Recent (2018) CMS results on b hadrons & quarkonia

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(on behalf of the CMS Collaboration)

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Outline

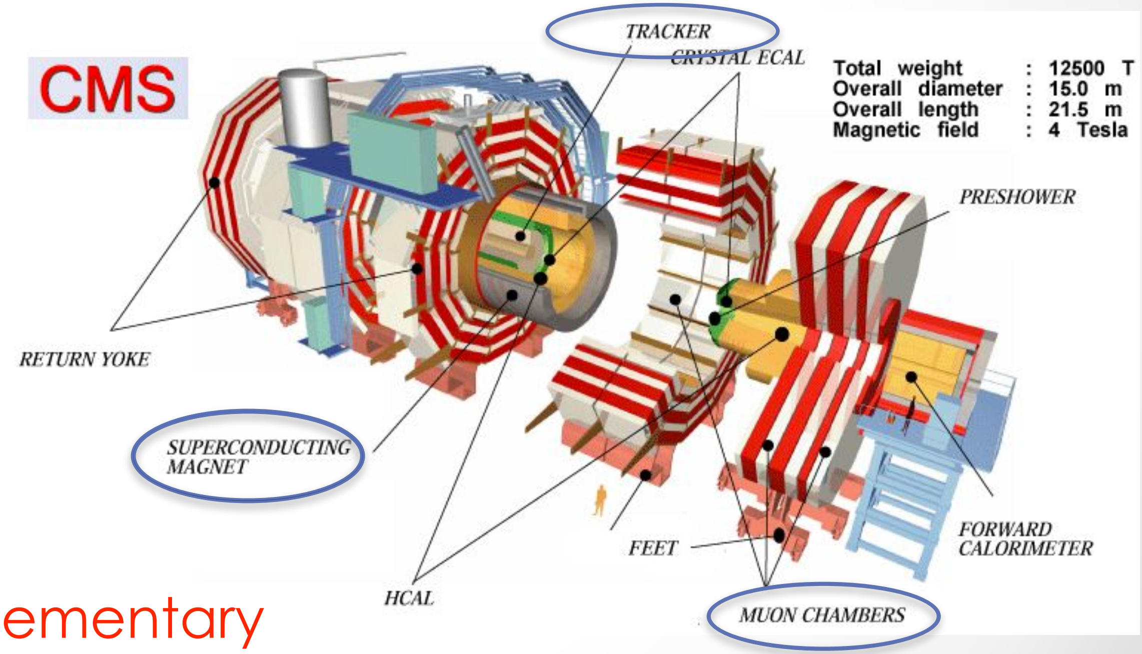
- Introduction & HF program.
- ⋆ b hadron lifetimes [arXiv:1710.08949, accepted by **EPJC**].
- ⋆ Λ_b polarization and parameters of the $\Lambda_b \to J/\psi\ \Lambda$ decay [**PRD** 97, 072010 (2018)].
- ⋆ Cross sections of J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ (n=1,2,3) [**PLB** 780, 251 (2018)].
- ⋆ Search for resonances in the $B_s\pi^\pm$ mass spectrum [**PRL** 120, 202005 (2018)].
- Summary.

Introduction

- **LHC**: pp collisions @ 7-8 (Run I) & 13 TeV (Run II) ⇒ large *b* and *c* hadron production.

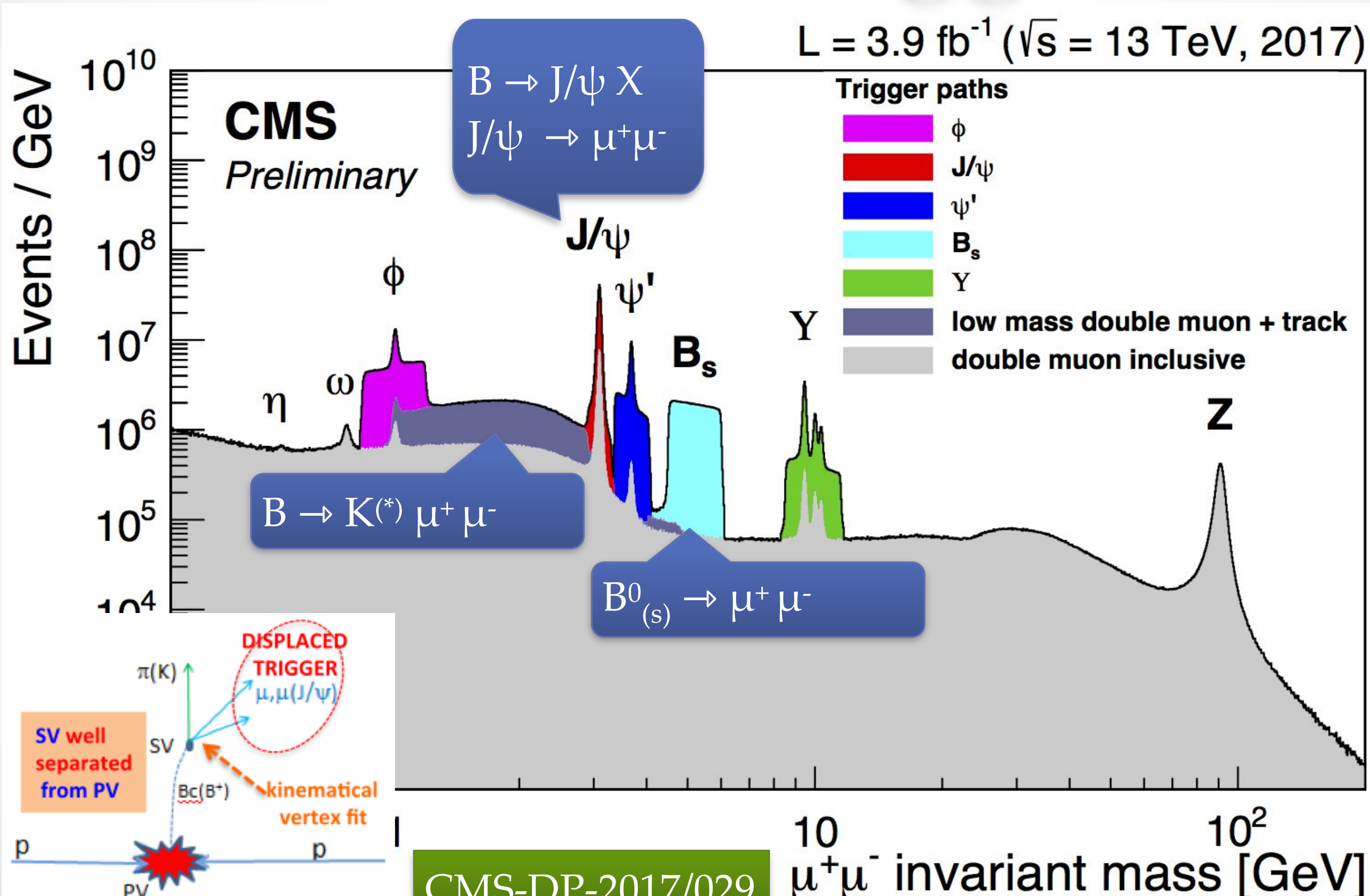
CMS heavy flavors program ↔ Excellent μ ID + Track and vertex reconstruction

- Precise measurements of b hadrons and $q\bar{q}$ properties help to improve or constrain QCD-inspired models.



- CMS heavy flavors physics results are competitive or complementary with respect to other experiments.

