Status and prospects on $b \to c \ell \nu$ transitions at LHCb

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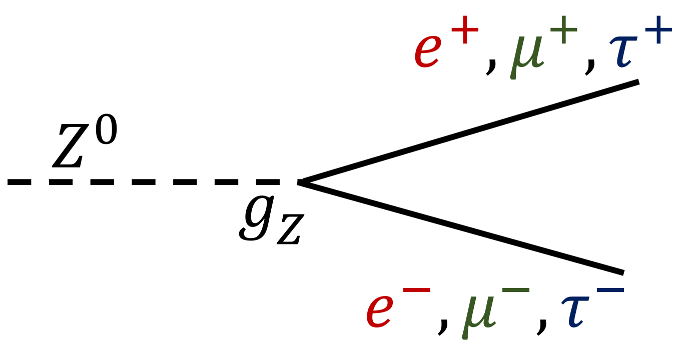
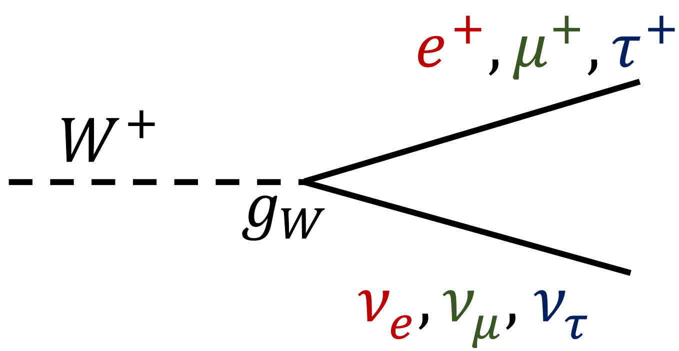
Workshop on status and perspectives of physics at high intensities 9-11 November 2022

Lepton Flavour Universality

2101.08326

The Standard Model (SM) predicts equal couplings between gauge bosons and the fermion families. In the lepton sector, this universality results in an accidental lepton flavour symmetry (broken only by Higgs Yukawa interactions). This is called **Lepton Flavour Universality (LFU)**





Lepton Flavour Universality Violation → Many SM extensions foresee new processes involving mostly the third generation of quarks and leptons

Some discrepancies between SM predictions and measurements have been reported in b-hadron decays

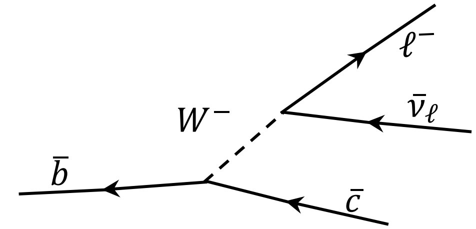
Neutral current: $b \to s\ell\ell$

Charged current: $b \to c\ell\nu_\ell$(this talk)

Ratios $R(H_c)$

LFU Tests in charged current decays

Semileptonic decays: $b \to c\ell\nu_\ell$



- Tree level diagrams with $\mathcal{B} \sim 10^{-2}$
- Sensitive to New Physics processes in couplings with different lepton generations

$$\frac{d\Gamma}{dq^2}(H_b \to H_c \tau^- \bar{\nu}_\tau) \propto G_F^2 |V_{cb}|^2 f(q^2)^2$$

$\ell' = \mu\ (LHCb)$

$\ell' = e/\mu\ (B\ factories)$

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell'^- \bar{\nu}_\ell)} = \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}}$$

Features:

- Partial cancellation of form factor uncertainties and dependence from $|V_{cb}|$
- Reduce experimental uncertainties (systematics)

$R(H_c) \neq 1$ due to different lepton masses $\quad m_\tau \sim \begin{cases} 17 \times m_\mu \\ 3500 \times m_e \end{cases}$

$$\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$$
$$\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$$

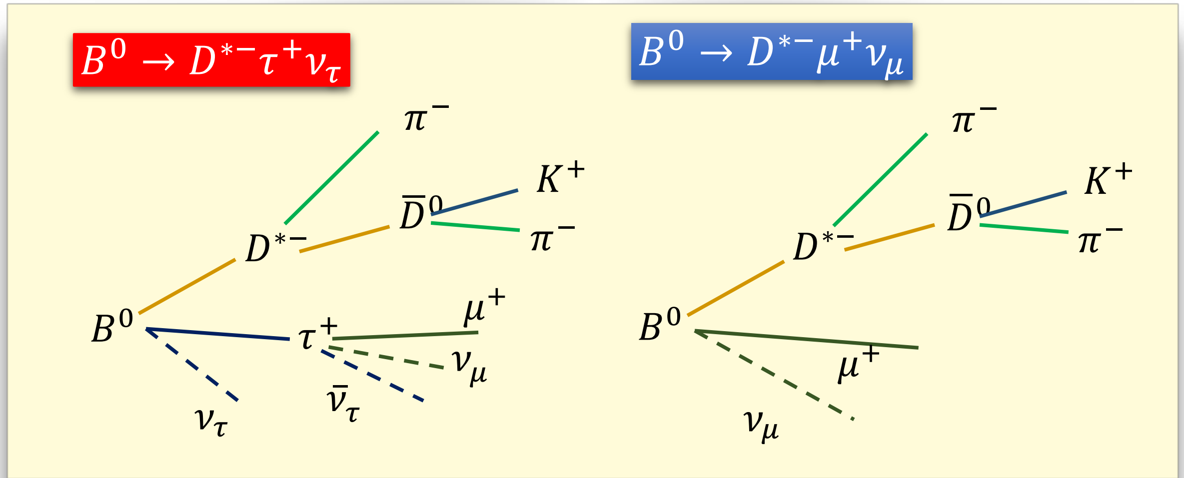
Challenges: missing neutrinos

- Don't know full momentum -> unknown rest frame
- Large partially-reconstructed B backgrounds

Needed approximations to reconstruct the b-hadron Momentum

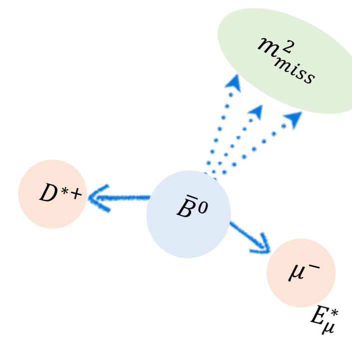
$R(D^*)$ with $\tau \to \mu\nu\nu$

[PRL 115 111803 (2015)]



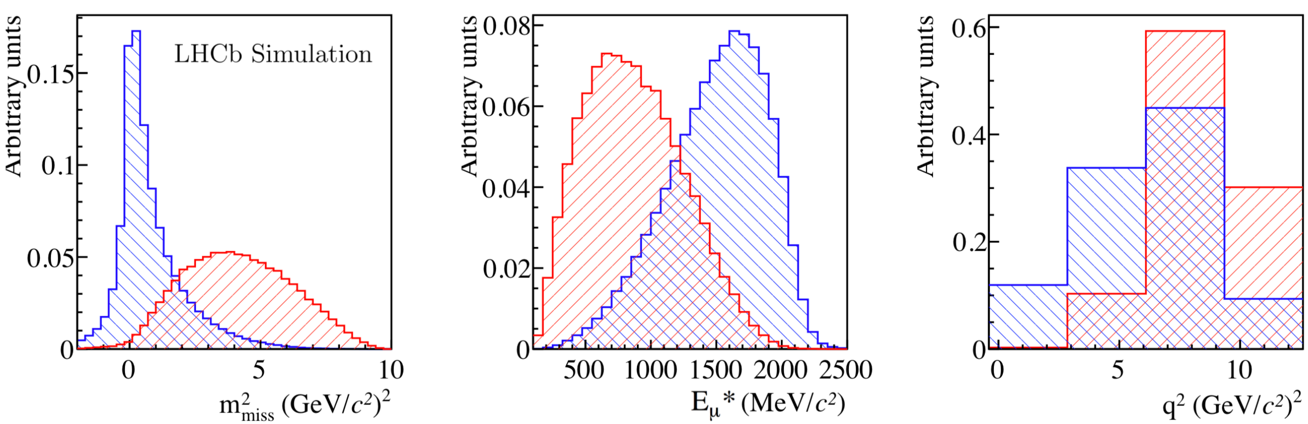
To obtain p_B:

$$(\gamma\beta_z)_B = (\gamma\beta_z)_{D^*\mu}$$



Signal and normalization channel separated by 3-D fit

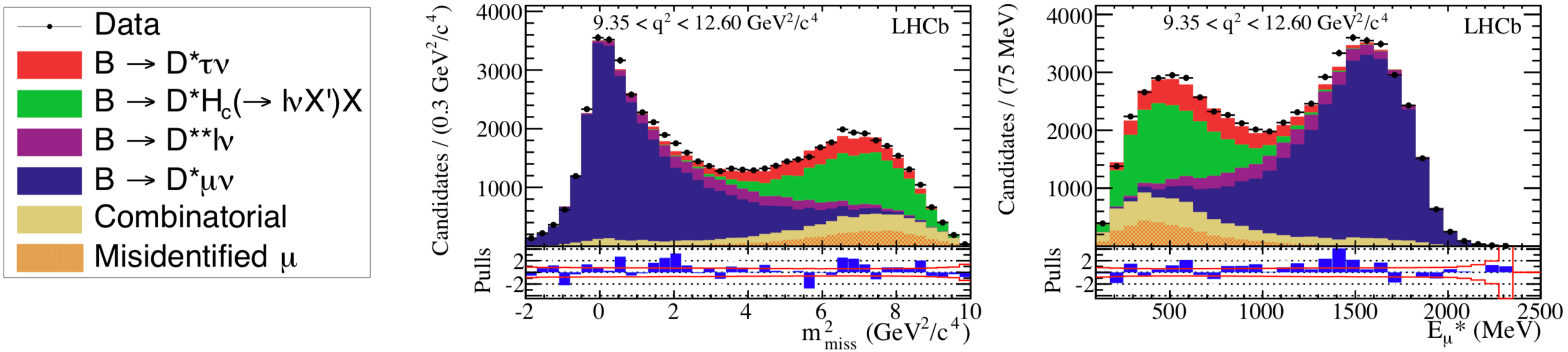
$$m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2 \qquad E^*_\mu \qquad q^2 = (p_B - p_{D^*})^2$$



