Semileptonic and rare heavy flavour decays at LHCb

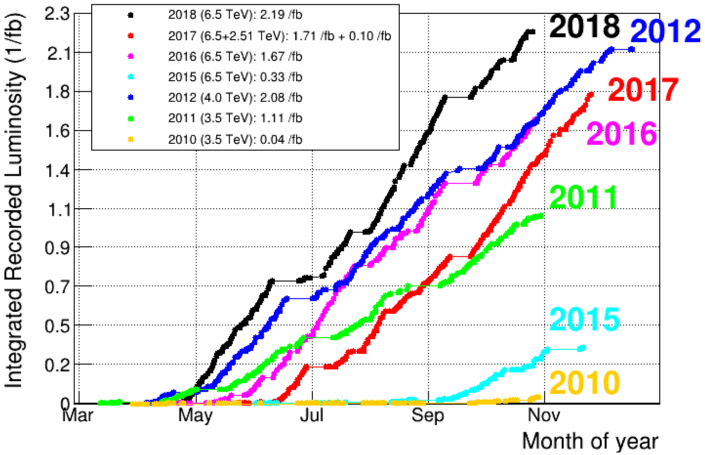
PIC 2019, Taipei

Mark Smith on behalf of the LHCb collaboration

September 2019

Imperial College London

LHCb



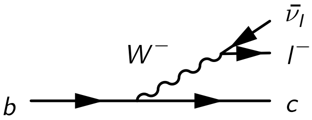
Data collected:

- Run 1 : $3\,\text{fb}^{-1}$ at 7–8 TeV
- Run 2 : $6\,\text{fb}^{-1}$ at 13 TeV

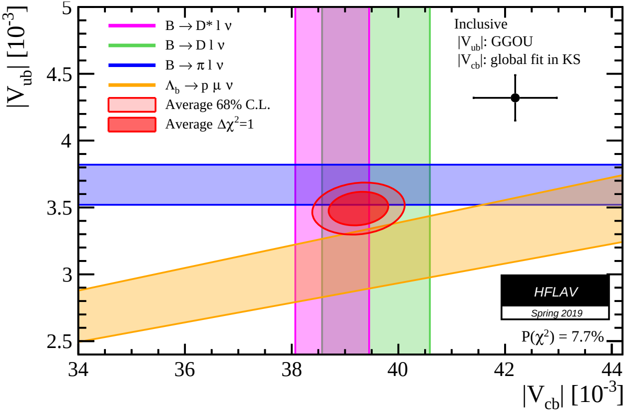
$\sigma(pp \to B^{\pm}X)$: JHEP 12, 026 (2017)

- 7 TeV - $43.0 \pm 0.2 \pm 2.5 \pm 1.7\,\mu\text{b}$.
- 13 TeV - $86.6 \pm 0.5 \pm 5.4 \pm 3.4\,\mu\text{b}$.

Semileptonic decays



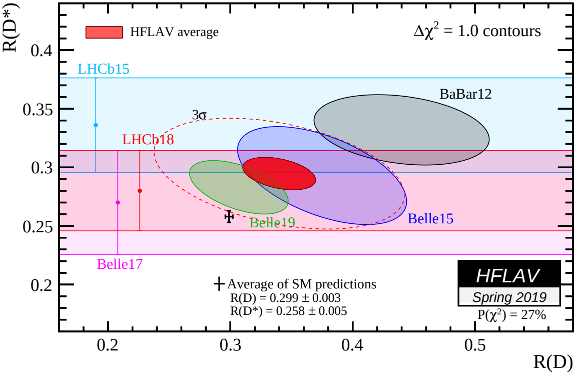
- Copious
- Theoretically ‘clean’ - FFs
- Access to CKM elements
- Experimentally difficult - neutrinos



LHCb:
Nature Physics 11, 743 (2015)

Semileptonic decays

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



BaBar:
PRL 109, 101802 (2012)
PRD 88, 072012 (2013)

Belle:
PRD 92, 072014 (2015)
PRL 118, 211801 (2017)
PRD 97, 012004 (2018)
arXiv:1904.08794 (2019)

LHCb:
PRL 120, 171802 (2018)
PRD 97, 072013 (2018)
PRL 115, 111803 (2015)

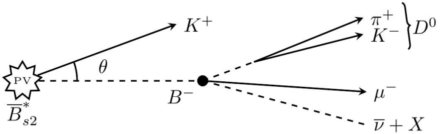
Uncertainty from $B \to D^{**} l^+ \nu_l$

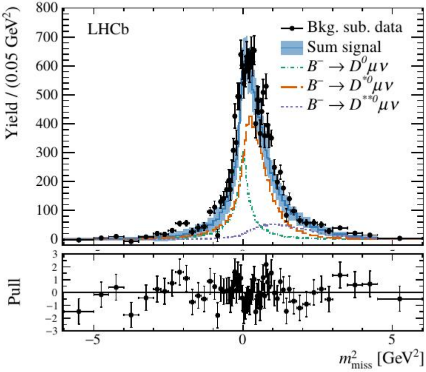
$B \to D^0 \mu^- \nu_\mu X$ branching fractions

PRD 99, 092009 (2019)

Run 1 dataset - $3\,\mathrm{fb}^{-1}$ at $7\text{–}8\,\mathrm{TeV}$:

Take B^- from $\bar{B}^*_{s2} \to B^- K^+$ and constrain B^- kinematics.





