LHCb prospects on semileptonic decays

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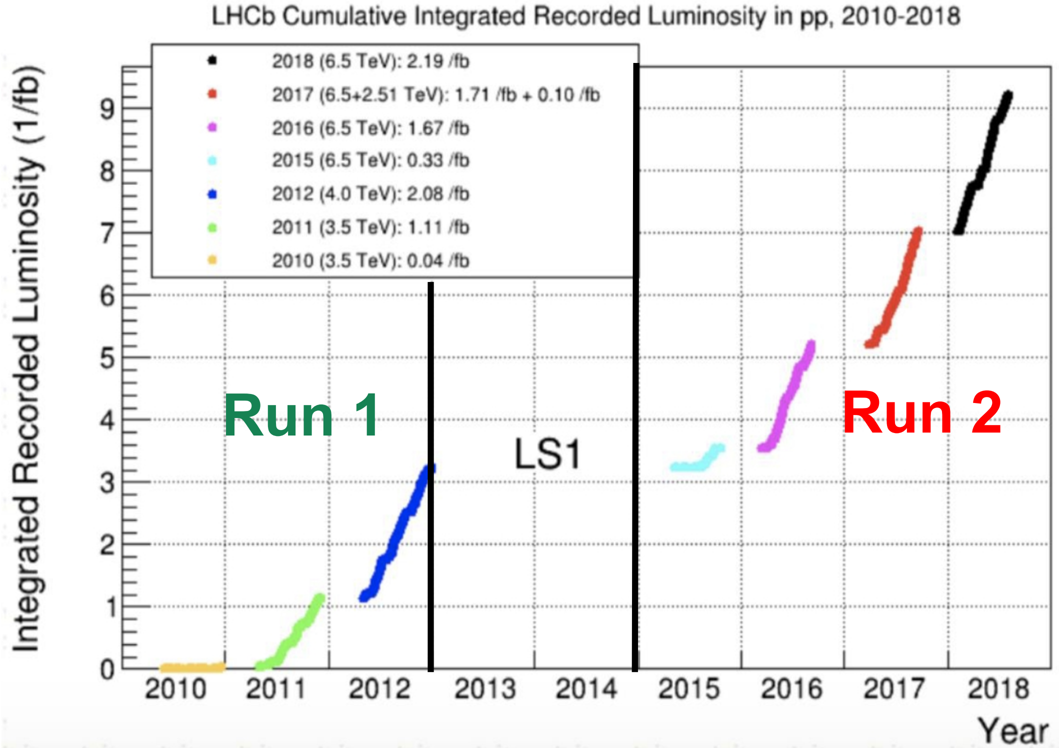
On behalf of LHCb Collaboration

LHCb SL measurements

- LFU test
  - R(D)-R(D*), R(J/ψ), R(Λ_c), **Run1**
  - R(D*), **Run1** + **Run2**(2015-16)
  - D* F_L, **Run1** + **Run2**(2015-16)
- CKM
  - $|V_{ub}/V_{cb}|$, $\Lambda_b \to p$, $B_b \to K$, **Run1**(2012)
  - $|V_{cb}|$, $B_s \to D_s/D_s^*$, **Run1**
- Exclusive $b \to c$
  - $\Lambda_b \to \Lambda_c \mu\nu$ differential rate, **Run1**
  - $B_s \to D_s^* \mu\nu$ differential rate, **Run2**(2016)
  - $D/D^*/D^{**}\mu\nu$ production rate, **Run1**
- Exclusive $b \to u$
  - $B \to p\bar{p}\mu\nu$, search for $B \to 3\mu\nu$, **Run1**
- H_b production: B_s, Λ_c, B_c at 7 and 13 TeV

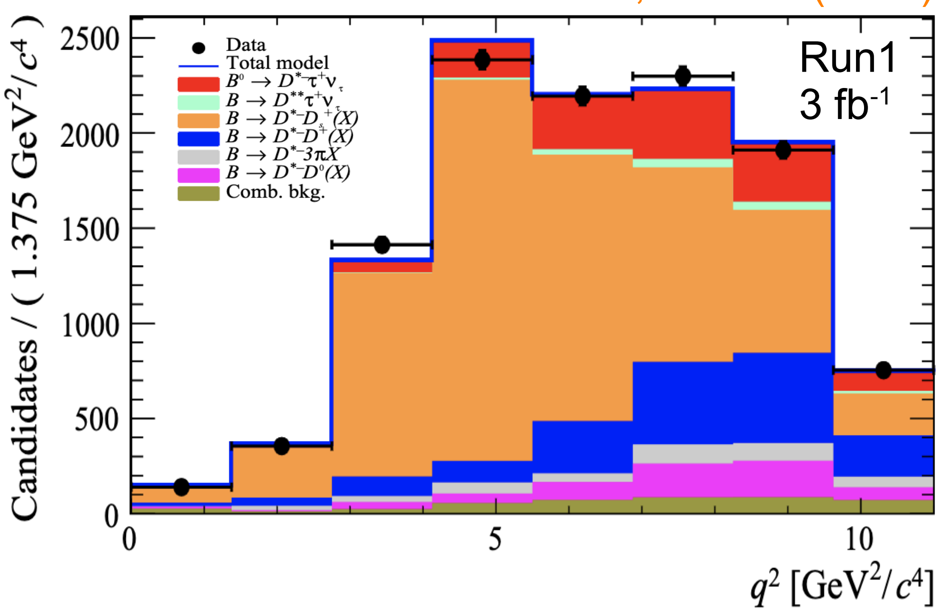


- Run2: larger dataset
  - 1.9 x Luminosity, 1.8 x σ(bb)
- Systematics usually non-negligible
- More data requires larger data controls samples (scale with L) and larger MC
  - <u>Fast MC crucial to exploit the data</u>

R(D*) with $\tau \to 3\pi(\pi^0)\nu$

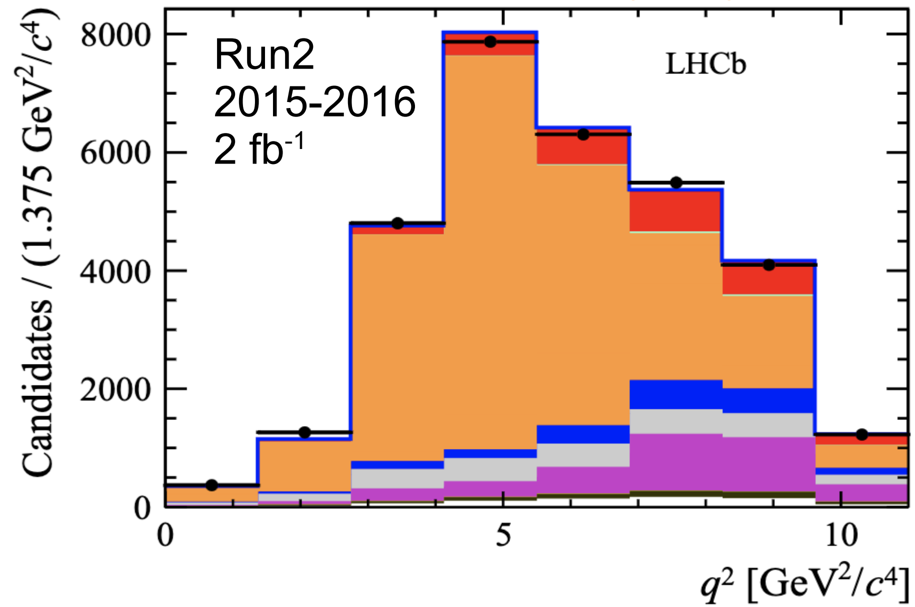
$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$

PRL 120, 171802 (2018)



N_{sig}=1296 ± 86

PRD 108(2023)1,012018



N_{sig}=2469 ± 154

$$\mathcal{K}(D^{*-}) = 1.97 \pm 0.13\,(\text{stat}) \pm 0.18\,(\text{syst})$$

10%

$$\mathcal{K}(D^{*-}) = 1.70 \pm 0.10(\text{stat})^{+0.11}_{-0.10}(\text{syst})$$

6%

MC size is the single dominant systematic (4.1%) → Reduced to 2% using fast MC ReDecay, EPJC 78, 1009 (2018)

R(D*) with $\tau \to 3\pi(\pi^0)\nu$

$$\mathcal{R}(D^{*-}) = 0.247 \pm 0.015\,(\text{stat}) \pm 0.015\,(\text{syst}) \pm 0.012\;(\text{ext})$$

$$\mathcal{R}(D^{*-})_{\text{comb}} = 0.257 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.012\;(\text{ext})$$

± 4.7% ± 5.4% ± 4.7%

Assuming experimental syst. scaling with L, with full Run2
σ_{tot} = 0.022 → 0.014
± 9% ± 5.5%

- Many systematic uncertainties scale down with increasing statistics
- Inputs from BESIII on D_s decay modeling is essential
- Crucial to improve external inputs (Belle II, LHCb)

$$\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-})\frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- A floor of 2-4% due to external inputs will remain
- Combined R(D)-R(D*) is ongoing

Source	systematic uncertainty (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-}D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-}D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\overline{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-}D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-}D^0(X)$ template shapes	1.2
$B \to D^{*-}D_s^+(X)$ template shapes	0.3
$B \to D^{*-}3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

Dedicated R(D**) analysis is ongoing

R(D)-R(D*) with $\tau \to \mu$

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**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

R(D*), Run1 PRL115, 111803 (2015)

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
Simulated sample size	1.5	4.5
$B \to D^{(*)}DX$ template shape	0.8	3.2
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2
$\mathcal{B}(\overline{B} \to D^*D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2
MisID template	0.1	0.8
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5
Combinatorial	< 0.1	0.1
Resolution	< 0.1	0.1
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4
Data/simulation corrections	0.4	0.8
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3
MisID template unfolding	0.7	1.2
Baryonic backgrounds	0.7	1.2
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2\times\mathcal{R}(D^*)$	$0.2\times\mathcal{R}(D^0)$
Total systematic uncertainty	2.4	6.6
Total uncertainty	3.0	8.9

R(D)-R(D*), Run1 PRL131, 111802 (2023)