$B \to D^*\tau\nu_\tau$	$B \to D^*\mu\nu_\mu$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E_μ spectrum is soft	E_μ spectrum is hard
$m^2_\tau \leq q^2 \leq 10.6$	$0 \leq q^2 \leq 10.6$

$\boldsymbol{R(D^*)}$ with $\boldsymbol{\tau \to \mu\nu\nu}$

[PRL 115 111803 (2015)]



$$\boldsymbol{R(D^*) = 0.336 \pm 0.027(stat.) \pm 0.030(syst.)}$$

Run 1
[3 fb^{-1}]

- Good agreement with the previous measurements
- Compatible in 2.1σ with the SM: $R(D^*) = 0.258 \pm 0.005$
- Systematic uncertainty dominated by MC statistics and MisID background

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$

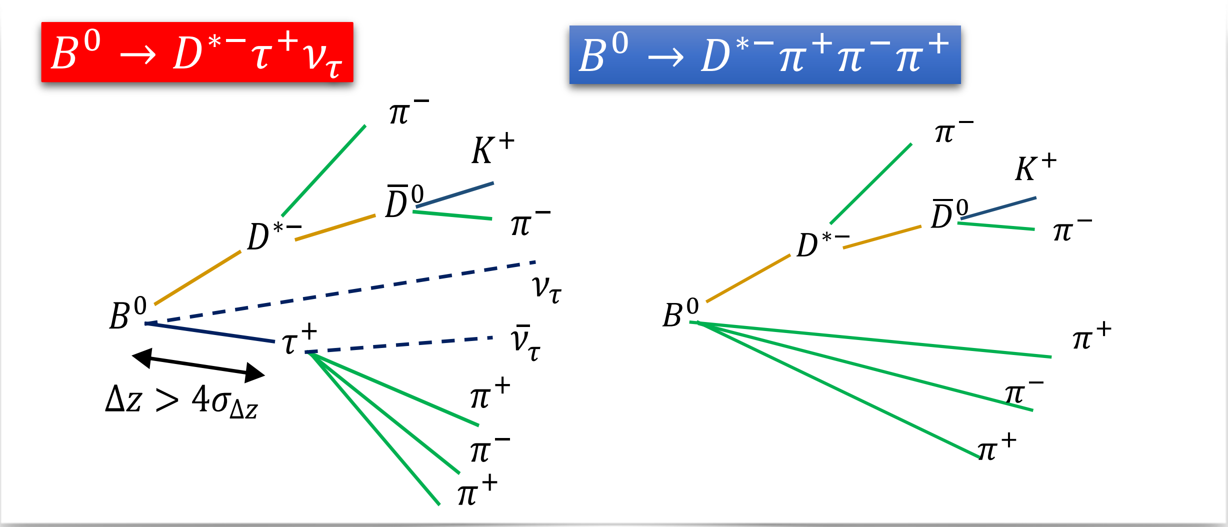
[PRD 97 072013 (2018), PRL 120 171802 (2018)]

$\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau) \sim 14\%$, similar to $\mathcal{B}(\tau^+ \to \bar{\nu}_\tau \mu^+ \nu_\mu)$

$$R(D^*) \equiv \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}}_{\mathrm{K}(D^*)} \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

[~ 4% precision, BaBar, Belle, LHCb]

[~ 2% precision, HFLAV2016]

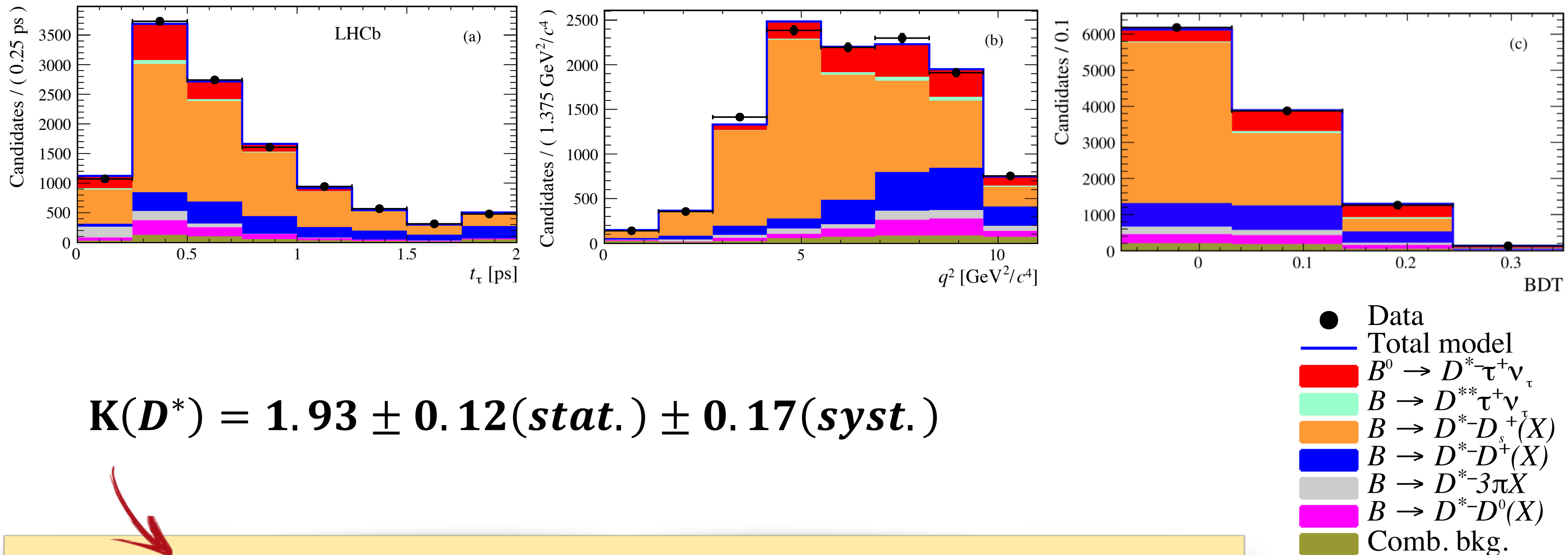


Approximations needed to determine p_B e p_τ

- Normalization yield from a fit to $M(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$
- Backgrounds: suppressed with kinematics properties and with a multivariate analysis (BDT)
- Signal yield from a 3D fit to: t_τ , q^2, BDT result

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$

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



$$\mathrm{K}(D^*) = \mathbf{1.93 \pm 0.12}(\boldsymbol{stat.}) \pm \mathbf{0.17}(\boldsymbol{syst.})$$

Run 1
[3 fb^{-1}]

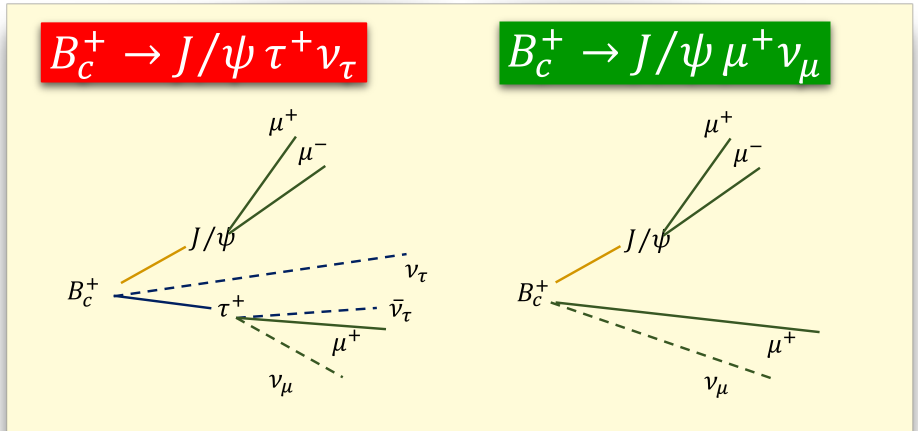
$$\boldsymbol{R(D^*) = 0.280 \pm 0.018(stat.) \pm 0.029(syst.)}$$

- first measurement obtained exploiting $\tau \to 3\pi\nu$;
- compatible into $\sim 1\sigma$ with the SM prediction: $\mathrm{R}(D^*) = 0.258 \pm 0.005$;
- systematic uncertainty dominated by MC statistics, external measurements and background shapes and models

$R(J/\psi)$ with $\tau \to \mu\nu\nu$

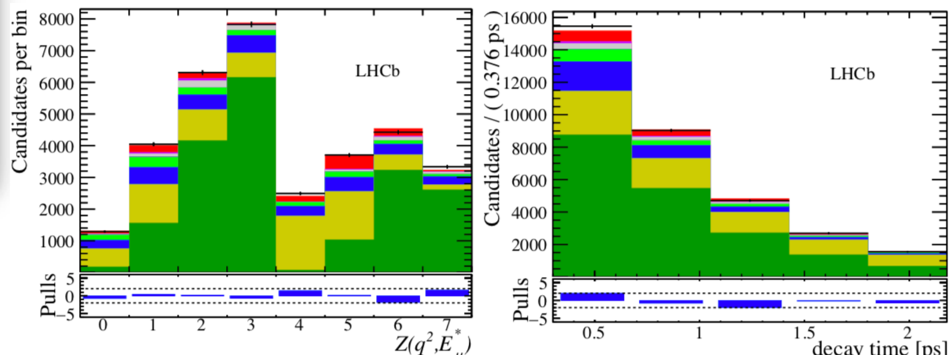
[PRL 120 121801(2018)]

[2007.06957]



