B anomalies at LHCb

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Anomalies: what's about?

- Flavour physics is a low-energy test bench for indirect observation of new interactions or particles up to energy scales higher than current LHC reach.

- In the Standard Model, lepton flavour universality (LFU) is an accidental symmetry, broken only by the Yukawa interactions.
- New Physics can couple differently to different lepton families.

- Recently few deviations from SM emerged in semileptonic B decays

  - b→c transitions, charged current
    tree level in the SM, high rates O(%)

  - b→s transitions, FCNC
    loop, GIM and CKM suppressed in the SM, rates $O(10^{-6})$

- Main test variables are ratios of decay rates that minimize both theoretical and experimental uncertainties

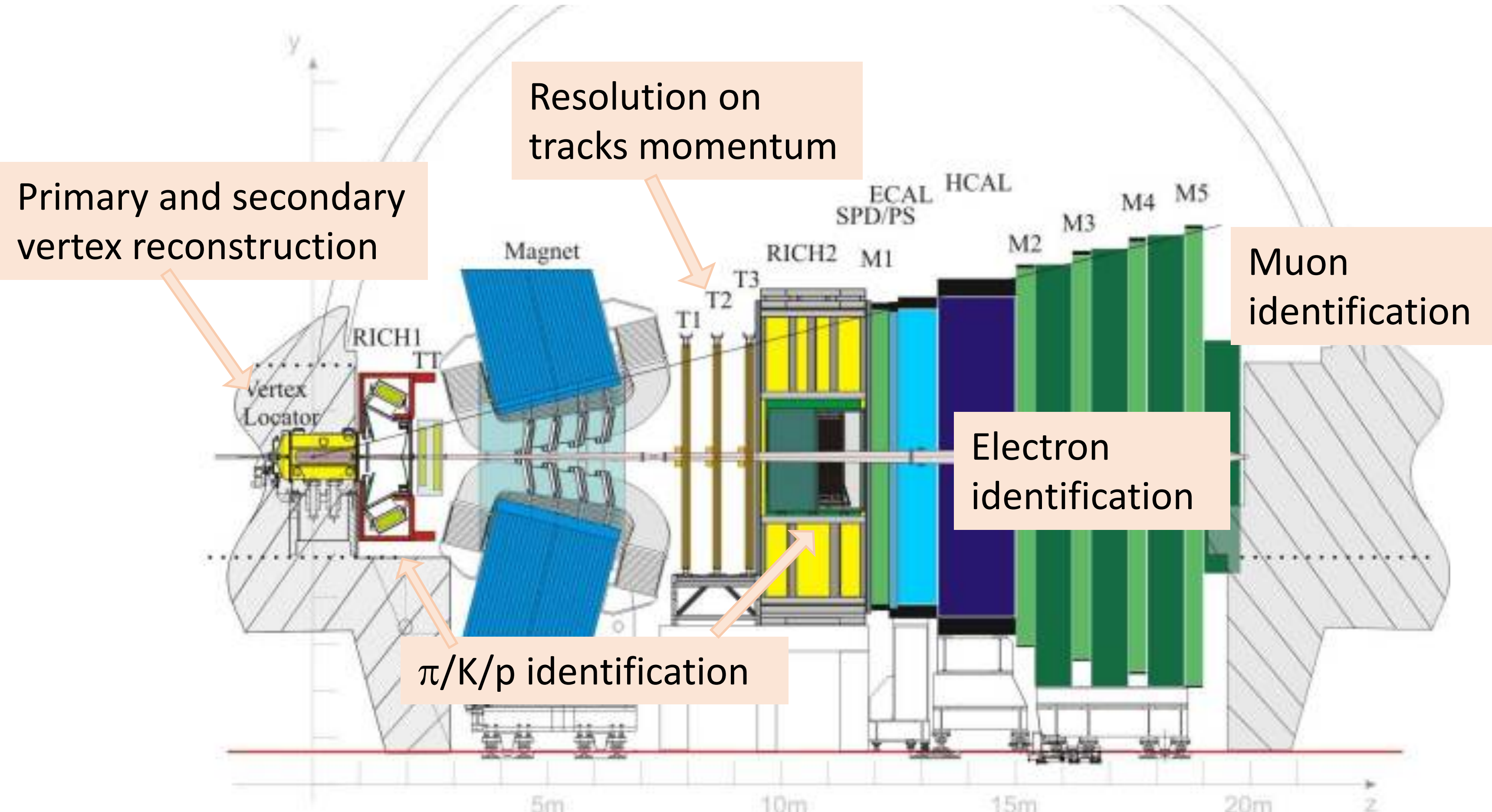
Outline

- Introduction
- Tests of Lepton Flavour Universality in $b\rightarrow c\tau\nu$ decays
  - $R(D^*)$ with $\tau\rightarrow\mu\nu\nu$
  - $R(D^*)$ with $\tau\rightarrow\pi\pi\pi\nu$ new
- Tests of Lepton Flavour Universality in $b\rightarrow s\, l^+l^-$ decays
  - $R(K^*)$ new
  - $R(K)$
- Other measurements in $b\rightarrow s\, l^+l^-$
- Conclusion

LHCb

JINST 3 (2008) S08005

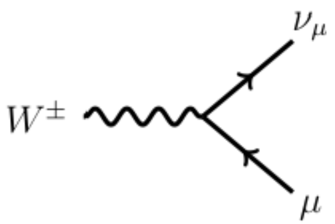
- Forward spectrometer $2<\eta<5$ at LHC, with excellent performance on



- 3 fb^{-1} pp collision collected at $\sqrt{s}$=7,8 TeV in Run1 → used for this talk.

  > 2.8 fb^{-1} already collected at $\sqrt{s}$=13 TeV in Run2.

Lepton Flavour Universality



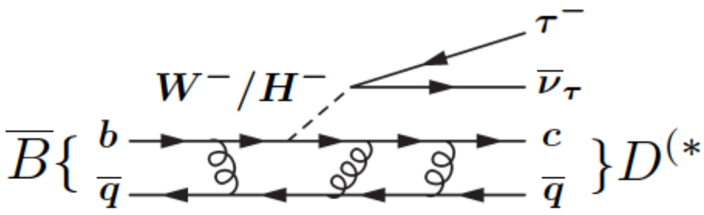
- Semileptonic decays of b hadrons, are mediated by a W boson with universal coupling to leptons.
- Differences for decays with electrons, muons or taus should originate only from their different masses. Any further deviation is a key signature of physics processes beyond the SM.

- Measurements of the Z and W couplings to leptons, mainly constrained by LEP and SLC experiments, are all compatible with LFU.
  - Except for a 2.8 σ difference between the measurement of the branching fraction of the $W \rightarrow \tau^+\nu_\tau$ decay with respect to $W \rightarrow \mu^+\nu_\mu$ and $W \rightarrow e^+\nu_e$ decays.