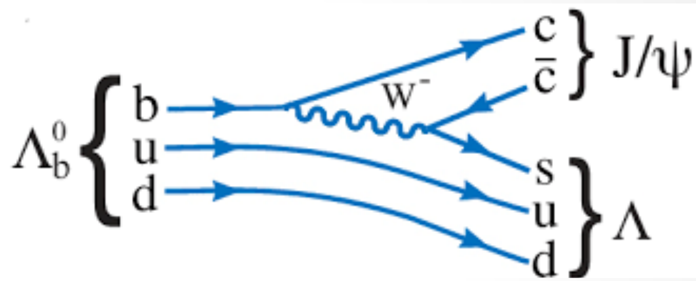
Dimuon trigger

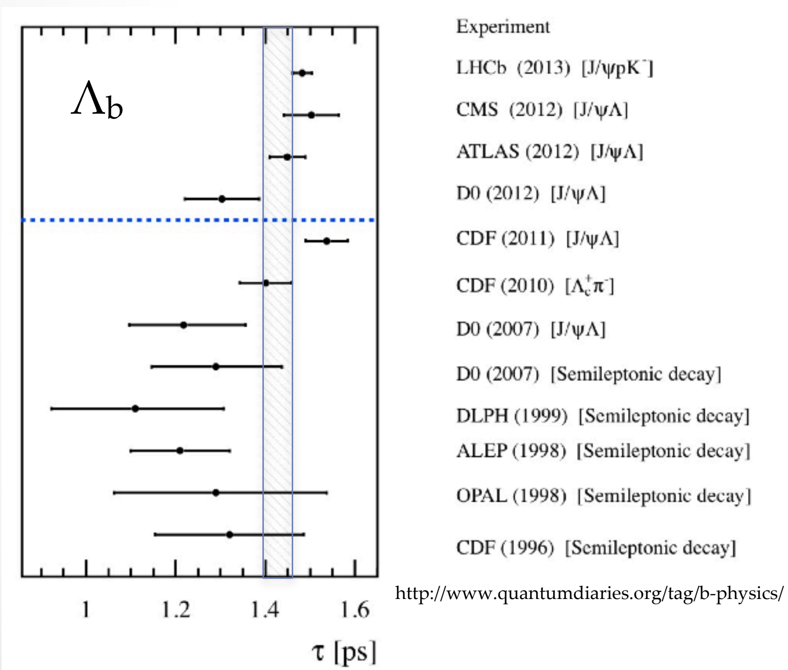


CMS-DP-2017/029

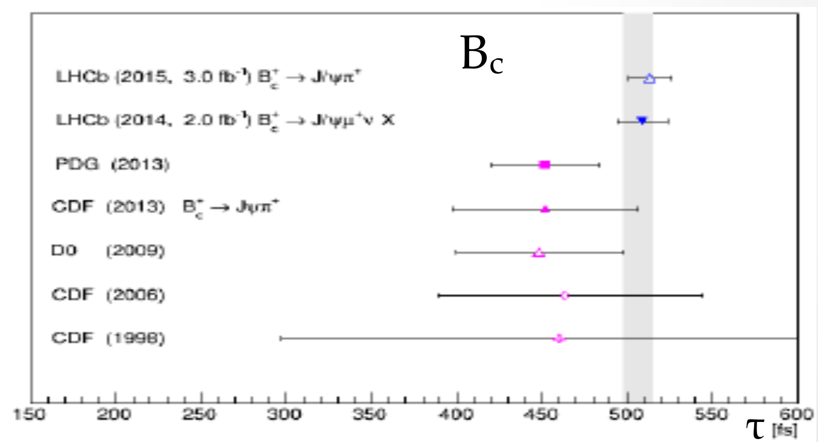
b hadron lifetimes

- B-lifetimes determine importance of non-spectator contributions.
- Discrepancies among previous measurements of, e.g., Λ_b & B_c^+ lifetimes:



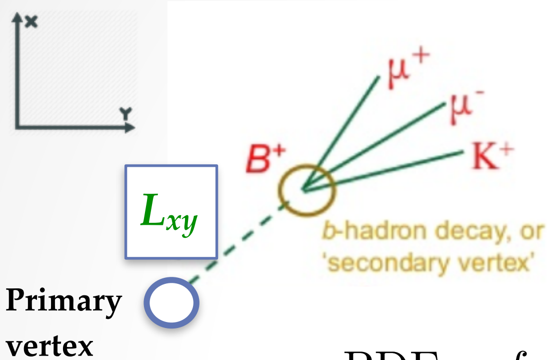


http://www.quantumdiaries.org/tag/b-physics/



LHCb results significantly larger than Tevatron measurements

Measurement strategy



- Measurements **based on reconstruction of** the transverse decay length $\boldsymbol{L_{xy}}$ and UML fits of reco. mass (M), ct and σ_{ct} of the b hadron:

$$ct = cL_{xy}\frac{M_B^{(\mathrm{PDG})}}{p_\mathrm{T}} \qquad (\ ct > 200\ \mu\mathrm{m}\ )$$

$$\mathrm{PDF} = f_S M_S(M) T_S(ct) E_S(\sigma_{ct}) + (1 - f_S) M_B(M) T_B(ct) E_B(\sigma_{ct})$$

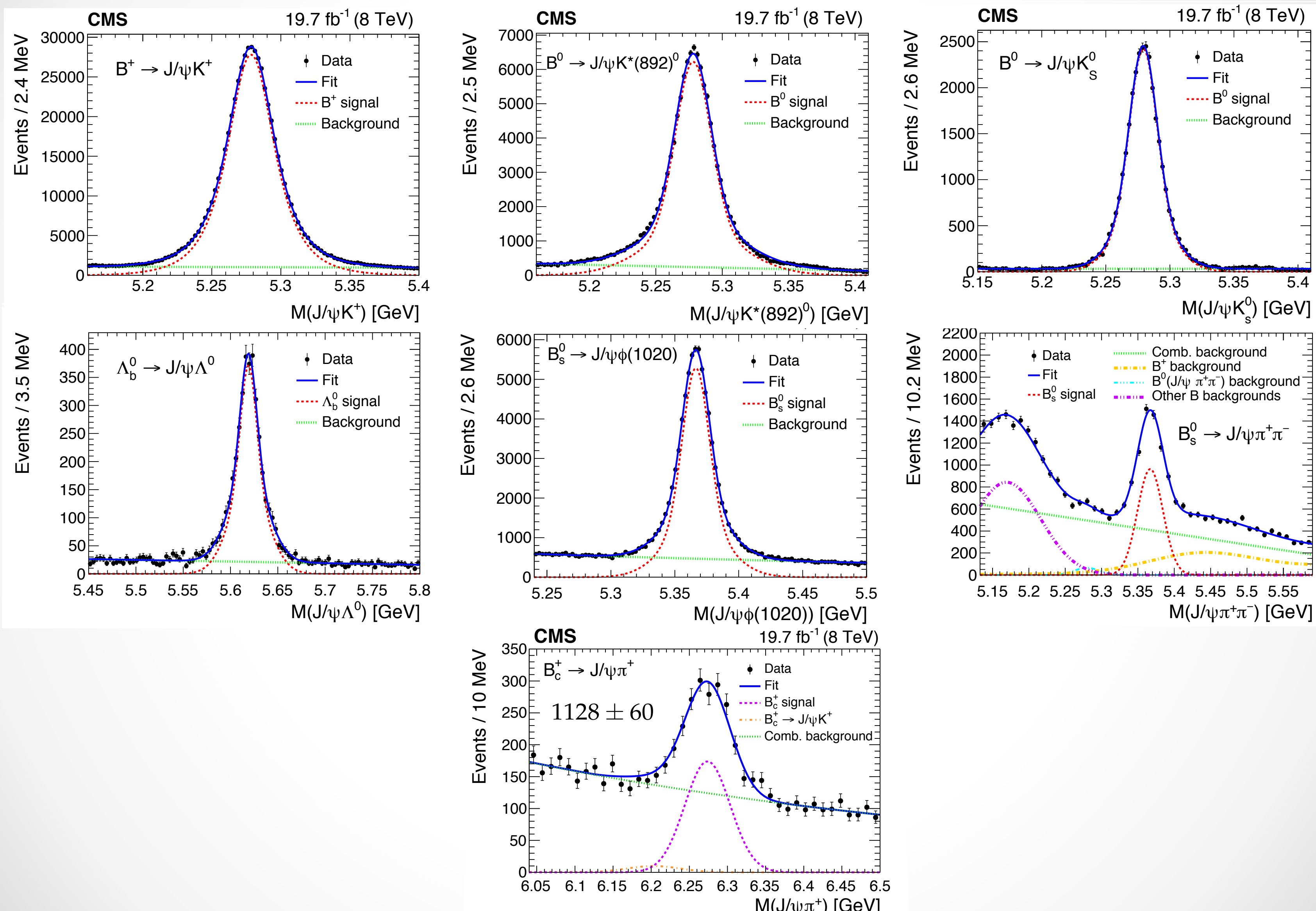
- This way, we measure $\tau_{B^0\to J/\psi K^*}$, $\tau_{B^0\to J/\psi K_S}$, $\tau_{\Lambda_b\to J/\psi\Lambda}$, the *effective B_s lifetime* $\tau_{B_s\to J/\psi\phi}$ (final states are admixture of CP eigenstates), and the CP-odd lifetime $\tau_{B_s\to J/\psi\pi\pi} \sim 1/\Gamma_H = \tau_H$ (lifetime of heavy mass state).

