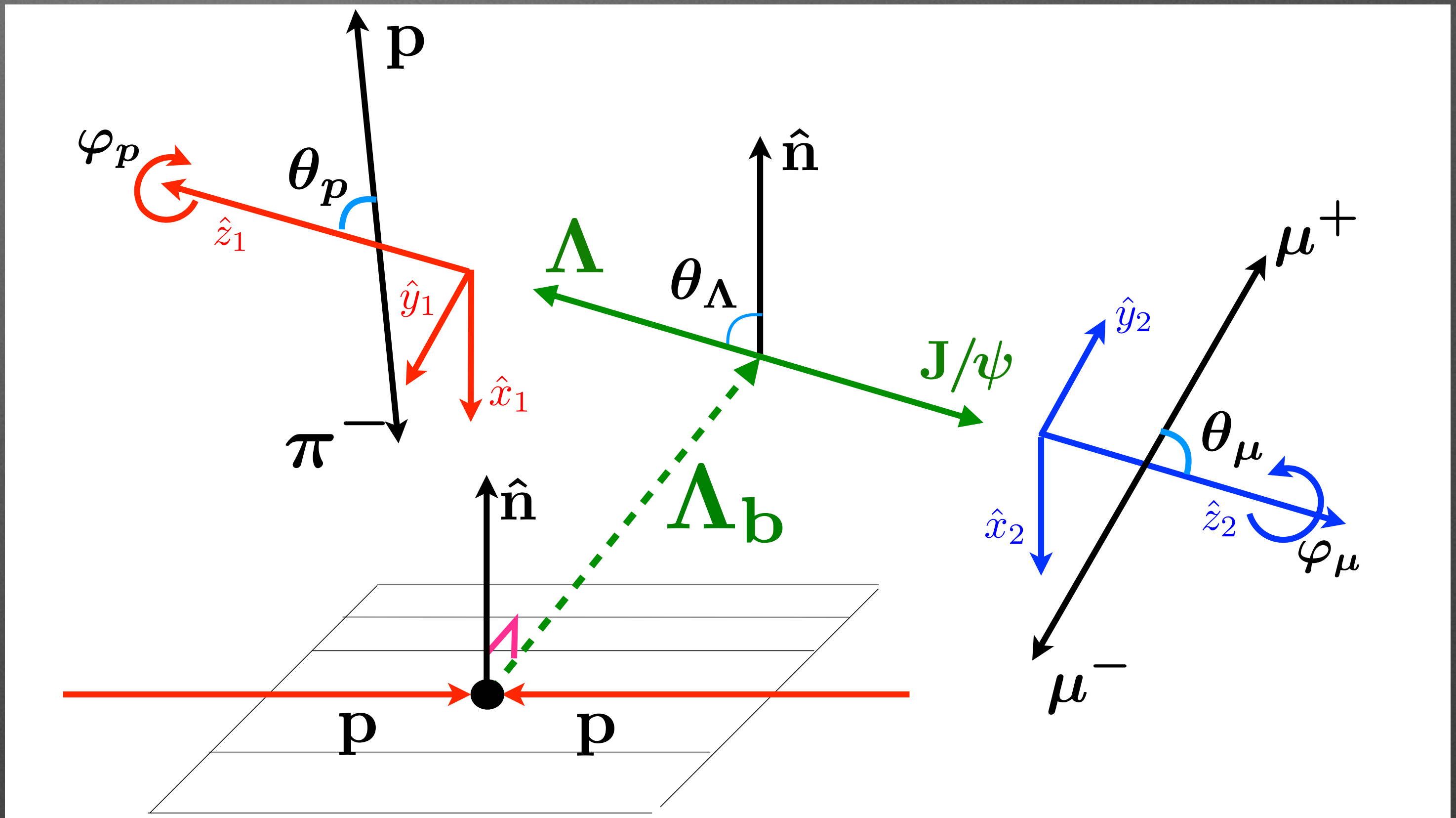
$p_{T,\mu} > 4\ GeV$

$|\eta_{\mu}| < 2.2$

$p_{T,\mu\mu} > 8\ GeV$

$|m_{\mu\mu} - m_{J/\Psi}| < 0.15\ GeV$

$cos\theta_{\vec{p}_{\mu\mu},\overline{BS,\mu\mu\ vertex}} > 0.99$



Λ_b

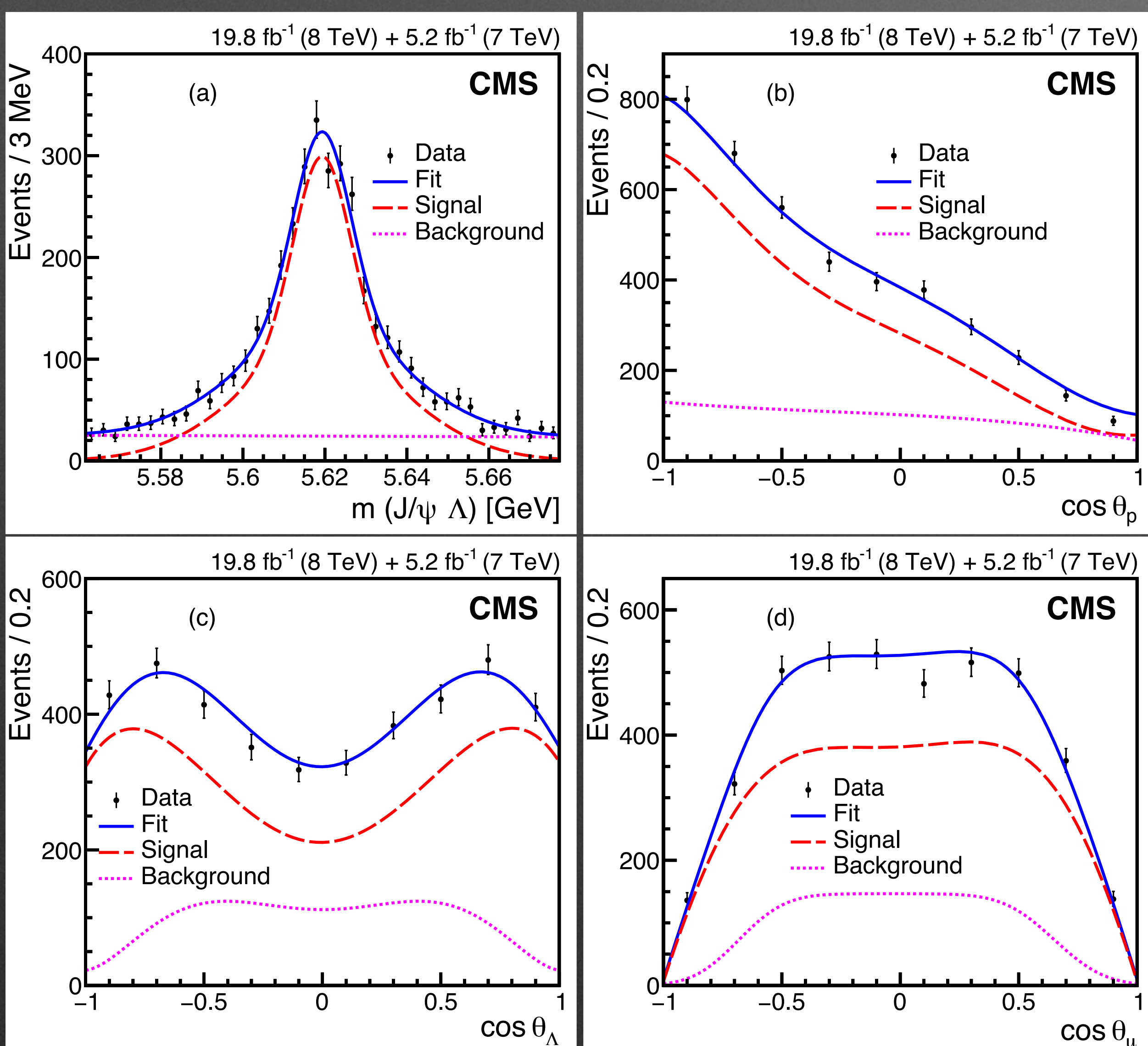
$p_{T,\Lambda J/\Psi} >$ 10 GeV

Vertex Prob(Λ_b) > 10 %

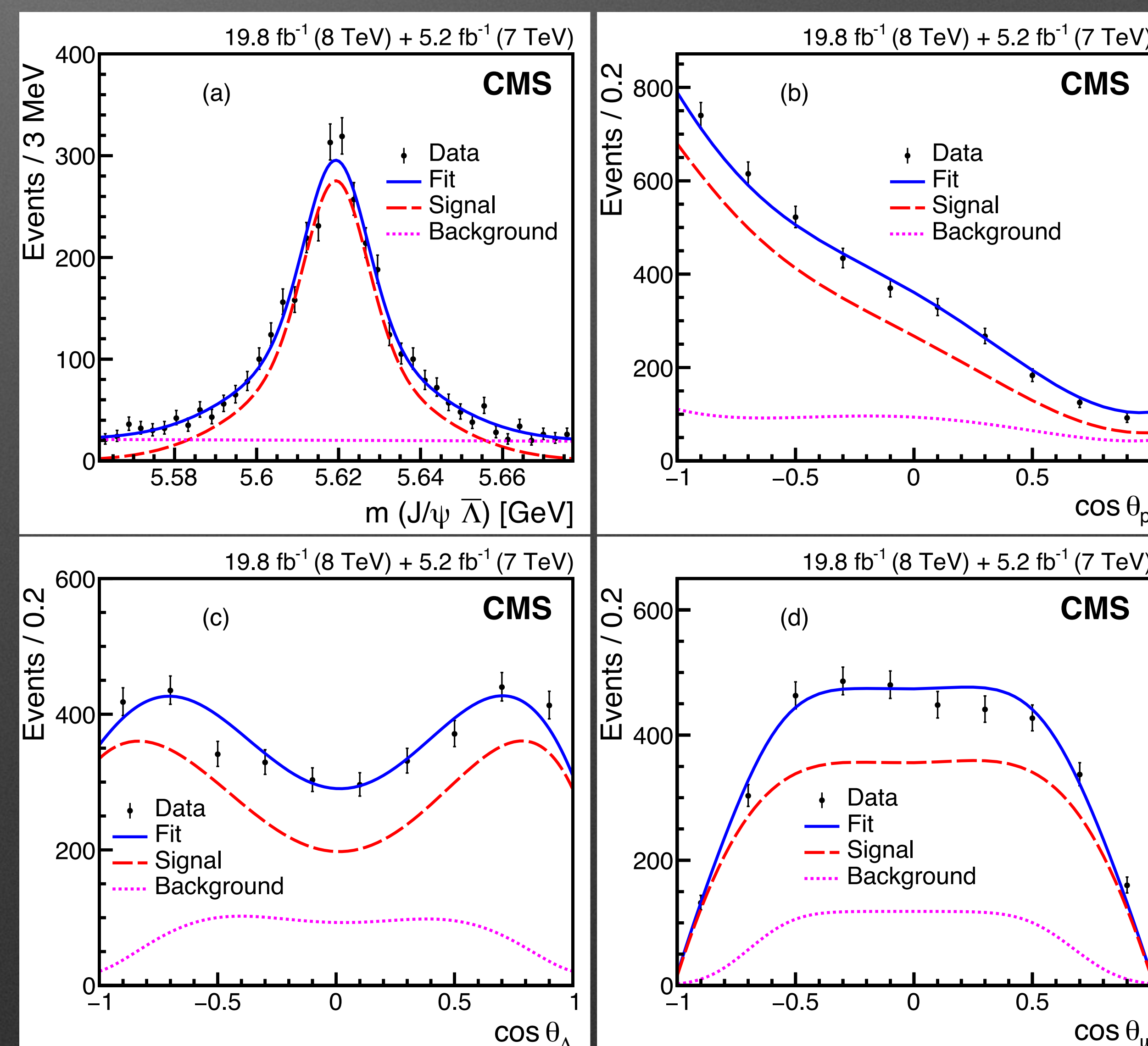
5.84 $GeV > m_{\Lambda J/\Psi} >$ 5.40 GeV

Λ_b Fitting result

$J/\psi\Lambda$



$J/\psi\bar{\Lambda}$



Syst. error of Λ_b angular parameters

Source	$P(\times 10^{-2})$	$\alpha_1(\times 10^{-2})$	$\alpha_2(\times 10^{-2})$	$\gamma_0(\times 10^{-2})$
Fit bias	0.1	0.3	0.1	0.2
