Determination of $|V_{ub}|$ using the Baryonic decays $\Lambda_b \rightarrow p\mu\nu$ and $\Lambda_b \rightarrow \Lambda_c\mu^-\nu_\mu$

LHCb Approval

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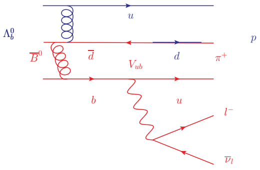
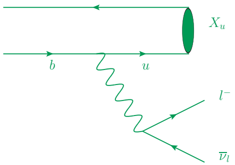
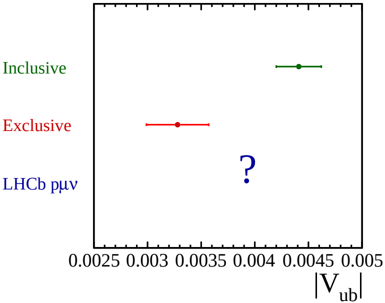
February 26, 2015

The $|V_{ub}|$ puzzle

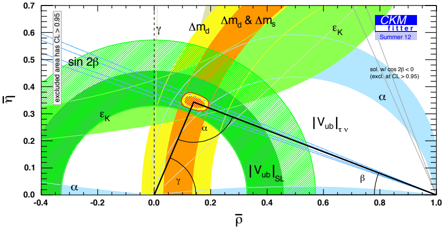


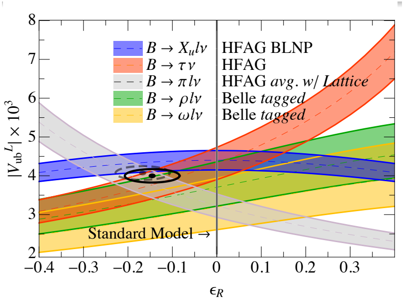




Why is $|V_{ub}|$ important?

- $|V_{ub}|$ is orthogonal to γ in constraining the UT.
- An inconsistency between $|V_{ub}|$ and β could signal new physics.





- Could a right handed current explain the $|V_{ub}|$ puzzle?

What makes $|\mathrm{V_{ub}}|$ possible at LHCb.

- Less final state protons + excellent proton PID ($\Lambda_b \to p\mu^-\nu_\mu$).
- Use of the corrected mass and its associated uncertainty..
- Effective control of q^2 uncertainty.
- Ability to effectively isolate our signal.
- Existing measurement for $\mathcal{B}(\Lambda_c \to pK\pi)$.

Analysis strategy

- The strategy is to normalise $\Lambda_b \to p\mu\nu$ to $\Lambda_b \to \Lambda_c(\to pK\pi)\mu\nu$ in the high q^2 region.

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = \frac{N(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{N(\Lambda_b \to (\Lambda_c \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} \times \frac{\epsilon(\Lambda_b \to (\Lambda_c \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}}{\epsilon(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}} \times \mathcal{B}(\Lambda_c \to pK^-\pi^+)$$

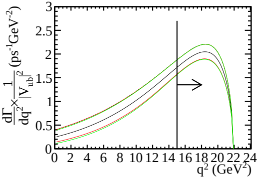
$$R_{exp} = R_{theory}\frac{|\mathrm{V_{ub}}|^2}{|\mathrm{V_{cb}}|^2}$$

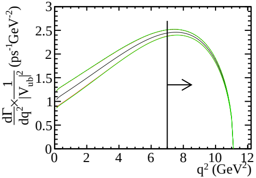
- Yields N fitted using corrected mass.
- Relative efficiency obtained from simulation.

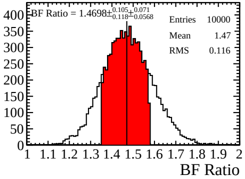
Theory ratio

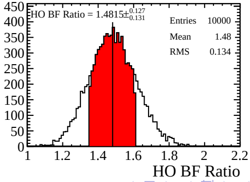
- Use the latest Lattice results for these decays to calculate:

$$R_{theory} = \frac{\int_{15\ \mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p \mu^- \overline{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{7\ \mathrm{GeV}^2/c^4}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c \mu^- \overline{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2}$$







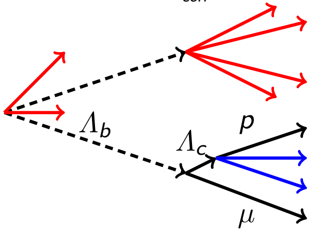


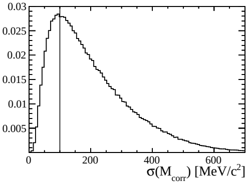
Datasets and preselection

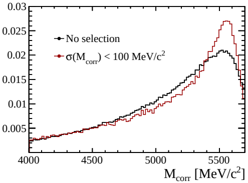
- 2012 dataset, 2fb^{-1} for $\Lambda_b \rightarrow p\mu^-\nu_\mu$ and 1fb^{-1} for $\Lambda_b \rightarrow \Lambda_c\mu^-\nu_\mu$.
- Stripping S20r0p2 StrippingLb2pMuNuVub Module
- Tight Proton PID and momentum cuts (DLL$(p-K) > 10$ & DLL$(p-\pi) > 10$ & $P > 15000\ \mathrm{MeV}/c$).
- Trigger decisions: L0Muon & (Hlt2SingleMuon || Hlt2TopoMu2Body) + TOS on these.
- ~16 MC samples (filtered + unfiltered for signal and normalisation)

