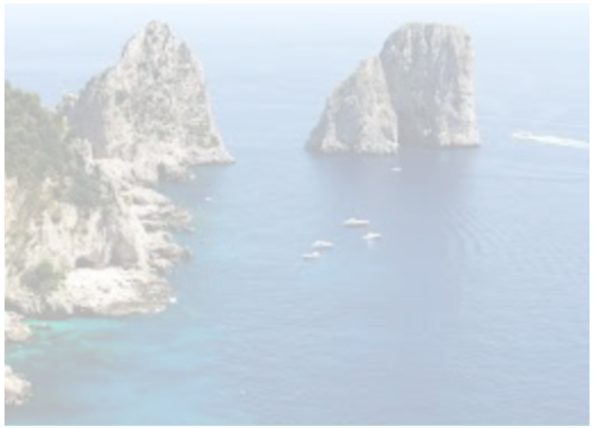
Experimental Review on Lepton Universality and Lepton Flavour Violation tests in B decays

P. de Simone (LNF-INFN),
on behalf of the **LHCb collaboration**
with contributions from Babar and Belle



Workshop on "Flavour changing and conserving processes" 2019 FCCP

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outline

1. Lepton Flavour Universality

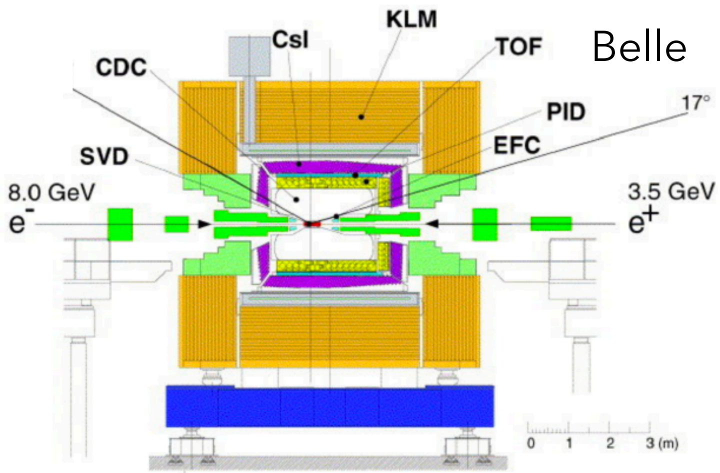
- ✓ lepton-flavour universality in $b \to sll$: R_K, $R_{K^{*0}}$
- ✓ lepton-flavour universality in $b \to c\tau\nu_\tau$: $R(D)$, $R(D^*)$, $R(J/\psi)$

2. Lepton Flavour Violation

- ✓ $B_{d,s} \to e\mu$
- ✓ $B_{d,s} \to \tau\mu$
- ✓ $B_d \to K^* e\mu$

the main players

the **Belle** detector [NIM A479 (2002) 117-232]
the **BaBar** detector [NIM A479 (2002) 1-116]

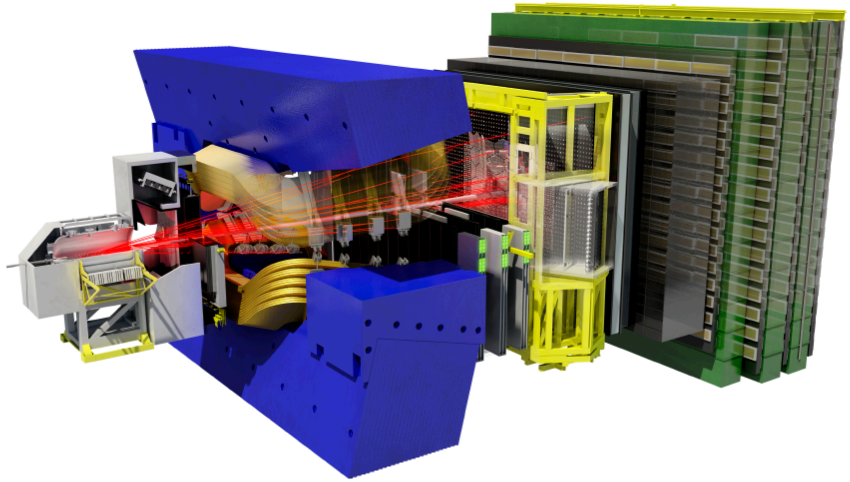


e⁺e⁻ colliders @ ϒ(4S) resonance

- b quarks produced from ϒ(4S) →B^+B^- or $B^0\overline{B}^0$, σ_{bb}~0.001 μb
- very clean environment
- well-constrained kinematics help reconstruct final states with νs

BaBar 1999–2008: 433 fb^{-1} @ ϒ(4S)
Belle 1999–2010: 711 fb^{-1} @ ϒ(4S)

the **LHCb** detector [JINST 3 (2008) S08005]



pp collisions @ LHC

- b quarks produced by gluon fusion forward direction, σ_{bb}~500 μb, but harsher environment
- boosted CM energy helps to reconstruct vertices, B mesons fly ~1 cm
- all b-hadron species are produced: B^+, B^0, B_s, B_c, Λ_b

Run 1 2011–2012: 3 fb^{-1} @ 7-8 TeV
Run 2 2015–2018: 6 fb^{-1} @ 13 TeV

anomalies about the Lepton Flavour Universality

- SM features Lepton Flavour Universality (**LFU**) ➔ the couplings of charged leptons to gauge bosons are lepton-flavour independent, and LFU is only broken by the Yukawa interaction, hence, *any further deviation is a key signature of physics processes beyond the SM*

- ***no evidence of deviation from the SM*** in the precise (per-mil) tests of LFU in semi-leptonic K and π decays, purely leptonic decays, and in the electroweak precision observables
✓ except for a 2.8 σ difference between the measurement of the branching fraction of the $W \to \tau\nu_\tau$ decay with respect to $W \to \mu\nu_\mu$ and $W \to e\nu_e$ decays [Phys. Rept. 532 (2013) 119]

- ***observed deviations from SM in B decays can naturally be grouped into two categories***
  - ✓ FCNC $b \to s\ell\ell$ transitions
  - ✓ tree level semileptonic $b \to c\tau\nu_\tau$ transitions

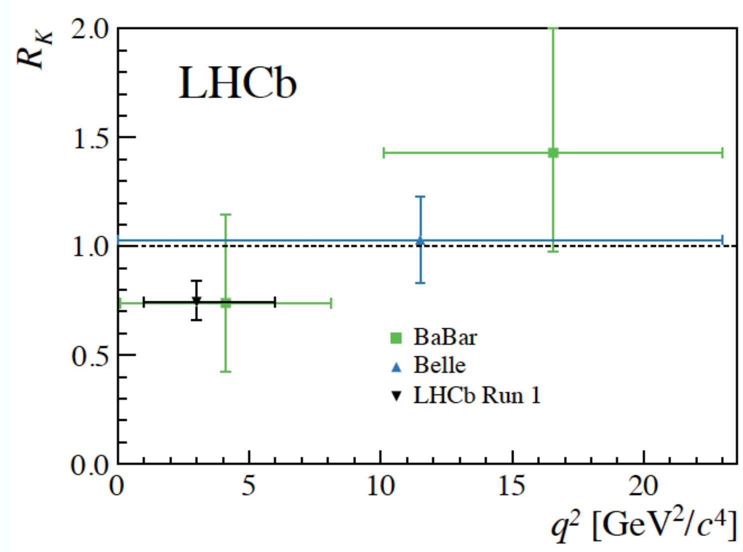
- possible BSM scenarios: leptoquarks, new heavy vector bosons, $H^{\pm}$, ...

- main test variables are ratios of decay rates
  - ✓ ***theoretically clean:*** cancellation of QCD effects
  - ✓ ***experimentally clean:*** cancellation of efficiency and reconstruction effects

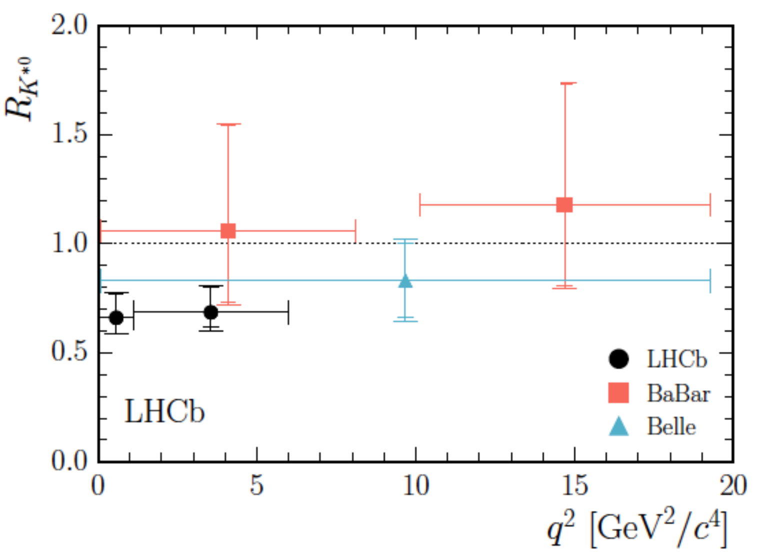
test of LFU in B→ K$^{(*)}\ell\ell$ decays

- FCNC transitions occur via loop in the SM ➔ expected BR < 10^{-6}
- $R_{K(*)}$ is close to unity in SM, with very small uncertainties: $R_{K^{(*)}} = \dfrac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$
  - ✓ hadronic uncertainties of O(10^{-4}) [JHEP 07 (2007) 040]
  - ✓ QED uncertainties can be O(10^{-2}) [EPJC 76 (2016) 8,440]

$B^+ \to K^+\ell^+\ell^-$



$B^0 \to K^{*0}\ell^+\ell^-$



RUN 1 (3 fb^{-1}) measurements @ LHCb are systematically below the SM expectations → 2.2 – 2.6 σ

[Belle, PRL 103 (2009) 171801]
[BaBar, PRD 86 (2012) 032012]
[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]

new R_K at LHCb

[LHCb, PRL 122 (2019) 191801]

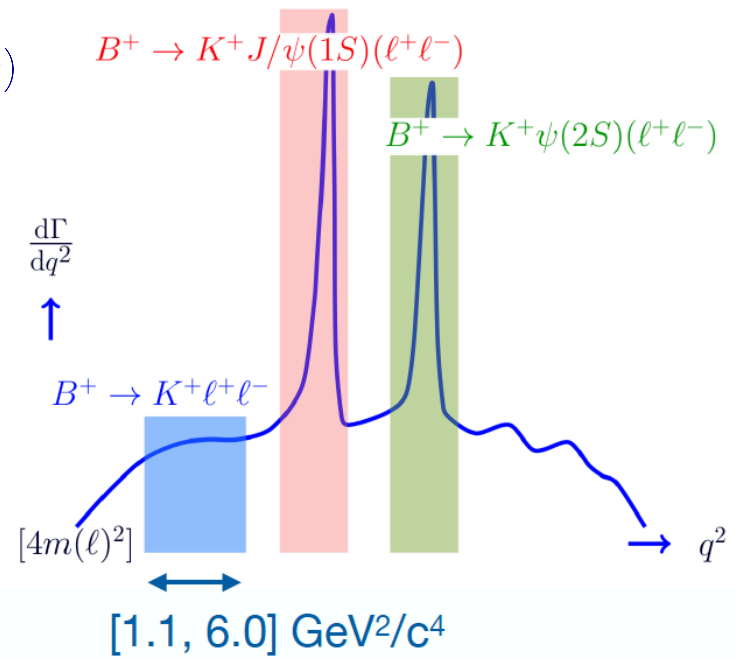
- ***new R_K measurement with about twice as many B's as previous measurement***
  - ✓ re-optimised analysis of RUN 1 data (3 fb^{-1})
  - ✓ added 2015 and 2016 datasets from RUN 2 (2 fb^{-1})

the ee channel is the challenge of these analysis

Bremsstrahlung affects the electron momentum

✓ **lower reconstruction + trigger efficiencies**

✓ **lower mass and q^2 resolution**



rare and resonant modes:

✓same event selection

✓separated by q^2

- to cancel most of the systematic effects R_K is measured as a double ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$

$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

new R_K at LHCb

[LHCb, PRL 122 (2019) 191801]

mass-shape models and efficiency ratios are derived from simulation carefully corrected using data control samples ➔

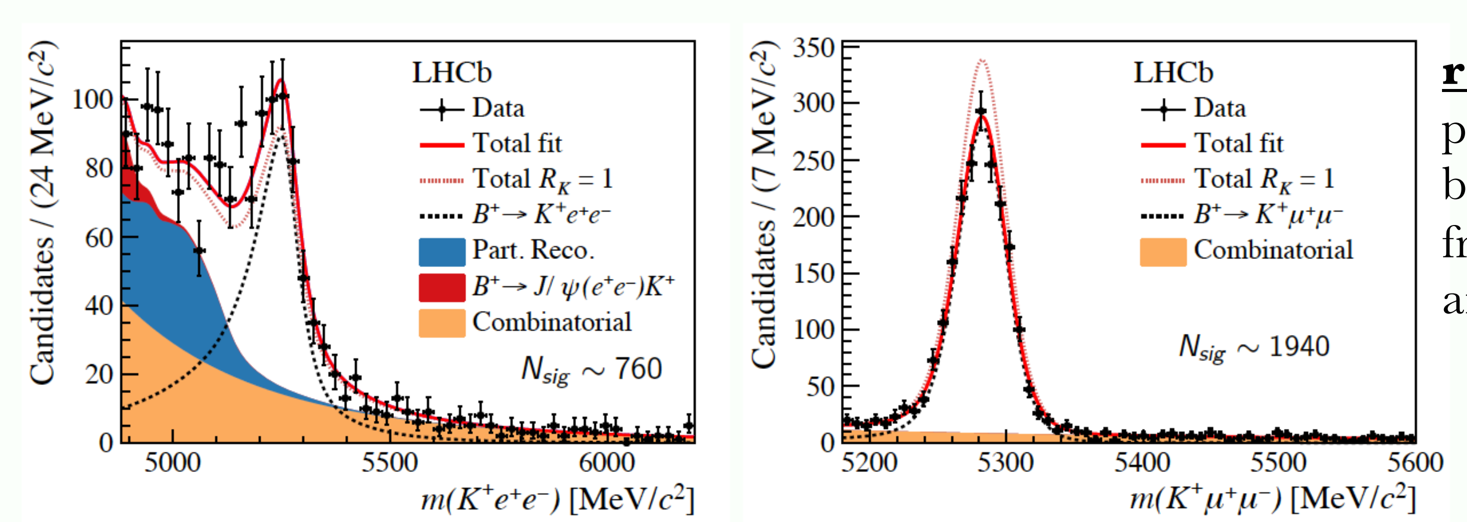
- ✓ B^+ kinematic
- ✓ Particle IDentification
- ✓ trigger

numerous cross-checks to ensure the effectiveness of the corrections

$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+ J/\psi(ee))} = 1.014 \pm 0.035$$

stringent test as it requires **muon** and **electron** efficiencies to be controlled individually

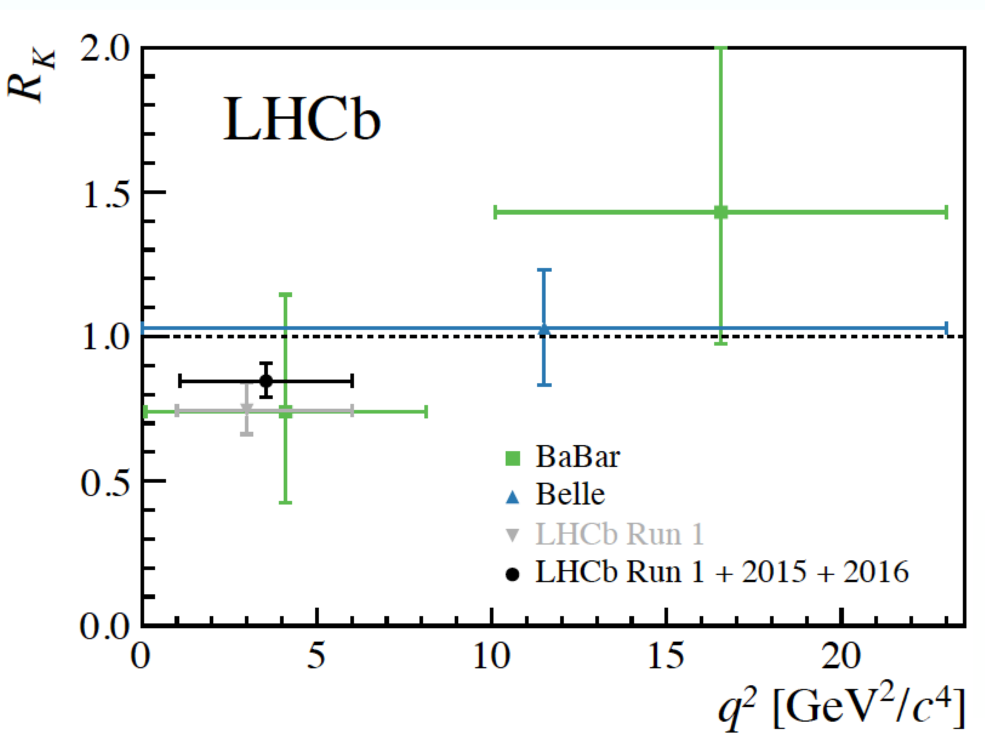
a simultaneous fit to rare + resonant electron and muon channels is performed to extract R_K



rare modes:
partially reconstructed background and tail from resonant mode are significant in ee

new R_K at LHCb: result

[LHCb, PRL 122 (2019) 191801]