Fit m^2_{miss} for $B^- \to D^0 \mu^- \overline{\nu}_\mu X$ components.

BFs of $B^- \to D^0 \mu^- \overline{\nu}_\mu$, $B^- \to D^{*0} \mu^- \nu_\mu$, $B^- \to D^{**0} \mu^- \nu_\mu$:

$$f_{D^0} = \frac{\mathcal{B}(B^- \to D^0 \mu^- \overline{\nu}_\mu)}{\mathcal{B}(B^- \to D^0 \mu^- \overline{\nu}_\mu X)}$$

$$f_{D^0} = 0.25 \pm 0.06$$
$$f_{D^{**0}} = 0.21 \pm 0.07$$
$$f_{D^{*0}} = 1 - f_{D^0} - f_{D^{**0}}$$

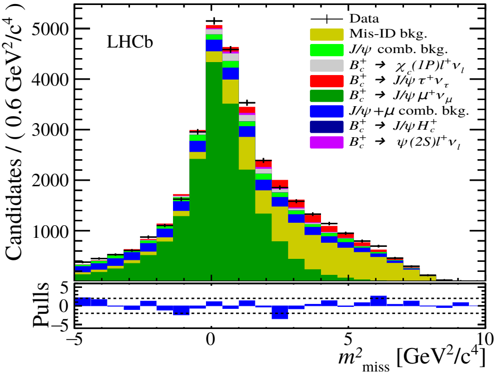
PRL 120 121801 (2018)

All hadron species at LHCb!

Consider B_c decays in Run 1:

- Take $\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$ (17.4%)
- 3D template fit to kinematic variables

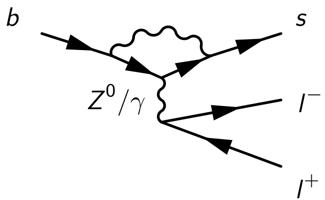
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$



Compatible with SM expectations at $\sim 2\,\sigma$

Major systematics:

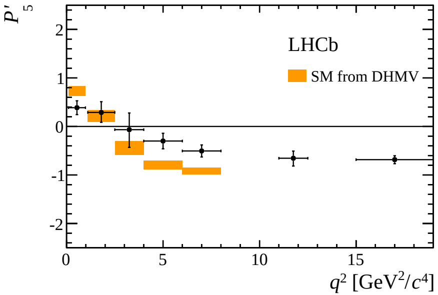
- Simulation stats: Reducible
- $B_c \to J/\psi$ FF: Reducible with lattice - see here

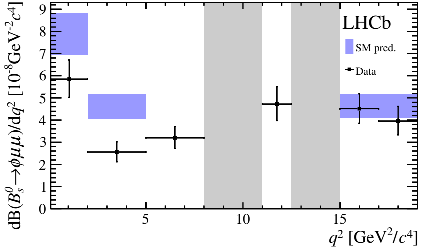


FCNC are rare processes
Good place to look for NP!

Some deviations from the SM observed in $b \to s l^- l^-$:

- $B \to K^* \mu^+ \mu^-$ angular analysis
  JHEP 1602, 104 (2016)
- $d\mathcal{B}(B_s^0 \to \phi \mu^+ \mu)/dq^2$
  JHEP 09, 179 (2015)
- $d\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)/dq^2$
  JHEP 06, 133 (2014)





A question of hadronic uncertainties?

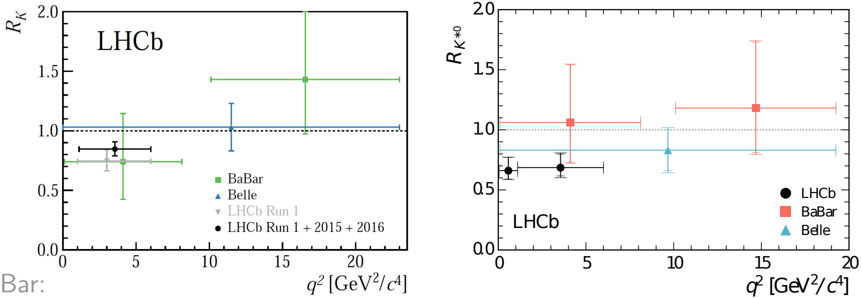
$R_{K^{(*)}}$

Test of lepton universality - theoretically clean.

PRL 122, 191801 (2019)
JHEP 08, 055 (2017)

$$R(K^{(*)}) = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[B\to K^{(*)}\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[B\to K^{(*)}e^+e^-]}{dq^2} dq^2}$$

Run 1 + 2015 + 2016 - 5 fb^{-1} | Run 1 - 3 fb^{-1}



BaBar:
PRD 86, 032012 (2012)
Belle:
PRL 103, 171801 (2009)

Best precision from LHCb
Deviations from SM of $\sim 2.5\,\sigma$

$R_{K^{(*)}}$

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PRL 122, 191801 (2019)
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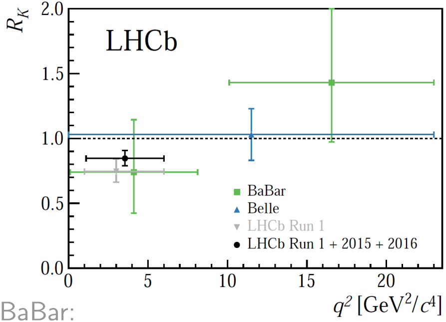
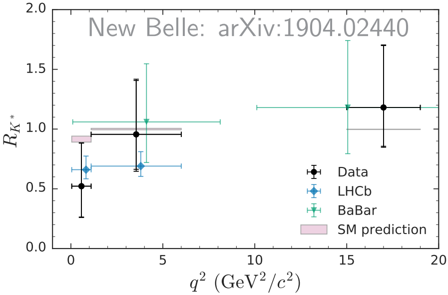




BaBar:
PRD 86, 032012 (2012)
Belle:
PRL 103, 171801 (2009)

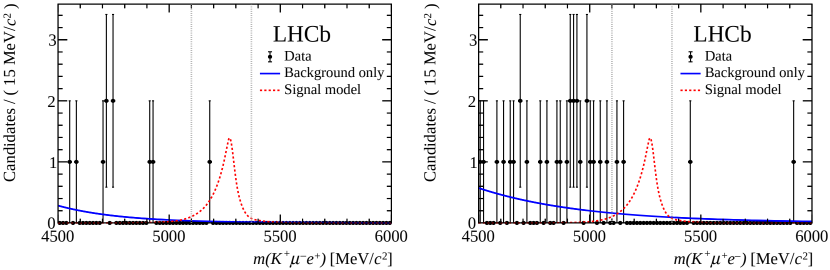
Best precision from LHCb
Deviations from SM of $\sim 2.5\,\sigma$

$B^+ \to K^+\mu^\pm e^\mp$

Run 1 dataset - $3\,\text{fb}^{-1}$ at 7–8 TeV:

arXiv:1909.01010

- Lepton flavour violation forbidden in SM.
- Models to explain $b \to sll$ can lead to LFV.
- BF of order 10^{-8} possible. JHEP 06, 072 (2015)



Mode	Expected	Observed	90% CL limit
$B^+ \to K^+\mu^+e^-$	3.9 ± 1.1	2	6.4×10^{-9}
$B^+ \to K^+\mu^-e^+$	0.9 ± 0.6	1	7.0×10^{-9}

Order of magnitude improvement on previous BaBar limits

PRD 73, 092001 (2006)

$B^0_{(s)} \to \tau^\pm \mu^\mp$

Run 1 dataset - $3\,\mathrm{fb}^{-1}$ at 7–8 TeV

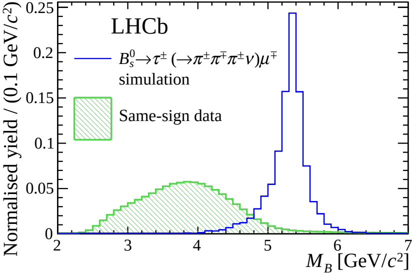
arXiv:1905.06614

Search for B^0 and B^0_s decays:

- Hadronic τ^+ decay:

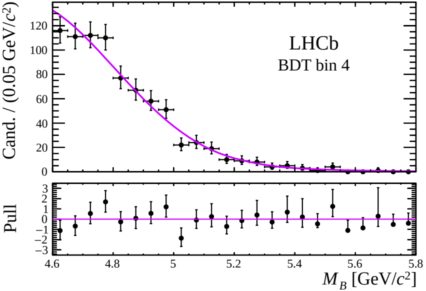
$$\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$$

- Can solve the B kinematics with a twofold ambiguity.
- Peak in M_B



No signal, limits set at 90% CL:

$$\mathcal{B}(B^0_s \to \tau^\pm\mu^\mp) < 3.4 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.2 \times 10^{-5}$$



- Factor 2 improvement for B^0 wrt BaBar search
  PRD 77, 091104 (2008)
- First search for B^0_s

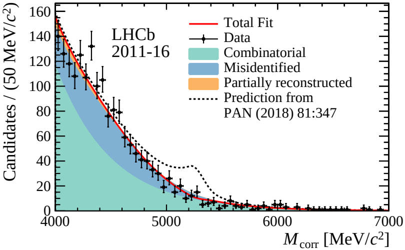
$B^+ \to \mu^+\mu^-\mu^+\nu_\mu$

Run 1 + 2016 datasets

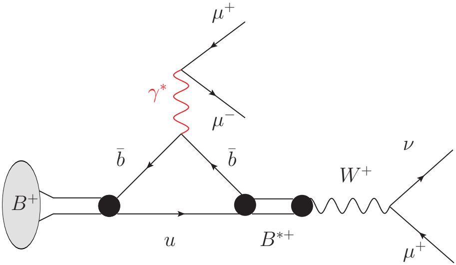
- $B^+ \to \mu^+\nu_\mu$ helicity suppressed.
- Belle: $(6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$
  PRL 121, 031801 (2018)
- Scope for observable new physics.
- One track final state.

Include $\gamma^* \to \mu^+\mu^-$:

- Lift helicity suppression
- 3-track vertex



EPJC 79, 675 (2019)



Fit corrected mass

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

peaks at B mass when missing a ν_μ.

No signal seen - limit set:

$$\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) < 1.6 \times 10^{-8}$$

Looking forward at LHCb

7 - 8 TeV	13 TeV	14 TeV	HL-LHC →	
Run 1 2010 - 2012	Run 2 2015 - 2018	Run 3 2021 - 2023	Run 4 2026 - 2029	Run 5 2031 -
$3\,\mathrm{fb}^{-1}$	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$

↑ **Upgrade I** (before Run 3) ↑ **Upgrade II** (before Run 5)

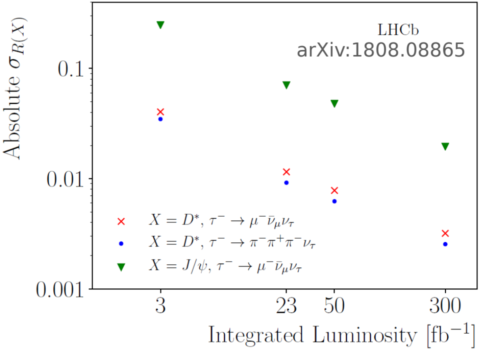
Upgrade I:
CERN-LHCC-2012-007
Upgrade II:
CERN-LHCC-2017-003

Much work done:

- LHCb has much high quality data.

Much work to be done:

- Many (unique) measurements still to make.
- These are exciting times.



BACKUP

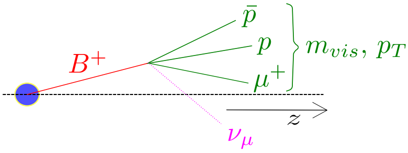
Semi-leptonic B decays at the LHC

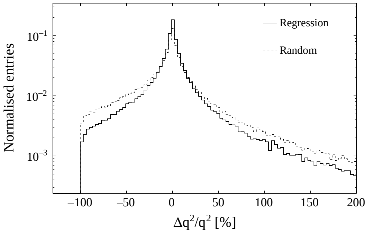
- High branching fraction: $\mathcal{BF}(B \to Xl\nu_l) \approx 10\%$.
- Theoretically 'clean' $\to$ only calculate one hadronic current.
- Large B production cross-section.
- Large quantity of Λ_b, B_s and B_c.
- Muon to trigger on at L0.

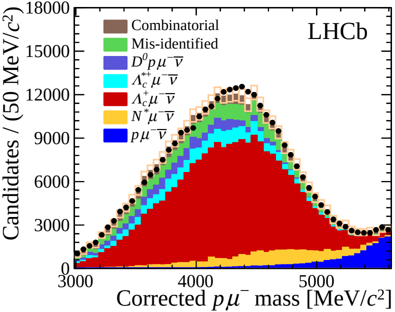
- Partially reconstructed signal.
- No beam energy constraint.
- Hard to make an exclusive HLT selection. Use an MVA.
- Many backgrounds.
- Need lots of simulation.

Semi-leptonic B decays at the LHC

Ascertain B kinematics up to two-fold ambiguity. Ciezarek et al. JHEP (2017):21





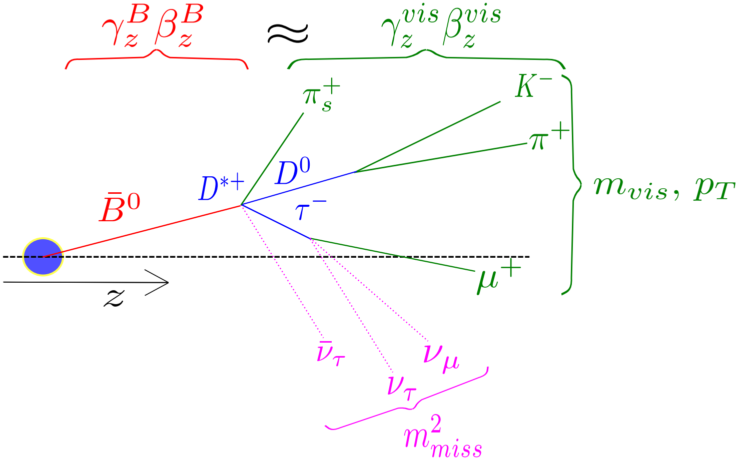


Estimate *corrected mass*:

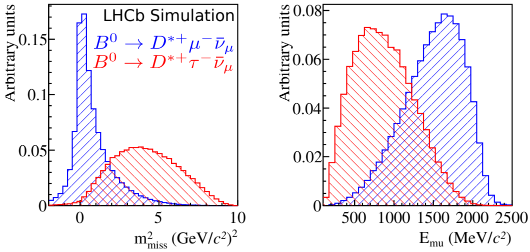
$$m_{corr} = |p'_T| + \sqrt{|p'_T|^2 + m_{vis}^2}$$

p'_T is visible momentum transverse to B flight.

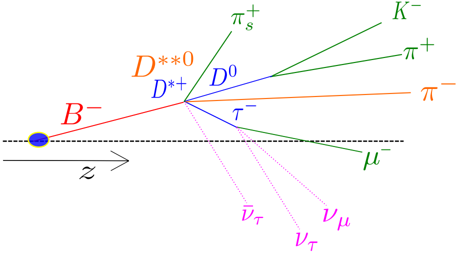
τ reconstruction : $\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$ (17.4%)



Variable	Definition	μ	τ
m^2_{miss}	$(p_B - p_{vis})^2$	peaks at 0	> 0
q^2	$(p_B - p_{D^*})^2$	$0\,\text{MeV} < q^2 < 3270\,\text{MeV}$	$m_\tau < q^2 < 3270\,\text{MeV}$
E^*_μ	E_μ in B frame	hard	soft

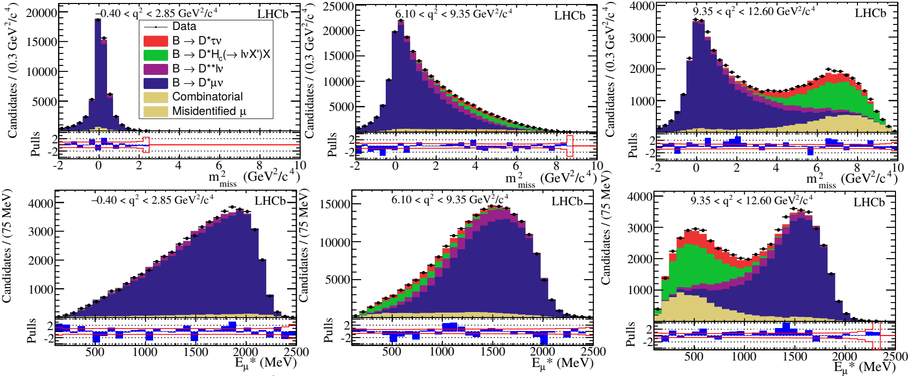


- 3D template fit.
  - μ mis-ID and combinatorial taken from data.
  - All other templates from simulation with systematic variations.
- Major backgrounds:
  - $B \to D^{**}\mu\nu$
  - $B \to D^{*+}X_c$, $X_c \to X\mu\nu$
  - Reduce with charged isolation.



Muonic $R(D^*)$- results PRL 115, 111803 (2015)

Run 1, $3\,\text{fb}^{-1}$:



$R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$

2.1 σ deviation from SM prediction

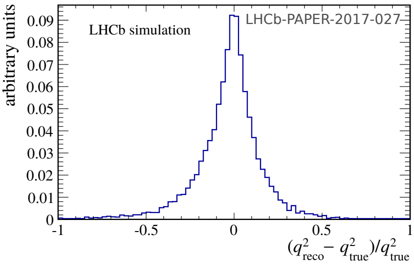
Major systematics:

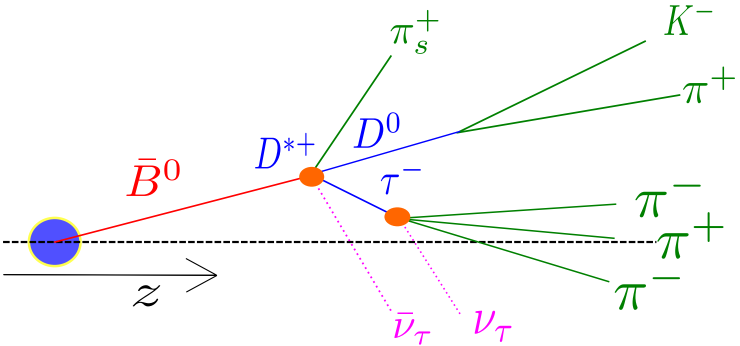
- Simulation sample size → reducible
- mis-ID sample size → reducible
- $B \to D^*\tau\nu$ form-factor → scale with data

τ reconstruction : $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau(\pi^0)$ (13.9%)

$$K(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\pi^+\pi^-\pi^+)}$$

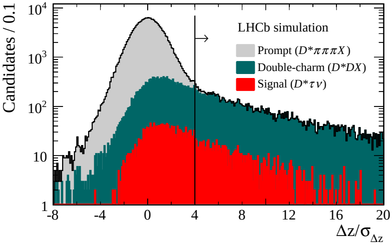
- Require external input to turn $K(D^*)$ into $R(D^*)$.
- Reconstructable τ decay vertex $\to$ background reduction!
- Estimate B kinematics (backup).



