Lepton universality tests at LHCb

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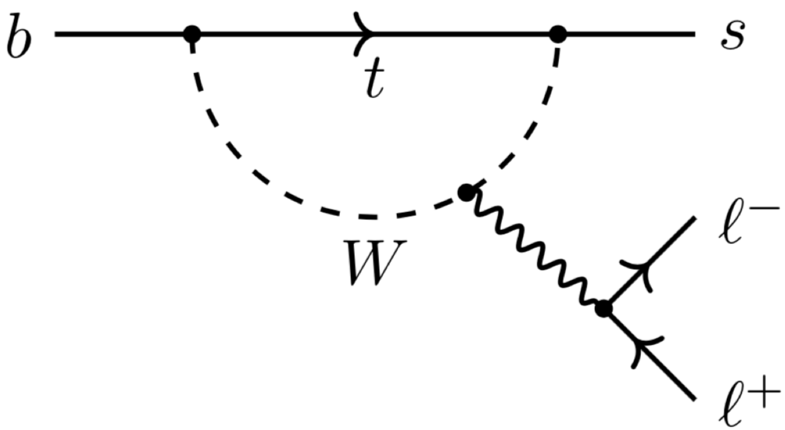
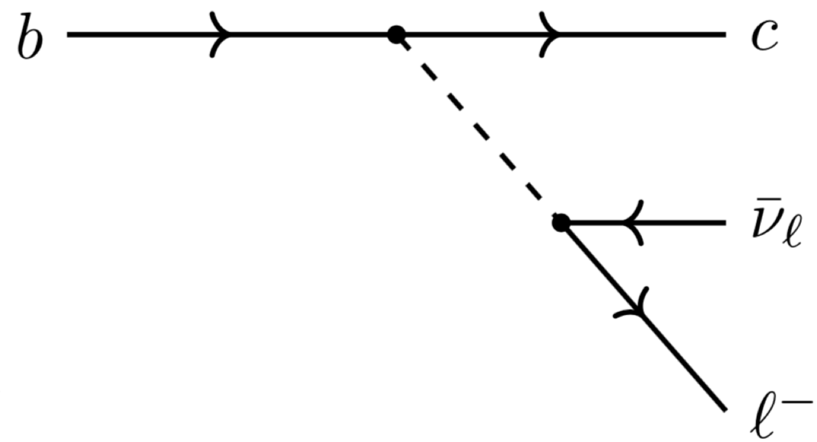
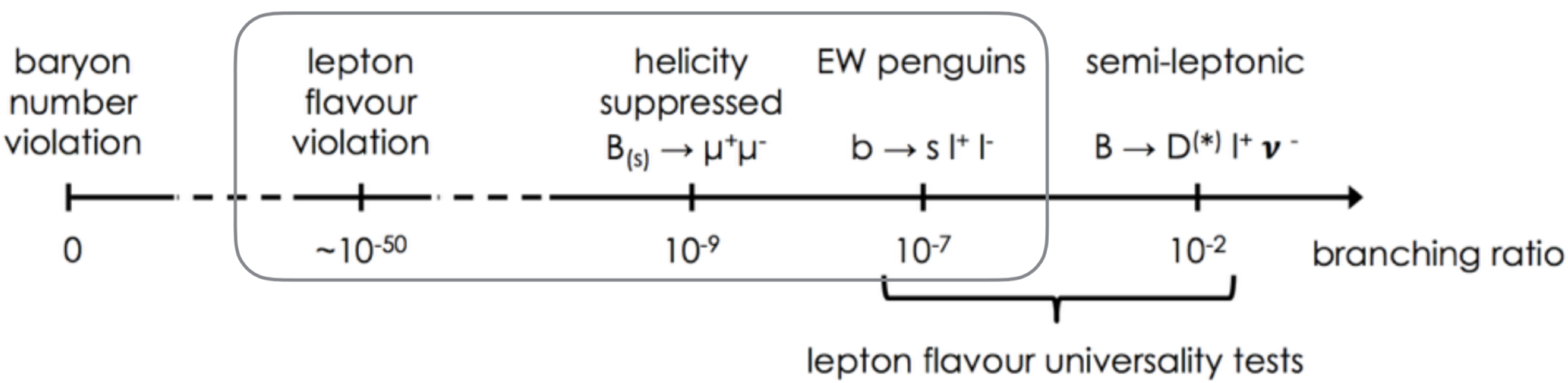
LFU in the Standard Model

- In SM, Lepton flavor universality $(g_e = g_\mu = g_\tau)$

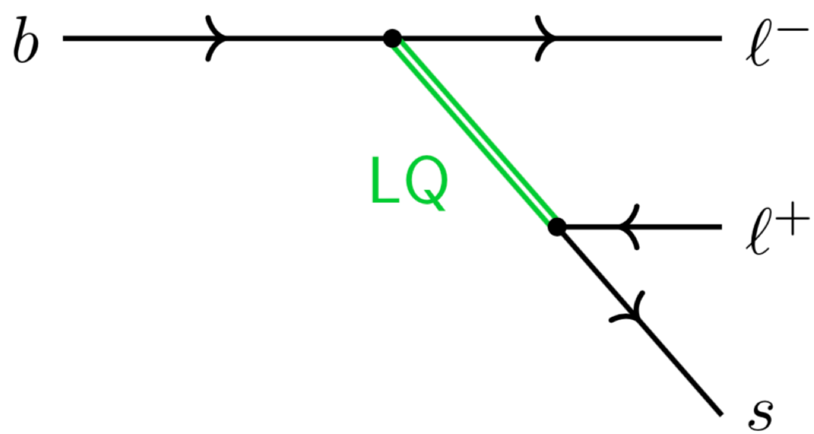


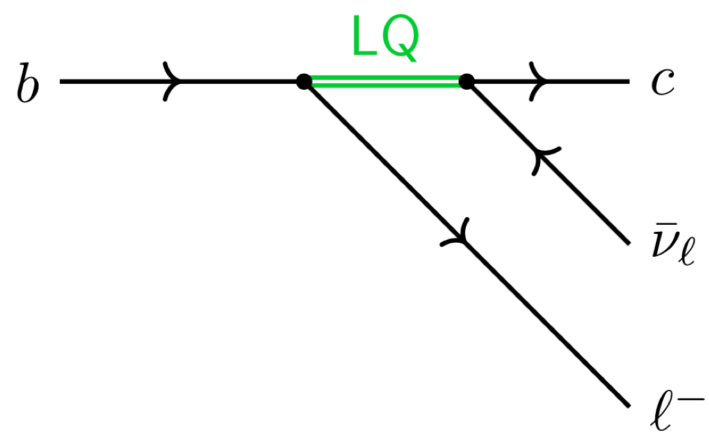


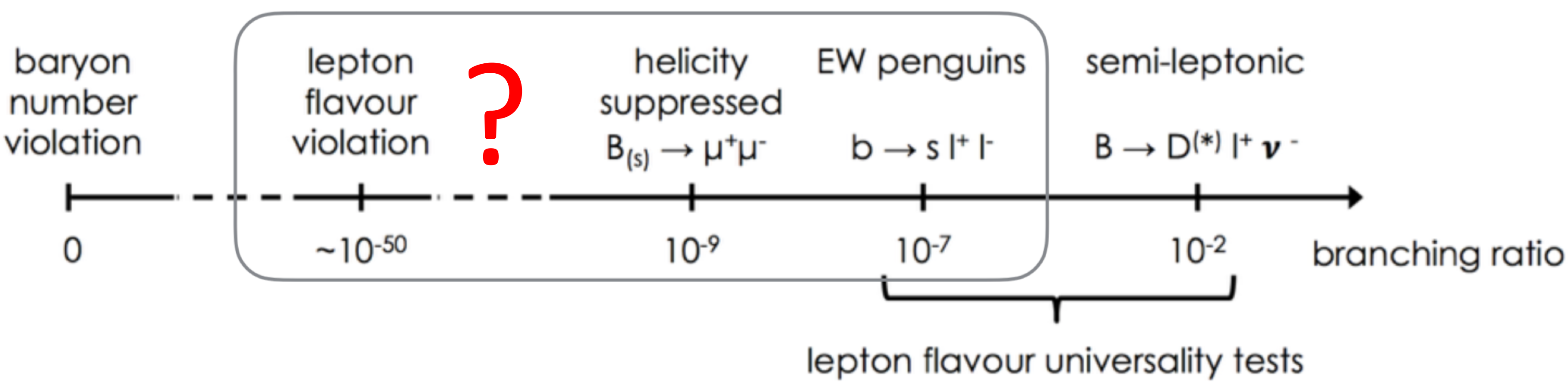


Effects of New Physics

- Effects of New Physics, e.g., Leptoquark?







