Lepton-flavour universality tests at LHCb

Marta Calvi

Università di Milano Bicocca and INFN, Milano

on behalf of the LHCb Collaboration

Rencontres de Physique de la Vallée d'Aoste, La Thuile, Italy 2018-02-25

Outline

- Introduction
- Tests of Lepton Flavour Universality in $b \to c\tau\nu$ decays
  - $R(D^*)$ with $\tau \to \mu\nu\nu$ and $\tau \to \pi\pi\pi\nu$
  - $R(J/\psi)$ with $\tau \to \mu\nu\nu$
  - Prospects
- Tests of Lepton Flavour Universality in $b \to s\, l^+ l^-$ decays
  - $R(K^*)$ and $R(K)$
- Conclusion

The flavour of indirect measurements

- Historically indirect measurements have signaled the existence of new particles or interactions before their direct observation.

- Well-known examples
  - Kaon decay → charm quark
  - CP violation → bottom quark
  - Bottom mixing → top quark
  - Neutrino scattering → Z boson

- Flavour physics is still the low-energy test bench for indirect observation up to energy scales higher than current LHC reach.

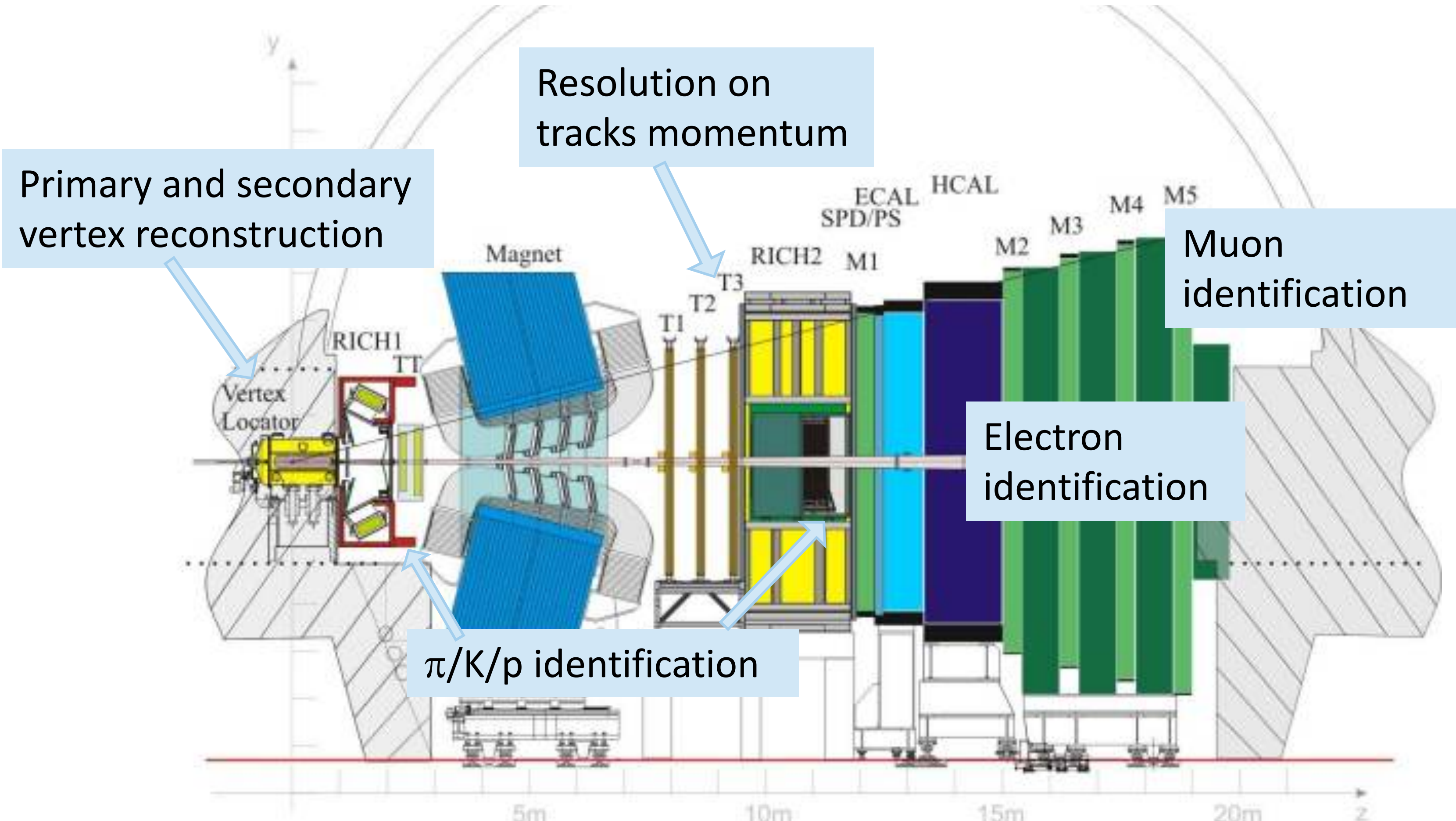
Lepton Flavour Universality

- The flavour-universality of electroweak couplings to charged leptons is an accidental symmetry in the Standard Model, broken only by the Yukawa interactions.
- New Physics might couple differently to different lepton families.
- Shall we put LFU under test?
- Recently few “anomalies” (deviations from the SM predictions) emerged in B hadron decays of two classes
    - Charged Currents $b \to c l \nu$ transitions
    - Neutral Currents $b \to s l l$ transitions

LHCb at LHC

JINST 3 (2008) S08005

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

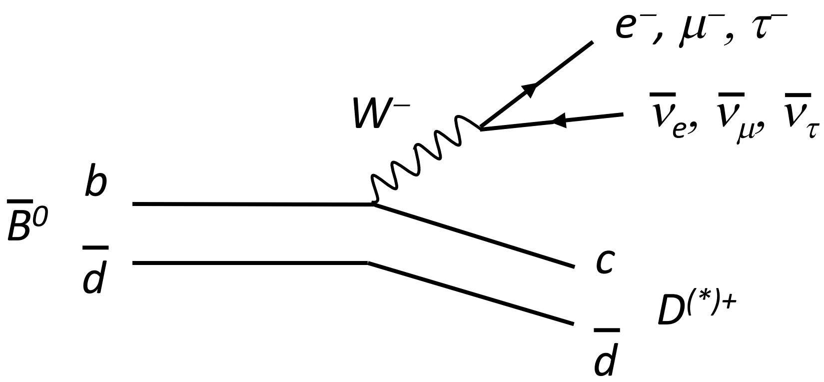


- 3 fb^{-1} pp collision collected at $\sqrt{s}$=7,8 TeV in Run1 → used for this talk

  3 fb^{-1} collected at $\sqrt{s}$=13 TeV in Run2 (2015-17).