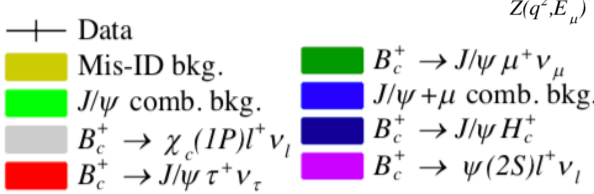
Same visible final state for **Signal** and **Normalization** channel

Similar to $R(D^*)$ with $\tau \to \mu\nu\nu$



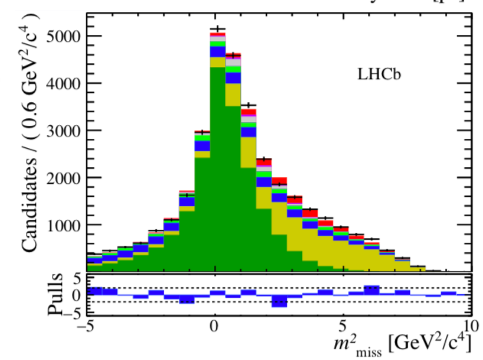
The ratio is obtained from a 3-D fit to:

- m^2_{miss};
- $Z\left(q^2, E^*_\mu\right)$;
- B_c^+ decay time



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

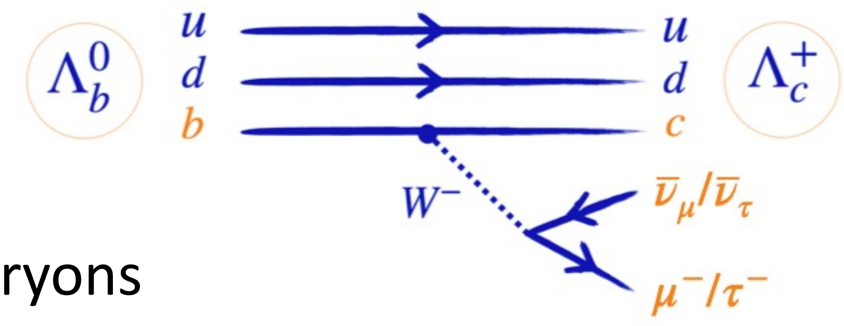
Run 1
[3 fb^{-1}]



- compatible into 2σ with the SM: $R(J/\psi) = 0.2582(38)$ [2007.06957]
- systematic uncertainty dominated by MC statistics and uncertainty on Form Factors

$R(\Lambda_c)$ with $\tau \rightarrow \pi\pi\pi\nu$

$$R(\Lambda_c) \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$



- First R(Hc) measurement using baryons
  - complementary constraints to NP w.r.t. $R(D^{(*)})$
- Different form factors than B → D decays
  - NP results in different scenarios
- Precise SM predictions: PRD99(2019)055008 JHEP08(2017)131
  - $R(\Lambda_c) = 0.324 \pm 0.004$

PRD99(2019)055008 with input from Lattice QCD FF: **PRD92034503(2015)**

$R(\Lambda_c)$ with $\tau \to \pi\pi\pi\nu$

[PRL.128.191803]

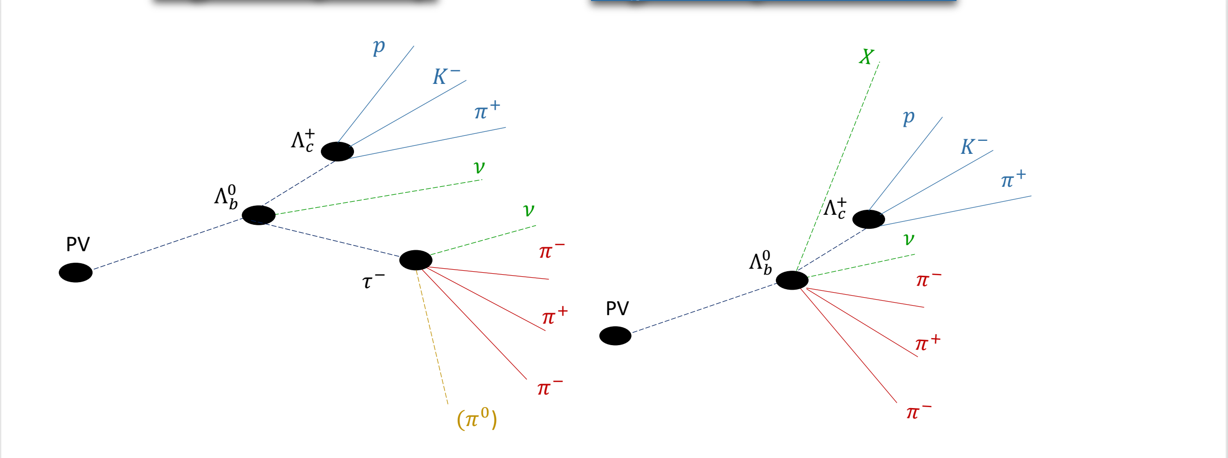
$$R(\Lambda_c) \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

$$R(\Lambda_c) \equiv \underbrace{\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)}}_{K(\Lambda_c)} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

measured

external

$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ | $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$

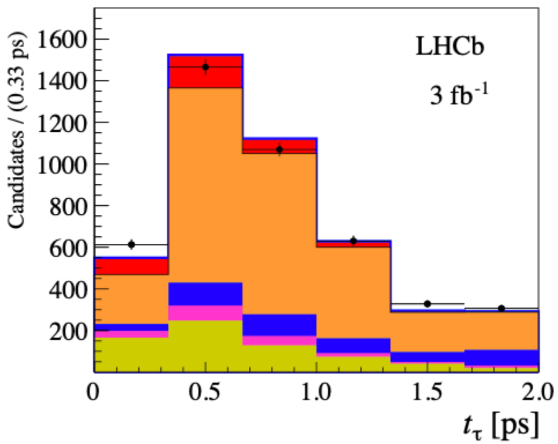


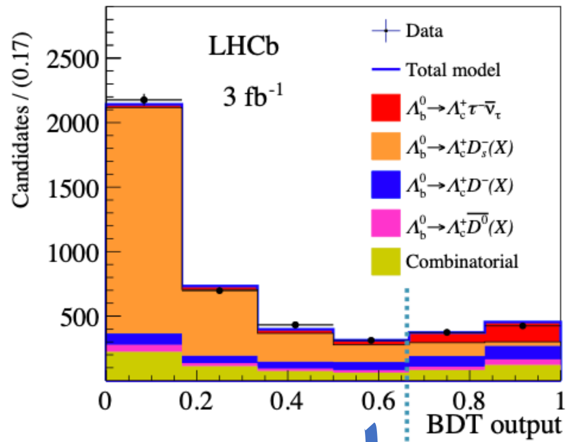
Approximations needed to determine p_{Λ_b} e p_τ

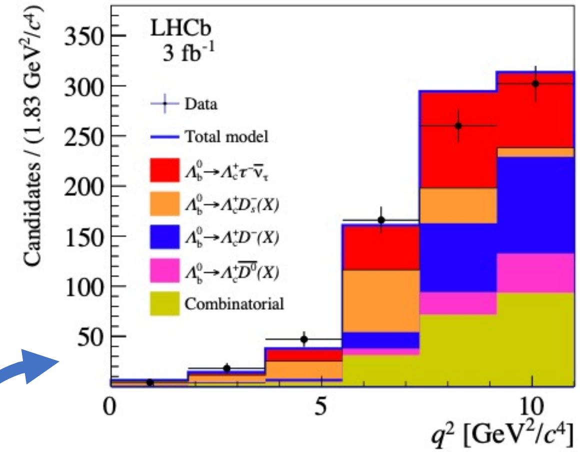
- Normalization yield from a fit to $M(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)$
- Backgrounds: suppressed with kinematics properties and with a multivariate analysis (BDT)
- Signal yield from a 3D fit to: t_τ , q^2, BDT result

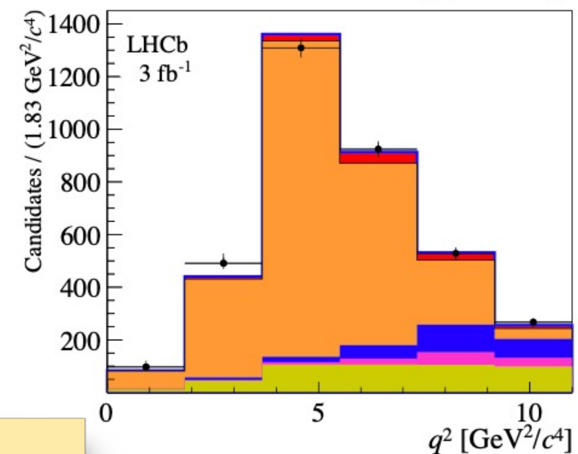
$R(\Lambda_c)$ with $\tau \to \pi\pi\pi\nu$

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









$$K(\Lambda_c) = 2.46 \pm 0.27(stat.) \pm 0.40(syst.)$$

- First observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ at 6.1σ

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) =$$
$$(1.50 \pm 0.16\,(stat.) \pm 0.25(syst.) \pm 0.23(ext.))\%$$

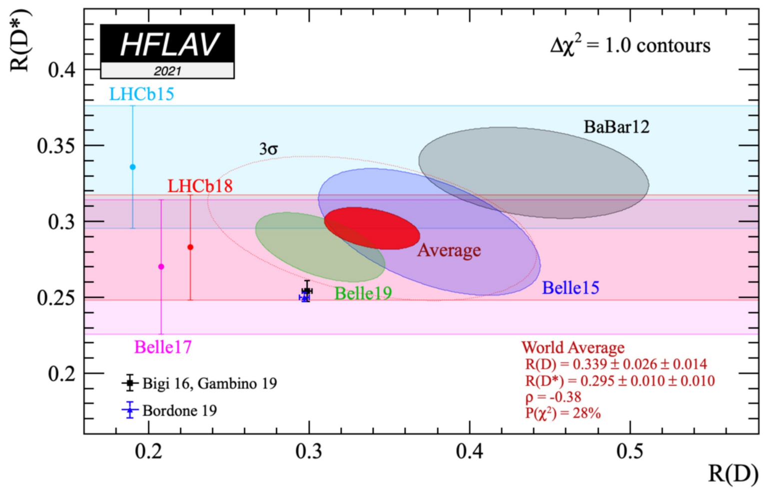
$$R(\Lambda_c) = 0.242 \pm 0.026(stat.) \pm 0.040(syst.) \pm 0.059(ext.)$$

