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$R(D^{(*)})$ and others

Experimental status and prospects

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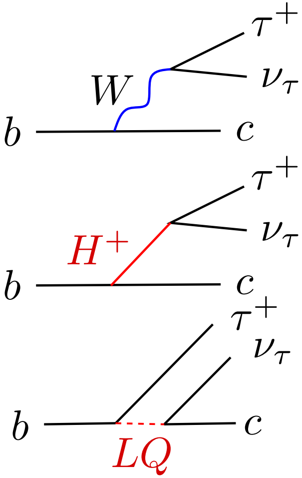
Reminder

Lepton universality measurements:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell^+\nu_\ell)} \neq 1$$

- $\neq 1$ due to τ^+ mass
  - Different phase space available
  - Extra form factor for the τ^+ mode
- NP at tree level
- Precise theory prediction
- Uncertainties cancel in ratio
  - Experimental and theoretical
- High experimental stats

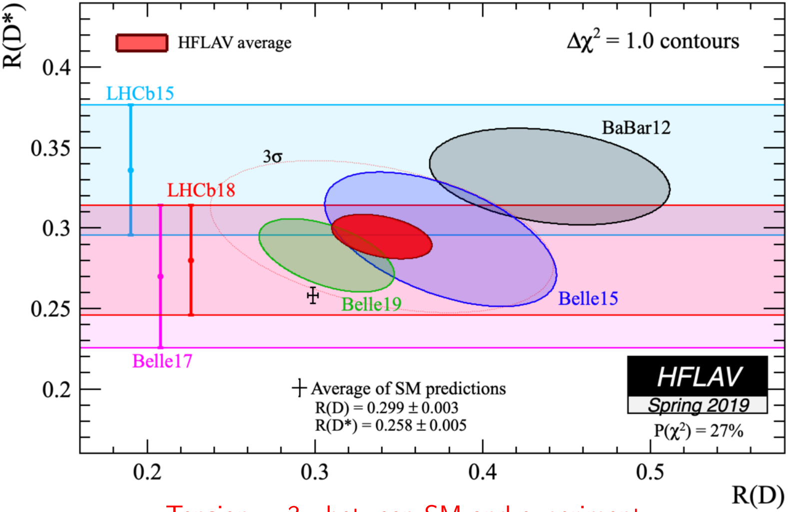


Leptonic: $\tau^+ \to \ell^+\overline{\nu}_\tau\nu_\ell \approx 17.4\%$
Hadronic: $\tau^+ \to n\pi\overline{\nu}_\tau \sim 10 - 25\%$

Always partially reconstructed $\to$ these are tricky analyses!

Status

From HFLAV:



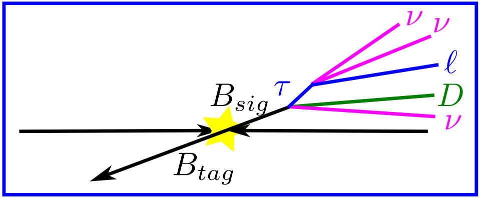
Tension $\sim 3\sigma$ between SM and experiment

The experimental data is consistent

Belle

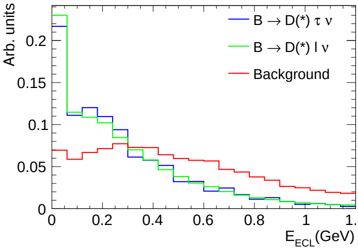
$0.7\,\text{ab}^{-1}$ at the $\Upsilon(4S)$ – 772×10^6 $B\bar{B}$

$$e^+e^- \to \Upsilon(4S) \to B_{tag} B_{sig}$$



$$P(B_{sig}) = P_{beam} - P(B_{tag})$$
$$m^2_{miss} = (P(B_{sig}) - P_{vis})$$

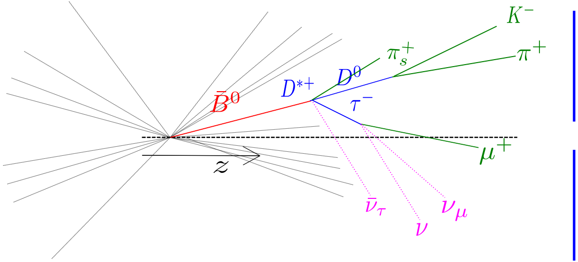
[arXiv:1904.08794]