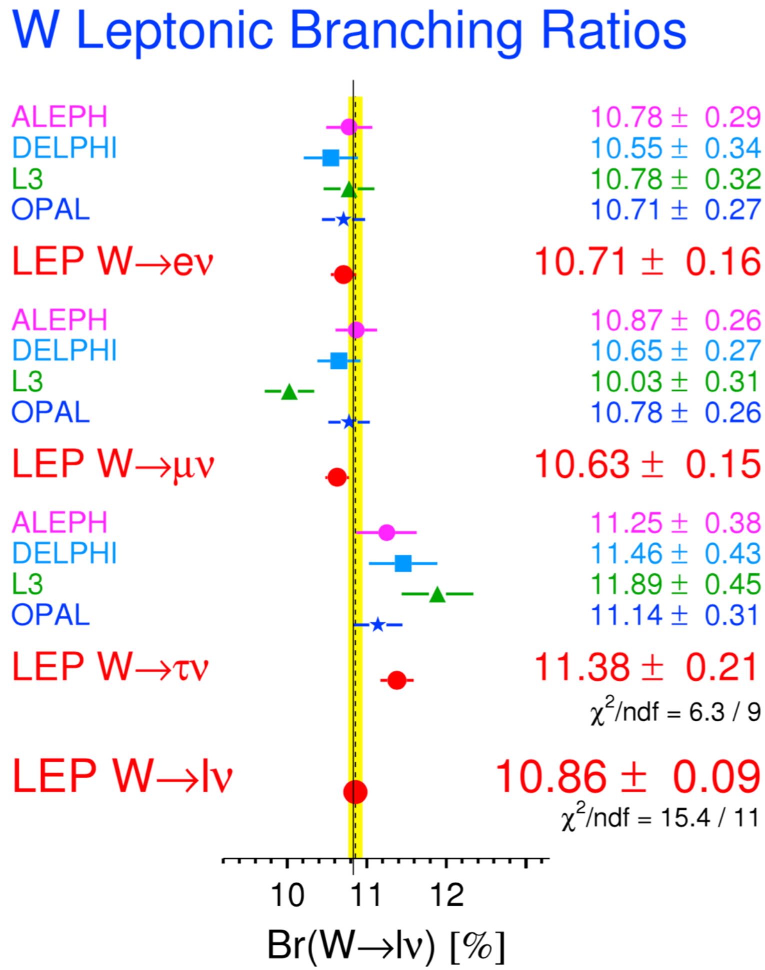
Experimental test of LFU

- Well established in SM, e.g. *W->lv*
  - Some tension

[LEP, PR 532 (2013) 119]

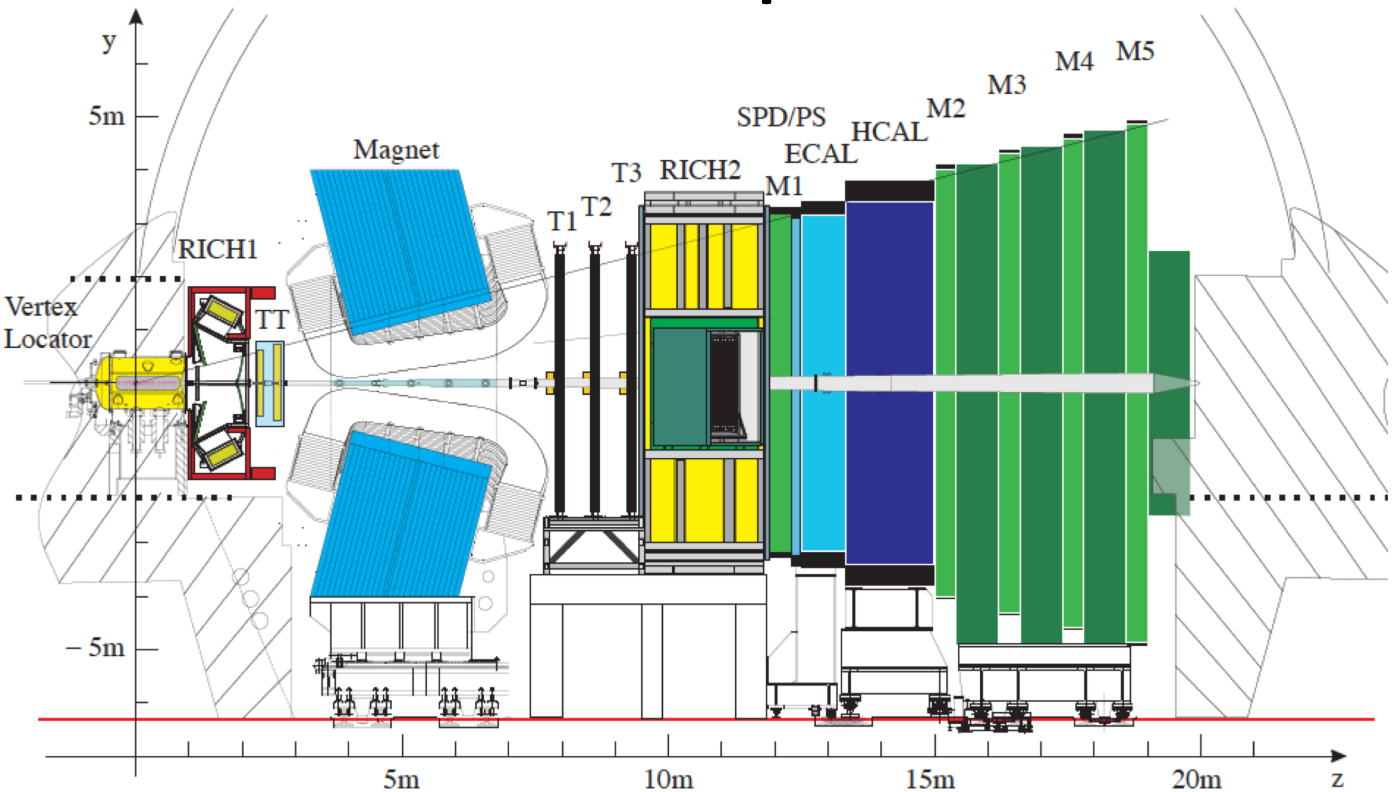
$$\mathcal{B}(W\to\mu\bar{\nu}_\mu)/\mathcal{B}(W\to e\bar{\nu}_e) = 0.993 \pm 0.019,$$
$$\mathcal{B}(W\to\tau\bar{\nu}_\tau)/\mathcal{B}(W\to e\bar{\nu}_e) = 1.063 \pm 0.027,$$
$$\mathcal{B}(W\to\tau\bar{\nu}_\tau)/\mathcal{B}(W\to \mu\bar{\nu}_\mu) = 1.070 \pm 0.026.$$

$$\frac{2\mathcal{B}(W\to\tau\bar{\nu}_\tau)}{\mathcal{B}(W\to e\bar{\nu}_e)+\mathcal{B}(W\to\mu\bar{\nu}_\mu)} = 1.066 \pm 0.025\ (2.6\sigma)$$



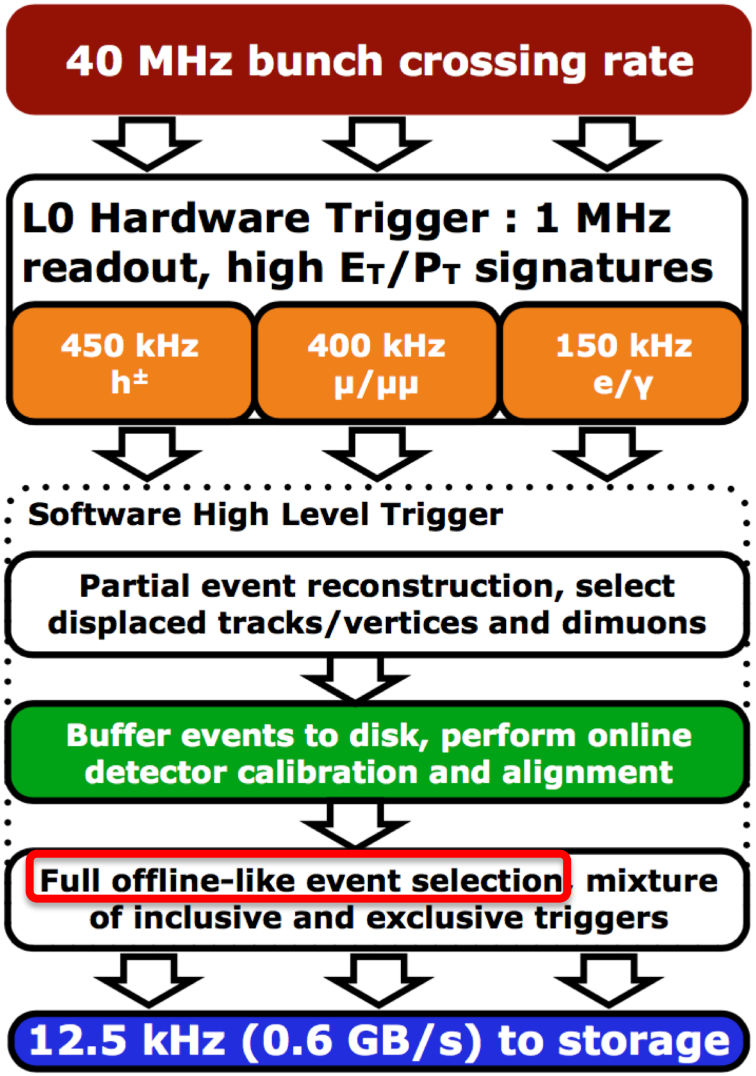
The LHCb experiment

[JINST 3 (2008) S08005]



Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (Run-II)



