First observation of $B^+ \to p\bar{p}\mu^+\nu_\mu$

arXiv:1911.08187 - for JHEP

LHCb UK meeting, Huddersfield

Mark Smith on behalf of the LHCb collaboration

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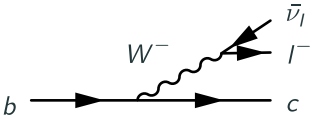
Lepton Universality

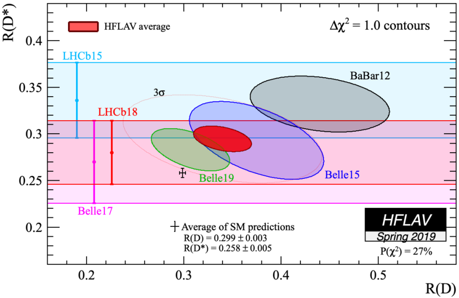
SM CC:

$$\mathcal{L}_{CC} = \frac{-g}{\sqrt{2}}[\bar{u}_i\gamma^\mu \frac{1-\gamma^5}{2} V_{ij}^{CKM} d_j + \bar{\nu}_i\gamma^\mu \frac{1-\gamma^5}{2} e_i] W_\mu^+ + h.c.$$



Compare μ and τ modes of semi-leptonic decays:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}$$



Tension with SM in $R(D)$ vs $R(D^*) \sim 3\,\sigma \to$ new physics at tree-level

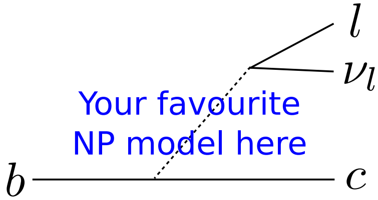
Possible measurements

τ decays:

$$\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu \sim 17.4\% \qquad \tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \overline{\nu}_\tau \sim 13.5\%$$

More $b \to c$:

- $R(J/\psi)$ - spectator mass
  PRL 120, 121810 (2018)
- $R(D_s^{(*)})$ - spectator mass
- $R(\Lambda_c^{(*)})$ - baryons



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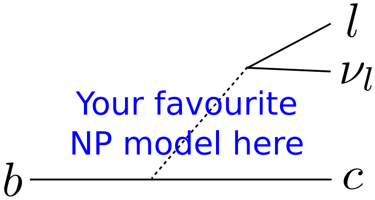


Flavour structure - $b \to u$:

- $B^+ \to \tau^+ \nu_\tau$ - not at LHCb
- $B^0 \to \pi^+ \tau^- \overline{\nu}_\tau$ - difficult
- $B^+ \to \pi^+ \pi^- \tau^+ \nu_\tau$ - difficult
  - Complicated $m(\pi^+ \pi^-)$ distribution.
  - Significant backgrounds.

- $\Lambda_b \to p \tau^- \overline{\nu}_\tau$
  - FF calculated.
  - Experimentally difficult.
- $B^+ \to p \bar{p} \tau^+ \nu_\tau$ - $R(p\bar{p})$
  - Experimentally preferred

Why $R(p\bar{p})$?

- Positively ID two protons
  - Reduce combinatorial background compared to final state pions
- $p\bar{p}$ vertex
  - Reduces background - tight $p\bar{p}$ vertex fit
  - Can use the $p\bar{p}$ vertex to help discriminate the τ

- Many partially reconstructed backgrounds.
  - Several poorly measured $N^* \to p\pi$
- High min p cut on protons $\to$ low efficiency.
  - RICH threshold for proton radiation $\approx 15\,\mathrm{GeV}$
- Theory
  - Mostly not attempted thus far
- $B^+ \to p\bar{p}\ell^+\nu_\ell$ not yet seen
  - Purpose of this measurement

$B \to p\bar{p}X$

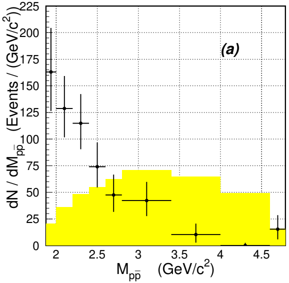
Why is the BF of $B^0 \to p\bar{p}$ so small?

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.32) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.12 \pm 0.19) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to p\bar{p}\pi^+\pi^-) = (2.87 \pm 0.19) \times 10^{-6}$$

Why the threshold enhancement in $B \to p\bar{p}X$ decays?

- $m(p\bar{p})$ peaks at low values.
- Also seen in $e^+e^- \to p\bar{p}$ cross-section PRD 73, 012005 (2006)
- Also seen in $J/\psi \to p\bar{p}\gamma$ - PRL 91, 022001
- Quirk of QCD?
- Resonance below threshold?
  - e.g. PRL 117, 042002 (2016)

$B^+ \to p\bar{p}K^+$



Belle - PRL 92, 131801 (2004)

pQCD model

Theory model attempted to tie together all $B \to Y\bar{Y}'X$, $Y =$ baryon
PLB 704, 495 (2011), PRD 74, 094023 (2006), PRD 78, 054016 (2008)

- Write down most general form of $B \to p\bar{p}$ transition matrix elements
  - $\langle p\bar{p}|\bar{q}'\gamma_\mu b|B\rangle$, $\langle p\bar{p}|\bar{q}'\gamma_\mu\gamma_5 b|B\rangle$
- 5 form-factors for each - g_i, f_i

Two inputs from model:

- Dependence of FF on $m(p\bar{p})$:

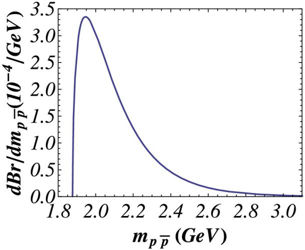
$$f_i \propto \frac{1}{t^3} \qquad\qquad t = (p_p + p_{\bar{p}})^2 = m(p\bar{p})^2$$

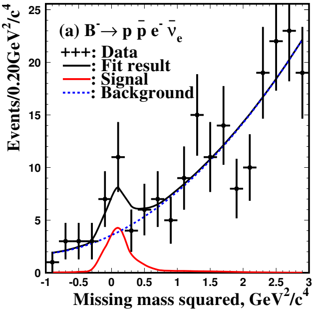
- FF depend on combinations of 6 underlying parameters: $D_{\|}^{1-5}$, $D_{\bar{\|}}$

Fit $B \to p\bar{p}X$, $X = \pi, K, D$, data to estimate $D_{\|}^{1-5}$, $D_{\bar{\|}}$.

- Produces the expected $m(p\bar{p})$ threshold enhancement shape
  - Obvious from $m_{p\bar{p}}^{-6}$ dependence of coefficients
- Predicts angular distributions and q^2
- Prediction of total branching fraction: $\mathcal{B}(B^- \to p\bar{p}e^-\overline{\nu}_e) = (1.04 \pm 0.26 \pm 0.12) \times 10^{-4}$

PLB 704, 495 (2011)





Motivated a search by the Belle collaboration: PRD 89, 011101 (2014)

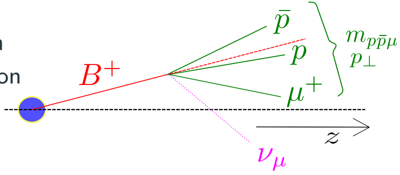
$$\mathcal{B}(B^- \to p\bar{p}e^-\overline{\nu}_e) = (8.2^{+3.7}_{-3.2} \pm 0.6) \times 10^{-6}$$
$$\mathcal{B}(B^- \to p\bar{p}\mu^-\overline{\nu}_\mu) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6}$$

$3\,\sigma$ significance in electron mode

Analysis strategy

Aim: Measure the branching fraction of $B^+ \to p\bar{p}\mu^+\nu_\mu$

- Measure in bins of $m(p\bar{p})$
  - Kinematics of the decay not known
  - Sum bins for total branching fraction
- Reconstruct $p\bar{p}\mu^+$ candidates
  - Fit m_{corr} to ascertain signal yield



$$m_{\text{corr}} = |p_\perp| + \sqrt{|p_\perp|^2 + m^2_{p\bar{p}\mu}}$$

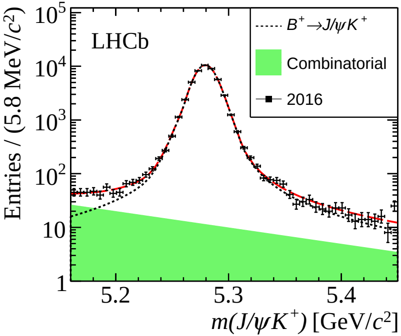
- Peaks at $m(B)$ if only one massless particle is unreconstructed
- Take shapes of signal and partially-reconstructed backgrounds from simulation
- Mis-ID and combinatorial background shapes from data

Analysis strategy

Normalise to $B^+ \to J/\psi K^+$, $J/\psi \to \mu^+\mu^-$

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

- Fit $m(J/\psi K^+)$ for normalisation yield
- Align signal and $J/\psi K^+$ selections:
  - μ^+ in $J/\psi K^+$ represents signal μ^+
  - μ^- and K^+ corresponds to $p\bar{p}$



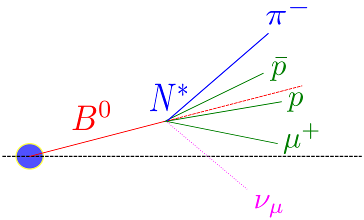
Efficiency evaluated with simulation:

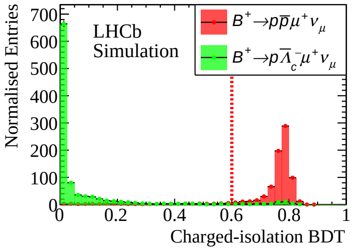
- PID efficiency from data calibration LHCb-PUB-2016-021
- Tracking efficiency corrected JINST 10, P02007 (2015)
- $B^+ \to p\bar{p}\mu^+\nu_\mu$ weighted to pQCD model

Backgrounds

Backgrounds with charged tracks:

- Use charged isolation
- Consider "other" tracks in event
- BDT trained to discriminate if the track came from the signal decay-vertex
- Pick 4 most likely tracks
- Train additional BDT to separate signal and background
- Less efficient for backgrounds that fly
  - i.e. $B \to p\bar{p}D$, $D \to X^- \mu^+ \nu_\mu$





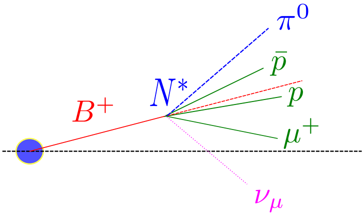
Cut efficiency:

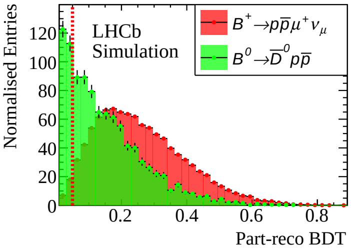
$$\epsilon(B^+ \to p\bar{p}\mu^+\nu_\mu) \approx 93\% \qquad \epsilon(B^+ \to p\bar{\Lambda}_c\mu^+\nu_\mu X) \approx 20\%$$

Backgrounds

Backgrounds without charged tracks:

- Use kinematic information of the decay
- BDT with 11 variables, including
  - B^+ vertex χ^2
  - $p\bar{p}$ momentum difference
  - Angle between B^+ flight vector and p vector
- Train to separate signal and bkg
- Less efficient than charged isolation





Cut efficiency:

$$\epsilon(B^+ \to p\bar{p}\mu^+\nu_\mu) \approx 98\% \qquad \epsilon(B \to p\bar{p}D) \approx 82\%$$

Backgrounds

Mis-ID - $h \to \mu$ and $h \to p$:

- Data samples where particle ID criteria not applied to one track
- Estimate efficiency for particle ID cut from data LHCb-PUB-2016-021
- Unfold true number of mis-IDs in data sample

$$N_h^{meas} = \sum_{h'=\pi,p,K,g} \epsilon(h' \to h) N_{h'}^{true}$$

- Estimate mis-ID probability for each track
- Extract fit template and estimate total mis-ID yields

Backgrounds

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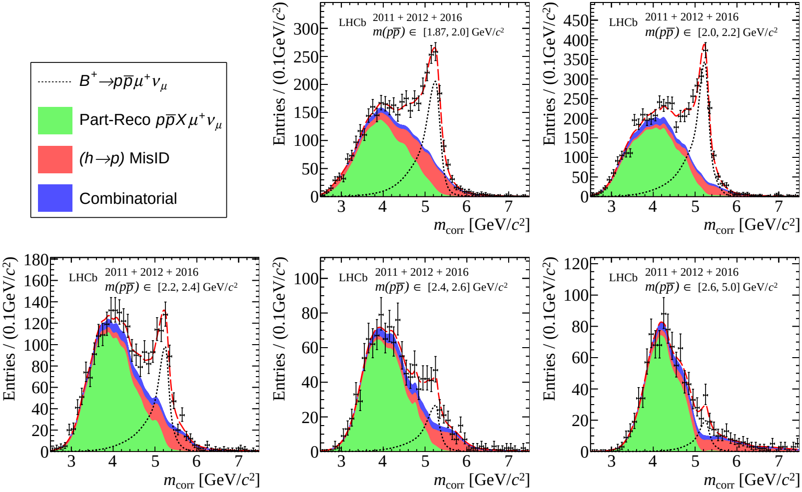
Optimisation:

- 5 quantities to cut on - add in uncertainty on m_{corr}
- Optimise all together with a 5D grid search - smallest σ_N / N
- Pseudoexperiments for each point with estimated yields for signal and backgrounds

Fit projections



Systematic uncertainties

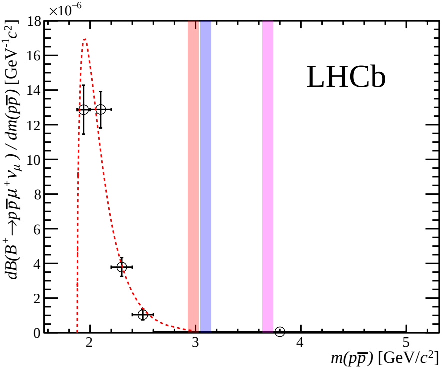
Measurement uncertainty is statistically dominated

$\sigma_{\text{stat}} = 0.24 \times 10^{-6}$ $\sigma_{\text{syst}} = 0.21 \times 10^{-6}$ $\sigma_{\text{norm}} = 0.15 \times 10^{-6}$

Source	Relative uncertainties on $\mathcal{B}$ [%] Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
Kinematic weighting	0.7	0.6	0.4	0.5	0.4
Data-simulation agreement	0.4	0.4	0.4	0.4	0.4
Tracking efficiency	2.7	2.7	2.7	2.7	2.7
Particle identification	1.0	0.7	1.3	1.0	1.7
Simulation sample size	3.6	3.2	3.2	3.1	3.0
Physics model	0.3	0.6	0.6	0.4	0.3
Run 1 and 2016 combination	2.1	1.6	1.7	1.7	1.6
Kernel smoothing	0.0	1.1	2.7	7.9	3.5
Signal model	0.6	2.0	3.0	4.8	9.9
Simulation sample size	0.3	0.0	0.3	2.4	5.2
misID model	0.9	0.1	0.6	5.2	13.5
Combinatorial model	0.9	1.2	1.2	8.5	4.7
Fit bias	0.2	0.1	0.9	2.5	7.8
Total systematic uncertainty	5.3	5.2	6.5	15.6	20.8
Total statistical uncertainty	9.1	5.5	12.5	25.3	29.8

Results

$m(p\bar{p})$ [GeV/c^2]	Signal Yield
Bin 1: 1.87 – 2.0	1210 ± 110
Bin 2: 2.0 – 2.2	1830 ± 110
Bin 3: 2.2 – 2.4	530 ± 70
Bin 4: 2.4 – 2.6	150 ± 40
Bin 5: 2.6 – 5.0	88 ± 26



$$\mathcal{B}(B^+ \to p\bar{p}\mu^+\nu_\mu) = (5.27^{+0.23}_{-0.24} \pm 0.21 \pm 0.15) \times 10^{-6}$$

First observation of $B^+ \to p\bar{p}\mu^+\nu_\mu$

Expected threshold enhancement in $m(p\bar{p})$ - not far off pQCD model.

Covariance matrix provided for you to do your own fit!

Prospect for $R(p\bar{p})$

Aim: Measure $B^+ \to p\bar{p}\tau^+\nu_\tau$ with full Run 2 data set, $6\,\mathrm{fb}^{-1}$

~ 3800 $B^+ \to p\bar{p}\mu^+\nu_\mu$ in Run 1 + 2016
Promising for the τ mode

- Will use the $\tau^+ \to \mu^+\overline{\nu}_\tau\nu_\mu$ decay (17.4%)
- Follow the muonic $R(D^*)$ analysis - PRL 115, 111803 (2015)
  - Normalise to the $B^+ \to p\bar{p}\mu^+\nu_\mu$ decay
  - 3D template fit to q^2, E_μ^*, m_{miss}^2

Potential for improvement:

- Exclusive HLT selection
- Rejection of backgrounds with only additional neutral particles
  - Use calorimeter information
- $p\bar{p}$ almost at rest in B frame - efficient background rejection

More to follow

END

BACKUP