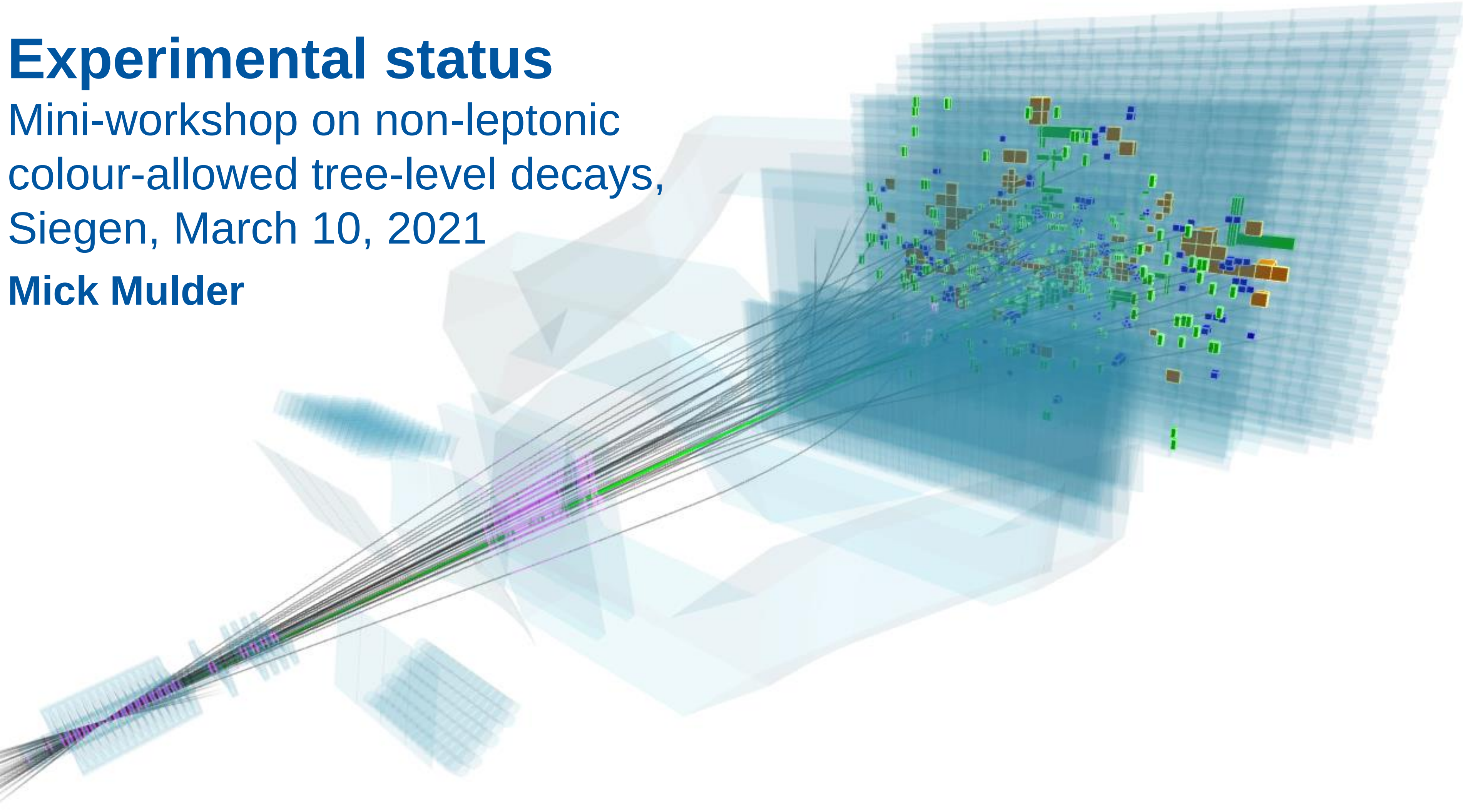
Experimental status

Mini-workshop on non-leptonic colour-allowed tree-level decays, Siegen, March 10, 2021

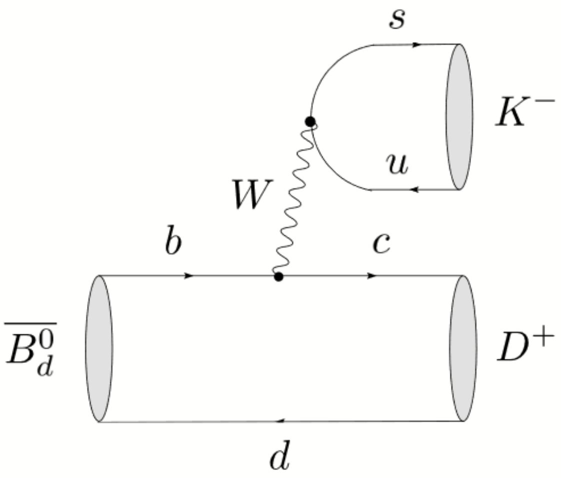
Mick Mulder



On the menu today: $B^0_{(s)} \to D^-_{(s)} h^+, \Lambda^0_b \to \Lambda^+_c h^-$

- **Non-leptonic tree-level:**
  $b \to c\bar{u}d(s)$ or $b \to u\bar{c}d(s)$ transitions
- **Colour allowed**: separate colour indices for $X_b - X_c$ and h systems
- **Main decay modes (focus of today):**
  - $B^0 \to D^{(*)-}\{K^+, \pi^+\}$
  - $B^+ \to \bar{D}^{(*)0}\{K^+, \pi^+\}$ (w. colour-suppressed contributions)
  - $B^0_s \to D_s^{(*)-}\{K^+, \pi^+\}$
  - $\Lambda^0_b \to \Lambda^+_c\{K^-, \pi^-\}$

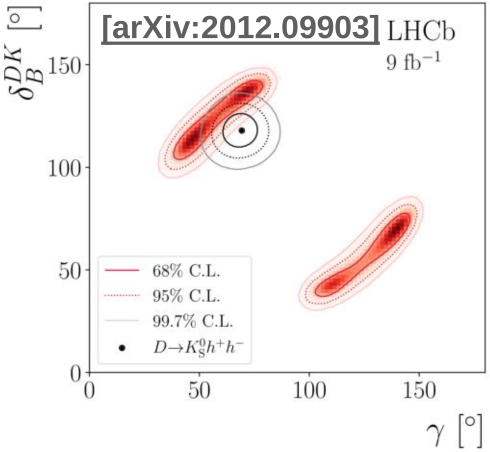
Example decay: $B^0 \to D^- K^+$

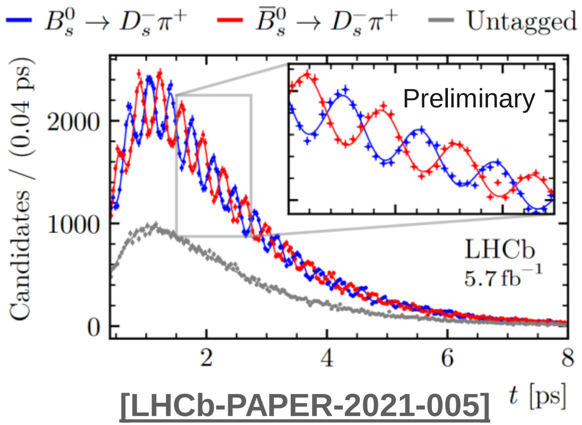


[Fleischer, arXiv:0802.2882]

Why study $B^0_{(s)} \to D^-_{(s)} h^+$?