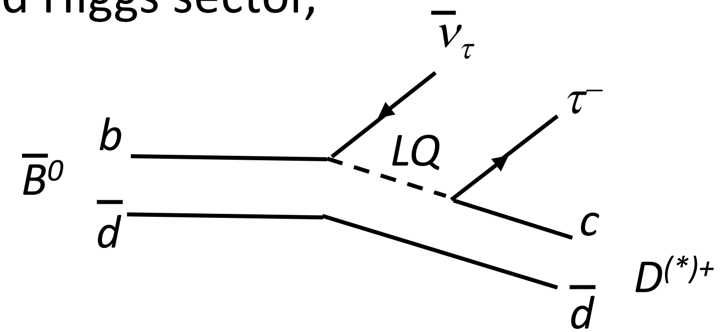
LFU in b→clν transitions

- Semileptonic
  tree level decays in the SM, mediated by a W boson with universal coupling to leptons



- Differences for decays with e, μ, τ should originate only from their different masses. Any further deviation is a key signature of physics processes beyond the SM.

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



Measurements in b→clν transitions

- Test variables are ratios of decay rates

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

- $R(D^*)^{SM} = 0.252 \pm 0.003$ (Phys. Rev. D85 (2012) 094025)
  uncertainties due to hadronic effects cancel in the ratio to a large extent.
- First deviations measured at B-Factories by BaBar and Belle.

At LHC

- Large statistics from high pp→ $b\bar{b}$ cross section
- But B momentum is unknown because production is mainly gg→ $b\bar{b}$

At LHCb

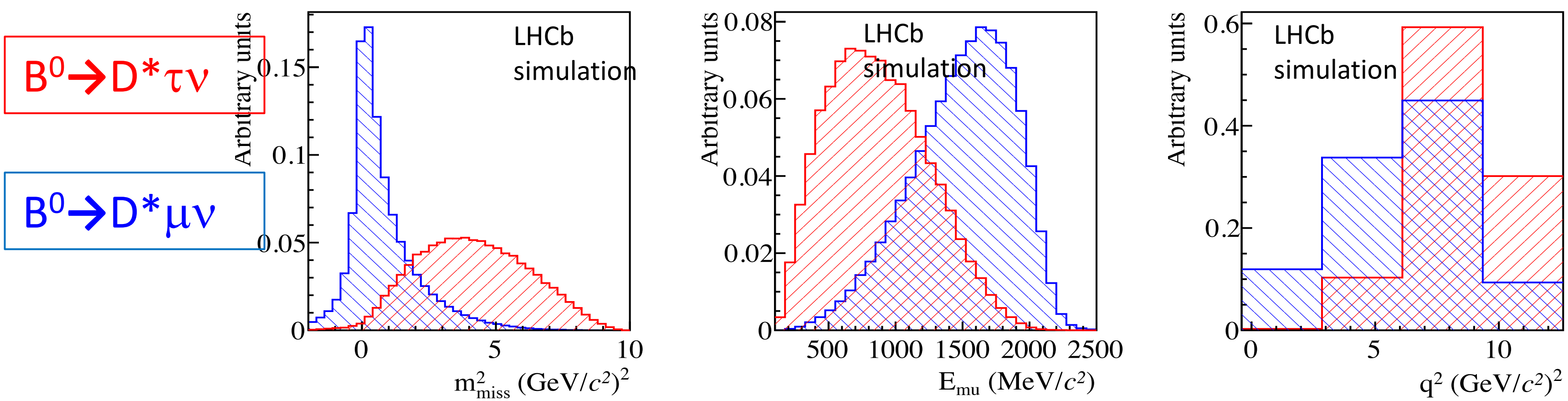
- Missing momentum of neutrinos is not measured
- But B direction well determined by vector from primary vertex to B vertex

$R(D^*)$ $\tau \rightarrow \mu\nu\bar{\nu}$

PRL 115, 11804 (2015)

- $B^0 \rightarrow D^*\tau\nu$ and $B^0 \rightarrow D^*\mu\nu$ have the same visible final state.
- Signal separated from normalization mode exploiting differences in 3 key kinematic variables, computed in the B rest frame.

m^2_{miss} $\quad E_\mu$ $\quad q^2 = (p_{B^0} - p_{D^{*+}})^2$

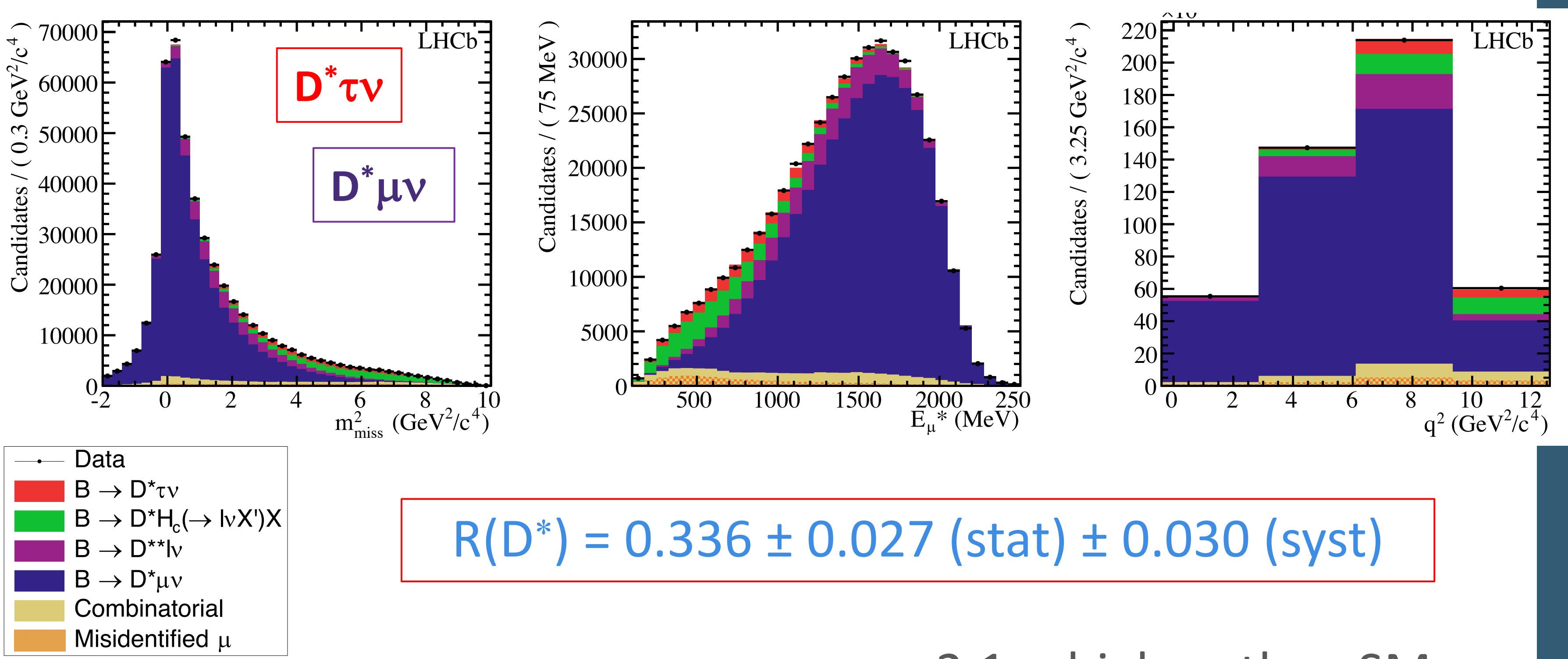


- B^0 boost along beam direction approximated with boost of the visible system. B momentum resolution ~18%, sufficient for good separation

