Study of b-hadron properties with semileptonic b-hadron decays

ICHEP 2020

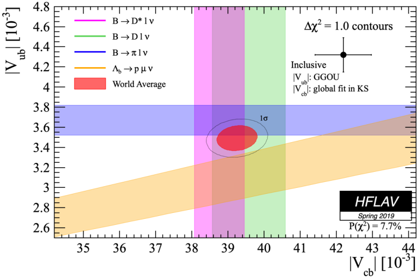
Florian Reiss
on behalf of the LHCb collaboration

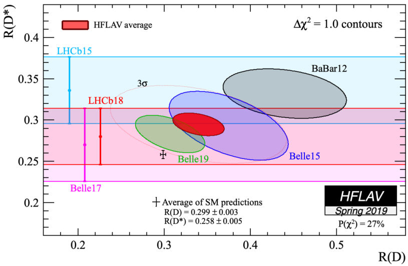
July 30th, 2020

Introduction

Why study b-hadron properties with semileptonic decays?

- large branching fractions
- theoretical uncertainties under control
  - only one hadronic current $\rightarrow$ parametrised by form factors
- many interesting phenomena
  - exclusive vs inclusive $|V_{cb}|$
  - lepton universality tests

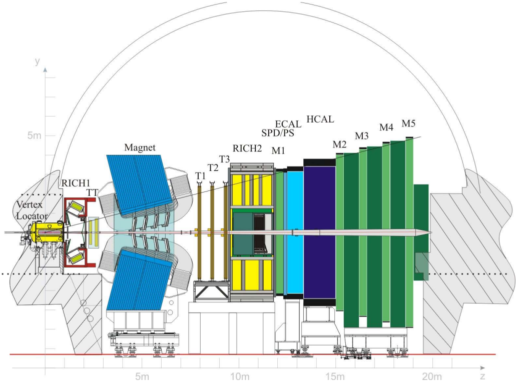




Introduction

Why study b-hadron properties with semileptonic decays at LHCb?

- trigger designed for displaced b-hadron decays
- large amount of b-hadrons produced
  - including B_s^0, B_c^+, Λ_b^0



Introduction

LHCb results covered in this talk:

- Measurement of b-hadron fractions in 13 TeV pp collisions
  Phys. Rev. D 100 (2019) 031102
- Measurement of the B_c^- meson production fraction and asymmetry in 7 and 13 TeV pp collisions
  Phys. Rev. D 100 (2019) 112006
- Observation of the semileptonic decay $B^+ \to p\bar{p}\mu^+\nu_\mu$
  JHEP 03 (2020) 146
- Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate
  arXiv:2003.08453 submitted to JHEP

Measurement of b-hadron fractions in 13 TeV *pp* collisions

$\overline{B}_s^0$ and Λ_b^0 production fractions

Goal:

- measure $\overline{B}_s^0$ and Λ_b^0 production fraction relative to sum of B^- and $\overline{B}^0$
- $1.67\,\text{fb}^{-1}$ at 13 TeV recorded in 2016
  - 7 TeV already measured PRD 85 (2012) 032008

Motivation:

- knowledge of production fractions necessary to determine absolute branching fractions
  - e.g. f_s needed for $\mathcal{B}(\overline{B}_s^0 \to \mu^+\mu^-)$
  - future $|V_{cb}|$ measurement from $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu$

Strategy:

- perform measurement in bins of transverse momentum p_{T} and pseudorapidity η of the b-hadron
- assume almost equal semileptonic width Γ_{SL} for b-hadrons JHEP 09 (2011) 012
- use inclusive $H_b \to H_c \mu\nu$ with $H_c = D^+_s, \Lambda^+_c, D^0, D^+$ decays
- determine efficiency and BF corrected yields n_{corr}

