Other LHCb studies requiring BR input

Selected topics

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on behalf of the LHCb collaboration

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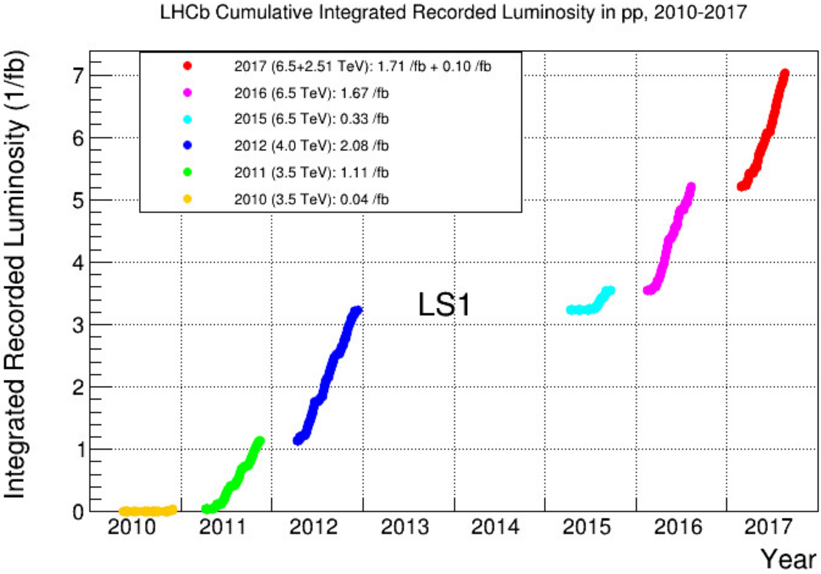
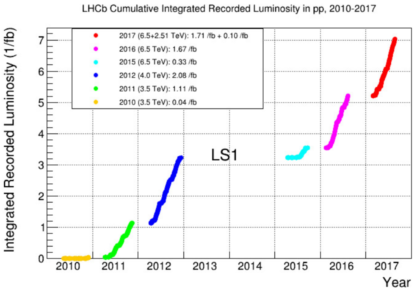
LHC IS A CHARM FACTORY





	Large production cross-sections, $\sigma(c\bar{c})_{\text{LHCb}}$
	JHEP 1603 (2016) 159 and errata
13 TeV	$2369 \pm 3 \pm 152 \pm 118\ \mu\text{b}$
	Nucl.Phys. B871 (2013) 1-20
7 TeV	$1419 \pm 12 \pm 116 \pm 65\ \mu\text{b}$
	JHEP 1706 (2017) 147
5 TeV	$1193 \pm 3 \pm 67 \pm 58\ \mu\text{b}$

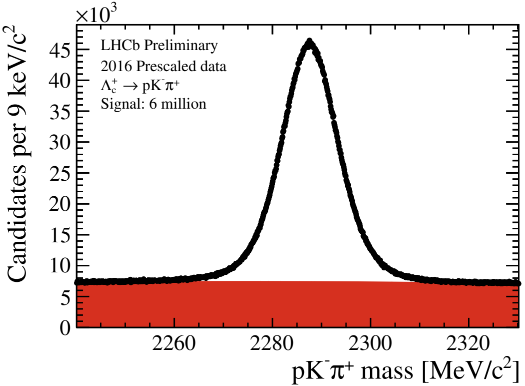
13 TeV cross-section into LHCb			N produced per fb^{-1}
$\sigma(pp \to D^0 X)$	$= 2072 \pm 2 \pm 124\ \mu\text{b}$	$\Rightarrow$	$\sim 2 \times 10^{12}\ D^0/\bar{D}^0$
$\sigma(pp \to D^+ X)$	$= 834 \pm 2 \pm 78\ \mu\text{b}$	$\Rightarrow$	$\sim 0.8 \times 10^{12}\ D^\pm$
$\sigma(pp \to D_s^+ X)$	$= 353 \pm 9 \pm 76\ \mu\text{b}$	$\Rightarrow$	$\sim 0.4 \times 10^{12}\ D_s^\pm$
$\sigma(pp \to D^{*+} X)$	$= 784 \pm 4 \pm 87\ \mu\text{b}$	$\Rightarrow$	$\sim 0.8 \times 10^{12}\ D^{*\pm}$

The LHC is the most prolific producer of *c*-hadrons yet constructed.