R(D)-R(D*) with τ → μ

Fast MC factor 10x, will cover Run2 and hopefully will be fine also beyond

Systematics internal to fit likelihood scale roughly with size of control data

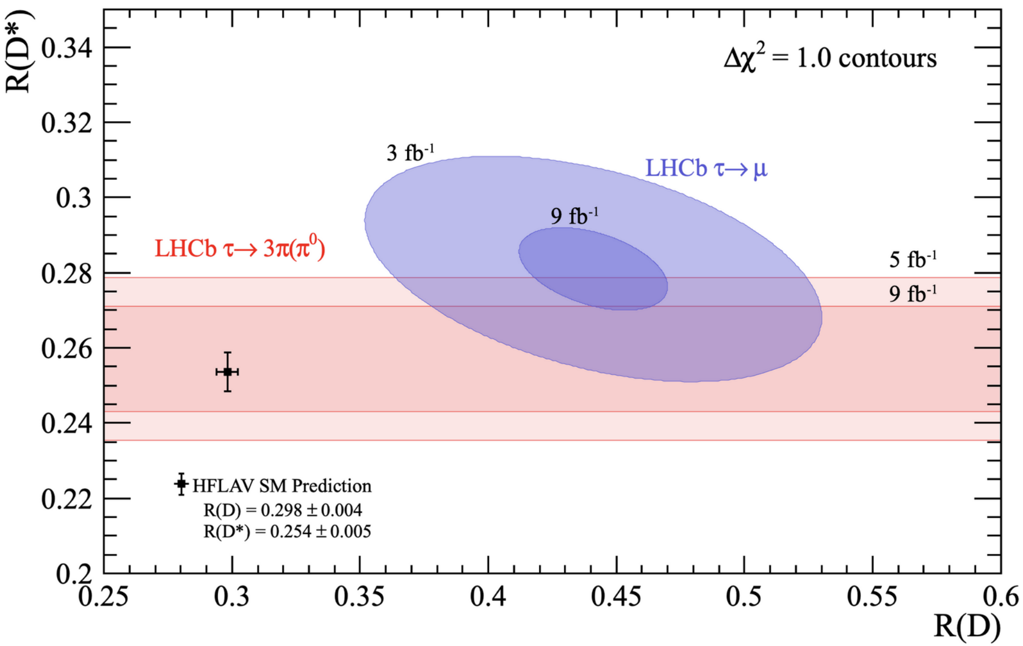
External to fit likelihood: requires dedicated studies/measurements. May be able to reduce on case-by-case basis

Most uncertainties are data driven: expected to be reduced with larger data samples
A systematic floor of 0.5-3% will probably remain

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
Simulated sample size	1.5	4.5
$B \to D^{(*)}DX$ template shape	0.8	3.2
$\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ form-factors	0.7	2.1
$\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu$ form-factors	0.8	1.2
$\mathcal{B}(\bar{B} \to D^* D_s^-(\to \tau^-\bar{\nu}_\tau)X)$	0.3	1.2
MisID template	0.1	0.8
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	0.5	0.5
Combinatorial	< 0.1	0.1
Resolution	< 0.1	0.1
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7
$\bar{B}_s^0 \to D_s^{**}\mu^-\bar{\nu}_\mu$ model uncertainty	0.6	2.4
Data/simulation corrections	0.4	0.8
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3
MisID template unfolding	0.7	1.2
Baryonic backgrounds	0.7	1.2
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$
$\tau^- \to \mu^-\nu\bar{\nu}$ branching fraction	$0.2\times\mathcal{R}(D^*)$	$0.2\times\mathcal{R}(D^0)$
Total systematic uncertainty	2.4	6.6
Total uncertainty	3.0	8.9

From M.F.Sevilla talk at SM@LHC workshop

R(D)-R(D*) with τ → μ



$$\mathcal{R}(D^0) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$

$$\mathcal{R}(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.024(\text{syst})$$

Adding full Run2, assuming irreducible syst uncertainty at 3% for both D and D*:

- σ_{tot}(R(D)) = 0.089 → 0.022 ±20% → ±8%
- σ_{tot}(R(D*)) = 0.030 → 0.012 ±11% → ±4%

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
Simulated sample size	1.5	4.5
$B \to D^{(*)}DX$ template shape	0.8	3.2
$\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ form-factors	0.7	2.1
$\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu$ form-factors	0.8	1.2
$\mathcal{B}(\bar{B} \to D^* D_s^-(\to \tau^-\bar{\nu}_\tau)X)$	0.3	1.2
MisID template	0.1	0.8
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	0.5	0.5
Combinatorial	< 0.1	0.1
Resolution	< 0.1	0.1
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7
$\bar{B}_s^0 \to D_s^{**}\mu^-\bar{\nu}_\mu$ model uncertainty	0.6	2.4
Data/simulation corrections	0.4	0.8
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MisID template unfolding	0.7	1.2
Baryonic backgrounds	0.7	1.2
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$
$\tau^- \to \mu^-\nu\bar{\nu}$ branching fraction	$0.2\times\mathcal{R}(D^*)$	$0.2\times\mathcal{R}(D^0)$
Total systematic uncertainty	2.4	6.6
Total uncertainty	3.0	8.9

Run3 and beyond

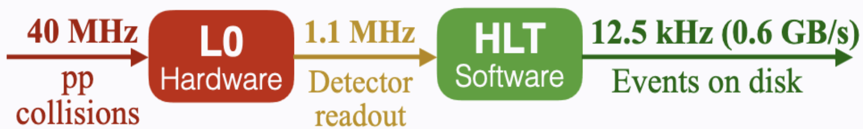
HL - LHC

9 fb^{-1} | Goal: 50 fb^{-1} | Goal: 300 fb^{-1}

Upgrade I | Consolidation | Upgrade II

Run 1	LS1	Run 2	LS2		Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022	2023 2024 2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2039	2040	2041 2042

Runs 1 and 2



Upgrade I (commissioning)

Flexible software trigger and 3 new/better trackers

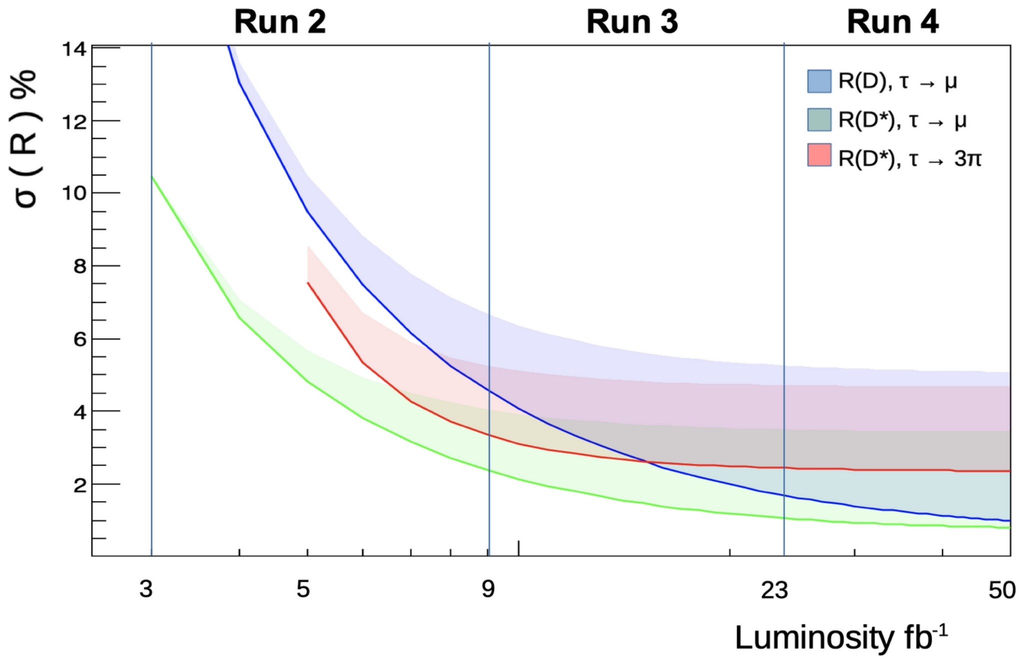
Upgrades Ib and II (proposed)

Even better granularity, improved calorimeter, and fast timing

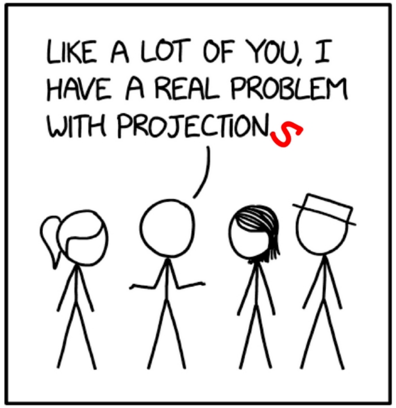
LHCb Physics with Upgrade II
arXiv:1808.08865

- Run3: currently taking data with Upgrade I detector
  - Completely new software-only trigger
  - No more required pT cut on the muon in L0
  - Exploit this to improve purity for tau decays
  - Improve analyses with electrons in final state
- Run4: maintenance and some upgrades (ECAL)
  - Steady data taking
- Run5-6: Upgrade II detector
  - Fully exploit the HL-LHC
  - Very challenging: average of ~50 PVs
  - Timing in sub-detectors is needed to fully exploit the higher luminosity

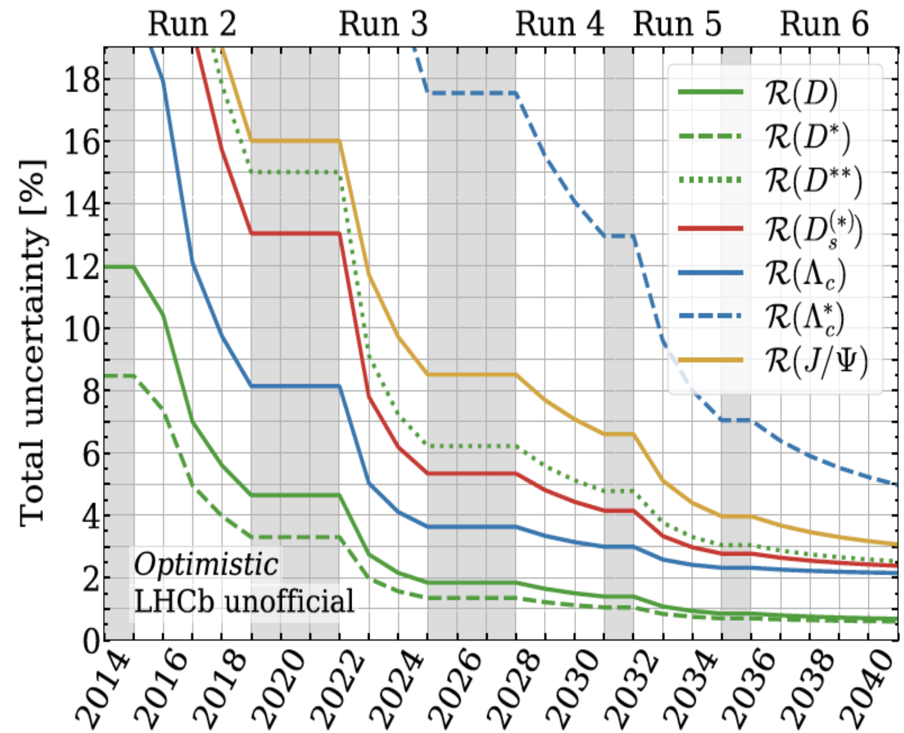
Projections on R(Hc) measurements



the bands represent the degree of optimism (pessimism) in our ability to reduce systematics



Projections on other ongoing analyses in LHCb. If the anomaly persists, it is crucial cross check with other decay modes