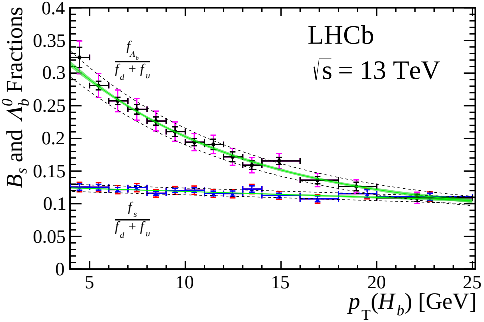
$$\frac{f_s}{f_u + f_d} = \frac{n_{\mathrm{corr}}(\overline{B}^0_s \to D\mu^-)}{n_{\mathrm{corr}}(B \to D^0\mu^-) + n_{\mathrm{corr}}(B \to D^+\mu^-)} \frac{\tau_{B^-} + \tau_{\overline{B}^0}}{2\tau_{\overline{B}^0_s}}(1 - \xi_s) - \frac{\mathcal{B}(B \to D_s \overline{K}\mu^-)}{\langle \mathcal{B}_{\mathrm{SL}} \rangle} \frac{\epsilon(\overline{B} \to D^+_s)}{\epsilon(\overline{B}^0_s \to D^+_s)},$$

$$\frac{f_{\Lambda^0_b}}{f_u + f_d} = \frac{n_{\mathrm{corr}}(\Lambda^0_b \to H_c\mu^-)}{n_{\mathrm{corr}}(B \to D^0\mu^-) + n_{\mathrm{corr}}(B \to D^+\mu^-)} \frac{\tau_{B^-} + \tau_{\overline{B}^0}}{2\tau_{\Lambda^0_b}}(1 - \xi_{\Lambda^0_b}).$$

- ξ_s: SU(3) symmetry breaking correction $\sim -1\%$
- $\xi_{\Lambda^0_b}$: chromomagnetic correction: $\sim 3\%$

Results:

- no dependence on η of H_b
- dependence on transverse momentum
  - light for f_s
  - strong for $f_{\Lambda_b^0}$



Integrating over $p_{\mathrm{T}} = 4 - 25$ GeV, $\eta = 2 - 5$:

$$\frac{f_s}{f_u + f_d} = 0.122 \pm 0.006(stat. + syst.)$$

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.259 \pm 0.018(stat. + syst.)$$

Measurement of the B_c^- meson production fraction in 7 and 13 TeV pp collisions

B_c^- production fraction

PRD 100 (2019) 112006

Goal:

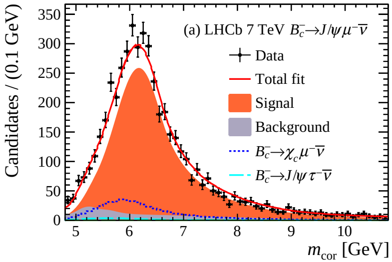
- measure relative B_c^- production fraction at 7 and 13 TeV

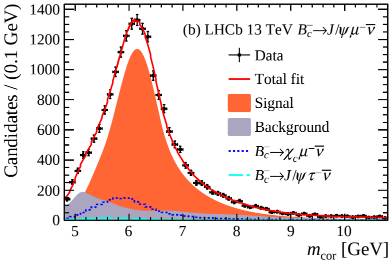
Strategy:

- reconstruct as $B_c^- \to J/\psi\, \mu^- \overline{\nu}_\mu$
- $\Gamma_{SL}(B_c^-) \neq \Gamma_{SL}(B)$
  - use average of predictions for $\mathcal{B}\,(B_c^- \to J/\psi\, \mu^- \overline{\nu}_\mu)$

$$\frac{f_c}{f_u + f_d} \equiv \frac{n_{\mathrm{cor}}(B_c^- \to J/\psi\, \mu^- \overline{\nu}_\mu)}{n_{\mathrm{cor}}(B \to D^0 X \mu^- \overline{\nu}) + n_{\mathrm{cor}}(B \to D^+ X \mu^- \overline{\nu})} \cdot \frac{\langle \mathcal{B}_{\mathrm{sl}} \rangle}{\mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu}_\mu)}$$