- Hadronic tag - full reconstruction of $P(B_{sig})$
- SL tag - less kinematic constraint, higher efficiency
- Hermetic detector → *ECL*
  - energy in calorimeter not from B_{tag} or B_{sig}
- Analyse charged and neutral B together

LHCb

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



- P_B can only be found with approximations
- Irreducible partially reconstructed backgrounds
- Hardware trigger
- No neutrals

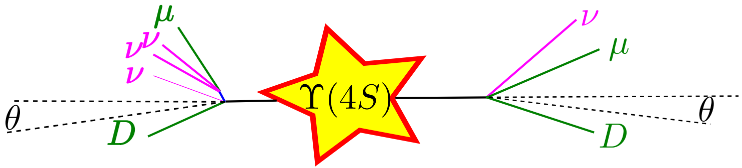
- Large B cross section
- Boosted B
- All hadron species - make unique measurements

772×10^6 $B\bar{B}$ events, SL tag, $\tau^+ \to \ell^+ \overline{\nu}_\tau \nu_\ell$

Signal:

- 8 D^0 modes, 6 D^+ modes
- 2 D^{*+} modes, 1 D^{*0} mode
- BDT to separate signal and normalisation: m^2_{miss}, E_{vis}, $\cos\theta_{B,D^{(*)}\ell}$

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m^2_{D^*\ell}}{2|\mathbf{p}_B||\mathbf{p}_{D^{(*)}\ell}|}$$



- 2D fit: BDT – ECL
- 4 samples: $D^{(*)\pm}$

$$R(D) = 0.307 \pm 0.037 \pm 0.016$$
$$R(D^*) = 0.283 \pm 0.018 \pm 0.014$$

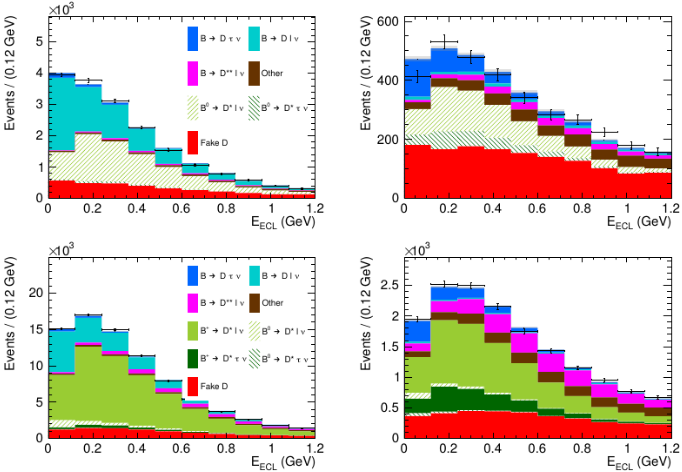


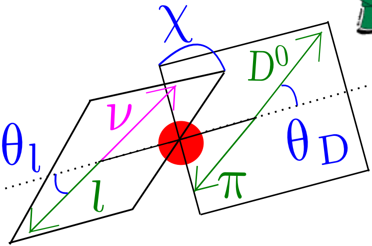
FIG. 2. $E_{\rm ECL}$ fit projections and data points with statistical uncertainties in the $D^+\ell^-$ (top) and $D^0\ell^-$ (bottom) samples, for the full classifier region (left) and the signal region defined by the selection `class` > 0.9 (right).

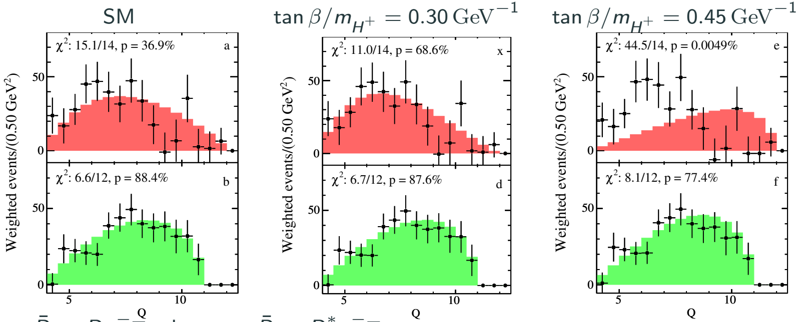
Differential measurements

$B \to D^* \ell \nu$ rate depends on:

- q^2, $\cos\theta_\ell$, $\cos\theta_D$, χ
- More information than integrated rate!

i.e. BaBar: [PRD 88, 072012 (2013)]



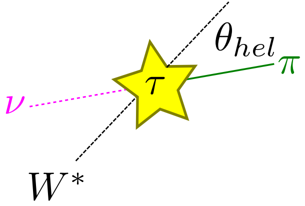


Top: $\bar{B} \to D\tau^-\overline{\nu}_\tau$, bottom: $\bar{B} \to D^*\tau^-\overline{\nu}_\tau$

Hadronic tag: $\tau^+ \to \pi^+ \overline{\nu}_\tau \approx 10.8\%$, $\tau^+ \to (\rho \to \pi^+ \pi^0) \overline{\nu}_\tau \approx 25.4\%$

What are the relative $\pm\frac{1}{2}$ τ helicities?

$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

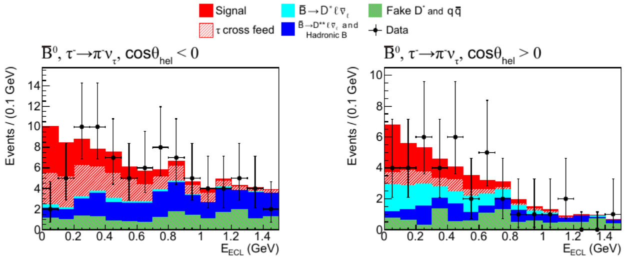


- Study helicity angle of the τ decay, θ_{hel}

$$\frac{d\Gamma}{d\cos\theta_{hel}} \propto 1 + \alpha P_\tau \cos\theta_{hel}$$

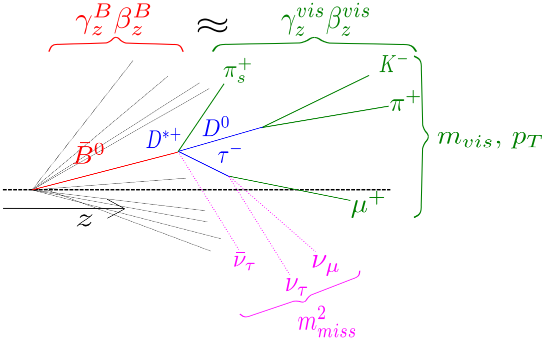
- Full $P(B_{sig}) \to$ measure $\cos\theta_{hel}$

$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$



Also D^* polarisation: $F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$ [BELLE-CONF-1805]

$3\,\mathrm{fb}^{-1}$ at 7 & 8 TeV– $\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$



- Make an approximation of velocity in z:

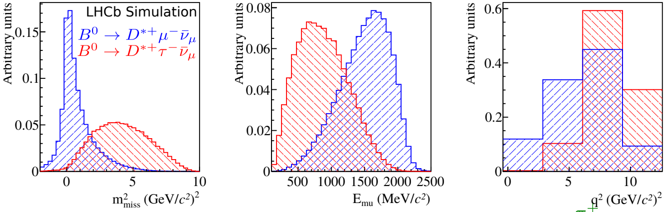
$$\gamma_z^B \beta_z^B \approx \gamma_z^{vis} \beta_z^{vis}$$