- $B^+\to J/\psi K^+$: reference mode, for evaluation of syst. uncertainties.

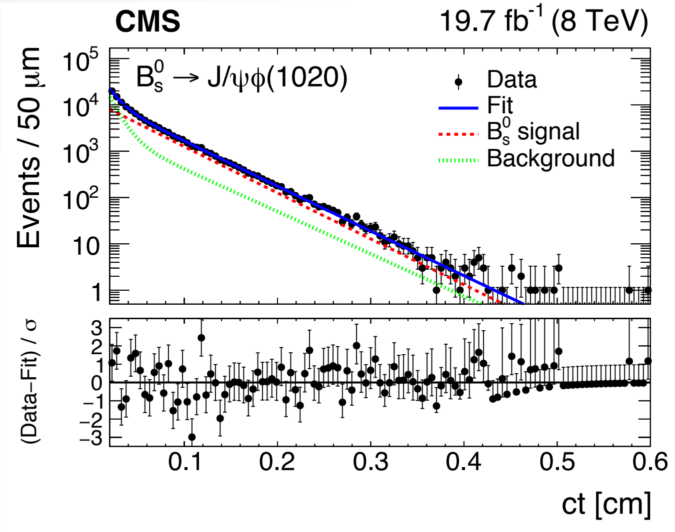
- The B_c^+ lifetime is obtained through the ratio of the B_c^+ & B^+ *ct* signal histograms, where the *ct* resolution "*r(ct)*" is shown to ~cancel out:

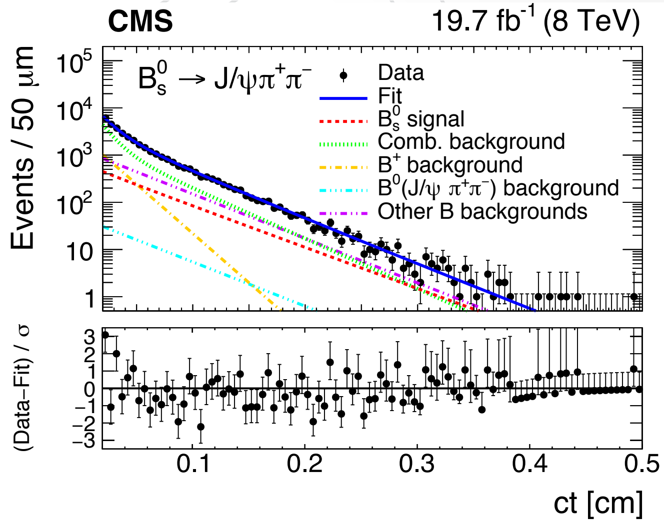
$$\frac{N_{B_c^+}(ct)}{N_{B^+}(ct)} \equiv R(ct) = \frac{\varepsilon_{B_c^+}(ct)[r(ct)\otimes E_{B_c^+}(ct)]}{\varepsilon_{B^+}(ct)[r(ct)\otimes E_{B^+}(ct)]} \approx R_\varepsilon(ct)\exp(-\Delta\Gamma t), \quad \Delta\Gamma \equiv \frac{1}{\tau_{B_c^+}} - \frac{1}{\tau_{B^+}}$$

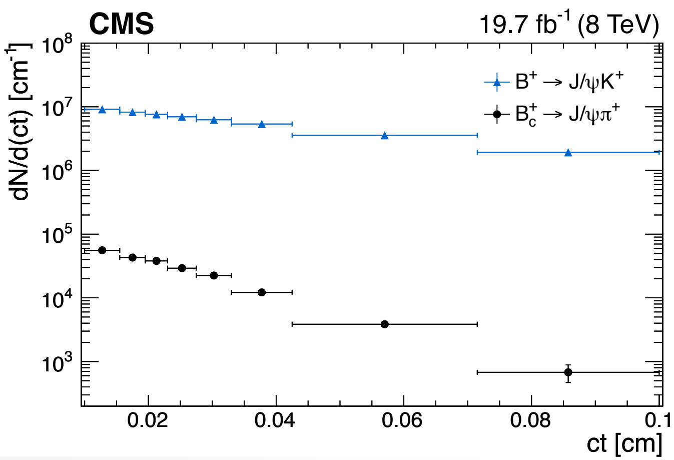
Mass distributions

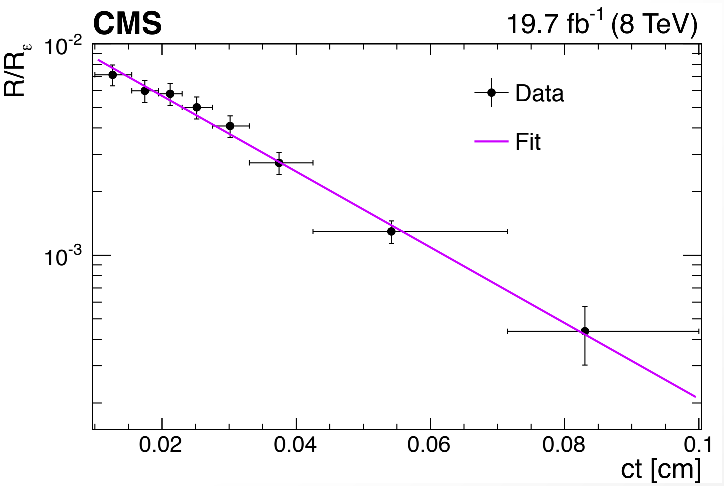


ct fits (e.g.)


CMS
19.7 fb^{-1} (8 TeV)
$B_s^0 \to J/\psi\phi(1020)$
Data
Fit
B_s^0 signal
Background
Events / 50 μm
(Data−Fit) / σ
ct [cm]


CMS
19.7 fb^{-1} (8 TeV)
$B_s^0 \to J/\psi\pi^+\pi^-$
Data
Fit
B_s^0 signal
Comb. background
B^+ background
$B^0(J/\psi\ \pi^+\pi^-)$ background
Other B backgrounds
Events / 50 μm
(Data−Fit) / σ
ct [cm]


CMS
19.7 fb^{-1} (8 TeV)
$B^+ \to J/\psi K^+$
$B_c^+ \to J/\psi\pi^+$
dN/d(ct) [cm^{-1}]
ct [cm]


CMS
19.7 fb^{-1} (8 TeV)
Data
Fit
R/R_ϵ
ct [cm]

Accepted by EPJC (arXiv:1710.08949)

Results

$c\tau_{B^0\to J/\psi K^*(892)^0} = 453.0 \pm 1.6\ (\text{stat}) \pm 1.8\ (\text{syst})\ \mu m$

$c\tau_{B^0\to J/\psi K^0_S} = 457.0 \pm 2.7\ (\text{stat}) \pm 2.8\ (\text{syst})\ \mu m$