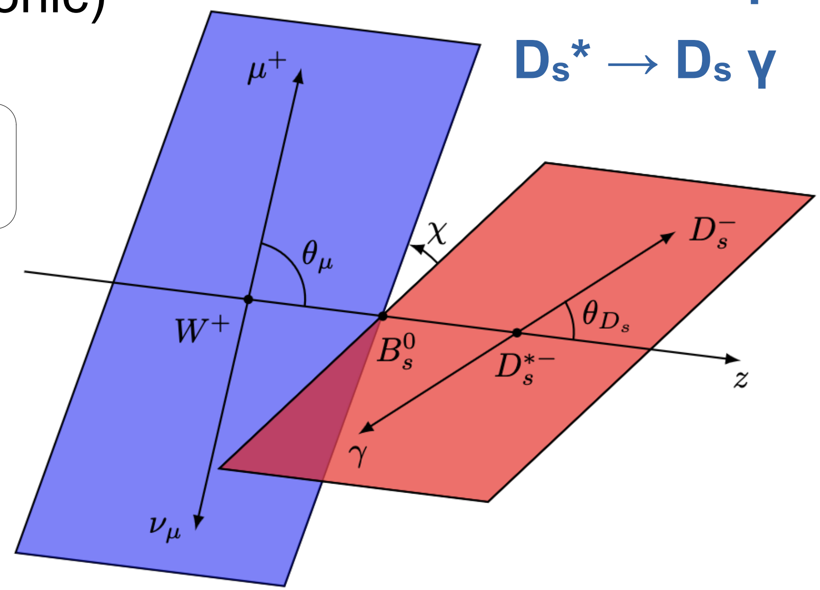
arXiv:2101.08326

Beyond $R(H_c)$: going differential

- Angular analyses with semitauonic (and semimuonic) to probe spin structure of physics beyond SM
  - Even in case $R(H_c)$ is SM-like, it will put strong constraints on NP models

$B_s \to D_s^* \mu\nu$

$D_s^* \to D_s \gamma$



$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

H_i sensitive to New Physic and Form Factors

Many observables can be derived by H_i

Recent literature (non-exhaustive list):

D.Hill et al. JHEP 11 (2019) 133

V. Dedu, A.Poluektov JHEP 07 (2023) 063

B. Bhattacharya et al. JHEP 05 (2019) 191

C.Bobeth et al. EPJ.C 81 (2021) 11, 984

M. Fedele et al. ArXiv;2305.15457

Z. Huang et al. PRD 105 (2022) 1, 013010

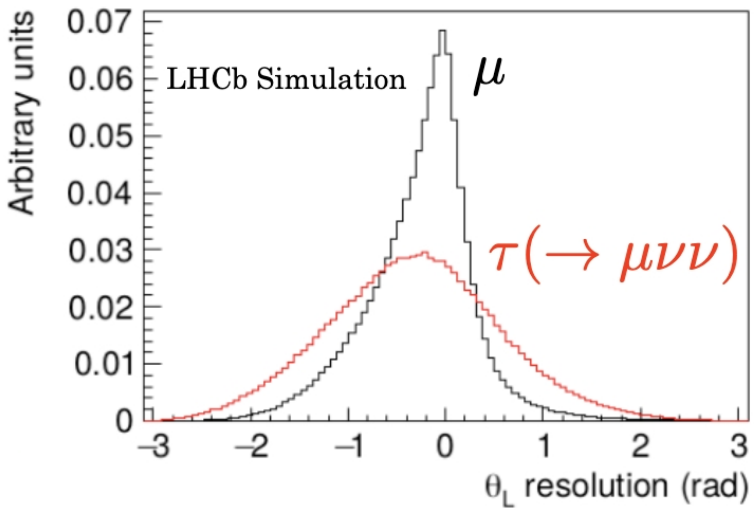
B. Bhattacharya et al. JHEP 07 (2020) 07, 194

M. Ivanov et al. PRD 95 (2017) 3, 036021

D. Becirevic et al. NPB 946 (2019) 114707

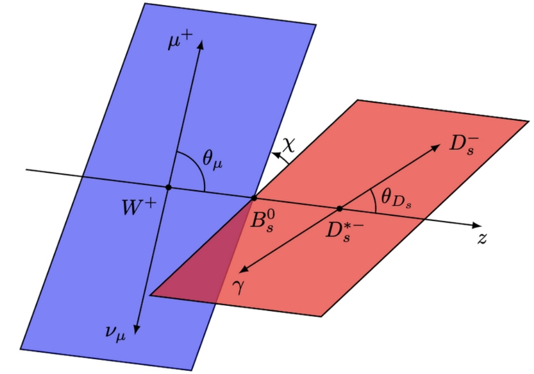
O. Colangelo, F.DeFazio, JHEP 06 (2018) 082

Differential measurements: B→D*τν



LHCb Physics with Upgrade II
arXiv:1808.08865

B momentum determined with boost-approximation

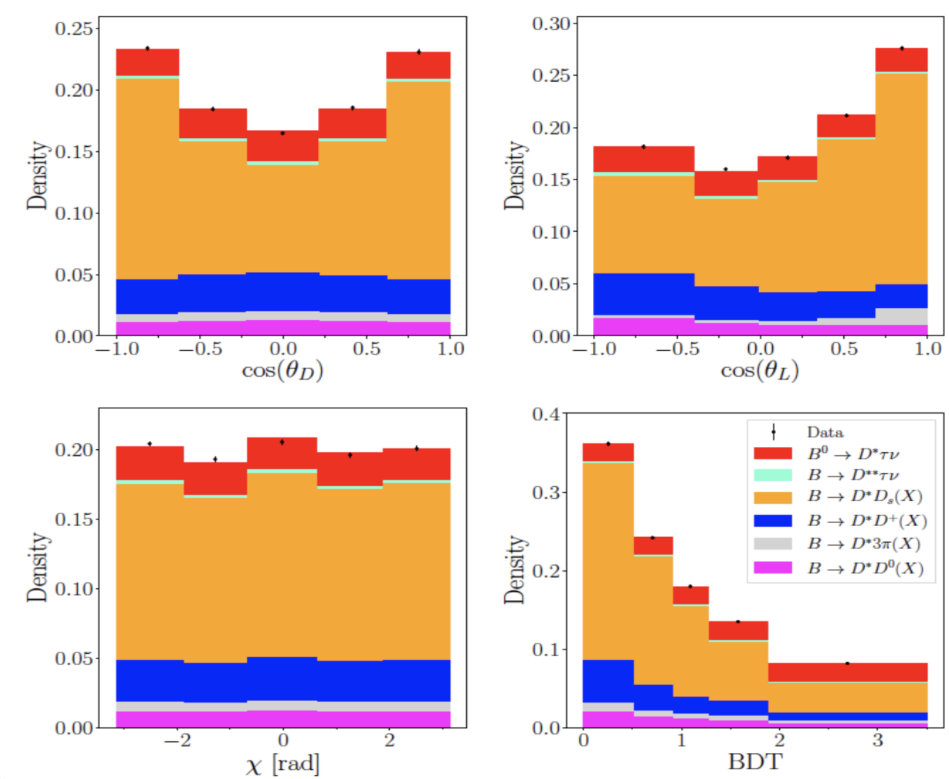


The broad resolutions for τ → μ demand very large samples to extract the underlying physics

Analyses using 3-prong hadronic τ decays, compared with τ → μ

- better angular resolutions
- lower statistics but better S/N

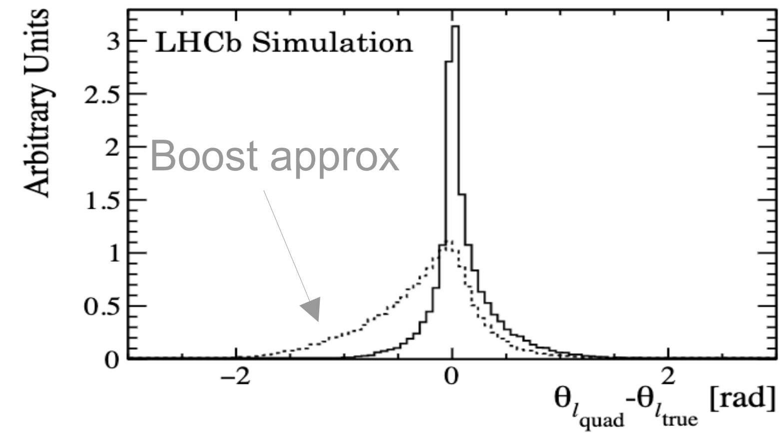
D. Hill et al.
JHEP11(2019)133

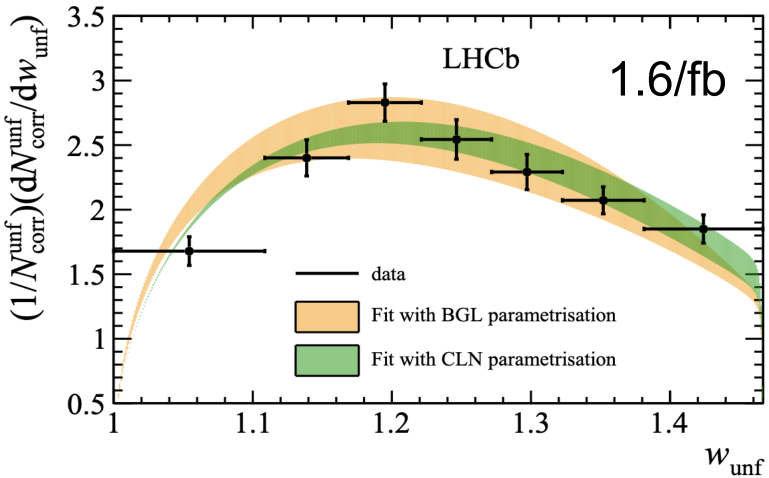


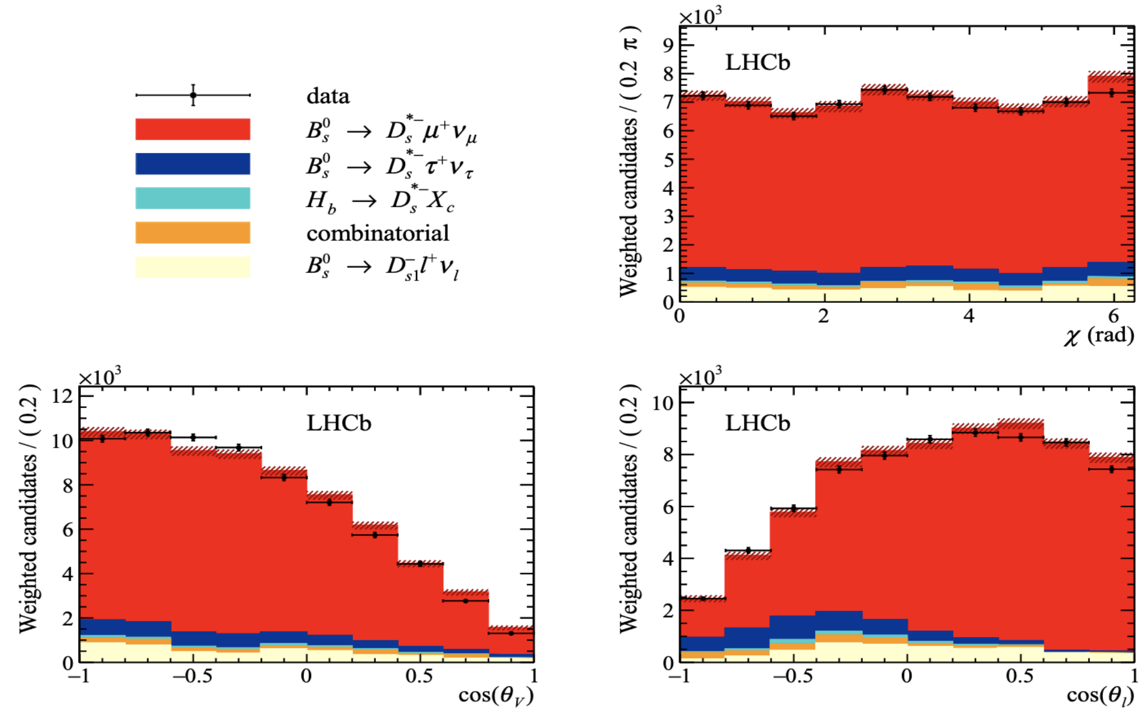
LHCb D* longitudinal polarization measurement in 2 q^2 bin