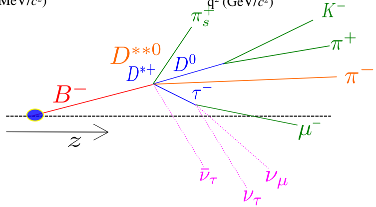
- Scale for B mass

$$p_z^B = \frac{m_B}{m_{vis}} p_z^{vis}$$

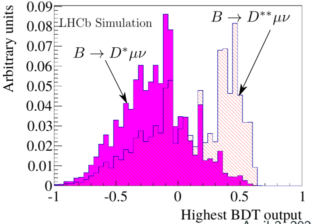
- Direction from PV and decay vtx

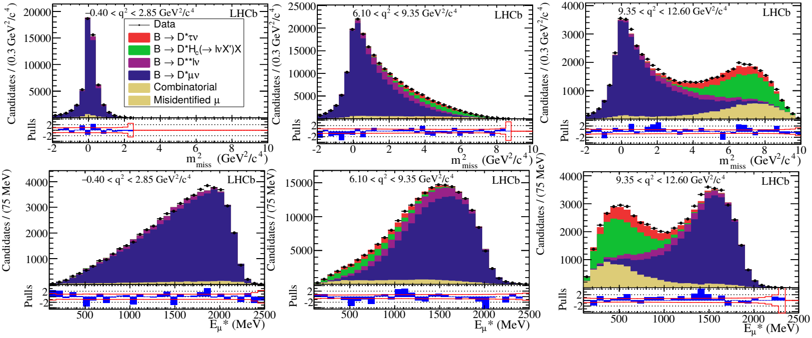
Variable	Definition	μ	τ
m^2_{miss}	$(p_B - p_{vis})^2$	peaks at 0	> 0
q^2	$(p_B - p_{D^*})^2$	$0\,\mathrm{MeV} < q^2 < 3270\,\mathrm{MeV}$	$m_\tau < q^2 < 3270\,\mathrm{MeV}$
E^*_μ	E_μ in B frame	hard	soft





- 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.





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

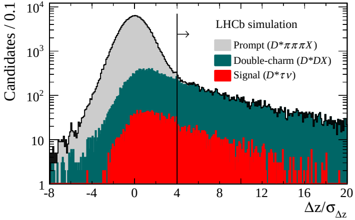
Major systematics:

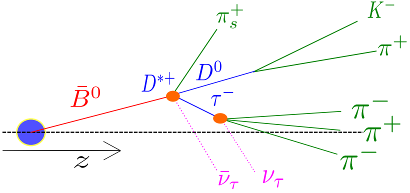
- Simulation sample size → reducible
- mis-ID sample size → reducible
- $B \to D^* \tau \nu$ form-factor

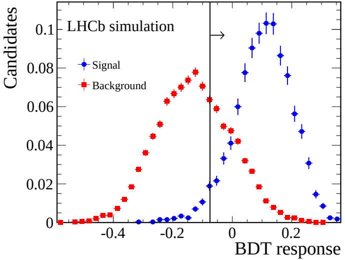
$3\,\text{fb}^{-1}$ at 7 & 8 TeV– $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$

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

- Require external input to turn $K(D^*)$ into $R(D^*)$.
- Reconstructable τ decay vertex $\to$ background reduction!
- BDT for $B \to D^{*+}X_c$
- Charged & neutral isolation
- Estimate B kinematics.

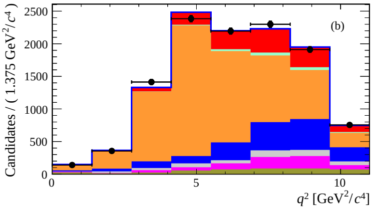


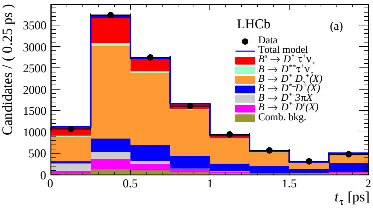




[PRL 120, 171802 (2018)]
[PRD 97, 072013 (2018)]

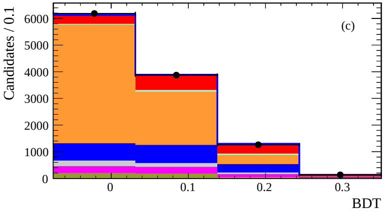
3D template fit: q^2, t_τ, BDT classifier:





Systematics:

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



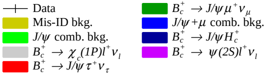
$$R(D^{*-}) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(BR)$$

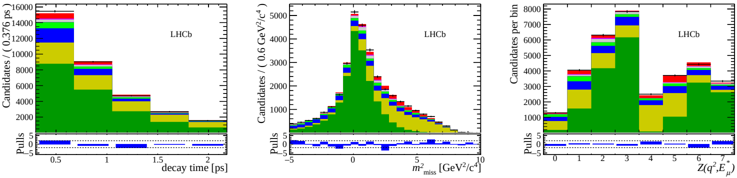
$3\,\text{fb}^{-1}$ at 7 & 8 TeV– $\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$

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

- Compatible with SM at $2\,\sigma$.
- Largest systematics from $B_c \to J/\psi$ form-factor and limited simulation sample size - both can be improved.