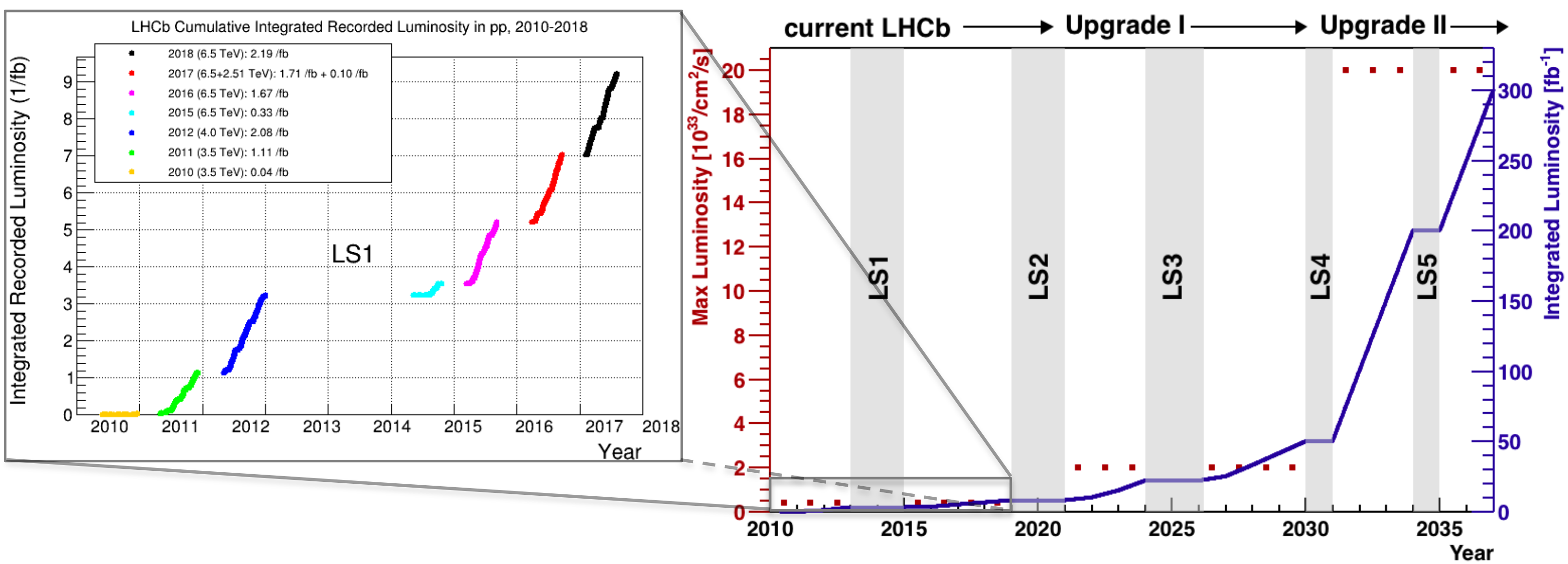
- Level-0, Hardware
  - Fully synchronous at 40 MHz
  - Selection of high p_T particles
    - $p_T(\mu) >\sim 1.5$ GeV/c, $p_T(\mu_1) \times p_T(\mu_2) >\sim (1.5\,\mathrm{GeV}/c)^2$
    - $E_T(h, e, \gamma) > 2.5 - 4$ GeV
- High Level Trigger (HLT), Software
  - Stage 1, tracking info, IP cuts
  - Stage 2, full reconstruction + selections

  $\sim$50 kB/event $\Rightarrow$ 0.25GB/s, $\sim$ 2 PB/year
- Offline data flow

  Raw data $\xrightarrow{\text{Rec}}$ Stripping $\xrightarrow{10\%}$ (μ)DST

  Stripping, also as HLT3, Pre-selections of all decay channels under study

LHCb luminosity prospects

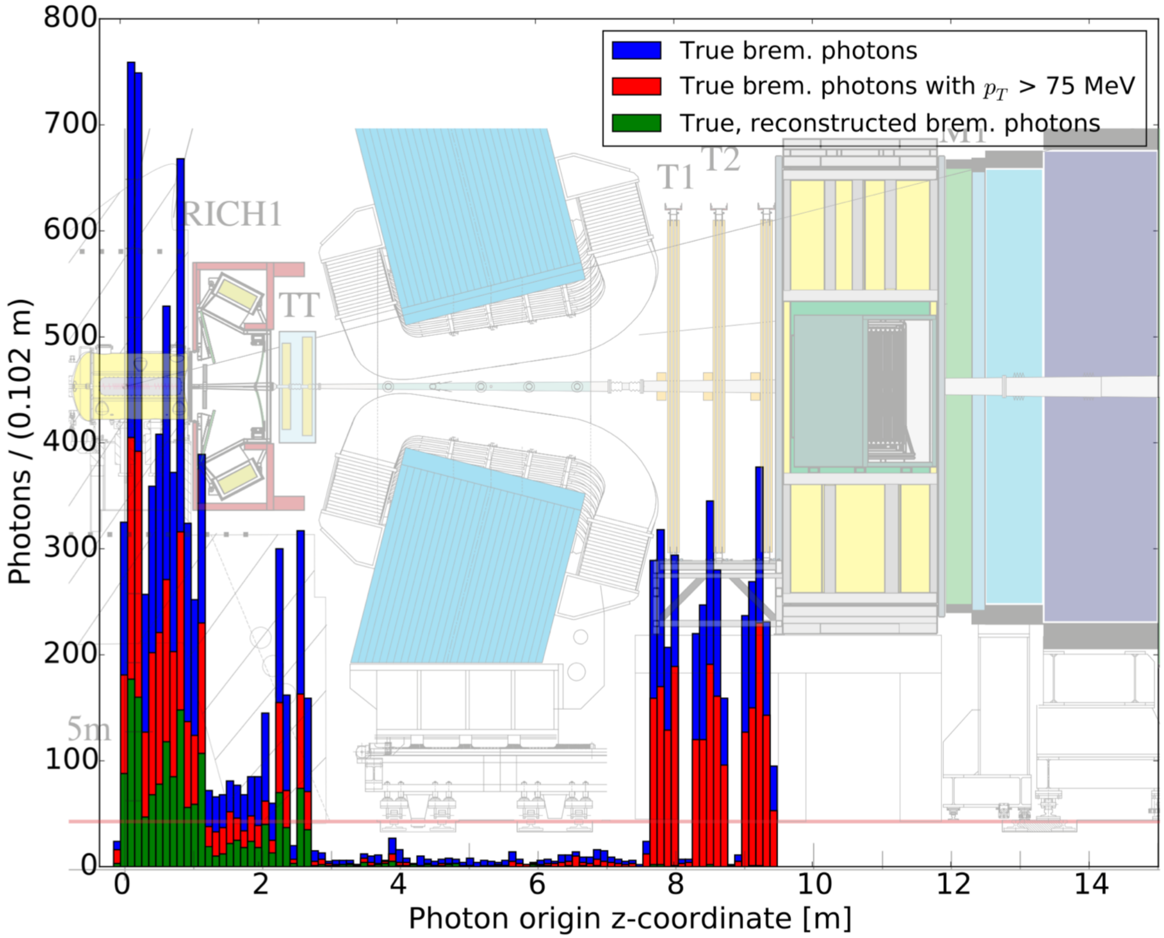


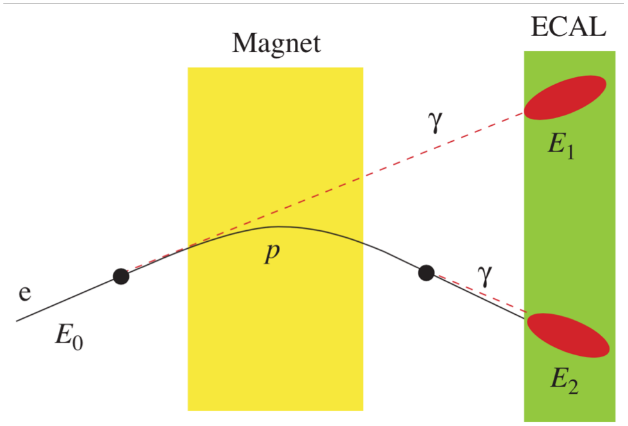
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

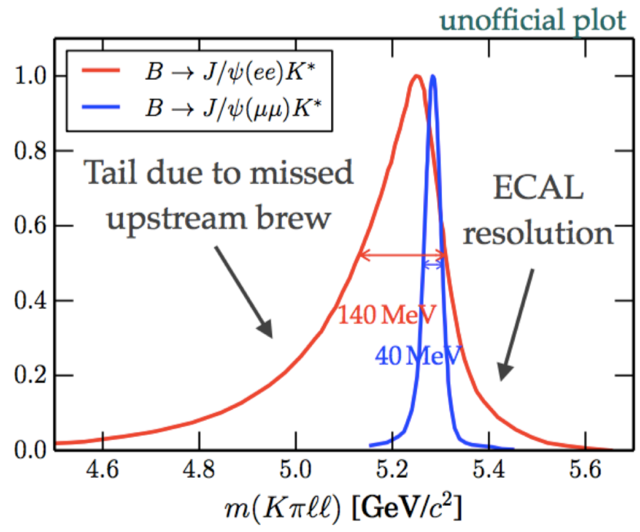
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