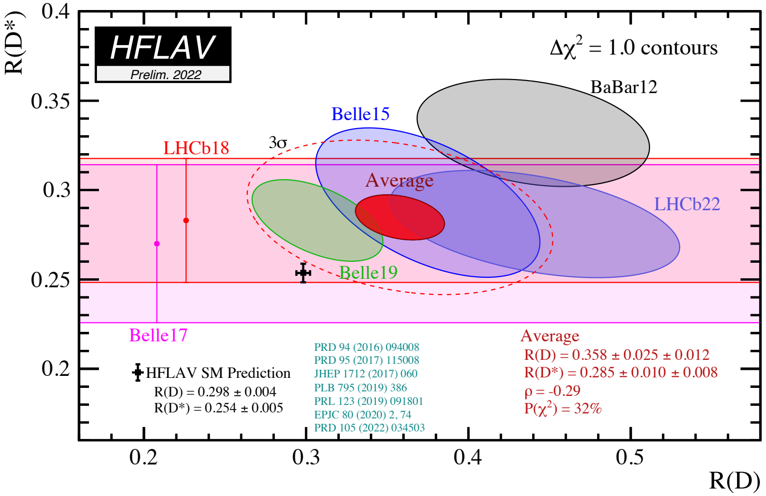
Run 1
[3 fb^{-1}]

- compatible into ~1σ with the SM prediction;
- systematic uncertainty dominated by MC statistics, external measurements and background shapes and models

Joint measurement of $R(D)$ vs. $R(D^*)$ with $\tau \to \mu\nu\nu$ [PRL 115 111803 (2015)]

Purpose: Extend LHCb Run1 muonic measurement ('LHCb15') from 1D band to 2D ellipse via a simultaneous fit to disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples





Based on 2015 R(D*) analysis

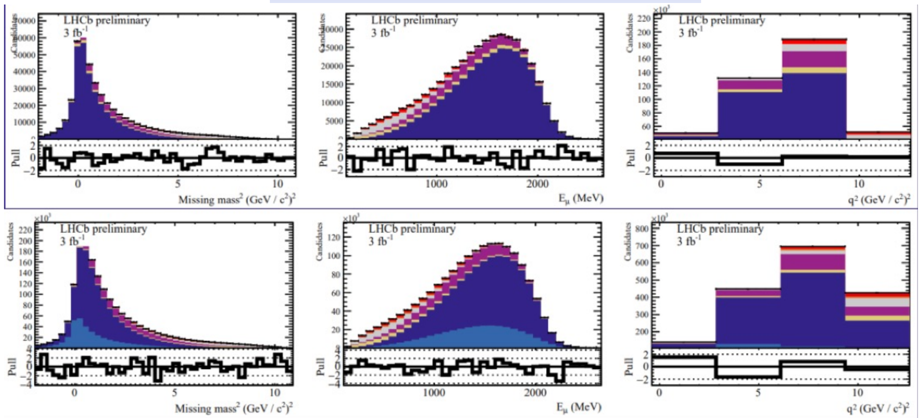
$$R(D) = 0.441 \pm 0.060(stat.) \pm 0.066(syst.)$$
$$R(D^*) = 0.280 \pm 0.018(stat.) \pm 0.024(syst.)$$

Excellent agreement with world average, 1.9σ from standard model

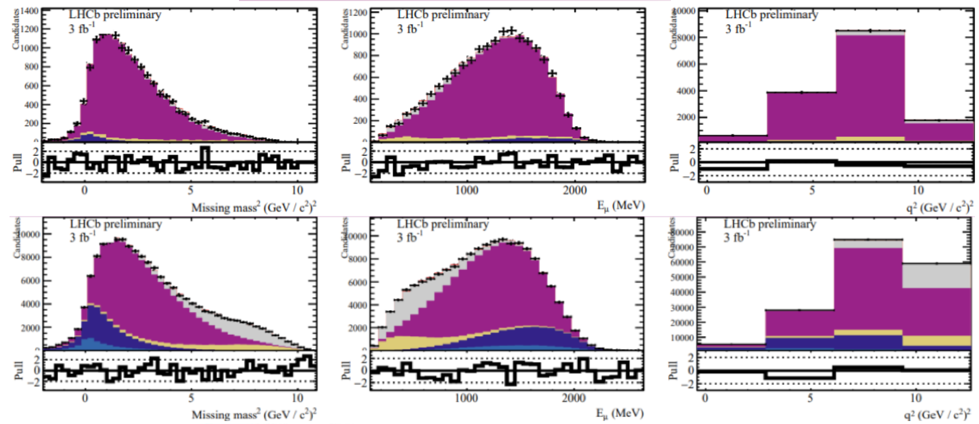
Joint measurement of $R(D)$ $vs.$ $R(D^{*})$ with $\tau \to \mu\nu\nu$

8 simultaneous maximum-likelihood fit to (2x) signal regions, (2x3x) anti-isolated control regions

$Signal$

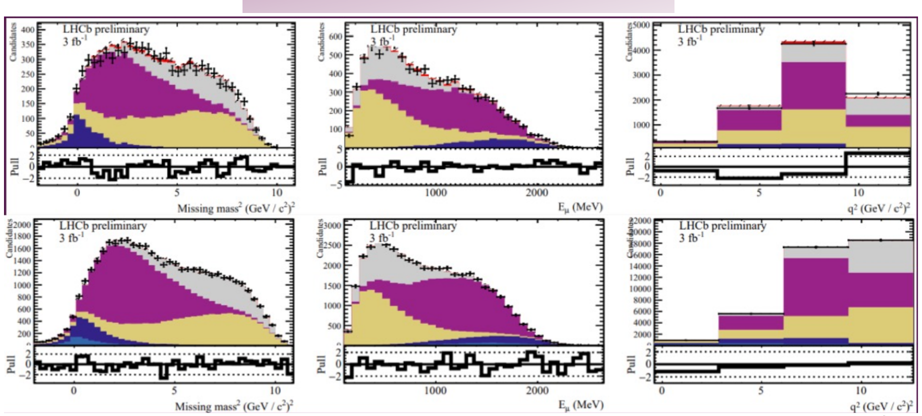


$D^{(*)}\mu^- + \pi^-$

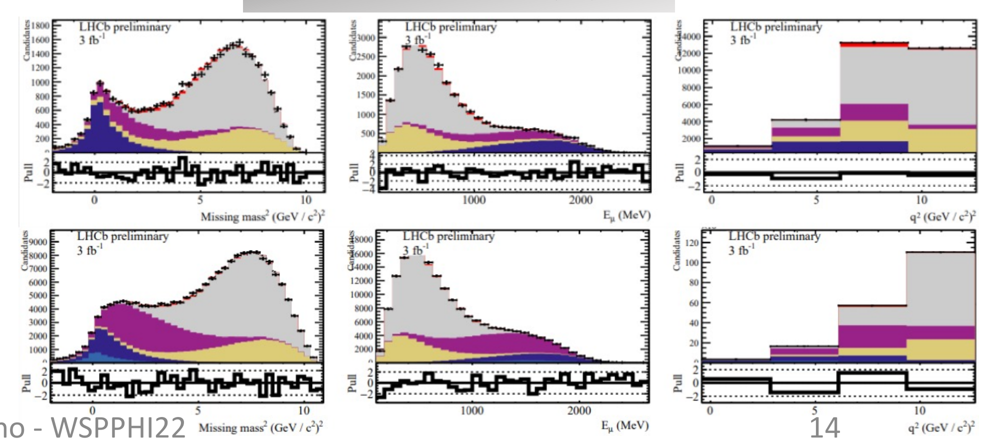


$B \to D^0 \mu \nu$ | Comb. + Fake | $B \to D \tau \nu$
$B \to D^{*0} \mu \nu$ | $B \to D^{**} \mu \nu$ | $B \to D^* \tau \nu$
$B \to D^{*+} \mu \nu$ | $B \to D^0 D X$ | Template stats

$D^{(*)}\mu^- + \pi^-\pi^+$

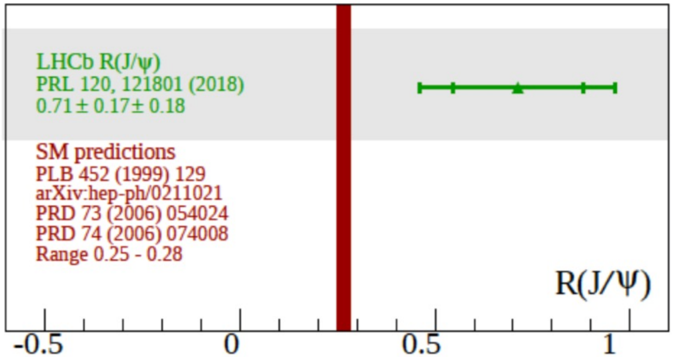


$D^{(*)}\mu^- + K(X)$

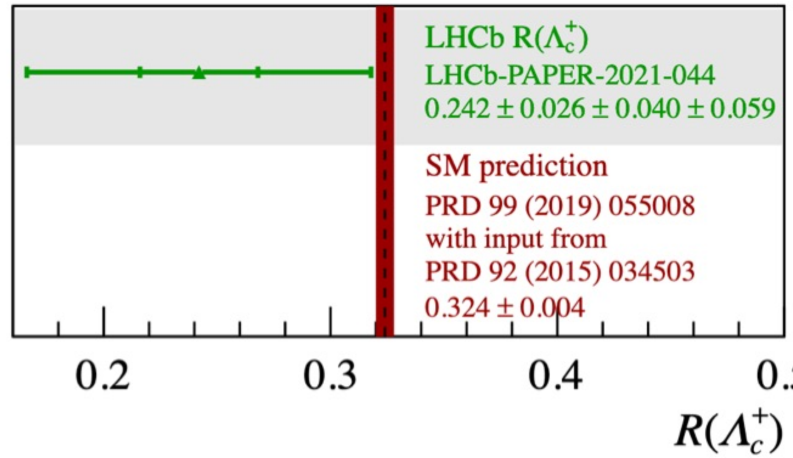


Current State of art:

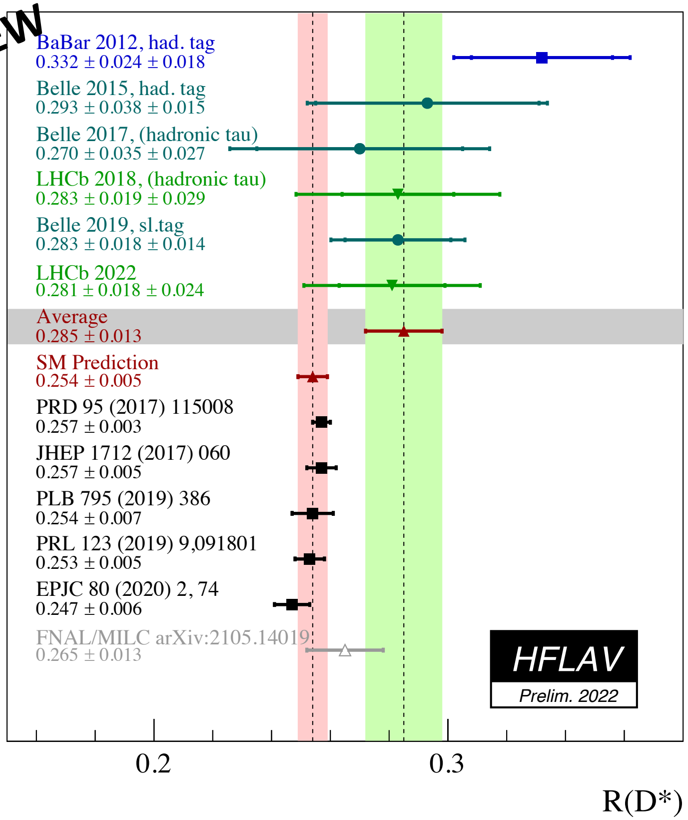
[HFLAV 2022]
[arXiv:1908.09398]



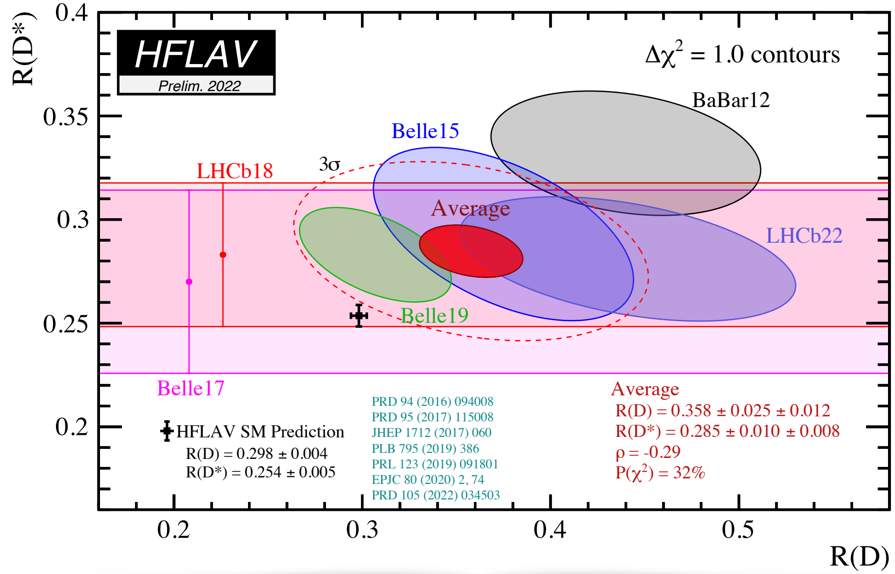
NEW



NEW



NEW



3.2σ above the SM prediction

Angular analysis

Angular analysis: $\Lambda_b \to \Lambda_c \mu \nu$

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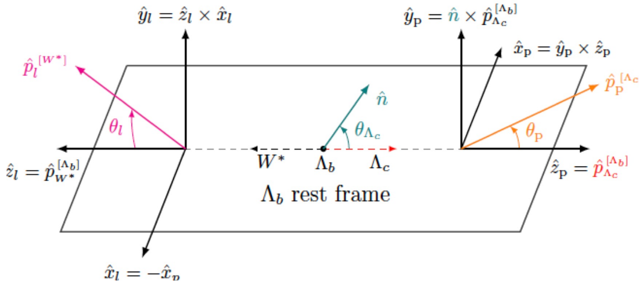
Enhanced sensitivity to potential NP compared to the ratio alone

Using $\Lambda_b \to \Lambda_c \mu \nu$ decays, enhanced sensitivity to tensor currents

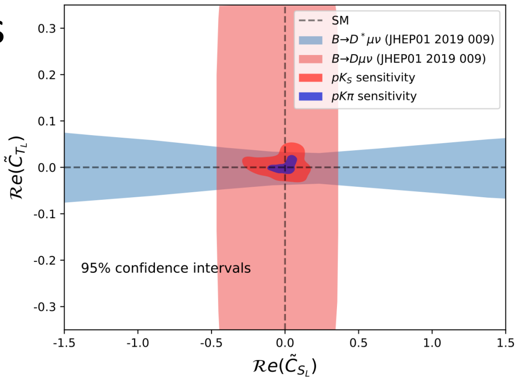
- Consider Λ_b production
  - Polarised: $\Lambda_c^+ \to p K_S^0$
  - Unpolarised: $\Lambda_c^+ \to p K^+ \pi^-$ and integrate over Λ_c^+ angles
    - 2D fit: q^2 and $\cos\theta_l$
    - Expected 7.5M events in Run1+Run2[9 fb^{-1}]

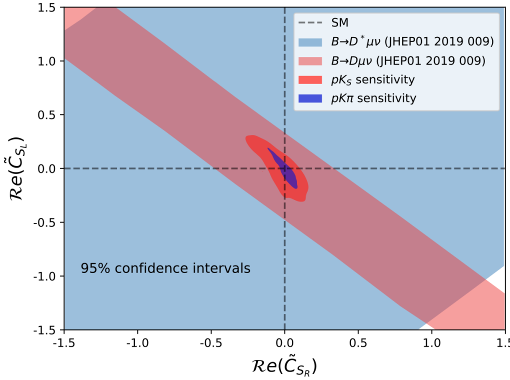


Two-dimensional sensitivity plots

Wilson coefficients

- Improvement compared to existing B → D(*) decays



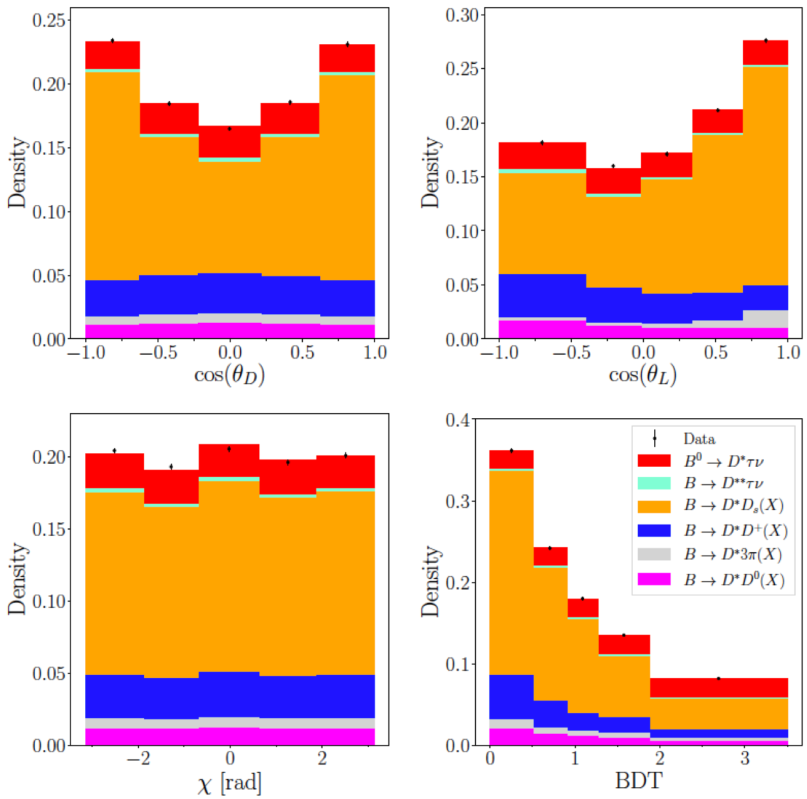


Angular analysis: $B^0 \to D^*\tau\nu$

[JHEP 11 (2019) 133]

WIP

- Angular analysis with τ decays
- $B^0 \to D^*\tau\nu$ very well described theoretically and NP may contribute at tree level
- D* longitudinal polarization fraction complementary to the already performed R(D*) and needed to compare to the value found by Belle collaboration 1903.03102
- Prospects with the Run 1+ part of Run 2 data sample[5fb^{-1}] shown here
- Using 4D fit on angular variables: $\cos\theta_l$, $\cos\theta_D$, χ, BDT output
  - Extract Wilson Coefficients