Selection

- Isolation BDT removes backgrounds with additional charged tracks that could vertex with $p\mu$ candidate.
  - Applied also to normalisation channel (ignoring kaon and pion).
- Fit the corrected mass: $M_{corr} = \sqrt{p_{\mathrm{T}}^2 + M_{p\mu}^2} + p_{\mathrm{T}}$
- Determine the corrected mass uncertainty, $\sigma_{M_{corr}}$.
- Cut at $\sigma_{M_{corr}} < 100\,\mathrm{MeV}/c^2$. Link

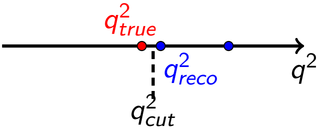




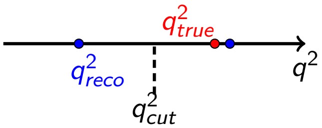


q^2 Selection

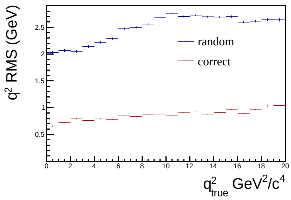
- Reconstruct neutrino and hence q^2 up to a 2-fold ambiguity.
- Cut on both solutions $> q^2_{cut}$ to minimise inwards migration.

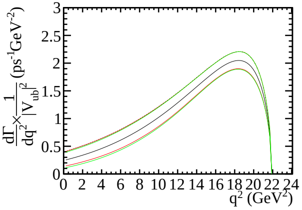


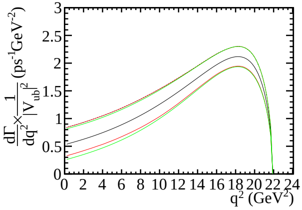
Inwards Migration



Outwards Migration

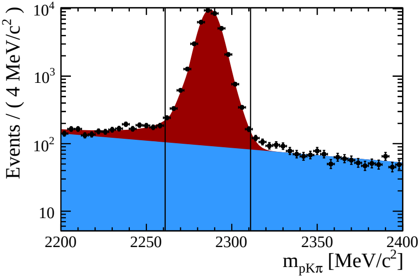


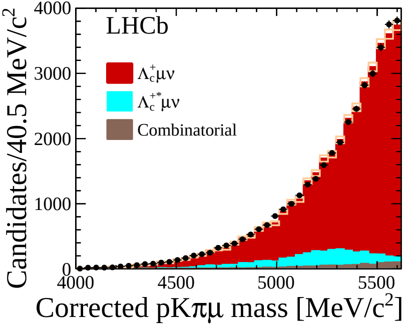




Normalisation fit

- Fit $pK\pi\mu$ corrected mass to determine N($\Lambda_b \rightarrow \Lambda_c(\rightarrow pK\pi)\mu\nu$).
- Non-Λ_c background shape and size obtained from $pK\pi$ fit.

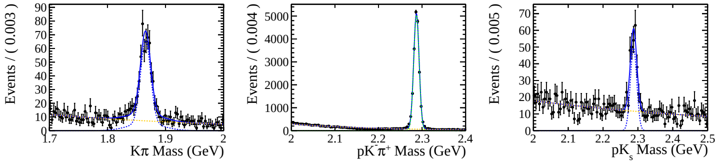




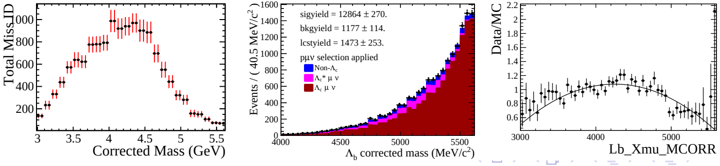
- Rate dominated by $\Lambda_b \rightarrow \Lambda_c\mu\nu$, $\Lambda_b \rightarrow \Lambda_c^*(2595) + \mu\nu$ and $\Lambda_b \rightarrow \Lambda_c^*(2625) + \mu\nu$.
- Fit yields $N(\Lambda_b \rightarrow \Lambda_c\mu^-\nu_\mu) = 34255 \pm 571$.

Data Driven Constraints

- Reconstruct a number of modes: $\varLambda_b \to (D^0 \to K\pi)p\mu^-\overline{\nu}_\mu$, $\varLambda_b \to (\varLambda_c \to pK^+\pi^-)\mu^-\overline{\nu}_\mu$ and $\varLambda_b \to (\varLambda_c \to pK^0)\mu^-\overline{\nu}_\mu$.



- $K/\pi \to p$ Miss ID (6 pb^{-1} no p PID)
- Combinatorial from SS data.
- $R(\Lambda_c^*)$, $P_{pK^0\pi^0}$ and $P_{pK^0\eta}$.