Asymmetry parameter α_Λ	0.4	0.7	2.0	0.6
Background $m_{J/\psi\Lambda}$ distribution	0.01	0.5	1.0	0.9
Background angular distribution	0.4	0.5	0.9	5.0
Signal $m_{J/\psi\Lambda}$ distribution	0.01	0.3	1.0	1.0
Angular efficiencies	0.1	0.3	3.0	1.0
Angular resolution	1.0	0.1	2.6	0.8
Azimuthal angle efficiency	0.1	1.0	0.3	0.1
Weighting procedure	0.1	1.3	0.4	2.0
Reconstruction bias	5.7	9.8	2.0	9.1
Total (quadrature sum)	5.8	10.0	5.1	11.1

Systematics in lifetime measurement

Source	$B^0 \to J/\psi K^*(892)^0$	$B^0 \to J/\psi K^0_S$	$B^0_s \to J/\psi \pi^+\pi^-$	$B^0_s \to J/\psi \phi$	$\Lambda^0_b \to J/\psi \Lambda^0$
PV selection	0.7	0.7	0.7	0.7	0.7
Detector alignment	0.3	0.7	0.3	0.3	0.7
MC statistical uncertainty	1.1	2.4	2.0	0.6	2.3
Mass modelling	0.3	0.4	0.2	0.4	0.9
Efficiency modelling	0.3	0.5	0.6	0.2	0.6
ct resolution	0.0	0.1	0.1	0.1	0.2
ct modelling	0.1	0.1	0.4	0.0	0.1
B^+ contamination	—	—	1.4	—	—
Mass window of $\pi^+\pi^-$	—	—	1.8	—	—
$K^\pm\pi^\mp$ mass assignment	0.3	—	—	—	—
ct range	—	—	—	0.1	—
S-wave contamination	—	—	—	0.4	—
Total (μm)	1.5	2.7	3.2	1.2	2.7

Source	$\Delta\Gamma$ [ps^{-1}]	$c\tau_{B_c}$ [μm]
PV selection	0.02	2.0
Detector alignment	0.01	0.6
MC statistical uncertainty	0.01	1.3
Mass modelling	0.04	3.7
ct binning	0.01	1.4
Total uncertainty	0.05	4.7