} $c\tau_{B^0} = 454.1 \pm 1.4\ (\text{stat}) \pm 1.7\ (\text{syst})\ \mu m$ vs. 455.7 ± 1.2 μm (HFAG)

$c\tau_{B^0_s\to J/\psi\pi^+\pi^-} = 502.7 \pm 10.2\ (\text{stat}) \pm 3.4\ (\text{syst})\ \mu m$ vs. 495 ± 10 (LHCb), 510 ± 36 (CDF), 508 ± 45 μm (D0)

$c\tau_{B^0_s\to J/\psi\phi(1020)} = 443.9 \pm 2.0\ (\text{stat}) \pm 1.5\ (\text{syst})\ \mu m$ vs. 443.4 ± 3.6 μm (HFAG)

$c\tau_{\Lambda^0_b} = 442.9 \pm 8.2\ (\text{stat}) \pm 2.8\ (\text{syst})\ \mu m$ vs. 440.7 ± 3.0 μm (HFAG)

$c\tau_{B^+_c} = 162.3 \pm 7.8\ (\text{stat}) \pm 4.2\ (\text{syst}) \pm 0.1\ (\tau_{B^+})\ \mu m$ vs. 152.0 ± 2.7 μm (HFAG)

Precision from each channel is as good as or better than previous measurements.

$\tau_{\Lambda^0_b}/\tau_{B^0\to J/\psi K^*(892)^0} = 0.978 \pm 0.018\,(\text{stat}) \pm 0.006\,(\text{syst})$, vs. 0.967 ± 0.007 (HFAG)

$\tau_{B^0_s\to J/\psi\phi(1020)}/\tau_{B^0\to J/\psi K^*(892)^0} = 0.980 \pm 0.006\,(\text{stat}) \pm 0.003\,(\text{syst})$. vs. 0.993 ± 0.004 (HFAG)

Ratios are compatible with the current W.A. values (≲1.5σ).

Combinations of previous results also lead to:

$\Gamma_d = 0.662 \pm 0.003\,(\text{stat}) \pm 0.003\,(\text{syst})\,\text{ps}^{-1}$,

$\Delta\Gamma_d = 0.023 \pm 0.015\,(\text{stat}) \pm 0.016\,(\text{syst})\,\text{ps}^{-1}$,

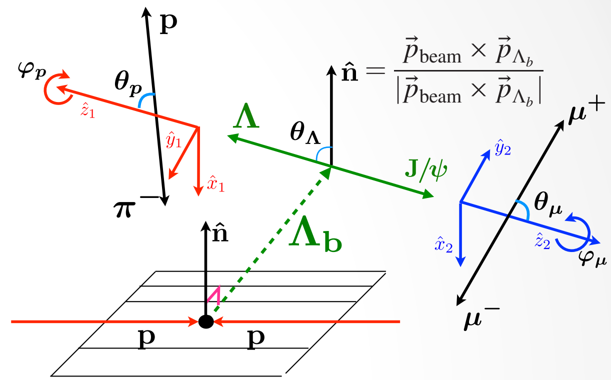
$\Delta\Gamma_d/\Gamma_d = 0.034 \pm 0.023\,(\text{stat}) \pm 0.024\,(\text{syst})$. (B^0) vs. -0.002 ± 0.010 (HFAG)

$c\tau_L = 420.4 \pm 6.2\,\mu m$ (B^0_s) vs. 423.6 ± 1.8 μm (HFAG)

All results are in agreement with current W.A. values and with HQE predictions and other theoretical models.

Λ_b polarization and $\Lambda_b \to J/\psi \Lambda$ decay parameters

- HQET: A large fraction of *transverse b-polarization* remains after hadronization.
- This analysis: $\Lambda_b \to J/\psi \Lambda$ 5D angular decay function [Kramer & Simma, NPB-P.S. 50, 125 (1996)] is partially integrated:



$$\frac{d^5\Gamma}{d\cos\theta_\Lambda d\Omega_p d\Omega_\mu}(\theta_\Lambda, \theta_p, \theta_\mu, \varphi_p, \varphi_\mu) \xrightarrow{\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} d\varphi_p d\varphi_\mu} \sim \sum_{i=1}^{8} u_i(|T_{\lambda_1\lambda_2}|^2) v_i(P, \alpha_\Lambda) w_i(\theta_\Lambda, \theta_p, \theta_\mu)$$

- α_Λ: asymmetry param. in $\Lambda \to p\pi^-$ decay (**fixed** to PDG 0.62 ± 0.013).
- ***P***: Λ_b polarization.
- Asymmetry param. in $\Lambda_b \to J/\psi \Lambda$: $\alpha_1 = |T_{++}|^2 - |T_{+0}|^2 + |T_{-0}|^2 - |T_{--}|^2$
- Long. polarization of the Λ: $\alpha_2 = |T_{++}|^2 + |T_{+0}|^2 - |T_{-0}|^2 - |T_{--}|^2$
- J/ψ long./transv. pol. parameter: $\gamma_0 = |T_{++}|^2 - 2|T_{+0}|^2 - 2|T_{-0}|^2 + |T_{--}|^2$

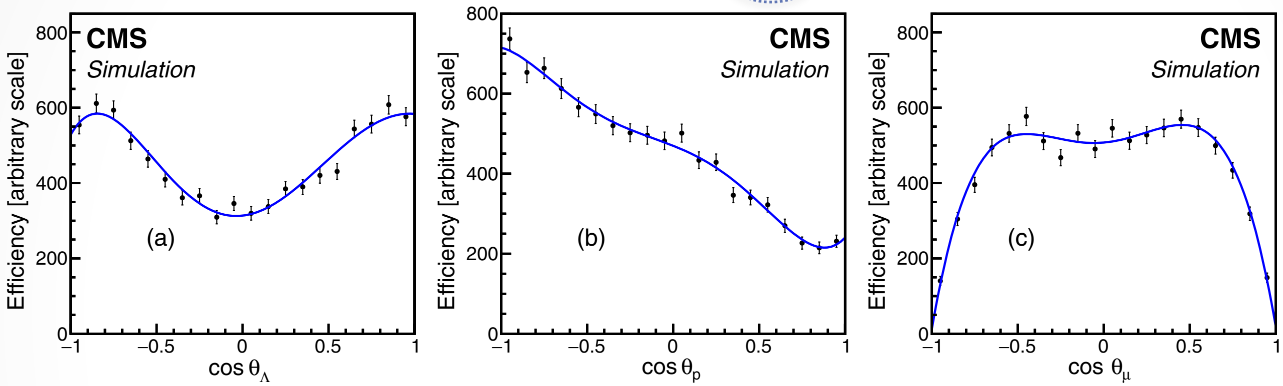
} 4 params. to fit

- Effects of integration of ϕ-angles propagated to syst. uncertainties.

Angular efficiencies and background

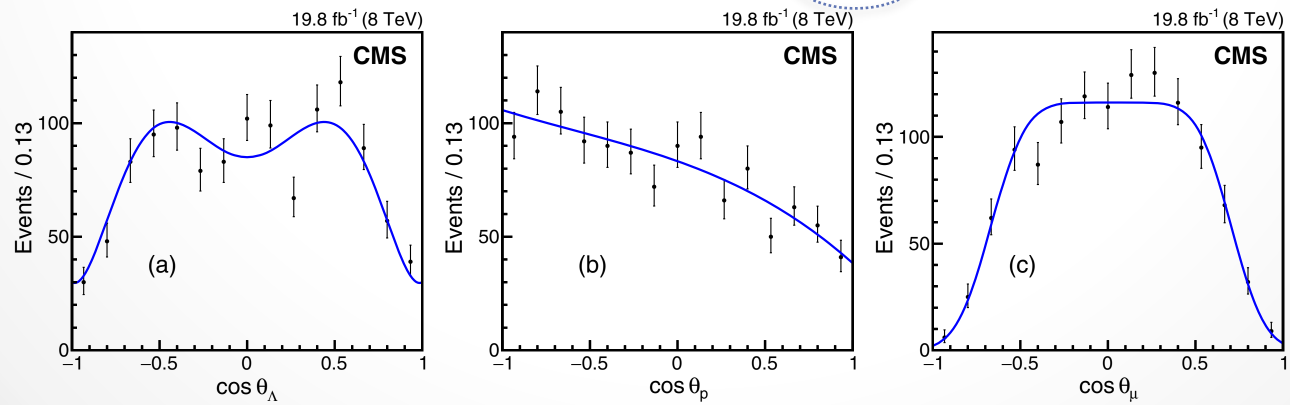
- Angular efficiencies obtained from simulations:

$$PDF_{\text{sig}} = F_{\text{sig}}(\Theta_3)\epsilon(\Theta_3)G(m_{J/\psi\Lambda})$$