$R(D^*)$ $\tau \rightarrow \mu\nu\bar{\nu}$

PRL 115, 11804 (2015)

- ML fit to m^2_{miss}, E_μ, q^2 distributions with 3D templates representing $B^0 \rightarrow D^*\tau\nu$, $B^0 \rightarrow D^*\mu\nu$ and background sources.
- Templates validated with separate fits on data control samples



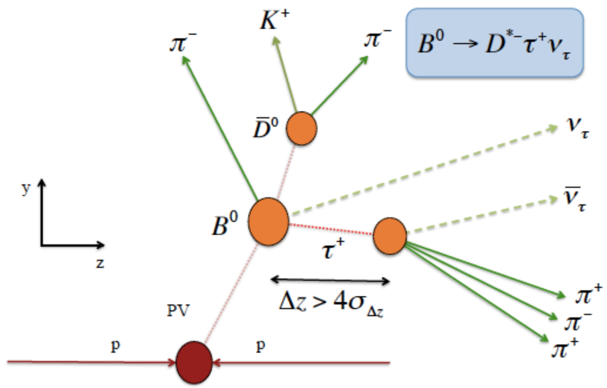
$R(D^*) = 0.336 \pm 0.027$ (stat) ± 0.030 (syst)

2.1 σ higher than SM

R(D*)   τ → πππ (π⁰)

arXiV:1708.08856 submitted to PRL
arXiv:1711.02505 submitted to PRD

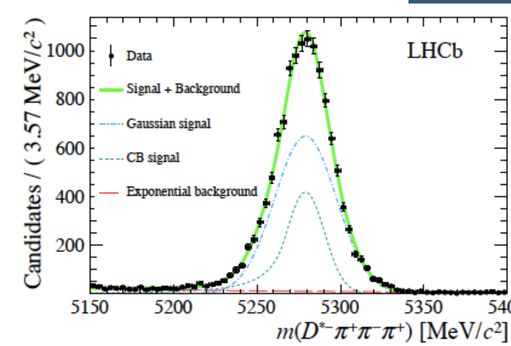
- 3-prong hadronic tau decays, data sample complementary to the muonic (



Details in Christos' talk on Friday

- Hadronic background suppressed exploiting the tau lifetime and the structure of tau decay.

$B^0 \to D^* 3\pi$



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

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

- Derive R(D*) using the known semimuonic branching fraction

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

$R(D^*)$ $\tau \rightarrow \pi\pi\pi\,(\pi^0)$

arXiv:1708.08856 submitted to PRL
arXiv:1711.02505 submitted to PRD

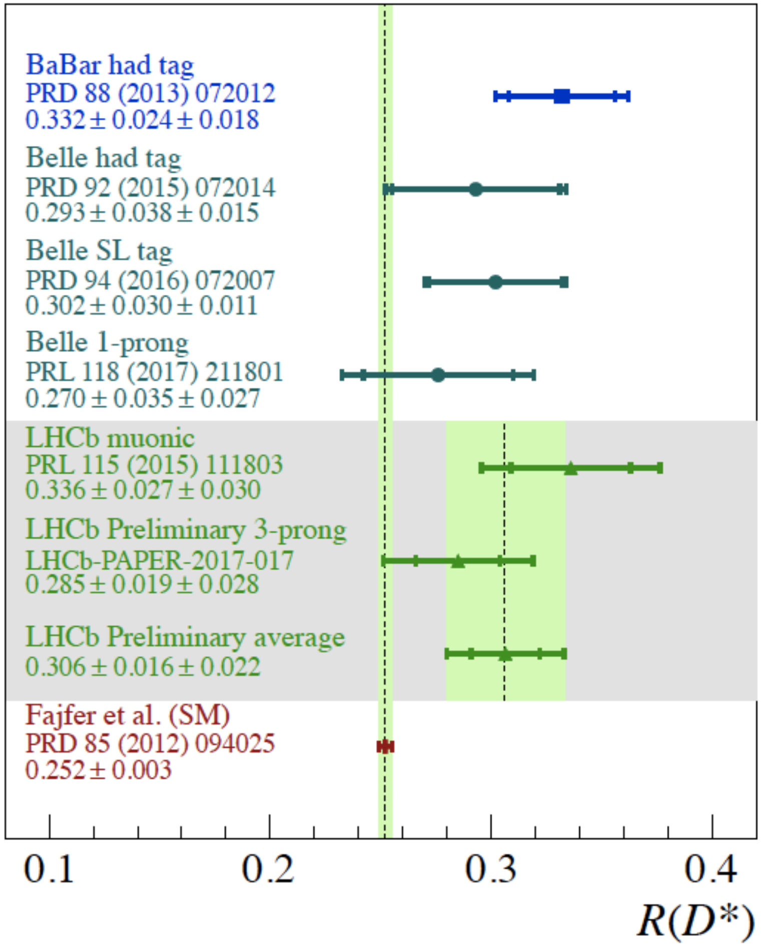
$$\mathcal{R}(D^{*-}) = 0.283 \pm 0.019\,(\text{stat}) \pm 0.025\,(\text{syst}) \pm 0.013\,(\text{ext})$$

- Compatible with the muonic results, with previous measurements and with SM expectation.