* See Y. Li's talk the LHCb upgrades

Bremsstrahlung corrections





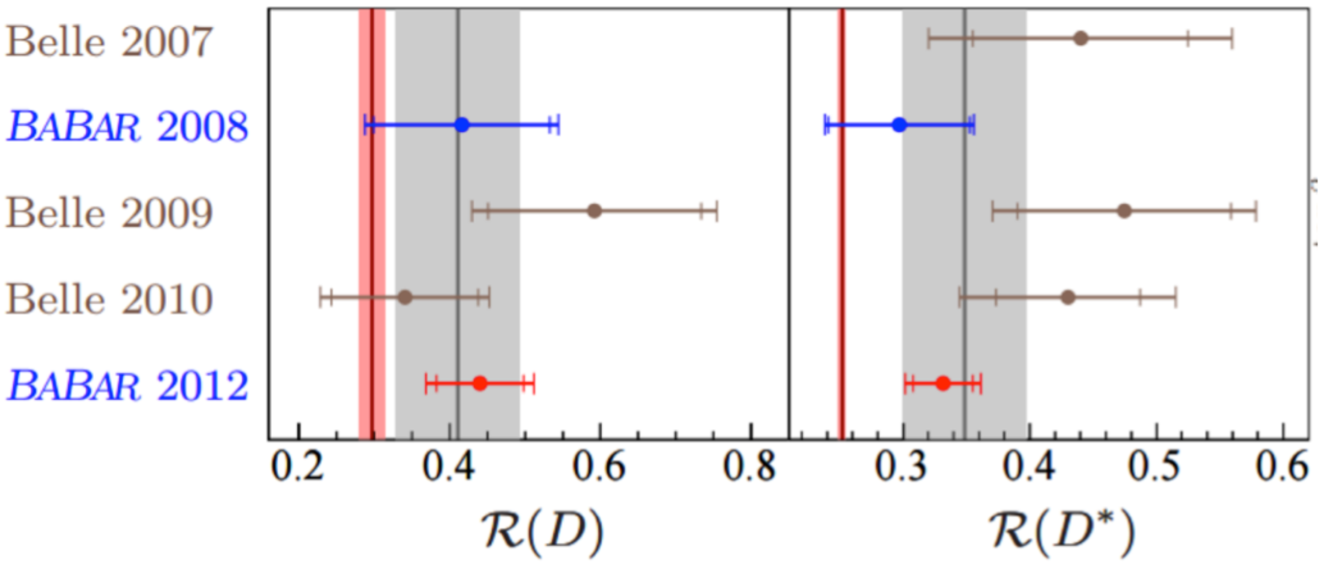


LFU in B system, pre-LHCb

- R(D$^{(*)}$), Babar reported deviation of ~3.2 σ

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

[Babar, PRD 88 (2013) 072012]



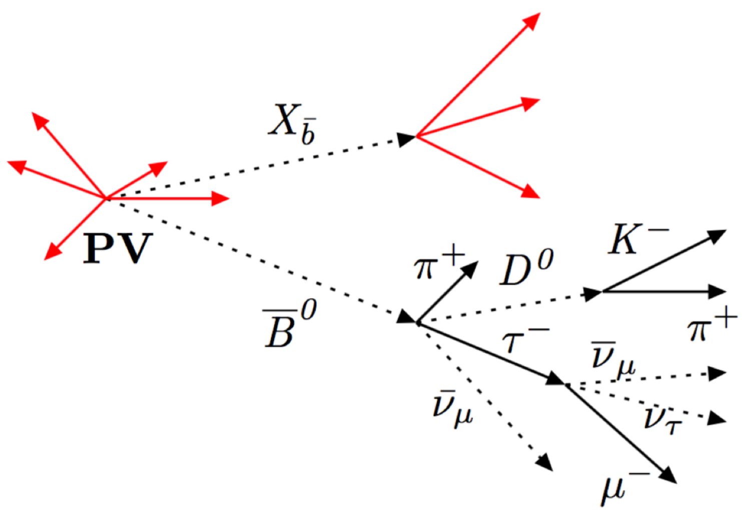
- No deviation seen in FCNC b->sll decays

R(D*) using munoic τ decays

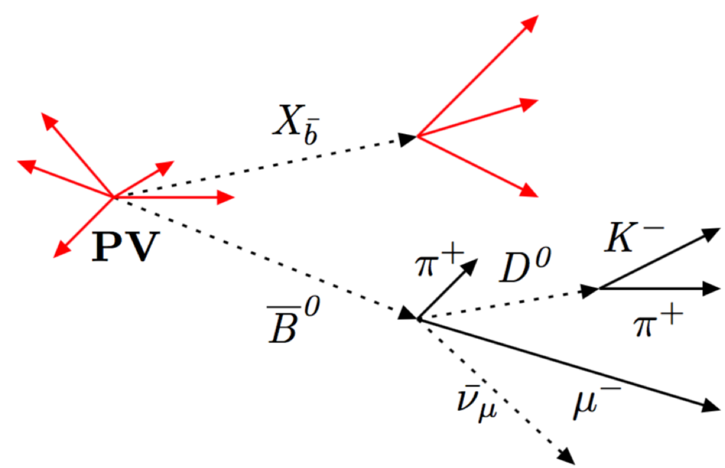
- Measure R(D*) using munoic τ decays
  - Pros: $\mathcal{B}$(τ->μX)~17.4%, B vertex rec'ible
  - Cros: no τ vertex

[PRL 115 (2015) 118003]

Signal $(B^0 \to D^{*+}\tau^-\overline{\nu}_\tau)$



Normalisation $(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$



$R(D^*)$, background

[PRL 115 (2015) 118003]

$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ (normalization)

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
(signal)

$\bar{B}^0 \to D^{**+}\mu^-\bar{\nu}_\mu + \bar{B}^0 \to D^{**+}\tau^-\bar{\nu}_\tau$
$\bar{B}^- \to D^{**0}\mu^-\bar{\nu}_\mu + \bar{B}^- \to D^{**0}\tau^-\bar{\nu}_\tau$
$D^{**} \to D^{*+}\pi$ (3 states each, 6 PDFs)

$\bar{B}^0_s \to D_s^{**+}\mu^-\bar{\nu}_\mu$
$D_s^{**+} \to D^{*+}K_S^0$, (2 states, 1 free param)

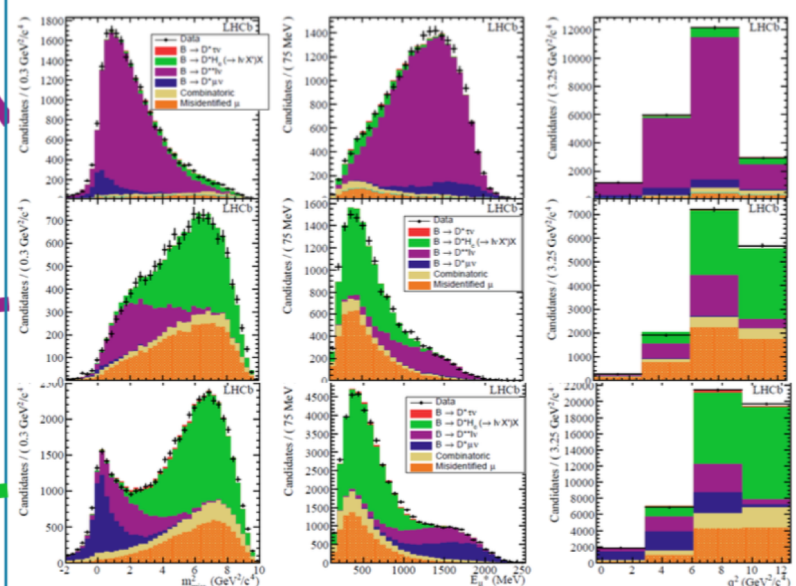
$B^{+,0} \to \bar{D}^{**}\mu^+\nu_\mu$
$\bar{D}^{**} \to D^{*-}\pi\pi$, (cocktail)

$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$
$+\bar{B} \to D^{*+}D_s^-(\to \tau^-\bar{\nu}_\tau)X$

combinatorial D^{*+}
combinatorial $D^{*+}\mu^-$

$h \to \mu$ misidentification

Control sample fits to constrain shapes



LHCb-PAPER-2015-025

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R(D*), systematics

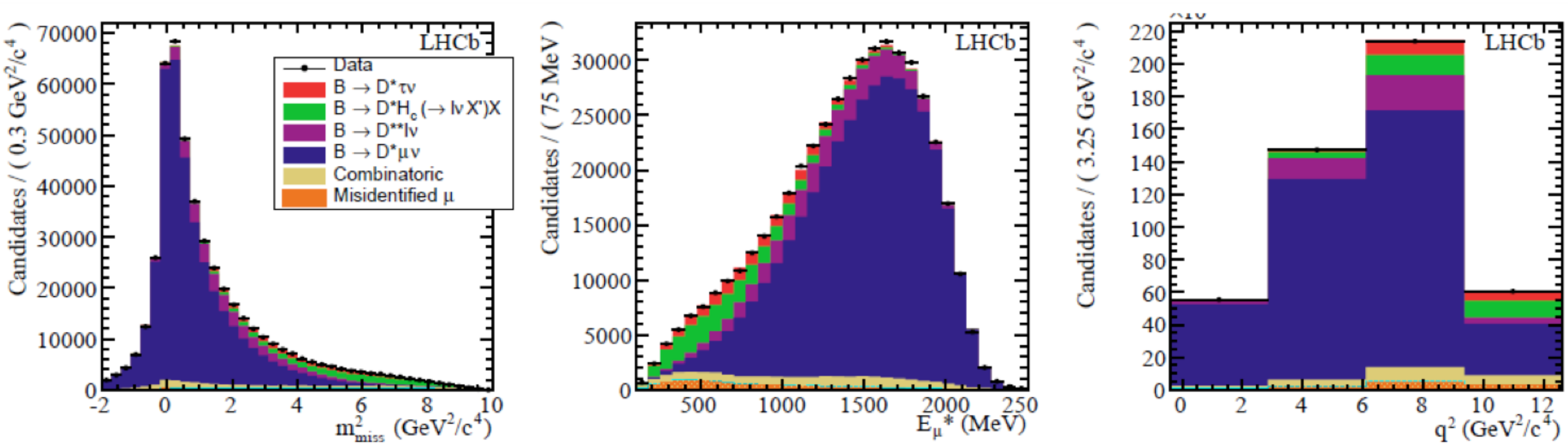
[PRL 115 (2015) 118003]

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*), results

- 3D fits, $\mathcal{R}_{D^*} = 0.336 \pm 0.027 \pm 0.030$
  - Signal yields: 16 500 ± 1 670