- LFU can be violated in many SM extensions with mass-dependent couplings, such as models with an extended Higgs sector, or leptoquarks.

LFU in R(D$^{(*)}$)

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



- The SM prediction for R(D*) has an uncertainty O(%), uncertainties due to hadronic effects cancel to a large extent.
- Deviations from SM predictions observed in some measurements at B factories.

At LHCb

- B momentum unknown in production from pp collisions (mainly gg→ $b\bar{b}$) at LHC
- Missing momentum of neutrinos not measured.

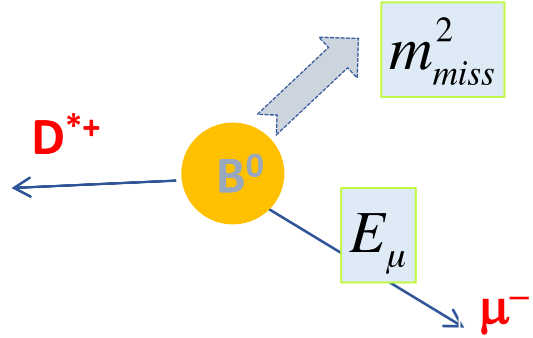
- Large statistics from high pp→ $b\bar{b}$ cross section at LHC.
- B direction can be determined by vector from primary to B vertex.

$R(D^*)$ from $\tau^+ \to \mu^+ \nu_\mu \nu_\tau$

PRL 115, 11804 (2015)

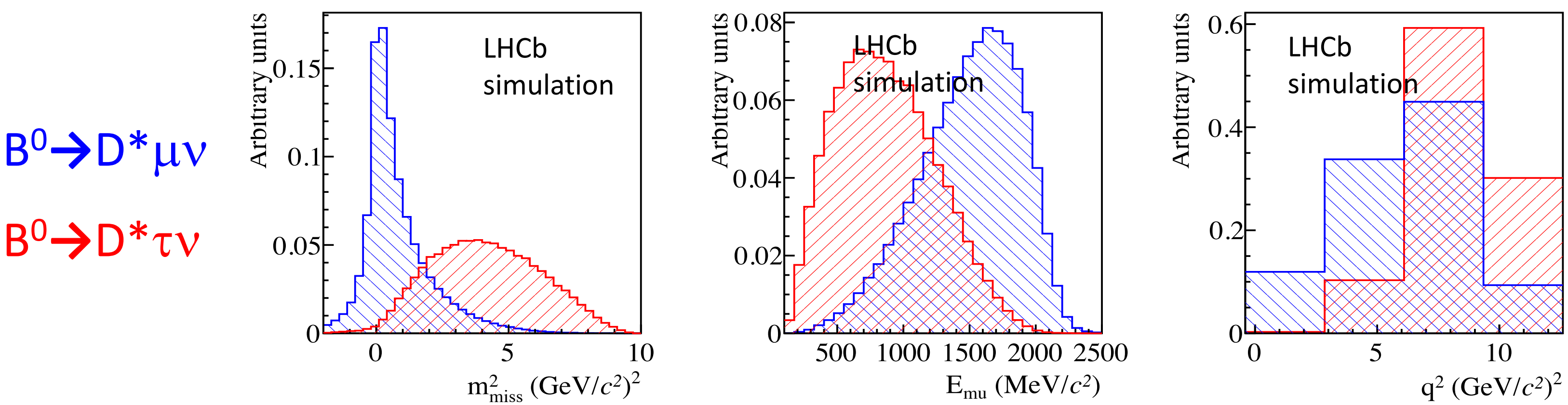
- $B^0 \to D^* \tau\nu$ separated from $B^0 \to D^* \mu\nu$ exploiting differences in 3 key kinematic variables computed in the B rest frame.

$$q^2 = (p_{B^0} - p_{D^{*+}})^2$$



$$q^2 = (p_\ell + p_\nu)^2$$

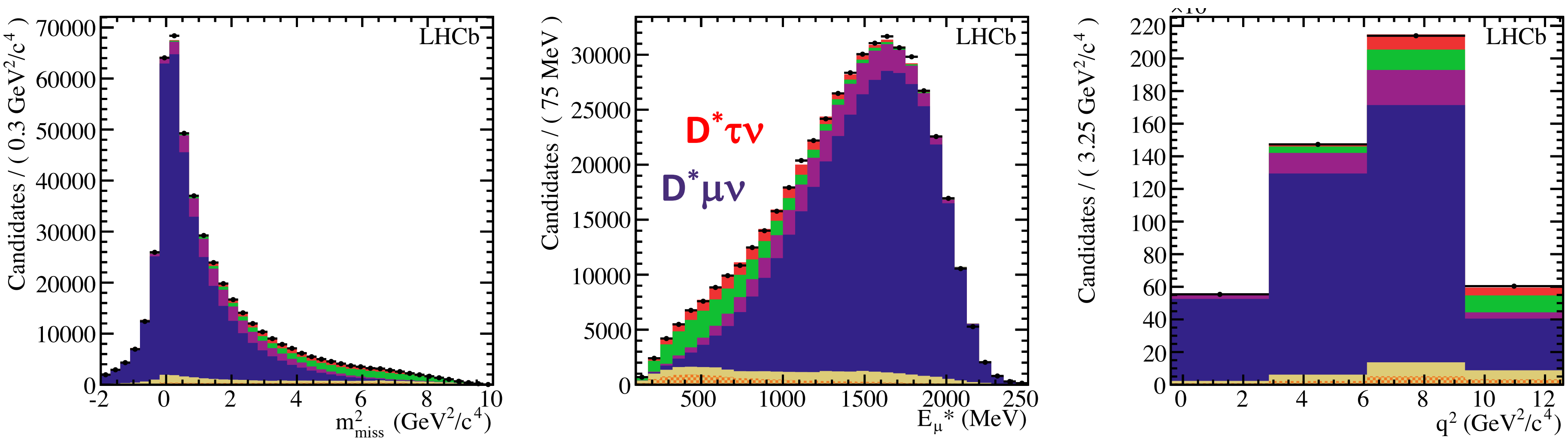
- B^0 boost along beam direction approximated with boost of the visible system ~18% resolution sufficient for good separation.

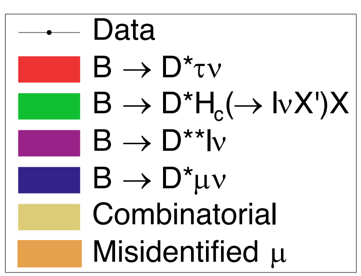


R(D*) from τ→μνν

PRL 115, 11804 (2015)

- ML 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.
  - Templates derived from simulation and data, validated with separate fits on data control samples.