Differential measurements: $B_q \to D_q^* \mu\nu$

- Good resolution of angular variables
  - Assuming single massless neutrino
- Publication of unfolded q^2 spectra
  - $d\Gamma(\Lambda_b \to \Lambda_c \mu\nu)/dq^2$ PRD96 (2017) 112005
  - $d\Gamma(B_s \to D_s^* \mu\nu)/dq^2$ JHEP 12 (2020) 144



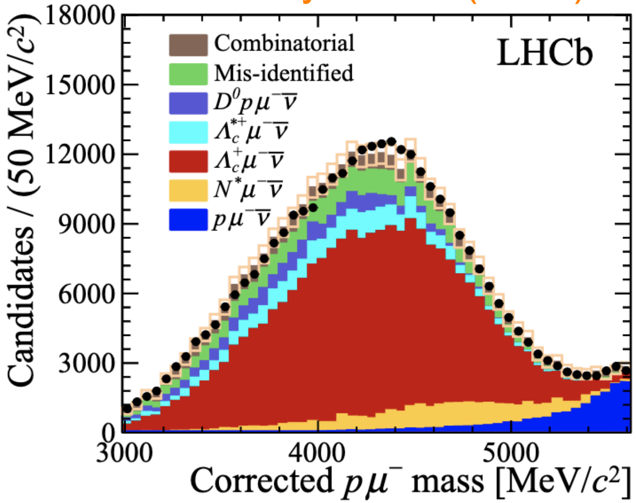




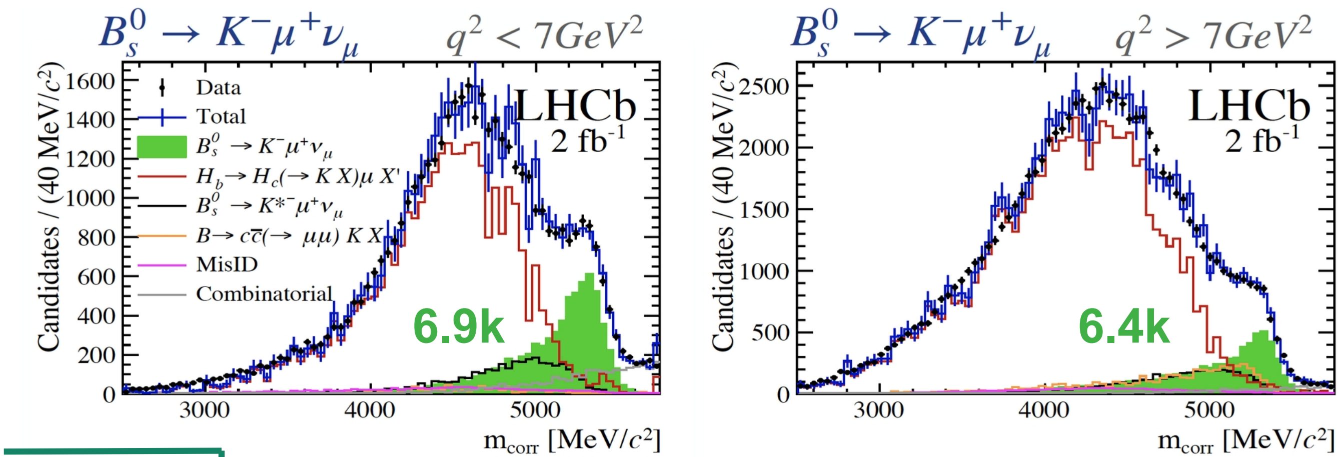
Update to a full angular analysis is ongoing
provide info on the unfolded spectrum

Unitarity Triangle sides: $|V_{ub}|/|V_{cb}|$

Nature Physics 11 (2015) 743



PRL 126 (2021) 081804



$$R_{BF} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)} \propto \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF_p}{FF_{\Lambda_c}}$$

S. Meinel at el. PRD 92 (2015) 3, 034503

- Update of $\Lambda_b \to$ p and Λ_c is ongoing: finite volume systematic will meet FLAG quality criteria

S. Meinel arXiv:2309.01821

$$R_{BF} = \frac{\mathcal{B}(B_b \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)} \propto \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF_K}{FF_{D_s}}$$

HPQCD Phys.Rev.D 90 (2014) 054506

FNAL/MILC Phys.Rev.D 100 (2019) 3, 034501

RBC/UKQCD Phys.Rev.D 107 (2023) 11, 114512

A.Khodjamirian, A.Rusov JHEP 08 (2017) 112

Golden mode for Lattice

Prospects on $B_s \to K \mu \nu$

$$R_{BF}(\text{low}) = (1.66 \pm 0.08\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.05\,(D_s)) \times 10^{-3},$$
$$R_{BF}(\text{high}) = (3.25 \pm 0.21\,(\text{stat})\,^{+0.16}_{-0.17}\,(\text{syst}) \pm 0.09\,(D_s)) \times 10^{-3},$$
$$R_{BF}(\text{all}) = (4.89 \pm 0.21\,(\text{stat})\,^{+0.20}_{-0.21}\,(\text{syst}) \pm 0.14\,(D_s)) \times 10^{-3},$$

Uncertainty	$\frac{\mathcal{B}(B_s \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)}$ [%]		
	No q^2 sel.	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle ID	1.0	1.0	1.0
m_{corr} error	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration		2.0	2.0
ε gen& reco	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
$\mathcal{B}(D_s^- \to K^- K^+ \pi^-)$	2.8	2.8	2.8

Analysis on the full Run2 dataset is ongoing

Expected signal yields:
- Low q^2: 39’000 signal events
- High q^2: 36’000 signal events

Largest systematics

- MC statistics: requires larger MC samples
- BF(Ds → K K π): reducible (planned in BESIII)
- Tracking: dominated by 2 additional tracks in the normalization channel

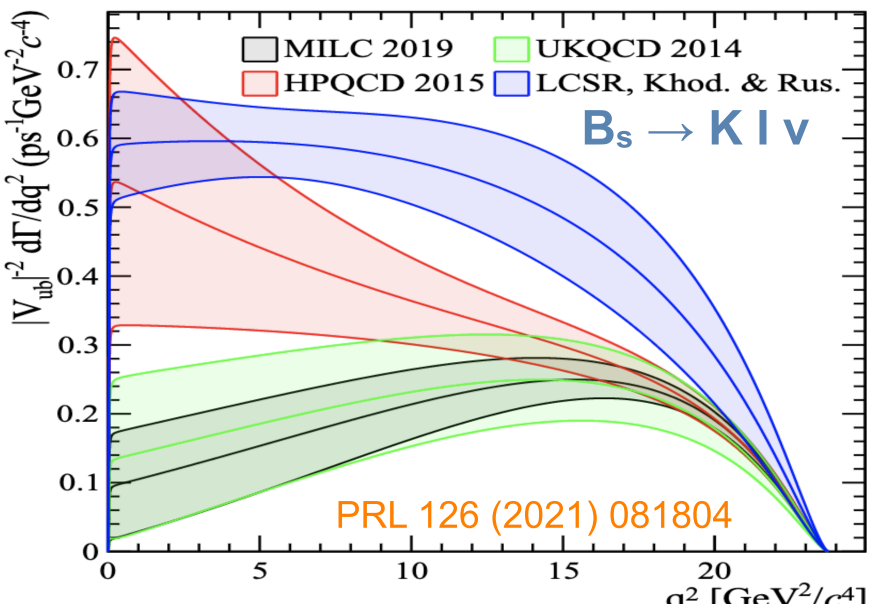
The high statistics allows to perform analysis in more q^2 bins

Differential distribution

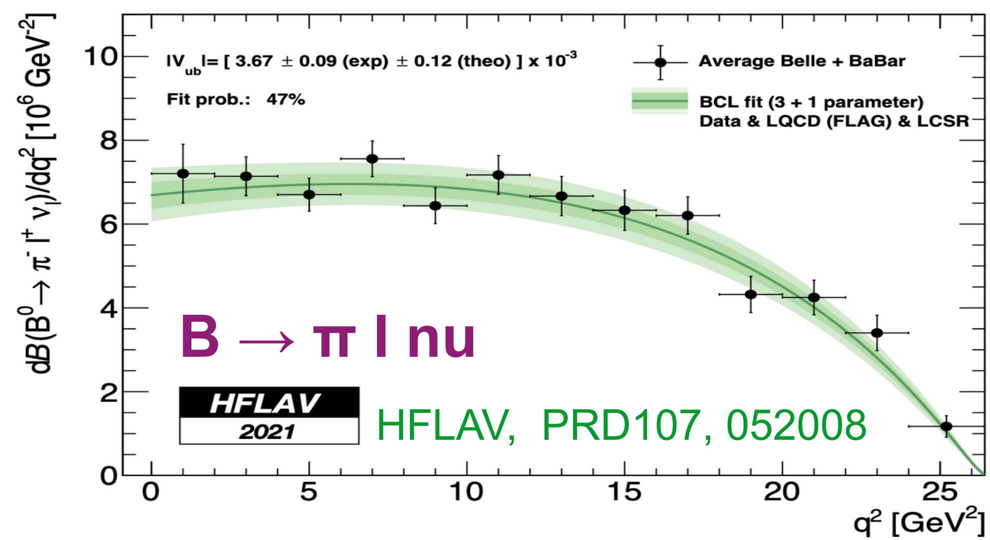
- Measuring partial rate in more q^2 bins
- Constrain the shape of the Form Factor $f_+(q^2)$
  - Large uncertainties due to the extrapolation to the full q^2

With Run2 it should be possible to have 6-8 q^2 bins, studies are ongoing

(differential shape of $\Lambda_b \to p\,\mu\nu$ would allow to validate the FF shape predictions)



It will be possible to perform global fits similar to what is done in HFLAV for $B \to \pi\,\mu\nu$

