Semi-leptonic decays at the LHC

FPCP 2018, Hyderabad

Mark Smith on behalf of the LHCb collaboration

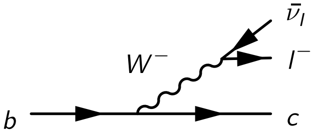
14 July 2018

Imperial College London

Lepton Universality

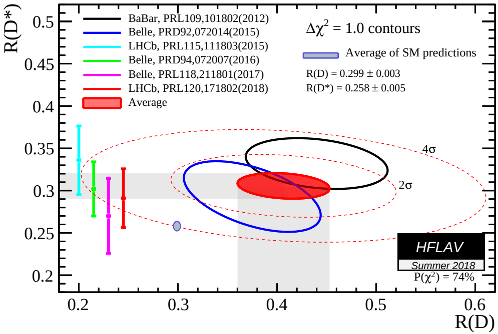
SM CC:

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



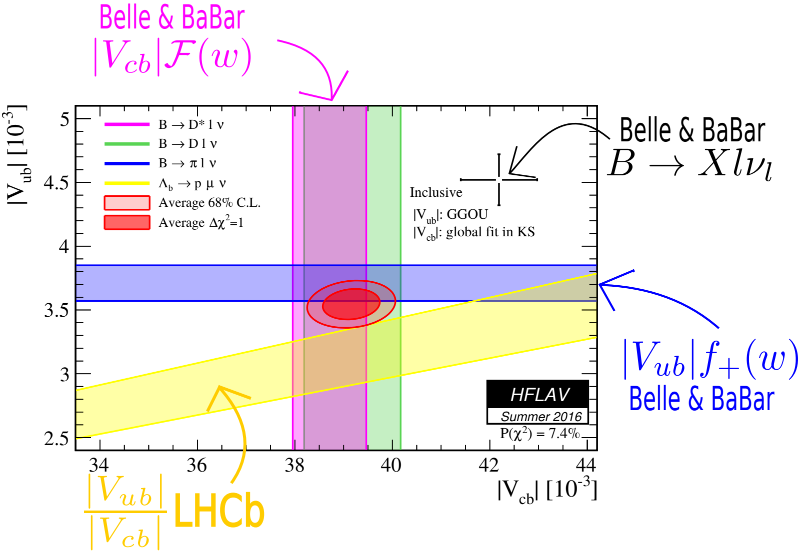
Compare μ and τ modes of semi-leptonic decays:

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$



Tension with SM in $R(D)$ vs $R(D^*) \sim 3.7\,\sigma \to$ new physics at tree-level?

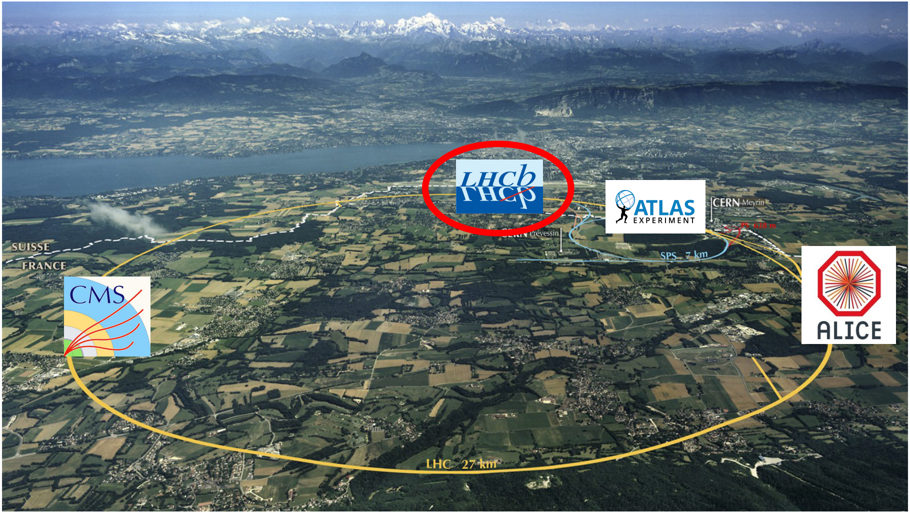
Inclusive/Exclusive $|V_{ub}|$ and $|V_{cb}|$