Run 1 (3 fb^{-1}) + Run 2 (2 fb^{-1}) analysis

$$R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.014}_{-0.016}\,(\text{syst})$$

compatible with the SM expectation at **2.5 σ**

by fitting Run 1 and Run 2 separately

$$R^{\text{new}}_{K\ \text{Run 1}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}$$

$$R_{K\ \text{Run 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017}$$

the new analysis on Run 1 data (new reconstruction and selection) agrees with the old one within 1σ

main contributions to systematic :

✓ uncertainty on fit shape

✓ corrections to B^+ kinematic and trigger efficiencies

new R_{K*} at Belle

[Belle, arXiv:1904.02440v2]

- ***new R_{K*} measurement for both charged and neutral B mesons***
  - ✓ data sample 711 fb^{-1}
    ➔ 772×10^6 B pairs

- dominant background due to combinatorial suppressed cutting on
  - ✓ the beam energy constrained mass $M_{\rm bc} = \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_B|^2/c^2}$
  - ✓ and on $\Delta E = E_B - E_{\rm beam}$

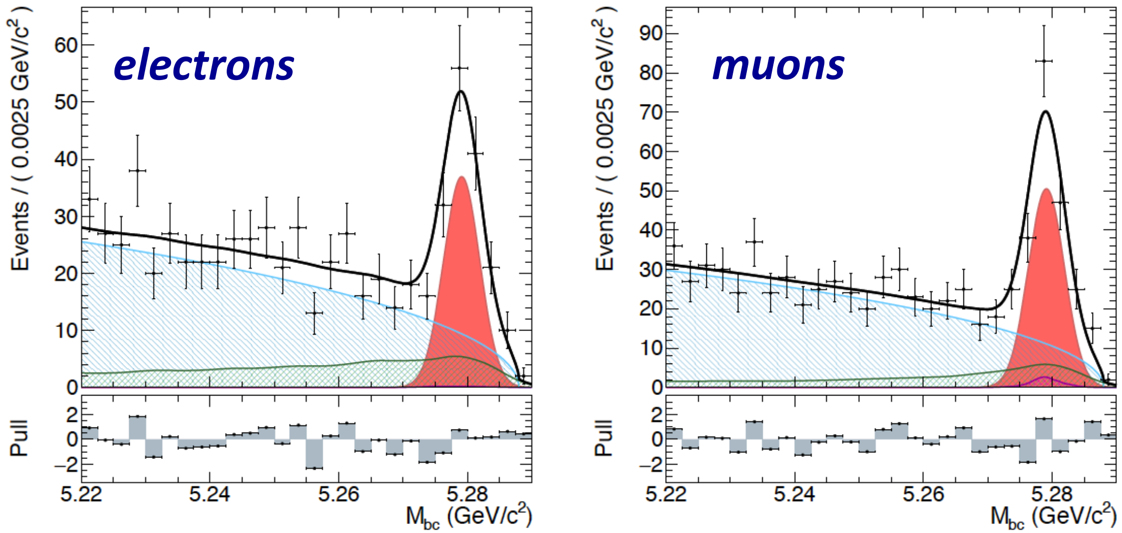
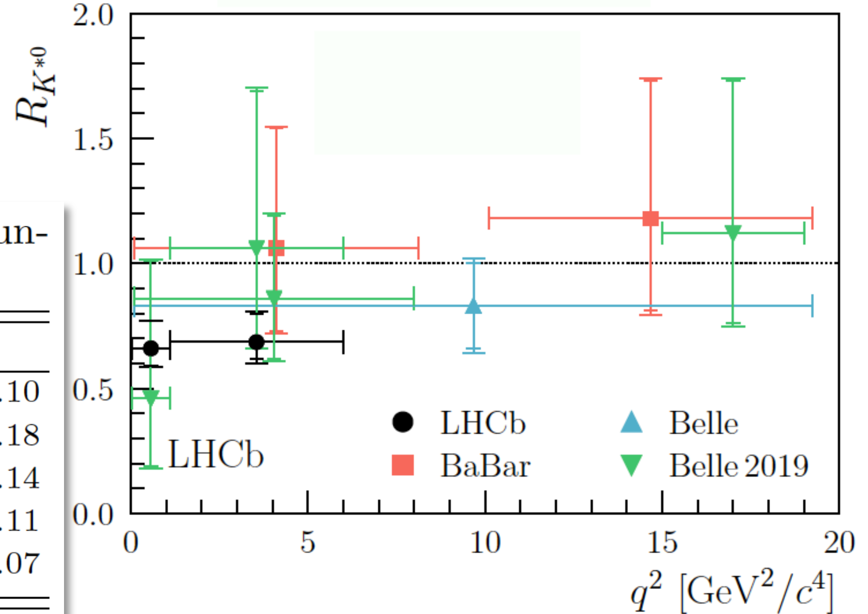


TABLE II. Result for R_{K^*}, $R_{K^{*0}}$ and $R_{K^{*+}}$. The first uncertainty is statistical and the second is systematic.

q^2 in GeV$^2/c^4$	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$



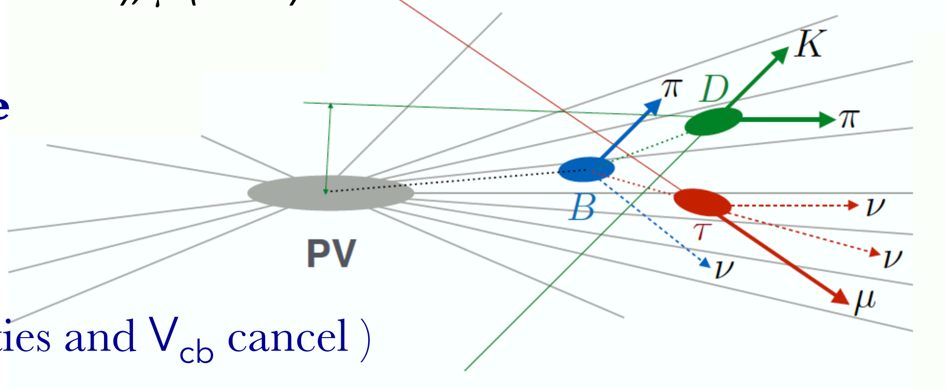
test of LFU in tree level semileptonic $b \to c\tau\nu_\tau$ transitions

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$$

τ ➔ ***signal channel***

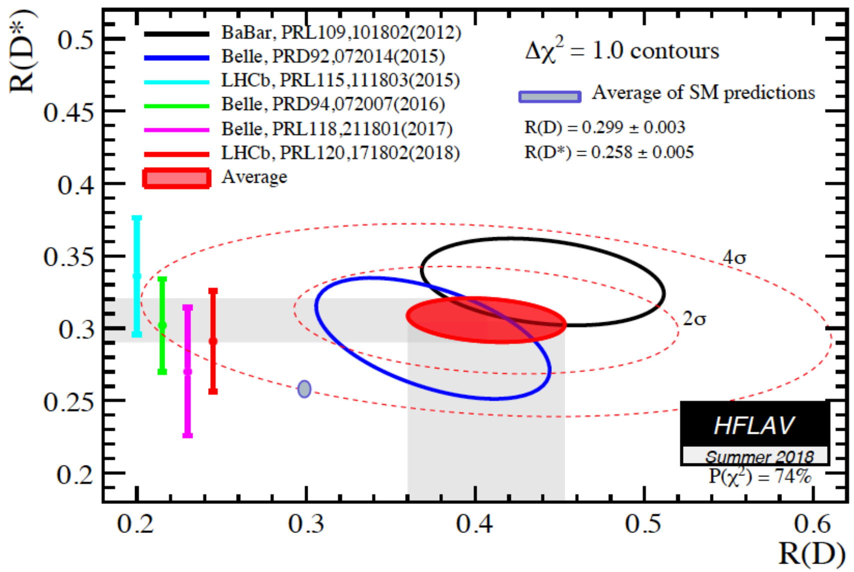
ℓ' = e/μ (B factories), μ (LHCb) ➔ ***normalization channel***

- **complicated experimentally by multiple missing neutrinos in the final state**



- R(D$^{(*)}$) theoretically clean (hadronic uncertainties and V_{cb} cancel)
  - ✓ $R(D)_{SM} = 0.299 \pm 0.003$
  - ✓ $R(D^*)_{SM} = 0.258 \pm 0.005$ *[PRD95 (2017) 115008, JHEP1711 (2017) 061, JHEP1712 (2017) 060]*

- before Moriond EW ➔ about 4σ tension with the SM for *R(D)* and *R(D*)* combination



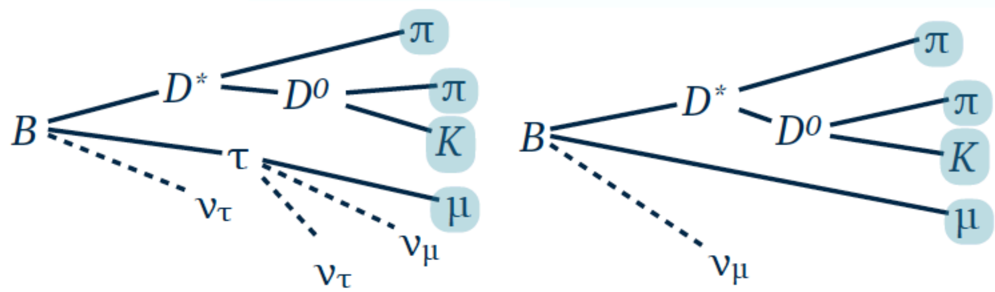
τ reconstruction

leptonic decays

Mode	BF (%)
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$	17.82 ± 0.04
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$	17.39 ± 0.04

<u>e$\nu\nu$ channel only at B factories</u>

✓ signal and normalization channels have same visible final states



✓ part of systematic cancels in the ratio

✓ backgrounds from inclusive semileptonic decays, with many unknowns (form factors, decay rate, etc.)

hadronic decays

Mode	BF (%)
$\tau^- \to \pi^- \pi^0 \nu_\tau$	25.49 ± 0.09
$\tau^- \to \pi^- \nu_\tau$	10.82 ± 0.05
$\tau^- \to 3\pi^\mp \nu_\tau$	9.31 ± 0.05
$\tau^- \to 3\pi^\mp \pi^0 \nu_\tau$	4.62 ± 0.05

✓ final states are not the same

✓ systematic do not cancel in the ratio between signal and normalization channels

➔ at LHCb measure with respect to another decay with similar final state, e.g. B→D*πππ

<u>1-prong channels only at B factories</u>

<u>3-prongs channels only at LHCb</u>

B factories vs LHCb

B factories

✓ Hadronic tag

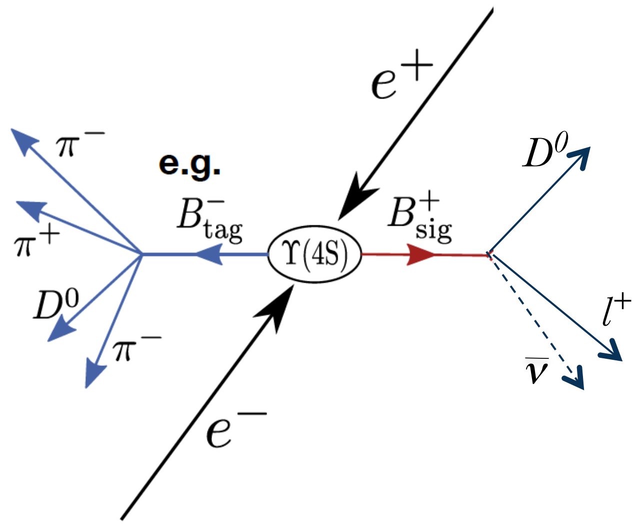
$\varepsilon = \mathcal{O}(0.3)\%$, signal sample pure,

B_{sig} momentum fully reconstructed

✓ SemiLeptonic tag

$\varepsilon = \mathcal{O}(1)\%$, signal sample less pure,

approximate B_{sig} momentum



LHCb

✓ use B flight direction to measure transverse component of missing momentum

✓ B boost along beam direction approximated with boost of the **visible final state**

$(p_B)_z = (m_B/m_{vis})(p_{vis})_z$ to access rest frame kinematics

✓ **~18% resolution** on B momentum

make the fit templates from most discriminating variables, e.g. the muonic R(D*) analysis from LHCb uses the B rest frame quantities ➔

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

R(D*) and R(J/ψ) with τ→μνν at LHCb

LHCb *[PRL 115 (2015) 111803]*

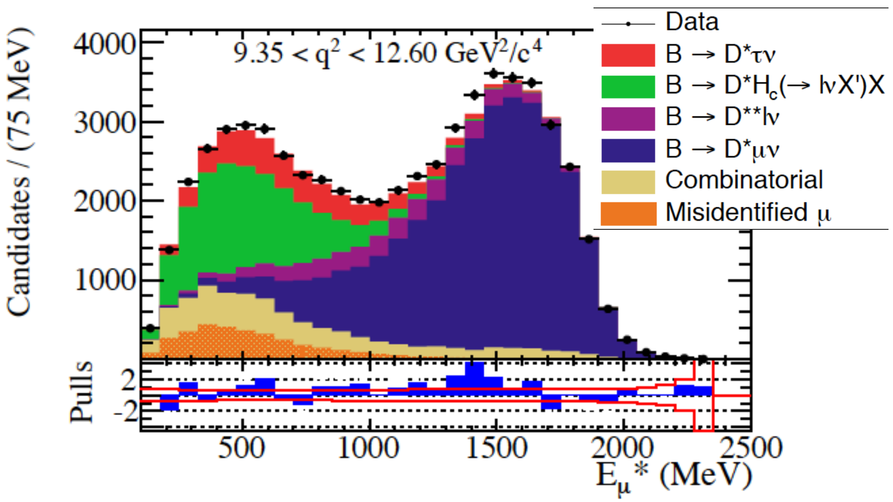
$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

using $D^{*-} \to D^0(\to K^+\pi^-)\,\pi^-$

visible final state ➔ π (Kπ) μ

large backgrounds from partially reco B decays

➔ ***MVA techniques based on μ isolation***



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

1.9 σ above Standard Model

LHCb *[PRL 120 (2018) 121801]*

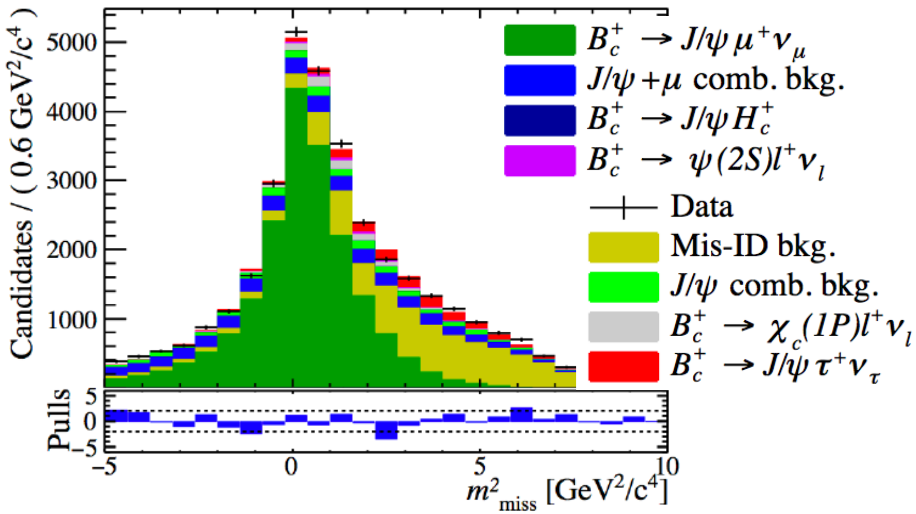
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)}$$

using $J/\psi \to \mu^+\mu^-$

visible final state ➔ (μμ)μ

shorter B_c decay time helps to discriminate

large background from lighter b hadrons



$R(J/\psi) = 0.71 \pm 0.17_{stat} \pm 0.18_{syst}$

~ 2. σ above Standard Model

Run 1 data sample, **about 3 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV**