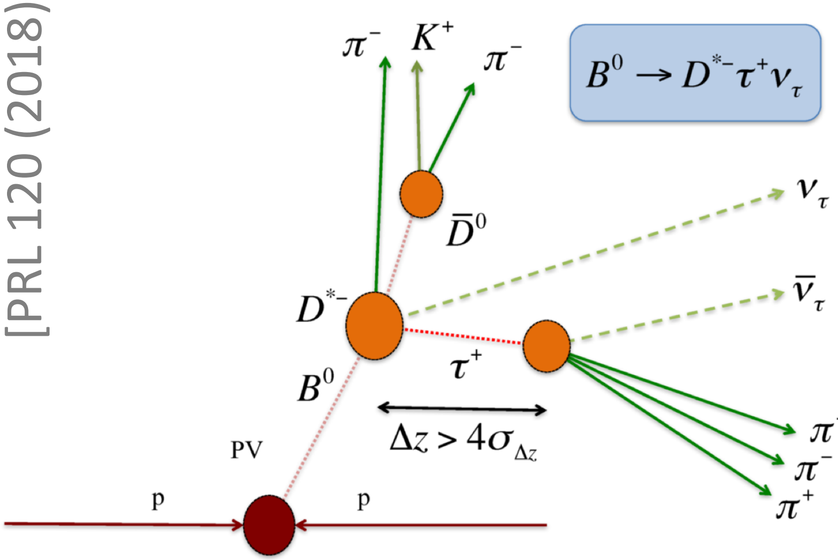
[PRL 115 (2015) 118003]

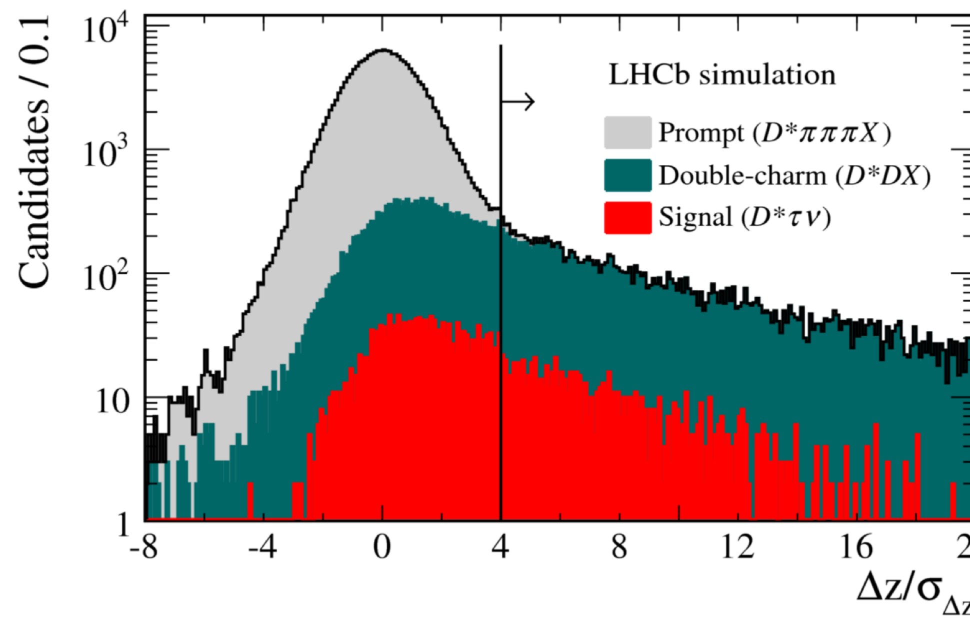


R(D*) using 3-prong τ decays

- Measure R(D*) using 3-prong τ decays
  - Pros: $\mathcal{B}(\tau \to 3\pi^{\pm}X) \sim 9\% + 4\%(\geq 1\pi^0)$, B/τ vertex rec'ible
  - Cros: soft $\pi^{\pm}$, bkg; different from norm. decay

[PRL 120 (2018) 171802]





R(D*), systematics

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Normalization channel	1.0
Particle identification	1.3
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Form factors (efficiency)	1.0
Total uncertainty	9.1

BES-III can help

[PRL 120 (2018) 171802]

R(D*), results

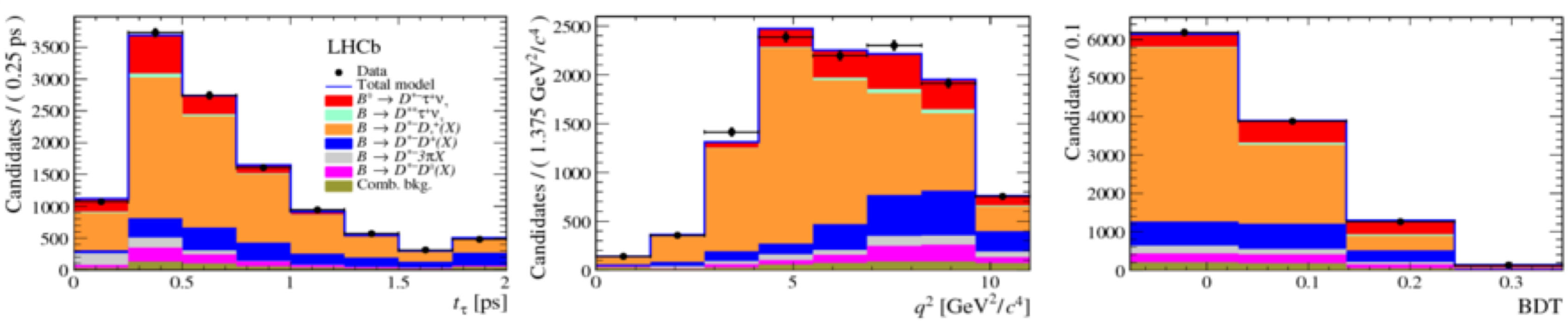
[PRL 120 (2018) 171802]

- Normalized to $B^0 \to D^{*-} 3\pi$

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

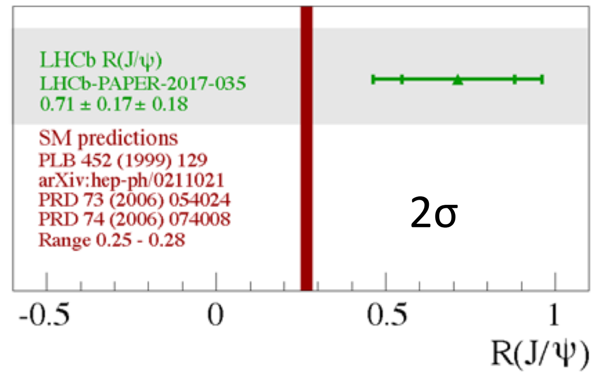
- 3D fits, R(D*)=0.286 ± 0.019 ± 0.025 ± 0.021
  - Signal yields: 1273 ± 85

    c.f. muonic: 16 500 ± 1 670

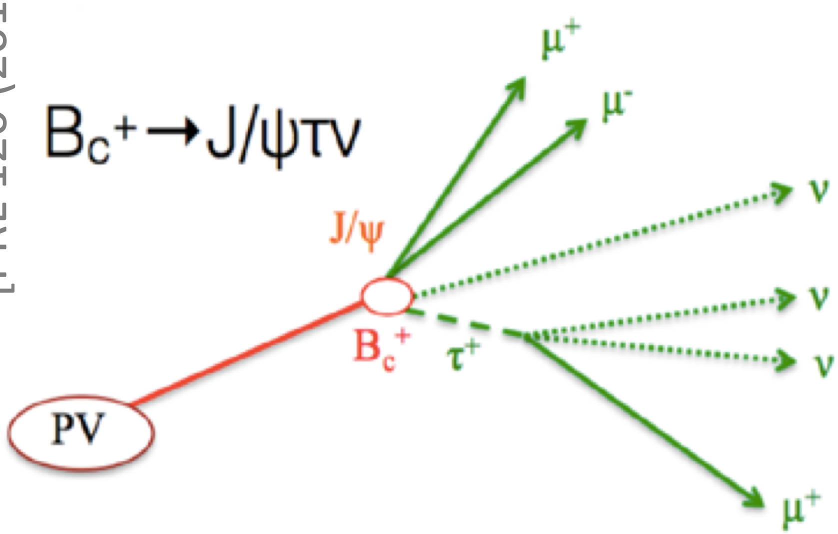


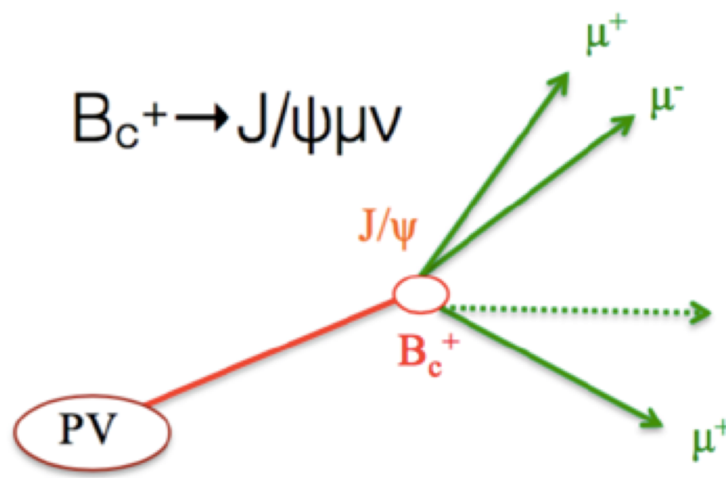
R(J/ψ) using munoic τ decays

- Measure R(J/ψ) using munoic τ decays
  - Pros: 3μ, $\mathcal{B}(\tau\text{->}\mu X)$~17.4%
  - Cros: small $\sigma(B_c^+)$, no τ vertex
- Run-I, 1400 ± 300 signal (3σ)



[PRL 120 (2018) 121801]