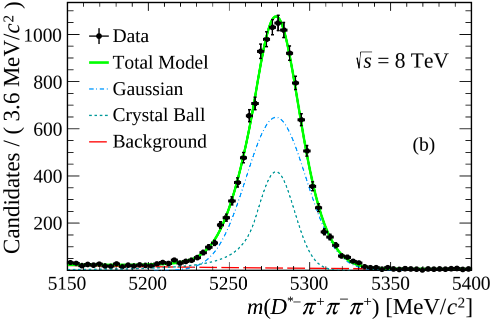


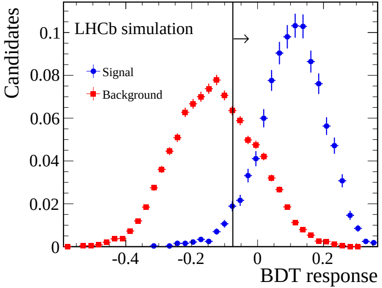
Major backgrounds:

- $B \to D^{*+}\pi^+\pi^-\pi^- X$.
  - Reduced with τ flight distance cut.
- $B \to D^{*+} X_c$
  - $X_c \to \pi^+\pi^-\pi^- X$.
  - Reduced with a multivariate discriminator.

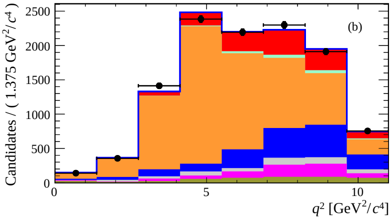


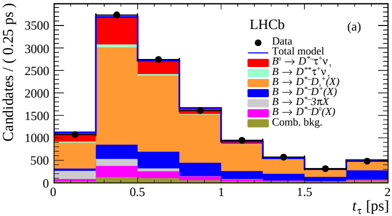
Normalisation fit to $m(D^{*+}3\pi)$:





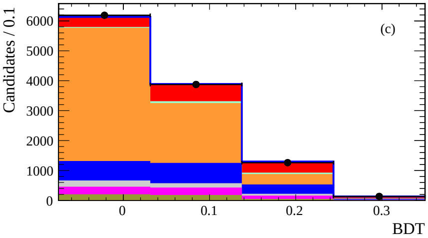
Run 1, $3\,\text{fb}^{-1}$. Fit q^2, t_τ, BDT classifier:





Systematics:

- Simulation sample size
- Double charm background
- $D^{*-}3\pi X$ background
- $D^{**}\tau\nu_\tau$ feed-down



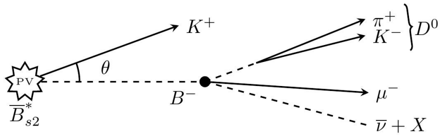
$$R(D^{*-}) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(BR)$$

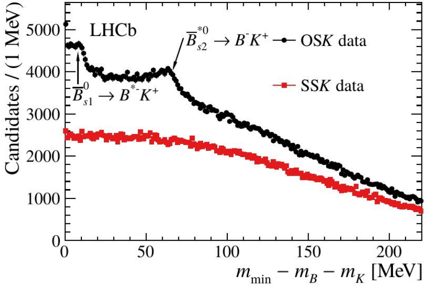
$B \to D^0 \mu^- \nu_\mu X$ branching fractions

$B \to D \mu^+ \nu_\mu X$ background significant source of uncertainty - measure it!

LHCb-PAPER-2018-024

Take B^- from $\bar{B}_{s2}^{*} \to B^- K^+$ and constrain B^- kinematics.





- Quadratic equation for $B^- K^+$ energy $\to$ pick minimum value for real solution.

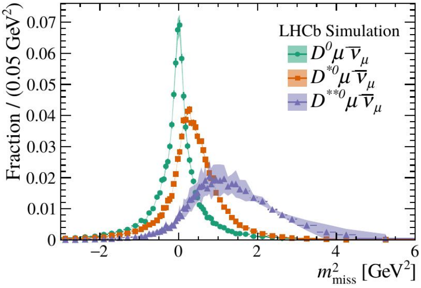
$$m_{min} = \sqrt{m_B^2 + m_K^2 + 2 m_B \sqrt{p_K^2 \sin^2\theta + m_K^2}}$$

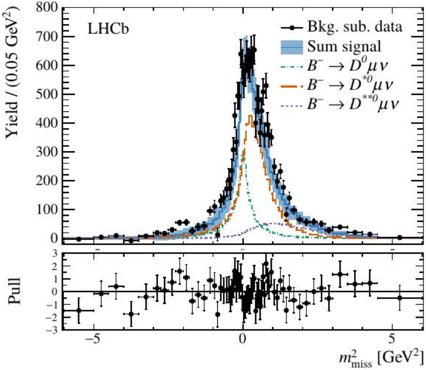
- Constrain signal and background from $m_{min} - m_B - m_K$ distribution.
- Calculate m_{miss}^2 assuming the signal decay.

$B \to D^0 \mu^- \nu_\mu X$ branching fractions

Fit m^2_{miss} for $B^- \to D^0 \mu^- \overline{\nu}_\mu X$ components.

LHCb-PAPER-2018-024





Relative BFs of $B^- \to D^0 \mu^- \overline{\nu}_\mu$, $B^- \to D^{*0} \mu^- \nu_\mu$, $B^- \to D^{**0} \mu^- \nu_\mu$:

$$f_{D^0} = 0.25 \pm 0.06$$
$$f_{D^{**0}} = 0.21 \pm 0.07$$

$f_{D^{*0}} = 1 - f_{D^0} - f_{D^{**0}}$

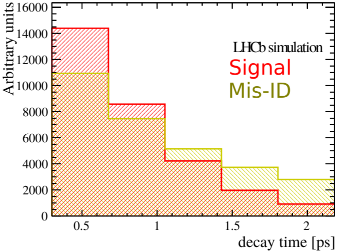
$R(J/\psi)$ PRL 120, 121801 (2018)

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} \qquad \tau^+ \to \mu^+\overline{\nu}_\tau\nu_\mu$$

- Probing same physics as $R(D^*)$. SM expectation 0.25 − 0.28.
  Phys. Lett. B452 (1999) 129, arXiv:hep-ph/0211021,
  Phys. Rev. D73 (2006) 054024, Phys. Rev. D74 (2006) 074008
- Only available at LHCb.

As per $R(D^*)$ use kinematic distributions: m_{miss}^2, $Z(q^2, E_\mu^2)$.

- Additionally consider B_c^+ decay-time.
- $B_c^+ \to J/\psi$ form-factors are unkown - estimated from fit to enriched sample of the normalisation mode.

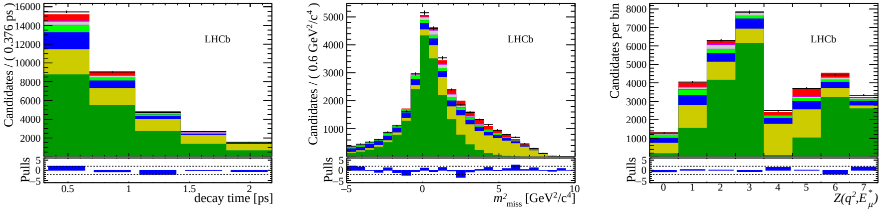


$R(J/\psi)$ results

3D template fit: B_c decay-time, m^2_{miss}, Z.

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

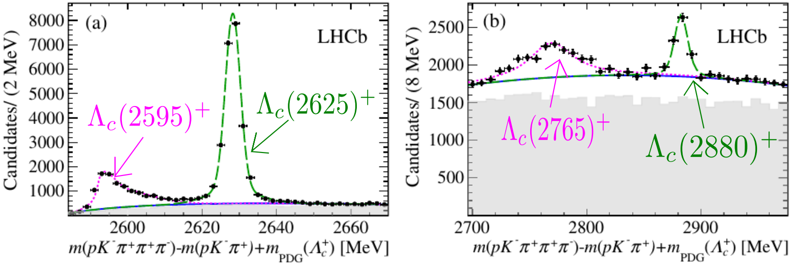
- Compatible with SM at $2\,\sigma$.
- First evidence of decay $B_c^+ \to J/\psi\,\tau^+\nu_\tau$
- Largest systematics from $B_c \to J/\psi$ form-factor and limited simulation sample size - both can be improved.
- Lattice form-factor calculation is on the way - see here



$\Lambda_b \to \Lambda_c$ form-factor

We can measure $\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu$ differential BF $\to$ form-factor shape.

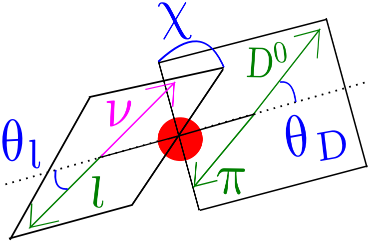
- Measure yield of $\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu$ in 14 bins of $1 < w < 1.43$.
- Take lower q^2 solution.
- Correct for selection efficiency.
- Correct for feed-down from $\Lambda_c^{*+} \to \Lambda_c^+ \pi^+ \pi^-$ - extracted from data.
- Unfold w resolution.

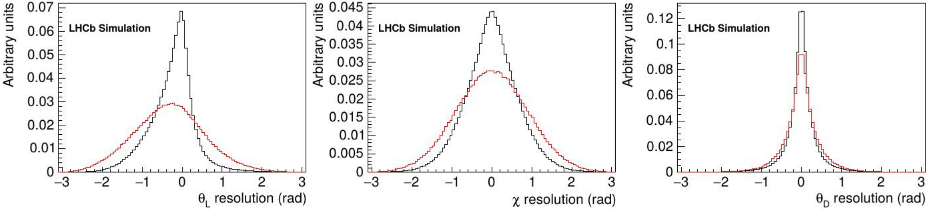


Angular analyses?

If the tension persists we can learn more about new physics with angular and kinematic variables.

- BaBar has compared q^2 with theory: PRD 88, 072012 (2013)
- Belle has measured τ polarisation: PRL 118, 211801 (2017)
- Unfolding needs careful consideration at LHCb.