Signal fit Model (26 parameters)

$\Lambda_b \to p\mu^-\nu_\mu$:
N($\Lambda_b \to p\mu^-\nu_\mu$)

$\Lambda_b \to N^*\mu^-\nu_\mu$:
$R_{N(1440)}$
$R_{N(1520)}$
$R_{N(1535}$
$R_{N(1720)}$

$\Lambda_b \to \Lambda_c\mu^-\nu_\mu$, pX neutrals:
$N(\Lambda_b \to (\Lambda_c \to pK^0)\mu^-\overline{\nu}_\mu)$,
$R_{pK^0\pi^0}$, $R_{pK^0\eta}$, $P_{pK^0\pi^0}$, $P_{pK^0\eta}$
$R_{p\pi^0}$, $R_{p\eta}$, $R_{p\eta'}$
$R_{\Delta^+\pi^0}$, $R_{\Delta^+\eta}$, $R_{\Delta^+\eta'}$

$\Lambda_b \to \Lambda_c\mu^-\nu_\mu$, pX charged:
$N(\Lambda_b \to (\Lambda_c \to pK^+\pi^-)\mu^-\overline{\nu}_\mu)$,
$R_{pK^0\pi^+\pi^-}$, $R_{pK^-\pi^+\pi^0}$, $R_{pK^{*-}\pi^+}$
$R_{pK^-\pi^+\pi^0\pi^0}$, $R_{p\pi^-\pi^+}$, R_{other}

$\Lambda_b \to \Lambda_c^*\mu^-\nu_\mu$:
$R(\Lambda_c^*)$

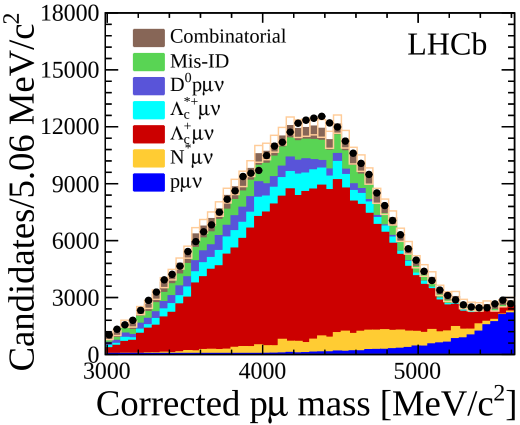
$\Lambda_b \to D^0 p\mu^-\overline{\nu}_\mu$:
$N(\Lambda_b \to D^0 p\mu^-\overline{\nu}_\mu)$

$K/\pi \to p$ Miss ID:
N_{MID}

Combinatorial:
N_{comb}

Signal fit

- Measure a signal yield of $N(\Lambda_b \to p\mu^-\nu_\mu) = 17687 \pm 733$
- First observation of $\Lambda_b \to p\mu^-\nu_\mu$ decays.



Relative efficiency

- Relative efficiency obtained from simulation.
- Main difference due to pion and kaon reconstruction for Λ_c.

Source	Relative efficiency & Slide	
DecProdCut	0.645	
Stripping & Trigger	8.71	
m_{corr} error	0.228	31
Truth matching	1.04 ± 0.001	
Isolation	1.049 ± 0.014	32
PID	1.173 ± 0.002	33
Tracking corr	0.995 ± 0.03	34
Trigger corr	1.032 ± 0.032	35
Λ_b production	1.073 ± 0.005	36
Λ_c decay model	0.998 ± 0.03	37
Λ_b lifetime	1.042 ± 0.015	38
q^2 migration	0.95 ± 0.004	39
Form factor corr	0.985 ± 0.01	40
Total	1.76 ± 0.10	

Systematic uncertainties

Source	Relative uncertainty (%)	Slide
$\mathcal{B}(\Lambda_c \to pK\pi)$	${}^{+4.7}_{-5.3}$	arXiv:1312.7826
Trigger	±3.2	35
Tracking	±3.0	34
Λ_c decay model	3.0%	37
N^{*+} form factors	2.2%	41
Λ_c & Λ_b lifetimes	1.5%	38
Isolation	1.4%	32
Form factor	1.0%	40
N^{*+} widths	0.7%	42
Λ_b production	0.5%	36
q^2 migration	0.4%	39
PID	0.2%	33
Truth matching	0.1%	

Measurement of the ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = \frac{N(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{N(\Lambda_b \to (\Lambda_c \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} \times \frac{\epsilon(\Lambda_b \to p\mu^-\nu_\mu)}{\epsilon(\Lambda_b \to \Lambda_c\mu^-\nu_\mu)}\mathcal{B}(\Lambda_c \to pK^-\pi^+)$$

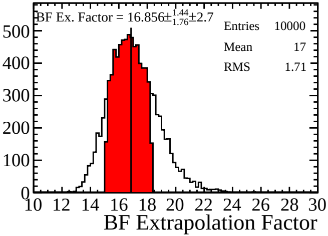
$$= (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