- **Very abundant B decays**
  (only semileptonic modes are more abundant)
- **Fully charged final states**:
  many modes easy to reconstruct
- **Excellent to study B-meson system**
  (CKM, mixing, CP violation):
  - Gamma measurements with $B^+ \to D^{(*)0} h^+$
  - Δm_s with $B^0_s \to D^-_s \pi^+$
  - CPV in $B^0_s \to D^-_s K^+$ or $B^0 \to D^- \pi^+$
- **BF measurements are performed as well, especially to study B-hadron production**





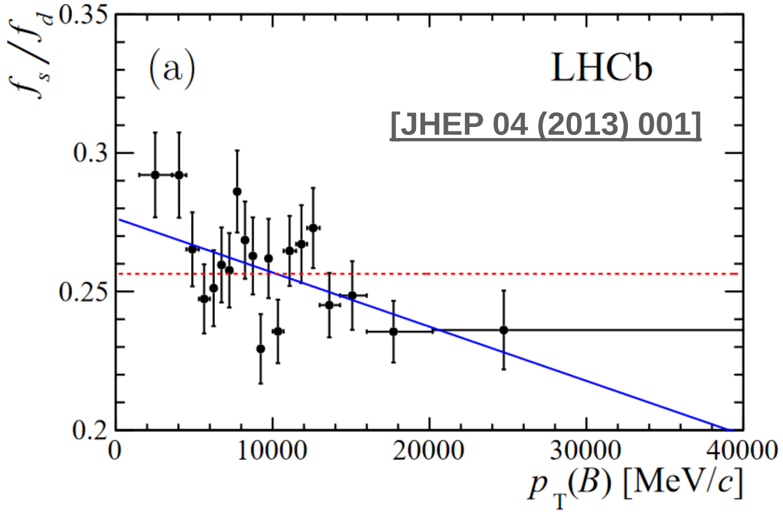
[LHCb-PAPER-2021-005]

$B^0_{(s)} \to D^-_{(s)} h^+$ decay rates and B production

[Fleischer et al., arXiv:1012.2784, Fleischer et al., arXiv:1004.3982]

- **Original experimental motivation** for rates of $B^0_{(s)} \to D^-_{(s)}\{K^+, \pi^+\}$ modes: determine $\boldsymbol{B^0_s / B^0}$ **production/hadronisation ratio** $\boldsymbol{f_s / f_d}$**!**
- **Study versus B-hadron kinematics**

- Example: Run 1 measurement of p_T dependence with $\frac{B^0_s \to D^-_s \pi^+}{B^0 \to D^- \pi^+}$, value with $\frac{B^0_s \to D^-_s \pi^+}{B^0 \to D^- K^+}$
- **Require BF prediction as input**



Predictions of $B(B^0_{(s)} \to D^{(*)-}_{(s)} h^+)$

[Fleischer et al., arXiv:1012.2784,
Fleischer et al., arXiv:1004.3982,
Bordone et al., arXiv:2007.10338]

- Two types of transitions:
  - $B^0 \to D^{(*)-}K^+, B^0_s \to D_s^{(*)-}\pi^+$: tree-only decays
  - $B^0 \to D^{(*)-}\pi^+, B^0_s \to D_s^{(*)-}K^+$: tree + exchange decays
- Require sufficient knowledge of
  - **π, K decay constants f_π, f_K**
  - **$B \to D$ form factors $F_0^{(s/d)}(m_h^2)$**
  - **Non-factorizable contributions $a_1(D_s^- h)$**
  - **Size of exchange contributions**
- **Let's go measure them at LHCb!**

Prediction for ratio of tree-only decays

$$\frac{\mathrm{BR}(\bar{B}^0_s \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}^0_d \to D^+K^-)} \sim \frac{\tau_{B_s}}{\tau_{B_d}} \left|\frac{V_{ud}}{V_{us}}\right|^2 \times \left(\frac{f_\pi}{f_K}\right)^2 \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2 \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2$$

Measuring branching fractions at LHCb

- No absolute measurement possible because of limited knowledge of b-hadron cross sections → **measure ratios**!

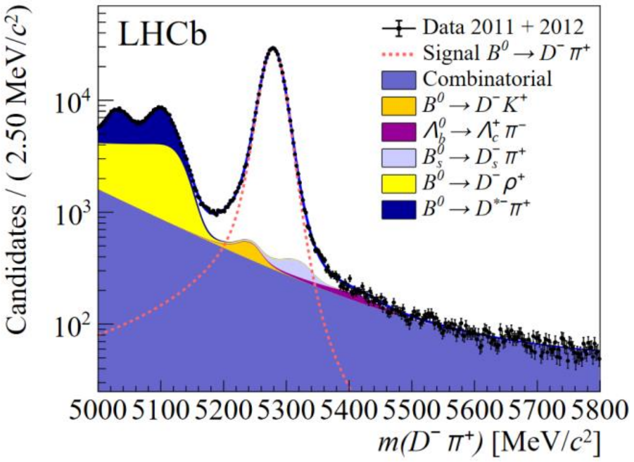
$$\frac{n_{\mathrm{corr}}(B_s^0 \to X)}{n_{\mathrm{corr}}(B^{0(+)} \to Y)} = \frac{\mathcal{B}(B_s^0 \to X)}{\mathcal{B}(B^{0(+)} \to Y)} \frac{f_s}{f_{d(u)}}$$

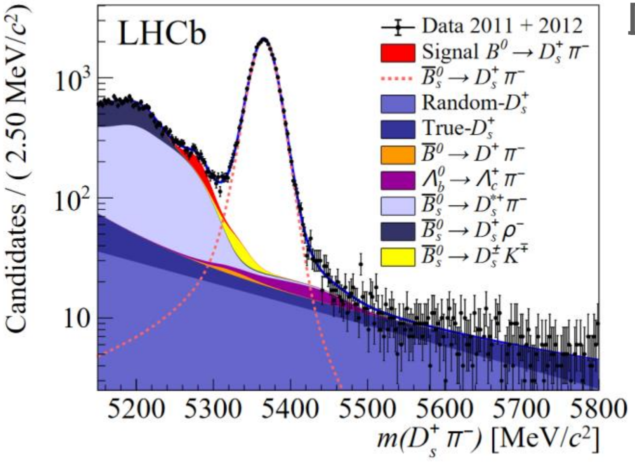
- Measure ratio of yields through fit to data
- Determine efficiency ratio with simulation calibrated on data
- Obtain efficiency-corrected yield n_{corr} per mode
- Correct for b-hadron production differences for B_s^0, Λ_b^0

Measuring $B^0_{(s)} \to D^-_{(s)} h^+$ at LHCb

- **LHCb is well-suited for hadronic tree-level decays:**
  - Large background reduction in VELO from detached B hadrons (~1 cm decay length)
  - Excellent mass resolution (~20 MeV) from tracking to separate B^0, B^0_s contributions
  - Good $\pi^+ - K^+$ separation with RICH to separate final states

[arXiv:2010.11986]





Sidenote: which final states are best?