R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$ at LHCb

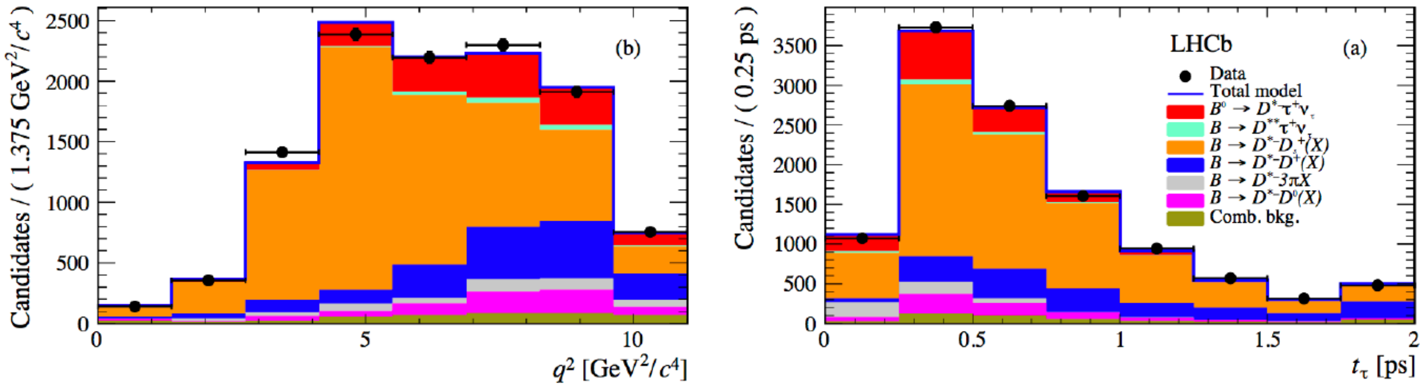
LHCb *[PRL 120 (2018) 171802]*
LHCb *[PRD 97 (2018) 072013]*

✓ using $D^{*-} \to D^0(\to K^+\pi^-)\,\pi^-$
✓ $\tau \to 3\pi$ vtx detached from B vtx suppresses $D^{*-}3\pi X$ background (~ 100 × signal)
✓ MVA technique to suppress the remaining backgrounds: $X_b \to D^{*-}D_{(s)}(X)$ (~ 10 × signal)
✓ experimental systematic uncertainty reduced normalizing to a decay **with same visible final state:** $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

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

Run 1 data sample
~ 3 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV



$$R(D^*) = 0.291 \pm 0.019_{\text{stat}} \pm 0.026_{\text{syst}} \pm 0.013_{\text{ext}}$$

~ 0.9 σ above Standard Model

compatible with the muonic channel

R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$ at LHCb

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

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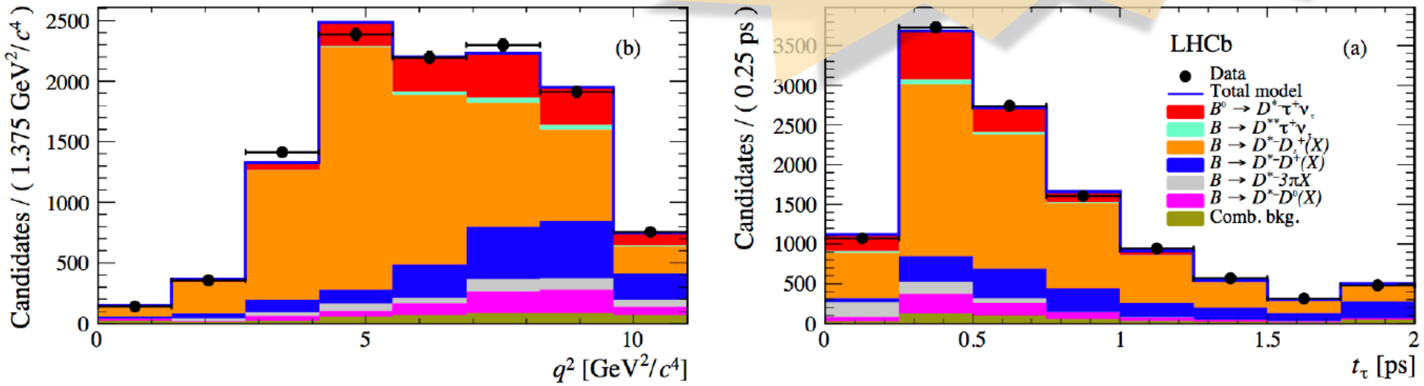
$\mathcal{K}(D^*) = 1.97 \pm 0.13_{\text{stat}} \pm 0.18_{\text{syst}}$

$\mathcal{B}(B^0 \to D^*\mu\nu)$ recently updated by HFLAV using separate average of B^0 and B^+ semileptonic $\mathcal{B}$

Run 1 data sample
~ 3 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV



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R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$ at LHCb

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

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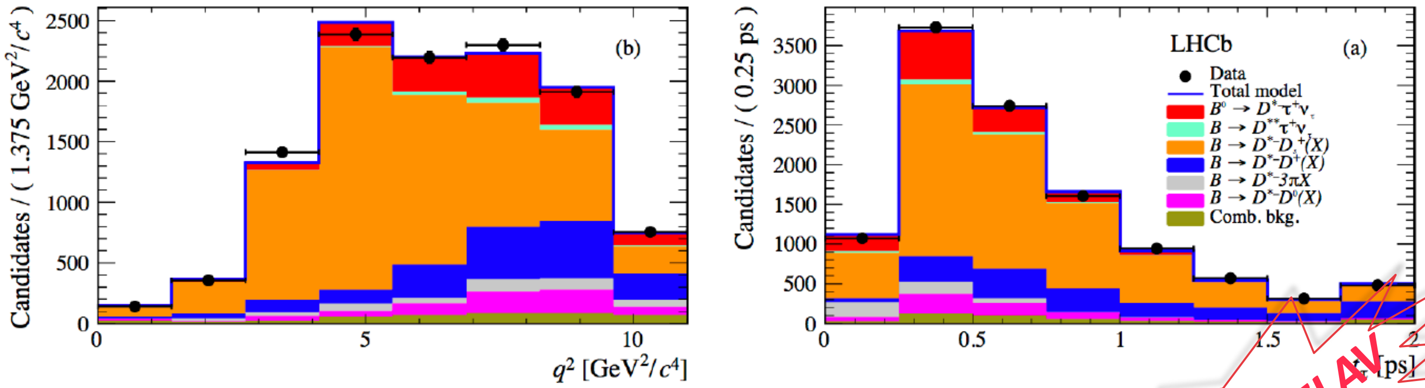
Run 1 data sample
~ 3 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV



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

~ 0.9 σ above Standard Model

compatible with the muonic channel

updated by HFLAV

SL-tagged R(D$^{(*)}$) with $\tau\to\ell\nu\nu$ at Belle

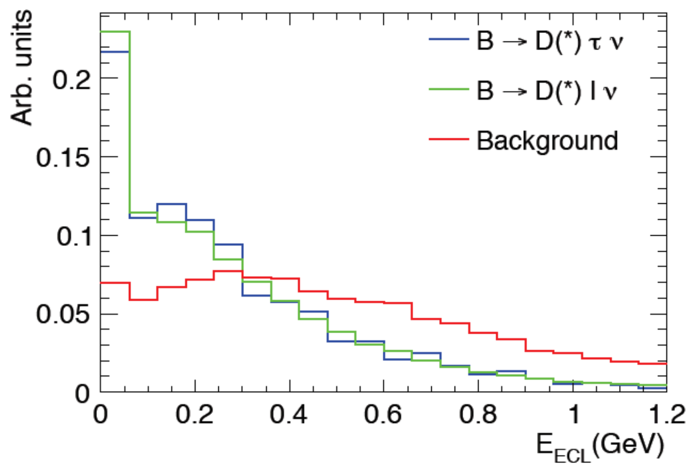
***Belle** [arXiv:1904.08794]*

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e,\mu)$$

update of the SL-tagged analysis: **from measuring R(D*) to a simultaneous measurement of R(D) and R(D*) by combining B^0 and B^+ decays**

- ✓ data sample 711 fb^{-1} ➔ 772 $\times 10^6$ B pairs
- ✓ MVA analysis technique to select B_{tag} in semileptonic modes ➔ $D\ell\nu$ and $D^*\ell\nu$
- ✓ on tag side, $\tau\to\ell\nu\nu$ vetoed by applying a cut on the angle between B and $D^{(*)}\ell$ in $\Upsilon(4S)$ rest frame: $\cos\theta_{B,D(*)\ell}$
- ✓ 4 data samples : $D^+\ell^-$, $D^0\ell^-$, $D^{*+}\ell^-$, $D^{*0}\ell^-$
  - D^0 reconstructed as $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+$, $K_S\pi^+\pi^-$, $K_S\pi^0$,$K_SK^+K^-$, K^+K^-, $\pi^+\pi^-$ ***30% of D^0 BRs***
  - D^+ reconstructed as $K^-\pi^+\pi^-$, $K_S\pi^+\pi^0$, $K_S\pi^+\pi^+\pi^-$, $K_S\pi^+$,$K^+K^-\pi^+$, K_SK^+ ***22% of D^+ BRs***
  - D^{*+} reconstructed as $D^0\pi^+$ and $D^+\pi^0$
  - D^{*0} reconstructed as $D^0\pi^0$ ($D^0\gamma$ higher background)
- ✓ B mesons are required to have opposite flavour to suppress combinatorial background

✓ to distinguish signal and normalization events from background process ➔ sum of energies of neutral clusters not associated with reconstructed particles **E_{ECL}**



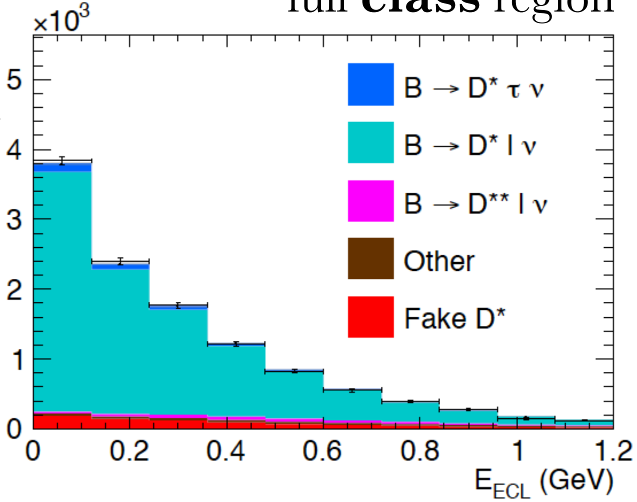
SL-tagged R(D$^{(*)}$) with $\tau \to \ell\nu\nu$ at Belle

Belle [arXiv:1904.08794]

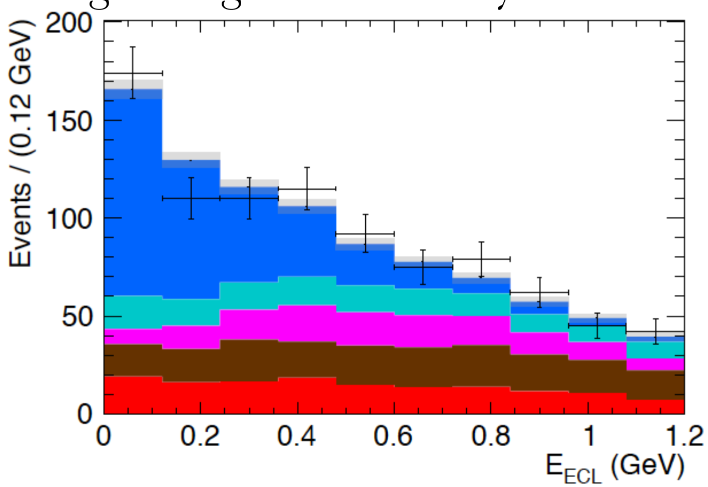
- ✓ to separate reconstructed signal and normalization events ➔ BDT based discriminating variable (**class**) using $\cos\theta_{B,D^{(*)}\ell}$, m^2_{miss} and E_{vis} and trained for each of the 4 $D^{(*)}\ell$ samples
- ✓ a 2D fit is performed simultaneously on the 4 $D^{(*)}\ell$ samples, on 10 bins of the $\mathbf{E_{ECL}}$ and **class** variables
- ✓ shape of the templates are based on MC samples
- ✓ MC samples corrected with data/MC(ε_{PID}) separately for e and μ using $e^+e^- \to e^+e^-\ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$

e.g. :
$\mathbf{E_{ECL}}$ projections for the $D^{*+}\ell^-$ sample

full **class** region



signal region defined by **class** > 0.9



SL-tagged $R(D^{(*)})$ with $\tau \to \ell\nu\nu$ at Belle

Belle *[arXiv:1904.08794]*

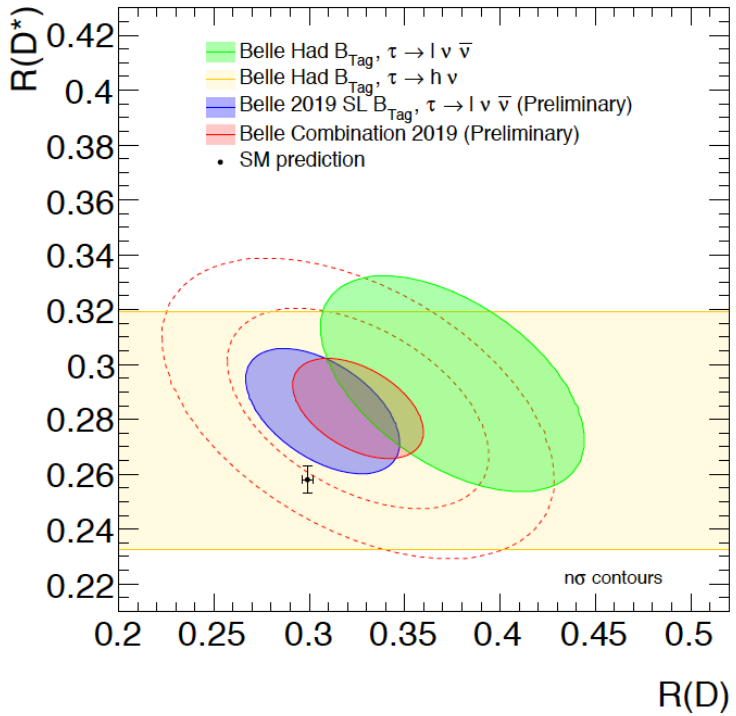
- ✓ **most precise measurements of R(D) and R(D*) to date**

$R(D) = 0.307 \pm 0.037_{stat} \pm 0.016_{syst}$

$R(D^*) = 0.283 \pm 0.018_{stat} \pm 0.014_{syst}$

in agreement with the SM within .2σ and 1.1 σ respectively

the combined result agrees with the SM within 1.2 σ



- ✓ main systematic contributions are due to the ε_{PID} corrections and to MC stat
- ✓ statistical correlation between the quoted R(D) and R(D*) values is -0.53, while the systematic correlation is -0.52

new HFLAV averages

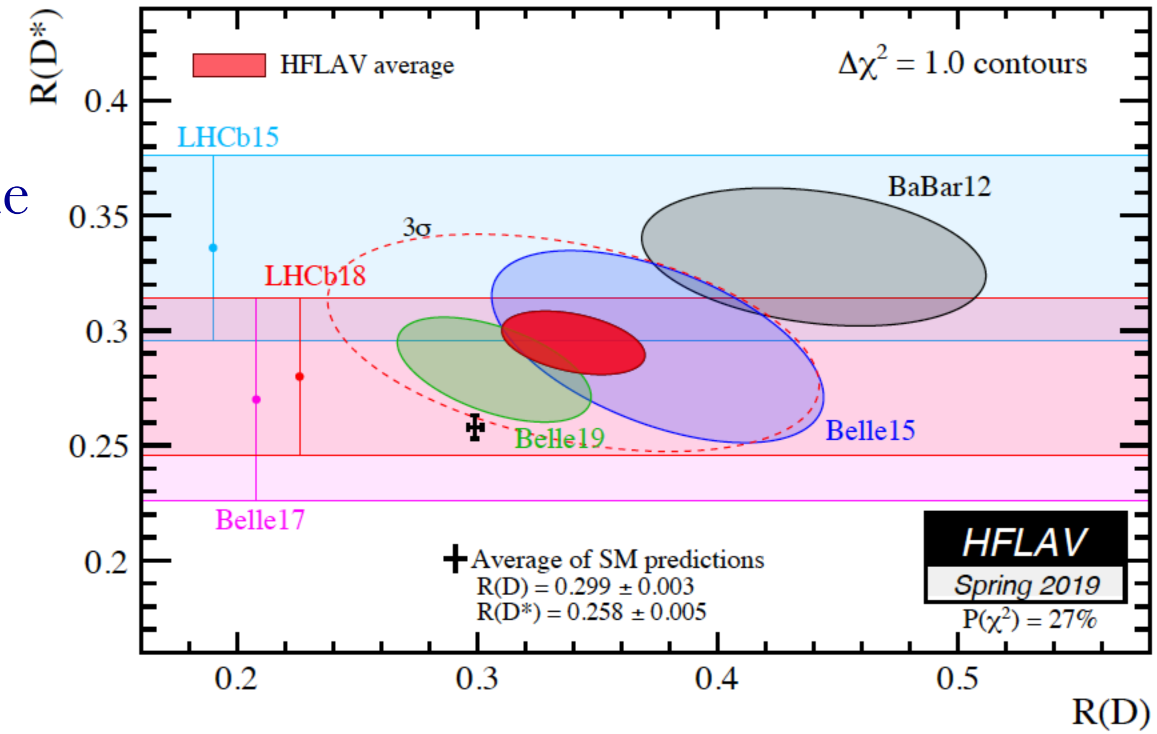
https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