Background from

- semileptonic decays with excited charm states "D**" ~12%
- Double charm decays $B \to D^{*+} H_c X$; $H_c \to \mu^- \nu X'$ ~ 6-8%
- Combinatorial and misidentified hadrons

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

PRL 115, 11804 (2015)

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

- 2.1 σ higher than SM $R(D^*)^{SM} = 0.252 \pm 0.003$

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**

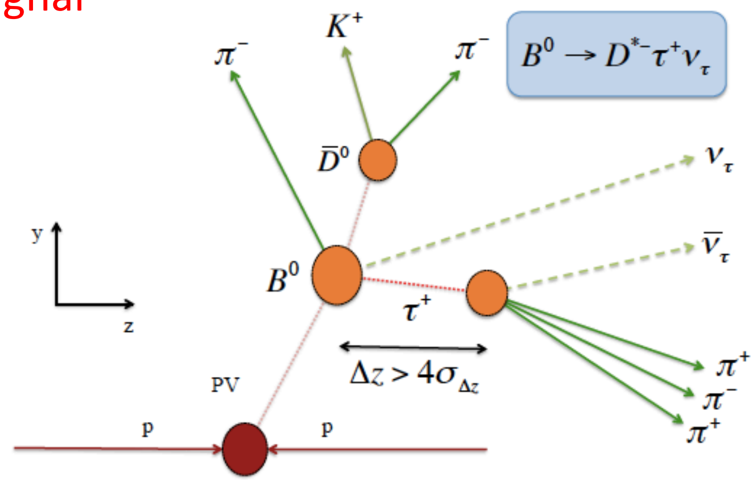
Background modelling; depends on control sample size

R(D*) from $\tau^+ \to \pi^+\pi^-\pi^+ (\pi^0)$

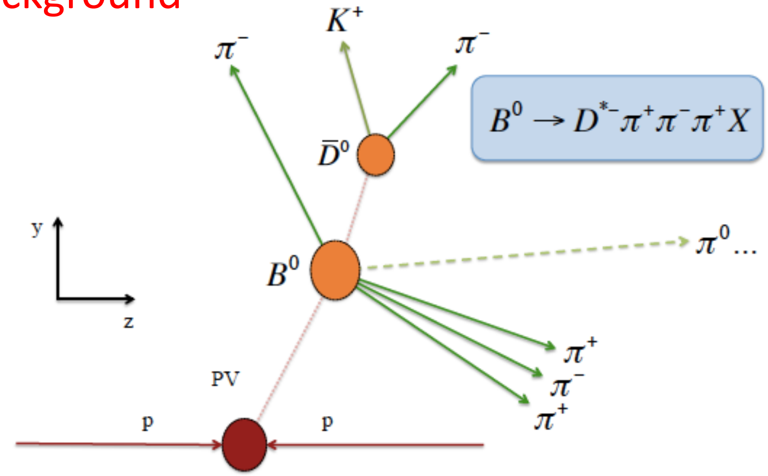
arXiV:1708.08856
submitted to PRL

- 3-prong hadronic tau decays, data sample complementary to the $\tau \to \mu\nu\nu$ sample.

Signal



Background



- Zero background from semileptonic decays.
- Suppress hadronic background exploiting tau lifetime and structure of tau decay
  - $O(10^{-3})$ reduction of $D^*\pi\pi\pi$ X requiring minimum tau flight distance.
  - Train BDT against double charm $B \to D^*D_{(s)}$ X decays.
  - Extensive studies performed in data control samples.

$R(D^*)$ from $\tau^+ \to \pi^+\pi^-\pi^+ (\pi^0)$

arXiV:1708.08856
submitted to PRL

- Experimental systematic uncertainty reduced normalizing to a decay with a very similar final state

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \frac{1}{\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)}$$

- Derive R(D*) by dividing by well known semimuonic $B^0 \to D^*\mu\nu$ branching fraction

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

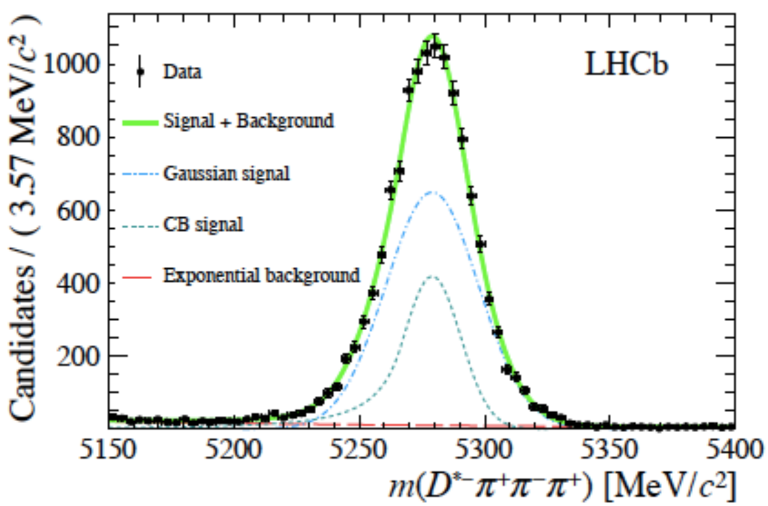
- Measure

  $B^0 \to D^*\tau\nu$ and $B^0 \to D^*\pi\pi\pi$ event yields.