- **Prefer final state with only charged particles**,
  so no $\rho^+ \to \pi^+\pi^0$, $K^{*+} \to K_S^0\pi^+$ or $D_s^{*+} \to D_s^+\pi^0$
- **Leaves 5 charm hadron modes**:
  $D^{*+} \to D^0\pi^+, D^0 \to K^+\pi^-, D^+ \to K^-\pi^+\pi^+, D_s^+ \to K^+K^-\pi^+$, and $\Lambda_c^+ \to pK^-\pi^+$
- **Resulting B decays for LHCb (require input on production)**:
  - $B^0 \to D^{(*)-}\{K^+, \pi^+\}$
  - $B^+ \to D^0\{K^+, \pi^+\}$
  - $B_s^0 \to D_s^-\{K^+, \pi^+\}$
  - $\Lambda_b^0 \to \Lambda_c^+\{K^-, \pi^-\}$
- **Belle II should be well suited to study other B^0, B^+ modes**
  - For example, $\mathrm{B}(B^+ \to D^0\{K^{*+}, \rho^+\})$ measured with ~ 10% precision at Belle

Overview of current results

- Brief summary:
  - $B(B^0 \to D^- K^+)$: Measured with Run 1 data
  - $B(B^0 \to D^{*-} K^+)$: Measured with Run 1 data

  - $B(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$: Measured with Run 1 data
  - $B(\Lambda_b^0 \to \Lambda_c^+ K^-)$: Measured with Run 1 data

- **Focus of today:**
  - $\boldsymbol{B(B_s^0 \to D_s^- \pi^+)}$**: Very recent update**
  - $B(B_s^0 \to D_s^- K^+)$: Measured with Run 1 data, **updated w. new** $\boldsymbol{B(B_s^0 \to D_s^- \pi^+)}$

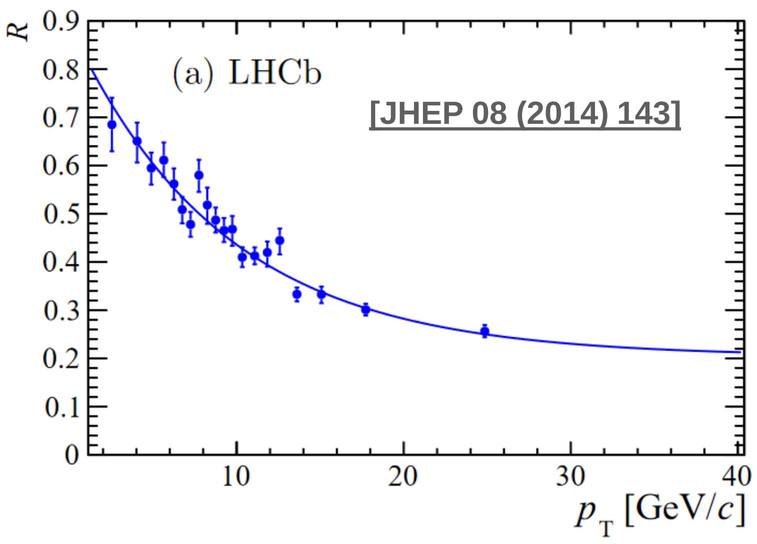
Run 1 measurements: B^0 modes

- **Relative measurements** of branching fractions
  which test exchange diagram contributions
- $\frac{B(B^0 \to D^- K^+)}{B(B^0 \to D^- \pi^+)}$, T/T+E, f_s/f_d analysis: $8.22 \pm 0.11(\text{stat.}) \pm 0.25(\text{syst.})$ % — JHEP 04 (2013) 001
- $\frac{B(B^0 \to D_s^- K^+)}{B(B^0 \to D^- \pi^+)}$, E/T+E, dedicated analysis: $1.29 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})\%$ — JHEP 05 (2015) 019
- $\frac{B(B^0 \to D^{*-} K^+)}{B(B^0 \to D^{*-} \pi^+)}$, T/T+E, $B^0 \to D^{*-} 3h$ study: $7.76 \pm 0.34(\text{stat.}) \pm 0.26(\text{syst.})\%$ — PRD87 (2013) 092001
- Similar systematic uncertainties, mainly trigger and PID
  (can probably be improved with current understanding of detector)
- **Do we need to improve handle on exchange diagram contributions by remeasuring these modes?**

Run 1 measurements: Λ_b^0 modes

- **Interesting modes, only accessible at LHCb**
  - Different helicity structure
  - Separate form factors
- **Could these modes provide complementary constraints?**
- No prediction yet (work ongoing by van Dyk et al., see link)

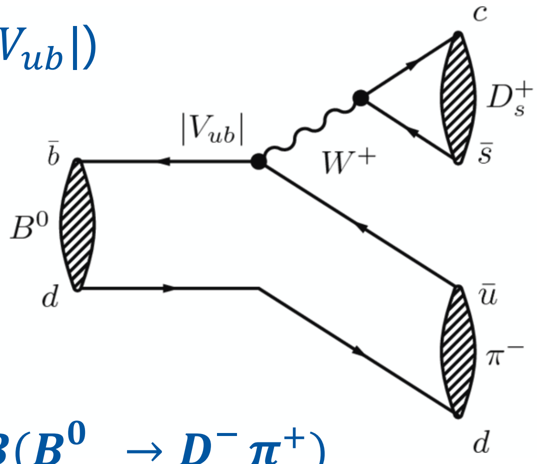
- **Results limited by $f_{\Lambda_b^0}/f_d$ from semileptonic decays (uncertainty down to ~6% for Run 2, no updates yet)**
- $B\left(\Lambda_b^0 \to \Lambda_c^+\pi^-\right) = (4.46 \pm 0.36) \times 10^{-3}$
  (combination of **[PRD89 (2014) 032001, JHEP 08 (2014) 143]**)
- $\frac{B\left(\Lambda_b^0 \to \Lambda_c^+\pi^+\right)}{B\left(B^0 \to D^-\pi^+\right)} = 1.60 \pm 0.01 \pm 0.04 \pm 0.10$
  (converted from **JHEP 08 (2014) 143**)
- $\frac{B\left(\Lambda_b^0 \to \Lambda_c^+K^+\right)}{B\left(\Lambda_b^0 \to \Lambda_c^+\pi^-\right)} = (7.31 \pm 0.16 \pm 0.16)\%$



Measurement of $B(B^0 \to D_s^- \pi^+)$ and $B(B_s^0 \to D_s^- \pi^+)$

[arXiv:2010.11986]

- **Recent study of rates in $D_s^- \pi^+$ final state**
- Main goal: $B(B^0 \to D_s^- \pi^+)$, tests factorisation (and $|V_{ub}|$)



- "By-product": efficiency-corrected yield ratio of $B_s^0 \to D_s^- \pi^+$/ $B^0 \to D^- \pi^+$
- **Essential input to new combination of f_s/f_d, leading to new measurement of $B(B_s^0 \to D_s^- \pi^+)/B(B^0 \to D^- \pi^+)$**

f_s/f_d combination: introduction

[arXiv:2103.06810]

- $f_s/f_d = B_s^0/B^0$ production ratio
  - **Required to measure B_s^0 branching fractions such as $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$**
  - Interesting per se as probe of hadronisation and fragmentation
  - Previously found to depend on p_T (not on η)
  - Assume equal production of B^0, B^+
- **f_s/f_d measured at LHCb with ratio of B_s^0/B^0 (or B^+) efficiency-corrected yields using prediction for branching fraction ratio:**

$$\frac{n_{\text{corr}}(B_s^0 \to X)}{n_{\text{corr}}(B^{0(+)} \to Y)} = \frac{\mathcal{B}(B_s^0 \to X)}{\mathcal{B}(B^{0(+)} \to Y)} \frac{f_s}{f_{d(u)}}$$

- Five previous measurements (2011 to 2020)**:**
  combination to determine single value with higher precision

f_s/f_d combination: methods

[arXiv:2103.06810]

- $B \to D\mu X$ (2 measurements)
  - **Precise prediction available ([Bigi et al., JHEP09(2011)012])**

$$\frac{f_s}{f_u+f_d} = \frac{n_{\rm corr}(B_s^0\to D_s^- X\mu^+\nu_\mu) + n_{\rm corr}(B_s^0\to \overline{D}\overline{K} X\mu^+\nu_\mu)}{n_{\rm corr}(B^{+,0}\to \overline{D}^0 X\mu^+\nu_\mu) + n_{\rm corr}(B^{+,0}\to D^- X\mu^+\nu_\mu)} \frac{\tau_{B^+}+\tau_{B^0}}{2\tau_{B_s^0}}(1-\xi_s) - \varepsilon_{\rm ratio}\frac{\mathcal{B}(B^{+,0}\to D_s^-\overline{K}X\mu^+\nu_\mu)}{\mathcal{B}_{\rm SL}},$$