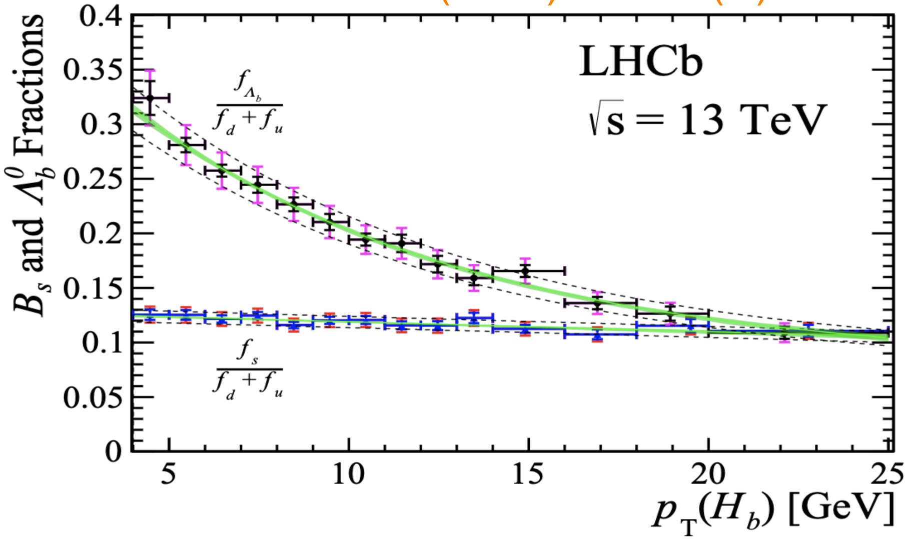


Global fits

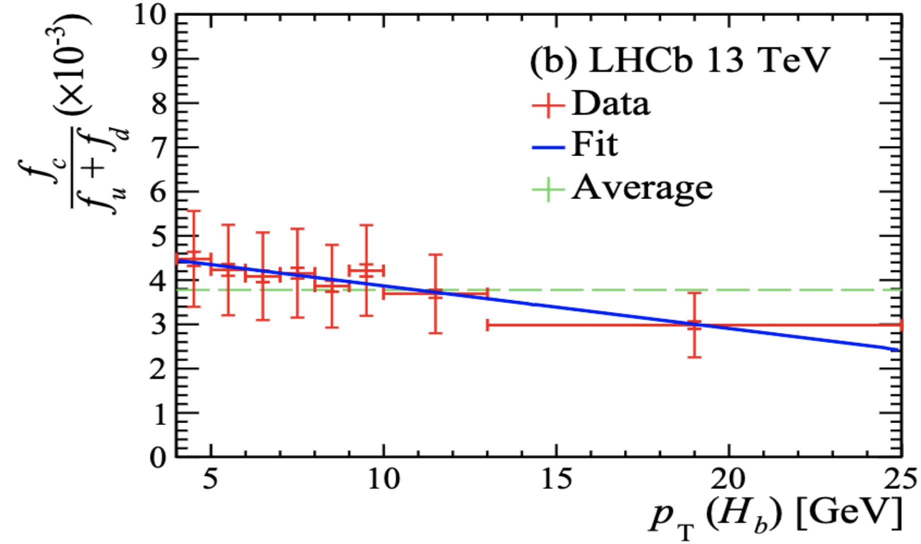
C. Bolognani et al. arXiv:2308.04347
A. Biswas et al. ArXiv:2212.02528
G. Martinelli et al. arXiv:2202.10285

B-hadron production fractions with SL decays

PRD100 (2019) 031102(R)



PRD100 (2019) 112006



- With inclusive semileptonic decays, measuring
  - $B_s \to X_c \mu\nu$ / $B \to (D^0+D^+) X \mu\nu$
  - $\Lambda_b \to X_c \mu\nu$ / $B \to (D^0+D^+) X \mu\nu$
- Rely on equality of SL decay widths

I. Bigi et al
JHEP 09 (2011) 012

$$\Gamma_{SL}(B_s) = (1 - 0.018(8)) \cdot \Gamma_{SL}(B_d)$$
$$\Gamma_{SL}(\Lambda_b) = (1 + 0.041(16)) \cdot \Gamma_{SL}(B_d)$$

Gambino, Bordone
ArXiv:2203.13107

- Using exclusive $B_c \to J/\Psi\ \mu\nu$
  - $B_c \to J/\Psi\ \mu\nu$ / $B \to (D^0+D^+) X \mu\nu$
  - Uses calculations of Form Factors to determine BF($B_c \to J/\Psi\ \mu\nu$)

Production fraction of Ξ^+_b Ξ^0_b Ω_b … ?

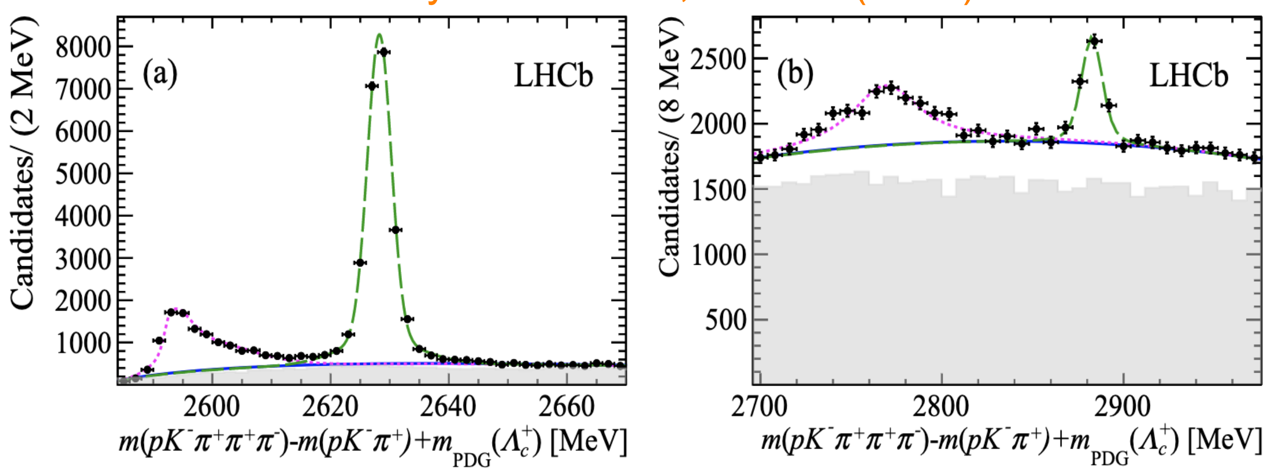
Requires: Form Factors, knowledge of absolute BFs of charm baryons

Opportunities with baryons

- Already measured $|V_{ub}/V_{cb}|$, $R(\Lambda_c)$, $d\Gamma(\Lambda_b \to \Lambda_c\, \mu\nu)/dq^2$
  - Expected 7.5M signal $\Lambda_b \to \Lambda_c\, \mu\nu$ ($\Lambda_c \to pK\pi$) in Run1+Run2
- Ongoing:
  1. Measurement of double differential rate as a function of q^2 and $\cos(\theta_{lep})$, expect good sensitivity to Right Handed currents
  2. Measurement of $|V_{cb}|$ exploiting equality of partial Γ_{SL}
  3. Decays into excited states:

M. Ferrillo et al. JHEP 12 (2019) 148

Phys. Rev. D 96, 112005 (2017) Run1



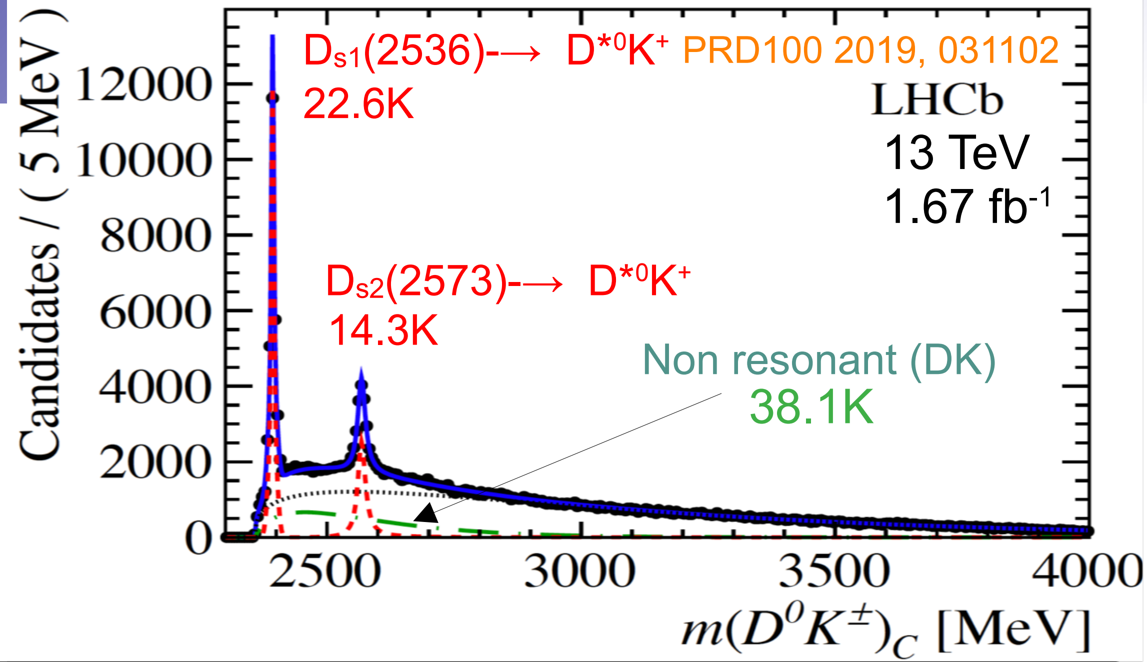
	J^P	Width
$\Lambda_c(2595)^+$	$1/2^-$	2.6 MeV
$\Lambda_c(2625)^+$	$3/2^-$	<1 MeV

Plenty of signal
Possibility to measure FFs and branching fractions
- crucial to bkg. constraint to $R(\Lambda_c)$

Study of $B_s \to D_s^{**}\mu\nu$

- Clean samples of $B_s \to D_{s1}(2536)\mu\nu$ and $B_s \to D_{s2}(2537)\mu\nu$

  - Various ongoing analyses on $B_s \to D_s^{**}\mu\nu$
    - FFs , relative BFs, $R(D_s^{**})$



- Spectrum of excited L=1 D_s^{**} states different with corresponding D^{**} states
- D_s^{**} are all narrow:
  1. New path to understand puzzles in $B \to D^{**}\mu\nu$
  2. SL decays into $D_{s0}(2317)$ and $D_{s1}(2460)$ can shed light on the nature of these states

- Precise measurements of exclusive $B_s \to H_{cs}^{**}\mu\nu$ decays allows determination of hadronic moments of X_{cs} in inclusive $B_s \to X_{cs}^{**}\mu\nu$ using a Sum-of-Exclusive Modes
  - Access to OPE parameters for B_s decays: improve predictions of B_s SL and total widths
  - Similar approach done by CDF and DELPHI for B mesons

Inclusive Bs
@ Barolo SL WS

What else?

- Many other SL decays can be accessed with increasing statistics
  - $B \to p\bar{p}\, \tau\nu$: promising LFU test in $b \to u$ transition in LHCb
    - Expected 10K events at the end of Phase II (300 fb^{-1})
    - but theory is not developed yet
  - $B \to KK\mu\nu(\pi)$: to constrain part of ss-popping in inclusive $B \to X_u\mu\nu$

    I. Bigi arXiv:1507.01842
  - $B \to \mu\nu\gamma$, via $B \to \mu\nu\gamma^*$ ($\gamma^* \to e+e-$)
    - Gives information to leading moment of B-meson dispersion amplitude A. Bharucha et al. arXiv:2102.03193
    - LHCb very stringent UL on $B \to \mu\nu\mu\mu$ with $m(\mu+\mu-) < 980$ MeV

      EPJC 79 (2019) 675
    - Will cross check Belle II measurement
  - Study more deply SL B_c decays
    - Measurement of $|V_{ub}|/|V_{cb}|$, for factors, BFs, $c\bar{c}$ spectroscopy studies

Colandego et al. PRD 106 (2022) 9, 094005

What else?