- External inputs

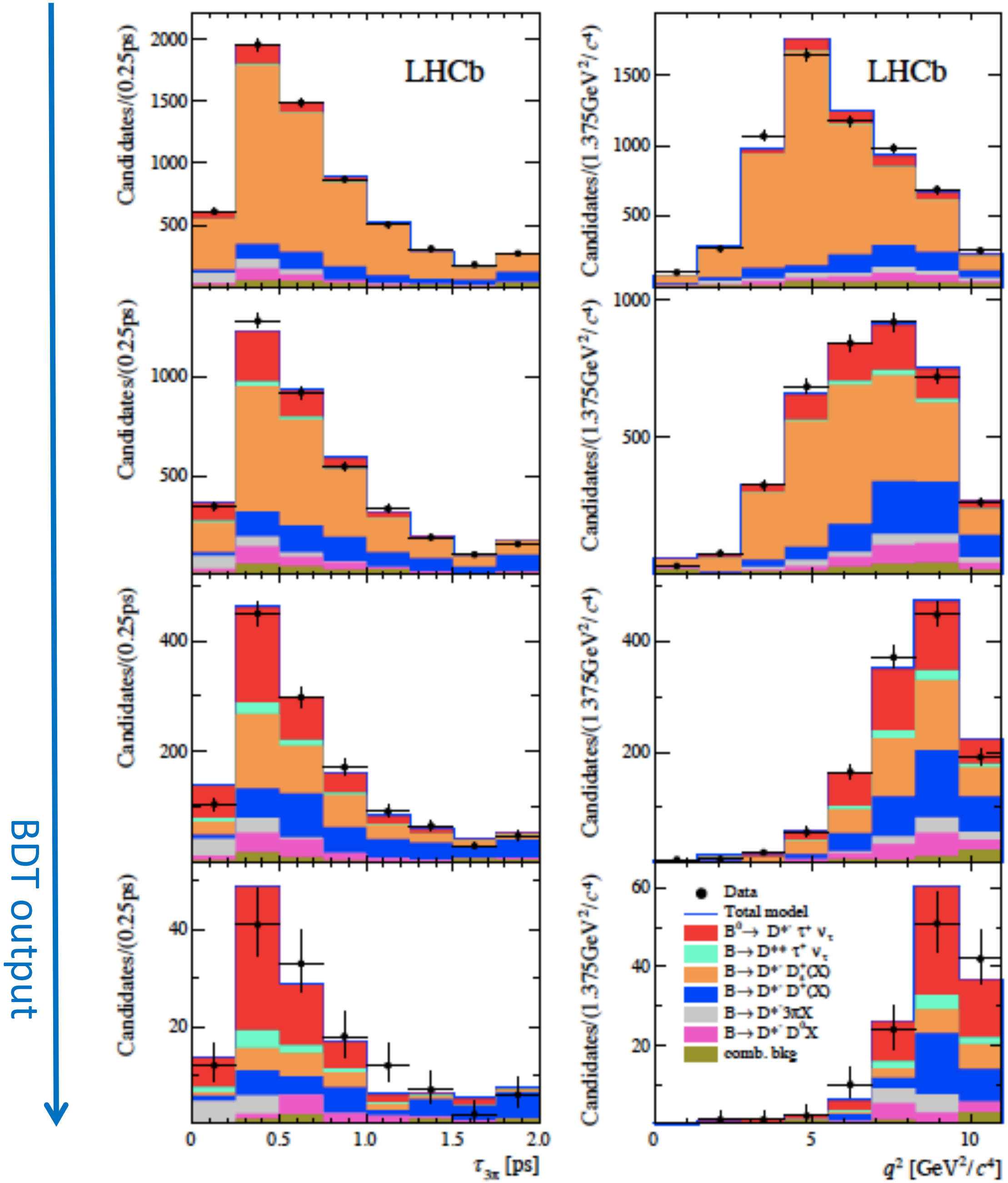
$$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.21 \pm 0.29) \times 10^{-3}$$
$$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$

(PDG, HFLAV)



N_{norm} = 17 660 ± 160

arXiV:1708.08856
submitted to PRL



- 3D templates representing $B^0 \to D^* \tau \nu$, and background sources.
- ML fit to q^2 and τ decay-time distributions in 4 bins of the BDT output.

$R(D^{*})$ from $\tau^{+}\longrightarrow\pi^{+}\pi^{-}\pi^{+}(\pi^{0})$

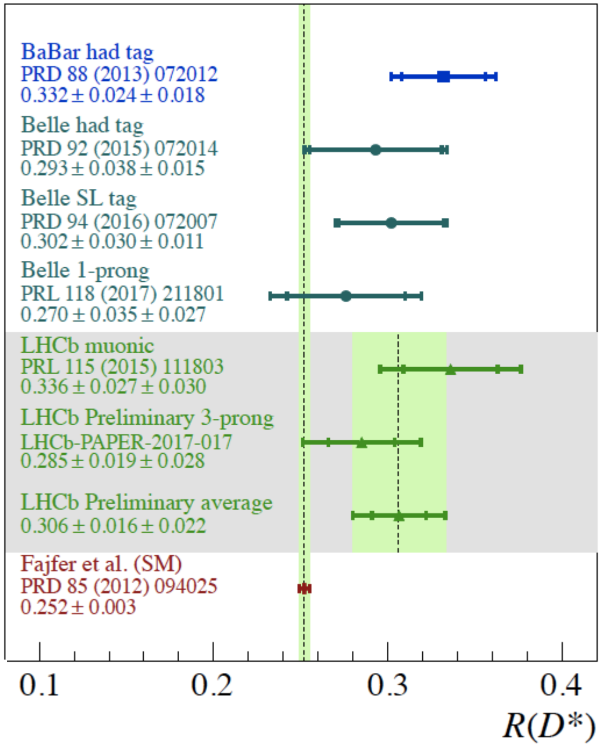
arXiV:1708.08856
submitted to PRL

$$\mathcal{R}(D^{*-}) = 0.283 \pm 0.019\,(\text{stat}) \pm 0.025\,(\text{syst}) \pm 0.013\,(\text{ext})$$

- Compatible with the muonic results, with previous measurements and with SM expectation.
- LHCb combination [FPCP 2017]