- after the HFLAV update of the LHCb hadronic R(D*) measurement, and the new R(D) and R(D*) Belle measurements, the new HFLAV averages are

$R(D) = 0.349 \pm 0.027_{stat} \pm 0.015_{syst}$

$R(D^{*}) = 0.298 \pm 0.011_{stat} \pm 0.007_{syst}$

- 3.1σ difference with the Standard Model



link to Lepton Flavour Violation

- Lepton Flavour Violating (**LFV**) HF decays may occur in the SM via one-loop diagrams with neutrinos oscillations, but are highly suppressed **~10^{-54}** : beyond experimental reach

- renewed interest of LFV phenomena in the HF sector : attempts to explain tensions in FCNC and FCCC point to enhancements to accessible levels [Phys. Rept. 114 (2015) 091801]

- NP models like Z' or LQ foresee BF enhancements to levels accessible: access to massive particles beyond the reach of direct searches

interesting correlations between observables in some leptoquarks models [ArXiv:1609.08895]

$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \sim 3 \cdot 10^{-8}\left(\frac{1-R_K}{0.23}\right)^2, \quad \mathcal{B}(B \to K(e^{\pm},\mu^{\pm})\tau^{\mp}) \sim 2 \cdot 10^{-8}\left(\frac{1-R_K}{0.23}\right)^2$$

$$\frac{\mathcal{B}(B_s \to \mu^+e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \sim 0.01\left(\frac{1-R_K}{0.23}\right)^2, \quad \frac{\mathcal{B}(B_s \to \tau^+(e^-,\mu^-))}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \sim 4\left(\frac{1-R_K}{0.23}\right)^2.$$

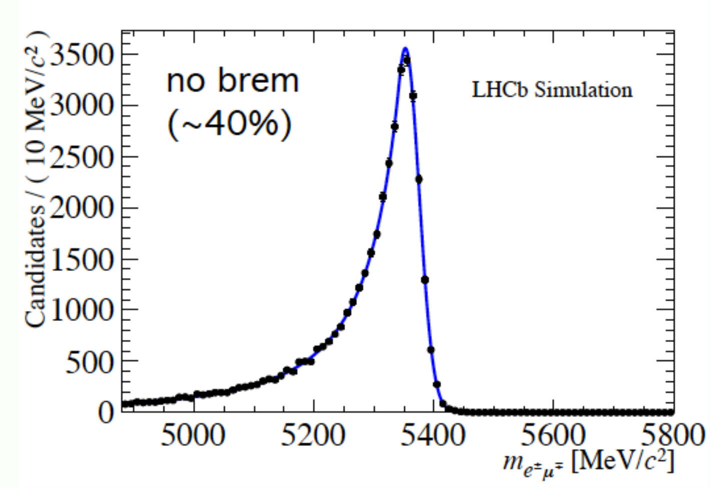
$B_{d,s} \to e\mu$ at LHCb

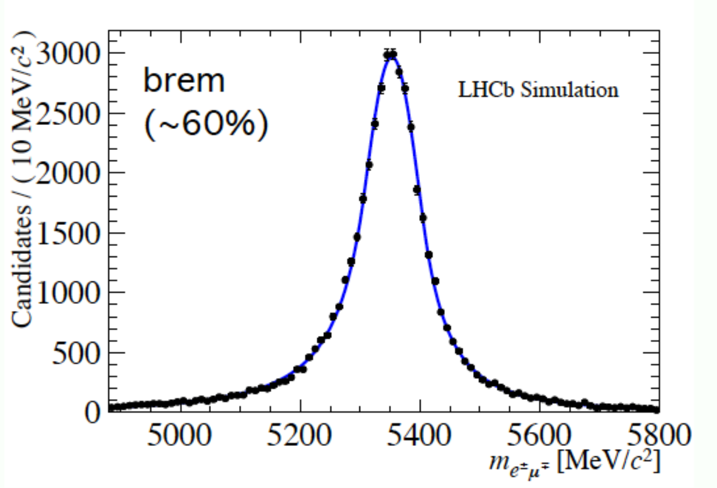
[LHCb, JHEP 1803 (2018) 078]

- NP models like Z′ or LQ ➔ BF enhanced up to $O(10^{-11})$
- improved analysis using all of RUN 1 data (3 fb^{-1})

event selection based on e and μ tracks forming a displaced vertex

- **e's emit significant bremsstrahlung γ's at LHCb** efficiencies and mass shapes depend on whether or not the bremsstrahlung is recovered ➔ <u>2 event categories are analyzed separately</u>





- $\varepsilon_{trigger}$ and ε_{PID} from data calibration samples, all the others from simulation

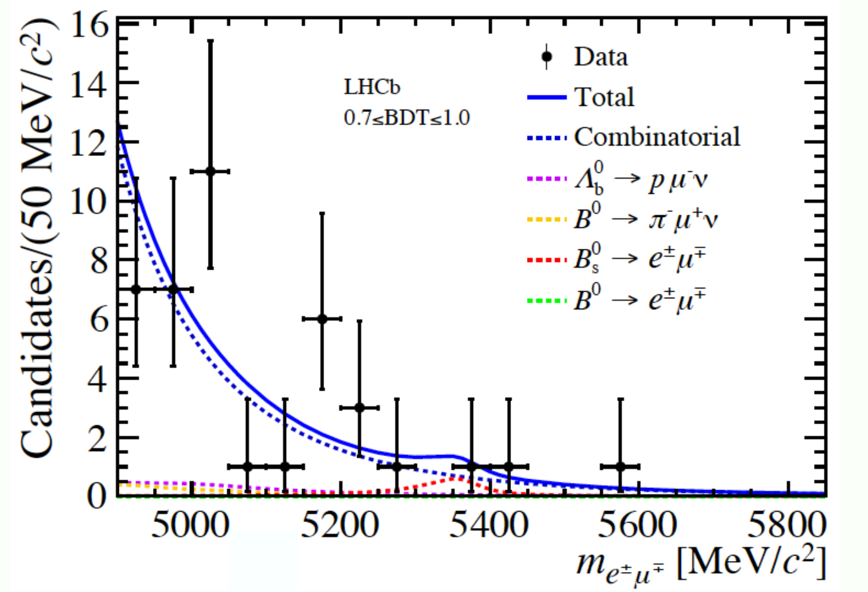
backgrounds

- combinatorial background is rejected by means of a topological BDT, trained on signal MC vs same-sign data and calibrated on $B \to K\pi$ data (proxy for the signal)
- $B \to hh$ ($h = K,\pi$) double-misID only peaking background ➔ 0.1 events survive the PID sel
- $B_d \to \pi\mu\nu$ and $\Lambda_b \to \pi\mu\nu$ with $\pi \to e$ misID are found to be sizeable and included in the mass fit

$B_{d,s} \to e\mu$ at LHCb

[LHCb, JHEP 1803 (2018) 078]

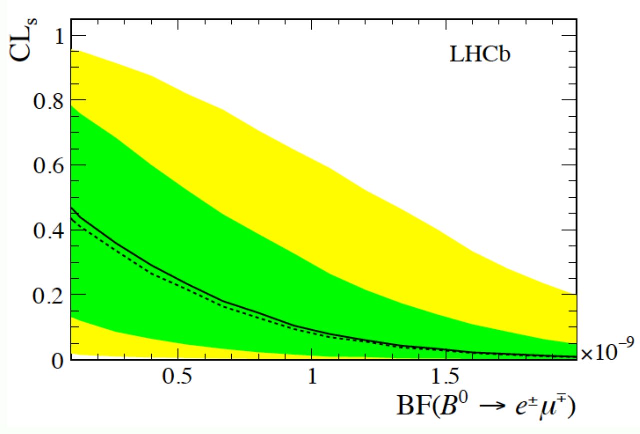
- to measure the BF, the signal events are normalised by means of two known channels: $B^+ \to J/\psi K^+$ (clean final state), $B^0 \to K^+\pi^-$ (same topology as the signal)
- the BF is extracted with a simultaneous invariant-mass fit to the <u>two bremsstrahlung categories and BDT bins</u>

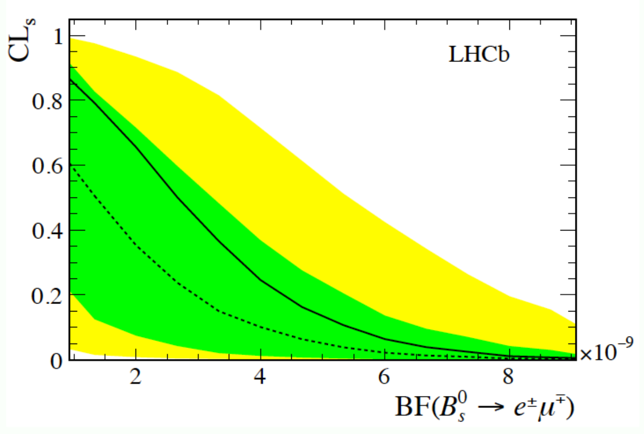


no excess in the signal region, set a limit with the CL_S method at 90% (95%) C.L.

$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3\,(1.0) \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 6.3\,(5.4) \times 10^{-9}$$

which supersedes the previous best limit (1 fb^{-1}) [LHCb, PRL 111 (2013) 141801]



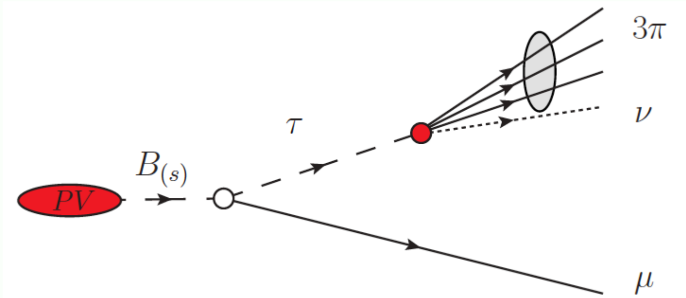


$B_{d,s} \to \tau\mu$ at LHCb

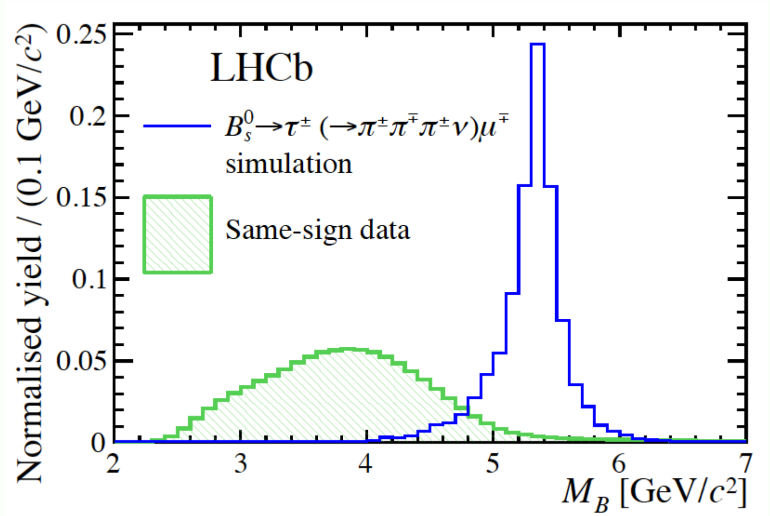
[LHCb, ArXiv:1905.06614]

- many BSM models predict large BF from $O(10^{-9})$ to $O(10^{-5})$
- $\mathcal{B}(B^0 \to \tau\mu) < 2.2\times10^{-5}$ [BaBar, PRD 77 (2008) 091104], **no limit yet on $B_s^0 \to \tau\mu$**

- **challenging search** ➔ at least one missing neutrino in the final state
  - ✓ at the B factories the reconstructed B_{tag} and $\Upsilon(4S)$ kinematic constrain the B_{sig} momentum ➔ can use 1-prong decays accessing ~70% of the τ decays
  - ✓ **at LHCb focus on $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu$ ~9.3% of the τ decays** ➔
  - ✓ the μ is combined with a opposite charged τ to form a displaced vertex
  - ✓ same sign candidates ($\mu^\pm\tau^\pm$) and simulation employed to study the background



topological and kinematic constraints allow to compute the M_B analytically with a two-fold ambiguity, the solution with the highest S/B is kept



only candidates with M_B > 4 GeV are retained

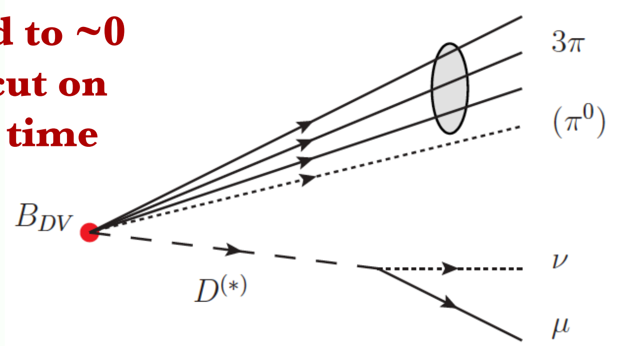
$B_{d,s} \to \tau\mu$ at LHCb

[LHCb, ArXiv:1905.06614]

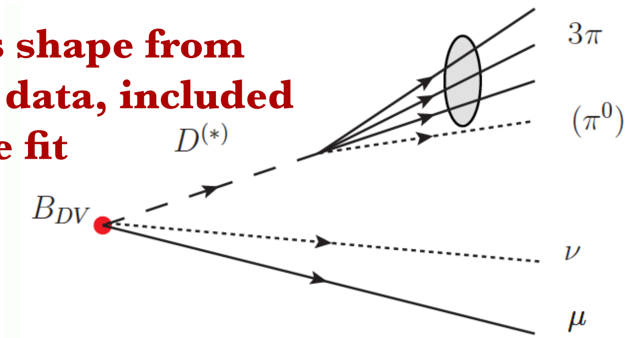
- more than 90% of background due to events with extra-tracks is rejected using isolation criteria, two background components survive the selection:

1. partially reconstructed ➔ two topologies

reduced to ~0 with a cut on τ decay time

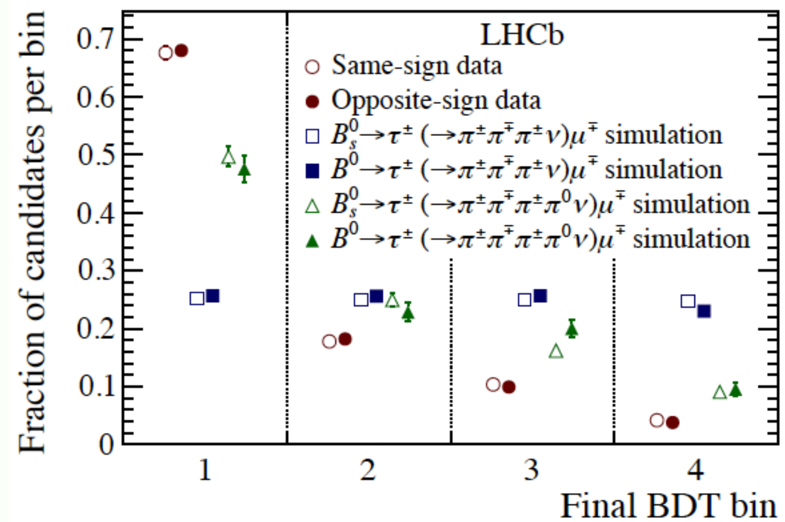


mass shape from ($\mu^\pm\tau^\pm$) data, included in the fit



2. combinatorial ➔ BDT trained on signal MC vs upper mass sideband (> 6.2 GeV) of same sign ($\mu^\pm\tau^\pm$)

- a final BDT trained on MC vs ($\mu^\pm\tau^\pm$) data (full mass range) to categorize the events ➔ the BDT signal distribution is flattened, while the background peaks at low BDT values

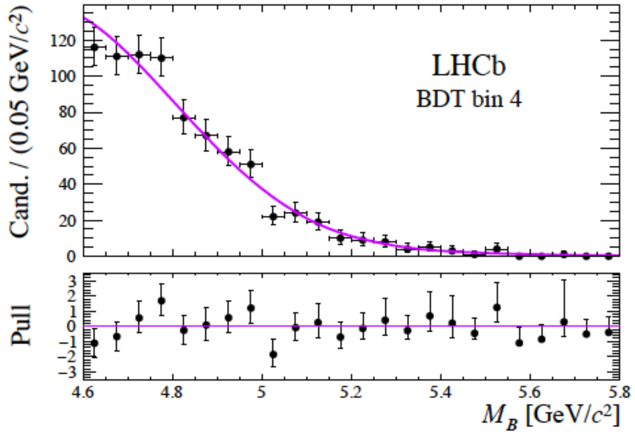


$B_{d,s} \to \tau\mu$ at LHCb

[LHCb, ArXiv:1905.06614]

- signal yields evaluated by performing a simultaneous unbinned maximum likelihood fit to the M_B distributions in 4 BDT bins and converted into BFs using the decay $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ as a normalization channel