LHCb's charm collection

Efficiencies depend analysis, but $\mathcal{O}$(a few %) is not uncommon.

LHCb has some of the world's largest charm data sets.



∼ 10% of 2016 data.

For example, large, high-purity samples of $\Lambda_c^+ \to pK^-\pi^+$ for Ξ_{cc}^{++} discovery,

- 2016 dataset: $\int \mathcal{L} = 1.7\,\text{fb}^{-1} \Rightarrow \sim$60 million $\Lambda_c^+ \to pK^-\pi^+$.

Precision relative BRs

e.g., arXiv:1711.01157 [hep-ex] (submitted to JHEP)

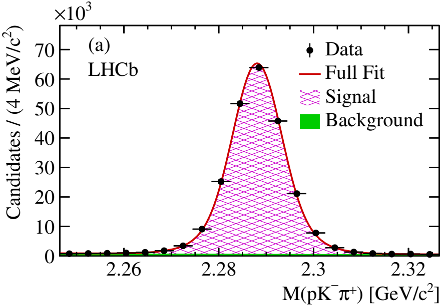
LHCb measures ratios of branching fractions of a hadron with high precision

Λ_c^+ BFs based on 1 fb^{-1} of 2011 data

- $226\,851 \pm 522$ $\Lambda_c^+ \to pK^-\pi^+$,
- A fraction of our current data set.

Dominant syst. uncertainties of ratios

- Scale with size of dataset,
- Or to be improved with amplitude analyses.



$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.44 \pm 0.08 \pm 0.18)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.70 \pm 0.03 \pm 0.03)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (0.165 \pm 0.015 \pm 0.005)\%.$$

. . . but what LHCb does not measure well are **absolute** branching fractions

Precision relative BRs

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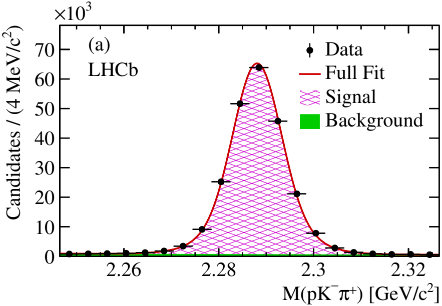


$$\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+) \times 10^3 = 4.72 \pm 0.05 \pm 0.11 \pm 0.25$$
$$\mathcal{B}(\Lambda_c^+ \to pK^-K^+) \times 10^3 = 1.08 \pm 0.02 \pm 0.02 \pm 0.06$$
$$\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+) \times 10^4 = 1.04 \pm 0.09 \pm 0.03 \pm 0.05$$

} external $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$

LHCb relies on external measurements of absolute branching fractions for many of its precision measurements.

KEY NORMALIZATION MODES OF OPEN CHARM

Some of our key normalization modes for open charm hadrons are

$D^0 \to K^-\pi^+$
$D^0 \to K^-\pi^+\pi^-\pi^+$
$D^+ \to K^-\pi^+\pi^+$

$D_s^+ \to K^-K^+\pi^+$
$\Lambda_c^+ \to pK^-\pi^+$

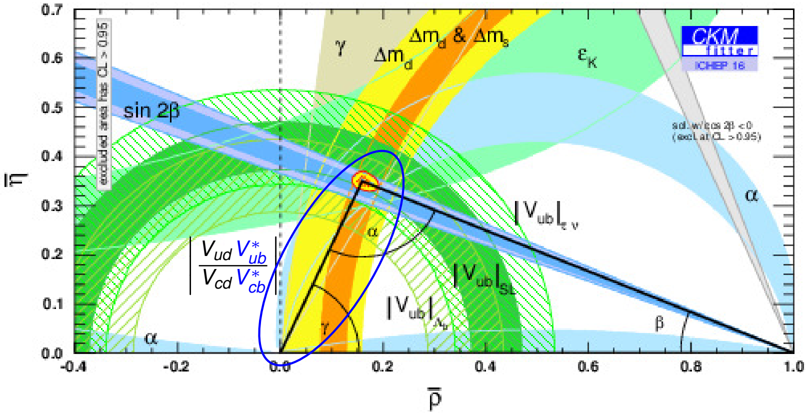
$\Xi_c^+ \to pK^-\pi^+$
$\Xi_c^0 \to pK^-K^-\pi^+$
$\Omega_c^0 \to pK^-K^-\pi^+$

Use of these channels in relative measurements is so common that we will be able to use absolute values of their branching fractions to almost any precision.