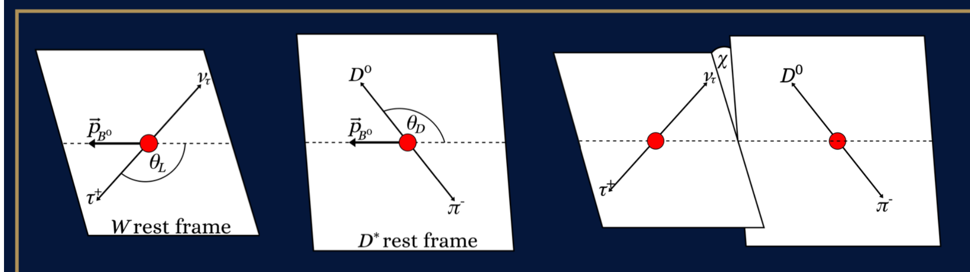
Angular analysis: $B^0 \to D^* \tau \nu$

angular

WIP

- Angular analysis with τ decays
- NP can be detected in angular coefficients even if R(D*) is compatible with SM
- Model agnostic measurement of $B^0 \to D^* \tau \nu$ angular coefficients

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_L d\chi} = \frac{9}{32\pi}\{I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L + [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L + [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D + [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D + [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\}$$



- Measure the 12 $B^0 \to D^* \tau \nu$ angular coefficients and R(D*)
- Multidimensional fit strategy with three decay angles and other discriminating variables
- Full Run 1 + 2 LHCb data set and simulation samples: 9fb^{-1}

CKM metrology

Probing the CKM picture using semileptonic decays

Semileptonic decays of heavy hadrons involve one hadronic current

→clean laboratory to perform CKM metrology

Long-standing tension (~3σ) between $|V_{\{c,u\}b}|$ **inclusive** and **exclusive** determinations.

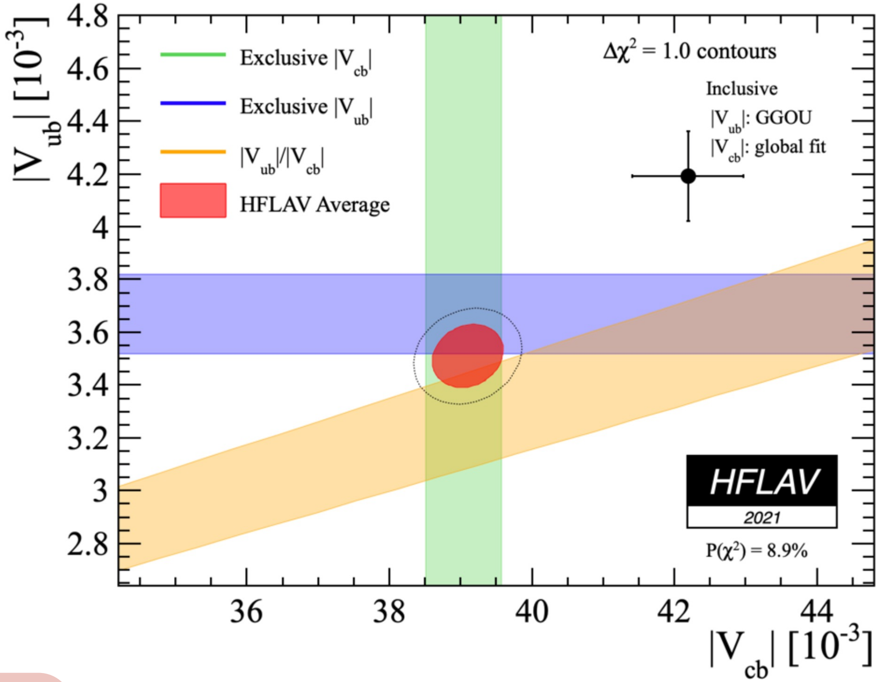
@LHCb:

$|V_{ub}|/|V_{cb}|$ via Λ^0_b decays

B^0_s system:

a) Theoretically advantageous
   $m_s \gg m_u, m_d$

b) Experimentally appealing:
   ~10^{10} B^0_s per fb^{-1} produced
   Reduced part-reco pollution than $B^{0/+}$



TODAY: Extraction of $|V_{cb}|$ via $B^0_s \to D^-_s \mu^+ \nu_\mu$

The differential decay rate of $B^0_s \to D^{*-}_s \mu^+ \nu_\mu$ JHEP12(2020)144

Extraction of $|V_{ub}|/|V_{cb}|$ and observation of $B^0_s \to K^- \mu^+ \nu_\mu$ PRL.126.081804

Extraction of |V$_{cb}$| via $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

PRD.101.072004

Signal: $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

Normalization: $B^0 \to D^{(*)-}\mu^+\nu_\mu$

Strategy:

Both channels reconstructed in the $[K^-K^+]_\phi\pi^+$

Fit data to simultaneously determine |V$_{cb}$| and FF

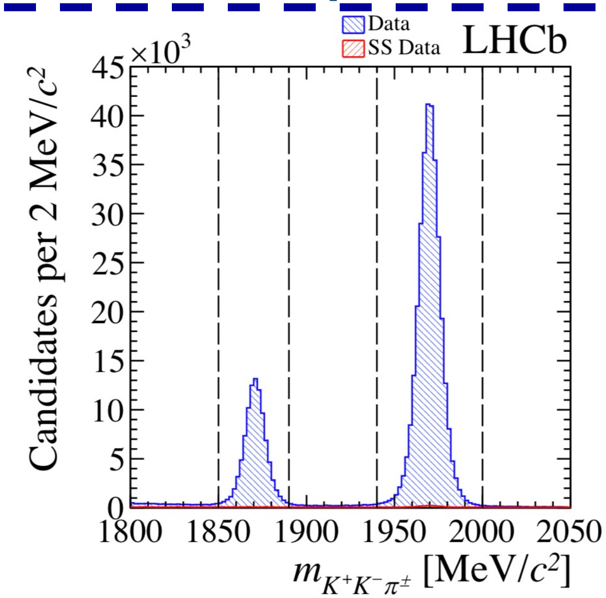
Challenge:

unreconstructed neutrino in the final state

Solution:

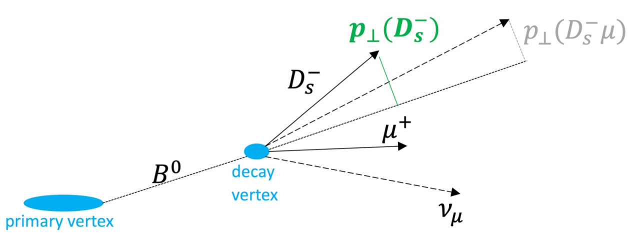
2D fit to the plane in:

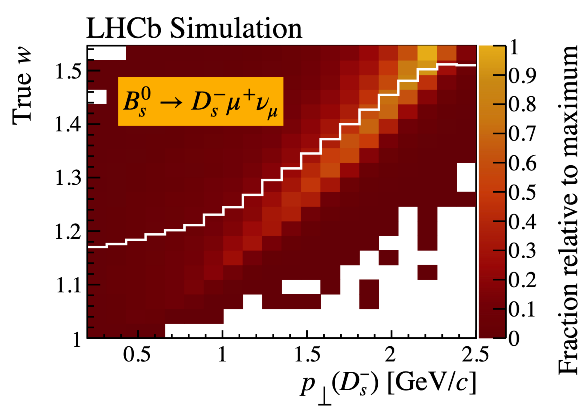
- Corrected mass: $m_{\rm corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$

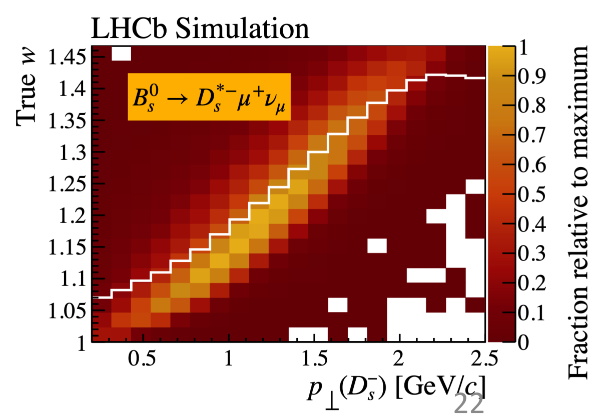


Run 1
[3 fb^{-1}]

- $p_\perp(D_s^-)$ correlated with q^2 which preserve information on the FF







Extraction of |V_{cb}| via $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

PRD.101.072004

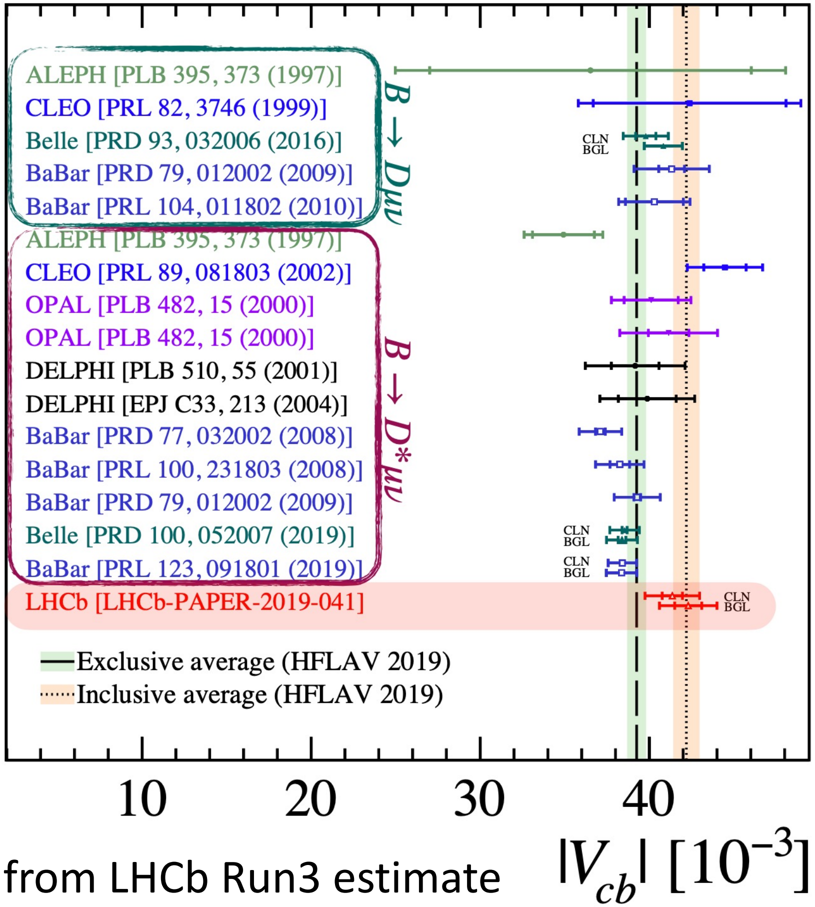
First exclusive |V_{cb}| extraction at a hadron collider and first determination using B_s^0 decays

$$|V_{cb}|_{\mathrm{CLN}} = (41.6 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

$$|V_{cb}|_{\mathrm{BGL}} = (42.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