  R(D*)= 0.306 ± 0.016 ± 0.022

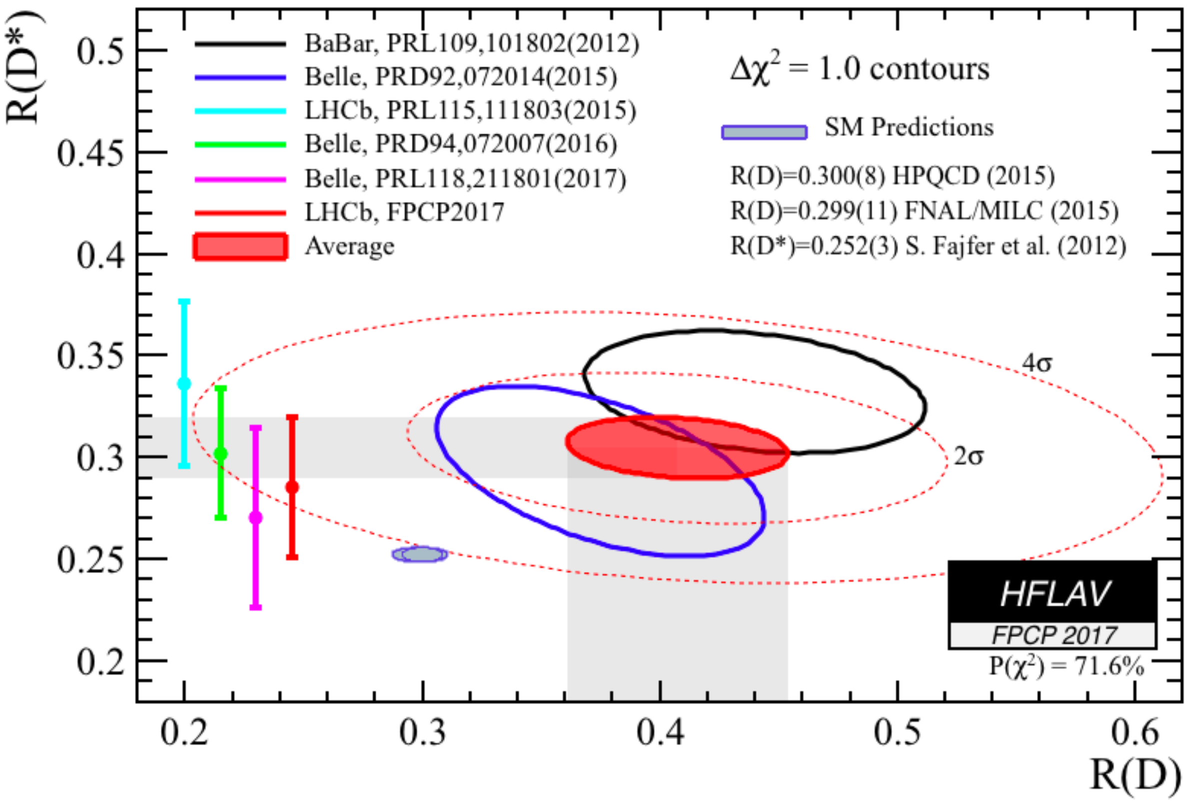
  2.1 σ above the SM



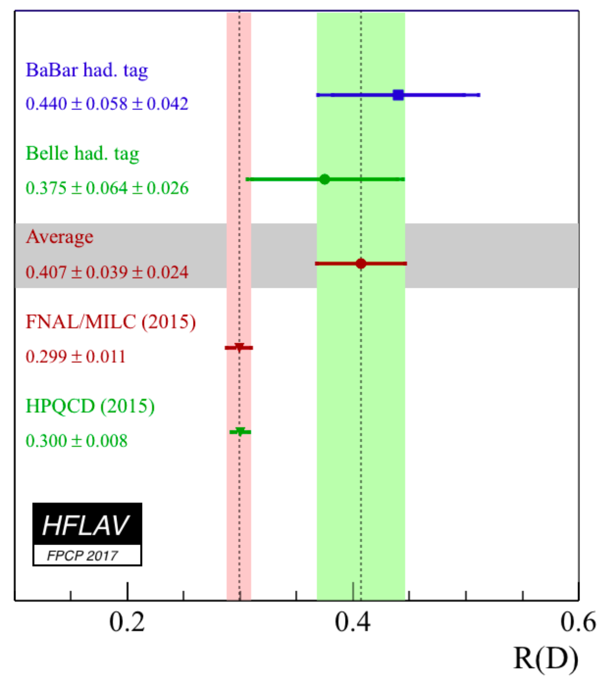
Systematics in $R(D^*)$ from $\tau\longrightarrow\pi\pi\pi$

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
$B \to D^{*-} D_s^+ X$, $B \to D^{*-} D^+ X$, $B \to D^{*-} D^0 X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-} 3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

R(D*) and R(D)



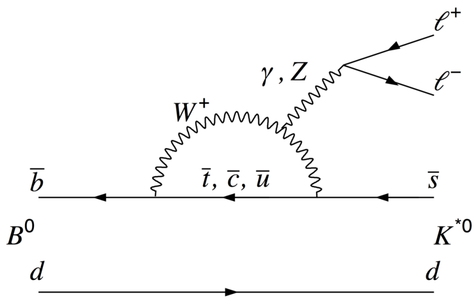
Mesurements of R(D)

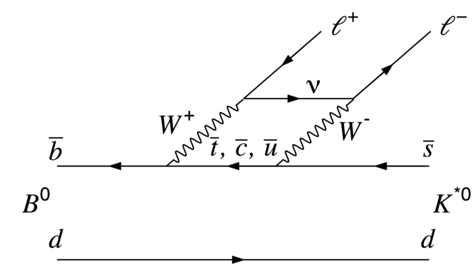


R(D) and R(D*) exceed the SM predictions by 2.3σ and 3.4σ respectively.
The combined difference with the SM predictions corresponds to about 4.1σ.

LFU in R(K$^{(*)}$)

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



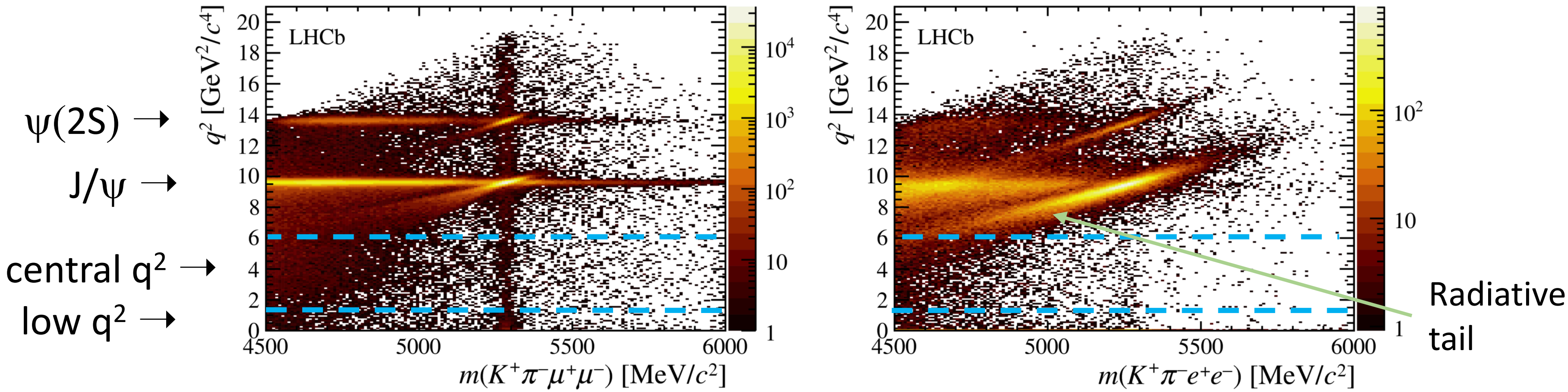


- Measurements performed in different regions of di-lepton invariant mass q^2 , outside charmonium resonances regions, sensitive to different NP contributions.
- Predicted to be close to unity in the SM with uncertainty O(10^{-3}), QED effects O(%) It is not affected by QCD effects (ex: charm loops)
- At e^+e^- colliders operating at the Y(4S) resonance it was measured to be consistent with unity with a precision of 20-50% .
- At LHCb
  - Large statistics from high pp→ $b\bar{b}$ cross section at LHC
  - Excellent muon reconstruction, lower efficiency and resolution on electrons (bremsstrahlung).