Charmed strange baryons are a particular point of ignorance,

- No absolute branching fraction measurements exist,
- The large charm and beauty baryon production at LHCb is opening many new interesting channels for key physics measurements, especially in LHCb's upgrade.

CLIENT: CKM $|V_{ub}/V_{cb}|$ AND $|V_{ub}|$



Leading measurements of $|V_{ub}|$ and $|V_{cb}|$ through $b \to u\ell\overline{\nu}_\ell$ and $b \to c\ell\overline{\nu}_\ell$

- $|V_{ub}|$ is one of the least precisely measured CKM parameters.

Precise measurements of $|V_{ub}/V_{cb}|$ (and thus $|V_{ub}|$) at LHCb require precise charmed branching fractions.

$|V_{ub}/V_{cb}|$ FROM SEMILEPTONIC Λ_b^0 DECAYS

Nature Phys. 11 (2015) 743-747

Using exclusive semileptonic Λ_b^0 decays,

$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\mathrm{FF}}$$

where R_{FF} is a ratio of form factors.

Lattice QCD predicts the form factors most precisely at large q^2

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2}} = (1.471 \pm 0.095 \pm 0.109)\left|\frac{V_{ub}}{V_{cb}}\right|^2$$

Detmold *et al.*, Phys.Rev. D92 (2015) no.3, 034503

And the branching ratio can be measured from counting observables

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{N(\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\mu^-\overline{\nu}_\mu)} \cdot r_\epsilon \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

where r_ϵ is a ratio of experimental detection efficiencies.

Measured $|V_{ub}/V_{cb}|$ and systematics

Nature Phys. 11 (2015) 743-747

Measured result in $2\,\text{fb}^{-1}$ of LHCb data

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\text{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\text{GeV}^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ has largest single uncertainty

- Must come from an external source,
- Cannot be reduced by larger LHCb data sets or more studies.

Carrying through

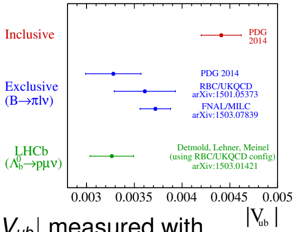
$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.083 \pm 0.004 \pm 0.004,$$

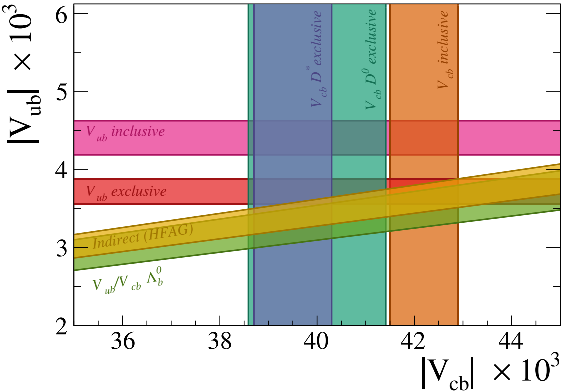
and using the world-average for $|V_{cb}|$

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

Comparisons with other experiments

Nature Phys. 11 (2015) 743-747





$|V_{ub}|$ measured with

- Exclusive decays, *e.g.*, $\Lambda_b^0 \to p\ell\overline{\nu}_\ell$
- Inclusive decays, $B \to X_u$