- $B \to Dh$ (2 measurements)
  - Nominal fit includes prediction
  - **Determine $B(B_s^0 \to D_s^-\pi^+)$ without prediction**

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

$$\frac{f_s}{f_d} = \Phi_{{\rm PS},D^-\pi^+}\frac{\tau_{B^0}}{\tau_{B_s^0}}\frac{1}{\mathcal{N}_a\mathcal{N}_F\mathcal{N}_E}\frac{\mathcal{B}(D^-\to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^-\to K^-K^+\pi^-)}\frac{n_{\rm corr}(B_s^0\to D_s^-\pi^+)}{n_{\rm corr}(B^0\to D^-\pi^+)},$$

- $B \to J/\psi X$ (1 measurement)
  - No prediction available
  - Larger experimental rate than $B \to Dh$
  - **Sensitive to dependence of f_s/f_d in $p_T, \eta, \sqrt{s}$**
  - **Determine $B(B_s^0 \to J/\psi\phi)$ from fit**

$$\frac{f_s}{f_u} = \frac{n_{\rm corr}(B_s^0\to J/\psi\phi)}{n_{\rm corr}(B^+\to J/\psi K^+)}\frac{\mathcal{B}(B^+\to J/\psi K^+)}{\mathcal{B}(B_s^0\to J/\psi\phi)\mathcal{B}(\phi\to K^+K^-)} = \frac{\mathcal{R}}{\mathcal{F}_R}$$

f_s/f_d combination: measurements

[arXiv:2103.06810]

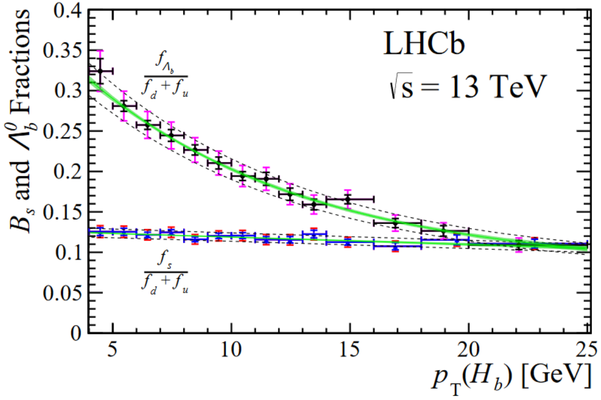
- $B \to D\mu X$
  - Integrated measurement at 7 TeV
  - Measurement vs p_T at 13 TeV, **dominates precision on scale**
- $B \to Dh$
  - Measurement vs p_T at 7 TeV with $B_s^0 \to D_s^- \pi^+ / B^0 \to D^- \pi^+$, value from integrated measurement with $B_s^0 \to D_s^- \pi^+ / B^0 \to D^- K^+$
  - Integrated measurement at 7, 8, 13 TeV with $B_s^0 \to D_s^- \pi^+ / B^0 \to D^- \pi^+$
- $B \to J/\psi X$
  - Measurement vs p_T at 7, 8, 13 TeV, **dominates dependence**

f_s/f_d combination: examples

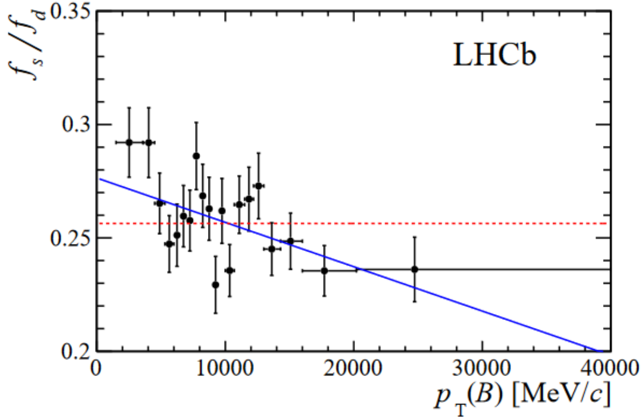
[arXiv:2103.06810]

- Previous LHCb measurements performed at 7, 8, 13 TeV, $p_T \in [0.5, 40]$ GeV, $\eta \in [2, 6.4]$
- Selection of plots:

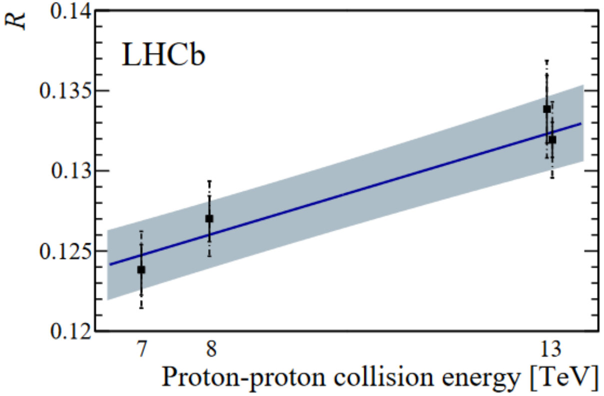
$B \to D\mu X$, 13 TeV



$B \to Dh$, 7 TeV



$B \to J/\psi X$, various $\sqrt{s}$



Combination of f_s/f_d measurements: inputs

[arXiv:2103.06810]

- Updated external inputs for $B \to D\mu X$, $B \to Dh$
  - D meson branching fractions, **incl. recent BESIII measurement, arXiv:2011.08041**
  - B meson lifetimes
  - $B \to D$ form factor update **thanks to Bordone et al., arXiv:1912.09335**
  - Exchange diagram estimates including LHCb BF
- **Significant reduction in overall uncertainty, especially due to recent BESIII measurement**
- Correlation between $B \to D\mu X$, $B \to Dh$, measurements estimated at around 68%, included in nominal fit

Input	Value	Reference
$\mathcal{B}(\overline{D}^0 \to K^+\pi^-)$	$(3.999 \pm 0.045)\%$	[6]
$\mathcal{B}(D^- \to K^+\pi^-\pi^-)$	$(9.38 \pm 0.16)\%$	[7]
$\mathcal{B}(D_s^- \to K^-K^+\pi^-)$	$(5.47 \pm 0.10)\%$	[6, 40]
$\tau_{B_s^0}/\tau_{B^0}$	1.006 ± 0.004	[6]
$(\tau_{B^+} + \tau_{B^0})/2\tau_{B_s^0}$	1.032 ± 0.005	[6]
$(1-\xi_s)$	1.010 ± 0.005	[34]
$\mathcal{N}_a$	1.000 ± 0.020	[37]
$\mathcal{N}_F$	1.000 ± 0.042	[19, 41]
$\mathcal{N}_E$	0.966 ± 0.062	[7, 37]
$\lvert V_{us}\rvert f_K/\lvert V_{ud}\rvert f_\pi$	0.2767	[9]

Combination of f_s/f_d: technicalities

[arXiv:2103.06810]

- Combination through χ^2 minimization
- External inputs included as Gaussian constraints