R(K*) at LHCb

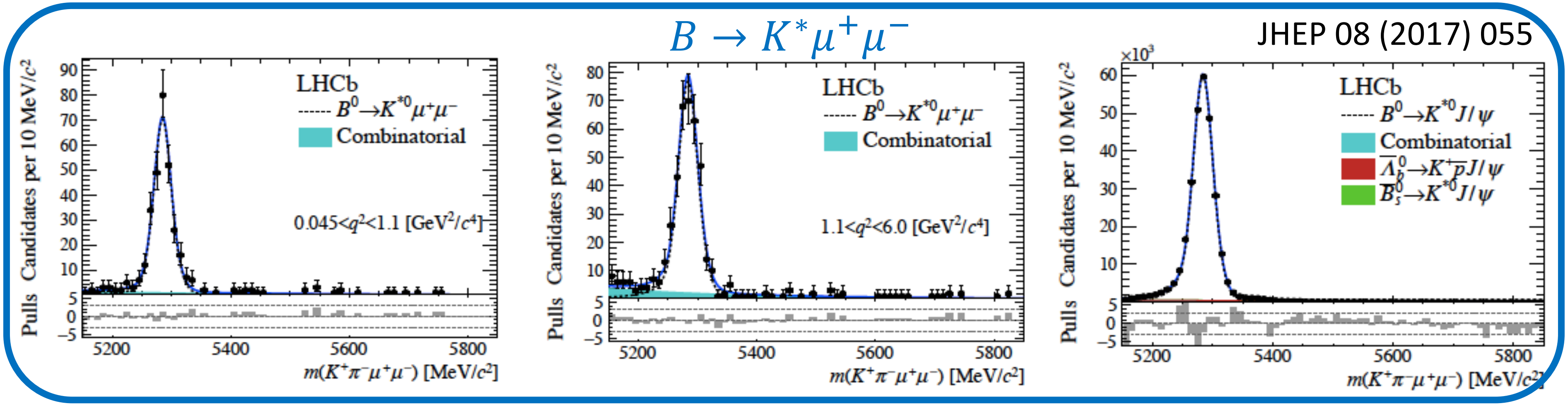
JHEP 08 (2017) 055

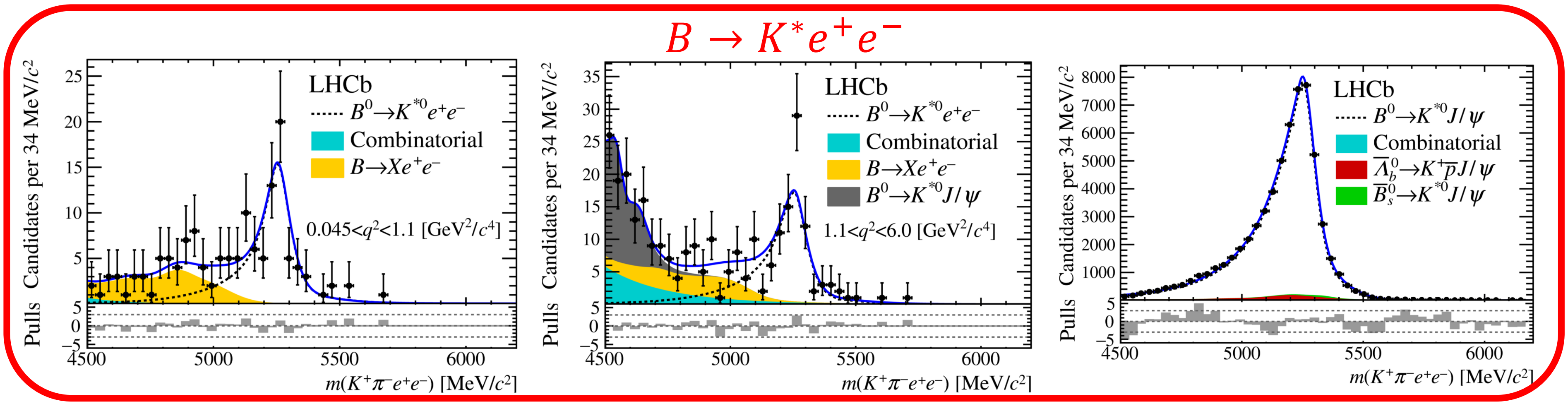
- Electron sample maximized recovering as many as possible photons (0γ, 1γ, ≥2γ)
- Degraded momentum and mass resolution for electrons, reconstructed B mass shifts towards lower values.



- B mass fit in two q^2 regions [0.045-1.1] and [1.1-6] GeV^2/c^4
- Systematic uncertainty due to different experimental efficiencies in reconstruction of muon and electron reduced by measuring a double ratio with the resonant mode

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$





Low q^2 | *central q^2* | *J/ψ*

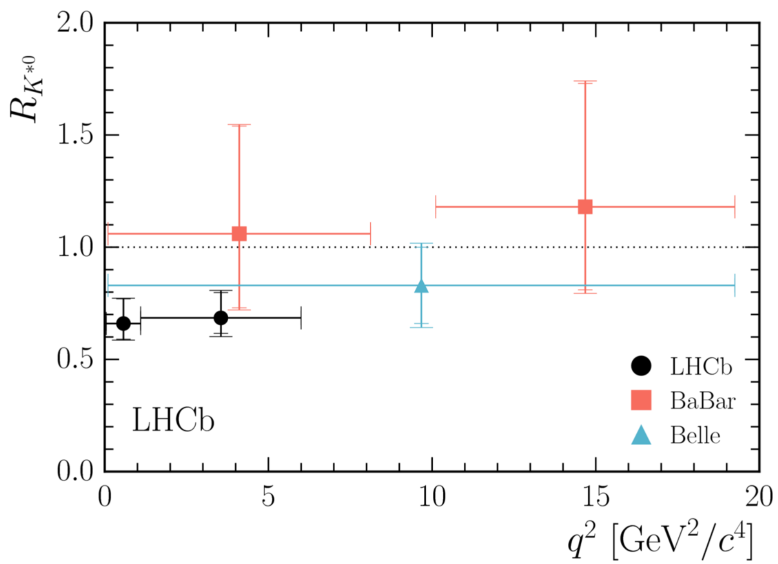
- Stringent test: ratio of branching fractions of the muon and electron resonant channels is measured to be 1.043 ± 0.006 ± 0.045, consistent with unity.

R(K*) at LHCb

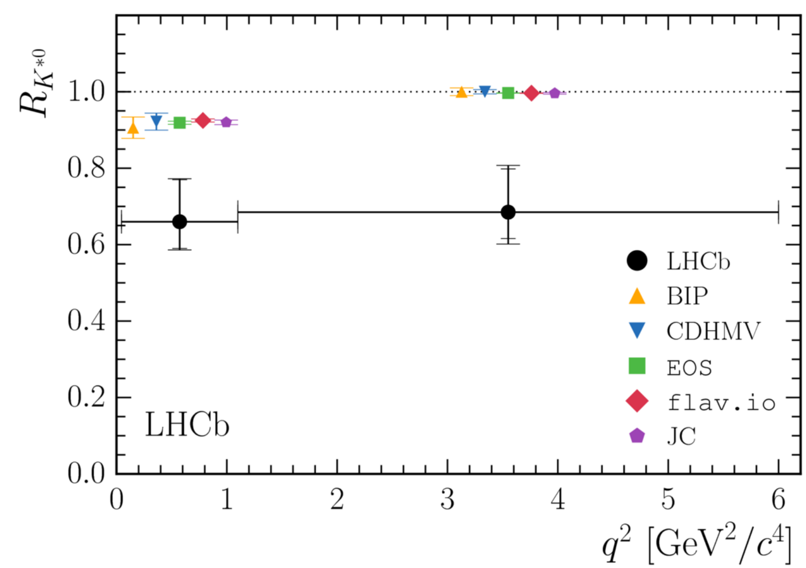
JHEP 08 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66 \ {}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \ \text{GeV}^2/c^4 \\ 0.69 \ {}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0 \ \ \text{GeV}^2/c^4 \end{cases}$$