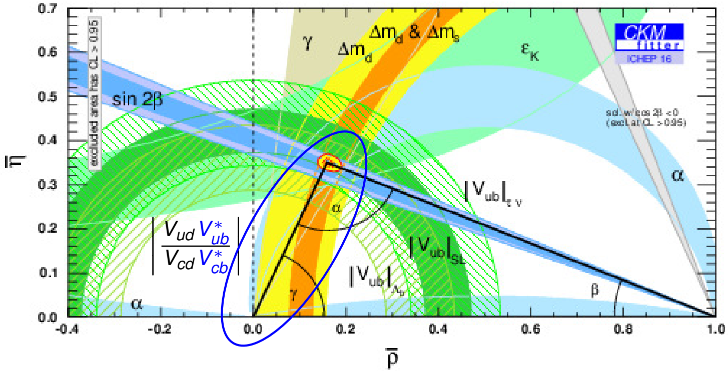
Independent theoretical and experimental uncertainties,

- Tension between the two methods.

LHCb's determination with $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ is consistent with B-factory exclusive measurements from $\bar{B} \to \pi\ell\overline{\nu}_\ell$.

Closing the triangle

Why this matters: overconstraining the CKM triangle with precision measurements of each side and angle is key to discovering non-CKM sources of CP violation.



In progress: similar analysis of $\mathcal{B}(\overline{B}{}^0_s \to K^+\mu^-\overline{\nu}_\mu)/\mathcal{B}(\overline{B}{}^0_s \to D_s^+(K^-K^+\pi^-)\mu^-\overline{\nu}_\mu)$, for which $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$ will be critical.

Client: Production ratios

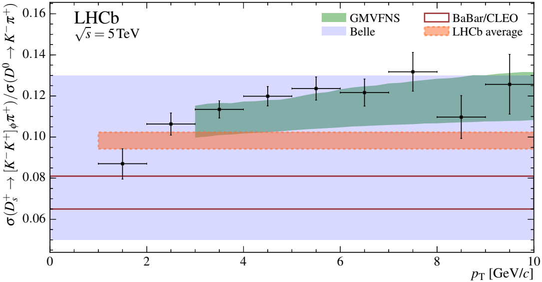
Heavy flavor production measurements are among LHCb's most cited and most broadly useful results.

They provide precise tests of QCD and probe proton structure at small gluon x.

Absolute cross-sections have uncertainties

- For both theory and experiment.

However, many of the largest uncertainties cancel in ratios.



Charm production ratios in $\sqrt{s} = 5\,\text{TeV}\,pp$ collisions, JHEP 1706 (2017) 147.

Thus production ratios and fragmentation functions can be more useful than the absolute measurements.

These ratios are measured precisely with specific decays modes,

- and thus require input from absolute branching fractions.

Ratios example: PROSA PDF fits

PROSA collaboration incorporates LHCb production measurements into proton PDF fits.

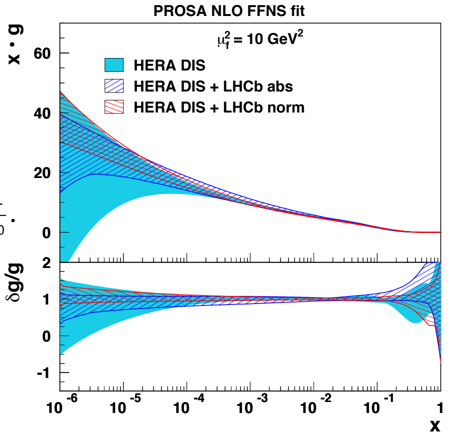
Two approaches

- Fit absolute measured cross-sections, $\frac{d^2\sigma}{dp_T dy}$,
- Fit normalized cross-sections, $\frac{d\sigma}{dy} / \frac{d\sigma}{dy_0}$.

Significant improvement in precision at small x and small Q^2.

Much smaller theory uncertainties in fit to normalized values,

- Absolute normalization subject to large uncertainties estimated by pQCD scale variation,
- Rapidity shape is largely scale invariant.



PROSA Collaboration, Eur.Phys.J. C75 (2015) 8, 396.

Incorporates LHCb D (Nucl.Phys. B871 (2013) 1-20) and B (JHEP 1308 (2013) 117) 7 TeV cross-section measurements.