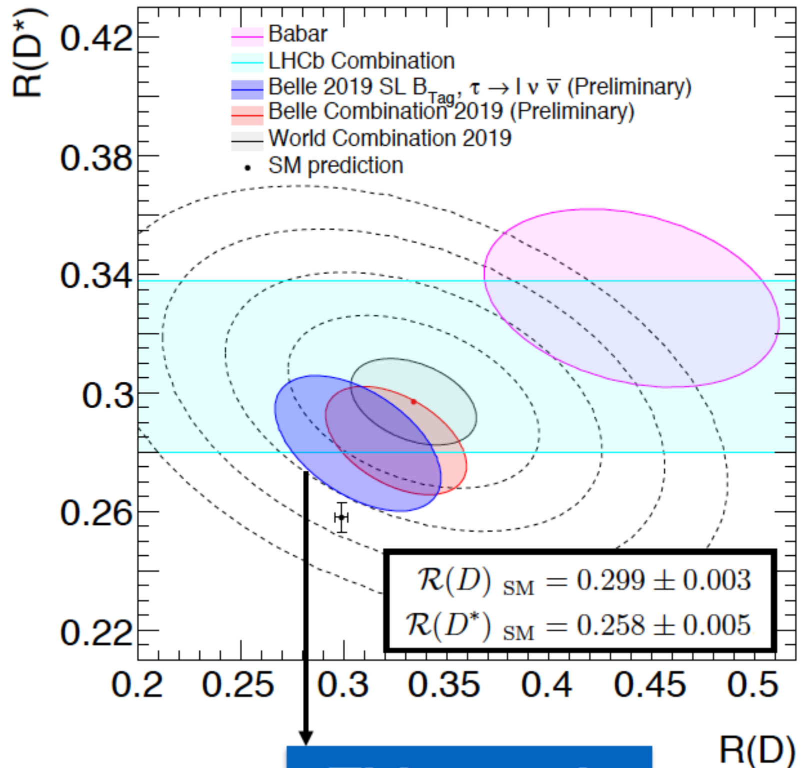
R(J/ψ), systematics

Source of uncertainty	Size ($\times 10^{-2}$)
Limited size of simulation samples	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau)$	0.2
B_c^+ lifetime	included in statistical uncertainty
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

[PRL 120 (2018) 121801]

Recent update from Belle

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



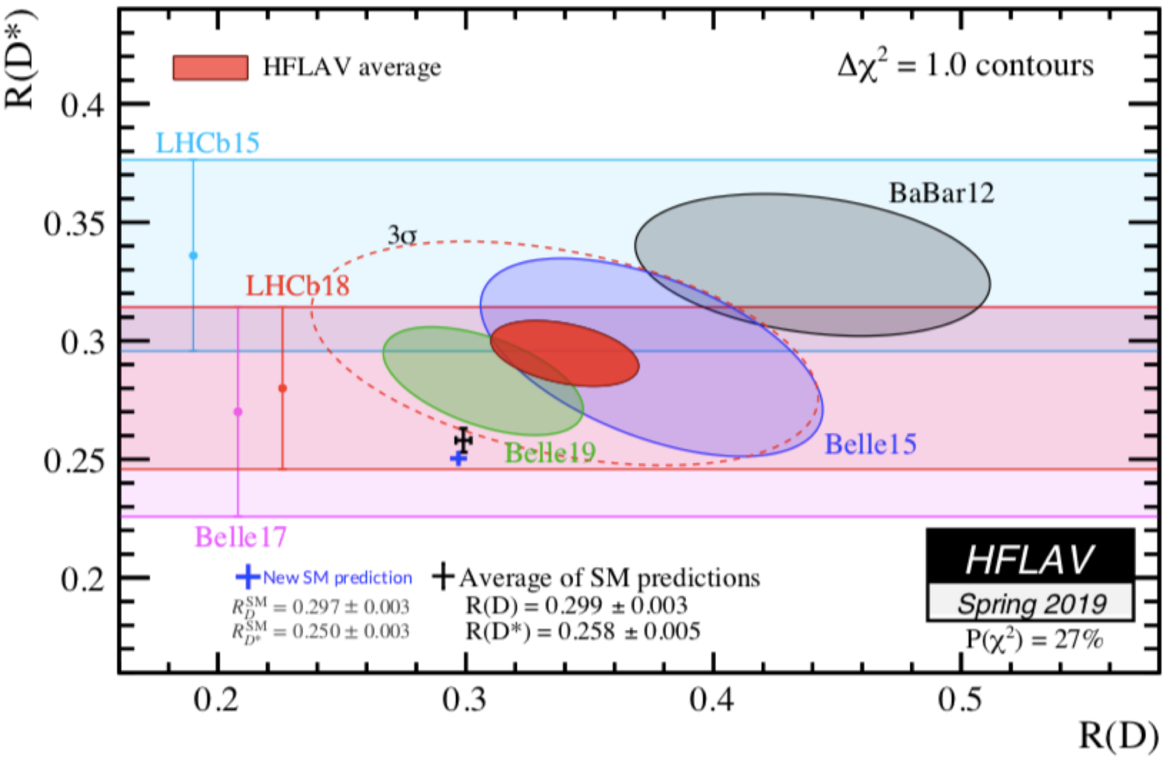
This result

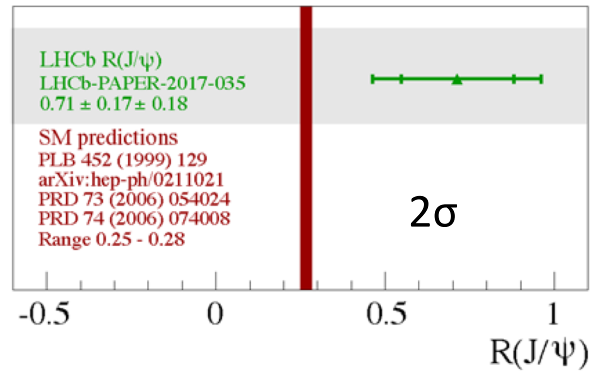
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

G. Caria, Moriond EW, March 19

Summary of LFU in b->clv decays

- Deviations from SM seen by Babar/Belle/LHCb



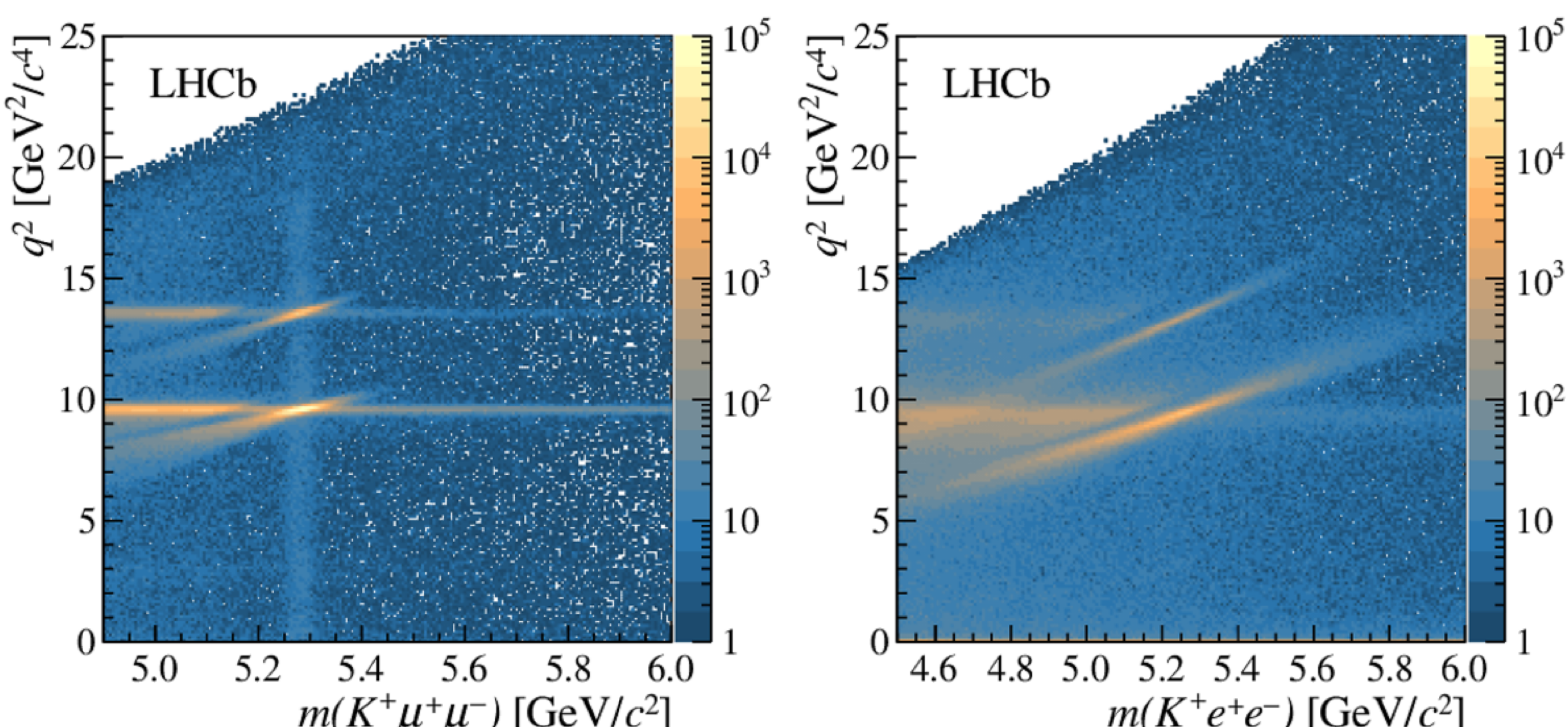


R(K), introduction

- Double ratio to control systematics

$$\mathcal{R}_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\varepsilon_{K^+e^+e^-}}{\varepsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\varepsilon_{J/\psi(\mu^+\mu^-)K^+}}{\varepsilon_{J/\psi(e^+e^-)K^+}}\right)$$