- extract yield by fitting $m_{corr} = \sqrt{m(J/\psi\, \mu^-)^2 + p_\perp^2} + p_\perp$

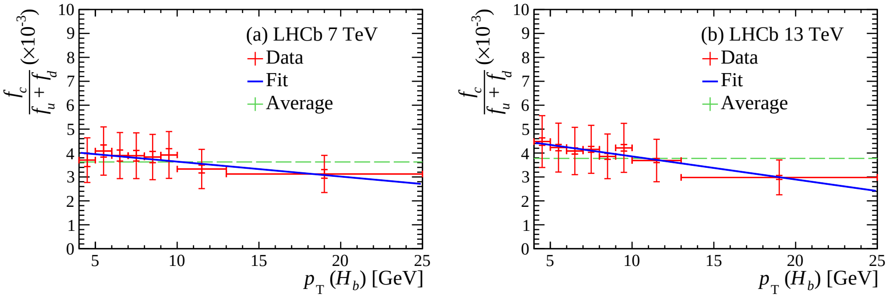




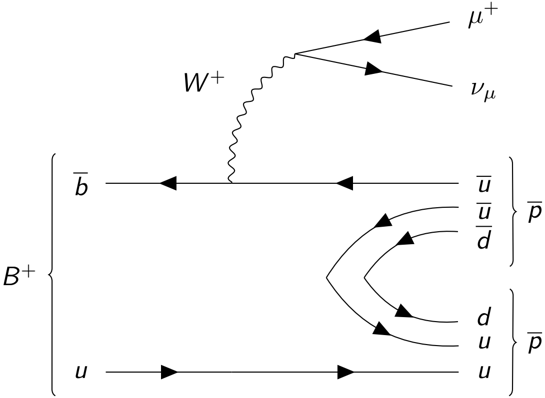
Results:

$$\frac{f_c}{f_u + f_d} = (3.63 \pm 0.08 \pm 0.12 \pm 0.86) \cdot 10^{-3} \text{ for } 7\,\text{TeV},$$
$$\frac{f_c}{f_u + f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89) \cdot 10^{-3} \text{ for } 13\,\text{TeV},$$

where uncertainties are stat., syst. and from prediction of $\mathcal{B}\left(B_c^- \to J/\psi\,\mu^-\overline{\nu}_\mu\right)$



Observation of the semileptonic decay $B^+ \to p\bar{p}\mu^+\nu_\mu$



Motivation:

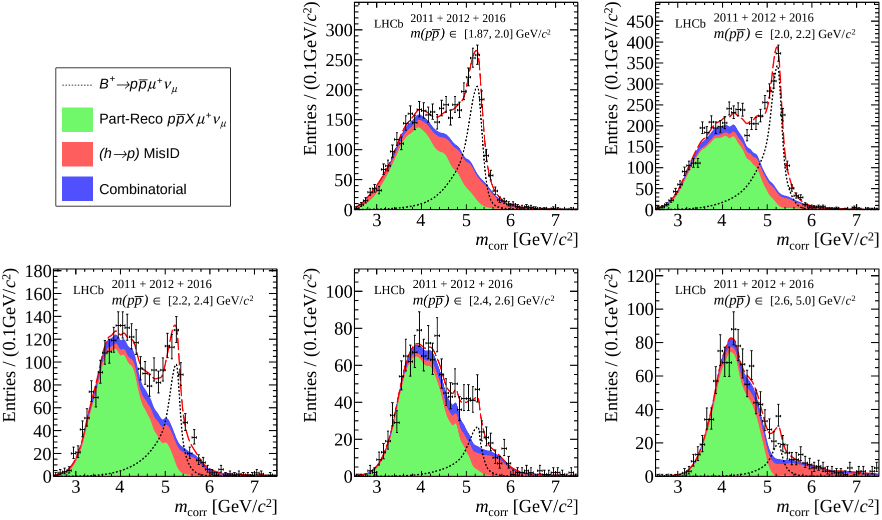
- $R(D)$ and $R(D^*)$ anomalies $\to$ also measure $b \to u$ transitions
- predictions by perturbative QCD:
  $BF(B^+ \to p\bar{p}\mu^+\nu_\mu) = (1.04 \pm 0.38) \times 10^{-4}$
  Physics Letters B704 (2011) 495
- evidence from Belle PRD 89 (2014) 011101