$f_{s(\Lambda_b^0)}/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

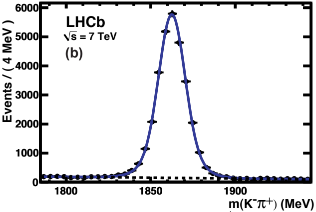
PHYS. REV. D 85 (2012) 032008

Attempt to reduce theoretical input by analyzing the abundances of the products of semileptonic b-hadron decays.

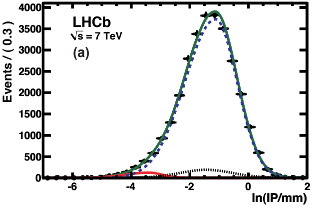
Six inclusive final states

- $\Lambda_c^+ \mu^+ \nu X$ and $D^0 p \mu^+ \nu X$ to determine abundance of Λ_b^0, $n_{\text{corr}}(\Lambda_b^0 \to D\mu)$,
- $D_s^- \mu^+ \nu X$ and $\bar{D}^0 K^- \mu^+ \nu X$ to determine abundance of B_s^0, $n_{\text{corr}}(B_s^0 \to D\mu)$,
- $\bar{D}^0 \mu^+ \nu X$ and $D^- \mu^+ \nu X$ with corrections from the other final states to determine the combined abundance of B^0 and B^+, $n_{\text{corr}}(B^0 \to D\mu) + n_{\text{corr}}(B^+ \to D\mu)$.

b-hadron semileptonic decays separated from prompt D production with characteristic distribution of D impact parameter.



Mass $m(K^-\pi^+)$



$\log(IP/\,\text{mm})$

$f_{s(\Lambda_b^0)}/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

PHYS. REV. D 85 (2012) 032008

From these,

$$\frac{f_s}{f_u + f_d} = \frac{n_{\text{corr}}(B_s^0 \to D\mu)}{n_{\text{corr}}(B^0 \to D\mu) + n_{\text{corr}}(B^+ \to D\mu)} \frac{\tau_{B^+} + \tau_{B^0}}{2\tau_{B_s^0}}$$

and

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = \frac{n_{\text{corr}}(\Lambda_b^0 \to D\mu)}{n_{\text{corr}}(B^0 \to D\mu) + n_{\text{corr}}(B^+ \to D\mu)} \frac{\tau_{B^+} + \tau_{B^0}}{2\tau_{\Lambda_b^0}}(1 - \xi)$$

where the factor ξ accounts for the chromomagnetic correction that affects b mesons but not b baryons.

The corrected yields, n_{corr}, are corrected for charm branching fractions,

$$n_{\text{corr}}(B_s^0 \to D\mu) = \frac{1}{\epsilon(\bar{B}_s^0 \to D_s^+)} \left[\frac{n(D_s^+ \mu)}{\mathcal{B}(D_s^+ \to K^+ K^- \pi^+)} - N(D_s^+ \text{ from } B) \right]$$

$f_{s(\Lambda_b^0)}/(f_u + f_d)$ WITH SEMILEPTONIC DECAYS

PHYS. REV. D 85 (2012) 032008

$$\frac{f_s}{f_u + f_d} = 0.134 \pm 0.004^{+0.011}_{-0.010}$$

$$\frac{f_{\Lambda_b^0}}{f_u + f_d}(p_{\mathrm{T}}) = (0.404 \pm 0.017 \pm 0.27 \pm 0.105) \times [1 - (0.031 \pm 0.004 \pm 0.003) \times p_{\mathrm{T}}]$$

Systematics on $f_s/(f_u + f_d)$

Source	Error (%)
Bin-dependent errors	1.0
$\mathcal{B}(D^0 \to K^-\pi^+)$	1.2
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	1.5
$\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$	4.9
$\bar{B}_s^0$ semileptonic decay modelling	3.0
Backgrounds	2.0
Tracking efficiency	2.0
Lifetime ratio	1.8
PID efficiency	1.5
$\bar{B}_s^0 \to D^0K^+X\mu^-\bar{\nu}$	$^{+4.1}_{-1.1}$
$\mathcal{B}((B^-, \bar{B}^0) \to D_s^+KX\mu^-\bar{\nu})$	2.0
Total	$^{+8.6}_{-7.7}$

Systematics on $f_{\Lambda_b}/(f_u + f_d)$.