- Lattice calculations have arrived!
  See presentation here





Systematics

BaBar: [PRL 109, 101802(2012)]

	$B \to D^{**}\ell\nu$	other bkg	MC stats
$\sigma\, R(D)$ %	5.8	4.9	2.6
$\sigma\, R(D^*)$ %	3.7	2.7	1.6

Belle (from Belle II physics book):

	Belle (Had, ℓ^-)	Belle (Had, ℓ^-)	Belle (SL, ℓ^-)	Belle (Had, h^-)
Source	R_D	R_{D^*}	R_{D^*}	R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

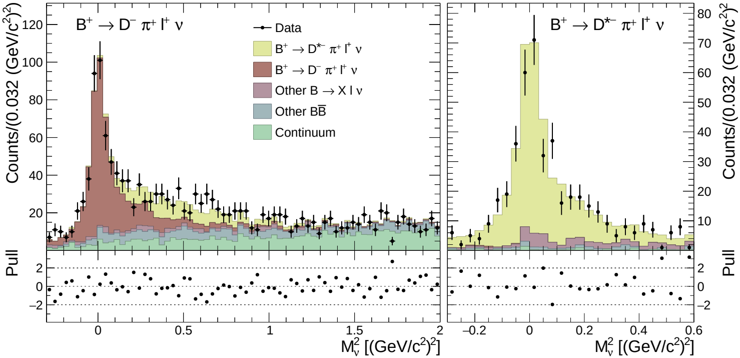
LHCb: [PRL 115, 111803 (2015)] & [PRL 120, 171802 (2018)]

Muonic	%
MC stats	6.0
μ misID	5.4
$D^{**}\ell\nu$	2.1
$B \to D^*\tau\nu$ FF	1.8

Hadronic	%
MC stats	4.7
D^*D bkg	3.9
$D^*3\pi X$ bkg	3.9
$D^{**}\tau\nu$	2.7

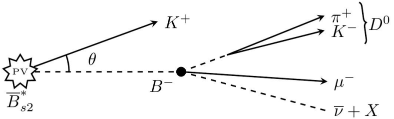
- Full data set, hadronic tag
- Full B kinematic
  - Template not so reliant on MC composition
- Still don't know which D^{**} states contribute

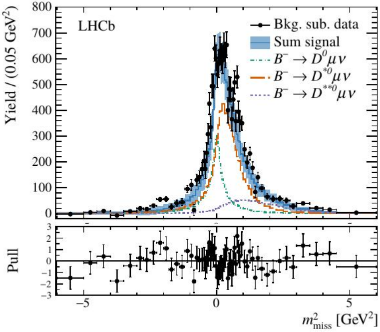
- $\mathcal{B}(B^+ \to D^-\pi^+\ell^+\nu)$ $= [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})]\ \times 10^{-3}$,
- $\mathcal{B}(B^0 \to \bar{D}^0\pi^-\ell^+\nu)$ $= [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})]\times 10^{-3}$,
- $\mathcal{B}(B^+ \to D^{*-}\pi^+\ell^+\nu)$ $= [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})]\times 10^{-3}$,
- $\mathcal{B}(B^0 \to \bar{D}^{*0}\pi^-\ell^+\nu)$ $= [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})]\times 10^{-3}$.

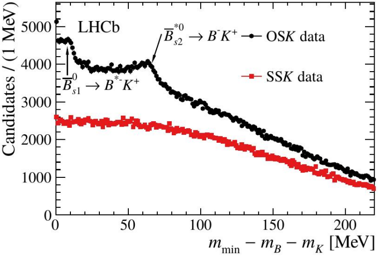


$B \to D\mu^+\nu_\mu X$ background significant source of uncertainty - measure it!

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







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

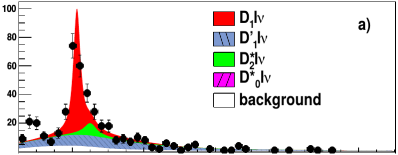
$$f_{D^{**0}} = 0.21 \pm 0.07$$

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

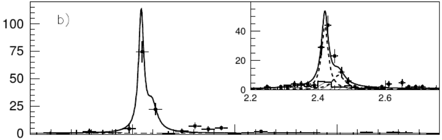
More $B \to D^{**}$ studies needed!