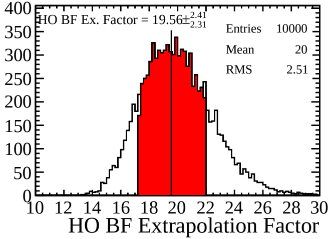
Result	Value	Slide
$N(\Lambda_b \to p\mu^-\nu_\mu)$	$17687 \pm 733(stat) \pm 408(syst)$	13
$N(\Lambda_b \to \Lambda_c\mu^-\nu_\mu)$	$68510 \pm 1142(stat)$	4
$\epsilon(\Lambda_b \to p\mu^-\nu_\mu)/\epsilon(\Lambda_b \to \Lambda_c\mu^-\nu_\mu)$	$1.76 \pm 0.10(syst)$	15
$\mathcal{B}(\Lambda_c \to pK\pi)$	$0.0684^{+4.7}_{-5.3}(syst)$	arXiv:1312.7826

Measurement of $\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)$

- Use theory to extrapolate to a full branching fraction for $\Lambda_b \to p\mu^-\nu_\mu$.

$$\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = \tau_{\Lambda_b}|V_{cb}|^2 F_{theory}\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$



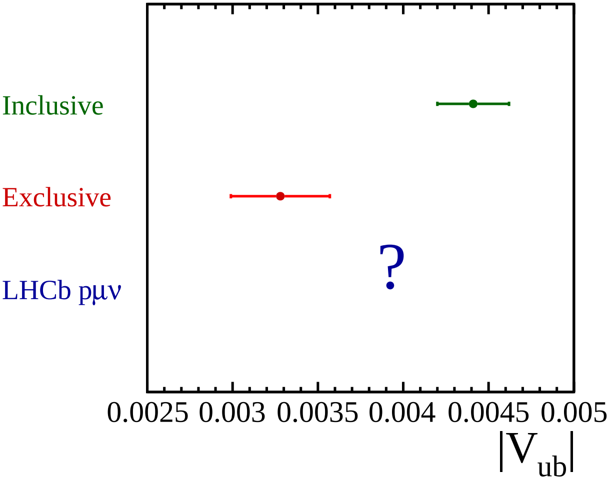


$$\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu) = (3.92\pm^{0.81}_{0.85}) \times 10^{-4}$$

- Constraint on $\Lambda_b \to p\mu^-\nu_\mu$ as a background for the decay $B_s \to \mu\mu$.

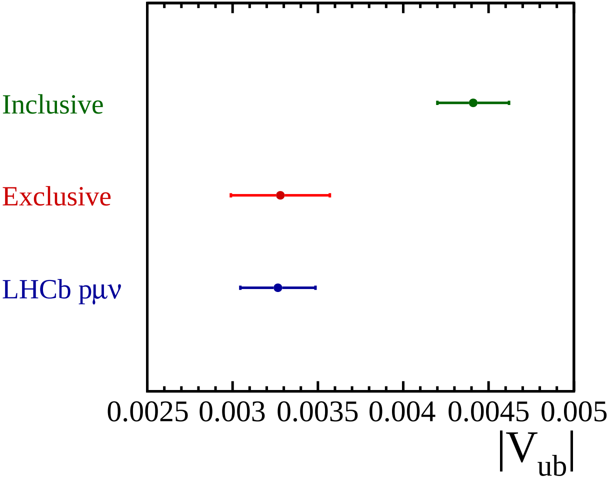
Measurement of $|V_{ub}|$

$$|V_{ub}|^2 = |V_{cb}|^2(R_{exp}/R_{theory})$$



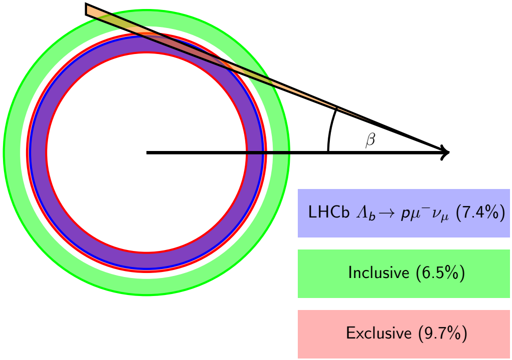
Measurement of $|V_{ub}|$

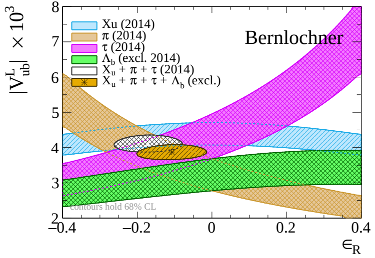
$$|V_{ub}| = (3.27 \pm 0.07(stat) \pm 0.13(syst) \pm 0.15(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$



Implications

- 6.7% uncertainty on $|V_{ub}|$ (8.8% current exclusive average).
- Value obtained is 3.7σ below the inclusive average.
- Can check the consistency of our $|V_{ub}|/|V_{cb}|$ with $\beta = 22.5\pm^{0.8}_{0.7}$.
- Our results appear to disfavour a right handed current.





Conclusion

- We measure the ratio of branching fractions of $\Lambda_b \to p\mu^-\nu_\mu$ and $\Lambda_b \to \Lambda_c\mu^-\nu_\mu$ at high q^2.
- First observation of $\Lambda_b \to p\mu^-\nu_\mu$.
- Provide a constraint on $\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)$ for $B_s \to \mu\mu$ analyses.
- From this we determine: $|V_{ub}| =$ $(3.27 \pm 0.07(stat) \pm 0.13(syst) \pm 0.15(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}$
- Our measurement is 3.7σ below the inclusive measurement reinforcing the $|V_{ub}|$ puzzle.
- Interesting prospects for exploring the implications on the UT and right handed currents.