Source	Error (%)
Bin dependent errors	2.2
$\mathcal{B}(\Lambda_b^{0\,0} \to D^0pX\mu^-\bar{\nu})$	2.0
Monte Carlo modelling	1.0
Backgrounds	3.0
Tracking efficiency	2.0
Γ_{sl}	2.0
Lifetime ratio	2.6
PID efficiency	2.5
Subtotal	6.3
$\mathcal{B}(\Lambda_c^{++} \to pK^-\pi^+)$	26.0
Total	26.8

f_s/f_d WITH $B \to Dh$

JHEP 1304 (2013) 001

Using theoretical expressions for the branching fractions, the ratio from $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$ and $B^0 \to D^-(K^+\pi^-\pi^-)K^+$ is

$$\frac{f_s}{f_d} = \frac{\mathcal{B}(B^0 \to D^-(K^+\pi^-\pi^-)K^+)}{\mathcal{B}(B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+)} \frac{\epsilon_{D^-K^+}}{\epsilon_{D_s^-\pi^+}} \frac{N_{D_s^-\pi^+}}{N_{D^-K^+}}$$

$$= \Phi_{\mathrm{PS}} \left|\frac{V_{us}}{V_{ud}}\right|^2 \left(\frac{f_K}{f_\pi}\right)^2 \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{1}{\mathcal{N}_a\mathcal{N}_F} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to K^+K^-\pi^-)} \frac{\epsilon_{D^-K^+}}{\epsilon_{D_s^-\pi^+}} \frac{N_{D_s^-\pi^+}}{N_{D^-K^+}}$$

Φ_{PS} is a phase space factor, $\mathcal{N}_a$ parameterizes nonfactorizable SU(3)-breaking, $\mathcal{N}_F$ is the ratio of form factors.

For the final result,

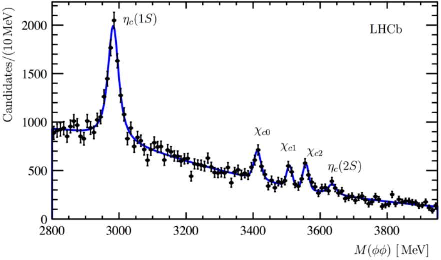
$$\frac{f_s}{f_d} = (0.261 \pm 0.004 \pm 0.017) \times \frac{1}{\mathcal{N}_a\mathcal{N}_F}$$

the 5% relative error of $\mathcal{B}(D_s^- \to K^+K^-\pi^-) = 5.50 \pm 0.27\%$ is the largest contributor to the total 6.5% systematic.

CHARMONIA BFS IN b DECAYS, $b \to CX$, $C \to \phi\phi$

EUR.PHYS.J. C77 (2017) NO.9, 609

Measure charmonium production in b decays by studying the $\phi\phi$ mass spectrum in $b \to \phi\phi$.



Determined relative production of $\eta_c(1S)$, $\eta_c(2S)$, χ_{c0}, χ_{c1}, and χ_{c2},

$$R^{C_1}_{C_2} \equiv \frac{\mathcal{B}(b \to C_1 X)}{\mathcal{B}(b \to C_2 X)} \frac{\mathcal{B}(C_1 \to \phi\phi)}{\mathcal{B}(C_2 \to \phi\phi)}$$

External charmonia branching fractions $\mathcal{B}(C \to \phi\phi)$ are the largest uncertainties for the b decay ratios, *e.g.*,

$$\frac{\mathcal{B}(b \to \chi_{c0} X)}{\mathcal{B}(b \to \eta_c(1S) X)} = 0.62 \pm 0.10\,(\text{stat}) \pm 0.05\,(\text{syst}) \pm 0.15(\mathcal{B})$$

$$\frac{\mathcal{B}(b \to \chi_{c1} X)}{\mathcal{B}(b \to \eta_c(1S) X)} = 0.56 \pm 0.12\,(\text{stat}) \pm 0.05\,(\text{syst}) \pm 0.13(\mathcal{B})$$

$$\frac{\mathcal{B}(b \to \chi_{c2} X)}{\mathcal{B}(b \to \eta_c(1S) X)} = 0.23 \pm 0.04\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.06(\mathcal{B})$$