[PRL 122 (2019) 191801]



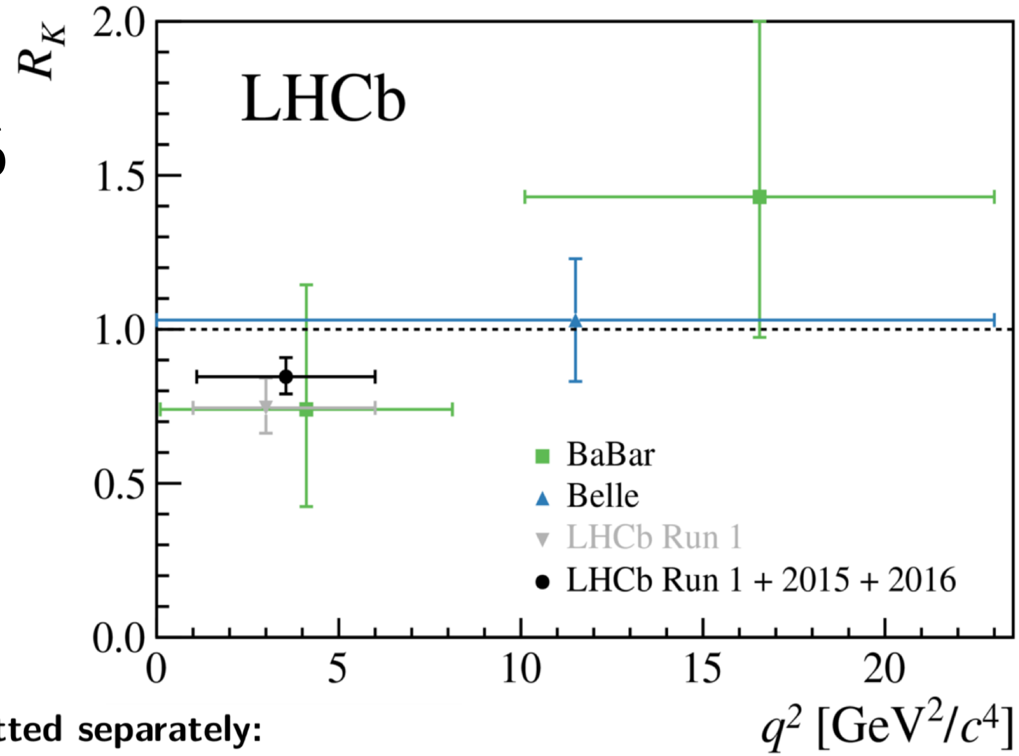
R(K), new results

[PRL 122 (2019) 191801]

- Include 2015+2016

$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$

$\sim 2.5\sigma$ from SM



If instead the Run 1 and Run 2 were fitted separately:

$$R^{\text{new}}_{K\ \text{Run 1}} = 0.717^{+0.083+0.017}_{-0.071-0.016}, \quad R_{K\ \text{Run 2}} = 0.928^{+0.089+0.020}_{-0.076-0.017},$$

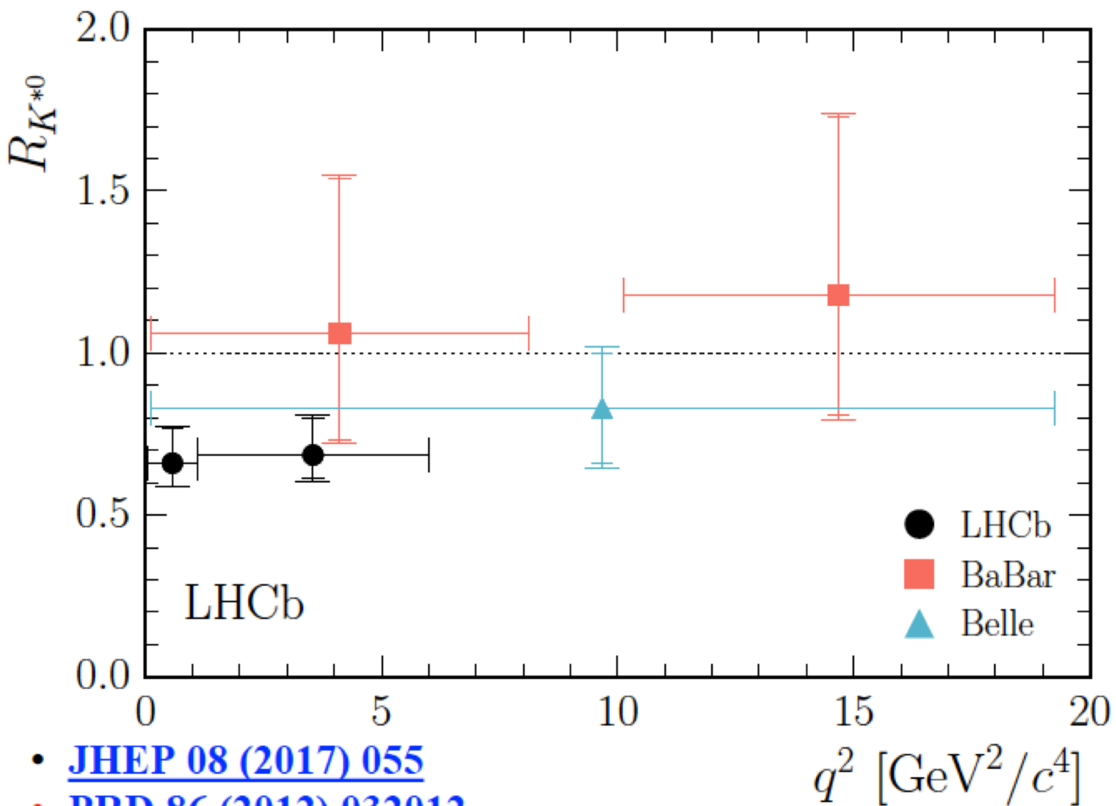
$$R^{\text{old}}_{K\ \text{Run 1}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad (\text{PRL113(2014)151601}),$$

Compatibility taking correlations into account:

- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\ \sigma$;
- Run 1 result vs. Run 2 result: $1.9\ \sigma$.

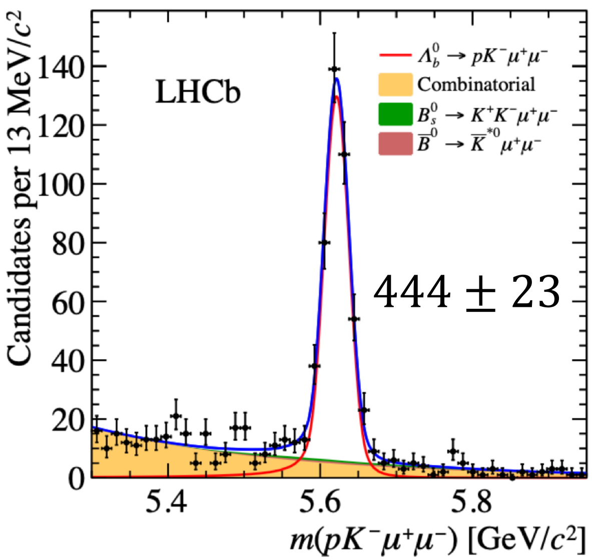
R(K^{*0}), results with Run-I data

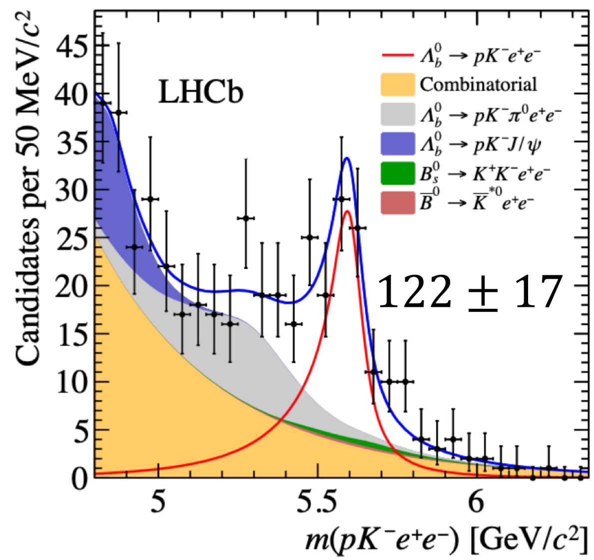
- Deviations from SM seen by LHCb ($\sim 2.4\sigma$)



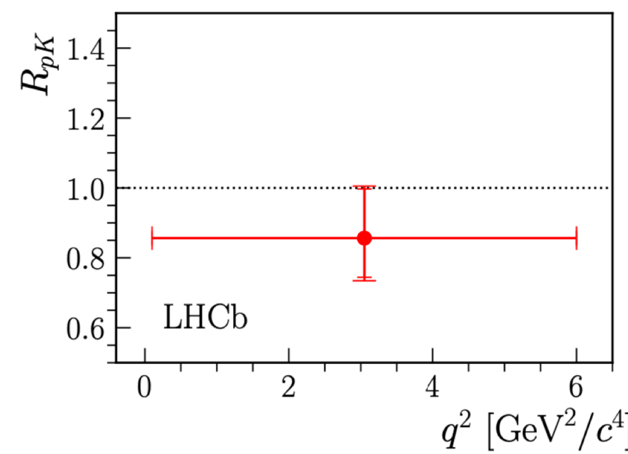
- [JHEP 08 (2017) 055]
- [PRD 86 (2012) 032012]
- [PRL 103 (2009) 171801]