- Many other SL decays can be accessed with increasing statistics
- $B \to p\bar{p}\tau\nu$: promising LFU test in $b \to u$ transition in LHCb
  - Expected 10K events at the end of Phase II (300 fb^{-1})
  - but theory is not developed yet (ever be?)
- $B \to \mu\nu\gamma$, via $B \to \mu\nu\gamma^*$ ($\gamma^* \to e^+e^-$)
  - Gives precious information on B meson DA

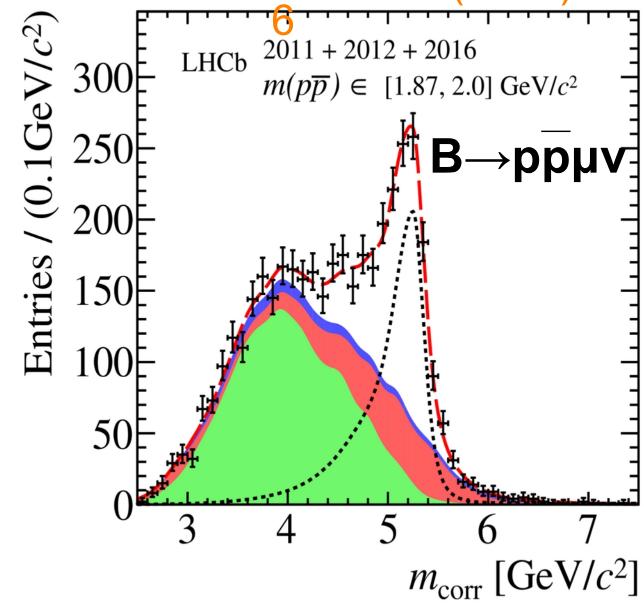
S.Kurten et al. PRD 107 (2023) 5, 053006
M.Beneke et al. EPJC 81 (2021) 7, 638
C.Wang et al. JHEP 02 (2022) 141
A.Bharucha et al. arXiv:2102.03193
M.Ivanov, D, Melikhov PRD 105 (2022) 1, 014028, PRD 106 (2022) 11, 119901

LHCb very stringent UL on $B \to \mu\nu\mu\mu$ with $m(\mu^+\mu^-) < 980$ MeV

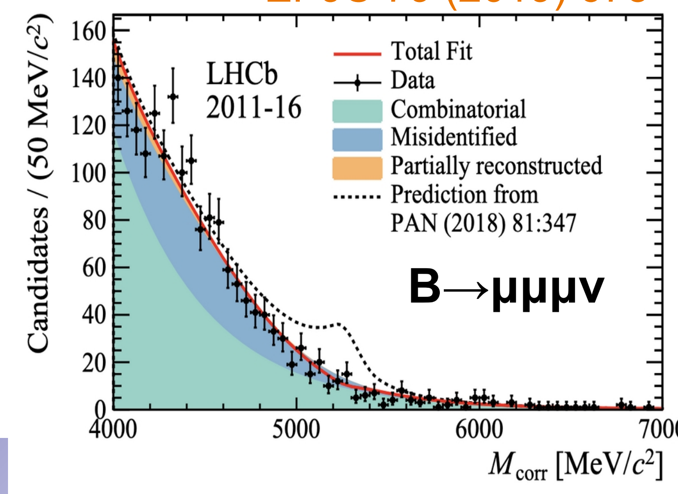
- $B \to KK\mu\nu(\pi)$: to constrain part of $s\bar{s}$ contribution in inclusive $B \to X_u\mu\nu$
- Semileptonic B_c decays: insight on $c\bar{c}$ spectroscopy

Colangelo et al. PRD 106 (2022) 9, 094005

JHEP 03 (2020) 146



EPJC 79 (2019) 675



Conclusions

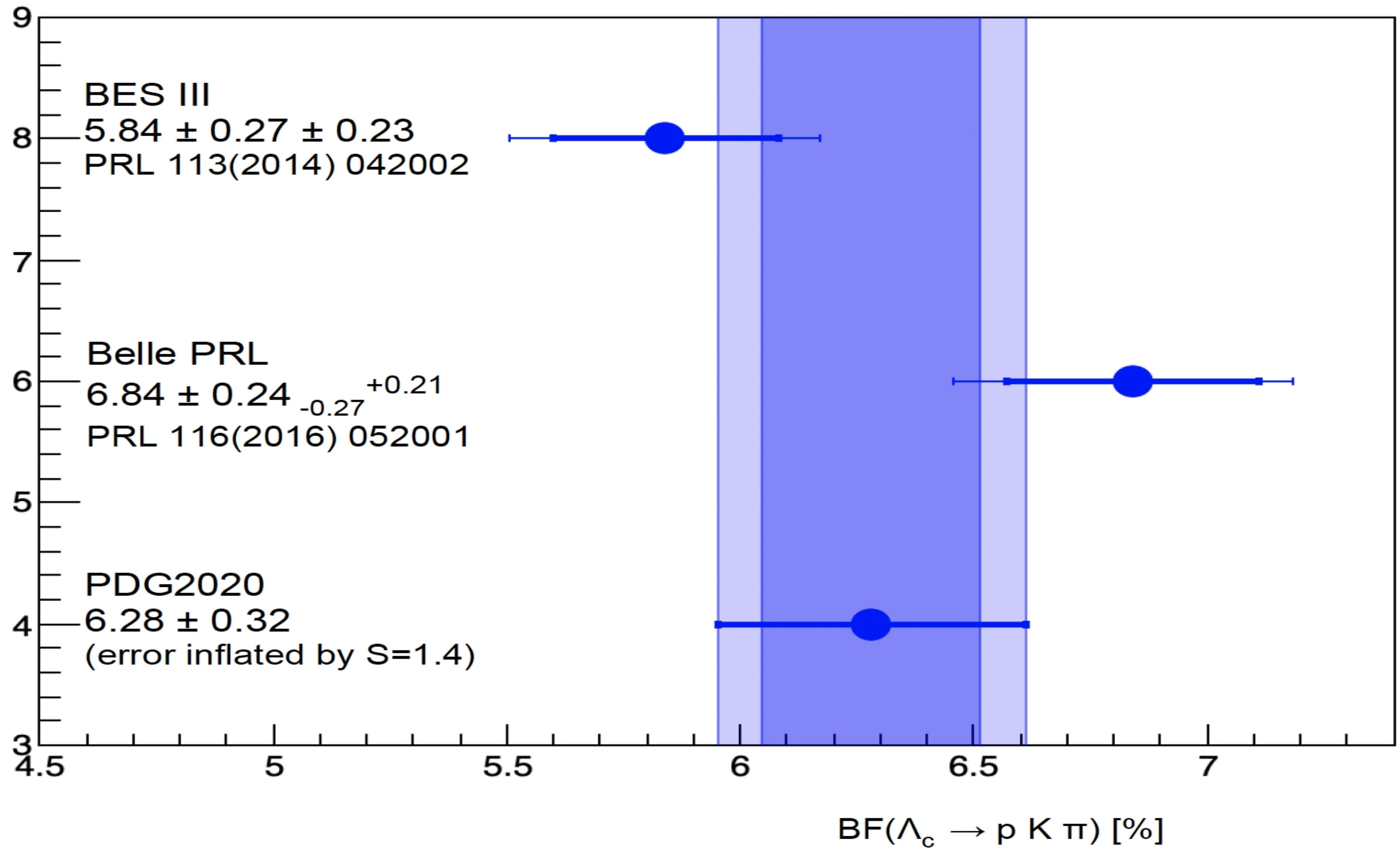
- Many ongoing analysis on full dataset
  - Major focus: $R(H_c)$ and full angular analysis of many different channels
- Statistics and detector performances foreseen in Run3-Run4 with Upgrade I is very promising
  - huge statistics, higher signal efficiency, interesting opportunities with electrons
  - Often systematics are limited by external inputs
    - Crucial inputs from other experiments (BES III, Belle, Belle II)
    - Crucial a close collaboration with theorists (both Continuum and Lattice)
- The motivation for a Upgrade II for SL decays is strong
  - Very high precision on measurement of differential shapes for many b-hadrons
  - Significant contribution to ultimate precision on $|V_{ub}|$, $|V_{cb}|$
  - Unique program to study semitauonic decays

Backup

FLAG21

Process	Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment
$\Lambda_b \to \Lambda_c^*(2625)\,\ell^-\bar{\nu}_\ell$	Meinel 21	[638]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda_c^*(2595)\,\ell^-\bar{\nu}_\ell$	Meinel 21	[638]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda^*(1520)\,\ell^+\ell^-$	Meinel 20	[648]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda\,\ell^+\ell^-$	Detmold 16	[643]	2+1	A	○	○	■	○	✓
$\Lambda_b \to p\,\ell^-\bar{\nu}_\ell$	Detmold 15	[516]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda_c\,\ell^-\bar{\nu}_\ell$	Detmold 15, Datta 17	[516, 637]	2+1	A	○	○	■	○	✓

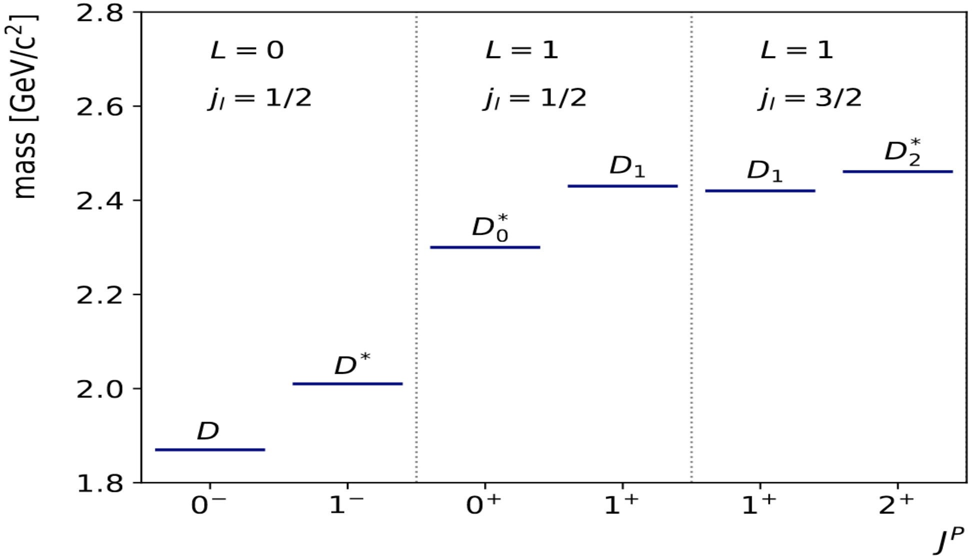
Update of $\Lambda_b \to p$ and Λ_b is ongoing: finite volume systematic will meet FLAG quality criteria!