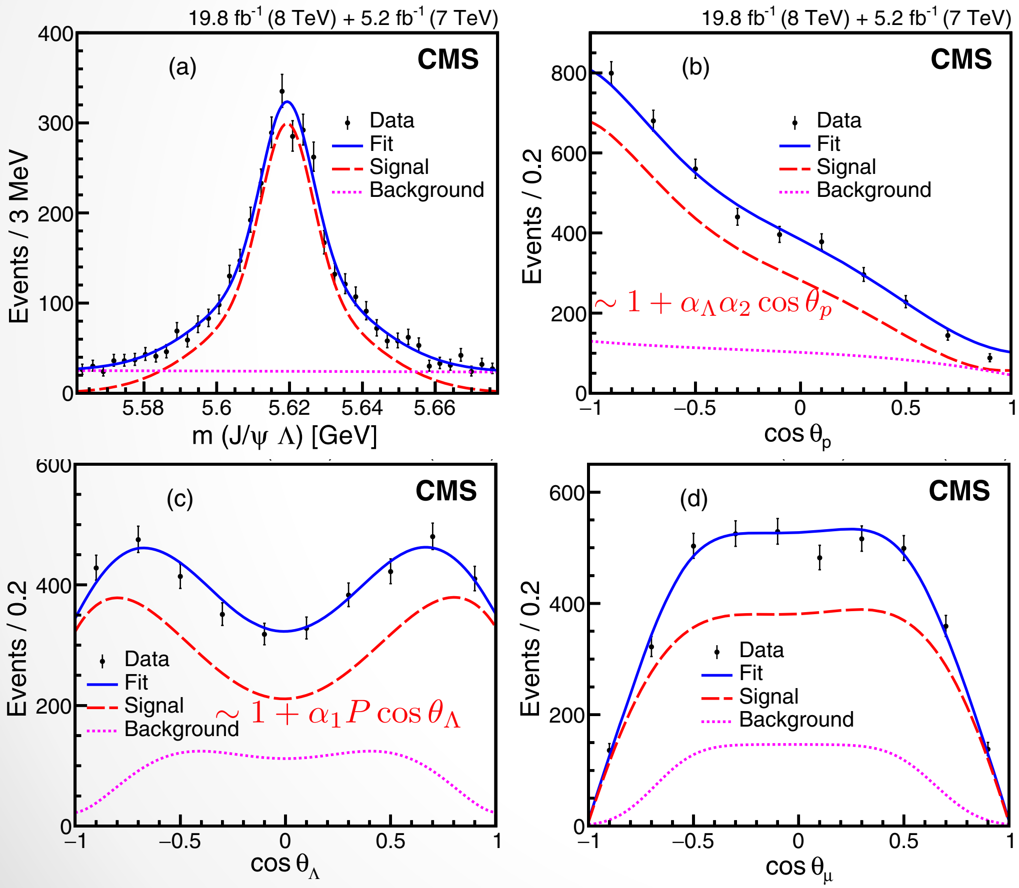
- Bkg. angular distributions obtained from J/ψΛ invariant mass sidebands:

$$PDF_{\text{bkg}} = \mathcal{P}(m_{J/\psi\Lambda})F_{\text{bkg}}(\Theta_3)$$



Results

- Simultaneous (Λ_b & $\bar{\Lambda}_b$, 7 & 8 TeV) 3D-UML fit:



$$P = 0.00 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}),$$
$$\alpha_1 = 0.14 \pm 0.14(\text{stat}) \pm 0.10(\text{syst}),$$
$$\alpha_2 = -1.11 \pm 0.04(\text{stat}) \pm 0.05(\text{syst})$$
$$\gamma_0 = -0.27 \pm 0.08(\text{stat}) \pm 0.11(\text{syst})$$

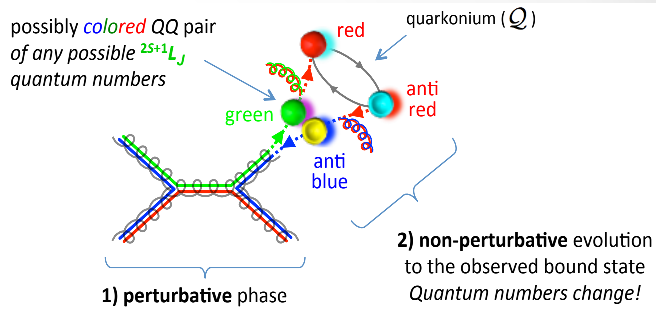
- $P^{(\text{LHCb})} = 0.06 \pm 0.07 \pm 0.02$
- $P^{(\text{HQET})} = 0.1 - 0.2$

- $\alpha_1^{(\text{LHCb})} = -\alpha_b^{(\text{LHCb})} = -0.05 \pm 0.17 \pm 0.07$
- Many theoretical predictions for α_1:
  - 0.1 - 0.2 (PQCD, factorization, several quark models).
  - -0.78 (HQET).

PRD 97, 072010 (2018)

Quarkonium production

- **Well established framework: NRQCD** ~ factorizes short-dist. (SDCs, perturbative calculations) and universal long-dist. (LDMEs, from fits to data) contributions.



- Contrary to expectations, LHC measurements indicate **quarkonia are produced unpolarized** ⇒ important to add more data to constrain LDMEs.

- **For J/ψ, ψ' and Υ(nS)** (n=1,2,3) @13 TeV, **CMS measures**:

$$\mathcal{B}(\mathcal{Q}\rightarrow\mu^-\mu^+)\,\frac{d^2\sigma}{dp_T\,dy}=\frac{N(p_T,y)}{\mathcal{L}\Delta y\Delta p_T}\left\langle\frac{1}{\epsilon(p_T,y)\mathcal{A}(p_T,y)}\right\rangle$$

prompt signal events (cannot distinguish feed-down decays of heavier $c\bar{c}$)

Acceptance

Integrated lumi

y and p_T bin widths ($|y| < 1.2$, p_T = 20 - 150 (130) GeV)

Reconstruction efficiency

Acceptance and efficiency

- Acceptance calculated w/ Pythia generated w/ data-derived p_T distribution & *unpolarized* J/ψ: **analysis provides scaling factors (0.75-1.20) to convert to polarized scenarios**.

- Dimuon reconstruction efficiency:

$$\epsilon_{\mu\mu}(p_T, y) = \epsilon(p_{T1}, \eta_1) \cdot \epsilon(p_{T2}, \eta_2) \cdot \rho(p_T, y) \cdot \epsilon_{tk}^2$$

Correction factor from data (TnP uses special trigger w/ **pT > 20 GeV**) accounts for correlation & effects due to detector granularity and coarse L1 trigger.