Some contradictions in measurement of composition

BaBar: [PRL 101, 261802 (2008)]
$B^+ \to D^{*-}\pi^+\ell^+\nu_\ell$



Belle: [PRD 77, 091503 (2008)]
$B^+ \to D^{*-}\pi^+\ell^+\nu_\ell$



$$\text{Belle: } \mathcal{B}(B^+ \to D_1'(2430)^0\ell^+\nu_\ell) \times \mathcal{B}(D_1'(2430)^0 \to D^{*+}\pi^-) < 0.07\%$$
$$\text{BaBar: } \mathcal{B}(B^+ \to D_1'(2430)^0\ell^+\nu_\ell) \times \mathcal{B}(D_1'(2430)^0 \to D^{*+}\pi^-) = 0.27\%$$

Input from LHCb would be nice

Model dependence

Not model independent

We need simulation!

↓

Pick a (Standard) model
CLN, BGL, parameter values

↓

Simulate physics

↓

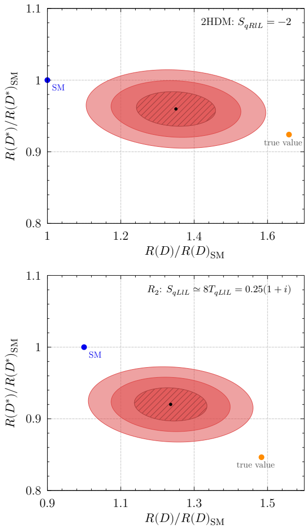
Simulate detector

↓

Calibrate

↙ ↓ ↘

Selection — Efficiency — Templates



[arXiv:2002.00020]

Reweight existing simulation from one physics model to another

Process	Form factor parametrizations
$B \to D^{(*)}\ell\nu$	ISGW2* [34, 35], BGL* [36–38], CLN*‡ [39], BLPR‡ [16]
$B \to (D^* \to D\pi)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$B \to (D^* \to D\gamma)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$\tau \to \pi\nu$	—
$\tau \to \ell\nu\nu$	—
$\tau \to 3\pi\nu$	RCT* [40–42]
$B \to D_0^*\ell\nu$	ISGW2*, LLSW* [43, 44], BLR‡ [45, 46]
$B \to D_1^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_1\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_2^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$\Lambda_b \to \Lambda_c\ell\nu$	PCR* [47], BLRS‡ [48, 49]
Planned for next release	
$B_{(c)} \to \ell\nu$	MSbar
$B \to (\rho \to \pi\pi)\ell\nu$	BCL*, BSZ
$B \to (\omega \to \pi\pi\pi)\ell\nu$	BCL*, BSZ
$B_c \to (J/\psi \to \ell\ell)\ell\nu$	
$\Lambda_b \to \Lambda_c^*\ell\nu$	PCR*, BLRS
$\tau \to 4\pi\nu$	RCT*
$\tau \to (\rho \to \pi\pi)\nu$	—

Table 3 Presently implemented amplitudes in the Hammer library, and corresponding form factor parametrizations. SM-only parametrizations are indicated by a $*$ superscript. Form factor parametrizations that include linearized variations are denoted with a ‡ superscript. These are named in the library by adding a "Var" suffix, e.g. "BGLVar".

See website

Helicity **A**mplitude **M**odule for **M**atrix **E**lement **R**eweighting

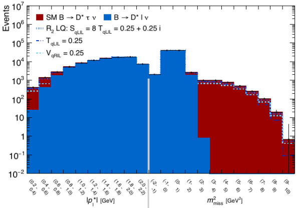


Fig. 2 The $B \to D\tau\bar{\nu}$ (top) and $B \to D^*\tau\bar{\nu}$ (bottom) distributions in $|\mathbf{p}_\ell^*|$ and m^2_{miss} in the Asimov data set. The number of events correspond to an estimated number of reconstructed events at Belle II with 5 ab^{-1}.

Would be nice to see in future analyses.

Where we are

BaBar and Belle:

- Full data sets analysed
- Measurements with hadronic and leptonic τ decays
- SL and hadronic tags
- First differential measurements

LHCb:

- Only Run 1 data published: $3\,\mathrm{fb}^{-1}$
  - Only $R(D^{*+})$ & $R(J/\psi)$ measured
  - Both hadronic and muonic τ decays
- $6\,\mathrm{fb}^{-1}$ of Run 2 data in hand
  - $12\,\mathrm{fb}^{-1}$ Run 1 equivalent!
- $R(D) - R(D^*)$ should arrive

Where can we go and how can we get there?