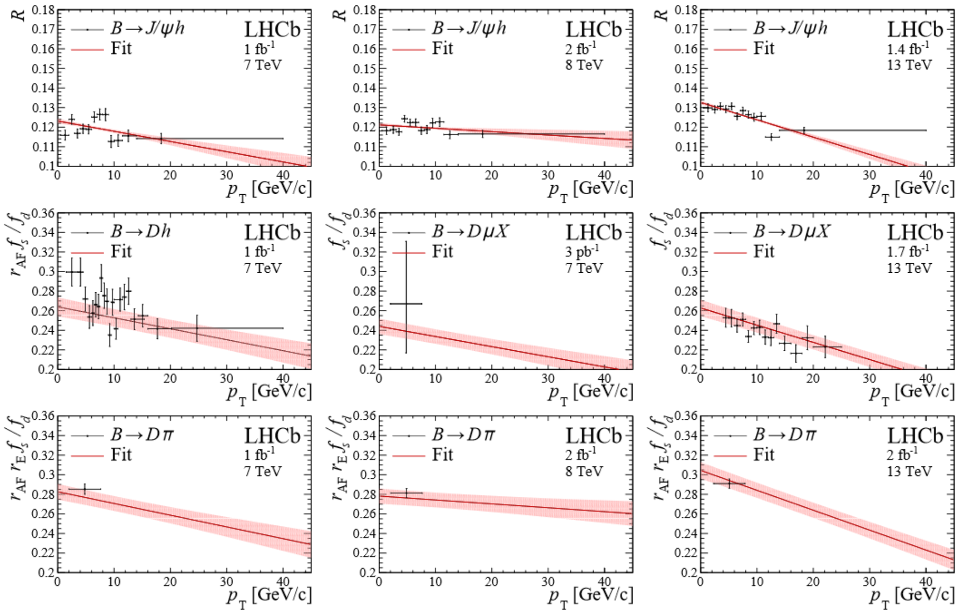
- $B \rightarrow Dh$ theoretical inputs defined as $r_{AF} = \frac{N_{AF,fit}}{N_{AF,theo}}$, $r_E = \frac{N_{E,fit}}{N_{E,theo}}$, **$\boldsymbol{r_{AF}}$ shared for hadronic measurements**
- **$\boldsymbol{r_{AF}}$ at tension with expectation (= 1);**
  to appropriately show fit result, $\boldsymbol{r_{AF}}$ included on y-axis for hadronic fits

- Fit procedure validated with pseudoexperiments,
  found to be unbiased and with proper coverage

Combination of f_s/f_d measurements: results

[arXiv:2103.06810]

- First observation of $\sqrt{s}$ dependence, hint of p_T dependence variation vs $\sqrt{s}$
- **Integrated value (13 TeV) in LHCb acceptance:** $\frac{f_s}{f_d} = 0.2539 \pm 0.0079$
- Shape not fully satisfactory, but effect on integrated value is negligible
- **Uncertainty reduced by ~ factor 2 to ~3%**
- **Also measure $B(B_s^0 \to J/\psi\phi)$:** $B(B_s^0 \to J/\psi\phi) = (1.018 \pm 0.032 \pm 0.037) \times 10^{-3}$
- Update previous B_s^0 branching fraction measurements (see backup)
- **Essential improvement for current/future measurements of $B(B_s^0 \to (\phi)\mu^+\mu^-)$**



Combination of f_s/f_d measurements: $B(B_s^0 \rightarrow D_s^- \pi^+)$

[arXiv:2103.06810]

- For $B(B_s^0 \rightarrow D_s^- \pi^+)$, fit without constraints on r_{AF}, r_E
- **Results: $r_{AF} = 1.16 \pm 0.06, r_E = 1.04 \pm 0.04$**
- **Measured value for $B(B_s^0 \rightarrow D_s^- \pi^+)$**:

$$\frac{B(B_s^0 \rightarrow D_s^- \pi^+)}{B(B^0 \rightarrow D^- \pi^+)} = 1.18 \pm 0.04,$$

$$B(B_s^0 \rightarrow D_s^- \pi^+) = (3.20 \pm 0.10 \pm 0.16) \times 10^{-3}$$

- Uncertainty reduced on BF measurement as main external parameters are correlated with $B \rightarrow D\mu X$
- **Same value of BF ratio, uncertainty reduced by factor 2 compared to previous measurement**
- Update B_s^0 branching fraction measurements, **including $B(B_s^0 \rightarrow D_s^- K^+)$**:
  $B(B_s^0 \rightarrow D_s^- K^+) = (2.41 \pm 0.05 \pm 0.06 \pm 0.14) \times 10^{-4}$

Table 8: Output parameters of the fit to the data without external theory constraints.

$a(7\,\text{TeV})$	0.238 ± 0.008
$b(7\,\text{TeV})$	$(-10.3 \pm 2.7) \times 10^{-4}$
S_1	1.000 ± 0.026
S_2	1.00 ± 0.04
r_{AF}	1.16 ± 0.06
$\mathcal{F}_R$	0.517 ± 0.017
$a(8\,\text{TeV})$	0.234 ± 0.008
$b(8\,\text{TeV})$	$(-3.3 \pm 2.3) \times 10^{-4}$
$a(13\,\text{TeV})$	0.256 ± 0.009
$b(13\,\text{TeV})$	$(-16.9 \pm 2.0) \times 10^{-4}$
S_3	1.000 ± 0.009
S_4	0.998 ± 0.023
r_{E}	1.04 ± 0.04

Interpretation

[Bordone et al., arXiv:2007.10338]

[Cai et al., arXiv:2103.04138]

- After updates of $B \to D$ form factors, multiple papers discussed $B \to Dh$ BFs
- As shown in table on right, **predictions consistently larger than experiment (around 15% level effect)**
- **Uncertainty implies 4,5σ effects in $B_s^0 \to D_s^- \pi^+, B^0 \to D^- K^+, B^0 \to D^- \pi^+$**
- **Effect from updated $\mathcal{B}(B_s^0 \to D_s^- h^+)$: reduced uncertainty on estimates**
- All LHCb measurements normalised to $B^0 \to D^- \pi^+$ BF from B-factories, any possible biases from there?

$\lvert a_1(D_{(s)}^{(*)+}L^-)\rvert$	LO	NLO	NNLO	Ref. [36]	Exp.
$\lvert a_1(D^+\pi^-)\rvert$	1.028	$1.059^{+0.017}_{-0.019}$	$1.073^{+0.005}_{-0.010}$	$1.073^{+0.012}_{-0.014}$	0.88 ± 0.03
$\lvert a_1(D^{*+}\pi^-)\rvert$	1.028	$1.059^{+0.017}_{-0.019}$	$1.075^{+0.006}_{-0.011}$	$1.071^{+0.013}_{-0.014}$	0.92 ± 0.04
$\lvert a_1(D^+\rho^-)\rvert$	1.028	$1.059^{+0.017}_{-0.019}$	$1.073^{+0.005}_{-0.010}$	$1.072^{+0.012}_{-0.014}$	0.92 ± 0.07
$\lvert a_1(D^{*+}\rho^-)\rvert$	1.028	$1.059^{+0.017}_{-0.019}$	$1.075^{+0.006}_{-0.011}$	$1.071^{+0.013}_{-0.014}$	0.85 ± 0.06
$\lvert a_1(D^+K^-)\rvert$	1.028	$1.059^{+0.018}_{-0.019}$	$1.075^{+0.008}_{-0.011}$	$1.070^{+0.010}_{-0.013}$	0.92 ± 0.04
$\lvert a_1(D^{*+}K^-)\rvert$	1.028	$1.059^{+0.018}_{-0.019}$	$1.078^{+0.009}_{-0.012}$	$1.069^{+0.010}_{-0.013}$	0.94 ± 0.11
$\lvert a_1(D^+K^{*-})\rvert$	1.028	$1.058^{+0.017}_{-0.019}$	$1.071^{+0.004}_{-0.009}$	$1.070^{+0.010}_{-0.013}$	1.01 ± 0.09
$\lvert a_1(D_s^+\pi^-)\rvert$	1.028	$1.059^{+0.017}_{-0.019}$	$1.073^{+0.005}_{-0.010}$	—	0.87 ± 0.05
$\lvert a_1(D_s^+K^-)\rvert$	1.028	$1.059^{+0.018}_{-0.019}$	$1.075^{+0.008}_{-0.011}$	—	0.79 ± 0.05

Table 3. Theoretical and experimental values for the effective coefficients $\lvert a_1(D_{(s)}^{(*)+}L^-)\rvert$. The experimental errors are estimated by adding the uncertainties of the non-leptonic branching ratios and the semi-leptonic differential decay rates in quadrature.