Form Factor Definitions

A. New definition (helicity form factors)

This definition is as in Ref. [1].

$$
\begin{aligned}
\langle X(p')|\overline{q}\,\gamma^\mu\, b|\Lambda_b(p)\rangle = \overline{u}_X \bigg[& f_0\, (m_{\Lambda_b} - m_X)\frac{q^\mu}{q^2} \\
& + f_+ \frac{m_{\Lambda_b} + m_X}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_X^2)\frac{q^\mu}{q^2}\right) \\
& + f_\perp \left(\gamma^\mu - \frac{2m_X}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right)\bigg] u_{\Lambda_b},
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\langle X(p')|\overline{q}\,\gamma^\mu\gamma_5\, b|\Lambda_b(p)\rangle = -\overline{u}_X\,\gamma_5 \bigg[& g_0\, (m_{\Lambda_b} + m_X)\frac{q^\mu}{q^2} \\
& + g_+ \frac{m_{\Lambda_b} - m_X}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_X^2)\frac{q^\mu}{q^2}\right) \\
& + g_\perp \left(\gamma^\mu + \frac{2m_X}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right)\bigg] u_{\Lambda_b},
\end{aligned} \tag{2}
$$

where $q = p - p'$ and

$$s_\pm = (m_{\Lambda_b} \pm m_X)^2 - q^2. \tag{3}$$

Form Factor Parametrisation

II. FINAL RESULTS

The form factors in the physical limit are parametrized using

$$f(q^2) = \frac{1}{1 - q^2/(m_{\rm pole}^f)^2}\left[a_0^f + a_1^f\, z(q^2)\right], \tag{15}$$

with

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \tag{16}$$

$$t_+ = (m_{\Lambda_b} + m_X)^2, \tag{17}$$

$$t_0 = (m_{\Lambda_b} - m_X)^2, \tag{18}$$

The pole masses are fixed to the exact values in Table I. Because of the constraint (14), which is at the point $z = 0$ for our choice of t_0, the form factors $g_\perp$ and g_+ share the common parameter $a_0^{g_\perp, g_+}$. The central values and covariances of the fit parameters are provided in data files.

Equation (15) and the corresponding parameters are referred to as the **main fit**. To estimate systematic uncertainties we also provide a **higher-order fit** (**HO fit**). The HO fit has the form

$$f_{\rm HO}(q^2) = \frac{1}{1 - q^2/(m_{\rm pole}^f)^2}\left[a_{0,\rm HO}^f + a_{1,\rm HO}^f\, z(q^2) + a_{2,\rm HO}^f\, z^2(q^2)\right]. \tag{19}$$

Form factor	J^P	$m_{\rm pole}(\Lambda_b \to p)$	$m_{\rm pole}(\Lambda_b \to \Lambda_c)$
f_+, $f_\perp$	1^-	5.325	6.332
f_0	0^+	5.656	6.725
g_+, $g_\perp$	1^+	5.706	6.768
g_0	0^-	5.279	6.276

TABLE I. . Masses (in GeV) of the relevant form factor poles in the physical limit.

Differential Branching Fraction and Theory Systematics

We define

$$s_{\pm} = (m_{\Lambda_b} \pm m_X)^2 - q^2. \tag{23}$$

The differential decay rate is

$$\begin{aligned}\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2 |V_{qb}|^2 \sqrt{s_+ s_-}}{768\pi^3 m_{\Lambda_b}^3} \left(1 - \frac{m_l^2}{q^2}\right)^2 \\ \times \Bigg\{ 4\left(m_l^2 + 2q^2\right)\left(s_+ \left[g_\perp\right]^2 + s_- \left[f_\perp\right]^2\right) \\ +2\frac{m_l^2 + 2q^2}{q^2}\left(s_+ \left[(m_{\Lambda_b} - m_X)\, g_+\right]^2 + s_- \left[(m_{\Lambda_b} + m_X)\, f_+\right]^2\right) \\ +\frac{6m_l^2}{q^2}\left(s_+ \left[(m_{\Lambda_b} - m_X)\, f_0\right]^2 + s_- \left[(m_{\Lambda_b} + m_X)\, g_0\right]^2\right) \Bigg\}.\end{aligned} \tag{24}$$

3. The final result for the observable is given by

$$O \pm \underbrace{\sigma_O}_{\text{stat.}} \pm \underbrace{\max\left(|O_{\mathrm{HO}} - O|, \sqrt{|\sigma_{O,\mathrm{HO}}^2 - \sigma_O^2|}\right)}_{\text{syst.}}. \tag{22}$$

Branching Fraction Extrapolation Factor

$$\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = \tau_{\Lambda_b} \frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} |V_{cb}|^2 F_{theory}$$

$$= \tau_{Lb}\mathcal{B}_{ratio}|V_{cb}|^2 \int_{7\,\mathrm{GeV}^2/c^4}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2 \quad (1)$$

$$\frac{\int_{0\,\mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{15\,\mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2} \quad (2)$$