- Most precise measurement to date.
- Compatible with SM at 2.1-2.3 σ (low q^2) and 2.4-2.5 σ (intermediate q^2)



BaBar PRD 86 (2012) 032012
Belle PRL 103 (2009) 171801



BIP	arXiv:1605.07633
CDHMV	arXiv:1510.04239, 1605.03156, 1701.08672
EOS	arXiv:1610.08761, https://eos.github.io
flav.io	arXiv:1503.05534, 1703.09189, flav-io/flavio
JC	arXiv:1412.3183

R(K) at LHCb

PRL 113, 151601 (2014)

- Measure $B(B \to K\mu^+\mu^-)/\mathrm{B}(B \to Ke^+e^-)$ for q^2 in [1-6] GeV^2/c^4

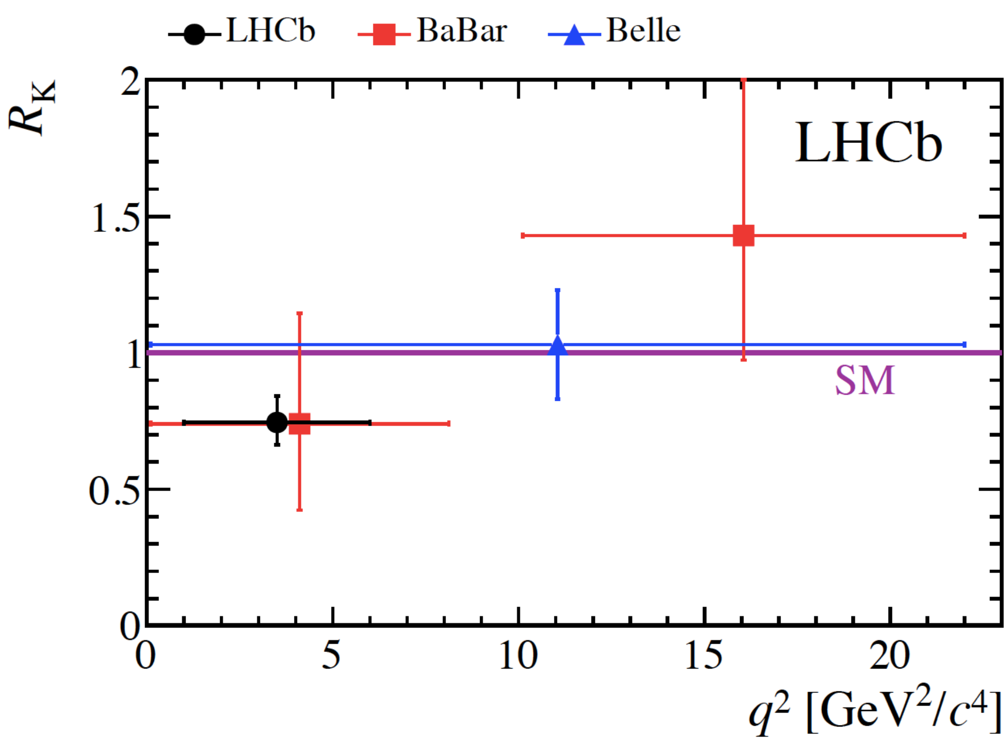
$$R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

- Most precise measurement to date.

- 2.6 σ from SM prediction

  $R(K)^{SM} = 1 \pm O(10^{-3})$

  JHEP12(2007)040; PRL111,162002(2013)

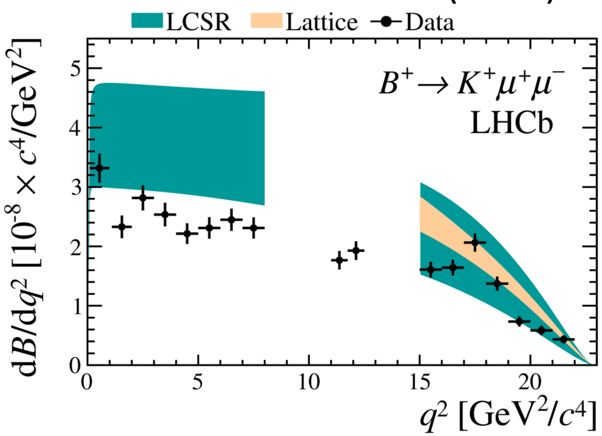


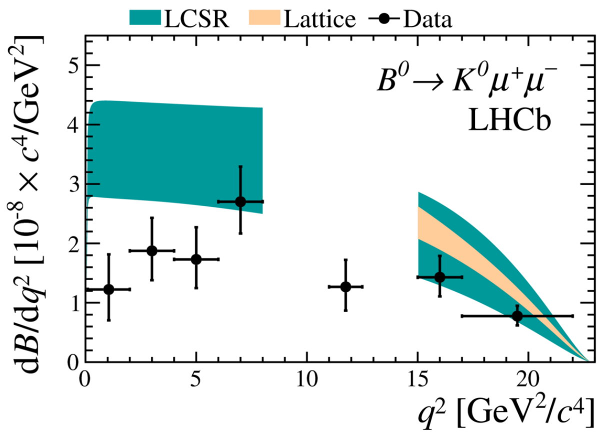
BaBar PRD 86 (2012) 032012
Belle. PRL 103 (2009) 171801

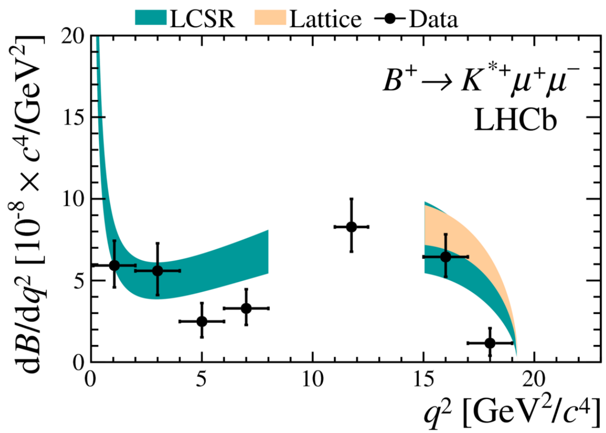
Other b→sl$^+$l$^-$ results

- Measured BR with muons are consistently lower than SM predictions.