Absolute BF measurements

- Absolute $B^0 \to D^{(*)-}\pi^+$ branching fractions measured at B-factories
- **Relevant systematic uncertainties: D branching fractions, f^{+-}/f^{00}** [Jung, PLB 753, 187]
- **Some measurements are input-independent!**
- For $B^0 \to D^-\pi^+$:
  - **Independent measurements differ from dependent measurements by ~1 sigma and 15%**
  - Redetermining average with updated inputs only affects result by <1%, unc by <10%. (compared with average, not fit)
  - **Does using PDG fit or average (6% difference) affect conclusions?**
- Dependent and independent measurements from Belle (II) essential to fully exclude issues

$\Gamma(B^0 \to D^-\pi^+)/\Gamma_{total}$ $\Gamma_{34}/$

VALUE (10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{2.52 \pm 0.13}$	**OUR FIT** Error includes scale factor of 1.1.				
$\mathbf{2.68 \pm 0.13}$	**OUR AVERAGE**				
$2.55 \pm 0.05 \pm 0.16$		[1] AUBERT	2007H	BABR	$e^+ e^- \to \Upsilon(4S)$
$3.03 \pm 0.23 \pm 0.23$		[2] AUBERT,BE	2006J	BABR	$e^+ e^- \to \Upsilon(4S)$
$2.68 \pm 0.12 \pm 0.24$		[1,3] AHMED	2002B	CLE2	$e^+ e^- \to \Upsilon(4S)$
$2.7 \pm 0.6 \pm 0.5$		[4] BORTOLETTO	1992	CLEO	$e^+ e^- \to \Upsilon(4S)$
$4.8 \pm 1.1 \pm 1.1$	22	[5] ALBRECHT	1990J	ARG	$e^+ e^- \to \Upsilon(4S)$
$5.1^{+2.8}_{-2.5}{}^{+1.3}_{-1.2}$	4	[6] BEBEK	1987	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$2.73 \pm 0.19 \pm 0.05$		[7,1] AUBERT,B	2004O	BABR	Repl. by AUBERT 2007H
$2.83 \pm 0.42 \pm 0.05$	81	[8] ALAM	1994	CLE2	Repl. by AHMED 2002B
$3.1 \pm 1.3 \pm 1.0$	7	[5] ALBRECHT	1988K	ARG	$e^+ e^- \to \Upsilon(4S)$

[1] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[2] Uses a missing-mass method. Does not depend on D branching fractions or B^+/B^0 production rates.

[3] AHMED 2002B reports an additional uncertainty on the branching ratios to account for 4.5% uncertainty on relative production of B^0 and B^+, which is not included here.

[4] BORTOLETTO 1992 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[5] ALBRECHT 1988K assumes $B^0\overline{B}^0 : B^+B^-$ production ratio is 45:55. Superseded by ALBRECHT 1990J which assumes 50:50.

[6] BEBEK 1987 value has been updated in BERKELMAN 1991 to use same assumptions as noted for BORTOLETTO 1992 .

[7] AUBERT,B 2004O reports $[\Gamma(B^0 \to D^-\pi^+)/\Gamma_{total}] \times [B(D^+ \to K^0_S \pi^+)] = (42.7 \pm 2.1 \pm 2.2) \times 10^{-6}$ which we divide by our best value $B(D^+ \to K^0_S \pi^+) = 0.01562 \pm 0.00031$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[8] ALAM 1994 reports $[\Gamma(B^0 \to D^-\pi^+)/\Gamma_{total}] \times [B(D^+ \to K^-2\pi^+)] = 0.000265 \pm 0.000032 \pm 0.000023$ which we divide by our best value $B(D^+ \to K^-2\pi^+) = 0.0938 \pm 0.0016$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

Naïve questions

- **How much is deviation an absolute effect only?**
  If so, any way to test in ratios (i.e. at LHCb)?

- How large are uncertainties on non-factorisable contributions?

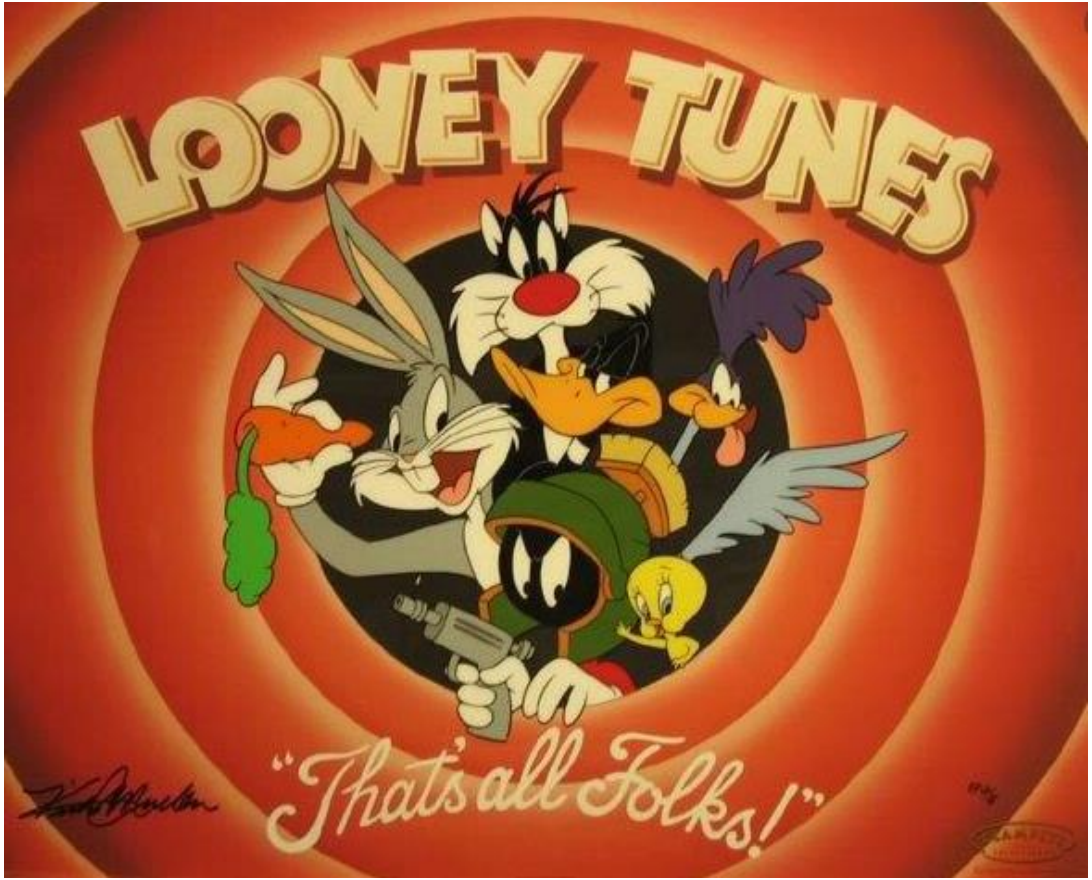
- Do uncertainties on exchange diagrams affect estimates?
  Sensible to add as additional “degree of freedom” in theoretical fit?