What else can we measure?

- $B_s \to D_s^{(*)}$
- $\Lambda_b \to \Lambda_c^{(*)}$
- $b \to u$
- $B \to D^{**}$

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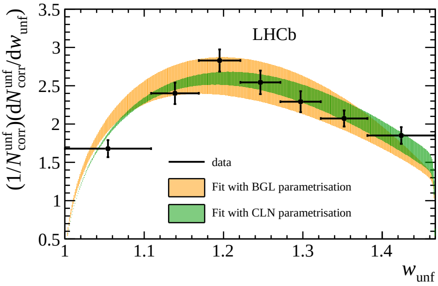
- $B_s \to D_s^{(*)}$
- $\Lambda_b \to \Lambda_c^{(*)}$
- $b \to u$
- $B \to D^{**}$

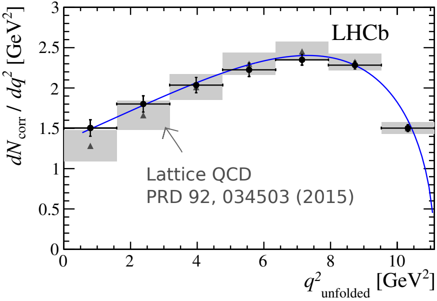
- Theory effort already
- Experimental effort already
  - FF parameters and $|V_{cb}|$ [arXiv:2001.03225]
  - FF parameters and unfolded w distribution [arXiv:2003.08453]
- Large sample already from LHCb
- Any expectations from Belle?
- Maybe Belle II?



What else can we measure?

- $B_s \to D_s^{(*)}$
- $\Lambda_b \to \Lambda_c^{(*)}$
- $b \to u$
- $B \to D^{**}$

- Theory effort already
  i.e. [PRD 99, 055008 (2019)]
- Experimental effort already
  - FF measurement
    [PRD 96, 112005 (2017)]
- Large sample already from LHCb
  - $\frac{f_{\Lambda_b}}{f_u+f_d} = 0.259 \pm 0.018$
    [PRD 100, 032001 (2019)]



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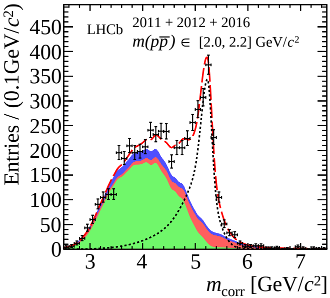
- $B \to D^{**}$



- Theory effort already for $B \to \pi \ell \nu$
- $R(\pi)$ waits for Belle II
  - Not feasible at LHCb

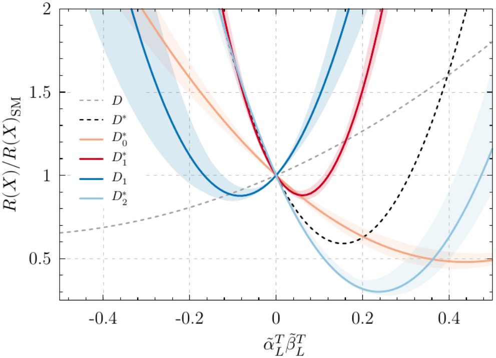
For LHCb:

- Maybe $B \to \rho \ell \nu$ if bkg can be dealt with
- Maybe $\Lambda_b \to p \ell \nu$ - tricky
  - Already some theory from V_{ub} analysis
- Recent first observation of $B^+ \to p\bar{p}\mu^+\nu_\mu$ [JHEP 13, 146 (2020)]
  - Minimal theory but experimentally feasible

What else can we measure?

- $B_s \to D_s^{(*)}$
- $\Lambda_b \to \Lambda_c^{(*)}$
- $b \to u$
- $B \to D^{**}$

- Well motivated theoretically i.e. [PRD 97, 075011 (2018)]
- Data from LHCb, Belle and Belle II
  - $B \to D^{**} \mu\nu$ hardly studied so far
  - Do you need an amplitude analysis?