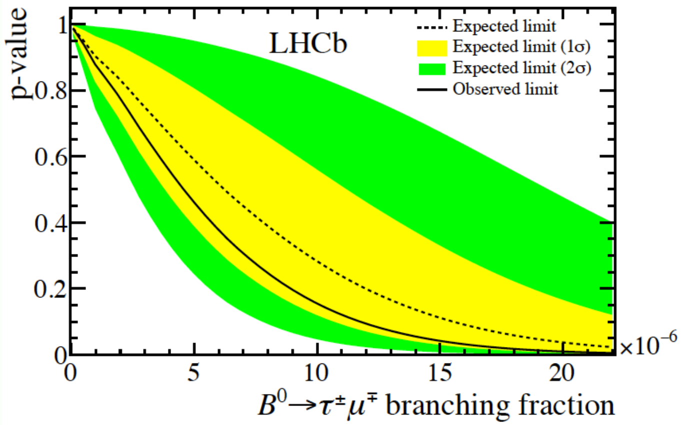
limited B_s and B_d separation ➔
B_s signal fit, assuming no B_d contribution
B_s yield = -16 ± 38
B_d yield = -65 ± 58

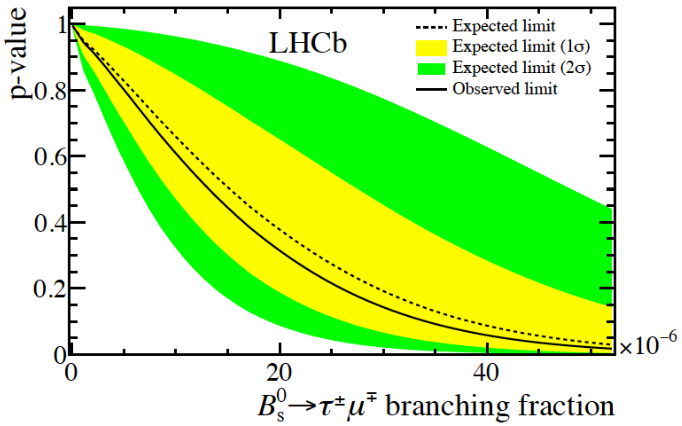


- no presence of signal, limit with CL_S method at 95% CL

$\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$ assuming no B_s signal
$\mathcal{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$ assuming no B_d signal

- **B_d limit improves by a factor of 2 BaBar's result, first limit on the B_s mode**





Run 1 data sample
~ 3 fb^{-1}

$B_d \to K^{*0} e\mu$ at Belle

[Belle, PR D 98 (2018) 071101]

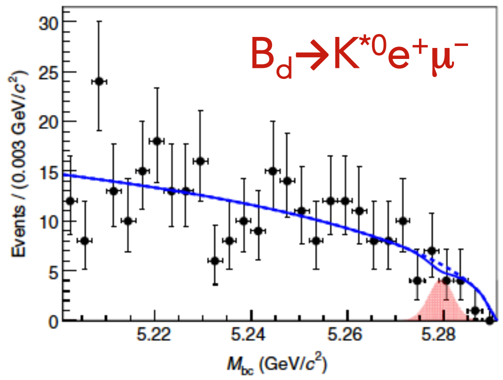
- ✓ data sample 711 fb^{-1} ➔ 772 $\times 10^6$ B pairs
- ✓ reconstruction of $B^0 \to K^*(K\pi)e^\pm\mu^\mp$
- ✓ to discriminate signal from background 2 discriminating variables ➔

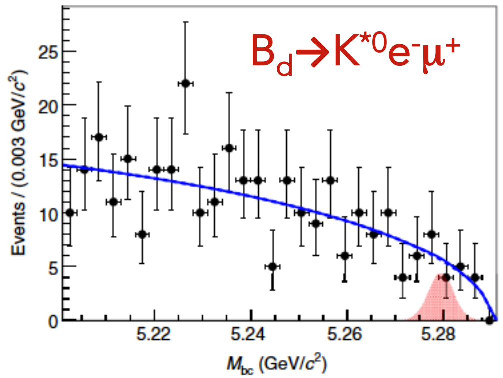
$$M_{bc} = \sqrt{E^2_{beam}/c^4 - |\vec{p}_B|^2/c^2}$$
$$\Delta E = E_B - E_{beam}$$

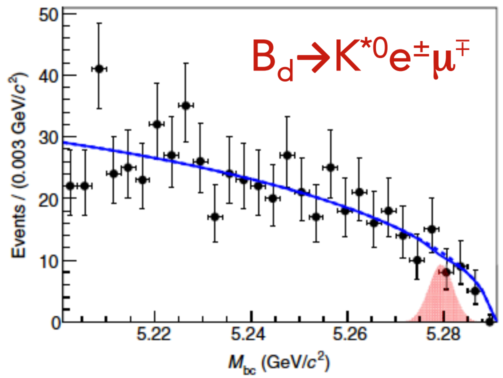
1. most significant background due to continuum $e^+e^- \to qq$, MVA analysis based on event topology ➔ bb events more spherically distributed
2. B decays with 2 identified leptons in final states, new MVA analysis
3. residual background due to $B^0 \to K^*(K\pi)J/\psi(\ell\ell)$ removed applying sets of vetoes around the J/ψ mass

no statistically significant signal
upper limits on $\mathcal{B}$ at 90% C.L.

Mode	ε (%)	N_{sig}	N^{UL}_{sig}	$\mathcal{B}^{UL}$ (10^{-7})
$B^0 \to K^{*0}\mu^+e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2
$B^0 \to K^{*0}\mu^-e^+$	9.3	$0.4^{+4.8}_{-4.5}$	7.4	1.6
$B^0 \to K^{*0}\mu^\pm e^\mp$ (combined)	9.0	$-1.2^{+6.8}_{-6.2}$	8.0	1.8







conclusions and outlook

because of time costrain I did not touch ...

✓ new R_K at Belle [Belle, EPS 2019, preliminary]

✓ $B^+ \to K^+ e\mu$ [LHCb, LHCB-PAPER-2019-022 *preliminary*]

- intriguing anomalies found in LFU tests using B meson decays

  ✓ *LHCb full Run 2 dataset ~ 4 times the number of B's available in Run1 ➔ all ratios R_K, R_{K^*}, $R(D^*)$, $R(J/\psi)$ will be updated*
  ✓ *new analysis ongoing are: R_ϕ, R_{KS}, ..., $R(D)$, $R(D_s^{(*)})$, $R(\Lambda_c^{(*)})$, $R(p)$ ...*
  ✓ *angular analysis of $b \to s\ell\ell$ transitions are under way*
  ✓ *$\Lambda_b \to \Lambda_c$ form factor measurement [**LHCb** PRD 96 (2017) 112005]*
  others are on the way: $\Lambda_b \to \Lambda_c^*$, $B_s \to D_s^{(*)}$ ...

- hints of lepton non-universality in B decays demand searches for LFV decays

  ✓ *LHCb is currently dominating the scene, Belle II will join soon on some channels*
  ✓ *all presented LHCb limits will be soon updated using the Run 2 dataset, many more LFV measurements being performed not only on B decays*

conclusions and outlook

- Belle II already started to collect data and is expected to record a 50 times larger data sample (50 ab^{-1} in 2027)

- LHCb upgrade installation started this January 2019 to be ready in 2021, upgrade detector qualified to accumulate 50 fb^{-1} at the end of 2029

- to take full advantage of the HL-LHC the LHCb collaboration is proposing a new major upgrade of the detector to increase data sample up to 300 fb^{-1}

- looking for a fruitful competition/collaboration between LHCb and Belle II

we are entering an exciting phase of precision measurements !

conclusions and outlook

- Belle II already started to collect data and is expected to record a 50 times larger data sample (50 ab^{-1} in 2027)

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we are entering an exciting phase of precision measurements !

Thank you
for your attention !

spares

new R_K at Belle

[Belle, EPS 2019, preliminary]

- ***new R_K measurement for both charged and neutral B mesons***
  - ✓ data sample 711 fb^{-1}
    ➔ 772 ×10^6 B pairs

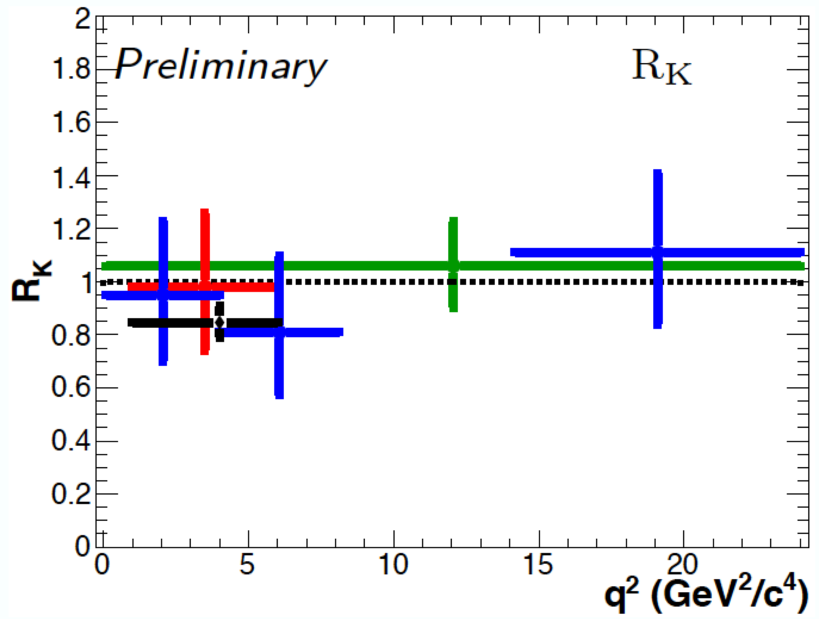
- R_K measured as the weighted average of charged and neutral modes
- R_K measured for **[0.1 , 4.0]**,**[4.0 , 8.12]**, **[1.0 , 6.0]**, **> 14.18** and **> 0.1** q^2 bins

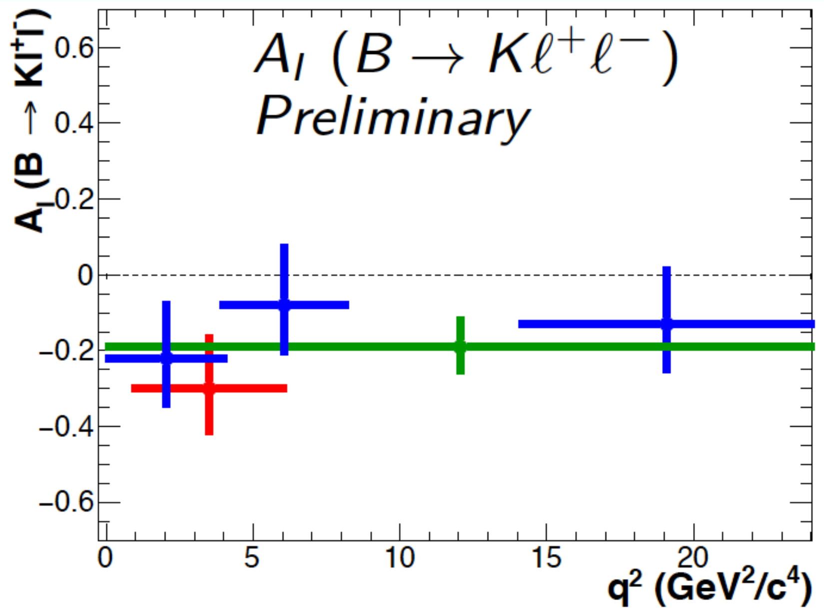
- isospin asymmetry A_I also measured

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) - \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) + \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}$$

deviation found at **~2.5σ** level in the **[1.0,6.0] bin**

- **Belle II is expected to record a 50 times larger data sample**



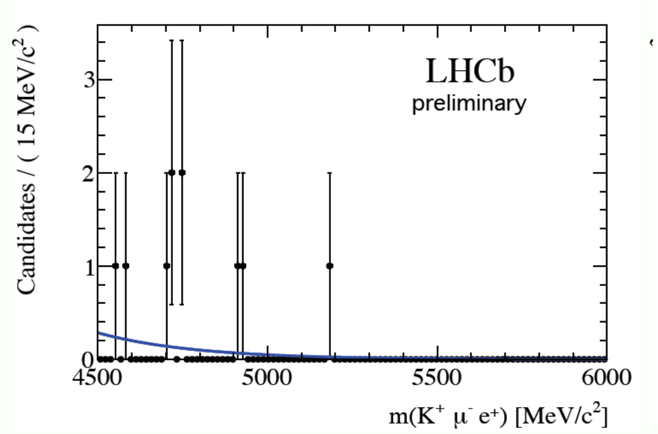


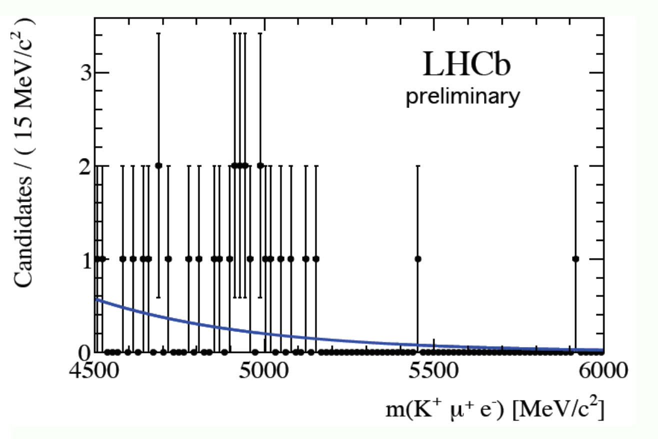
$B^+ \to K^+ e\mu$ at LHCb

[LHCb, LHCB-PAPER-2019-022 *preliminary*]

- ✓ data sample 3 fb^{-1}, trigger on high p_t μ
- ✓ K, $e^{\pm}$ and $\mu^{\mp}$ reconstructed tracks from a common displaced vertex
- ✓ normalization channel with similar topology $B^+ \to J/\psi(\mu^+\mu^-)K^+$
- ✓ simulated samples needed for efficiencies, signal and background modelling

1. partially reconstructed most abundant $B^+ \to D^0(K^+ Y \ell^- \nu) X \ell^+ \nu$ rejected by requiring $m(K^+\ell^-) > 1885$ MeV
2. decays via charmonium resonances e.g. $B^+ \to J/\psi(\ell\ell)K^+$ rejected via mass vetoes
3. combinatorial background reduced with a dedicated BDT exploiting event topology and isolation
4. fully (partially) reconstructed B decays with misidentified particles e.g. $B^+ \to K\ell\ell$ rejected via dedicated BDT





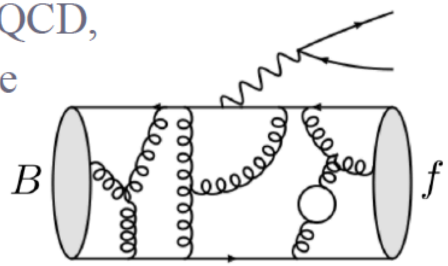
no statistically significant signal →

$\mathcal{B}/10^{-9}$	90% C. L.	95% C. L.
$B^+ \to K^+\mu^- e^+$	7.0	9.5
$B^+ \to K^+\mu^+ e^-$	7.1	9.1

previous best limits from Babar are improved by more than one order of magnitude

great variety of observables

- Observe hadronic decay, not the quark-level transition
  - $b \to s\ell\ell \longrightarrow B^+ \to K^+\ell\ell\,,\, B^0 \to K^{*0}\ell\ell\,,$
    $B_s \to \phi\ell\ell$, etc.
- Needs to compute hadronic matrix elements
  - Non-perturbative QCD, difficult to compute