Questions: additional modes

- How about constraints from
  - $B^+ \to \overline{D}^0\{K^+,\pi^+\}$?
    Experimental measurements have similar precision,
    significant deviation from isospin for colour-suppressed contribution?
  - Baryonic modes $\Lambda_b^0 \to \Lambda_c^+\{K^+,\pi^+\}$?
    Additional uncertainty from $f_{\Lambda_b^0}/f_d$, work on predictions ongoing (link)
  - Higher multiplicity modes ($X_b \to X_c\{K^+,\pi^+\}\pi^+\pi^-$)
    Theoretically complicated because of resonances?

Summary

- Non-leptonic colour-allowed tree-level decays are outstanding laboratory to study flavour physics and strong interactions
- **Significant step in precision for B_s^0 modes through simultaneous measurement of f_s/f_d and $B_s^0 \to D_s^+\pi^-$**
- Possible hints of deviation in absolute branching fractions?
- Thinking of future studies:
  - Absolute branching fraction measurements from Belle II
  - Updated measurements at LHCb (eager to hear which to prioritise ☺)
  - Additional studies of baryonic modes
- **Looking forward to discussing with all of you!**


LOONEY TUNES
"That's all Folks!"

Backup

f_s/f_d: conversion from rates

$B \to D\mu X$

$$\frac{f_s}{f_u+f_d} = \frac{n_{\rm corr}(B_s^0\to D_s^- X\mu^+\nu_\mu) + n_{\rm corr}(B_s^0\to \overline{D}\overline{K} X\mu^+\nu_\mu)}{n_{\rm corr}(B^{+,0}\to \overline{D}^0 X\mu^+\nu_\mu) + n_{\rm corr}(B^{+,0}\to D^- X\mu^+\nu_\mu)} \frac{\tau_{B^+}+\tau_{B^0}}{2\tau_{B_s^0}}(1-\xi_s) - \varepsilon_{\rm ratio}\frac{\mathcal{B}(B^{+,0}\to D_s^-\overline{K}X\mu^+\nu_\mu)}{\mathcal{B}_{\rm SL}}, \quad (2)$$

$B \to Dh$

$$\frac{f_s}{f_d} = \Phi_{{\rm PS},D^-K^+}\left|\frac{V_{us}}{V_{ud}}\right|^2\left(\frac{f_K}{f_\pi}\right)^2 \frac{\tau_{B^0}}{\tau_{B_s^0}}\frac{1}{\mathcal{N}_a\mathcal{N}_F}\frac{\mathcal{B}(D^-\to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^-\to K^-K^+\pi^-)}\frac{n_{\rm corr}(B_s^0\to D_s^-\pi^+)}{n_{\rm corr}(B^0\to D^-K^+)}, \quad (3a)$$

$$\frac{f_s}{f_d} = \Phi_{{\rm PS},D^-\pi^+}\frac{\tau_{B^0}}{\tau_{B_s^0}}\frac{1}{\mathcal{N}_a\mathcal{N}_F\mathcal{N}_E}\frac{\mathcal{B}(D^-\to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^-\to K^-K^+\pi^-)}\frac{n_{\rm corr}(B_s^0\to D_s^-\pi^+)}{n_{\rm corr}(B^0\to D^-\pi^+)}, \quad (3b)$$

$B \to J/\psi h'$

$$\frac{f_s}{f_u} = \frac{n_{\rm corr}(B_s^0\to J/\psi\phi)}{n_{\rm corr}(B^+\to J/\psi K^+)}\frac{\mathcal{B}(B^+\to J/\psi K^+)}{\mathcal{B}(B_s^0\to J/\psi\phi)\mathcal{B}(\phi\to K^+K^-)} = \frac{\mathcal{R}}{\mathcal{F}_R}$$

B_s^0 branching fraction updates

- Take previous result
- Update B^0/B^+ normalisation BF if needed, including correction for f^{+-}/f^{00}
- Scale for change in f_s/f_d and normalisation branching fraction
- **Reduction of f_s/f_d uncertainty by factor 2**
- **Also update $|V_{cb}|$:**

The recent measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays using Run 1 data [52], also relies on an estimate of f_s/f_d and is independent of the uncertainty on the product $\mathcal{B}(D_s^- \to K^-K^+\pi^-) \times \tau_{B_s^0}$. For this estimate, the correlation of f_s/f_d with $\mathcal{B}(D_s^- \to K^-K^+\pi^-)$ from the semileptonic measurement is used. The resulting estimates for $|V_{cb}|$ are $|V_{cb}|_{\mathrm{CLN}} = (40.8 \pm 0.6 \pm 0.9 \pm 1.1) \times 10^{-3}$, $|V_{cb}|_{\mathrm{BGL}} = (41.7 \pm 0.8 \pm 0.9 \pm 1.1) \times 10^{-3}$, where CLN [53] and BGL [54] stand for two hadronic form-factor parametrisations. Both results are consistent with the current world average (see for example Ref. [7]).

Table of normalisation BFs

Table 2: The branching fractions of B^0 and B^+ normalisation channel decays used to update previous measurements of B_s^0 branching fractions, as reported in Ref. [7] for all but the $B^0 \to J/\psi K^{*0}$ branching fraction, which is taken from the amplitude analysis in Ref [50], and corrected for the relative production fraction of B^+ and B^0 mesons at B Factories [49].

Decay mode	Branching fraction	Decay mode	Branching fraction
$B^0 \to J/\psi K^{*0}$	$(1.21 \pm 0.08) \times 10^{-3}$	$B^0 \to D^- \mu^+ \nu_\mu$	$(2.31 \pm 0.10)\%$
$B^0 \to J/\psi \rho^0$	$(2.58 \pm 0.18) \times 10^{-5}$	$B^0 \to D^{*-} \mu^+ \nu_\mu$	$(5.05 \pm 0.14)\%$
$B^0 \to J/\psi K^0_S$	$(4.40 \pm 0.17) \times 10^{-3}$	$B^0 \to D^{*\pm} D^{\mp}$	$(6.2 \pm 0.6) \times 10^{-4}$
$B^0 \to J/\psi K^0_S \pi^+ \pi^-$	$(2.18 \pm 0.19) \times 10^{-3}$	$B^0 \to D^+ D^-$	$(2.14 \pm 0.19) \times 10^{-4}$
$B^0 \to \psi(2S) K^{*0}$	$(5.98 \pm 0.42) \times 10^{-4}$	$B^0 \to D^- D_s^+$	$(7.3 \pm 0.8) \times 10^{-3}$
$B^0 \to \psi(2S) K^+ \pi^-$	$(5.88 \pm 0.42) \times 10^{-4}$	$B^+ \to \overline{D}^0 D_s^+$	$(9.0 \pm 0.9) \times 10^{-3}$
$B^0 \to K^+ \pi^-$	$(1.98 \pm 0.07) \times 10^{-5}$	$B^0 \to \overline{D}^0 \pi^+ \pi^-$	$(8.8 \pm 0.5) \times 10^{-4}$
$B^0 \to K^0_S \pi^+ \pi^-$	$(2.51 \pm 0.11) \times 10^{-5}$	$B^0 \to \overline{D}^0 \rho$	$(3.21 \pm 0.21) \times 10^{-4}$
$B^0 \to K^{*+} \pi^-$	$(7.60 \pm 0.43) \times 10^{-6}$	$B^0 \to \overline{D}^0 K^0_S$	$(5.3 \pm 0.7) \times 10^{-5}$
$B^0 \to p\overline{p} K^+ \pi^-$	$(6.30 \pm 0.50) \times 10^{-6}$	$B^0 \to \overline{D}^0 K^+ K^-$	$(6.1 \pm 0.6) \times 10^{-5}$
$B^0 \to p \overline{\Lambda} \pi^-$	$(3.18 \pm 0.30) \times 10^{-6}$		
$B^0 \to K^{*0} \gamma$	$(4.13 \pm 0.26) \times 10^{-5}$		
$B^0 \to \phi K^0_S$	$(3.70 \pm 0.36) \times 10^{-6}$		
$B^0 \to \phi K^{*0}$	$(1.01 \pm 0.05) \times 10^{-5}$		

Example table with BFs

Table 6: Updated branching fractions of B_s^0 decays to open-charm final states. The uncertainties are statistical, systematic, due to f_s/f_d, and due to the normalisation branching fraction. The $B_s^0 \to D_s^{\mp}K^{\pm}$, $B_s^0 \to D_s^-\pi^+\pi^-\pi^+$ and $B_s^0 \to D_s^-K^+\pi^-\pi^+$, $B_s^0 \to D_{s1}(2536)^-\pi^+$ branching fractions are normalised with respect to $B_s^0 \to D_s^-\pi^+$ and $B_s^0 \to D_s^-\pi^+\pi^-\pi^+$, respectively, and their third uncertainty covers the full normalisation uncertainty. Results with the $\star$ symbol have had their normalisation branching fraction updated as well.

Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$	$(5.19 \pm 0.24 \pm 0.47 \pm 0.13 \pm 0.14) \times 10^{-2}$	$(5.38 \pm 0.25 \pm 0.48 \pm 0.20 \pm 0.15) \times 10^{-2}$	[52]	
$B_s^0 \to D_s^-\mu^+\nu_\mu$	$(2.40 \pm 0.12 \pm 0.15 \pm 0.06 \pm 0.10) \times 10^{-2}$	$(2.49 \pm 0.12 \pm 0.16 \pm 0.09 \pm 0.11) \times 10^{-2}$	[52]	
$B_s^0 \to D^+D_s^-$	$(3.01 \pm 0.32 \pm 0.10 \pm 0.08 \pm 0.34) \times 10^{-4}$	$(2.7 \pm 0.3 \pm 0.1 \pm 0.2 \pm 0.3) \times 10^{-4}$	[81]	
$B_s^0 \to D^+D^-$	$(2.47 \pm 0.46 \pm 0.23 \pm 0.08 \pm 0.22) \times 10^{-4}$	$(2.2 \pm 0.4 \pm 0.1 \pm 0.1 \pm 0.3) \times 10^{-4}$	[82]	
$B_s^0 \to D^0\overline{D}^0$	$(1.83 \pm 0.29 \pm 0.29 \pm 0.05 \pm 0.18) \times 10^{-4}$	$(1.9 \pm 0.3 \pm 0.2 \pm 0.2 \pm 0.3) \times 10^{-4}$	[82]	
$B_s^0 \to D_s^+D_s^-$	$(4.38 \pm 0.23 \pm 0.31 \pm 0.11 \pm 0.49) \times 10^{-3}$	$(4.0 \pm 0.2 \pm 0.2 \pm 0.2 \pm 0.4) \times 10^{-3}$	[82]	
$B_s^0 \to D^{*\pm}D^{*\mp}$	$(8.38 \pm 1.02 \pm 0.12 \pm 0.26 \pm 0.81) \times 10^{-5}$	$(8.41 \pm 1.02 \pm 0.12 \pm 0.39 \pm 0.79) \times 10^{-5}$	[83]	
$B_s^0 \to D_s^{+(*)}D_s^{-(*)}$	$(3.36 \pm 0.11 \pm 0.14 \pm 0.09 \pm 0.38) \times 10^{-2}$	$(3.05 \pm 0.10 \pm 0.13 \pm 0.14 \pm 0.34) \times 10^{-2}$	[84]	
$B_s^0 \to D_s^{*\pm}D_s^{\mp}$	$(1.49 \pm 0.06 \pm 0.07 \pm 0.04 \pm 0.17) \times 10^{-2}$	$(1.35 \pm 0.06 \pm 0.06 \pm 0.06 \pm 0.15) \times 10^{-2}$	[84]	
$B_s^0 \to D_s^{*+}D_s^{*-}$	$(1.39 \pm 0.09 \pm 0.10 \pm 0.04 \pm 0.16) \times 10^{-2}$	$(1.27 \pm 0.08 \pm 0.09 \pm 0.06 \pm 0.14) \times 10^{-2}$	[84]	
$B_s^0 \to \overline{D}^0K_S^0$	$(4.69 \pm 0.51 \pm 0.28 \pm 0.15 \pm 0.64) \times 10^{-4}$	$(4.3 \pm 0.5 \pm 0.3 \pm 0.3 \pm 0.6) \times 10^{-4}$	[85]	
$B_s^0 \to \overline{D}^{*0}K_S^0$	$(3.05 \pm 1.13 \pm 0.40 \pm 0.10 \pm 0.41) \times 10^{-4}$	$(2.8 \pm 1.0 \pm 0.3 \pm 0.2 \pm 0.4) \times 10^{-4}$	[85]	
$B_s^0 \to \overline{D}^0\overline{K}^{*0}$	$(5.31 \pm 1.22 \pm 0.54 \pm 0.17 \pm 0.35) \times 10^{-4}$	$(4.72 \pm 1.07 \pm 0.48 \pm 0.37 \pm 0.74) \times 10^{-4}$	[86]	$\star$
$B_s^0 \to \overline{D}^0K^-\pi^+$	$(1.11 \pm 0.05 \pm 0.07 \pm 0.04 \pm 0.06) \times 10^{-3}$	$(1.00 \pm 0.04 \pm 0.06 \pm 0.08 \pm 0.10) \times 10^{-3}$	[87]	$\star$
$B_s^0 \to \overline{D}^0\phi$	$(3.25 \pm 0.38 \pm 0.19 \pm 0.11 \pm 0.18) \times 10^{-5}$	$(3.0 \pm 0.3 \pm 0.2 \pm 0.2 \pm 0.2) \times 10^{-5}$	[88]	$\star$
$B_s^0 \to \overline{D}^{*0}\phi$	$(4.01 \pm 0.48 \pm 0.27 \pm 0.13 \pm 0.23) \times 10^{-5}$	$(3.7 \pm 0.5 \pm 0.2 \pm 0.2 \pm 0.2) \times 10^{-5}$	[88]	$\star$
$B_s^0 \to \overline{D}^0K^+K^-$	$(6.13 \pm 0.59 \pm 0.28 \pm 0.20 \pm 0.56) \times 10^{-5}$	$(5.7 \pm 0.5 \pm 0.2 \pm 0.3 \pm 0.5) \times 10^{-5}$	[89]	$\star$
$B_s^0 \to D_s^{\mp}K^{\pm}$	$(2.41 \pm 0.05 \pm 0.06 \pm 0.14) \times 10^{-4}$	$(2.29 \pm 0.05 \pm 0.06 \pm 0.17) \times 10^{-4}$	[90]	$\star$
$B_s^0 \to D_s^-\pi^+\pi^-\pi^+$	$(6.43 \pm 1.18 \pm 0.64 \pm 0.38) \times 10^{-3}$	$(6.01 \pm 1.11 \pm 0.60 \pm 0.48) \times 10^{-3}$	[91]	$\star$
$B_s^0 \to D_s^-K^+\pi^-\pi^+$	$(3.34 \pm 0.32 \pm 0.19 \pm 0.73) \times 10^{-4}$	$(3.13 \pm 0.30 \pm 0.18 \pm 0.76) \times 10^{-4}$	[92]	$\star$
$B_s^0 \to D_{s1}(2536)^-\pi^+$	$(2.57 \pm 0.64 \pm 0.26 \pm 0.56) \times 10^{-5}$	$(2.41 \pm 0.60 \pm 0.24 \pm 0.58) \times 10^{-5}$	[92]	$\star$

Fit with Tsallis function