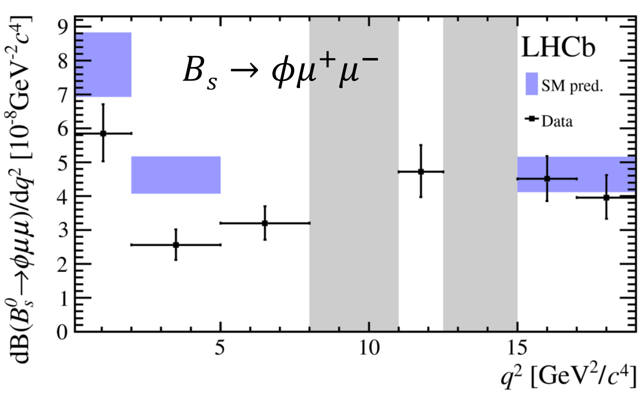
JHEP 06 (2014) 133



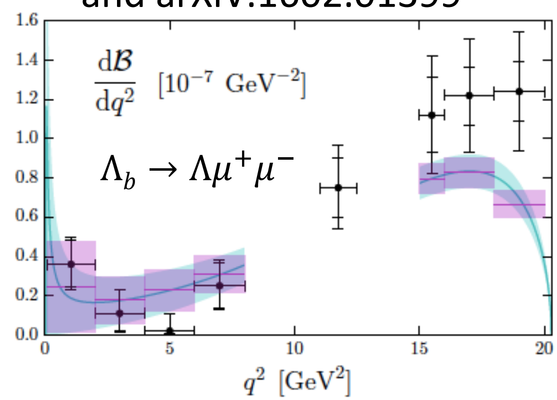




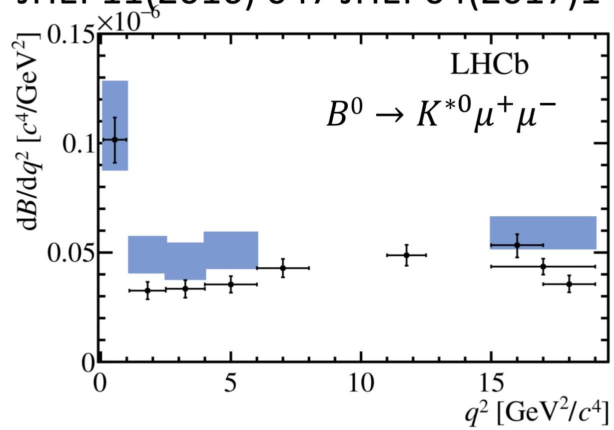
JHEP 09 (2015) 179



JHEP 06 (2015) 115
and arXiV:1602.01399



JHEP11(2016) 047 JHEP04(2017)142



Other b→sl⁺l⁻ results

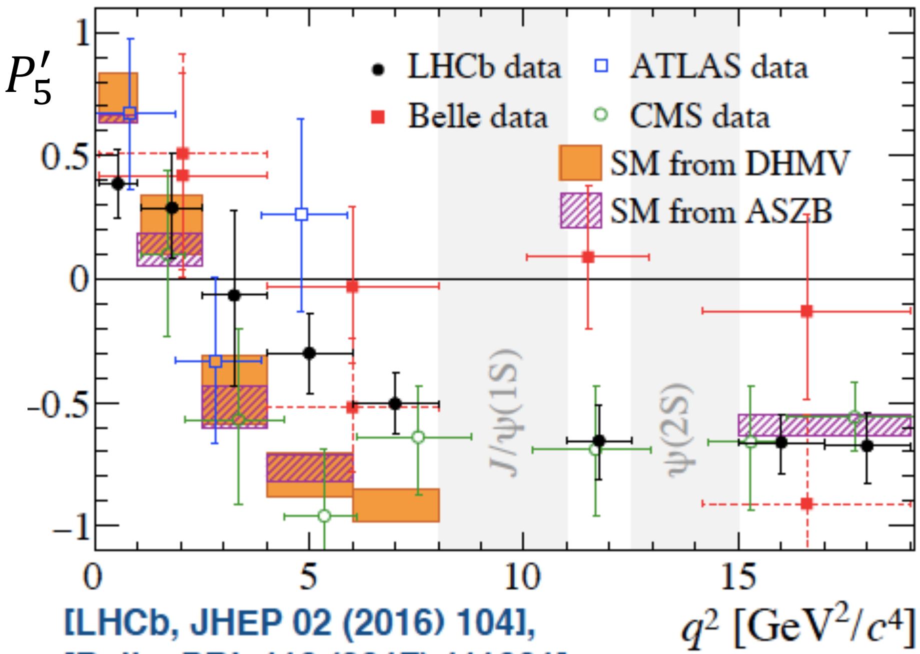
JHEP 02 (2016) 104

- Global analysis of CP-averaged angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ indicate about 3.4 σ deviation from SM predictions.

- Ratio of observables almost independent on form-factors

$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

- Could be explained by an unexpectedly large hadronic effect that changes the SM predictions, also by contributions to the decay from non-SM particles.



[LHCb, JHEP 02 (2016) 104],
[Belle, PRL 118 (2017) 111801],
[ATLAS-CONF-2017-023],
[CMS-PAS-BPH-15-008]

Conclusion

- LHCb is completing the analysis of Run 1 data with several measurements in $b \rightarrow c\tau\nu$ and $b \rightarrow s l^+ l^-$ $(l=e,\mu)$
  - New results on $R(D^*)$ with 3-prong hadronic tau decay and $R(K^*)$ with $K^{*0} \rightarrow K\pi$.

- Few deviations from LFU and SM predictions.
  - Can suggest BSM models with new vector or scalar interactions.

- Other decay modes are under study and Run 2 data will be fully exploited.

Examples are $B_c \rightarrow J/\psi\tau\nu$; $\Lambda_b \rightarrow \Lambda_c\mu\nu$; $B \rightarrow D\,\mu\nu$ ...

$R(\phi)$; $P_5'(\mu)$- $P_5'(e)$ ...

backup

R(K*)

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi (\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285 \,^{+\,18}_{-\,18}$	$353 \,^{+\,21}_{-\,21}$	$274416 \,^{+\,602}_{-\,654}$
e^+e^- (L0E)	$55 \,^{+\,9}_{-\,8}$	$67 \,^{+\,10}_{-\,10}$	$43468 \,^{+\,222}_{-\,221}$
e^+e^- (L0H)	$13 \,^{+\,5}_{-\,5}$	$19 \,^{+\,6}_{-\,5}$	$3388 \,^{+\,62}_{-\,61}$
e^+e^- (L0I)	$21 \,^{+\,5}_{-\,4}$	$25 \,^{+\,7}_{-\,6}$	$11505 \,^{+\,115}_{-\,114}$

- Systematics

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low- q^2			central- q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

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

- CP-averaged angular distribution of the $B^0 \to K^{*0} \mu^+\mu^-$ decay and optimized variables that cancels leading form-factor uncertainties

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\
&+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l \\
&-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\
&+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi \\
&+\frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi \\
&+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]
\end{aligned}
$$

$$
P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}
$$