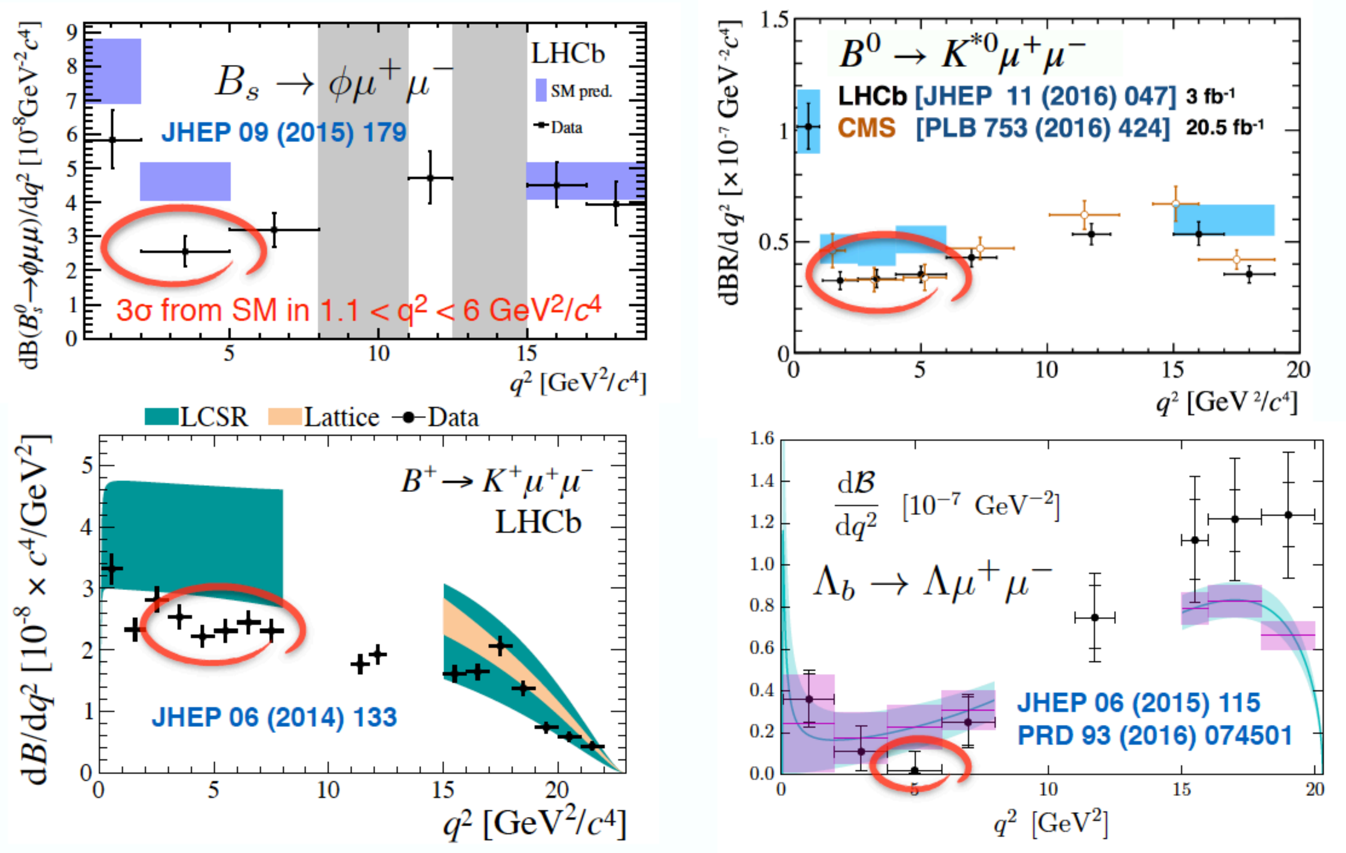
DIRTY

- Branching ratios:
  large theory uncertainties
- Angular observables:
  reduced theory uncertainties
- Lepton Flavour Universality tests (ratio of BR, etc.):
  clean, uncertainties cancels

CLEAN

decay rates

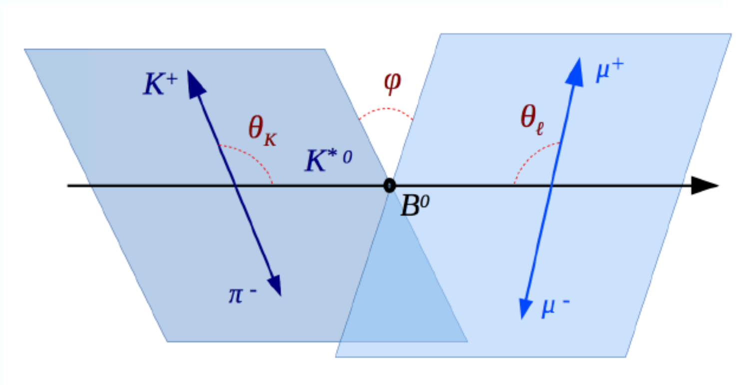
Measured BR are consistently lower than predicted in SM

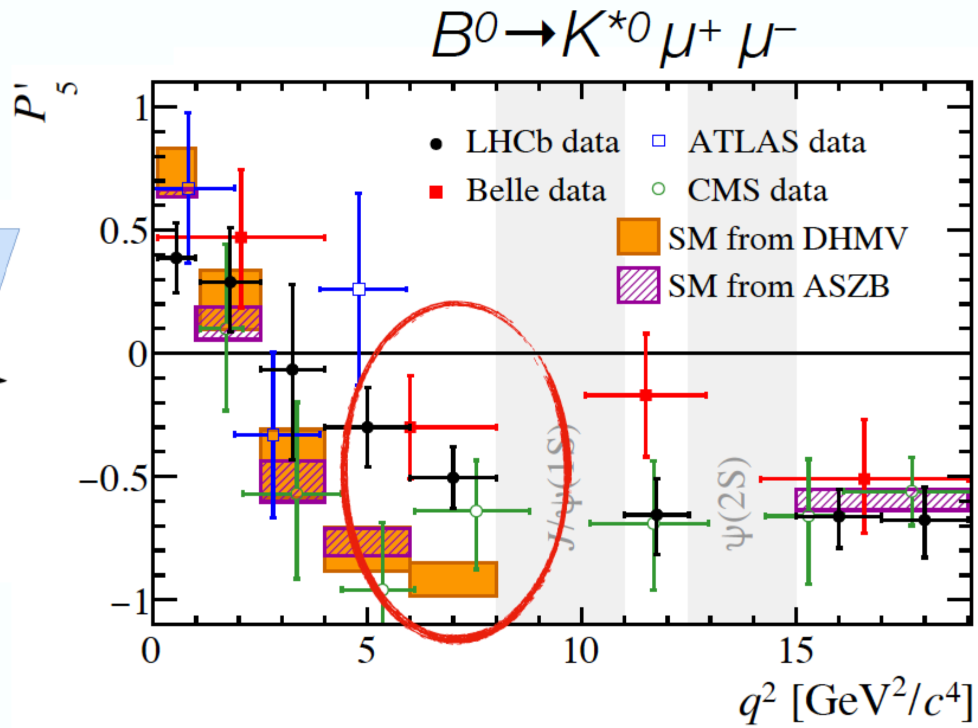


q^2: squared di-lepton invariant mass

though SM suffers from large uncertainties…

angular distributions





- Give access to observables with reduced dependence on hadronic effects
  [JHEP 1204 (2012) 104]
- LHCb finds deviation from the SM prediction at the level of 3.4σ

LHCb [JHEP 02 (2016) 104], CMS [PLB 781 (2018) 517], ATLAS [JHEP 10 (2018) 047], BaBar [PRD 93 (2016) 052015], Belle [PRL 103 (2009) 171801], CDF [PRL 108 (2012) 081807]

controlling efficiencies

[LHCb, PRL 122 (2019) 191801]

efficiency ratios are computed from simulation carefully corrected using data control samples

✓ B^+ kinematic ✓ trigger

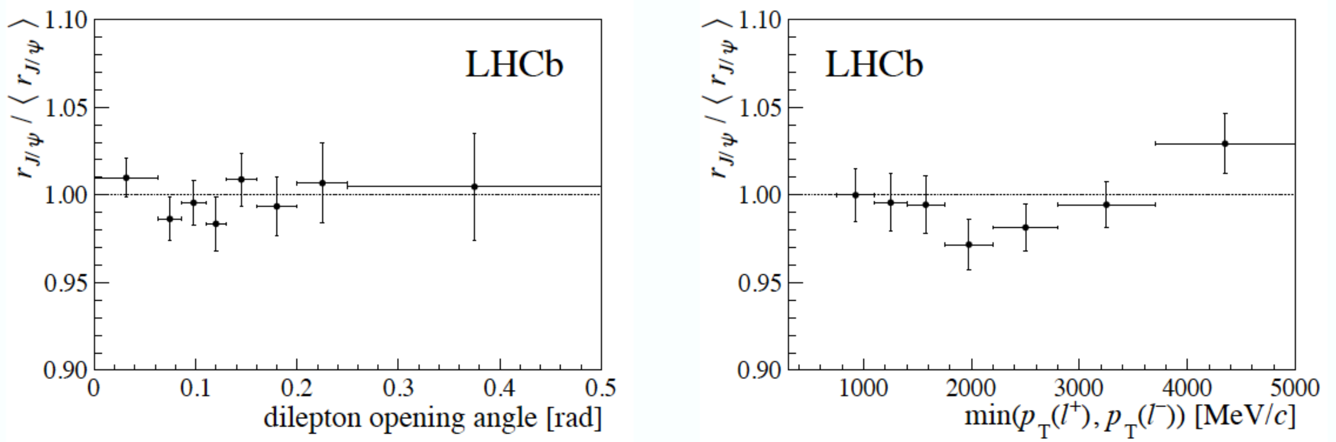
✓ mass resolution ✓ Particle IDendification

numerous cross-checks to ensure the effectiveness of the corrections :

$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+ J/\psi(ee))} = 1.014 \pm 0.035$$

stringent test as it requires **muon** and **electron** efficiencies to be controlled individually

- check that efficiencies are understood in all kinematic regions ➔ $r_{J/\psi}$ is flat for all variables examined, e.g.

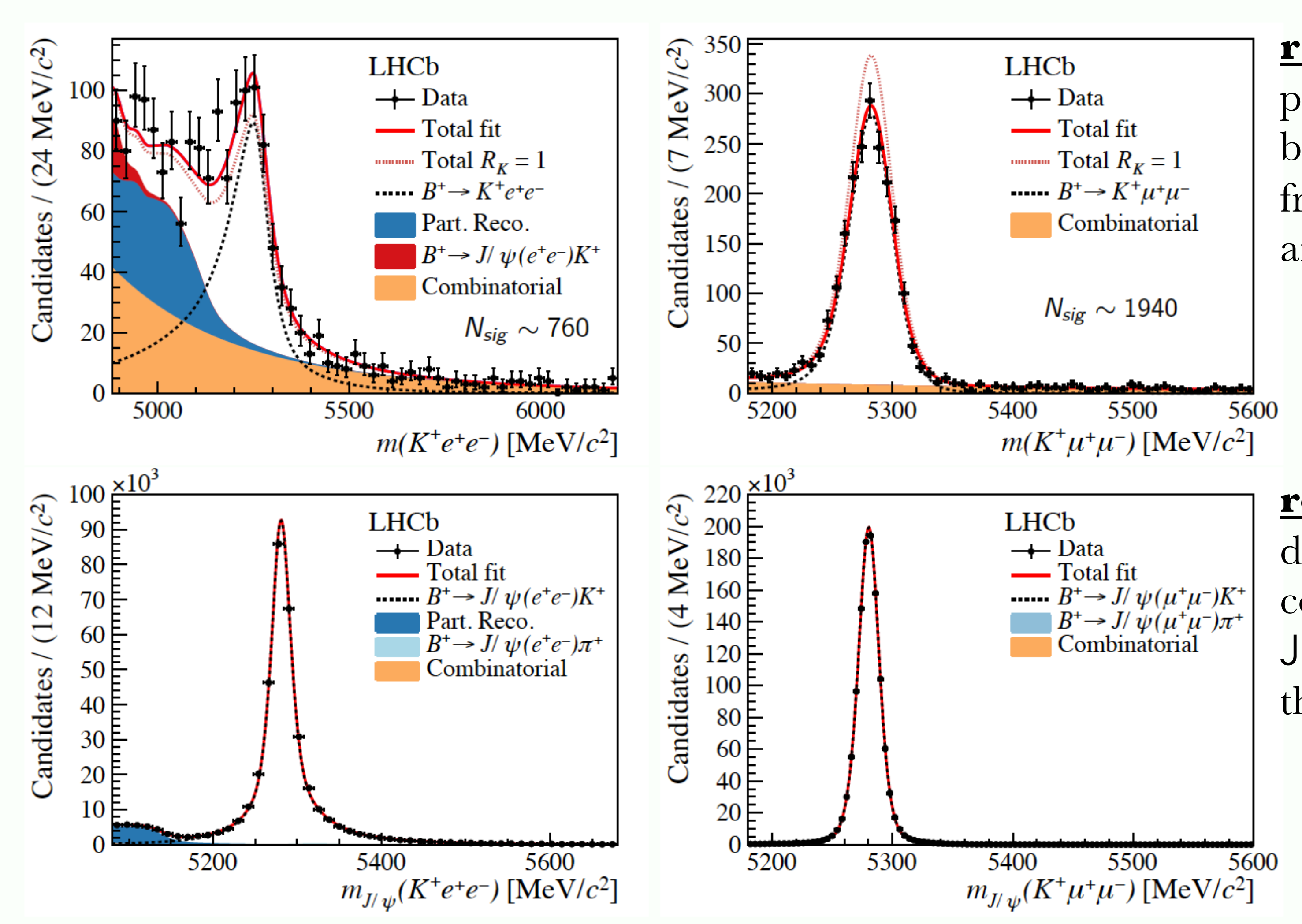


- cross-checks done independently for Run1 and Run 2 samples and excellent agreement found

invariant mass fits

[LHCb, PRL 122 (2019) 191801]

a simultaneous fit to rare + resonant electron and muon channels is performed to extract R_K



rare modes:

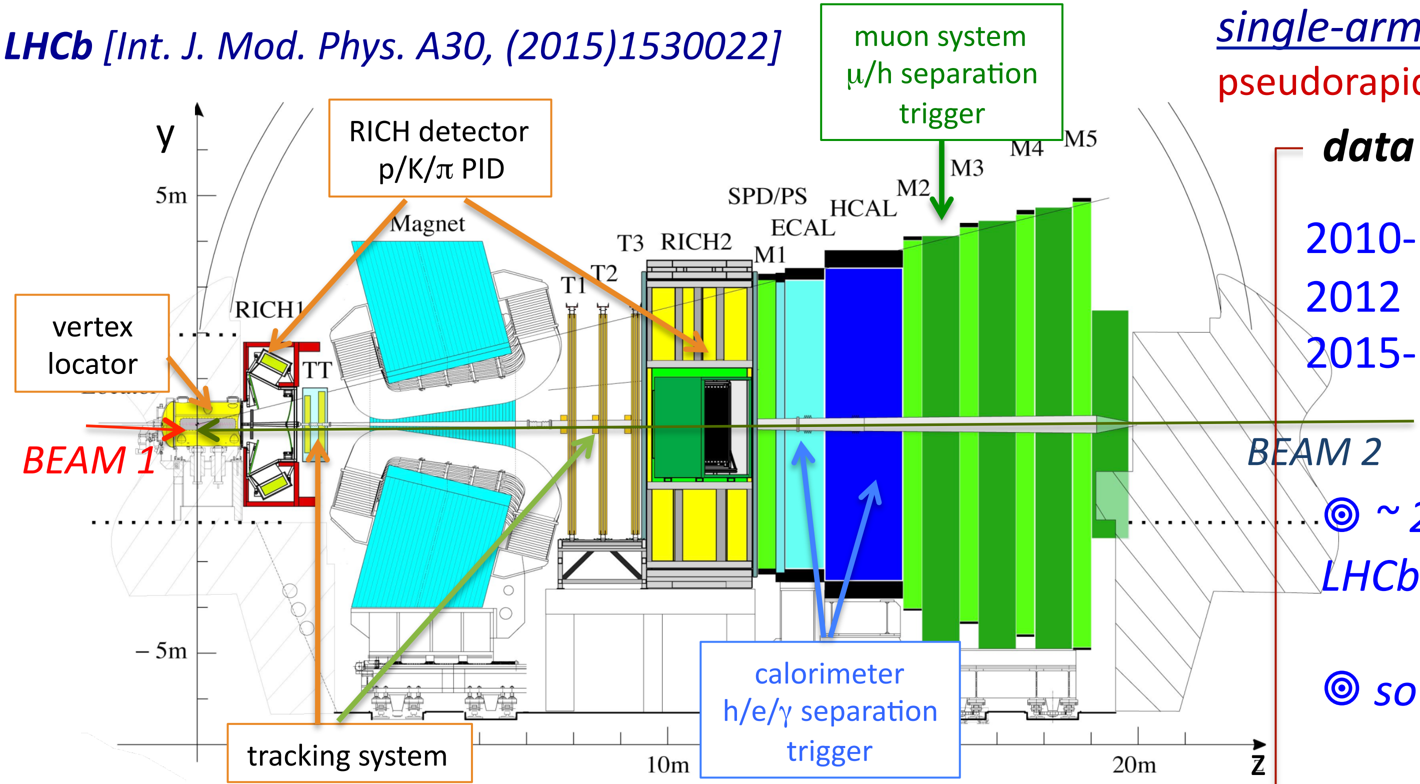
partially reconstructed background and tail from resonant mode are significant in ee

resonant modes:

dilepton mass constrained to the J/ψ mass to improve the resolution

detection of B semileptonic decays at LHCb

***LHCb** [Int. J. Mod. Phys. A30, (2015)1530022]*



<u>*single-arm forward spectrometer*</u>

pseudorapidity range ➔ $2 < \eta < 5$

data samples

2010-11 ~**1.1 fb^{-1}** at 7 TeV

2012 **~2.1 fb^{-1}** at 8 TeV

2015-18 ~**6. fb^{-1}** at 13 TeV

◎ *~ 25% of bb-bar pairs in LHCb acceptance*

◎ *so far > 10^{12} bb-bar pairs*

◎ *large boost → B mesons fly ~1 cm*

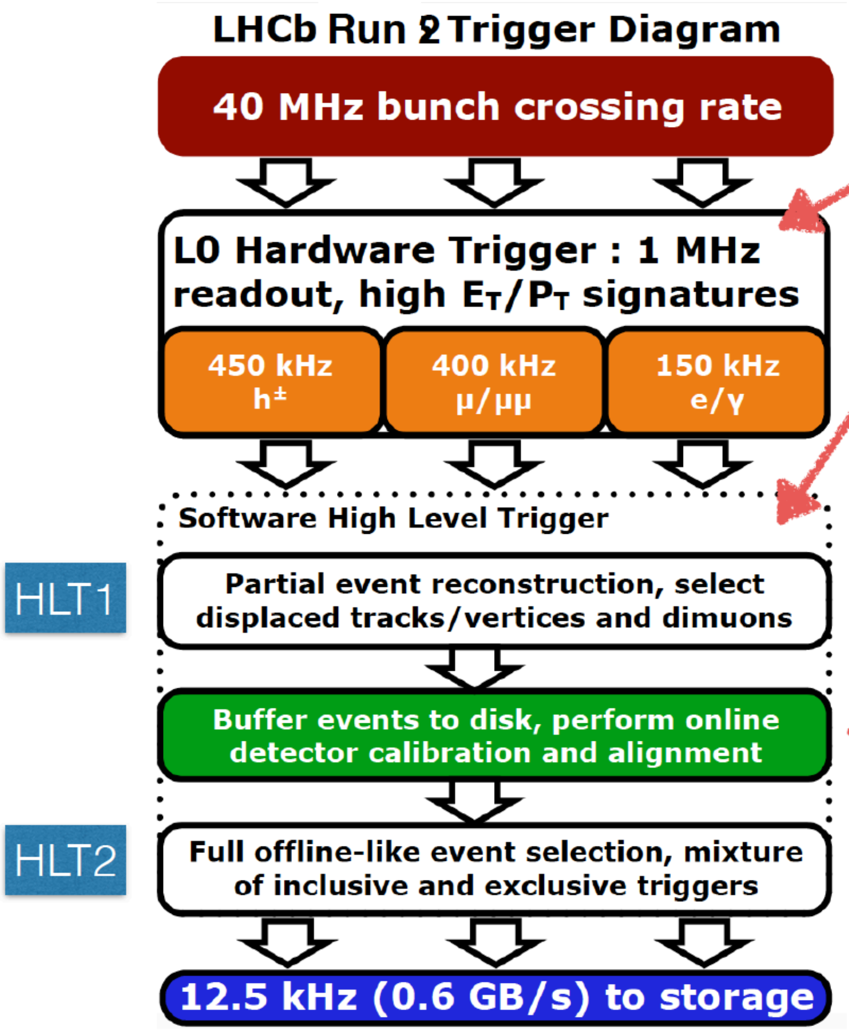
precise tracking → excellent resolutions