Analysis strategy:

- use 1.0, 2.0, 1.7 fb^{-1} at centre-of-mass energies 7, 8, 13 TeV recorded by LHCb in 2011, 2012, 2016
- branching fraction measured in bins of $p\bar{p}$ invariant mass
- extracted signal yield by fitting corrected mass
$m_{corr} = |p_\perp| + \sqrt{|p_\perp|^2 + m^2_{p\bar{p}\mu}}$
- $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ as normalisation channel

$$\mathcal{B}_i(B^+ \to p\bar{p}\mu^+\nu_\mu) = \frac{N_i(B^+ \to p\bar{p}\mu^+\nu_\mu)}{N_i(B^+ \to J/\psi K^+)} \times \frac{\epsilon(B^+ \to J/\psi K^+)}{\epsilon_i(B^+ \to p\bar{p}\mu^+\nu_\mu)} \times \mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

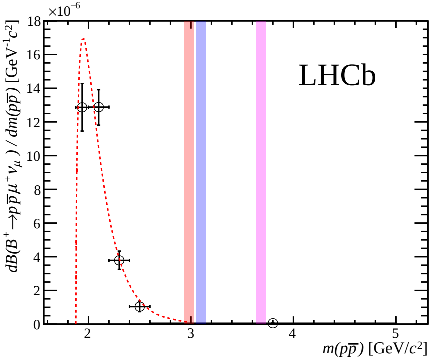
Signal yield extraction:



- 2011, 2012, 2016 samples combined to increase fit stability

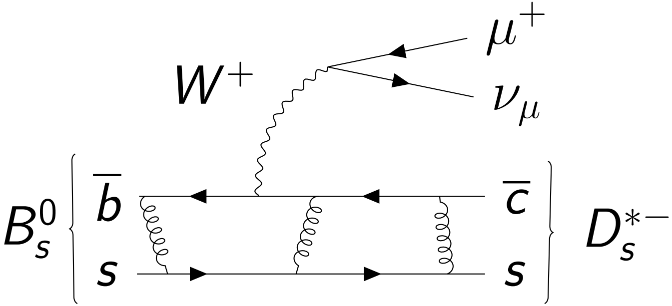
Results:

- $\mathcal{B}(B^+ \to p\bar{p}\mu^+\nu_\mu) =$ $(5.27^{+0.23}_{-0.24}(stat.) \pm 0.21(syst.) \pm 0.15(ext.)) \times 10^{-6}$
- absolute value lower than theory prediction
- shape of differential branching fraction consistent with theory
- threshold enhancement observed



colour bands: veto regions for η_c, J/ψ, $\psi(2S)$

Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate



Motivation:

- discrepancy between inclusive and exclusive $|V_{cb}|$
- exclusive $|V_{cb}|$ relies on form factors
- measured form factors input of prediction for $\mathcal{R}(D_s^{*+}) = \frac{\mathcal{B}(B_s^0 \to D_s^{*+}\tau^+\nu_\tau)}{\mathcal{B}(B_s^0 \to D_s^{*+}\mu^+\nu_\mu)}$ $\to$ lepton universality test
- spectator s-quark heavy $\to$ more precise predictions

Form factors:

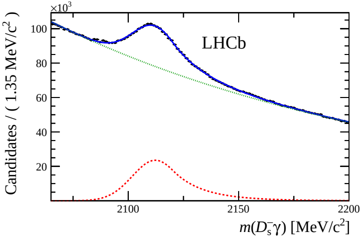
- parametrise hadronic current
  - CLN Nucl. Phys. B530 (1998) 153
  - BGL Phys. Lett. B353 (1995) 306

Strategy:

- obtain efficiency-corrected yield in bins of hadron recoil w:

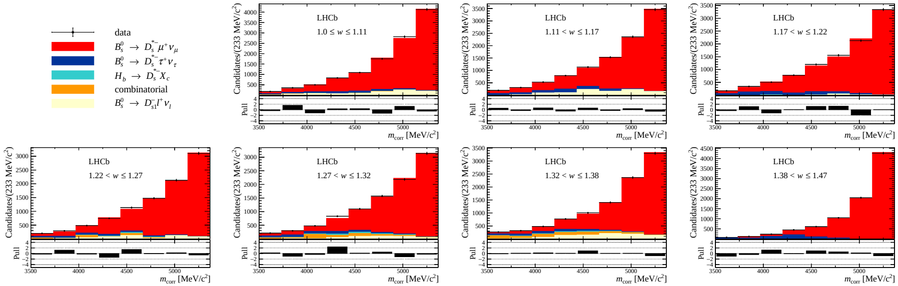
$$w = \frac{p_{B_s^0}}{m_{B_s^0}} \frac{p_{D_s^{*-}}}{m_{D_s^{*-}}} = \frac{m_{B_s^0}^2 + m_{D_s^{*-}}^2 - q^2}{2 m_{B_s^0} m_{D_s^{*-}}}$$

- use $1.7\,\mathrm{fb}^{-1}$ recorded in 2016 at 13 TeV
- use decay $D_s^{*-} \to D_s^- \gamma$
  - $D_s^- \to \phi(\to K^+K^-)\pi^-$
  - $D_s^- \to K^{*0}(\to \pi^- K^+)K^-$



signal background

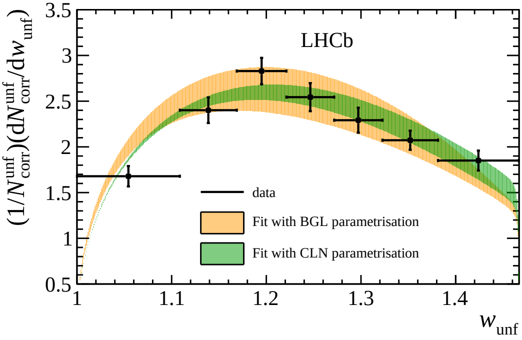
Signal yield extraction:



- template fit to corrected mass $m_{corr} = \sqrt{m^2_{D_s^{*-}\mu^+} + |p_\perp|^2} + |p_\perp|$

Form factor fit:

- fit unfolded and efficiency-corrected w distribution with form factor model



- CLN and BGL parametrisations consistent with each other and data

Summary

Many properties of b-hadrons can be measured at LHCb:

- relative production fractions for $\overline{B}^0_s$, Λ^0_b and B^+_c
- first observation of $B^+ \to p\overline{p}\mu^+\nu_\mu$
- first time measurement of unfolded normalised differential decay rate for $B^0_s \to D^{*-}_s \mu^+\nu_\mu$

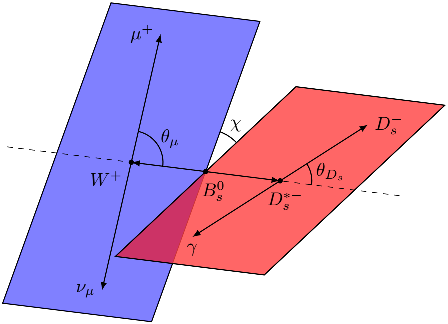
These properties are important input for theory and experiment:

- production fractions for absolute branching ratios
- test of perturbative QCD predictions
- form factors for R(X) predictions

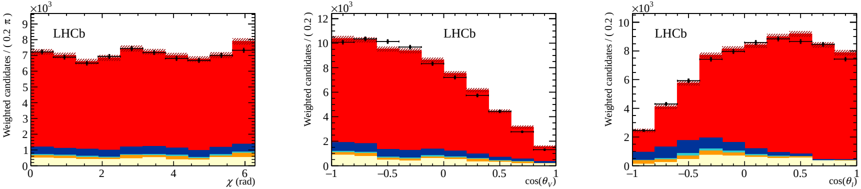
Thanks for your attention!
Any questions?

Back-up

$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate



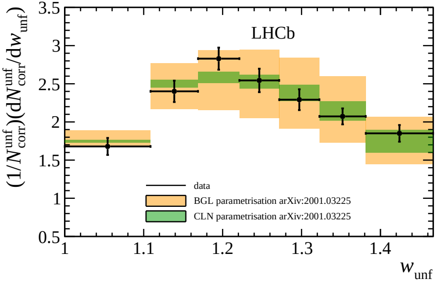
$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate



Cross-check:

- compare data and simulation using fitted fractions
- MC describes $\cos(\theta_\mu)$, $\cos(\theta_\mu D_s^+)$, χ^2 well

$\rightarrow$ can measure differential decay rate as function of only w



- measured w spectrum consistent with results from PRD 101 (2020) 072004

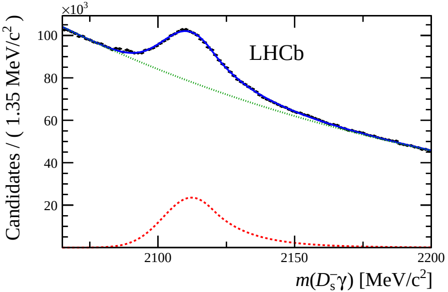
$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate arXiv:2003.08453

Differential decay rate:

$$\frac{\mathrm{d}\Gamma(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)}{\mathrm{d}q^2} = \frac{G_F^2\,|Vcb|^2\,|\eta_{EW}|^2|\vec{p}|q^2}{96\pi^3 m_{B_s^0}^2}\left(1-\frac{m_\mu^2}{q^2}\right)^2 \times\left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\frac{m_\mu^2}{2q^2}\right)+\frac{3}{2}\frac{m_\mu^2}{q^2}|H_t|^2\right] \tag{1}$$

Analysis strategy:

- highest $p_{\mathrm{T}}\gamma$ in cone around D_s^- direction of flight
- γ separated from π^0 by neural network
- random D_s^--γ combinations subtracted via *sPlot*
- signal: Gaussian with power-law tail on right side
- background: exponential distribution
- $H_b \to D_s^{*-} H_c(\to \mu^+\nu_\mu X)$ suppressed by MVA selecting isolated muons
- X: one or more hadrons



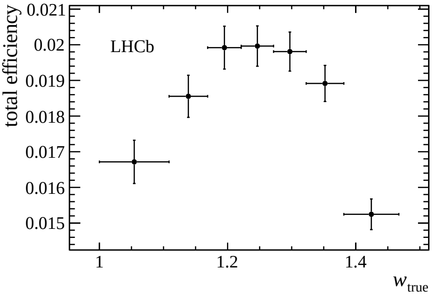
$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate

arXiv:2003.08453

- most templates obtained from corrected simulation
- largest background: $B_s^0 \to D_s^{*-}\tau^+(\to \mu^-\overline{\nu}_\mu\nu_\tau)\nu_\tau$
- $B_s^0 \to D_{s1}(2460)^-\ell^+\nu_\ell$, $\ell = \tau, \mu$
- $H_b \to D_s^{*-}H_C$, mixture of H_b=B_s^0, B^0, $B^+\Lambda_b^0$
- combinatorial background obtained from wrong-sign data sample $D_s^{*-}\mu^-$