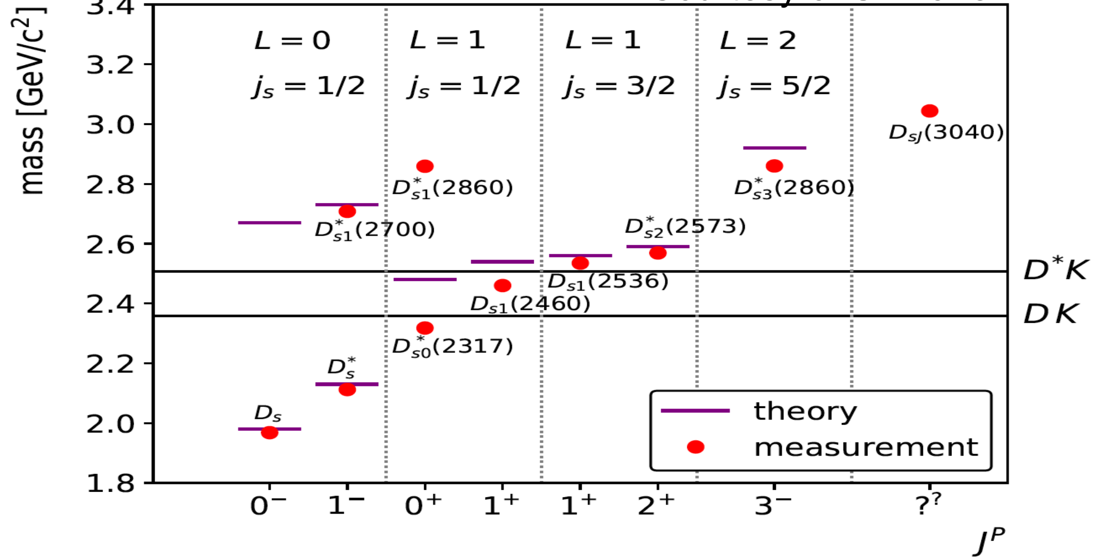
BES III
5.84 ± 0.27 ± 0.23
PRL 113(2014) 042002
Belle PRL
6.84 ± 0.24 -0.27 +0.21
PRL 116(2016) 052001
PDG2020
6.28 ± 0.32
(error inflated by S=1.4)
9
8
7
6
5
4
3
4.5
5
5.5
6
6.5
7
BF(Λc → p K π) [%]

Spectroscopy of $(c\bar{d})$ and $(c\bar{s})$

Spectrum of excited D_s^{**} states different with corresponding D^{**} states



Courtesy of S. Klaver



	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_0^*	0^+	2352 ± 50	261 ± 50	$D\pi$
D_1'	1^+	2427 ± 36	384^{+130}_{-105}	$D^*\pi$
D_1	1^+	2421.3 ± 0.6	27.1 ± 2.7	$D^*\pi, D^0\pi^+\pi^-$
D_2^*	2^+	2462.6 ± 0.7	49.0 ± 1.4	$D^*\pi, D\pi$

	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_{s0}^*	0^+	2317.8 ± 0.6	< 3.8	$D_s^+\pi^0$
D_{s1}'	1^+	2459.5 ± 0.6	< 3.5	$D_s^{*+}\pi^0, D_s^+\gamma, D_s^+\pi^+\pi^-$
D_{s1}	1^+	2535.28 ± 0.20	< 2.5	$D^{*+}K^0, D^{*0}K^+$
D_{s2}^*	2^+	2572.6 ± 0.9	20 ± 5	D^0K^+

Similar effect for $B_s \to D_s^*$

HPQCD 21

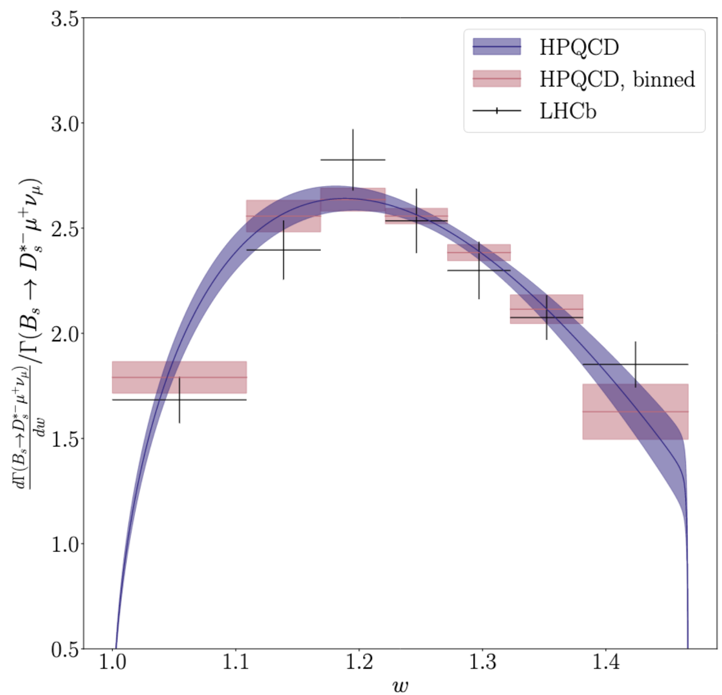


FIG. 13. The differential rate $d\Gamma/dw$ for $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ as a function of the recoil $w = v_{B_s} \cdot v_{D_s^*}$ and normalised by the total decay rate calculated from our form factors is given by the purple band. We also show our rate integrated across bins and measurements by LHCb [56].

HPQCD 23

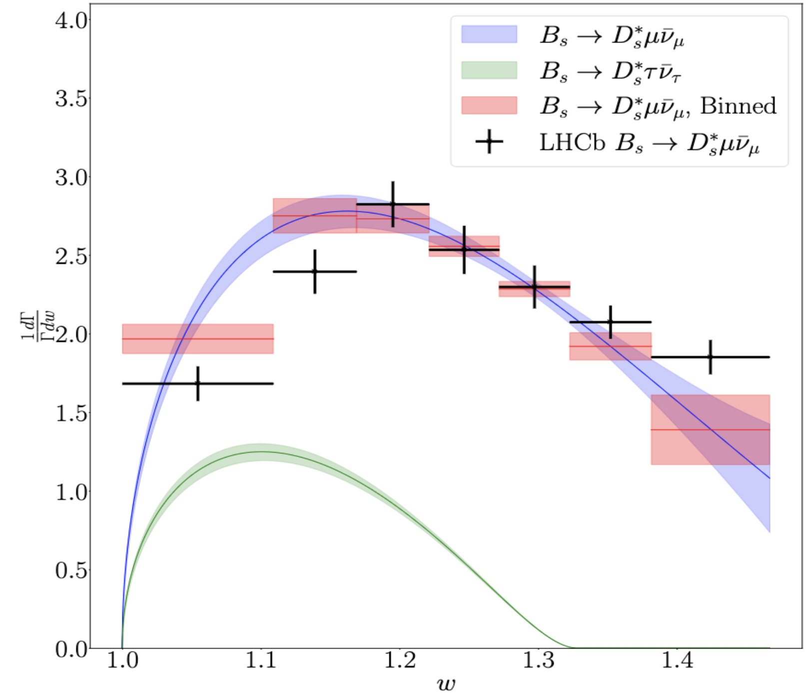
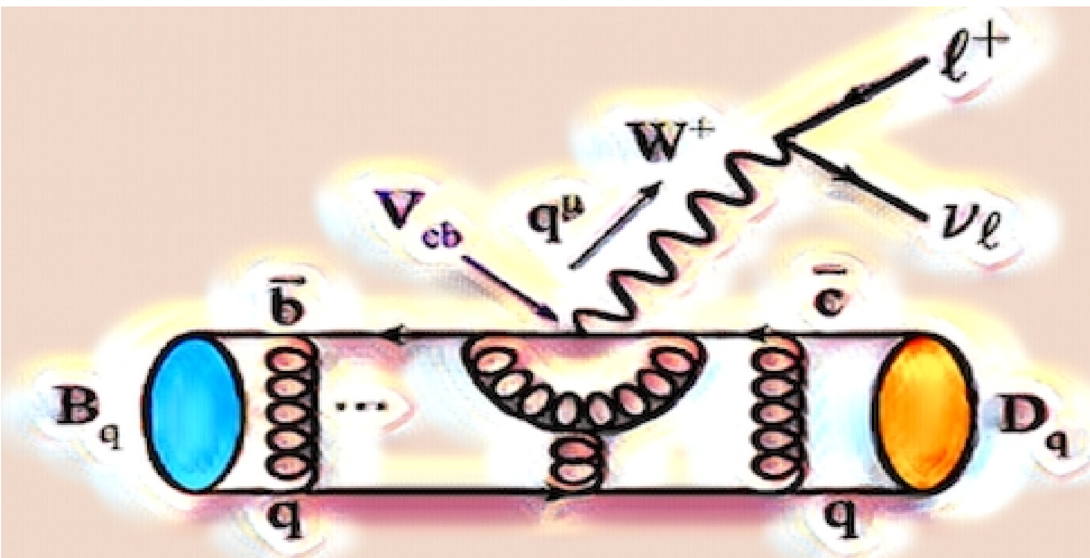


FIG. 10. Our normalised differential decay rate for $B_s \to D_s^* \ell \bar{\nu}$ with respect to w is shown as the blue band. We also include binned data from LHCb [65]. Here, as for $B \to D^*$, we see a similar difference in shape between SM theory and experiment to that seen for Belle $B \to D^*$ data in Fig. 9. The semitauonic mode is plotted as the green band.

Summary

M. Jung

Central lesson:
Experiment and theory (lattice + pheno) need to work closely together!