- ✓ decay time resolution ~ 45 fs
- ✓ Impact Point resolution ~ 20 μm for high-P_t tracks
- ✓ $\Delta p/p \sim 0.4\%$ at 5 GeV

excellent particle IDentification

- ✓ π/K separation over 2-100 GeV, $\varepsilon_K \sim 90\%$ for ~5% (π→K) misID
- ✓ powerful muon ID, $\varepsilon_\mu \sim 97\%$ for 1-3% π→μ misID

the LHCb trigger



- Fully optimised for flavour physics
- At first stage (L0) a hardware trigger fires on single hadrons, leptons and photons
- High Level Trigger (HLT): software application designed to reduce event rate from 1 M to ~10 k events/s, executed on a large computing cluster. Flexible design that can adapt to changing machine conditions and evolving physics programme
- Split HLT in two steps: buffer events to disk after HLT1 to perform online calibration & alignment
- HLT2 uses offline-quality calibration → more discriminant trigger
- Offline-quality reconstruction up-front

the LHCb upgrade

- upgrade started this January 2019
- restart data taking in 2021 at $\mathcal{L}$ up to 2×10^{33} cm^{-2}s^{-1}
- upgrade detector qualified to accumulate 50 fb^{-1} ➔

upgrade all sub-detector electronics to 40 MHz readout
make all trigger decision in software and some new detectors

VELO from microstrip sensors (R,ϕ) to 55×55 μm^2 pixel sensors
closer to the beam, from 5.5 mm to 3.5 mm

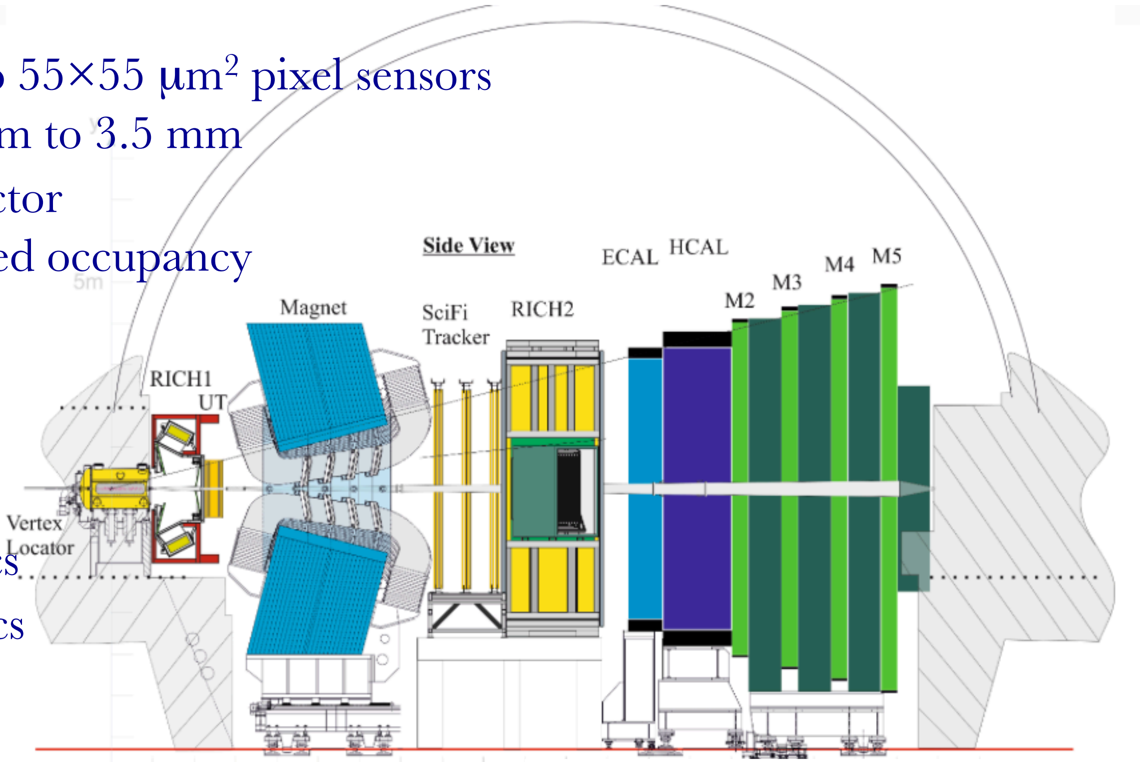
Upstream Tracker silicon strip detector
adapt segmentation to increased occupancy

SciFi Tracker 3 stations of X-U-V-X
scintillating fibre planes

PID new photodetectors for RICH1
and RICH2

Calorimetry new readout electronics

Muon System new readout electronics

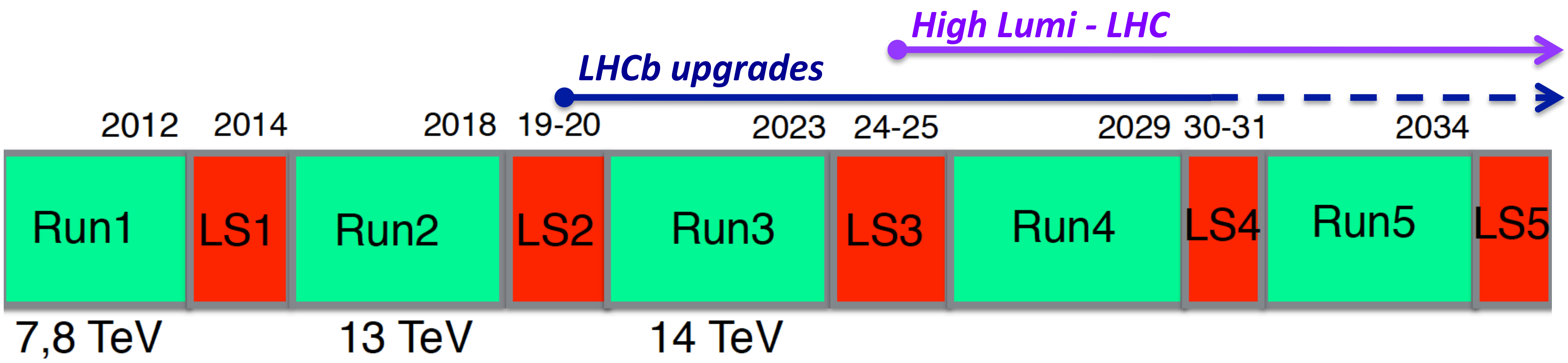


➔ ***less than 10% of all channels will be kept***

LHCb-TDR-{13,14,15,66}

the next years @ LHCb

- upgrade installation started this January 2019 to be ready at the end of Long Shutdown 2 (LS2)
- restart data taking in 2021 at Run3
- higher instantaneous luminosity ➔ from $2{\times}10^{32}$ cm^{-2}s^{-1} to $2{\times}10^{33}$ cm^{-2}s^{-1}



- more visible interactions per bunch crossing ➔ from 1 to about 5
- upgrade detector qualified to accumulate 50 fb^{-1} at the end of Run4, ***LHCb-TDR{13,14,15,66}***
- LS3: consolidation of the detector
- LS4: to take full advantage of the High Lumi-LHC, $\mathcal{L}$ up to 1-2 $\times 10^{34}$ cm^{-2}s^{-1}, the collaboration is proposing a major upgrade of the detector with the intent to collect 300 fb^{-1} at the end of Run5, ***CERN/LHCC 2017-003, CERN/LHCC 2018-027***

outlook for $R(D^*)$ and $R(J/\psi)$

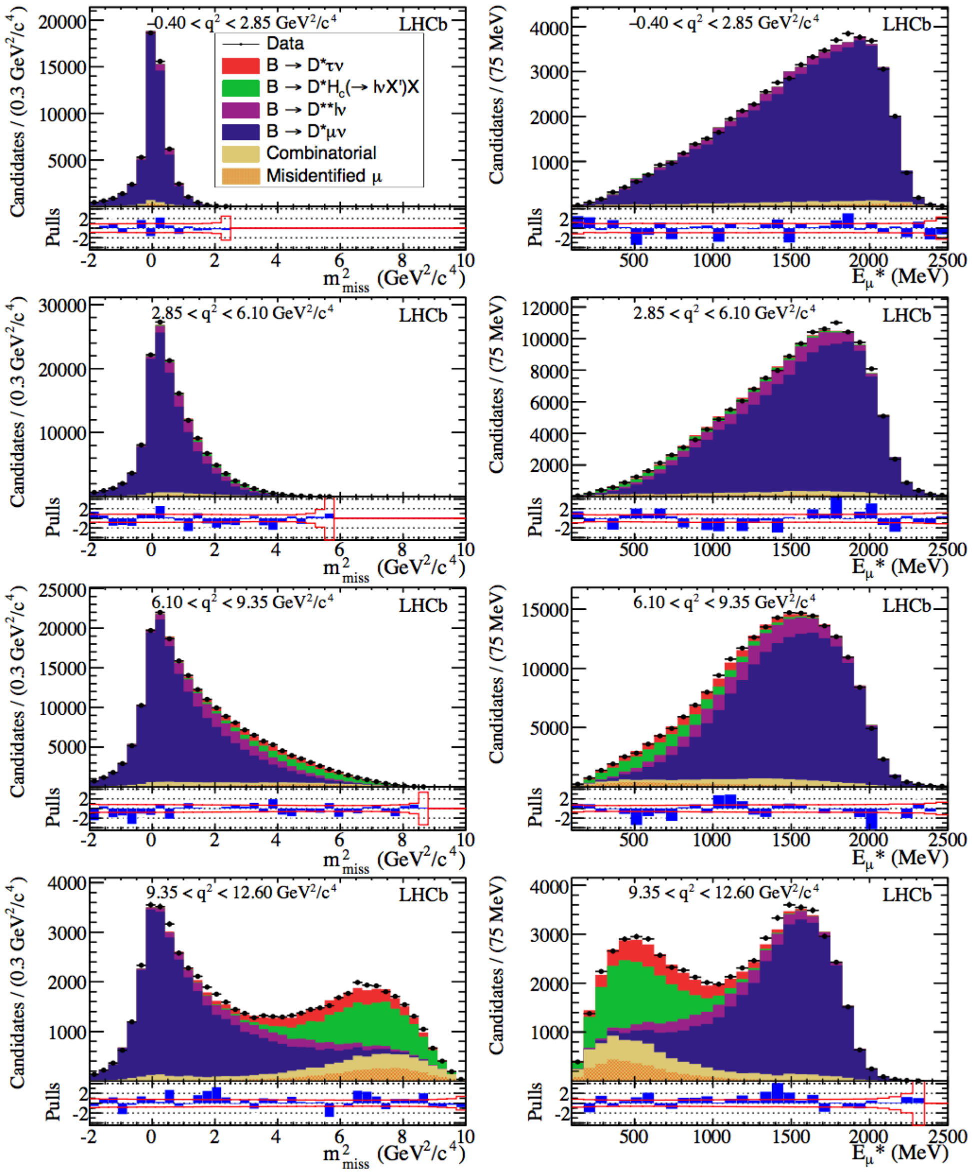
Physics case for LHCb Upgrade II arXiv:1808.08865 (2018)	$\sigma(R_{D^*})$	$\sigma(R_{J/\psi})$
➢ All results based on **3/fb** at 7-8TeV (Run 1 2010-2012)	0.027 0.030	0.17 (stat) 0.18 (syst)
➢ We have another **6/fb** at 13TeV (Run 2 2015-2018) x4 in B statistics due to increased production X-section	0.014	0.10
➢ LHCb upgrade during shutdown (2019-2020) 40MHz readout and trigger entirely in software Better vertexing for reducing backgrounds to τ, D and B	After upgrade can reduce syst errors	
➢ Integrated luminosity **50/fb** in Runs 3 & 4 Higher instantaneous luminosity $2 \times 10^{33}/cm^2/s$	0.007	0.07
➢ Possible major upgrade in ~2030 Much higher luminosity 2×10^{34}, with target of **300/fb**	0.002	0.02
	similar to $\sigma(SM)$	

R(D*) from $\tau \to \mu\nu_\mu\bar{\nu}_\tau$

LHCb [PRL 115 (2015) 111803]

- maximum likelihood fit to m^2_{miss}, E^*_μ, q^2 distributions with 3D templates representing $B^0 \to D^*\tau\nu$, $B^0 \to D^*\mu\nu$, and background sources:
  - D^{**} **feed-down**
  - **double charm**
  - **combinatorial**
  - **misidentified muons**

background and signal shapes extracted from control samples and simulations validated against data



- dominant component is $B^0 \to D^*\mu\nu$
- $B^0 \to D^*\tau\nu$ component increases with q^2

R(D*) from $\tau \to \mu\nu_\mu\bar{\nu}_\tau$

LHCb *[PRL 115 (2015) 111803]*

- dominant systematic is due to the size of the simulation sample
- systematic due to the modeling of the mis-ID μ template

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

1.9σ above Standard Model

$R(D^*)^{SM} = 0.258 \pm 0.003$

TABLE I. 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
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ 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
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

R(D*) from $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$

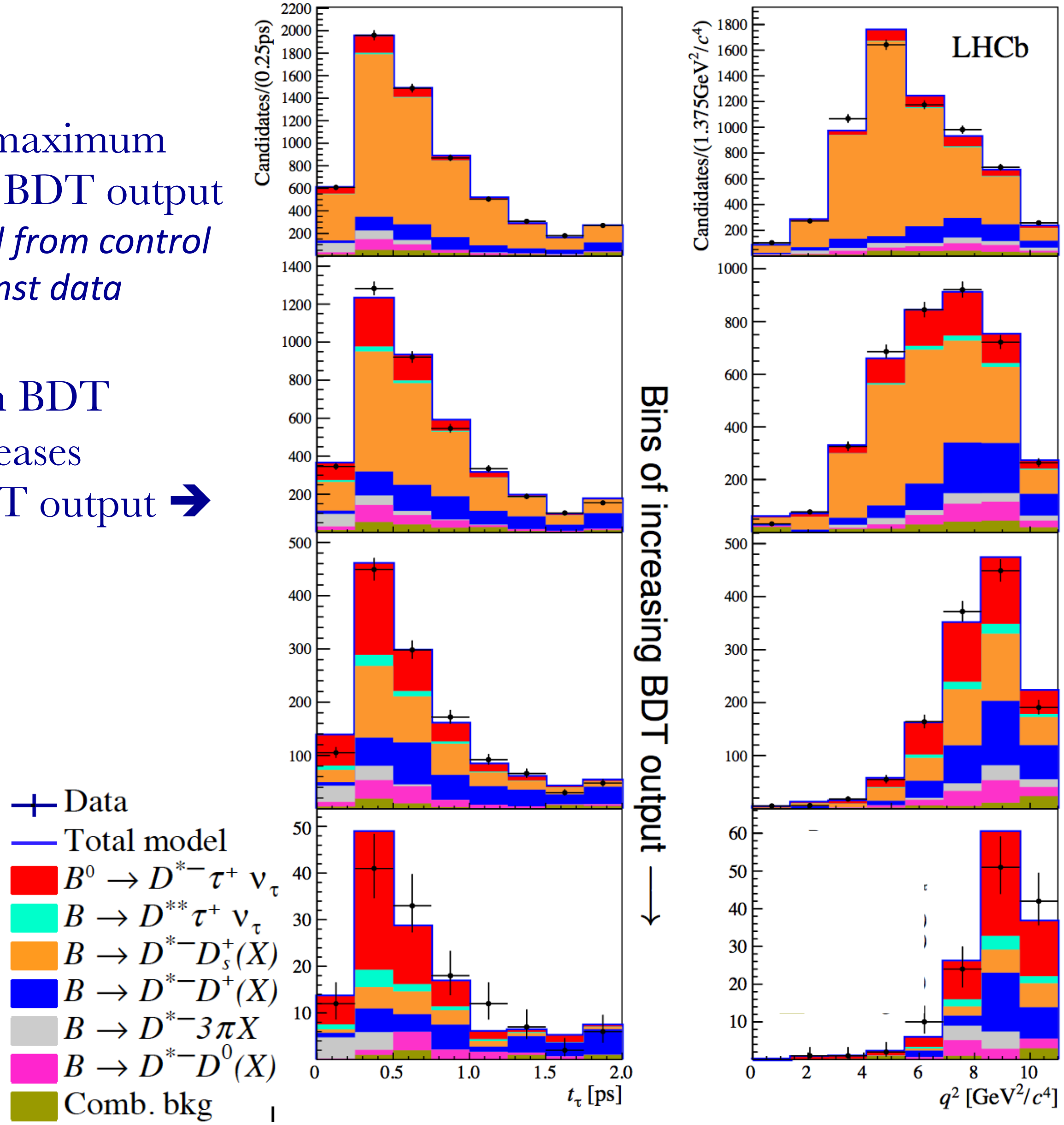
***LHCb** [PRL 120 (2018) 171802]*
***LHCb** [PRD 97 (2018) 072013]*