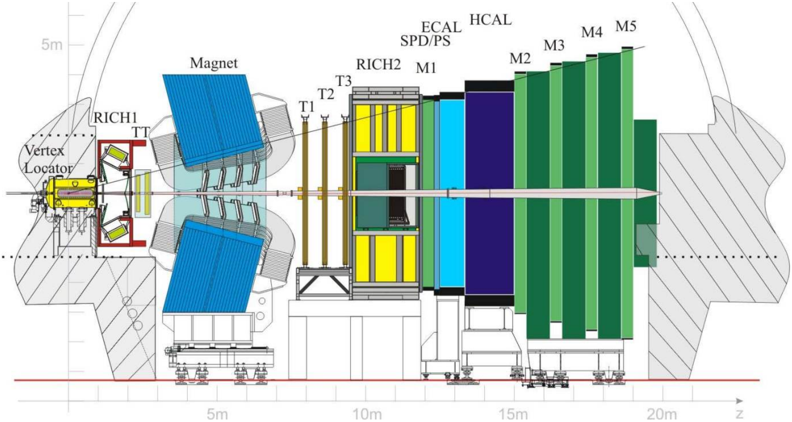
LHCb: Nature Physics 10 (2015) 1038. $\Lambda_b \to p\mu^- \nu_\mu$

Semi-leptonic B decays at the LHC

Only LHCb $\rightarrow$ nothing yet from ATLAS or CMS.



LHCb



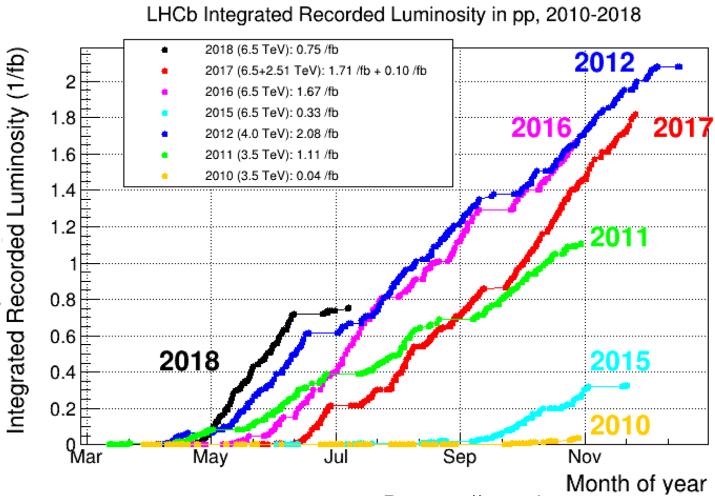
Two stage trigger:

- L0 hardware - basic selection.
- HLT software - reconstructed events.

Data collected:

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

LHCb



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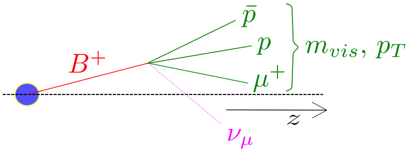
- Run 2 : $6\,\text{fb}^{-1}$ at $13\,\mathrm{TeV}$

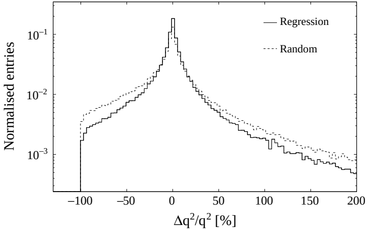
Semi-leptonic B decays at the LHC

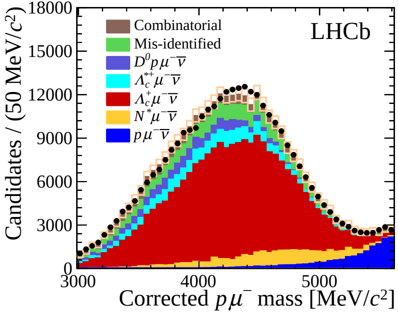
- High branching fraction: $\mathcal{BF}(B \to Xl\nu_l) \approx 10\%$.
- Theoretically 'clean' $\to$ only calculate one hadronic current.
- Large B production cross-section.
- Large quantity of Λ_b, B_s and B_c.
- Muon to trigger on at `L0`.