MC Samples

Decay	Stats	B Decay Model
$\Lambda_b \rightarrow \Lambda_c^+ \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$ Neutral	3m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c^+ \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$ Charged	3m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c^+ \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pK\pi$ Normalisation	0.6m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c^+ \tau^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pK\pi$ Normalisation	0.05m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c \pi^+ \pi^- \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$	0.15m filt	EvtPHSP
$\Lambda_b \rightarrow \Lambda_c \pi^0 \pi^0 \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$	0.15m filt	EvtPHSP
$\Lambda_b \rightarrow \Lambda_c \pi^0 \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$	0.15m filt	EvtPHSP
$\Lambda_b \rightarrow \Lambda_c(2625) \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$	0.6m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c(2595) \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pX$	0.3m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c(2625) \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pK\pi$	0.1m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow \Lambda_c(2595) \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pK\pi$	0.1m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow D^0 p \mu^- \overline{\nu}$	0.6m filt	EvtPHSP
$\Lambda_b \rightarrow p \mu^- \overline{\nu}$	0.6m filt	EvtLb2plnuLQCD
$\Lambda_b \rightarrow N^{*+} \mu^- \overline{\nu}$, $N^{*+} \rightarrow pX$	0.5m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow p \pi^0 \mu^- \overline{\nu}$	1m filt	EvtLb2Baryonlnu
$\Lambda_b \rightarrow p \mu^- \overline{\nu}$	5m	EvtLb2plnuLCSR
$\Lambda_b \rightarrow p \mu^- \overline{\nu}$	1m	EvtLb2plnuLQCD
$\Lambda_b \rightarrow \Lambda_c^+ \mu^- \overline{\nu}$, $\Lambda_c^+ \rightarrow pK\pi$ Normalisation	10m	EvtBaryonPCR

Signal Selection

Proton cuts	cuts	Mother/Comb cuts
$P > 15000$ MeV	$P > 3000$ MeV	$cos\theta_{\Lambda_b(p\mu)} > 0.9994$
$p_T > 1000\,\mathrm{MeV}/c$	$p_T > 1500\,\mathrm{MeV}/c$	$M_{p\mu} > 1000\,\mathrm{MeV}/c$
Track $\chi^2 < 6.0$	Track $\chi^2 < 4.0$	Vertex $\chi^2 < 4.0$
Min IP $\chi^2 > 16.0$	Min IP $\chi^2 > 16.0$	FD $\chi^2 > 150.0$
$\Delta LL(p - K) > 10$	isMuon $=$ true	$p_T > 1500 MeV$
$\Delta LL(p - \pi) > 10$	Ghost Prob. < 0.35	
Ghost Prob. < 0.35		

Normalisation Selection

Kaon cuts	Pion cuts	Mother/Comb cuts
$P > 2000$ MeV	$P > 2000$ MeV	$cos\theta_{\Lambda_b\Lambda_c} > 0.9$
$p_T > 300\,\mathrm{MeV}/c$	$p_T > 300\,\mathrm{MeV}/c$	$cos\theta_{\Lambda_b(\Lambda_c\mu)} > 0.99$
Min IP $\chi^2 > 9.0$	Min IP $\chi^2 > 9.0$	$pK\pi$ Vertex $\chi^2 < 6$
$\Delta LL(K-\pi) > 0$	$\Delta LL(\pi-K) > 0$	$\Lambda_c\mu$ Vertex $\chi^2 < 6$
Ghost Prob. < 0.35	Ghost Prob. < 0.35	$2650 < M_{pK\pi} < 3050$MeV

Corrected Mass Error

$$\sigma_{M_{corr}} = \left(\frac{p_T}{\sqrt{M_{p\mu}^2 + p_T^2}} + 1\right)\sigma_{p_T} \qquad (3)$$

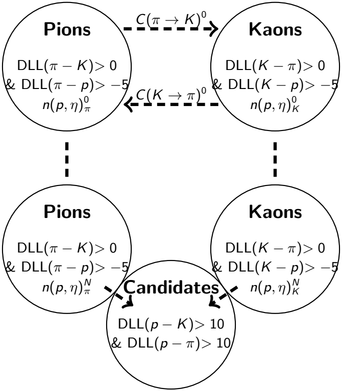
$$p_T^2 = \left(p_x - (x - x')\frac{(p_x(x-x') + p_y(y-y') + p_z(z-z'))}{((x-x')^2 + (y-y')^2 + (z-z')^2)}\right)^2 +$$
$$\left(p_y - (y - y')\frac{(p_x(x-x') + p_y(y-y') + p_z(z-z'))}{((x-x')^2 + (y-y')^2 + (z-z')^2)}\right)^2 +$$
$$\left(p_z - (z - z')\frac{(p_x(x-x') + p_y(y-y') + p_z(z-z'))}{((x-x')^2 + (y-y')^2 + (z-z')^2)}\right)^2$$