R(pK), results with Run-I+2015/16



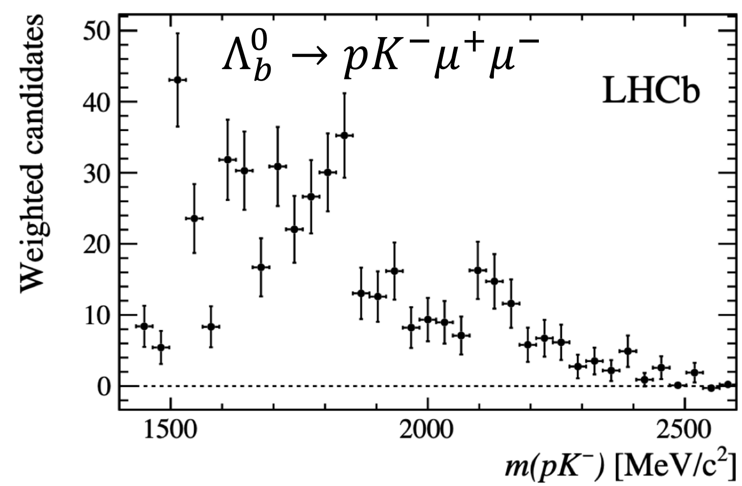


[LHCb-PAPER-2019-040]



$$R_{pK}\Big|_{0.1<q^2<6\ \mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

- UCAS started angular analysis of $\Lambda_b^0 \to pK^-\ell^+\ell^-$



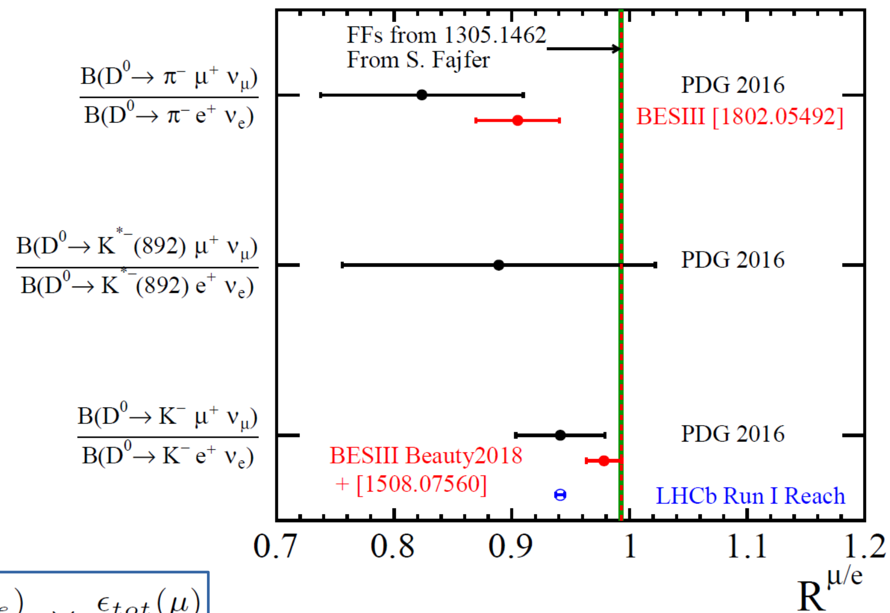
Test of LFU in D decays

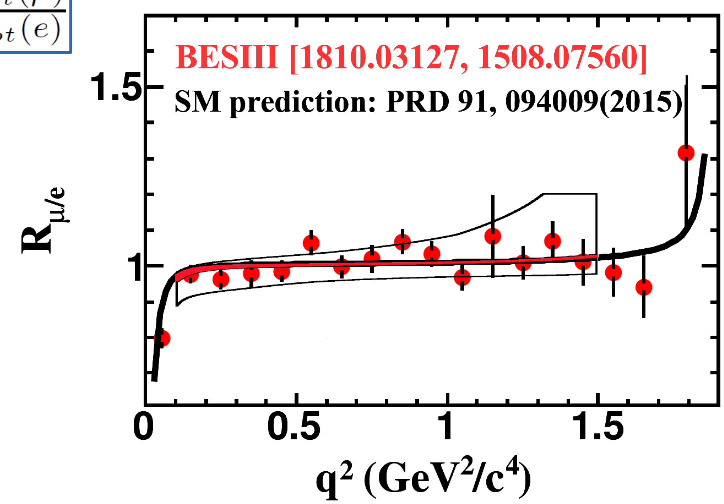
- LFU in the charm sector is a relatively unexplored area
- LHCb is expected to collect millions of $D^{*+}\to D^0\pi^+$, $D^0\to h^-\ell^+\nu$ events with Runs 1-2 datasets, about three orders of magnitude higher than BESIII statistics
- Measurement on the ratio of

$$R^{e/\mu} = \frac{\mathcal{B}(D^0\to K^- e^+\nu_e)}{\mathcal{B}(D^0\to K^-\mu^+\nu_\mu)} = \frac{N(D^0\to K^- e^+\nu_e)}{N(D^0\to K^-\mu^+\nu_\mu)} \times \frac{\epsilon_{tot}(\mu)}{\epsilon_{tot}(e)}$$

in bins of q^2, which can be rec'ed with the cone-closure method [FERMILAB-THESIS-1995-05]

- Uncertainties will be dominated by systematics





Preparations

- BDT-based line developed in 2015, better performance than the cut-based one

	Decay modes	Stripping lines	Efficiency [%]
e^+e^-	$B^+ \to K^+e^+e^-$	Bu2LLK_eeLine2	8.89 $\pm$0.02
		B2LLXBDT_Bu2eeKLine	11.83 $\pm$0.02
	$B^0 \to K^0_S e^+e^-$	Bu2LLK_eeLine2	2.23 $\pm$0.01
		B2LLXBDT_Bd2eeKsLine	3.48 $\pm$0.01
	$B^0_s \to \phi e^+e^-$	Bu2LLK_eeLine2	3.98 $\pm$0.01
		B2LLXBDT_Bs2eePhiLine	6.20 $\pm$0.01
	$\Lambda^0_b \to \Lambda e^+e^-$	Bu2LLK_eeLine2	21.79 $\pm$0.11
		B2LLXBDT_Lb2eeLambdaLine	25.62 $\pm$0.11
	$\Lambda^0_b \to p^+K^-e^+e^-$	Bu2LLK_eeLine2	5.19 $\pm$0.02
		B2LLXBDT_Lb2eePKLine	12.63 $\pm$0.03
$\mu^+\mu^-$	$B^+ \to K^+\mu^+\mu^-$	B2XMuMu_Line	20.68 $\pm$0.03
		B2LLXBDT_Bu2mumuKLine	24.26 $\pm$0.03
	$B^0 \to K^{*0}\mu^+\mu^-$	B2XMuMu_Line	12.43 $\pm$0.03
		B2LLXBDT_Bd2mumuKstarLine	13.48 $\pm$0.03
	$B^0_s \to \phi\mu^+\mu^-$	B2XMuMu_Line	10.49 $\pm$0.02
		B2LLXBDT_Bs2mumuPhiLine	15.81 $\pm$0.02
	$\Lambda^0_b \to \Lambda\mu^+\mu^-$	B2XMuMu_Line	3.14 $\pm$0.01
		B2LLXBDT_Lb2mumuLambdaLine	4.68 $\pm$0.01
	$\Lambda^0_b \to p^+K^-\mu^+\mu^-$	B2XMuMu_Line	19.10 $\pm$0.04
		B2LLXBDT_Lb2mumuPKLine	22.89 $\pm$0.15

Expected sensitivity

- Signal yields with Run-I (3 fb^{-1}) data

Mode	$N_{\mathbf{Sig}}$ (μ mode)	$N_{\mathbf{Sig}}$ (e mode) (q^2 [GeV^2/c^4])
$B^+ \to K^+ l^+ l^-$	1226±41	254±29 (q^2: 1-6)
$B_d \to K^{*0} l^+ l^-$	638±28	200±18 (q^2: 0.045-6)
$B_d \to K_S l^+ l^-$	176±17	~30 (estimate)
$B_s \to \phi l^+ l^-$	435±23	~80 (estimate)
$\Lambda_b \to \Lambda l^+ l^-$	368±25	~70 (estimate)
$\Lambda_b \to p K^- l^+ l^-$	600±44	~120 (estimate)

Prospects

- LHCb upgrades (2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

Observable	Current LHCb	LHCb 2025	Belle-II	LHCb Upgrade-II	ATLAS &CMS
$R_K(1 < q^2 < 6\ \mathrm{GeV})$	0.1	0.025	0.036	0.007	
$R_{K^*}(1 < q^2 < 6\ \mathrm{GeV})$	0.1	0.031	0.032	0.008	
R_ϕ		0.08		0.02	
R_{pK}	0.14	0.035		0.008	
$R(D^*)$	0.026	0.0072	0.005	0.002	
$R(J/\psi)$	0.24	0.071		0.02	

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Person-power

- UCAS
  - J. He
  - Postdocs: N. Beliy ($R_{J/\psi}$), A. Campoverde
  - PhD students: W. Huang ($R_{J/\psi}$), Y. Zhou, Z. Xiang, Y. Fan
- Wuhan Univ.
  - L. Sun
  - PhD students: B. Fan (R_{D^*} update), L. Bian

Summary

- Working on lepton flavor universality
  - in semileptonic B/D decays, $R(D^{(*)})$, $R(J/\psi)$
  - in FCNC process, $R(K)$

  and related analysis
- Very strong competitions in LHCb
- Your continuous strong supports always appreciated