Branching ratios of η_c

Eur.Phys.J. C77 (2017) no.9, 609

We measure $\mathcal{B}(B_s^0 \to \phi\phi)$ as a byproduct of the $b \to CX$ analysis,

$$\mathcal{B}(B_s^0 \to \phi\phi) = \frac{N_{B_s^0}}{N_{\eta_c}} \times \frac{\epsilon_{\eta_c}}{\epsilon_{B_s^0}} \times \left[\frac{\mathcal{B}(b \to \eta_c X)\,\mathcal{B}(\eta_c \to p\bar{p})}{\mathcal{B}(b \to J/\psi X)\,\mathcal{B}(J/\psi \to p\bar{p})}\right]$$
$$\times \left[\frac{\mathcal{B}(\eta_c \to \phi\phi)}{\mathcal{B}(\eta_c \to p\bar{p})}\right] \times \mathcal{B}(b \to J/\psi X) \times \mathcal{B}(J/\psi \to p\bar{p}) \times \frac{1}{f_s}$$
$$= (2.18 \pm 0.17\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}) \pm 0.14(f_s) \pm 0.65(\mathcal{B})) \times 10^{-5}$$

where the first two terms are from the analysis and the others are external,

$$\left[\frac{\mathcal{B}(\eta_c \to \phi\phi)}{\mathcal{B}(\eta_c \to p\bar{p})}\right] = 1.17 \pm 0.18$$

which comes from PDG, where the BFs are dominated by BES-III.

Using an independent measurement of $\mathcal{B}(B_s^0 \to \phi\phi)$, can invert to measure

$$\left[\frac{\mathcal{B}(\eta_c \to \phi\phi)}{\mathcal{B}(\eta_c \to p\bar{p})}\right] = 1.79 \pm 0.14 \pm 0.09 \pm 0.10(f_s/f_d) \pm 0.03(f_{\Lambda_b^0}) \pm 0.29(\mathcal{B})$$

Tension. Can BES-III measure the ratio of BFs to better precision?

IDEA: CHARMONIA BRS TO $\Lambda^*\overline{\Lambda}^*$

Inspired by the previous analysis and by the BES-III measurement 'Study of J/ψ and $\psi(3686) \to \Sigma(1385)^0\overline{\Sigma}(1385)^0$ and $\Xi^0\overline{\Xi}^0$', Phys.Lett. B770 (2017) 217-225.

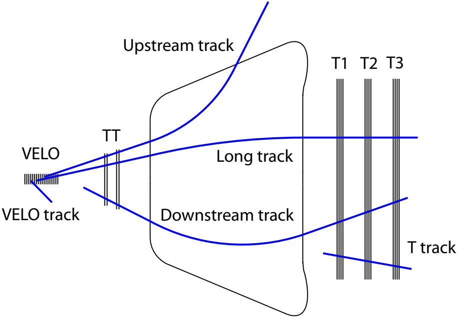
Examining the feasibility of precision $\mathcal{B}(C \to \Lambda^*\overline{\Lambda}^*)$.

Obtainable from analogous $\mathcal{B}(b \to CX)$ measurements.

Like the $C \to \phi\phi$ analysis, a four-track final state, $(pK^-)(\overline{p}K^+)$.

Also can search for $X(3872)$ and other states.

Λ^* instead of Λ: all Λ^* decay within VELO.



Will need one or more independent normalization measurements, which BES-III can provide.

. . . AND MUCH MORE

More precise absolute branching fraction measurements of key normalization modes will broadly benefit LHCb physics

- Charm and beauty relative branching ratios,
- CKM element measurements, especially $|V_{ub}|$ and γ,
- Fragmentation fractions and production ratios,
  - Which are themselves important for background studies and normalization.
- Spectroscopy with *b*-hadron decays, including pentaquark searches,
- And many others that I am sure to have missed.

Can anything be done about Ξ_c^0, Ξ_c^+, and Ω_c^0?

- A lack of absolute branching fractions may severely limit the impact of baryon physics.