$$\sigma_{p_T}^2 = \sigma_x^2\left(\frac{\partial p_T}{\partial x}\right)^2 + \sigma_y^2\left(\frac{\partial p_T}{\partial y}\right)^2 + \sigma_z^2\left(\frac{\partial p_T}{\partial z}\right)^2$$
$$\sigma_{x'}^2\left(\frac{\partial p_T}{\partial x'}\right)^2 + \sigma_{y'}^2\left(\frac{\partial p_T}{\partial y'}\right)^2 + \sigma_{z'}^2\left(\frac{\partial p_T}{\partial z'}\right)^2$$
$$+ 2cov(x, y)\frac{\partial p_T}{\partial x}\frac{\partial p_T}{\partial y} + 2cov(x, z)\frac{\partial p_T}{\partial x}\frac{\partial p_T}{\partial z} + 2cov(y, z)\frac{\partial p_T}{\partial y}\frac{\partial p_T}{\partial z}$$
$$+ 2cov(x', y')\frac{\partial p_T}{\partial x'}\frac{\partial p_T}{\partial y'} + 2cov(x', z')\frac{\partial p_T}{\partial x'}\frac{\partial p_T}{\partial z'} + 2cov(y', z')\frac{\partial p_T}{\partial y'}\frac{\partial p_T}{\partial z'}$$

Miss ID Approach

$$n(P,\eta,TM)_{\pi}^{i+1} = \frac{N(P,\eta,TM)_{\pi} - M(P,\eta,TM)_{K\to\pi}\, n(P,\eta,TM)_{K}^{i}}{\epsilon(P,\eta,TM)_{\pi}} \quad (4)$$

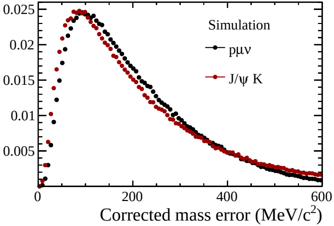
$$n(P,\eta,TM)_{K}^{i+1} = \frac{N(P,\eta,TM)_{K} - M(P,\eta,TM)_{\pi\to K}\, n(P,\eta,TM)_{\pi}^{i}}{\epsilon(P,\eta,TM)_{K}} \quad (5)$$

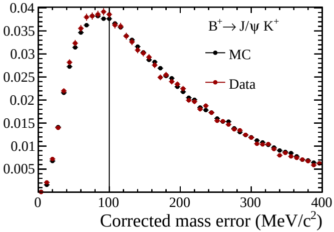


Corrected Mass Error Efficiency

(14, 15)

- Good agreement in MC between $\Lambda_b \to p\mu^- \nu_\mu$ and $B^+ \to J/\psi K^+$.
- Derive correction to relative efficiency using Data vs MC for $B^+ \to J/\psi K^+$.

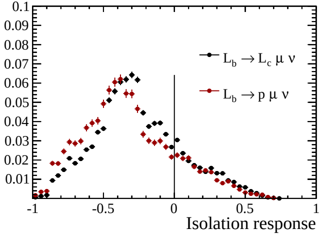


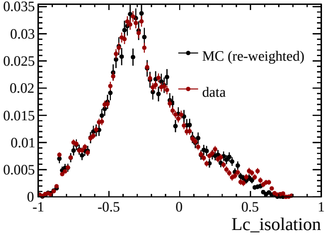


Isolation Efficiency

(14, 15)

- Relative efficiency almost unity in simulation.
- Reweight simulation BDT Isolation to that of normalisation in data to evaluate a systematic.

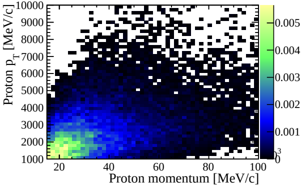


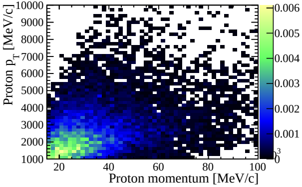


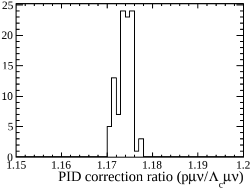
PID efficiency

(14, 15)

- PID callib, $\Lambda_b \to \Lambda_c \mu^- \nu_\mu$ sample
- Main difference in relative efficiency is due to the extra K and π.
- 100 variations of PID histograms used for evaluating a systematic



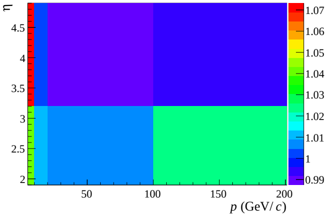


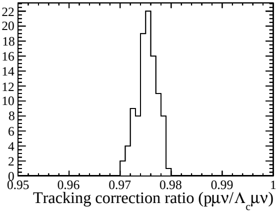


Tracking efficiency

(14, 15)

- Reweight according to track multiplicity and efficiency maps from J/ψ tag and probe.
- 1.5% systematic for kaon and pion to account for material interactions.

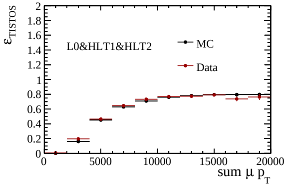


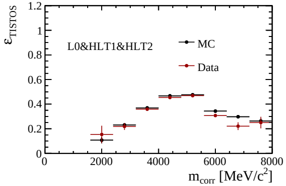


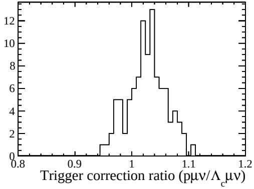
Trigger efficiency

(14, 15)

- TISTOS method applied using $B^+ \to J/\psi K^+$ in p_T and M_{corr}.
- Reweight according to this for a number of variations of the correction histograms to obtain systematic.