Both extractions are compatible with each other

Agreement with exclusive via $B^{0/+}$ and inclusive |V_{cb}| determination

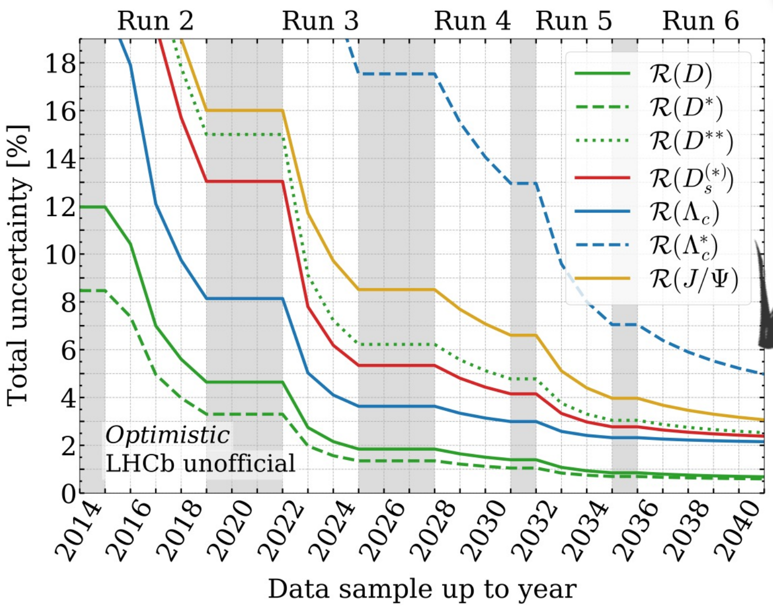


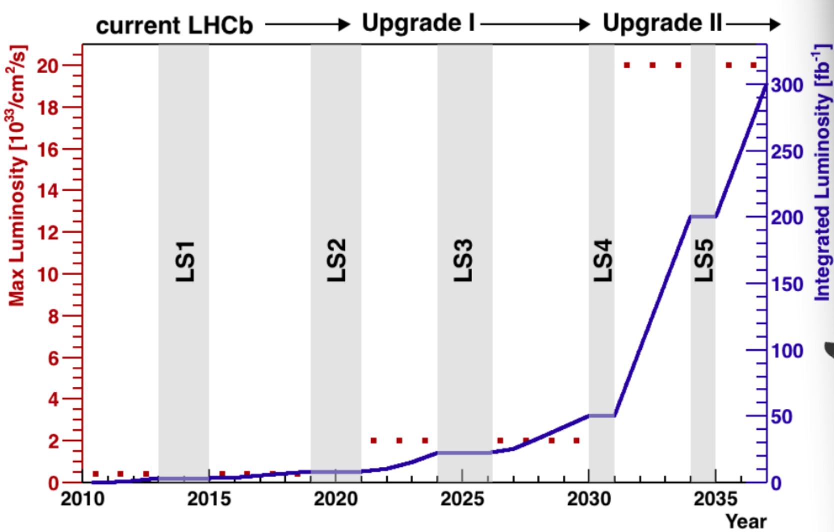
Measurement limited by external inputs→ profit from LHCb Run3 estimate of fs/fd and any update from Belle II on the $K^-K^+\pi^+$ resonance

Next steps:

[JoP G 46 2 (2019)]
[PRD 96(2017) 112005]

2101.08326





New results are expected from:

- Data collected by LHCb during Run2 (statisticsx4);
- Total uncertainties reduction
- Ongoing analyses:

$$R(D^0): B^+ \to D^0\tau\nu_\tau$$
$$R(D^+): \bar{B}^0 \to D^+\tau\nu_\tau$$
$$R\left(D_s^{(*)}\right): B_s \to D_s^{(*)}\tau\nu_\tau$$
$$R\left(\Lambda_c^{(*)}\right): \Lambda_b \to \Lambda_c^{(*)}\tau\nu_\tau$$
$$R(J/\psi): B_c^+ \to J/\psi\,\tau\nu_\tau$$

- Angular analysis and CKM metrology
- Form factors measurements:

$$\Lambda_b \to \Lambda_c\ell\nu_\ell$$
$$\Lambda_b \to \Lambda_c^*\ell\nu_\ell$$
$$B_s \to D_s^{(*)}\ell\nu_\ell$$

- Increased Luminosity

To Conclude:

- Presented measurements using the $b \to c\ell\nu_\ell$ b-hadron decays
- Discrepancies have been reported with respect to the SM predictions
- Many other analyses are ongoing at LHCb and there is an updating with Run2 data the previous measurements
- The LHCb upgrade in the near future will allow to increase the luminosity

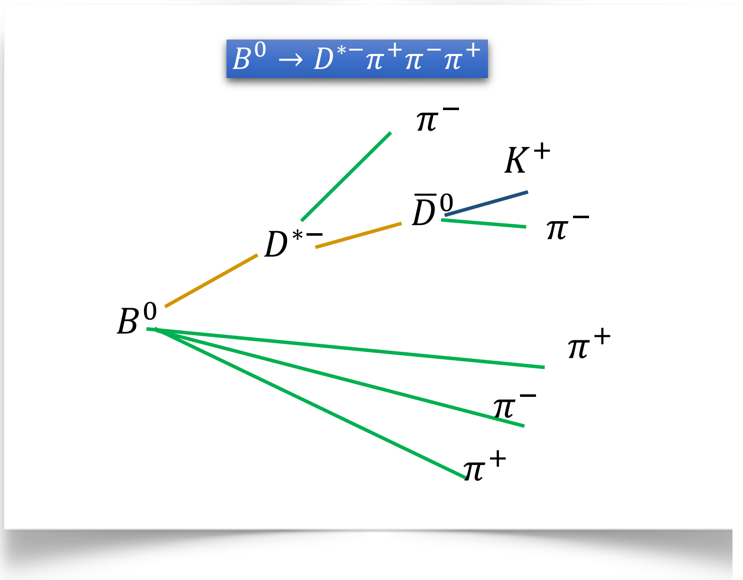
big chance for more precise measurements!

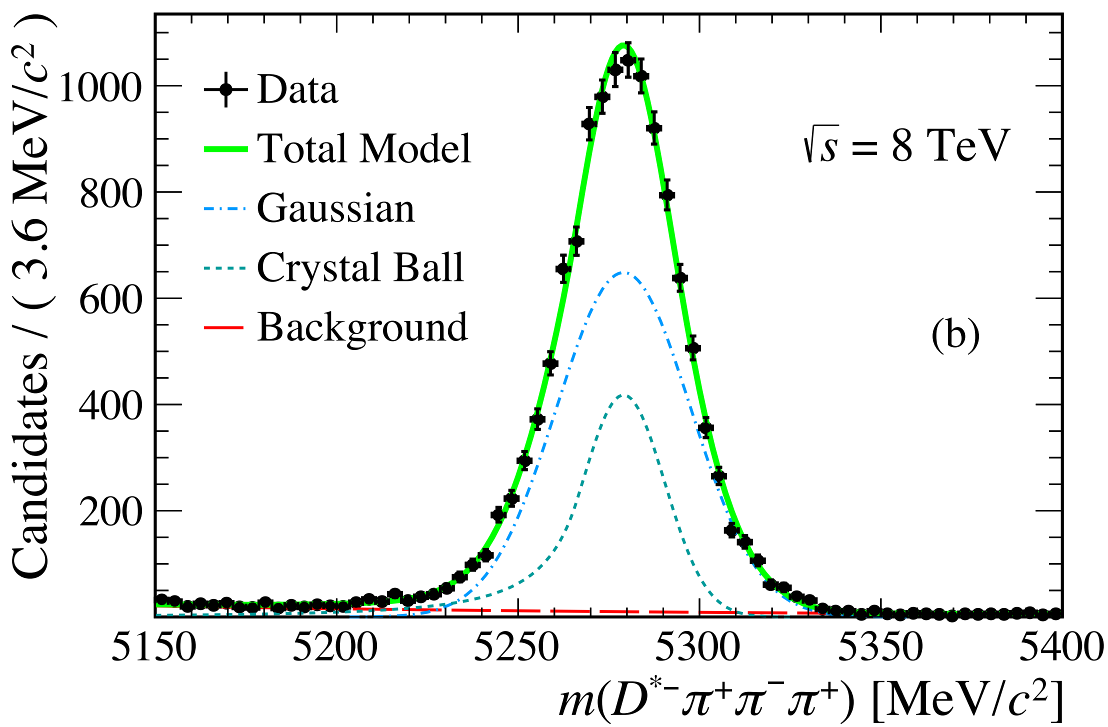
Thank you
for the attention!