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

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





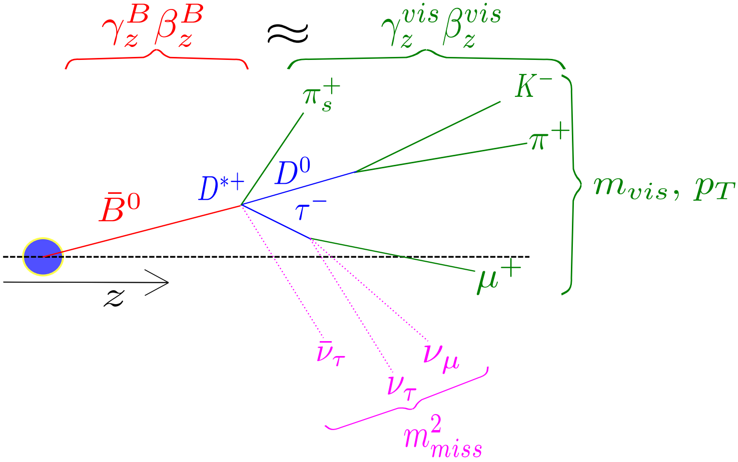


Estimate *corrected mass*:

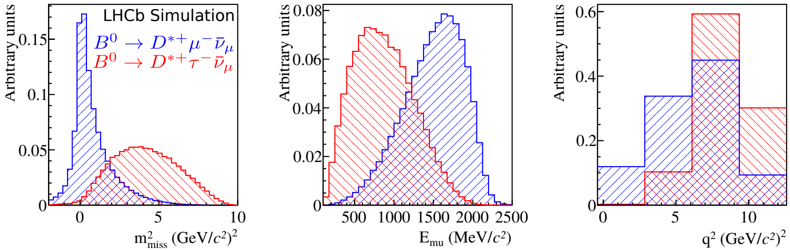
$$m_{corr} = |p'_T| + \sqrt{|p'_T|^2 + m_{vis}^2}$$

p'_T is visible momentum transverse to B flight.

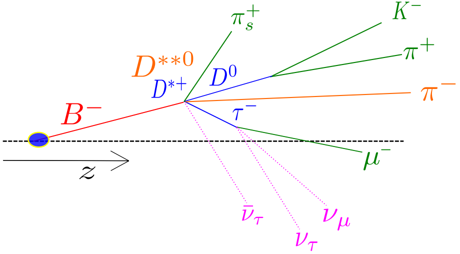
τ reconstruction : $\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$ (17.4%)



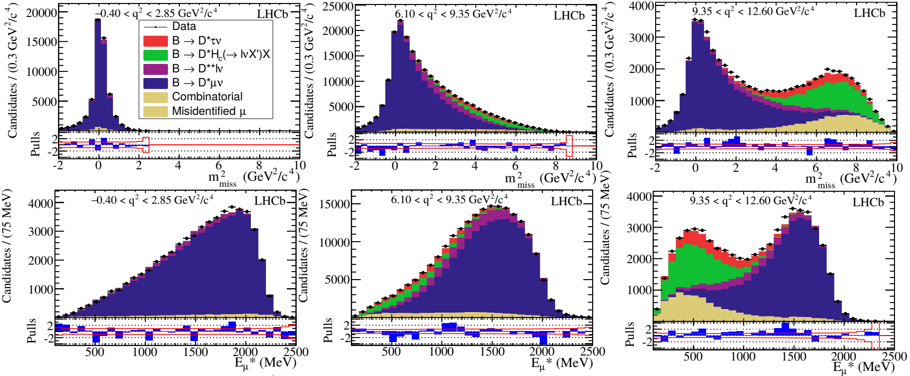
Variable	Definition	μ	τ
m^2_{miss} q^2 E^*_μ	$(p_B - p_{vis})^2$ $(p_B - p_{D^*})^2$ E_μ in B frame	peaks at 0 $0\,\mathrm{MeV} < q^2 < 3270\,\mathrm{MeV}$ hard	> 0 $m_\tau < q^2 < 3270\,\mathrm{MeV}$ soft



- 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.