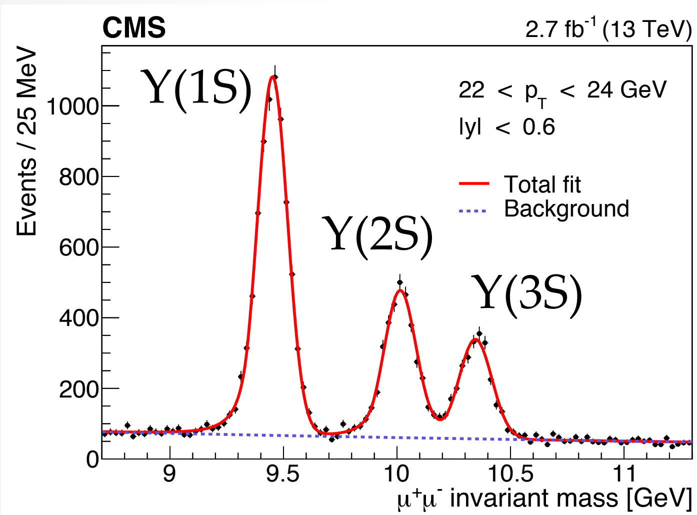
Single muon TnP efficiency from data and independent triggers. Multiplied & parametrized.

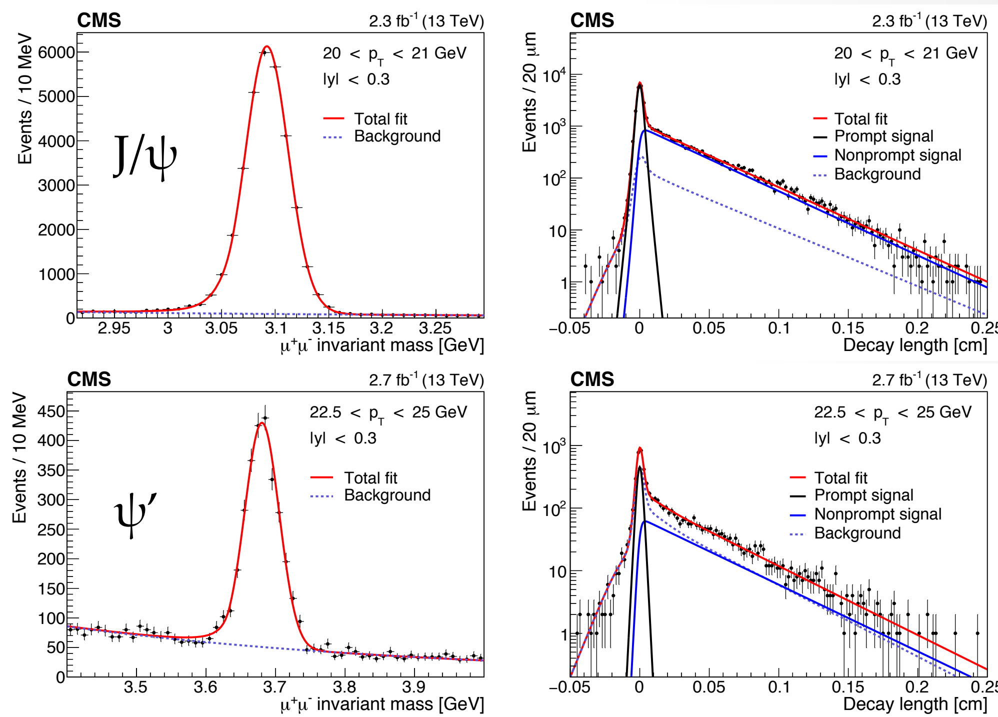
Tracking efficiency ~ 99%.

$\epsilon_{\mu\mu}$ ~ 85%, decreases w/ p_T mainly due to ρ

Yields and prompt fraction

- **UML fits to $M_{\mu\mu}$ ($M_{\mu\mu}$-ct) in each y-p_T bin (for J/ψ and ψ'):**



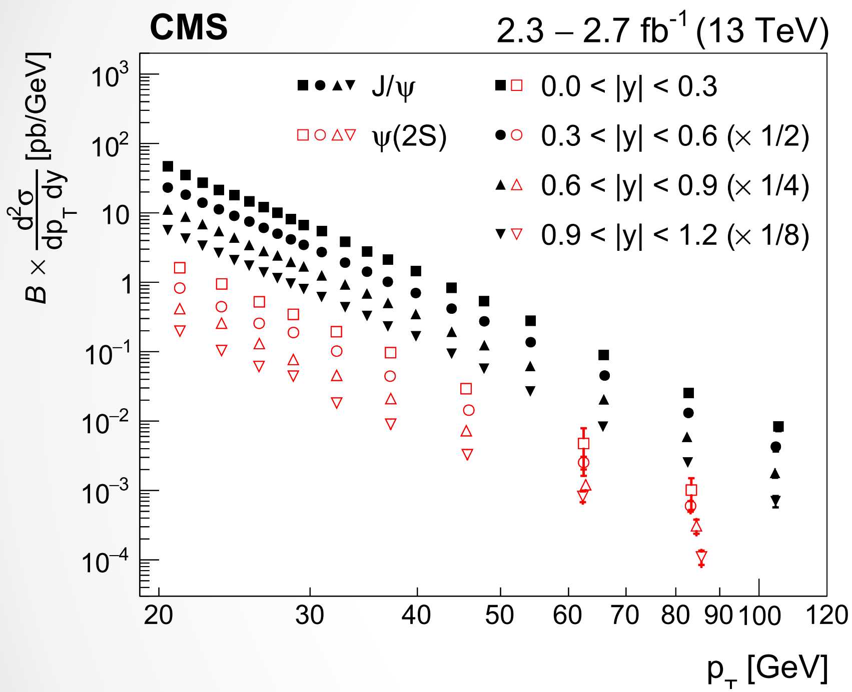


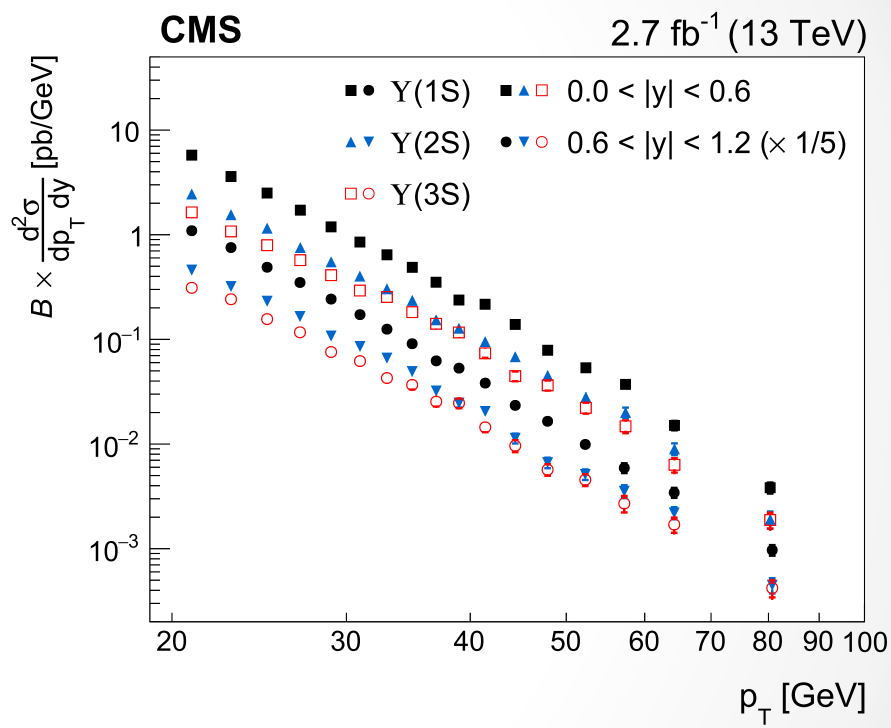
- Each: CB + Gaussian core.
- Means: fixed · common factor.
- Widths: ~common.
- CB params: constrained to the fit of the pT-integrated distribution.
- Bkg.: exponential.

- CB (+ Gauss. J/ψ) + exponential bkg.
- Mean and CB params. constrained to p_T-int.

- Prompt = Res. (R): event-by-event-scaled double-Gauss.
- Non-prompt: Exp ⊗ R.
- Bkg.: R′ + exp ⊗ R′.