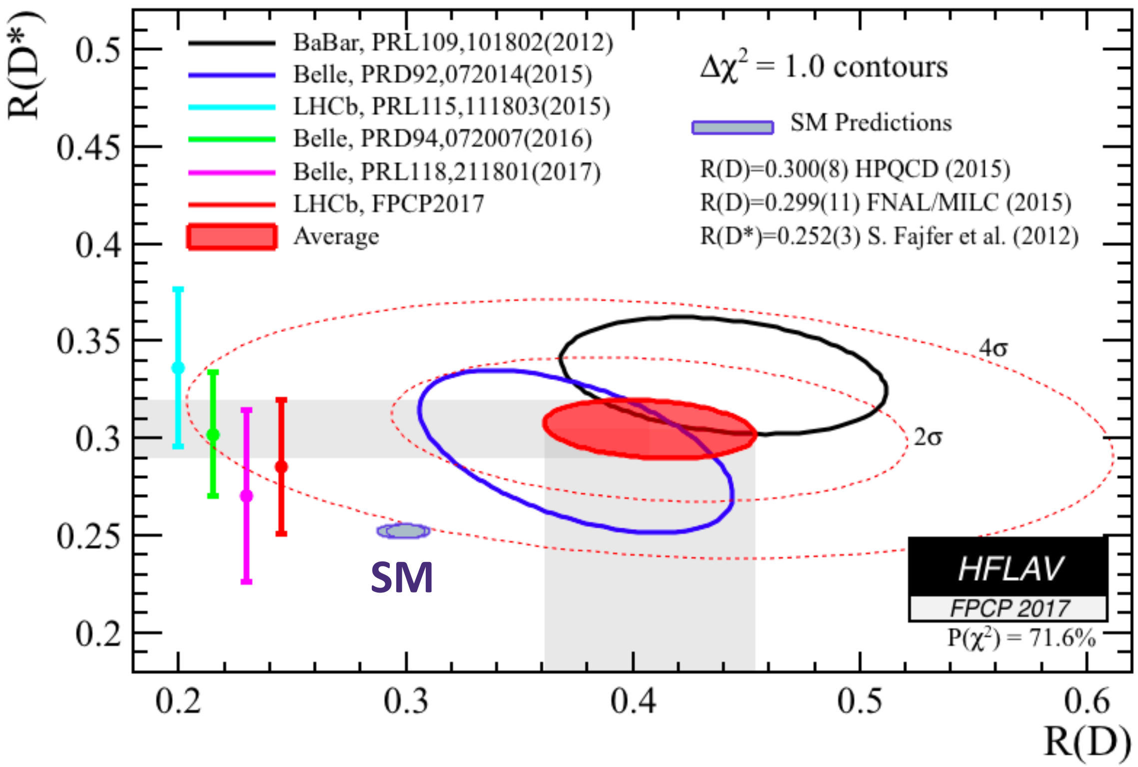
- LHCb combination

  $R(D^*) = 0.306 \pm 0.016 \pm 0.022$

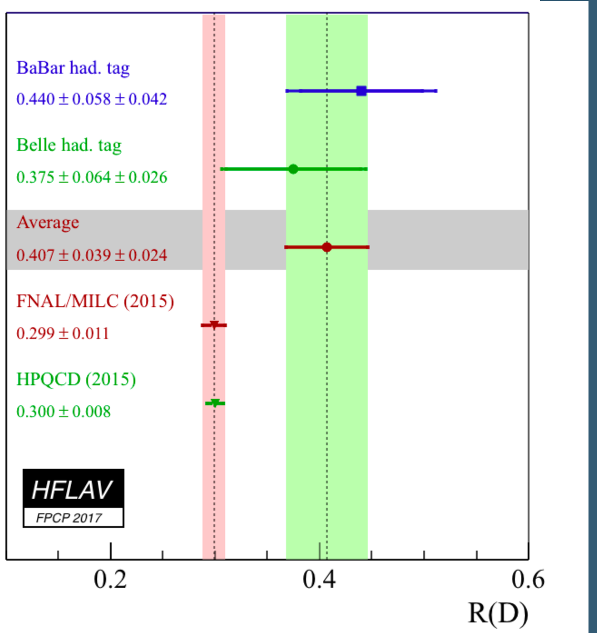
  2.1 σ above the SM



R(D*) and R(D)



Mesurements of R(D)



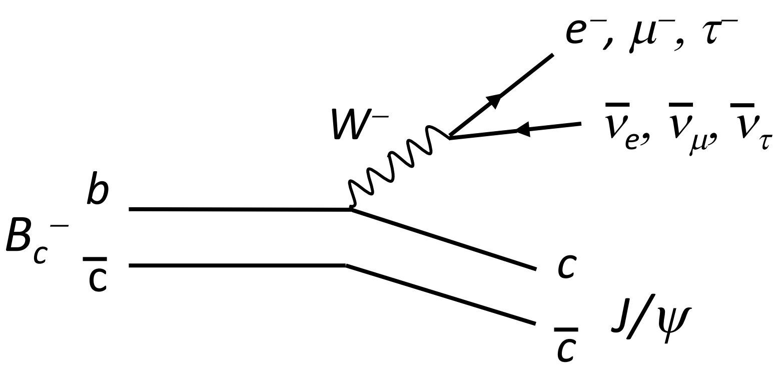
- R(D*) and R(D) exceed the SM predictions by 3.4σ and 2.3σ respectively. Combined it is a 4.1 σ deviation.

- Updates to the SM prediction for R(D*) reduce the deviation to ~3σ.
  arXiv:1703.05330, 1707.09509, 1707.09977

$R(J/\psi)$ $\tau \to \mu\nu\bar{\nu}$

arXiv:1711.05623 accepted by PRL

- Important to add more LFU test on other b-hadrons.
- Copious B_c production at LHC.
- $B_c \to J/\psi\tau\nu$ is the direct counterpart of $B \to D^{(*)}\tau\nu$ in the B_c sector.



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

- Theoretical predictions for $R(J/\psi)$ in the range 0.25-0.28, spread due to form factors uncertainty (not yet constrained experimentally).

Phys. Lett. B452 (1999) 129, arXiv:hep-ph/0211021, Phys. Rev. D73 (2006) 054024, Phys. Rev. D74 (2006) 074008

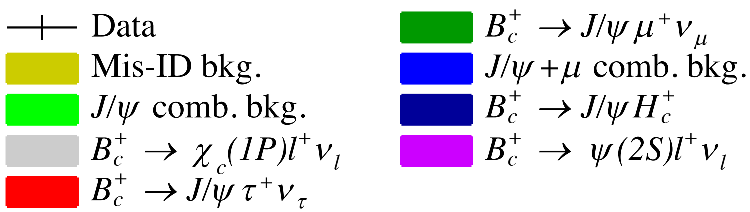
$R(J/\psi)$ $\tau \rightarrow \mu\nu\bar{\nu}$