Unfolding:

- determine efficiency as function of w_{true}
- unfold measured w to get w_{true} distribution
- corrected unfolded distribution by efficiency



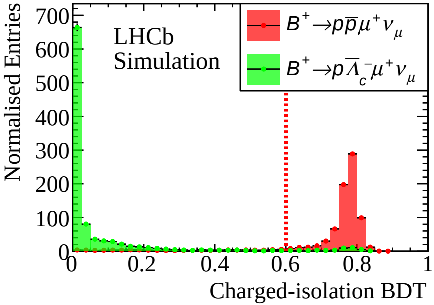
Selection:

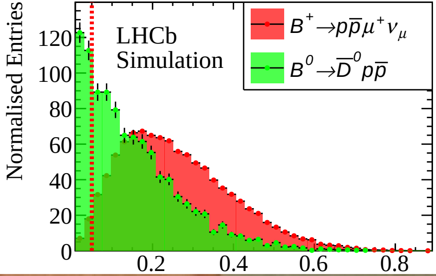
Charged-isolation BDT

- $B \to \bar{\Lambda}_c^- p\mu^+\nu_\mu X$, $\bar{\Lambda}_c^- \to \bar{p}Y$, X: any number of charged or neutral pions
- trained on simulated $B^+ \to p\bar{\Lambda}_c^- \mu^+\nu_\mu$ decays
- 80% of $B \to \bar{\Lambda}_c^- p\mu^+\nu_\mu X$ rejected, 93% signal efficiency

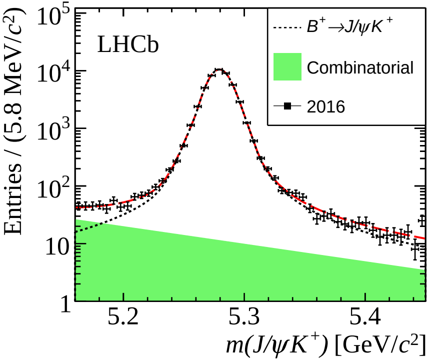
Part-reco BDT

- $B \to p\bar{p}\bar{D}X$
- trained on mixture of simulated background decays
- removes 18% of $B \to p\bar{p}\bar{D}$, 98% signal efficiency





Normalisation mode fit:

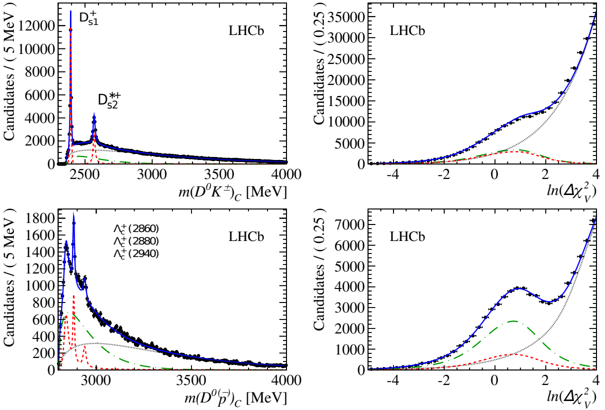


- 2011, 2012, 2016 fitted separately for control mode

$\overline{B}_s^0$ and Λ_b^0 production fractions PRD 100 (2019) 031102

Correct for $\overline{B}_s^0$ and Λ_b^0 to $B^{0,-} \to D$ cross-feed, e.g. from $\overline{B}_s^0 \to D^0 K^+ \mu^- \overline{\nu}_\mu$

- perform 2D fit to separate resonant and non-resonant contributions
  - $m(D^0 h)_C = m(D^0 h) - m(D^0) + m(D^0)_{PDG}$, $h = K, p$
  - difference in vertex χ^2 when hadron added to $(D\mu)$



B_c^- production fraction

PRD 100 (2019) 112006