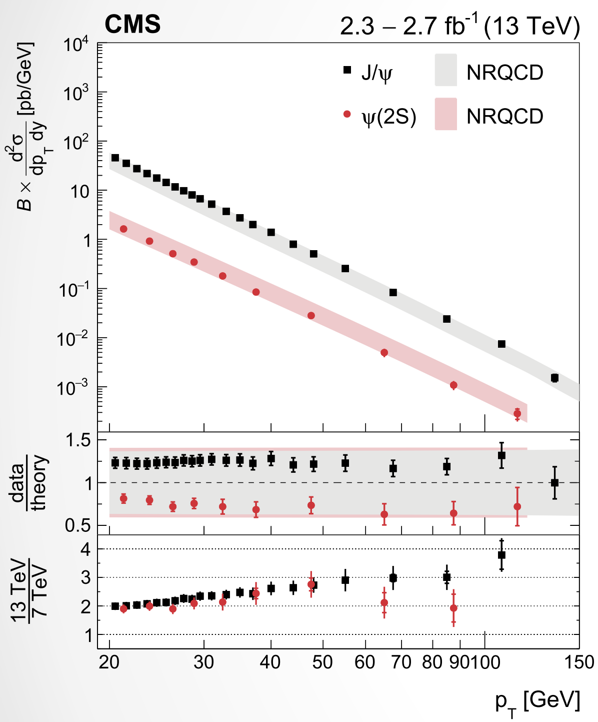
Results

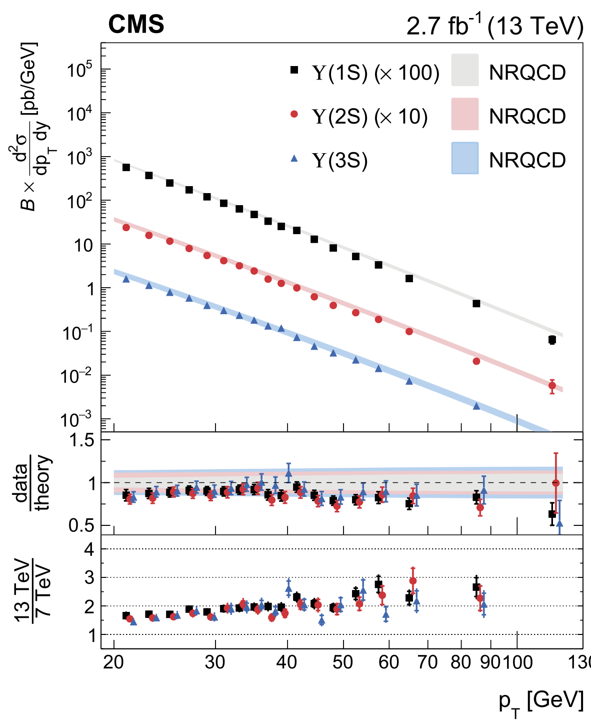


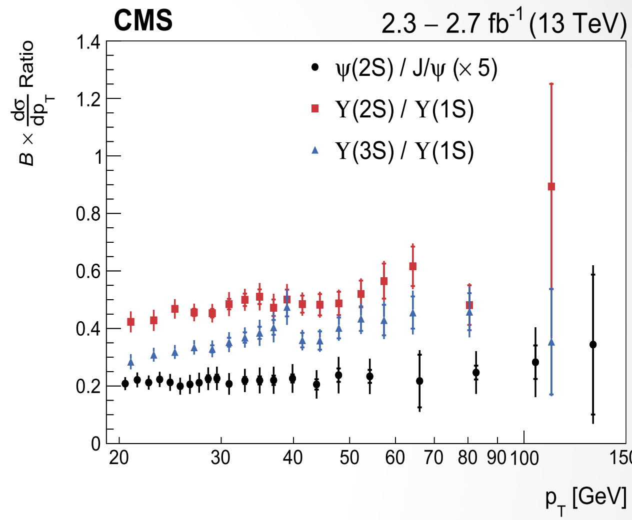


Shapes consistent across *y* region: **can *integrate over y*.**

y-integrated comparisons and ratios (to 1S)







~ flat for J/ψ & ψ′

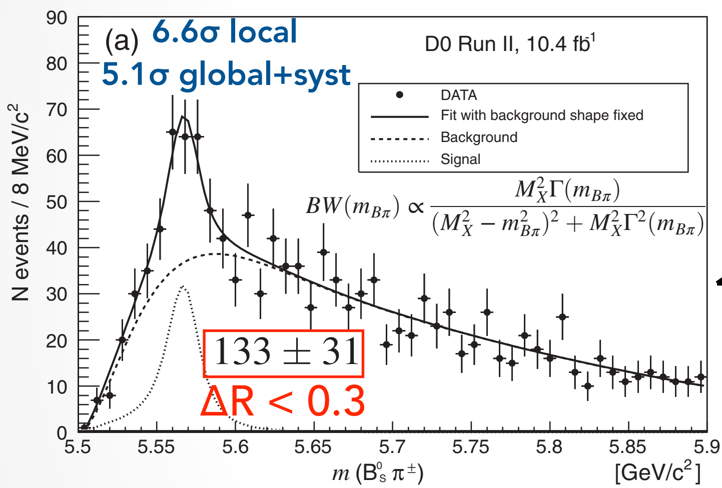
* increases slowly for Υ

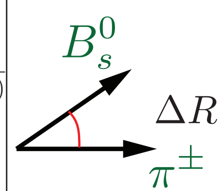
PLB 780, 251 (2018)

- NLO NRQCD predictions in agreement with data.
- As expected from evolution of PDFs, cross sections increase with energy.
- **These measurements should reduce theoretical uncertainties from the extraction of LDMEs.**

X(5568) → $B_s\pi^\pm$

- Resonance found by the D0 experiment in the $B_s\pi^\pm$ mass spectrum: state w/ **4 different flavors of quarks.**





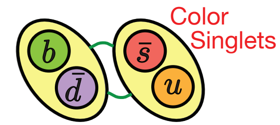
$$M_X = 5567.8 \pm 2.9 ^{+0.9}_{-1.9}\,\text{MeV}$$

$$\Gamma_X = 21.9 \pm 6.4 ^{+5.0}_{-2.5}\,\text{MeV}$$

Strong decay!

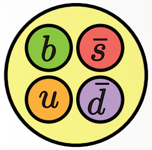
$$N_X = 133 \pm 31 \pm 15\,\text{cand.}$$

PRL **117**, 022003 (2016)



Loosely Bound Hadronic Molecule?

Not favored due to mass far from B-K thresh.



Tetraquark?

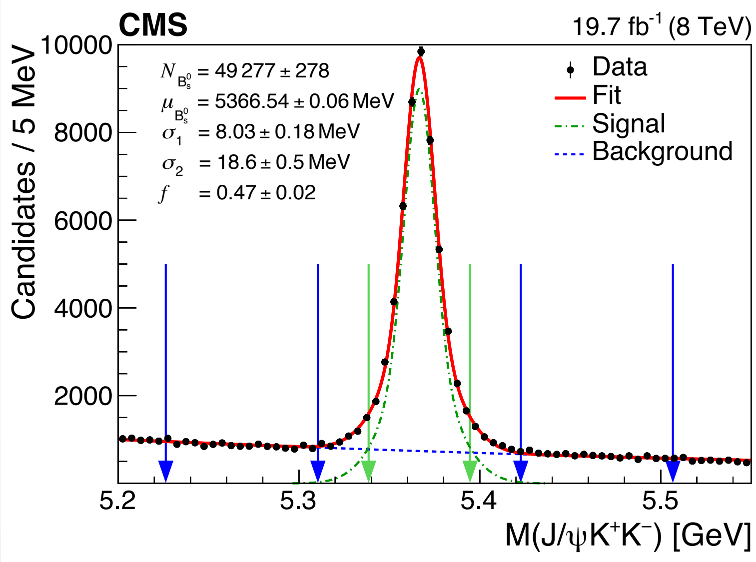
Possible, but theory predicts more states