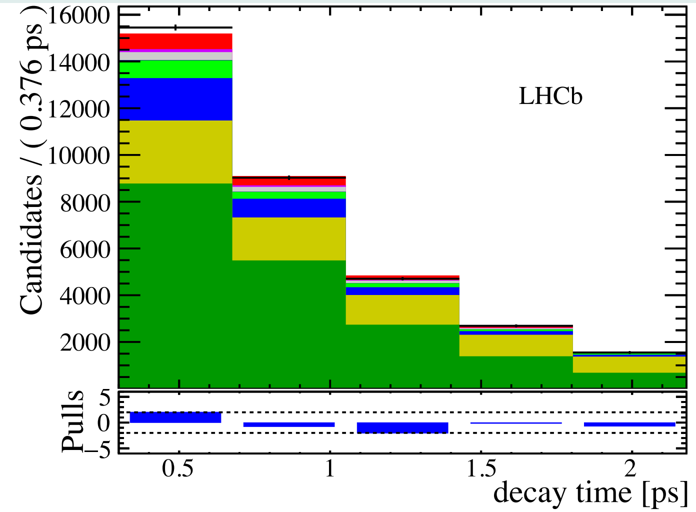
arXiv:1711.05623 accepted by PRL

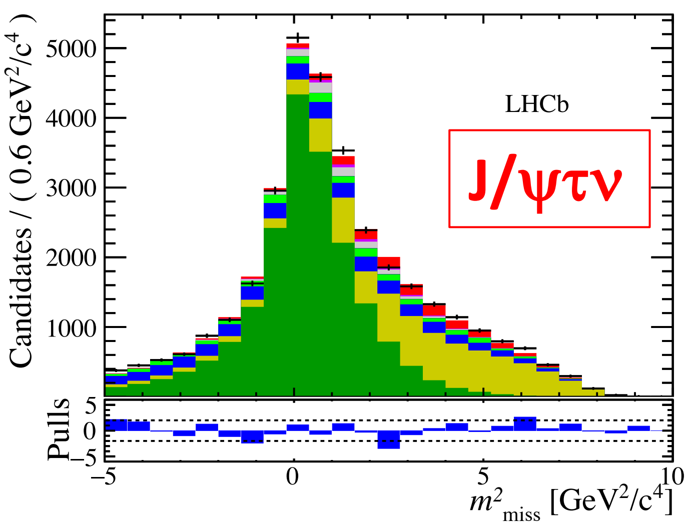
- Efficient trigger at LHCb with $J/\psi \rightarrow \mu^+\mu^-$
- Background from $B_c \rightarrow \psi(2S)\mu^+\nu_\mu$, $B_c \rightarrow J/\psi\ D(\mu^+\nu_\mu X)$, combinatorial and mis-ID.
- Short B_c lifetime helps to distinguish the signal from semileptonic decays of lighter b-hadrons.
- Analysis along same lines as R(D*).
- ML fit to m^2_{miss}, t_τ and E_μ, q^2 distributions with templates derived from simulation and data.
- First evidence (3σ) of $B_c \rightarrow J/\psi\tau^+\nu_\tau$

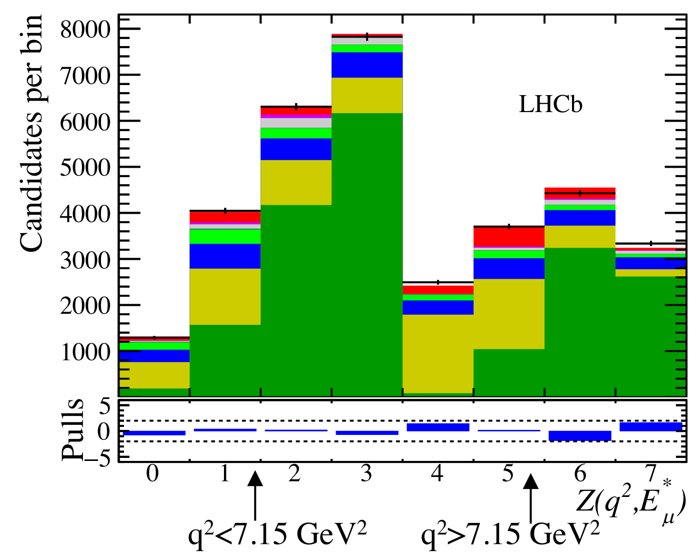
R(J/ψ) $\tau \to \mu \nu \bar{\nu}$

arXiv:1711.05623 accepted by PRL









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

Within 2 σ from SM prediction

LFU prospects, examples

Tests of LFU in $b \to cl\nu$ transitions, with different hadrons

- $R(\Lambda_c^{(*)}) = B(\Lambda_b \to \Lambda_c^{(*)}\tau\nu)/B(\Lambda_b \to \Lambda_c^{(*)}\mu\nu)$
  - Barionic modes with different spectator quarks and different spin structure.
  - $\Lambda_c^* \to \Lambda_c\pi^+\pi^-$ gives extra reconstructable vertex. Little feed-down from excited states. Form factors to be measured.
- $R(\Lambda_c)$ benefits of larger data sample. Work ongoing for both measurements.

Test of LFU in $b \to ul\nu$ transitions

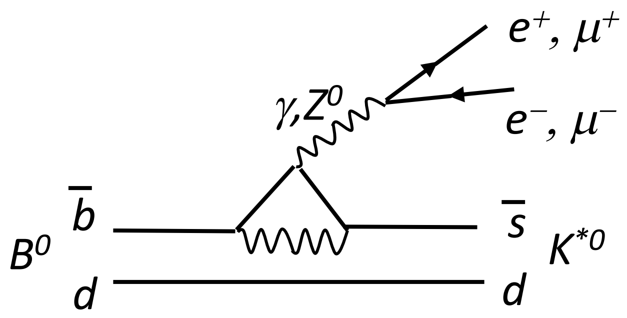
- Several options under study, large background to be defeated.
- $B(B^+ \to p\bar{p}\,\tau\nu)/B(B^+ \to p\bar{p}\,\mu\nu)$ combinatorial background reduced thanks to proton identification. Form factors needed.

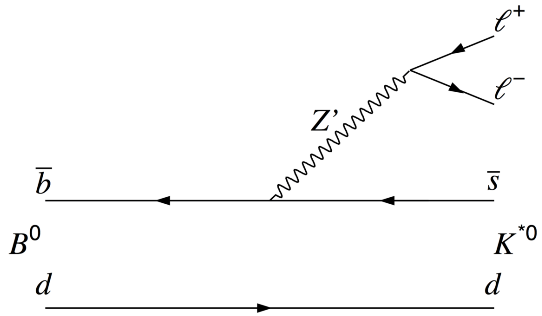
$$\mathcal{B}(B^- \to p\bar{p}\mu^-\overline{\nu}_\mu) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6}$$

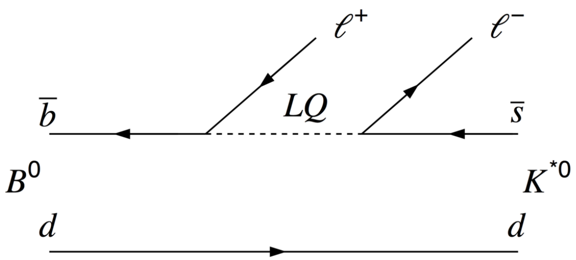
Belle - PRD 89, 011101 (2014)

LFU in b→ sl^+l^- transitions

- Neutral current b→sll transitions are loop, GIM and CKM suppressed in the SM, rates $O(10^{-6})$
- BSM contributions can come from new gauge bosons or LQ







- The test variable is the ratio of decay rates, predicted to be close to unity in the SM with uncertainty $O(10^{-3})$, QED effects at O(%).
  Not affected by QCD effects (ex: charm loops).

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

LFU in $b \to sl^+l^-$ transitions

- Measurements are performed in different regions of di-lepton invariant mass q^2 , outside charmonium resonances regions, sensitive to different BSM contributions.
- At B-Factories $R(K^{(*)})$ was measured to be consistent with unity with a precision of 20-50% .

- At LHCb
  - Large statistics from high $pp \to b\bar{b}$ cross section at LHC
  - Excellent muon reconstruction, but lower efficiency and resolution on electrons (bremsstrahlung).
- Systematic uncertainty due to different experimental efficiencies in reconstruction of muon and electron, reduced by measuring a double ratio with the resonant mode

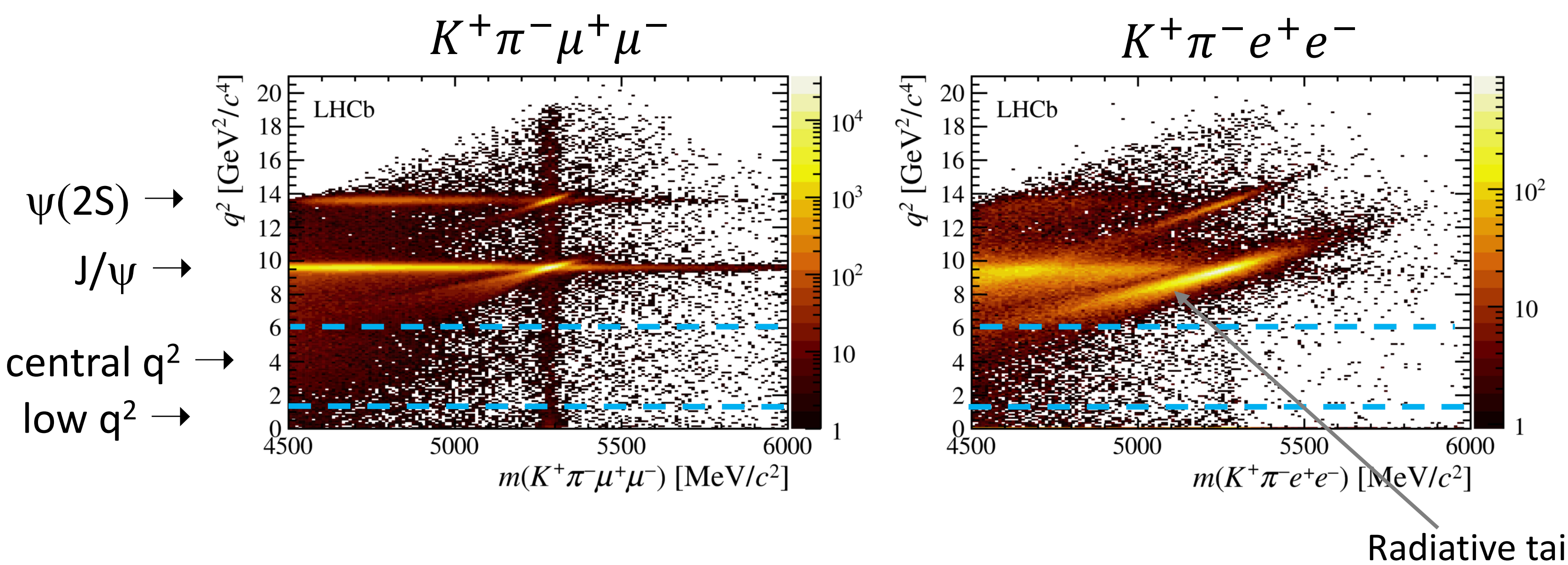
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

R(K*) at LHCb

JHEP 08 (2017) 055

Electron sample:

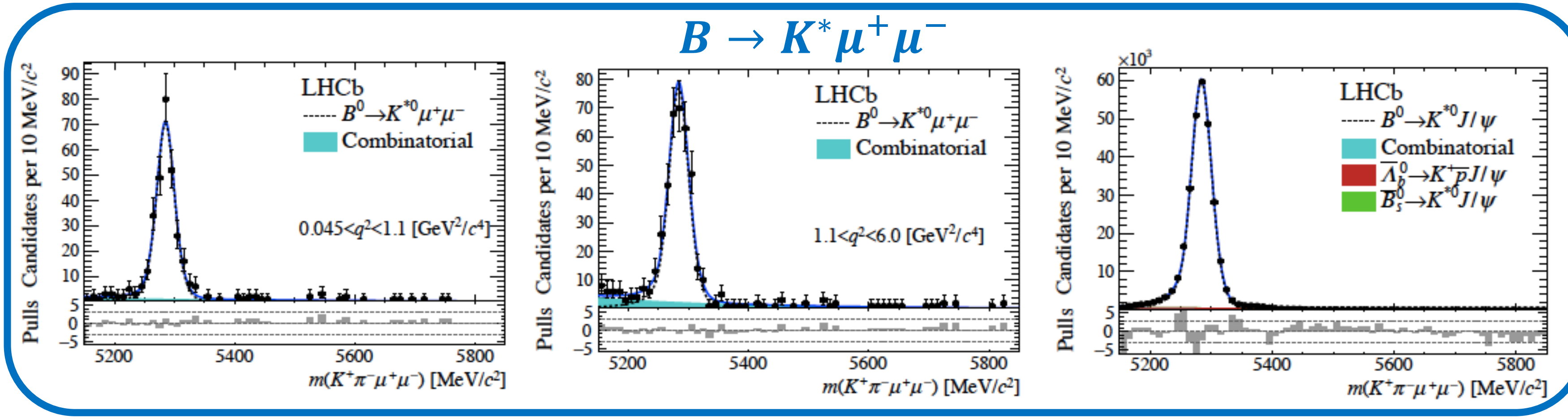
- yield maximized recovering as many as possible photons (0γ, 1γ, ≥2γ)
- reconstructed B mass shifts towards lower values

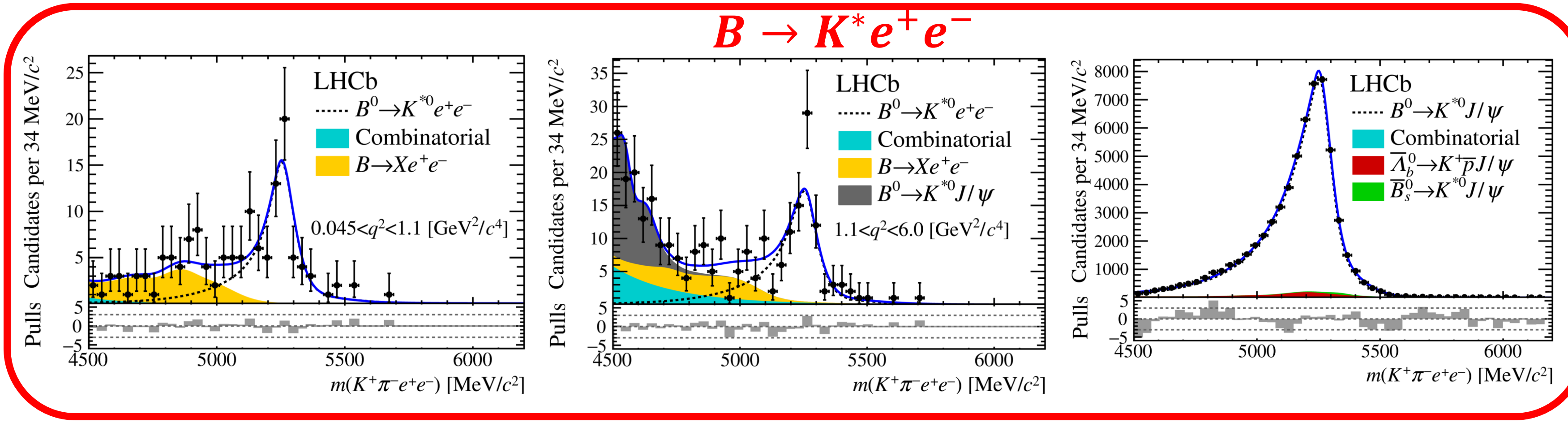


- B mass fit in two q^2 regions [0.045-1.1] and [1.1-6] GeV^2/c^4

B→K*μμ / B→K*ee

JHEP 08 (2017) 055





Low q^2 *central q^2* *J/ψ*

- Stringent test on the J/ψ resonance, ratio consistent with unit, within 1 σ.

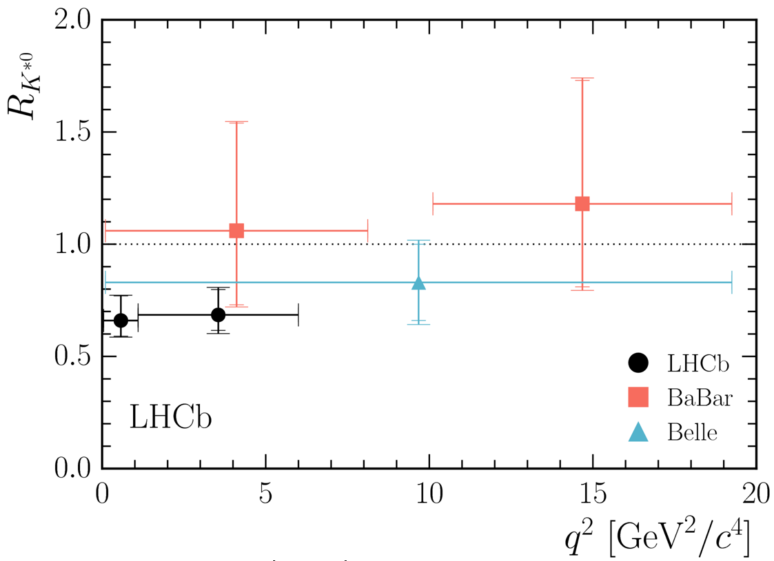
$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$

R(K*) at LHCb

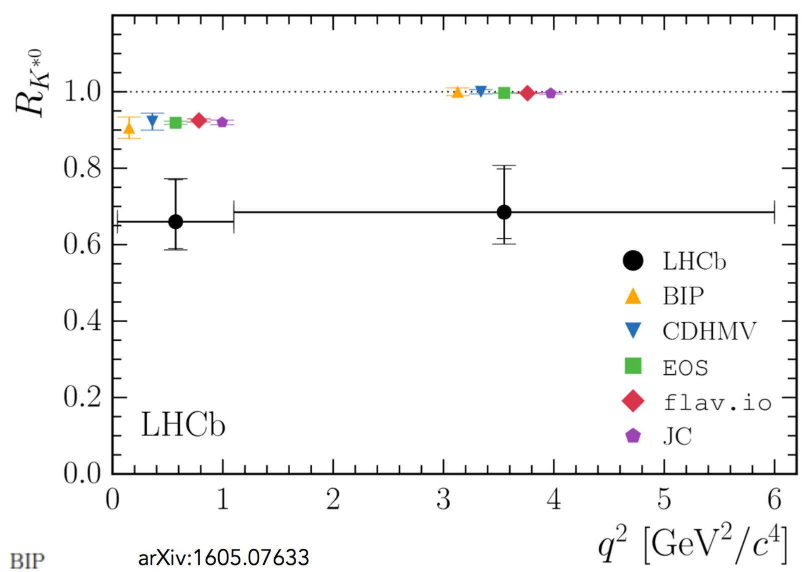
JHEP 08 (2017) 055

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

- Most precise measurement to date. Statistically limited by the electron sample



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

- Compatible with SM at ~2.2 σ (low q^2) and ~2.4 σ (intermediate q^2)

R(K) at LHCb

PRL 113, 151601 (2014)

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

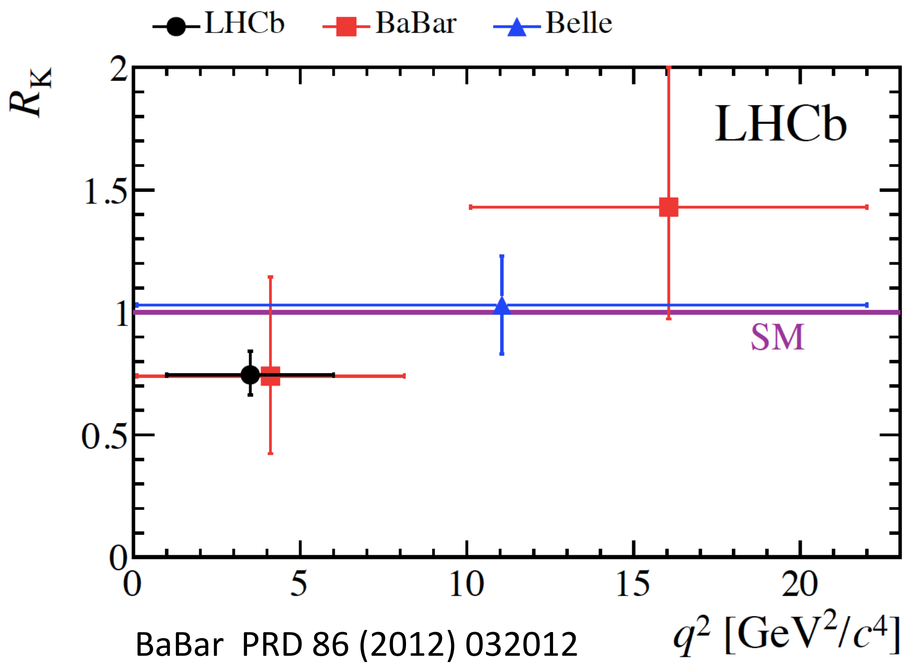
$$R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

- 2.6 σ from SM prediction

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

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

- Update on RUN2 data ongoing.



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

Conclusion

- LHCb is completing the analysis of Run 1 data with several measurements on $b \to c\tau\nu$ and $b \to sl^+l^-$ ($l=e,\mu$) decays.
- Few deviations from LFU and SM predictions.
  - Can suggest BSM models with new vector or scalar interactions.

- Other decay modes are under study in LHCb and Run 2 data will be fully exploited. Many possible directions

  Explore $b \to c\tau\nu$ with different b-hadrons and various final states

  Explore $b \to u\tau\nu$ transitions

  Explore $b \to sl^+l^-$ with different b-hadrons and various final states

  Full angular analysis

backup

R(D*), $\tau \to \mu\nu\nu$

PRL 115, 11804 (2015)

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

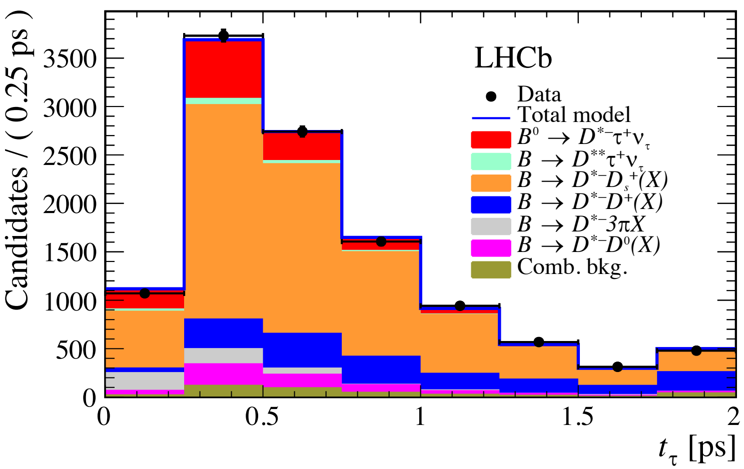
Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	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**

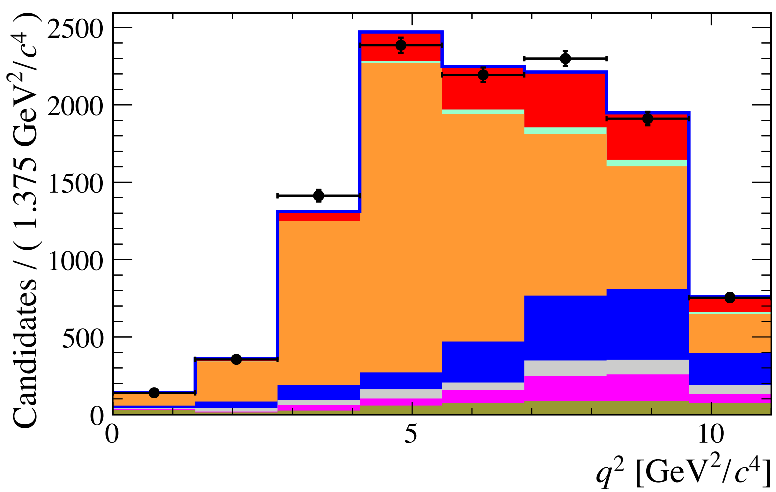
Background modelling; depends on control sample size

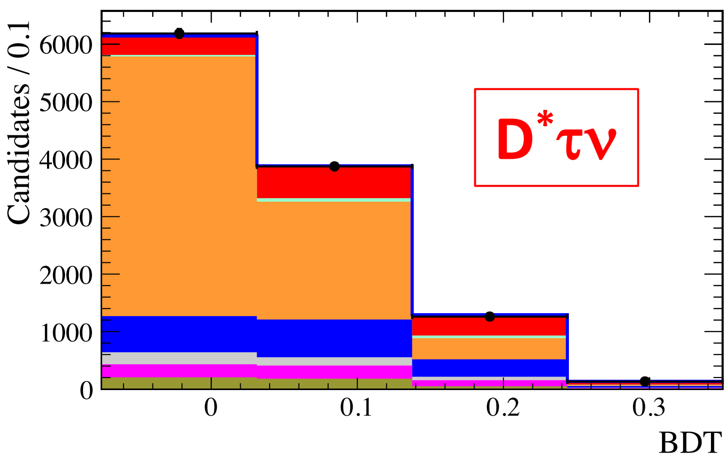
R(D*) $\tau \rightarrow \pi\pi\pi(\pi^0)$

arXiV:1708.08856 submitted to PRL
arXiv:1711.02505 submitted to PRD

- Train a BDT against background of double charm $B \rightarrow D^{*}D_{(s)}X$ decays.
- Extensive studies performed in data control samples.



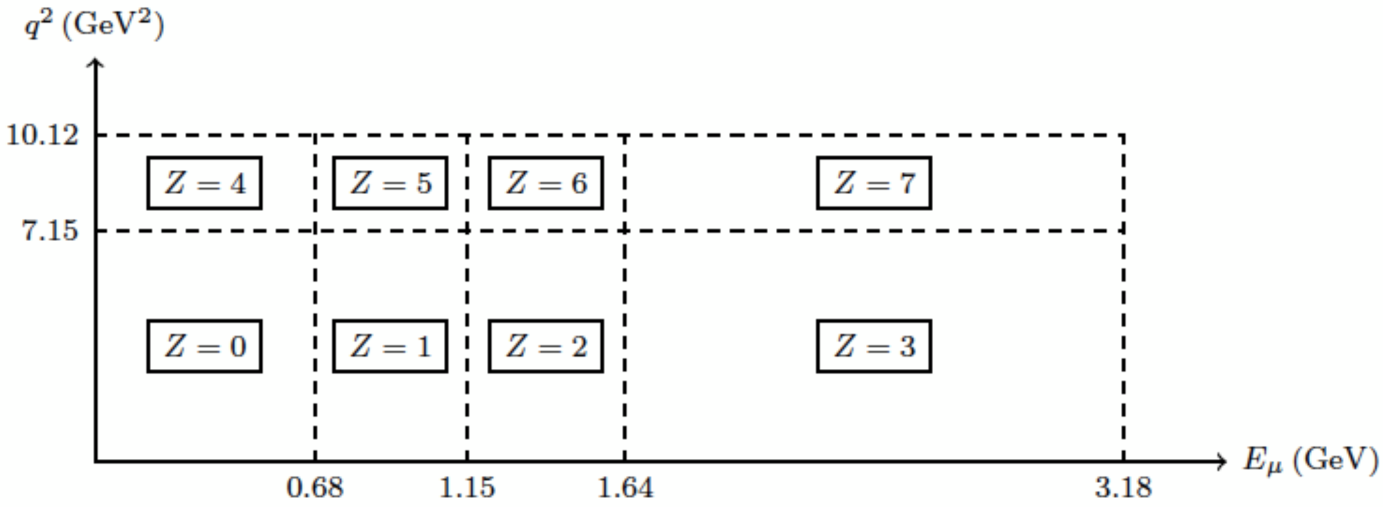




- 3D templates representing $B^0 \rightarrow D^{*}\tau\nu$, and background sources.
- ML fit to q^2, τ decay-time and BDT output distributions.

Lepton Flavour Universality

Z variable: 2 regions in q^2 and four in Emuon



R(D*) $\tau \rightarrow \pi\pi\pi\,(\pi^0)$

arXiv:1708.08856 submitted to PRL
arXiv:1711.02505 submitted to PRD

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

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
$D_s^+ \rightarrow 3\pi X$ decay model	2.5
$B \rightarrow D^{*-}D_s^+X$, $B \rightarrow D^{*-}D^+X$, $B \rightarrow D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \rightarrow D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

External inputs

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

$R(K^*)$

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi (\to \ell^+\ell^-)$
	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

Ref.	$R(D)$	Deviation
Experiment [HFLAV update]	$0.407(39)(24)$	—
2016/17 theory results, using new lattice and exp. data:		
[Bigi Gambino 1606.08030]	$0.299(3)$	2.4σ
[Bernlochner Ligeti Papucci Robinson 1703.05330]	$0.299(3)$	2.4σ
[Jaiswal Nandi Patra 1707.09977]	$0.302(3)$	2.3σ
2012 theory results:		
[Fajfer Kamenik Nisandzic 1203.2654]	$0.296(16)$	2.3σ
[Celis Jung Li Pich 1210.8443]	$0.296\binom{8}{6}(15)$	2.3σ
[Tanaka Watanabe 1212.1878]	$0.305(12)$	2.2σ

Good consensus of theory predictions. Belle data and lattice data beyond zero recoil allow for good determination of form factors, including S_1.