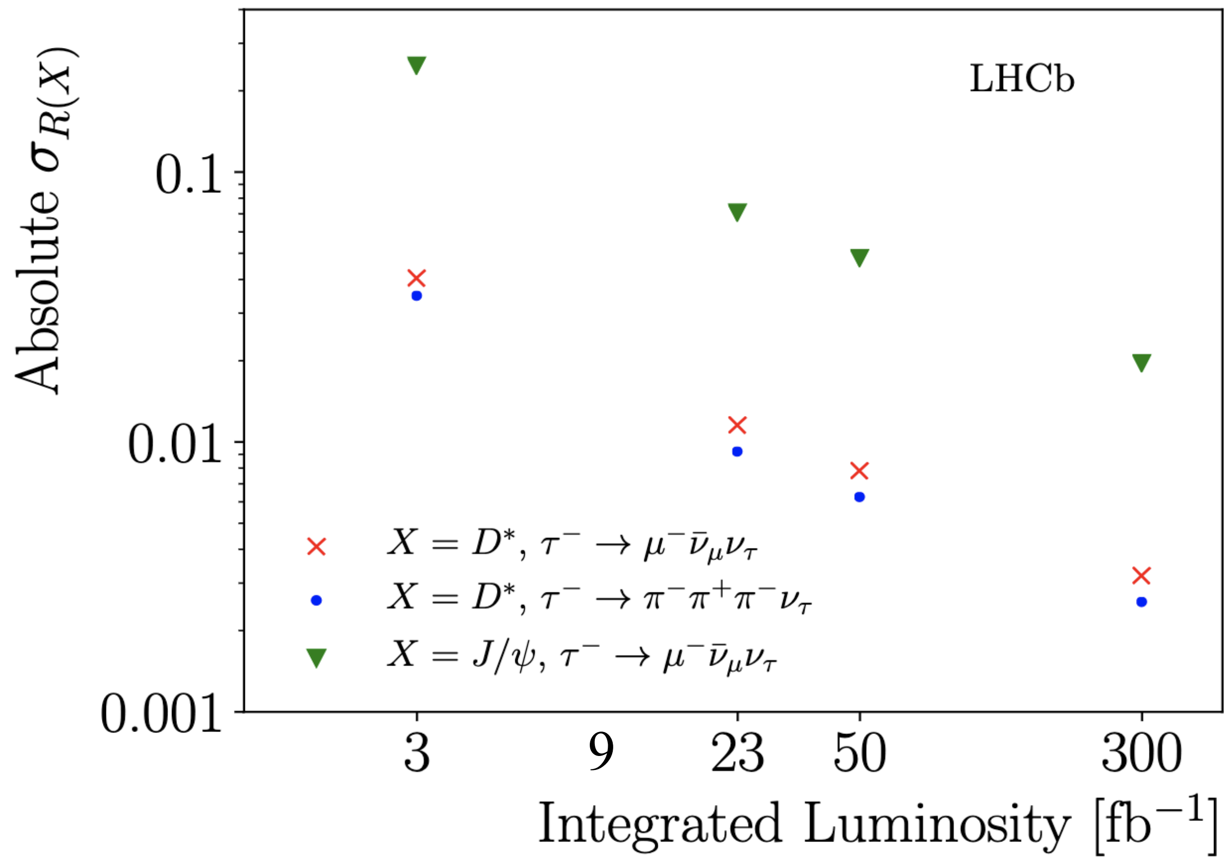


Projections on $R(H_c)$ measurements

Physics case for an LHCb Upgrade II

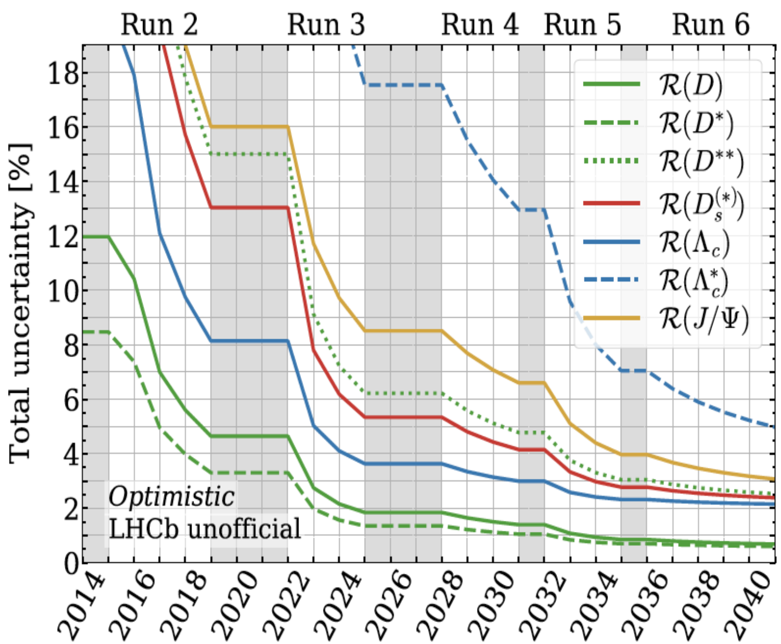
arXiv:1808.08865

- 9 fb^{-1} (Run 1-2)
- 23 fb^{-1} (Run 1-3)
- 50 fb^{-1} (Run 1-4)
- 300 fb^{-1} (Run 1-5)



Projections on $R(H_c)$ measurements

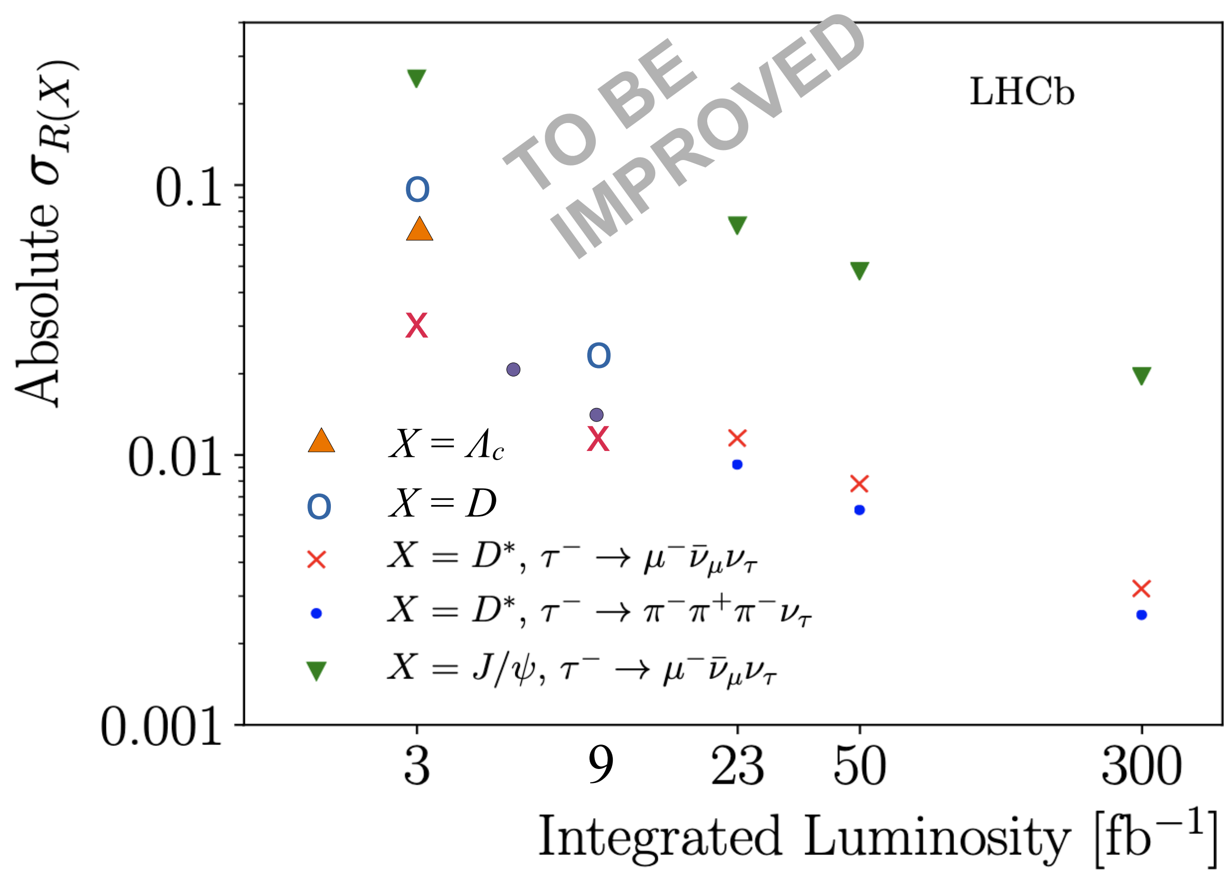
Projections on other ongoing analyses in LHCb
If the anomaly persists, crucial cross check with other decay modes



arXiv:2101.08326

Physics case for an LHCb Upgrade II

arXiv:1808.08865



Run3 and beyond: b-hadron samples

Updated from Bernlochner, MFS, Robinson, Wormser, RMP, 94, 015003 (2022)

Experiment	*BABAR*	Belle	Belle II	LHCb Run 1	LHCb Run 2	LHCb Runs 3–4	LHCb Runs 5–6
Completion date	2008	2010	2035	2012	2018	2032	2043
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4)\times10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	424	711/121	$(50/4)\times10^3$	3	6	40	300
B^0 mesons [10^9]	0.47	0.77	50	100	350	2,500	19,000
B^+ mesons [10^9]	0.47	0.77	50	100	350	2,500	19,000
B_s mesons [10^9]	-	0.01	0.5	24	84	610	4,600
Λ_b baryons [10^9]	-	-	-	51	180	1,300	9,800
B_c mesons [10^9]	-	-	-	0.8	4.4	19	150

Upgrade I Upgrade II

- Upgrade I and II datasets **orders of magnitude larger**

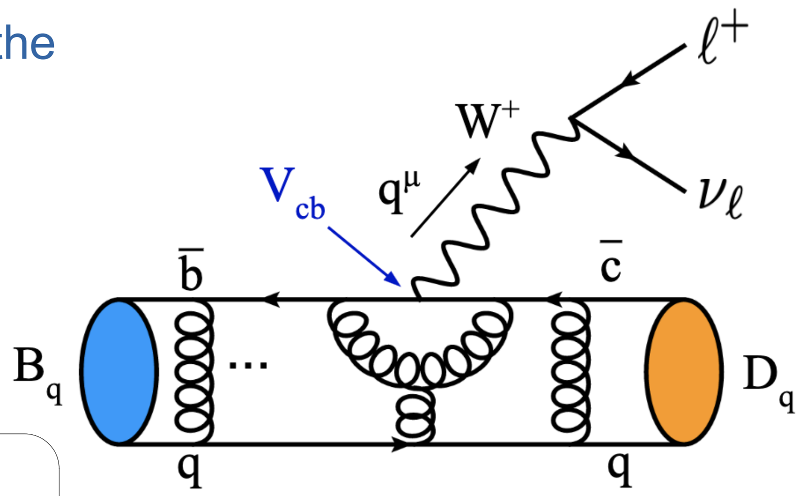
New era of **unprecedented precision** starting at LHCb

From M.F.Sevilla talk at SM@LHC workshop

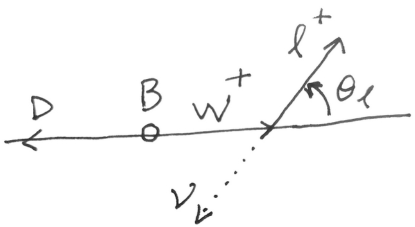
B→Dℓν and |V$_{cb}$|

- In the SM the amplitude for B→Dℓν depends only from the Vector interaction term

$$\langle D|\bar{c}\gamma_\mu b|\overline{B}\rangle_V = f_+(q^2)\left((p_B+p_D)_\mu - \frac{(p_B+p_D)\cdot q}{q^2}q_\mu\right) + f_0(q^2)\frac{(p_B+p_D)\cdot q}{q^2}q_\mu$$



For light leptons ℓ=e,μ
$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \frac{G_F^2|V_{cb}|^2\eta_{EW}^2}{32\pi^3}k^3|f_+(q^2)|^2\sin^2\theta_\ell$$



- |V$_{cb}$| via measurement of differential decay width shape

  + Knowledge of BF(B→Dℓν) from external inputs

  + Points or parameters for form factor normalization using Lattice QCD

P. Gambino's talk 29/5

- Form factors parameterization:
  - **CLN**: model dependent, unaccounted uncertainties
  - **BGL**: less model assumptions

Caprini, Lellouch, Neubert Nucl. Phys. B530,153(1998)
Boyd, Grinstein, Lebed, Nucl.Phys.B462,493(1996)