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

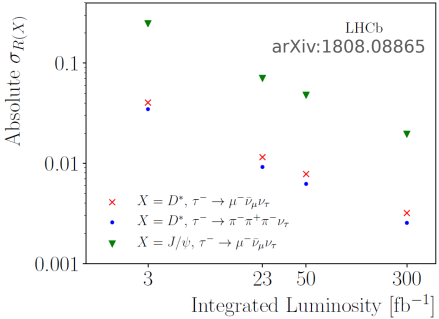
- Higher $\mathcal{L}_{inst}$, no L0 trigger

Upgrade II: CERN-LHCC-2017-003

- Improvements (i.e. protons)?

Contingent on:

- Simulation, i.e. Re-decay [EPJC 78, 1009 (2018)]
- Theory
- Backgrounds



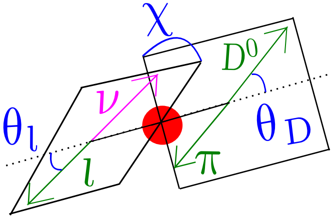
Relative σ on $R(\Lambda_c) \sim 4\%$ ($23\,\mathrm{fb}^{-1}$)

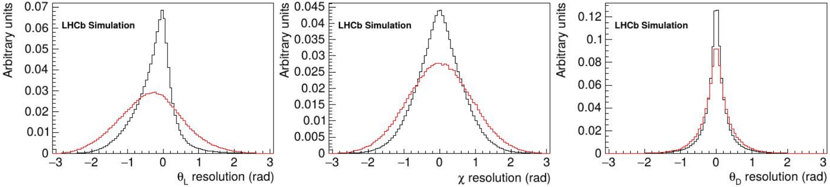
Prospects - LHCb

Hopefully won't be measuring $R(D^{(*)})$ in 2040

Can LHCb measure angular observables?

- Not so promising resolution
- Large samples (but large bkg)
- Start with $B \to D\mu\nu$
- Unfolding?



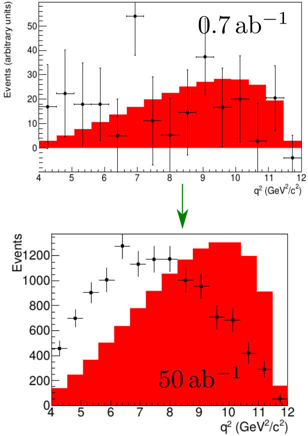


Approximate $\gamma_z^B \beta_z^B \approx \gamma_z^{vis} \beta_z^{vis}$ - $B \to D^* \mu\nu$, $B \to D^* \tau\nu$, $\tau \to \mu\nu\nu$

Expected $\mathcal{L}_{int} \sim 50\,\text{ab}^{-1}$

[PRD 92, 072014 (2015)]

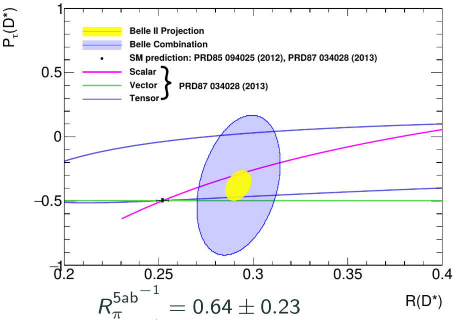
$\tan\beta/m_H = 0.5\,\text{GeV}^{-1}$



Expected relative σ:

	$5\ \text{ab}^{-1}$	$50\ \text{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

$R(D^*)$: Belle $\approx 6\%$, LHCb $23\,\text{fb}^{-1} \approx 3\%$



$$R_\pi^{5\text{ab}^{-1}} = 0.64 \pm 0.23$$
$$R_\pi^{50\text{ab}^{-1}} = 0.64 \pm 0.09$$

Summary

$R(D) - R(D^*)$ tension! $\sim 3\,\sigma$

Present:

- Belle and BaBar data sets mostly exploited
- Still much to come from LHCb
  - Plus complementary modes

Future:

- Exciting prospects from Belle II
  - Will likely lead precision on the ratios + $R(\pi)$
  - Differential measurements
- LHCb will be important
  - Competitive ratio precision
  - Potentially angular measurements?

These are exciting times

BACKUP

DON'T LOOK HERE

NOTHING TO SEE HERE