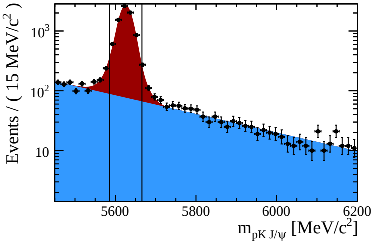


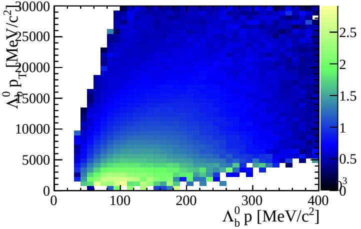


Λ_b Production

(14, 15)

- Use $\Lambda_b \to J/\psi\, pK$ in data to reweight simulation.
- Large effect due to tight proton P cut.

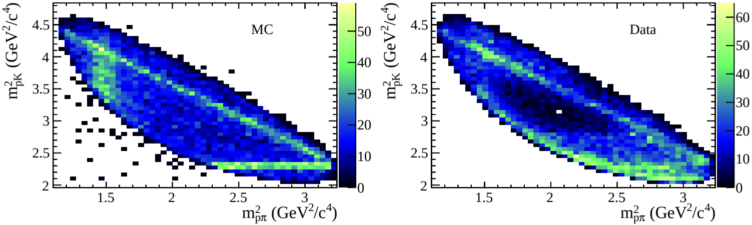




Λ_c Dalitz distribution

(14, 15)

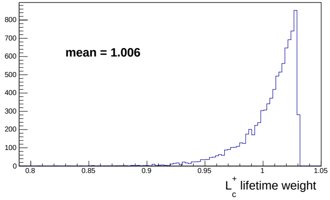
- Reweight simulation dalitz distribution to data.
- For systematic compare with a square dalitz parametrisation.

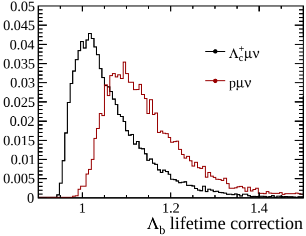


Λ_b Lifetime

(14, 15)

- Reweight simulation for latest Λ_b lifetime.

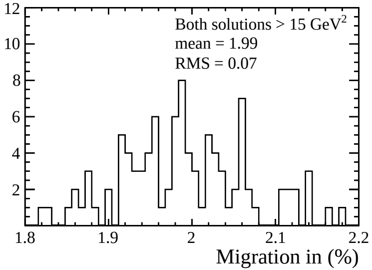


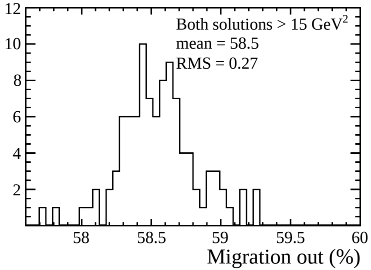


q^2 Migration

(14, 15)

- Correct for unphysical solutions and by $(1 - \mathrm{mig_{in}})/(1 - \mathrm{mig_{out}})$.

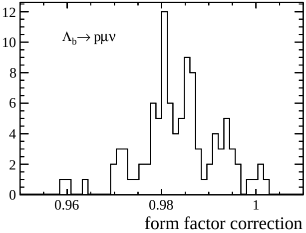


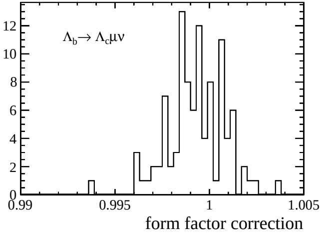


Form factors

(14, 15)

- Reweight by EvtGen probabilities to 100 variations of the form factors.
- Look at effect on the trigger, stripping and DecProdCut efficiencies.

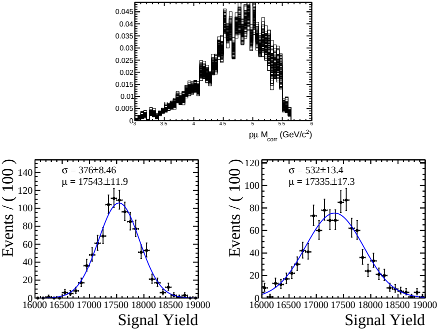




N^* factors

(14, 15)

- Generate large scale variations of the form factors.
- Run toy fits with datasets generated with FF reweighted corrected mass shapes for N^* states.
- Fit with nominal fit model.
- Difference in spreads in quadrature over signal yield is taken as a systematic.



N^* widths

(14, 15)

- A factor 2π too narrow in simulations (bug).
- Use $\Lambda_b \to p\pi^0\mu\nu$ MC to derive a correction based on reweighting the $p\pi^0$ mass to different Breit Wigner shapes.
- Use toy fits to quantify the systematic on the signal yield associated with such corrections.