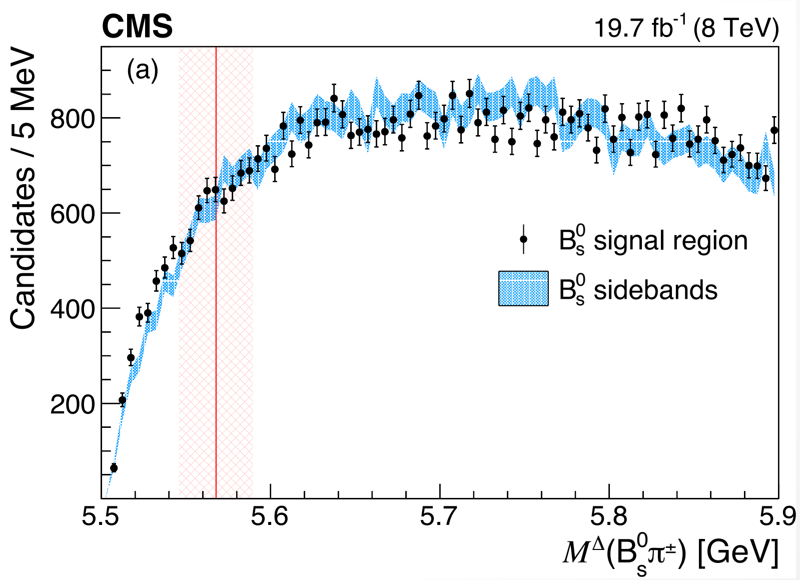
- If $X(5568)^- \rightarrow B_s^0\pi^-$ then $J^P = 0^+$
- If $X(5617)^- \rightarrow B_s^{0*}\pi^-$, $\hookrightarrow B_s^0\gamma$ miss! then $J^P = 1^+$

Not confirmed by LHCb

Search for the X(5568) at CMS

- Search for resonances in the $B_s \pi^{\pm}$ invariant mass spectrum: B_s ($\rightarrow J/\psi\phi(1020)$) + prompt pion.





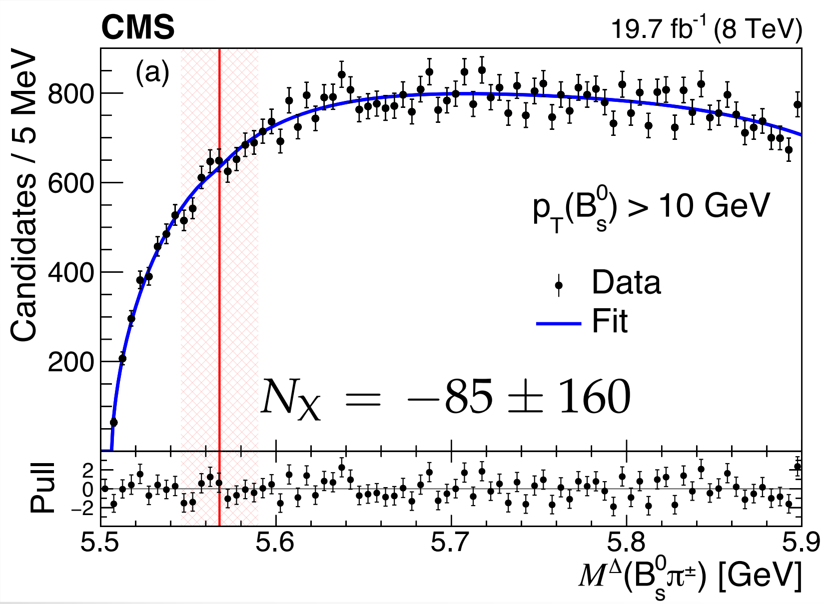
No excess is visible.

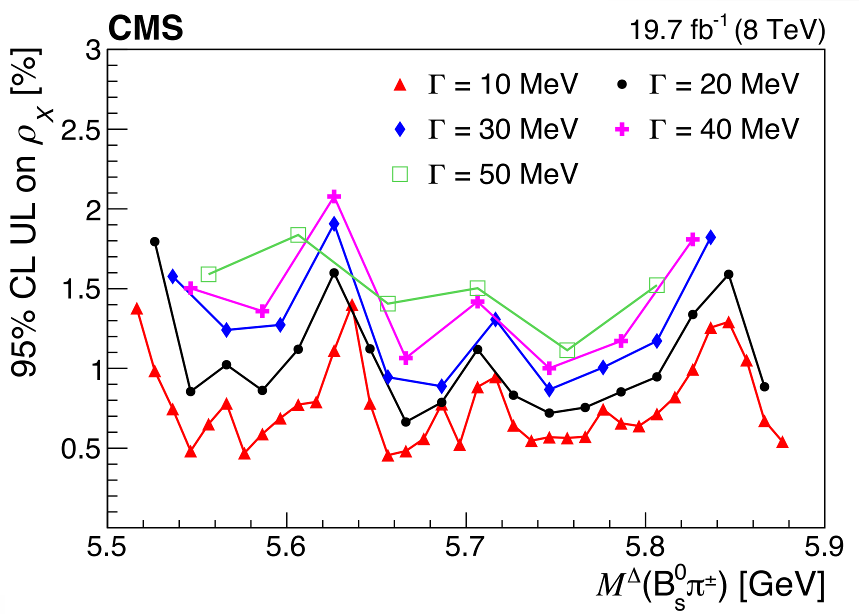
Search for resonances

- Signal modeled w/ relativistic BW (eff. and resol. variations considered in syst. unc.).
- Bkg. shape inspired from MC (modeling varied or fixed for syst. uncertainty estimations).

$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything})\mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

$$= \frac{N_X}{\epsilon_{\text{rel}} N_{B_s^0}}, \qquad \epsilon_{\text{rel}} \text{ from MC}$$





Summary of the search

- No significant structure in $M(B_s\pi^{\pm})$ is found for masses up to 5.9 GeV, disfavoring predictions of tetraquark models.
- No signal found despite trying different kinematic & quality cuts, variants of bkg. modeling and fit regions.

$\rho_X < 1.1\%$ at 95% CL for $p_T(B_s^0) > 10$ GeV and
$\rho_X < 1.0\%$ at 95% CL for $p_T(B_s^0) > 15$ GeV.
$|y| \lesssim 2$

CMS PAS BPH-16-002

PRL 120, 202005 (2018)

Previous results: $\rho = (8.6 \pm 1.9 \pm 1.4)\%$ for $p_T(B^0_s) > 10$ GeV & $|y| \lesssim 2$ **D0**

$\rho_X^{\mathrm{LHCb}}[p_T(B_s^0) > 5\ \mathrm{GeV}] < 0.011\,(0.012)$,
$\rho_X^{\mathrm{LHCb}}[p_T(B_s^0) > 10\ \mathrm{GeV}] < 0.021\,(0.024)$, at 90 (95)% C.L.
$\rho_X^{\mathrm{LHCb}}[p_T(B_s^0) > 15\ \mathrm{GeV}] < 0.018\,(0.020)$.

LHCb [PRL 117, 152003 (2016)] $2 < |y| < 4.5$

More recently (pub. last week)

CDF: $\rho < 6.7\%$ for $p_T(B_s) > 10$ GeV & $|y| \lesssim 1$ does not favor D0 results [PRL 120, 202006 (2018)]

ATLAS: $\rho < 1.6\%$ for $p_T(B_s) > 10$ GeV & $|y| \lesssim 2$ [PRL 120, 202007 (2018)]

D0: reconfirms with 6.7σ using B_s semileptonic decays [PRD 97, 092004 (2018)]

Summary and outlook

- CMS has produced several competitive results related to searches, production, polarization, lifetimes, and other properties of B hadrons and quarkonia.
- The B_c, B-baryon, quarkonium and exotic hadrons program will continue and benefit from the additional data in Run II.