- **signal yield** from a 3D binned maximum likelihood fit to q^2, decay time, and BDT output
  background and signal shapes extracted from control samples and simulations validated against data

- **signal** component increases with BDT output, while $D^*D_s^+X$ fraction decreases
- dominant backgrount at high BDT output → D^*D^+X due to D+ lifetime

$N(B^0 \to D^*\tau\nu) = 1296 \pm 86$

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



R(D*) from $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$

***LHCb** [PRL 120 (2018) 171802]*
***LHCb** [PRD 97 (2018) 072013]*

- dominant systematic is due to the size of the simulation sample
- uncertainties on double charm backgrounds should improve with more data and improved external measurements
- uncertainty on efficiency ratio should improve with more statistics

TABLE I. Relative systematic uncertainties on $\mathcal{R}(D^{*-})$.

Source	$\delta R(D^{*-})/R(D^{*-})$ [%]
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

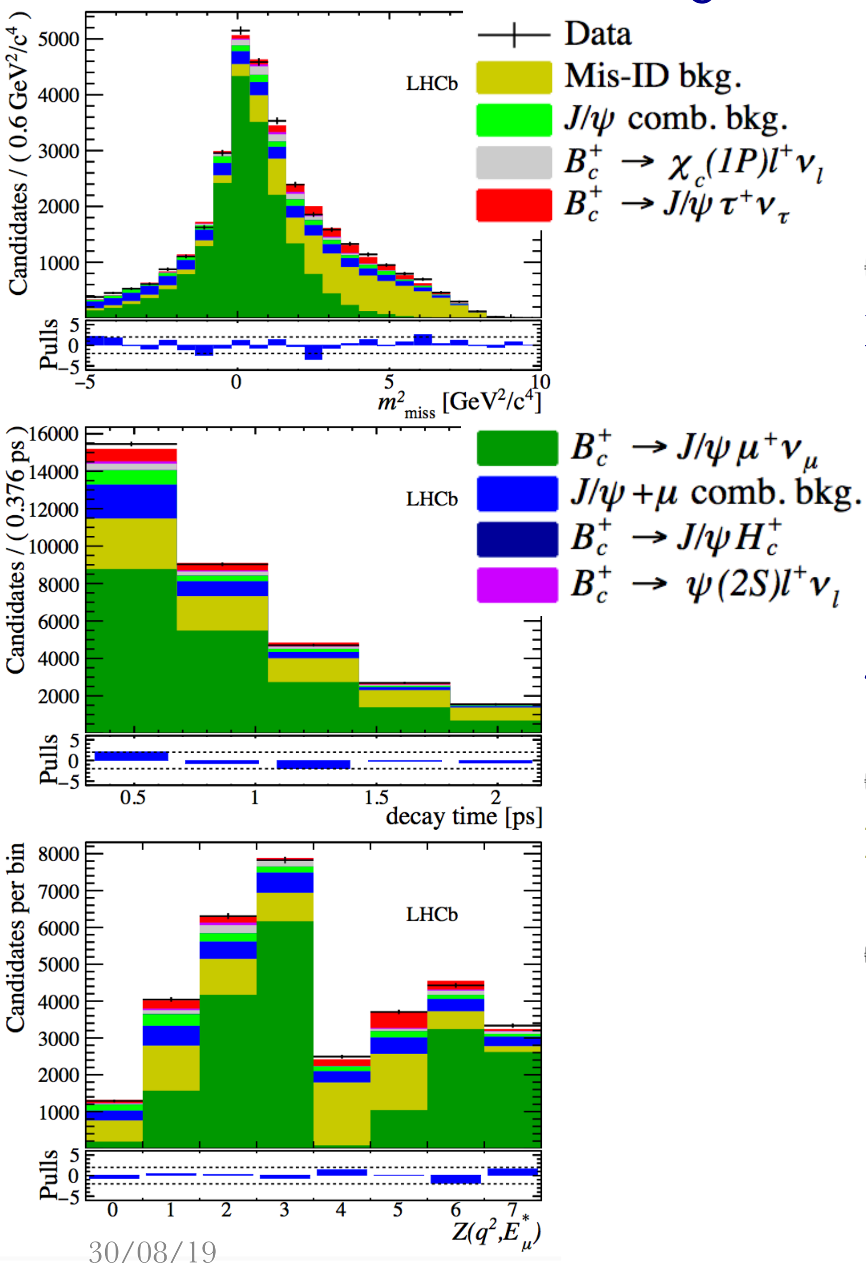
$$R(D^*) = 0.291 \pm 0.019_{stat} \pm 0.026_{syst} \pm 0.013_{ext}$$

~ 0.9 σ above Standard Model

compatible with the muonic channel

R(J/ψ), LFU with B_c decays

***LHCb** [PRL 120 (2018) 121801]*



- signal yield from a 3D binned maximum likelihood fit to
  - ✓ m^2_{miss}
  - ✓ B_c decay time
  - ✓ $Z(E^*_\mu,q^2)$ ≡ flattened 4×2 histos of E^*_μ and q^2

background and signal shapes extracted from control samples and simulations validated against data

- main backgrounds due to **misidentified hadrons** and **combinatorial muons**

- first evidence of the decay $B_c \to J/\psi\tau\nu_\tau$ (3σ)

R(J/ψ), LFU with B_c decays

***LHCb** [PRL 120 (2018) 121801]*

- $B_c^+ \rightarrow J/\psi$ form factors
- size of the simulation sample
  second-largest systematic

TABLE I. Systematic uncertainties in the determination of $\mathcal{R}(J/\psi)$.

Source of uncertainty	Size ($\times 10^{-2}$)
Finite simulation size	8.0
$B_c^+ \rightarrow J/\psi$ form factors	12.1
$B_c^+ \rightarrow \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Mis-ID background strategy	5.6
combinatorial background cocktail	4.5
combinatorial J/ψ background scaling	0.9
$B_c^+ \rightarrow J/\psi H_c X$ contribution	3.6
$\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau)$	0.2
Systematic uncertainty	17.7
Statistical uncertainty	17.3

$$R(J/\psi) = 0.71 \pm 0.17_{stat} \pm 0.18_{syst}$$

~ 2. σ above Standard Model

$B_{d,s} \to e\mu$: additional material

The BF is measured with respect to normalisation channels to remove some systematic errors

$$\mathcal{B}(B^0_{(s)} \to e^{\pm}\mu^{\mp}) = \sum_i w^i \frac{\mathcal{B}^i_{\text{norm}}}{N^i_{\text{norm}}} \frac{\varepsilon^i_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{f_q}{f_{d(s)}} \frac{\mathcal{L}^i_{\text{norm}}}{\mathcal{L}_{\text{sig}}} \times N_{B^0_{(s)} \to e^{\pm}\mu^{\mp}}$$

weights proportional to BF and yield

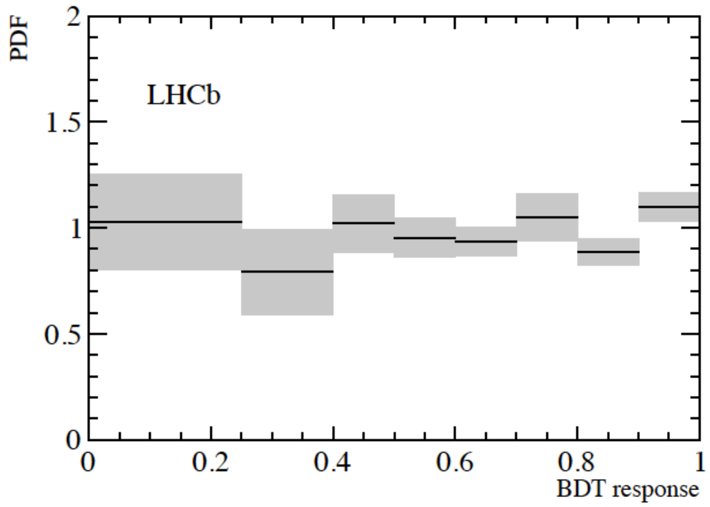
normalisation/signal efficiency ratio

hadronisation ratio

The correctness of the normalisation procedure is validated by measuring:

$$R_{\text{norm}} = \frac{N_{B^0 \to K^+\pi^-} \times \varepsilon_{B^+ \to J/\psi K^+}}{N_{B^+ \to J/\psi K^+} \times \varepsilon_{B^0 \to K^+\pi^-}} = 0.332 \pm 0.002\,(\text{stat}) \pm 0.020\,(\text{syst})$$

BDT calibration is performed on $B \to K\pi$ data, triggered independently of the signal presence (TIS)



$\Lambda_b \to \Lambda_c \mu \nu$ form factors

LHCb *[PRD 96 (2017) 112005]*

✓ differential distributions are crucial for comparisons with HQET and lattice QCD, also a first step towards measuring |Vcb|

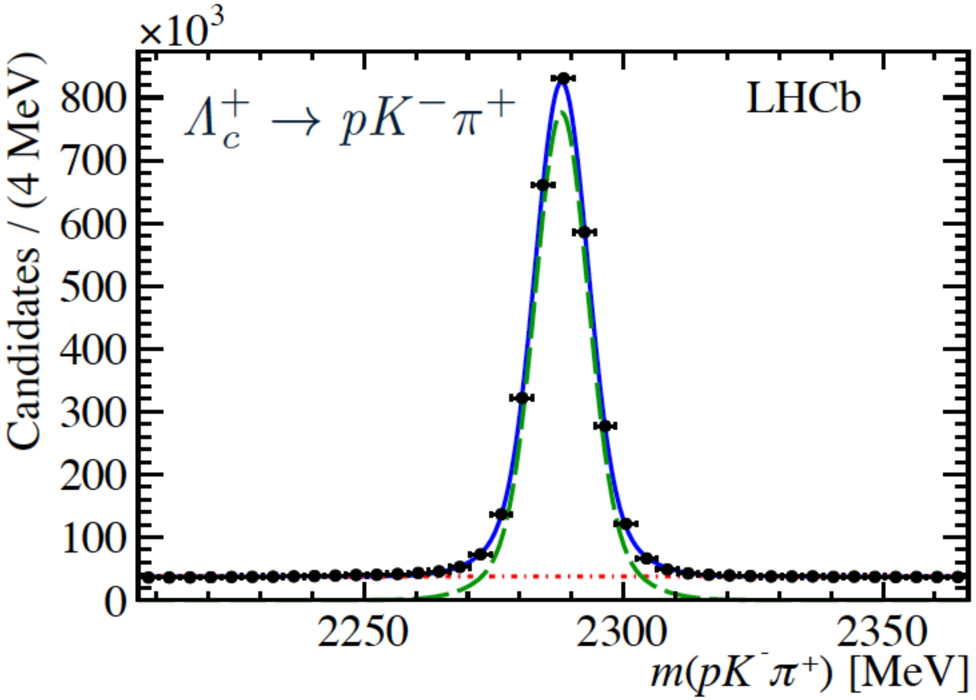
✓ the decay $\Lambda_b \to \Lambda_c \mu \nu$ is described by 6 form factors, reducing to a single function in heavy quark limit ➔ the Isgur-Wise function $\xi_B(w)$:

$$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w) \qquad w = v_{\Lambda_b} \cdot v_{\Lambda_c} = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c}}$$

✓ expanding $\xi_B(w)$ around w=1 yields: $\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma(w-1)^2 + \ldots$ used for fitting the decay rate

✓ **large and clean samples of $\Lambda_b \to \Lambda_c \mu \nu$ decays: 2.7×10^6 in analyses Run1 sample**

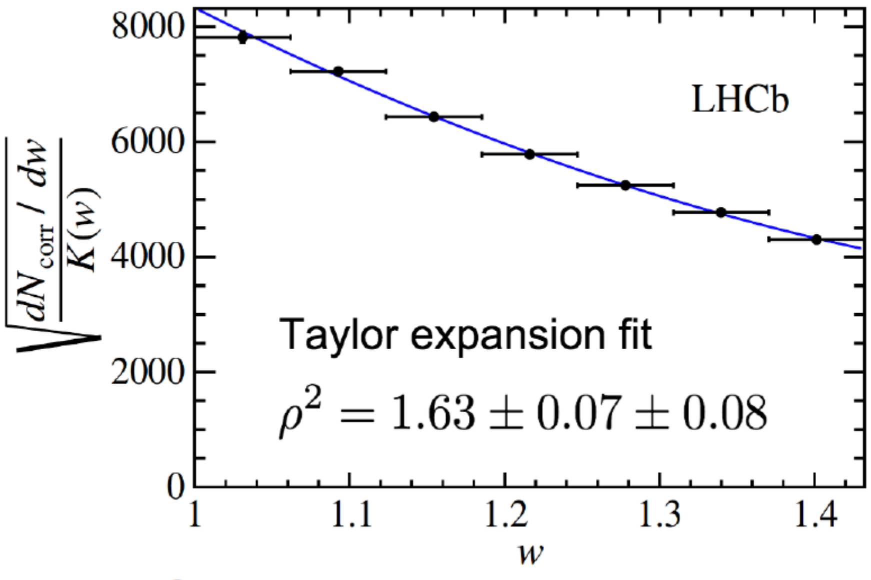
✓ subtract feed-down from higher resonances $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Lambda_c(2765)$, $\Lambda_c(2880)$

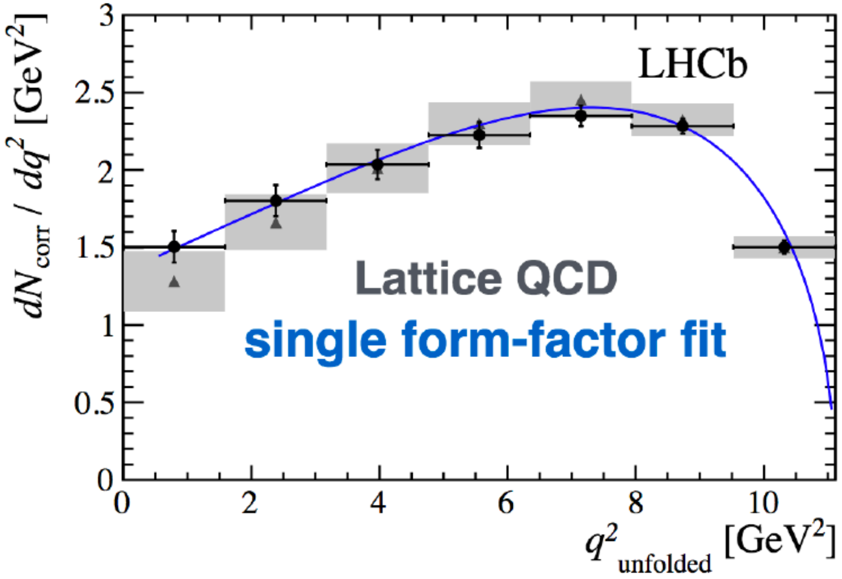


$\Lambda_b \to \Lambda_c \mu \nu$ form factors

***LHCb** [PRD 96 (2017) 112005]*

✓ w distributions are unfolded and corrected for efficiencies
✓ then they are fit using 3 approaches, here is example from Taylor expansion ➔ they are in good agreement with HQET predictions





✓ also comparison with dΓ/dq2 distributions with lattice QCD shows excellent agreement *[PRD92 (2015) 034503]*