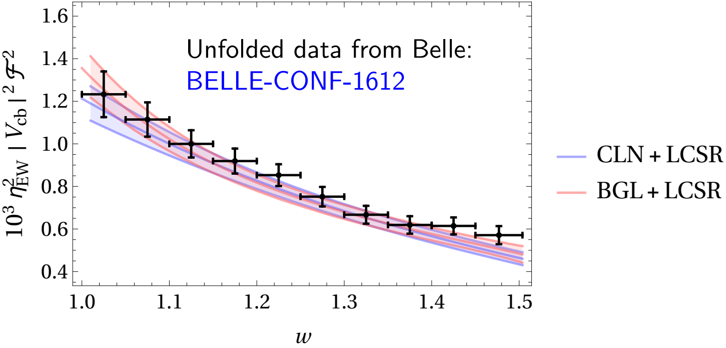




Approximate $\gamma_z^B \beta_z^B \approx \gamma_z^{vis} \beta_z^{vis}$ - $B \to D^* \mu\nu$, $B \to D^* \tau\nu$, $\tau \to \mu\nu\nu$

Theoretical uncertainties

Bigi, Gambino, Schacht: PLB 769, 441-445 (2017)
Grinstein, Kobach: PLB 771, 359-364 (2017)



	BGL: Data + lattice	CLN: Data + lattice
$\lvert V_{cb} \rvert$	$0.0417(^{+20}_{-21})$	0.0382(15)

- Slight change in $R(D) - R(D^*)$ prediction.
- Hard to make a model independent measurement.

More data needed → new Belle result!

Hadronic $R(D^*)$ - kinematics

Two-fold ambiguity in determing τ momentum:

$$|p_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)\,|p_{3\pi}|\cos\theta_{\tau,3\pi} \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2\,|p_{3\pi}|^2\sin^2\theta_{\tau,3\pi}}}{2(E_{3\pi}^2 - |p_{3\pi}|^2\cos^2\theta_{\tau,3\pi})}$$

where $\theta_{\tau,3\pi}$ is the angle between the 3π system 3-momentum and the τ flight.
Take maximum allowed angle:

$$\theta_{\tau,3\pi}^{max} = \arcsin\left(\frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau\,|p_{3\pi}|}\right)$$

Same for B momentum where Y represents the $D^{*-}\tau^+$ system:

$$|p_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)\,|p_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2\,|p_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |p_Y|^2\cos^2\theta_{B^0,Y})}$$

with:

$$\theta_{B^0,Y}^{max} = \arcsin\left(\frac{m_{B^0}^2 - m_Y^2}{2m_{B^0}\,|p_Y|}\right)$$

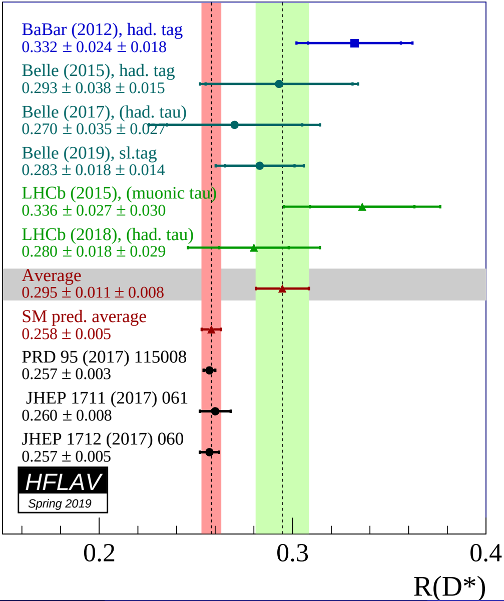
Muonic $R(D^*)$ - uncertainties

PRL 115, 111803 (2015)

Table 1: Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	**Absolute size** $(\times 10^{-2})$
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**

$R(D^*)$ average


BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018
Belle (2015), had. tag
0.293 ± 0.038 ± 0.015
Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027
Belle (2019), sl.tag
0.283 ± 0.018 ± 0.014
LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030
LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029
Average
0.295 ± 0.011 ± 0.008
SM pred. average
0.258 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005
HFLAV
Spring 2019
0.2
0.3
0.4
R(D*)

$\Lambda_b \to \Lambda_c$ form-factor PRD 96, 112005 (2017)

$\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu$ decay described by 6 FF.

- Take infinite heavy quark mass → Isgur-Wise function $\xi_B(w)$

$$w = v_{\Lambda_b} \cdot v_{\Lambda_c^+} = (m^2_{\Lambda_b} + m^2_{\Lambda_c} - q^2)/2m_{\Lambda_b} m_{\Lambda_c^+}$$

- Differental decay rate:

$$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w)$$

G is a constant, $K(w)$ is a known kinematic factor.
Parametrise $\xi_B(w)$, i.e. with Taylor expansion:

$$\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma^2(w-1)^2 + \ldots$$

ρ^2	Approach	Ref.
1.35 ± 0.13	QCD sum rules	PLB 629, 27 (2005)
$1.2^{+0.8}_{-1.1}$	Lattice	PRD 57, 6948 (1998)
1.51	HQET + relativistic wave function	PRD 73, 094002 (2006)