Run 1, 3 fb^{-1}:



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

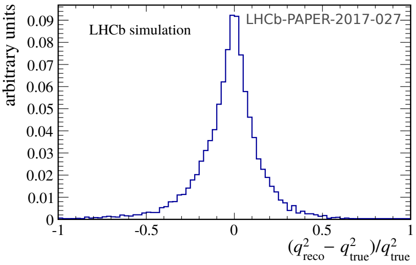
2.1 σ deviation from SM prediction

Major systematics:

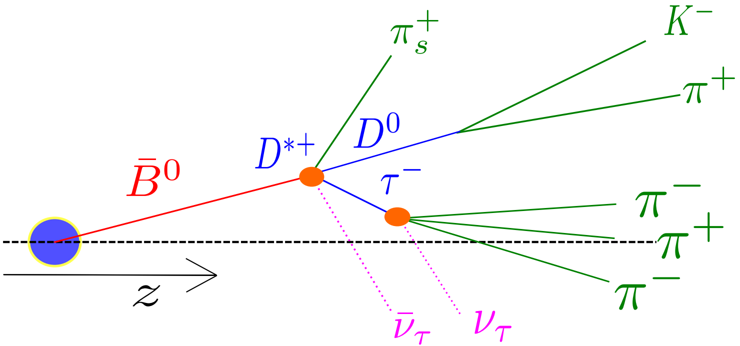
- Simulation sample size → reducible
- mis-ID sample size → reducible
- $B \to D^* \tau \nu$ form-factor → scale with data

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

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



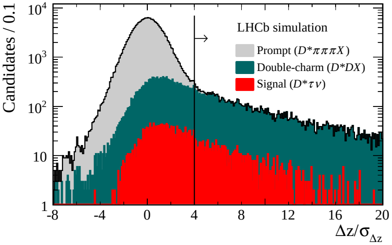
- Require external input to turn $K(D^*)$ into $R(D^*)$.
- Reconstructable τ decay vertex $\to$ background reduction!
- Estimate B kinematics (backup).



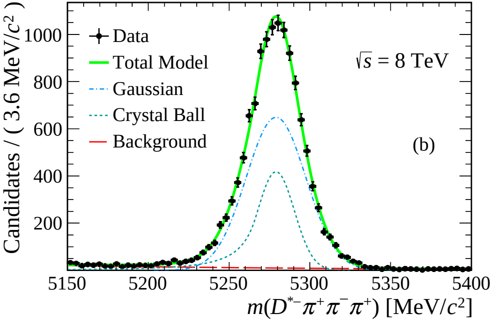
Hadronic $R(D^*)$- I

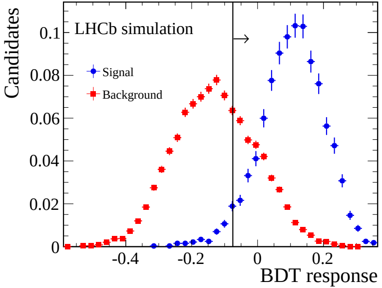
Major backgrounds:

- $B \to D^{*+}\pi^+\pi^-\pi^- X$.
  - 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 $m(D^{*+}3\pi)$:

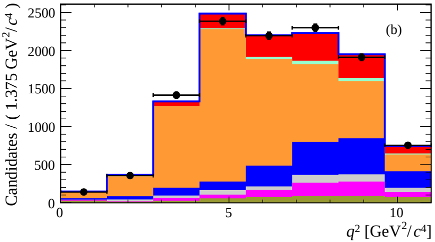


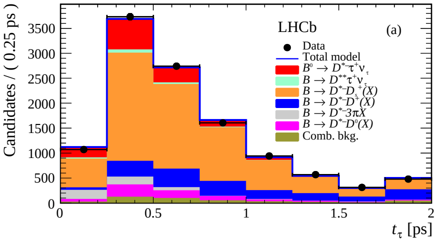


Hadronic $R(D^*)$- II

PRL 120, 171802 (2018)
PRD 97, 072013 (2018)

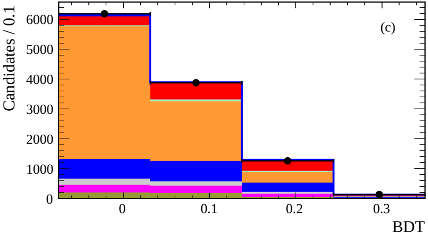
Run 1, $3\,\text{fb}^{-1}$. Fit q^2, t_τ, BDT classifier:





Systematics:

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



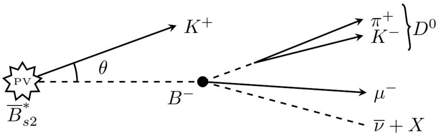
$$R(D^{*-}) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(BR)$$

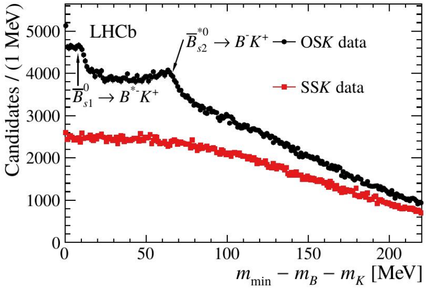
$B \to D^0\mu^-\nu_\mu X$ branching fractions

$B \to D\mu^+\nu_\mu X$ 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.

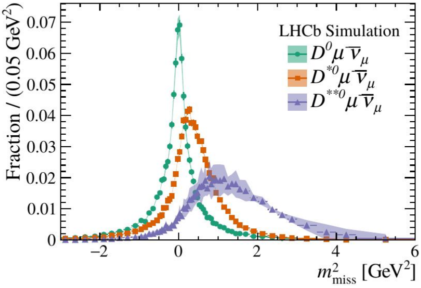
$$m_{min} = \sqrt{m_B^2 + m_K^2 + 2m_B\sqrt{p_K^2 \sin^2\theta + m_K^2}}$$

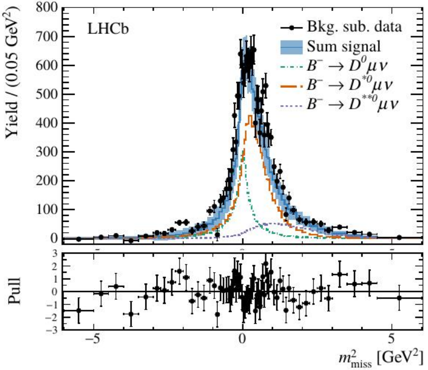
- Constrain signal and background from $m_{min} - m_B - m_K$ distribution.
- Calculate m^2_{miss} assuming the signal decay.

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

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

LHCb-PAPER-2018-024



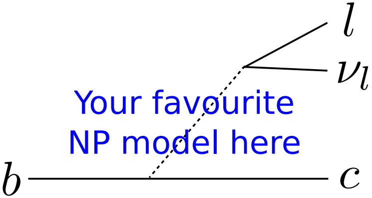


Relative BFs of $B^- \to D^0\mu^-\overline{\nu}_\mu$, $B^- \to D^{*0}\mu^-\nu_\mu$, $B^- \to D^{**0}\mu^-\nu_\mu$:

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

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

What else to measure?



More $b \to c$:

- $\bar{B}_s^0 \to D_s^{(*)-}\tau^+\nu_\tau$
- $B_c^+ \to J/\psi\,\tau^+\nu_\tau$
- $B \to D^{**}\tau^+\nu_\tau$ (arXiv:1606.09300)
- Lower statistics
- Theoretically studied

Baryons:

- $\Lambda_b^+ \to \Lambda_c^{(*)}\tau^+\nu_\tau$
- Decent statistics
- Theoretically studied

$b \to u$ transitions:

- Probe flavour structure
- $\Lambda_b^0 \to p\tau^+\nu_\tau$
- $B^+ \to \rho^0\tau^+\nu_\tau$
- $B^+ \to p\bar{p}\tau^+\nu_\tau$
- Statistically challenged
- Theoretically challenged

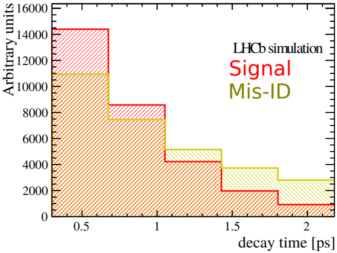
$R(J/\psi)$ PRL 120, 121801 (2018)

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

- 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^2_{miss}, $Z(q^2, E^2_\mu)$.

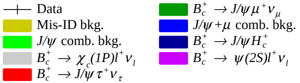
- Additionally consider B_c^+ decay-time.
- $B_c^+ \to J/\psi$ form-factors are unkown - estimated from fit to enriched sample of the normalisation mode.

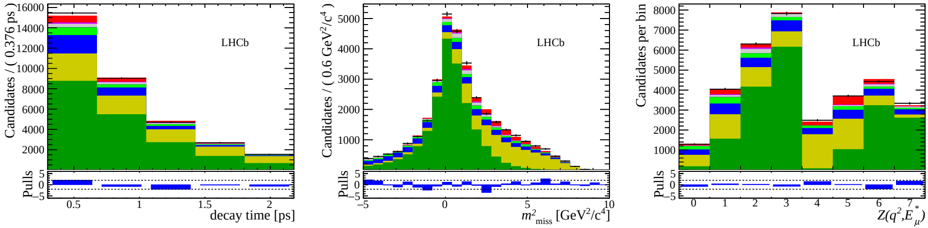


3D template fit: B_c decay-time, m^2_{miss}, Z.

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

- 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

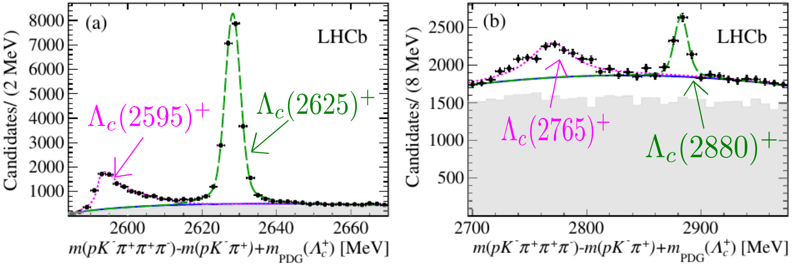




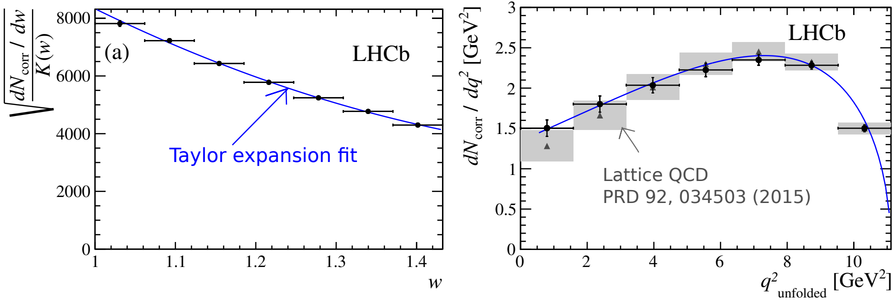
$\Lambda_b \to \Lambda_c$ form-factor PRD 96, 112005 (2017)

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.



$\Lambda_b \to \Lambda_c$ form-factor



Shape	ρ^2	σ^2	correlation coefficient	χ^2/ DOF
Exponential*	1.65 ± 0.03	2.72 ± 0.10	100%	5.3/5
Dipole*	1.82 ± 0.03	4.22 ± 0.12	100%	5.3/5
Taylor series	1.63 ± 0.07	2.16 ± 0.34	97%	4.5/4

- With a suitable normalisation mode $|V_{cb}|$ can be extracted.
- Knowledge of the $\Lambda_b \to \Lambda_c$ form-factors are vital for $R(\Lambda_c)$ measurements.

Looking forward at LHCb

7 - 8 TeV | 13 TeV | 14 TeV | HL-LHC →

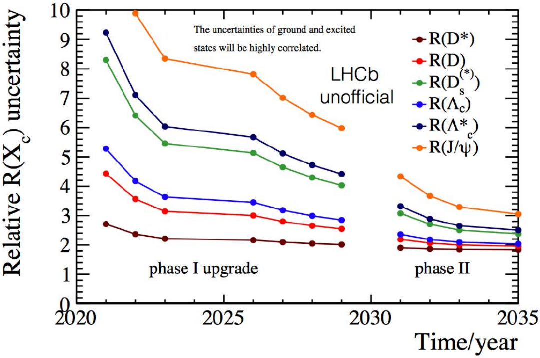
Run 1 2010 - 2012	Run 2 2015 - 2018	Run 3 2021 - 2023	Run 4 2026 - 2029	Run 5 2031 -
$3\,\text{fb}^{-1}$	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$

↑ **Upgrade I** ↑ **Upgrade II**

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

Continued improvement reliant on:

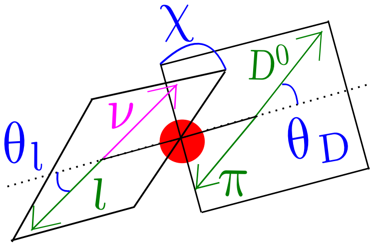
- Simulation size
- Theory collaboration
- Experimental input

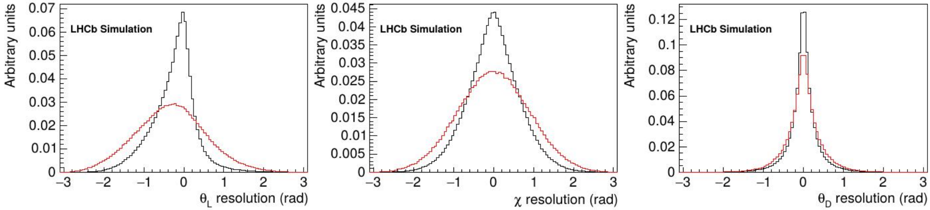


Angular analyses?

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

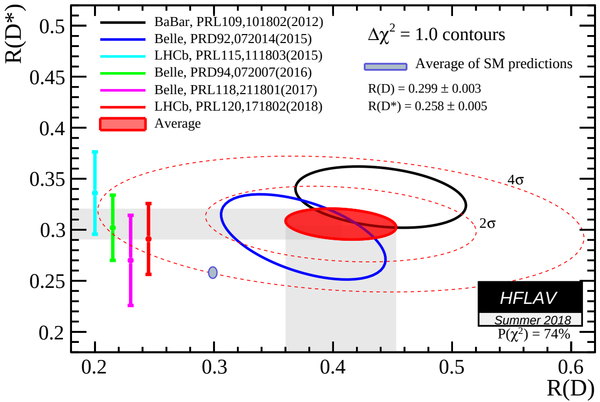
- BaBar has compared q^2 with theory: PRD 88, 072012 (2013)
- Belle has measured τ polarisation: PRL 118, 211801 (2017)
- Unfolding needs careful consideration at LHCb.





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

Conclusions



Much work done:

- LHCb has collected a lot of high quality data.
- Measurements are consistent with the experimental average.

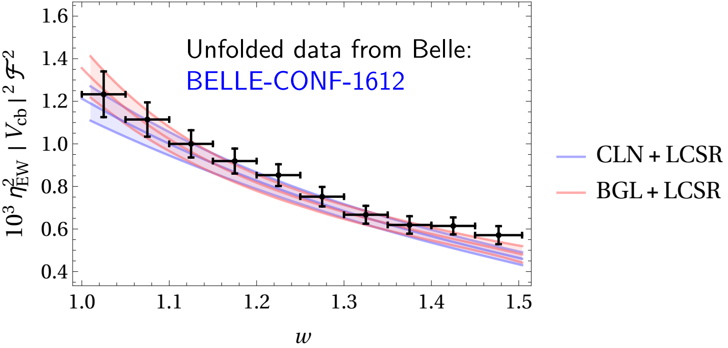
Much work to be done:

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

BACKUP

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 $\rightarrow$ 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:

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

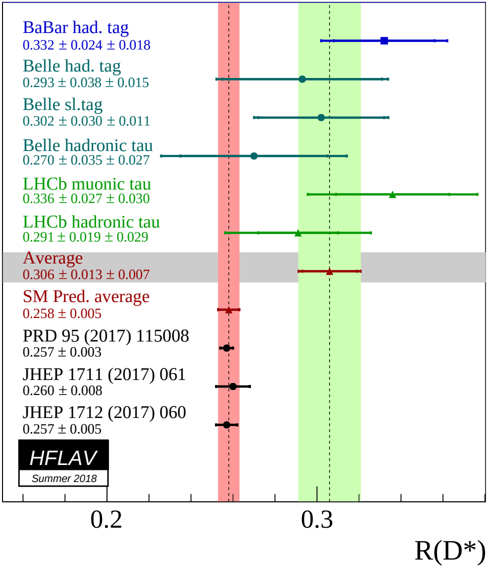
Muonic $R(D^*)$ - uncertainties

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 had. tag
0.332 ± 0.024 ± 0.018
Belle had. tag
0.293 ± 0.038 ± 0.015
Belle sl.tag
0.302 ± 0.030 ± 0.011
Belle hadronic tau
0.270 ± 0.035 ± 0.027
LHCb muonic tau
0.336 ± 0.027 ± 0.030
LHCb hadronic tau
0.291 ± 0.019 ± 0.029
Average
0.306 ± 0.013 ± 0.007
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
Summer 2018
0.2
0.3
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 $\to$ 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:

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

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)