Backup

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]
[PRD95 (2017) 115008, JHEP1711 (2017) 061, JHEP1712 (2017) 060]



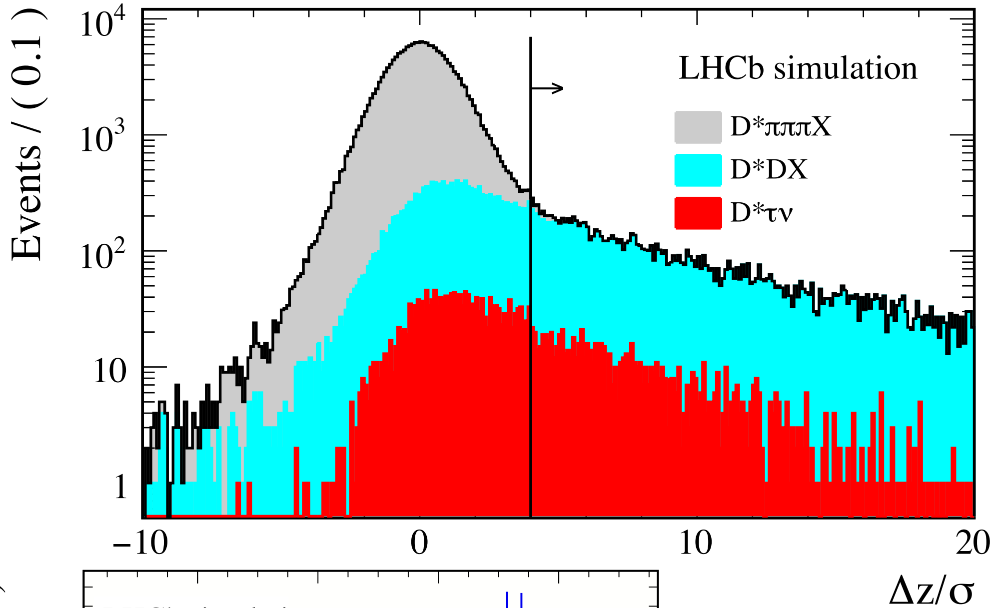


- Normalization yield from a fit to $M(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$

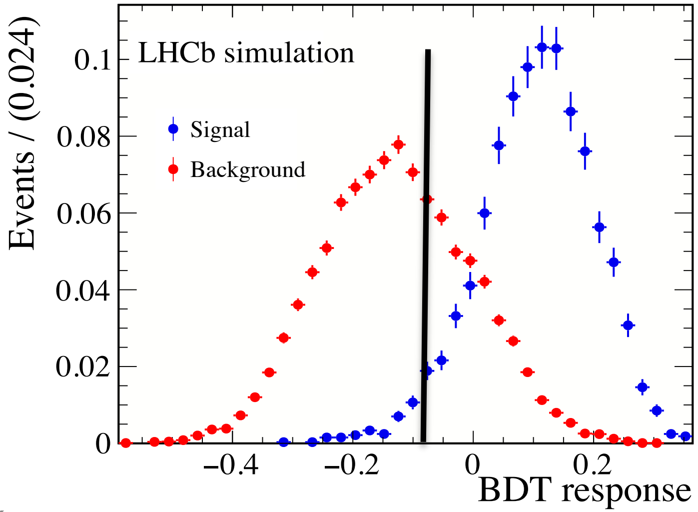
$R(D^*)$ with $\tau\to\pi\pi\pi\nu$

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]
[PRD95 (2017) 115008, JHEP1711 (2017) 061, JHEP1712 (2017) 060]

Main background: $(B^0 \to D^{*-}\pi^+\pi^-\pi^+X)$ ($\sim$ 100 signal) suppressed with τ and B^0 vertices displacement



Other backgrounds $B^0 \to D^{*-}D_s^+X$ ($\sim$ 10 signal) suppressed with BDT exploiting:
$\pi^+\pi^-\pi^+$ isolation,
Kinematics variables,
Intermediate resonances.



$R(\Lambda_c)$ with $\tau\to\pi\pi\pi\nu$

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

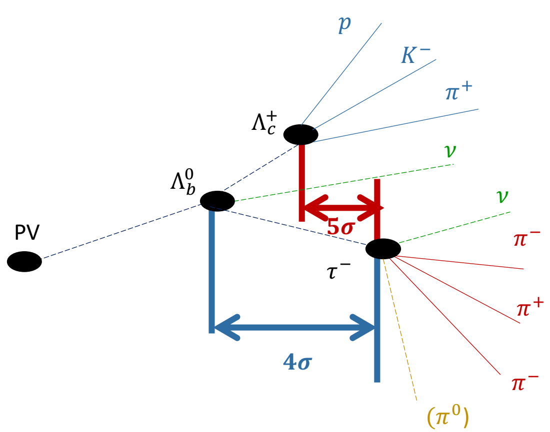
$$R(\Lambda_c) \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}$$

measured

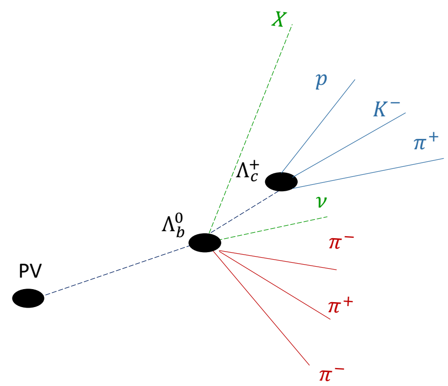
external

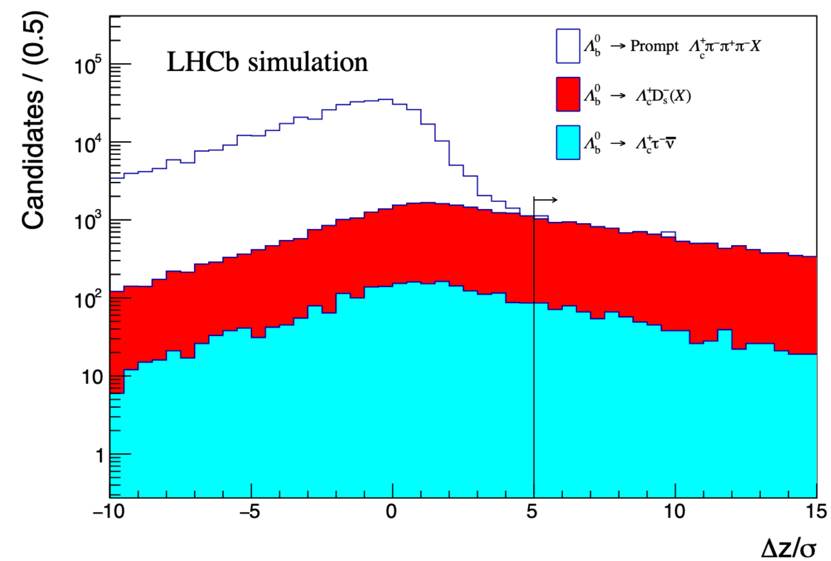
$$R(\Lambda_c) \equiv \underbrace{\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)}}_{K(\Lambda_c)} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}$$

$\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau$



$\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$





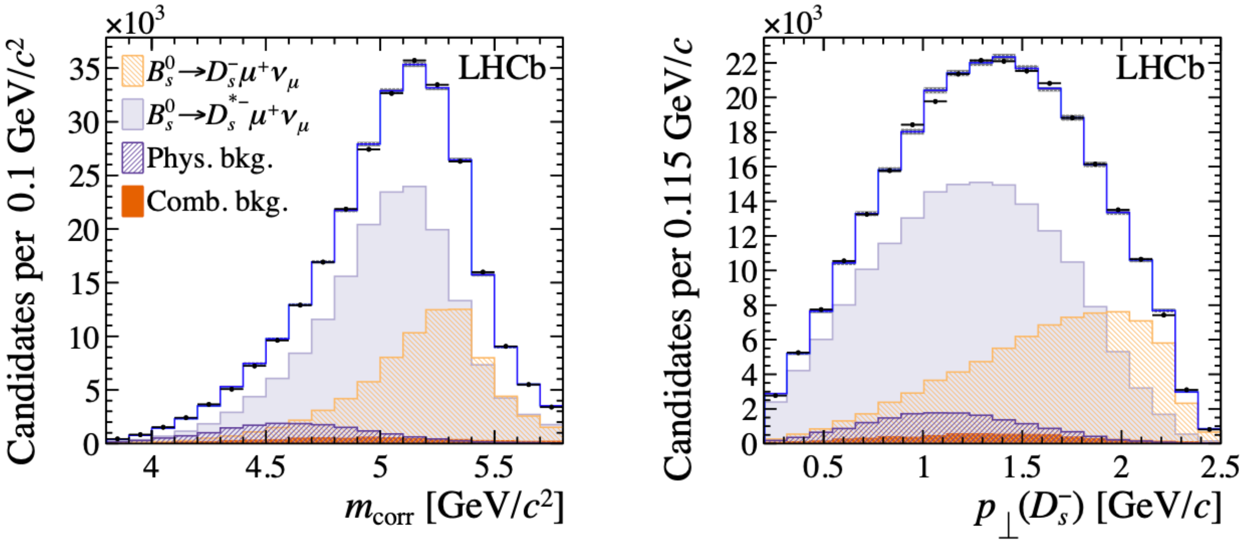
Cutting at distance between vertices:
$\Delta z = z(3\pi) - z(\Lambda_c) > 5\,\sigma_{vtx}$,
reduces prompt background to be negligible

Isolation requirements:
- no extra tracks around 3π

Extraction of |V$_{cb}$| via $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

PRD.101.072004

Signal fit using the **CLN** parameterisation:



$\chi^2/\mathrm{ndf} = 279/285$

$p\text{-value} = 58\%$

Bkg-subtracted distributions: