University of Zurich^UZH

Tests of lepton flavour universality at LHCb

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Outline

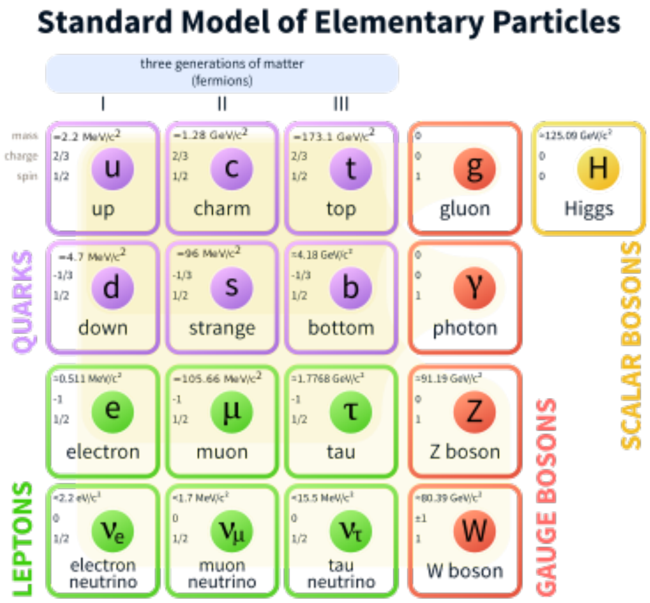
- Introduction
    - What is lepton flavour universality
    - Tests of lepton flavour universality
    - The LHCb detector
- Lepton flavour universality violation in $b \rightarrow c \ell \nu$ decays
    - R(D) and R(D*)
- Lepton flavour universality violation in $b \rightarrow s \ell \ell$ decays
    - R(K) and R(K*)
    - The P_5' anomaly
- Summary and outlook

Introduction

Lepton Flavour Universality in the SM

- In the Standard Model (SM) quarks and leptons exist in 3 generations of 2 members each
  - The 3 generations are distinguished only because of the different mass
- **In the SM Lepton Flavour Universality (LFU) is assumed**

→ **the gauge couplings are equal for the 3 generations**



- Testing of LFU probes the validity of the SM
  - LFU precision tests performed over the years, but **no definite deviation observed**
- **Violation of LFU → hint for New Physics (NP) beyond the SM**

Tests of LFU in b-decays

Theory talk by Javier Fuentes-Martin this morning

- **LFU violation searched for in processes involving third generation of quarks (B) and all lepton generations at LHCb**

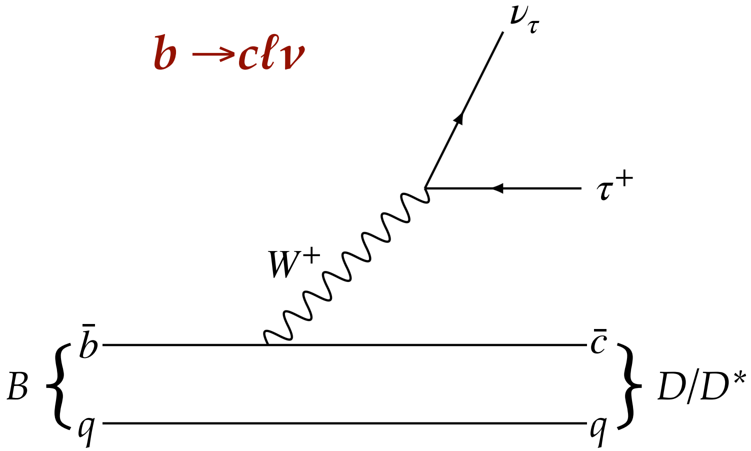
Charged current (Semileptonic decays, SL):

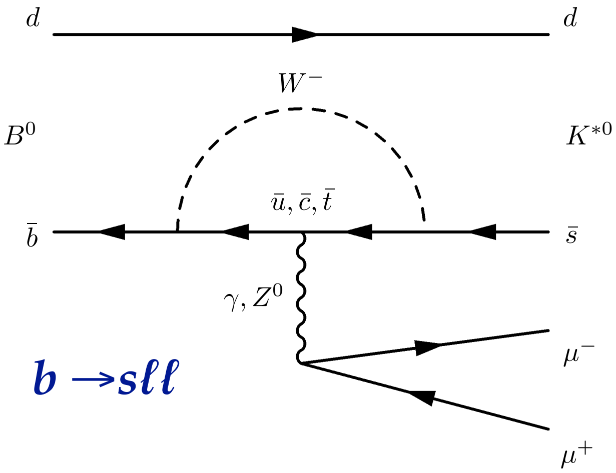
- Tree level, BR of few %
- strong and weak part factorise => clean SM predictions
- NP sensitivity up to ~ 1 TeV

Neutral currents (Rare decays, RD):

- FCNC processes → only at loop level → BR ~ $10^{-7} \div 10^{-6}$
- new particles can enhance SM-suppressed amplitudes
- NP sensitivity up to ~ 100 TeV

$b \rightarrow c\ell\nu$





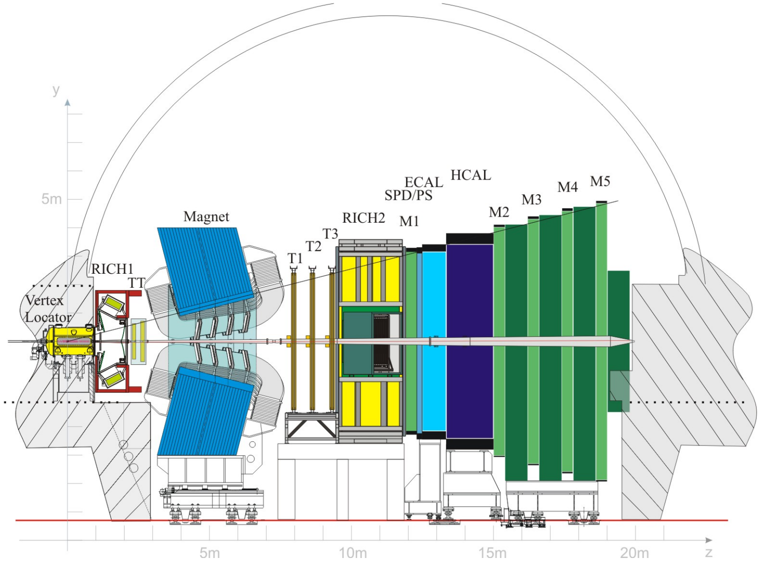
$b \rightarrow s\ell\ell$

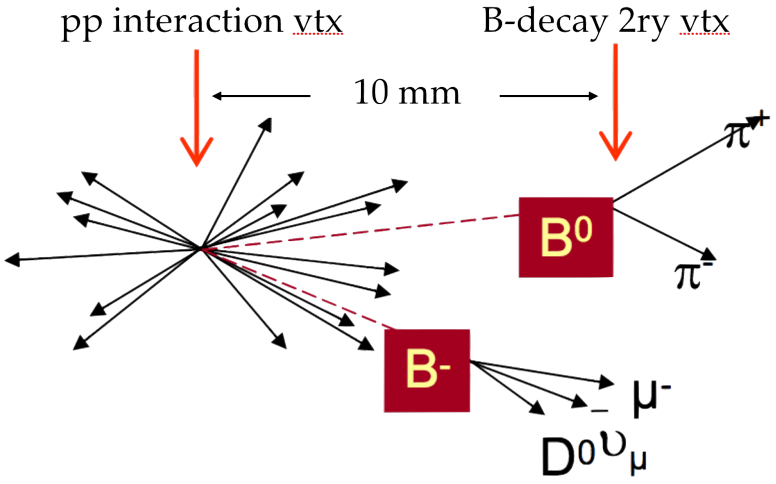
The LHCb Detector

[JINST 3 (2008) S08005]

The measurements reported in this presentation have all been obtained at LHCb

- Forward spectrometer optimised for heavy flavour physics at the LHC:
  - Acceptance of $2 < \eta < 5$
  - Large boost: B mesons fly ~ 1 cm





- B mesons produced forward in pp collisions at center of mass energies ranging from 7 → 13 TeV
- So far produced > 10^{12} bb-bar pairs

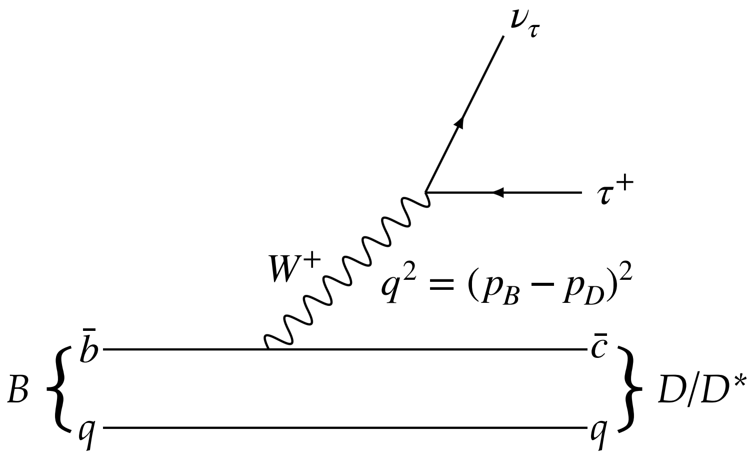
LFU Violation in semileptonic ($b \rightarrow c\ell\nu$) decays

LFU violation in semileptonic b-decays

- In a semileptonic decay the products are part leptons and part hadrons.

$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto G_F^2 |V_{cb}|^2 f(q^2)^2$$

q^2 = transferred momentum by the W



- Measurement of ratio of branching fractions allows to:
  - Remove dependence from $|V_{cb}|$
  - Partially cancel out theoretical uncertainties

  } **Theoretically clean**
  - Reduce experimental uncertainties → **experimentally clean**

R(D$^{(*)}$) measurement

$$\boxed{R(X) = \frac{BR(B \to X\tau\bar{\nu}_\tau)}{BR(B \to X\mu\bar{\nu}_\mu)}}$$

signal

normalization

where: $X = D, D^*$ and: $\tau \to \mu\nu_\tau\bar{\nu}_\mu$ or: $\tau \to 3h\nu_\tau$

- Main experimental challenge constituted by presence of more than one neutrino in the signal final state

  ➡ No narrow peak to fit

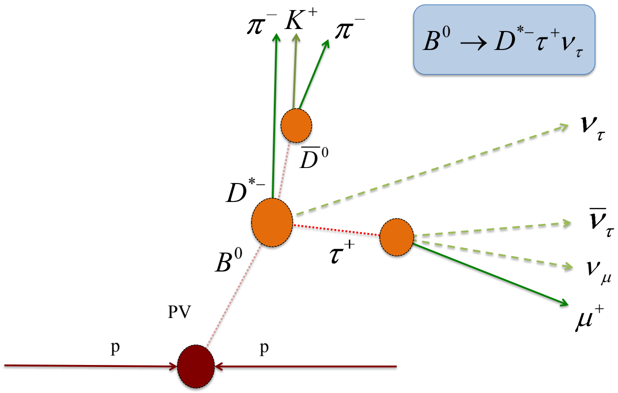
- Main backgrounds:
  - partially reconstructed B-decays
  - combinatorial background
  - misidentification background
- R(D$^{(*)}$) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs).

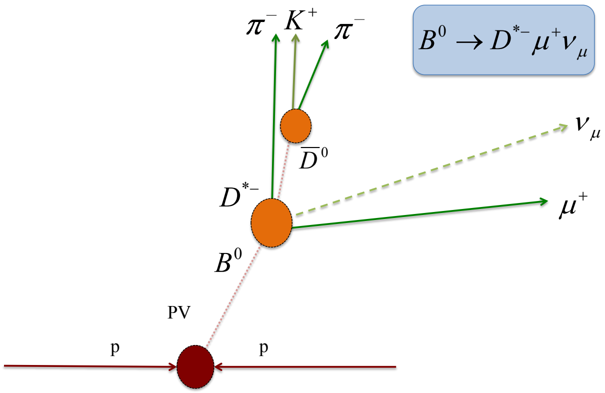
R(D*) muonic

[PRL115(2015)111803]

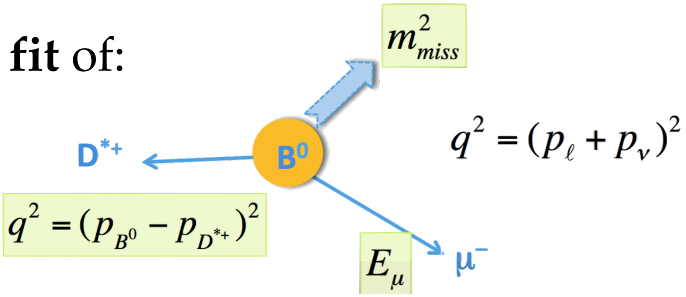
$$R(D^*) = \frac{BR(B \to D^*\tau\bar{\nu}_\tau)}{BR(B \to D^*\mu\bar{\nu}_\mu)} \qquad \text{where: } \tau \to \mu\bar{\nu}_\mu\nu_\tau \quad \text{and: } D^* \to \pi D^0(\to K\pi)$$

- Signal and normalization mode share same visible final state ($K\pi\pi + \mu$)





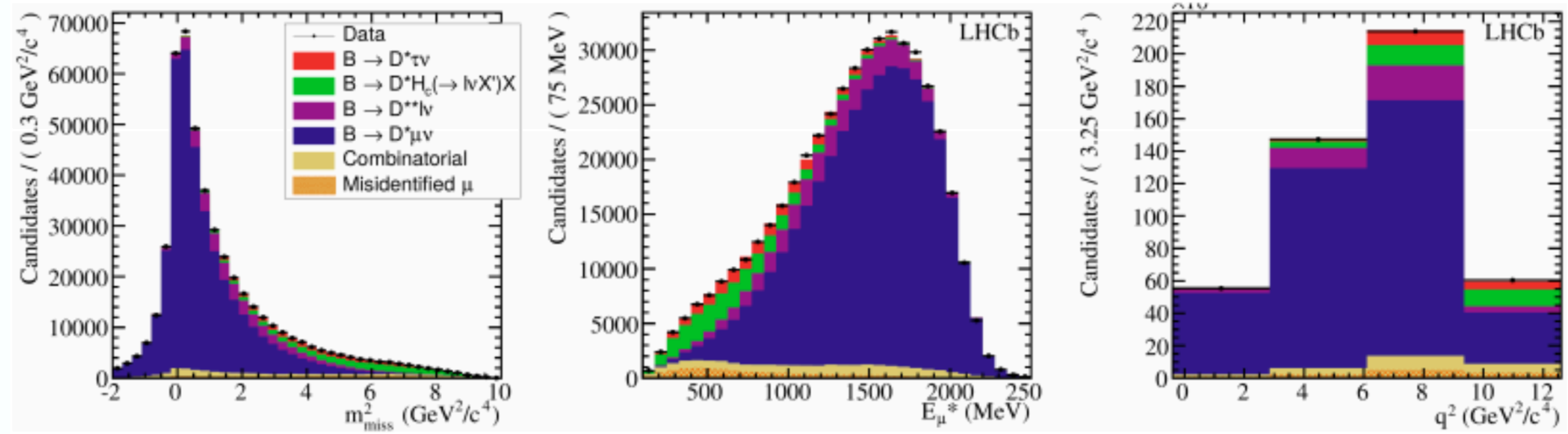
- τ and μ separated via a ***3D* binned template fit** of:
  - $m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2$
  - E^*_μ in B rest frame
  - $q^2 = (p_B - p_{D^*})^2$



R(D*) muonic

[PRL115(2015)111803]

- Fit components:
  - **τ signal** and **μ normalisation**.
  - Backgrounds: **feed-down** from excited *D* states, **double charm** *DD* (where one *D* decays semileptonically), combinatorial, **muon mis-ID**.



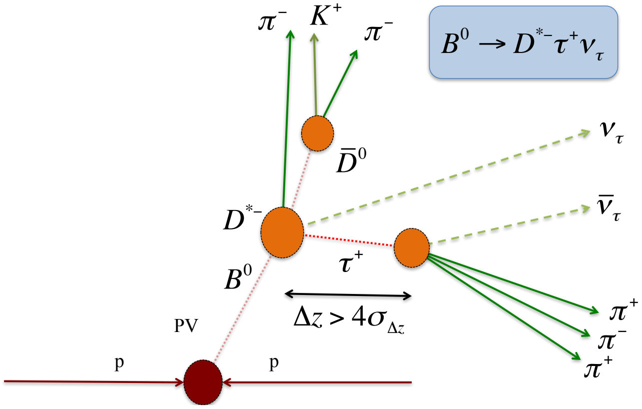
R_{D^*}=0.336±0.027±0.030, **1.9σ above the SM**

R(D*) hadronic

[PRL 120, 171802 2018], [PRD 97,072013 2018]

- This time used events where the τ decays in 3-prongs:

$$\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$$



- Normalisation channel chosen to have same visible final state as signal one to reduce systematic uncertainties:

$$B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$$

- Measured:

$$K(D^*) = \frac{BR(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)}{BR(B^0 \rightarrow D* - \mu^+\nu_\mu)}$$

⇨ $$R(D^*) \equiv K(D^*)\frac{BR(B^0 \rightarrow D^{*-}3\pi)}{BR(B^0 \rightarrow D^{*-}\mu^+\nu_\mu)}$$

[∼4% precision, BaBar, Belle, LHCb]

[∼2% precision, HFLAV 2016]

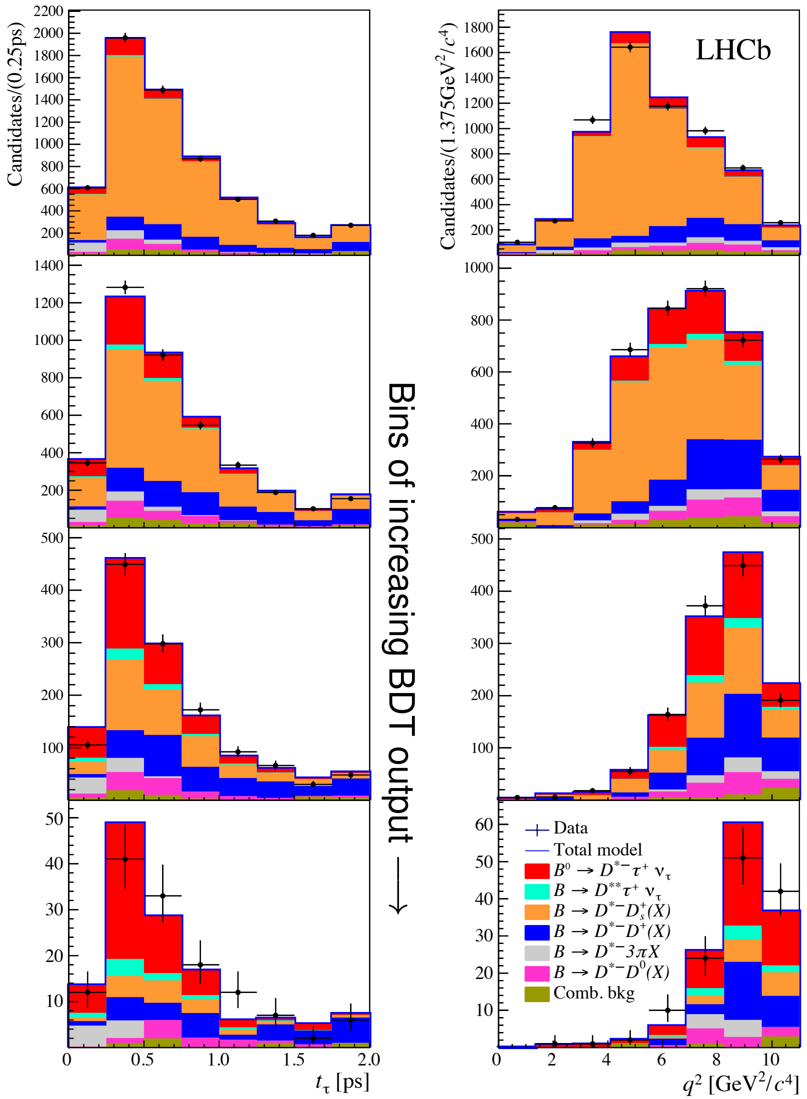
R(D*) hadronic

[PRL 120, 171802 2018], [PRD 97,072013 2018]

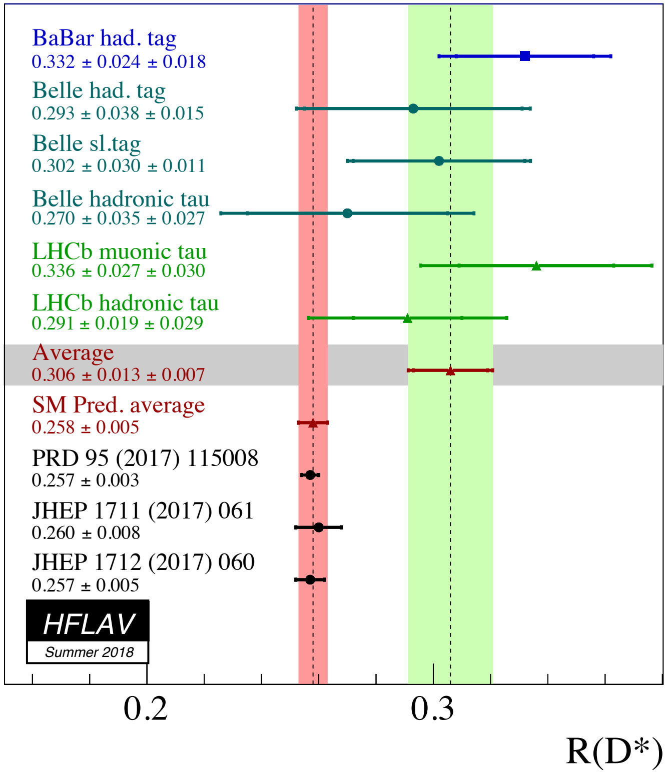
- **Fit variables:**
  - output from BDT against double charm bkg
  - τ decay time (against D^*D^+X, due to the large D^+ lifetime)
  - q^2.

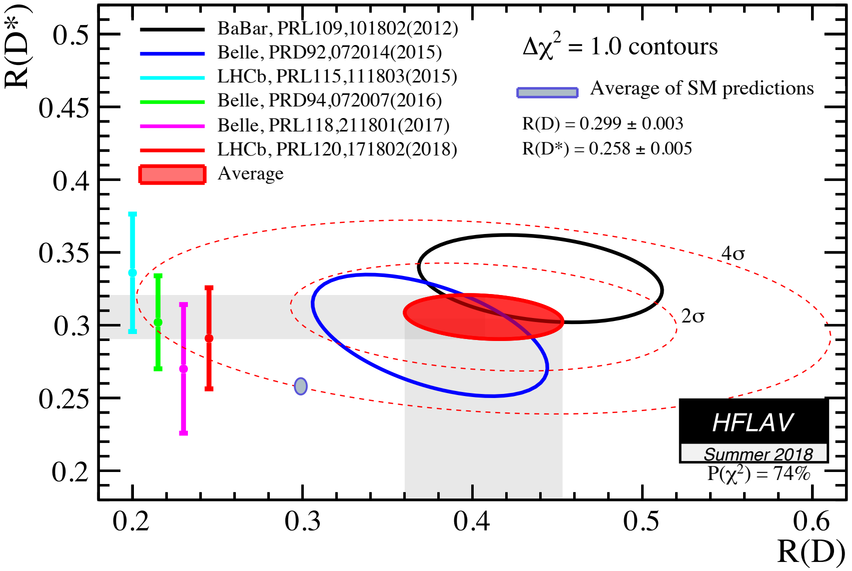
$R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$

1σ above the SM



R(D) and R(D*) combination



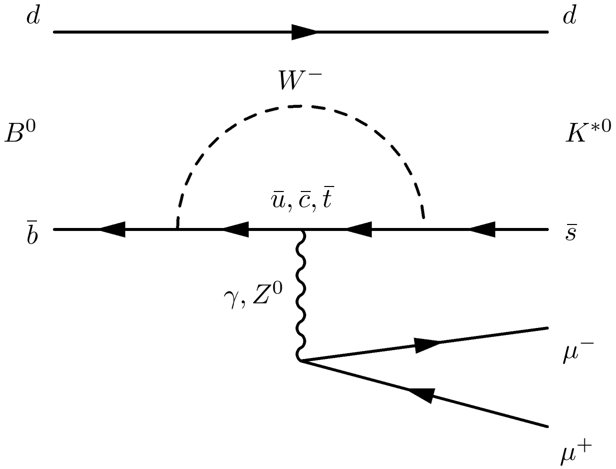


- All $R(D^*)$ measurements lie above the SM expectation (0.258 ± 0.005) [PRD95, 115008 (2017)], [JHEP 1711 (2017) 061], [JHEP 1712 (2017) 060]
- R_{D^*} world average: **3.0 σ** above SM prediction
- Combining $R(D) + R(D^*)$ measurements: **overall tension with SM of 3.8 σ**

LFU Violation
in rare ($b \rightarrow s\ell\ell$) decays

The $b \to s\ell^+\ell^-$ transition

- Not allowed at tree level → highly sensitive to virtual particles and interactions
  - NP effects can be sizeable compared to the $b \to s\ell^+\ell^-$ SM amplitude
  - Can probe models with e.g. charged Higgs, Z' bosons or leptoquarks



- Comparison of decays with different leptons in the final state allows to probe NP involving LFU violation among different generations.

R(K*)

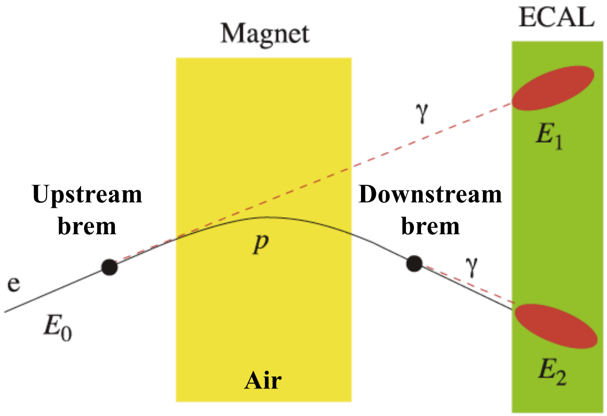
[JHEP08 (2017) 055]

- Exploits: $B^0 \to K^{*0} (\to K^+ \pi^-) \ell^+ \ell^-$
- Measured at LHCb using Run1 data for $q^2 \in [0.045,1.1]$ and $[1.1,6]$ GeV^2
- Double ratio with respect to the resonant decay mode $B^0 \to K^{*0} J/\psi$

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

- Electrons more difficult to reconstruct w.r.t. muons due to Bremsstrahlung

➡ Lower efficiency

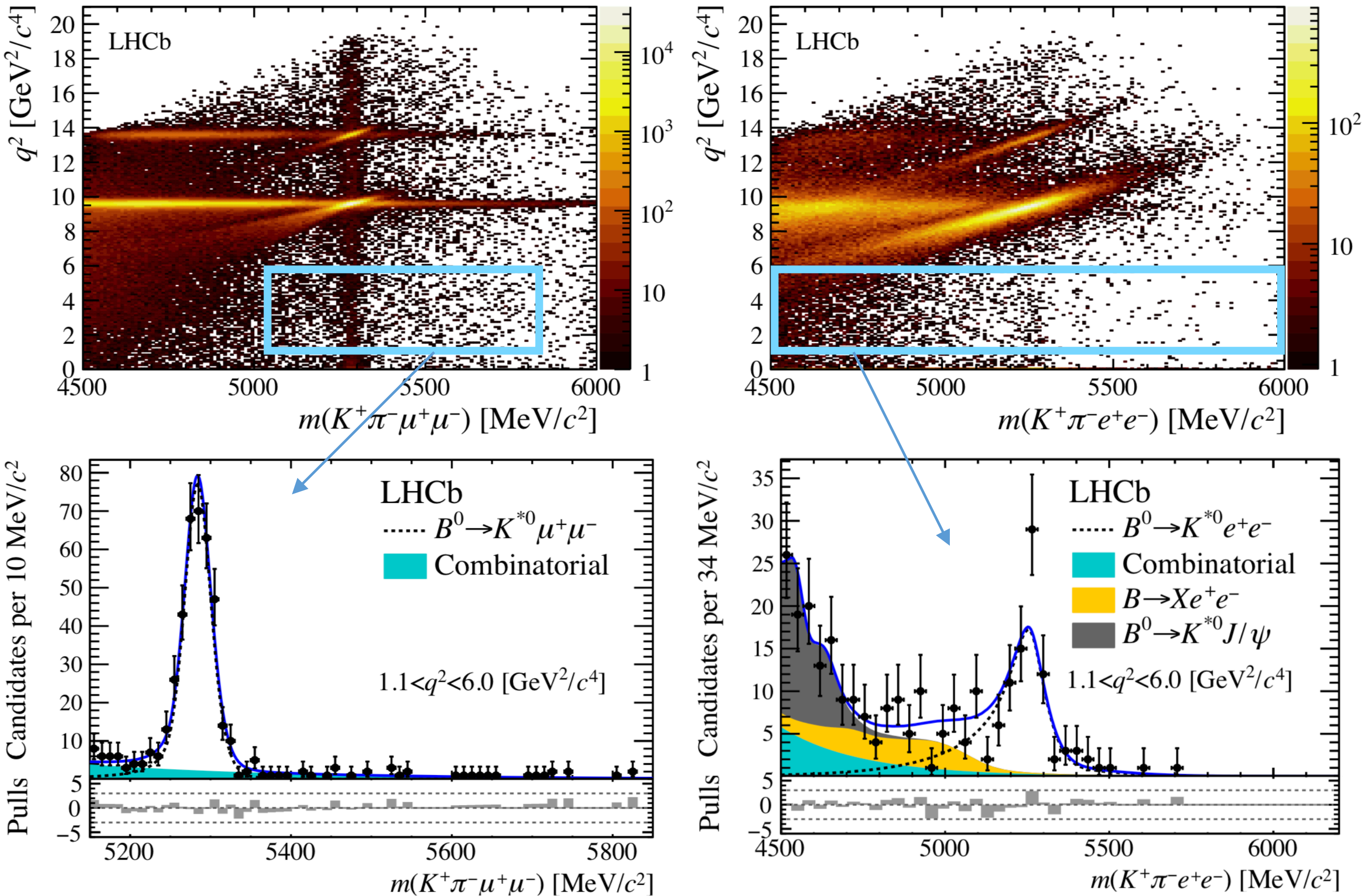


*NB: q^2 = dilepton invariant mass

R(K*)

[JHEP08 (2017) 055]

- Event yield obtained from simultaneous $M(K^+\pi^-\ell^+\ell^-)$ fit to the J/ψ and non-resonant channels.



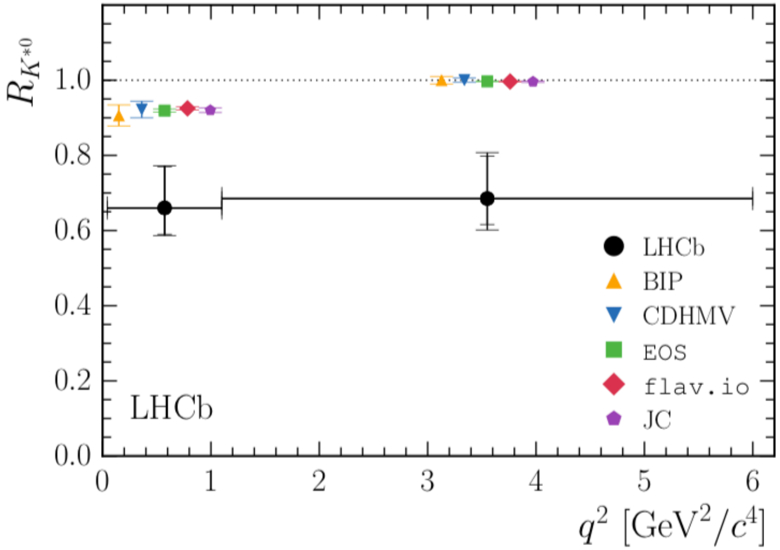
R(K*)

[JHEP08 (2017) 055]

- Event yield obtained from simultaneous $M(K^+\pi^-\ell^+\ell^-)$ fit to the J/ψ and non-resonant channels.

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$

2.2 σ deviation from SM



R(K) at LHCb

[PRL 113, 151601 (2014)]

- Measured at LHCb in 2014 using Run1 data for $q^2 \in [1,6]\mathrm{GeV}^2$
- Double ratio with respect to the resonant decay mode $B^+ \to J/\psi K^+$

$$R(K) = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \Big/ \frac{BR(B^+ \to K^+e^+e^-)}{BR(B^+ \to K^+J/\psi(\to e^+e^-))}$$

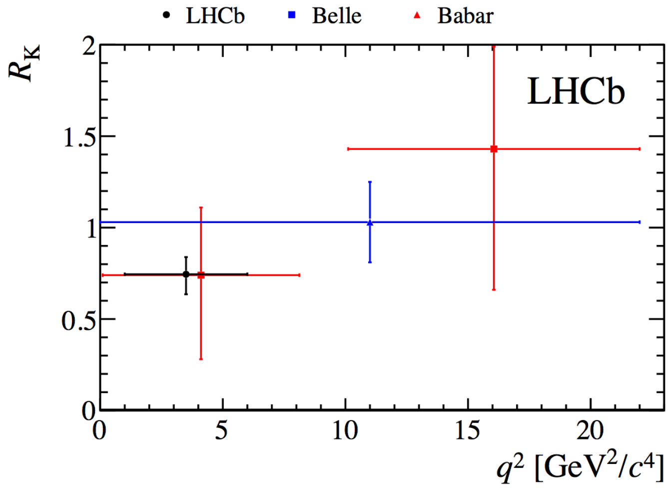
- As for R(K*) event yields determined using fits to the K+ℓ+ℓ- mass distribution

$$\mathbf{R(K)} = 0.745^{+0.090}_{-0.074}(\mathbf{stat.}) \pm 0.036(\mathbf{syst.})$$

2.6σ from the SM *

* SM prediction for $R_K = 1 \pm 0.01$

Bordone, Isidori Eur.Phys.J. C76 (2016) no.8, 440



Summary and Outlook

Summary

- Tests of lepton universality are excellent ways to look for new physics in a complementary way w.r.t. direct searches
- In B-meson decays there are *intriguing deviations* with respect to SM that seem to form a coherent pattern
  - Measurements of ratios of branching fractions in both $b \to c\ell\nu$ and $b \to s\ell^+\ell^-$
    - **3.8σ tension in $R(D)$ - $R(D^*)$** when combining BaBar, Belle and LHCb
    - **2.6(2.4)σ** below SM prediction in **$R(K^{(*)})$ at central q^2**
    - **2.2σ** below SM prediction in **$R(K^*)$ at low q^2**
  - Discrepancies observed also in angular distributions of $B^0 \to K^{*0} \mu^+\mu^-$
- Anomalies in both $b \to c\ell\nu$ and $b \to s\ell^+\ell^-$ decays could be described with same new physics particles

Outlook

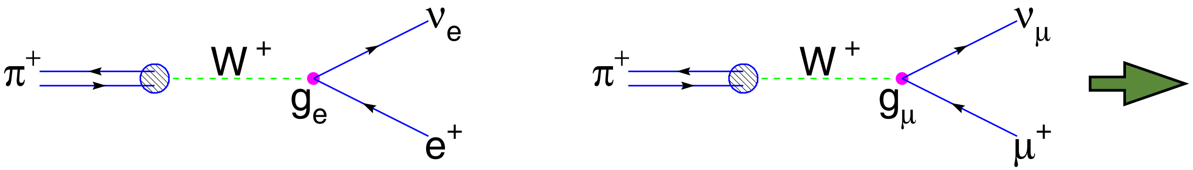
- All presented results are based on Run I data: full Run II analyses will have 4× as much statistics
  - expected improvement on both statistical and systematic uncertainties
- In $b \to c\ell\nu$ decays:
  - Update of $R(D^{(*)})$ ongoing
  - Analysis with baryonic decays (e.g: $R(\Lambda_c) = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR(\Lambda_b \to \Lambda_c\mu\nu)$) ongoing:
    - Provide complementary information w.r.t. semileptonic B-meson decays
    - Can only be performed at LHCb
- For $b \to s\ell^+\ell^-$ transitions:
  - Update of $R(K^{(*)})$ ongoing
  - Measurements of $R(K_s)$,$R(K^{*+})$,$R(K\pi\pi)$,$R(pK)$,$R(\phi)$ and others planned

Exciting times ahead! Stay tuned!

Back-up

Tests of LFU

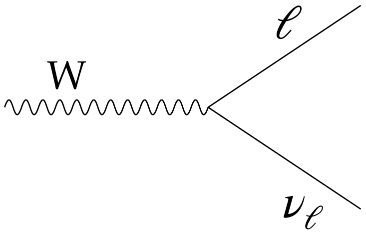
- LFU precision tests performed over the years
- **No definite deviation observed**



From PDG

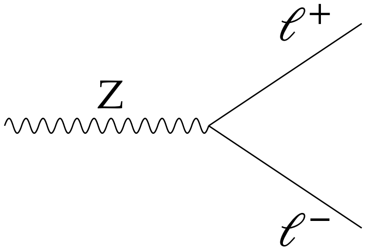
$$\frac{g_\mu}{g_e} = 1.0023 \pm 0.0016$$

(from TRIUMF and PSI measurements)



From PDG

$W^+ \to \ell\nu_\ell$	Fraction (Γ_i/Γ)
$e^+\nu$	$(10.71 \pm 0.16)\%$
$\mu^+\nu$	$(10.63 \pm 0.15)\%$
$\tau^+\nu$	$(11.38 \pm 0.21)\%$



From PDG

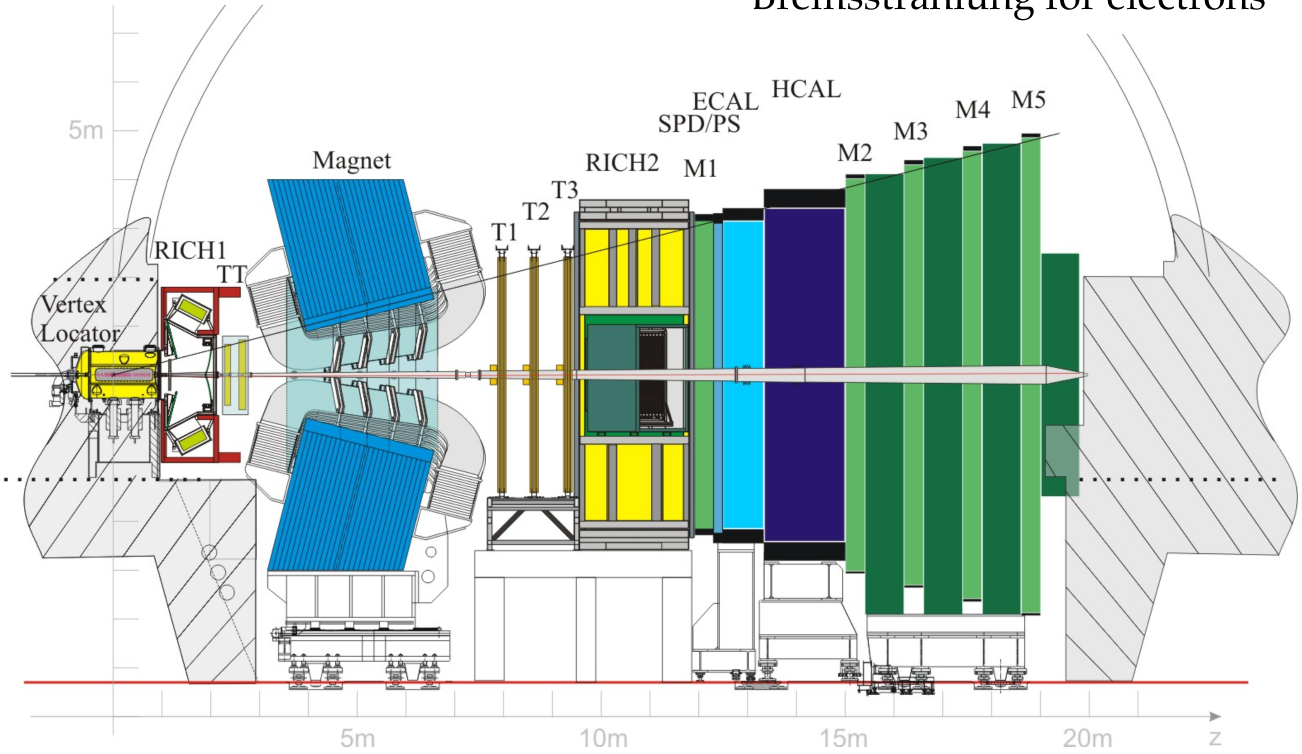
$Z \to \ell^+\ell^-$	Fraction (Γ_i/Γ)
e^+e^-	$(3.3632\pm0.0042)\%$
$\mu^+\mu^-$	$(3.3662\pm0.0066)\%$
$\tau^+\tau^-$	$(3.3696\pm0.0083)\%$

- **Violation of LFU → hint for New Physics (NP) beyond the SM**
- **LFU violation searched for in processes involving third generation of quarks (B) and all lepton generations at LHCb**

The LHCb Detector

- **Advantages:**
  - Excellent vertexing, tracking and PID
  - Trigger also on low momentum hadrons
  - Enormous data sample from LHC high *bb* cross section
  - All type of b-hadrons, including B_c^+ and Λ_b

- **Challenges:**
  - Unconstrained kinematics due to missing neutrinos
  - Large track multiplicity → significant amount of background
  - High particle momenta → significant Bremsstrahlung for electrons

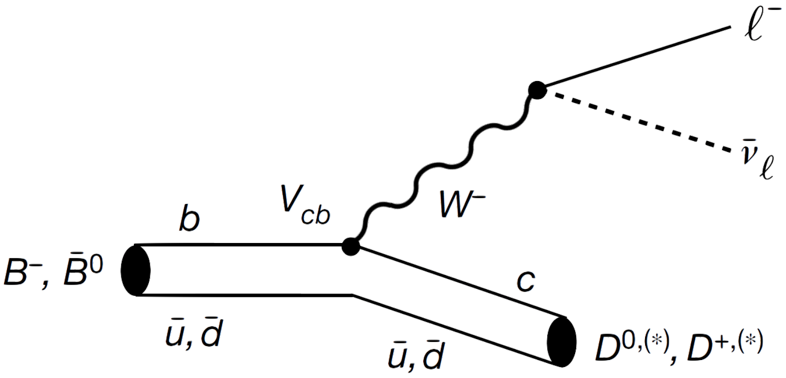


Semileptonic b-decays

- Differential decay rate, dΓ, for semileptonic decays involving D(*):

$$\frac{d\Gamma^{SM}(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2} = \underbrace{\frac{G_F^2|V_{cb}|^2|p^*_{D^{(*)}}|q^2}{96\pi^3 m_B^2}\left(1-\boxed{\frac{m_\ell^2}{q^2}}\right)^2}_{\text{Universal and phase space factors}} \times \underbrace{\left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\boxed{\frac{m_\ell^2}{2q^2}}\right)+\boxed{\frac{3m_\ell^2}{2q^2}}|H_s|^2\right]}_{\text{Hadronic effects}}$$

- **$H_{+,-,0,s}$** are helicity amplitudes:
  - depend on the spin of the charm meson and on q^2
  - only $H_{0,s}$ contribute to D-meson decays (it is a scalar)
- Larger m_τ affects the rate + the kinematics of the decays via H_s amplitude.



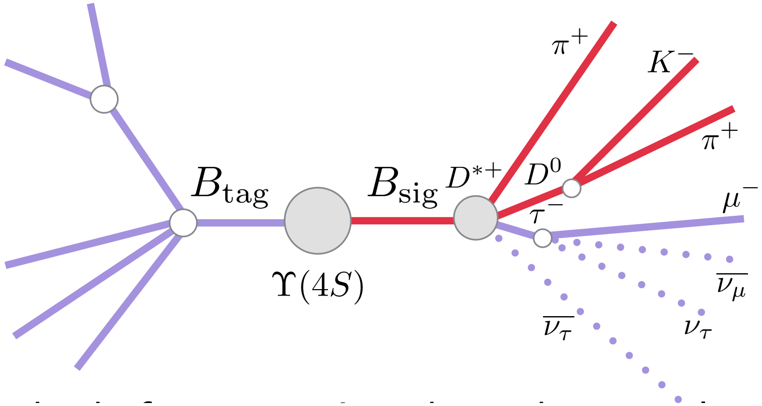
R(D$^{(*)}$) measurement

@ B-factories

- At BABAR and Belle $B\bar{B}$ produced from:

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0(B^+B^-)$$

  - Center of mass fixed
  - Nothing else produced in the event
- Presence of multiple final state neutrinos controlled using *B-tagging*
  - Other B fully reconstructed → measurement of signal B kinematics
  - Signal B + other B should be entire event → strong rejection against other missing reconstructible particles
- Drawback: small efficiency



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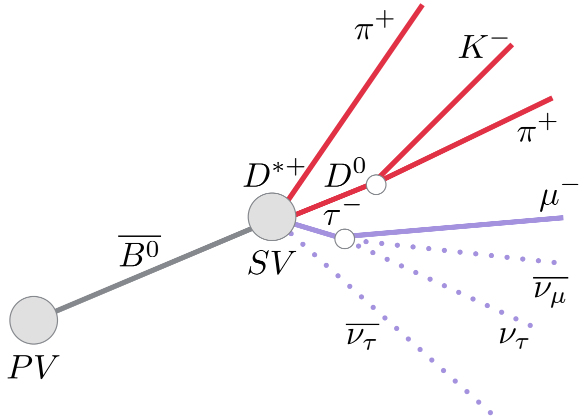
@ LHCb

- At LHCb no B-tagging possible
- Compensate using large boost (flight information) and huge B production
- B flight direction given by PV and SV
- Approximated B momentum along the beam: $p_z = (m/m_{rec})p_{rec,z}$

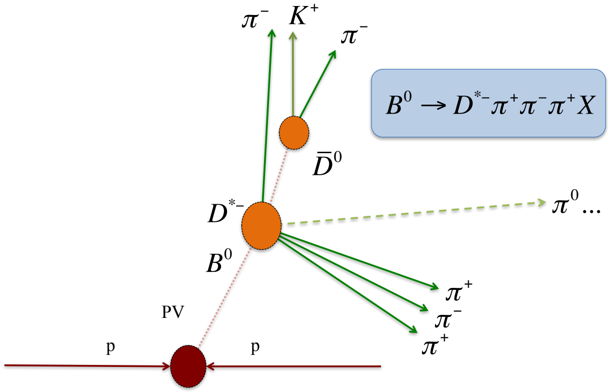


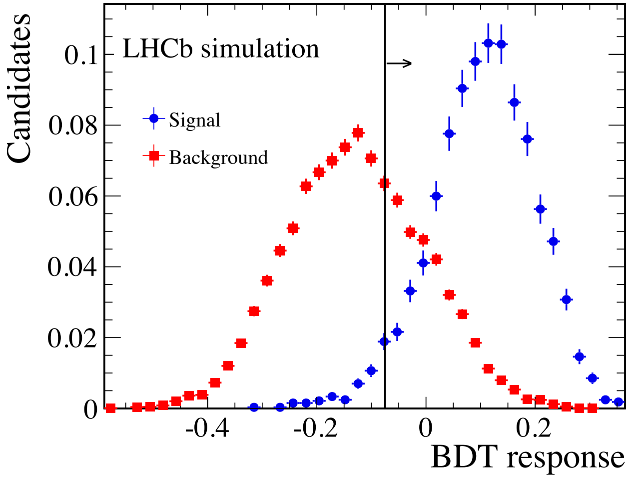
R(D*) hadronic

[PRL 120, 171802 2018], [PRD 97,072013 2018]

- **No charged leptons** in the final state ➙ Major background in R(D*) muonic not present

- **Main backgrounds:**
  - prompt $D^{*}\pi^{+}\pi^{-}\pi^{+}X$ ➙ suppressed by requiring 3π vertex to lie further away than B^0 vertex from *pp* interaction point
  - double-charm $D^{*}D_s$ (X) decays ➙ suppressed with BDT exploiting the different resonant structure of the 3π system + other features





R(J/ψ)

[PRL120(2018)121801]

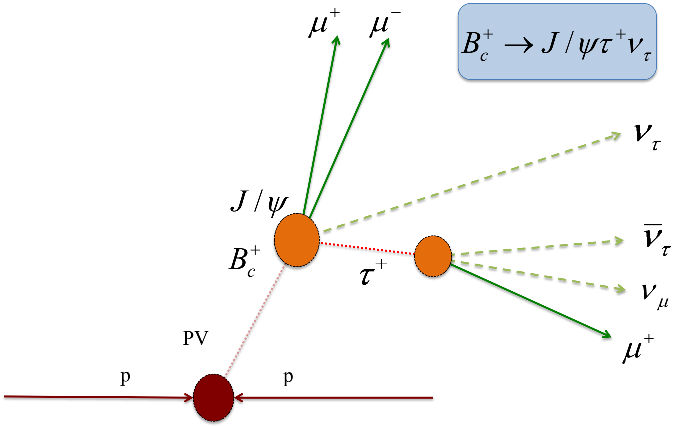
Possible only at LHC

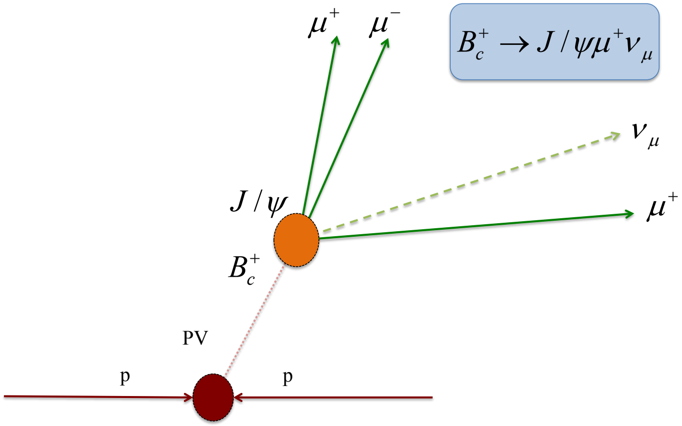
- Semitauonic decays of other *B* hadrons allow to investigate sources of theoretical + exp. uncertainties and origin of lepton non universal couplings
- Test LFU violation in B_c decays:

$$R(J/\psi) = \frac{BR(B_c \to J/\psi\tau(\to \mu\nu\nu)\nu)}{BR(B_c \to J/\psi\mu\nu)} \qquad \text{where: } J/\psi \to \mu^+\mu^-$$

  - Final state with 3 visible muons

- B_c^+ decay form factors unconstrained experimentally: $R^{\text{theo}}(J/\psi) \in [0.25,0.28]$*





* [PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]

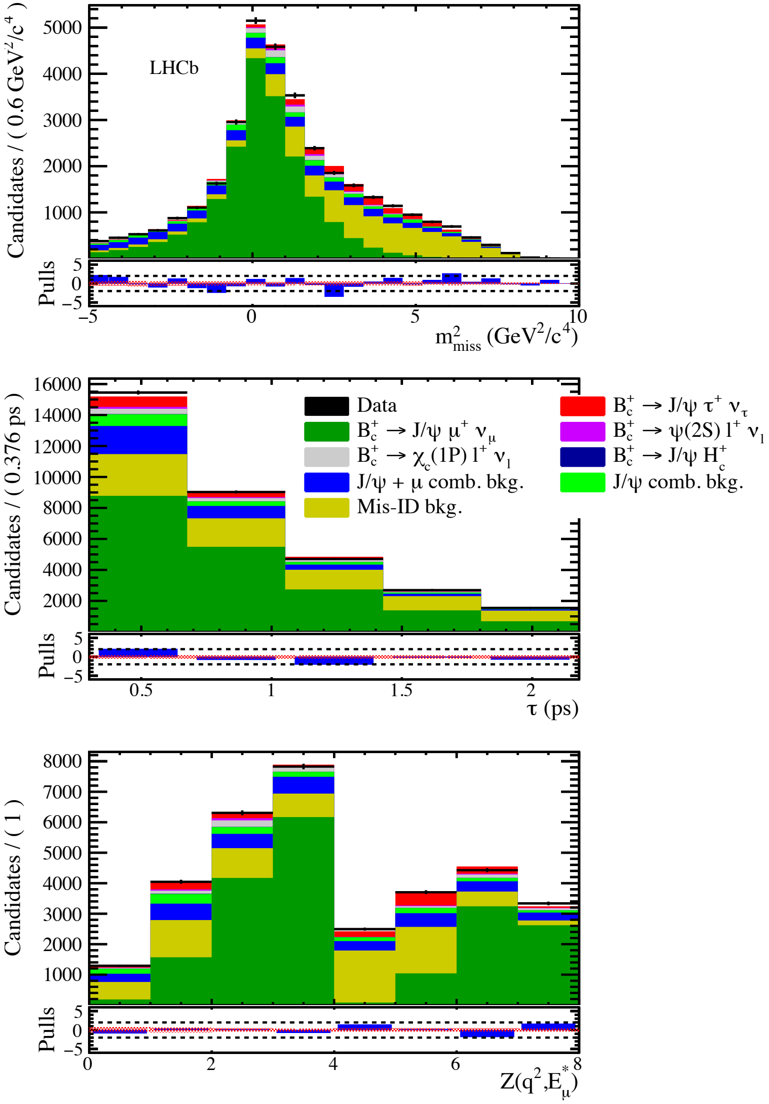
R(J/ψ)

[PRL120(2018)121801]

- Low B_c^+ production rate and short lifetime, but no D background
- Like in $R(D^*)$, used m^2, B^+ decay time (τ) and a categorical quantity z representing 8 bins in (E^*, q^2)
- Main background is $b \rightarrow J/\psi +$ mis-ID hadron
- Main systematics: form factor and size of simulation sample

$R(J/\psi) = 0.71 \pm 0.017 \pm 0.018$

2σ above the SM



NP in $b \to s\ell^+\ell^-$ transition

- Model independent parametrisation of NP:

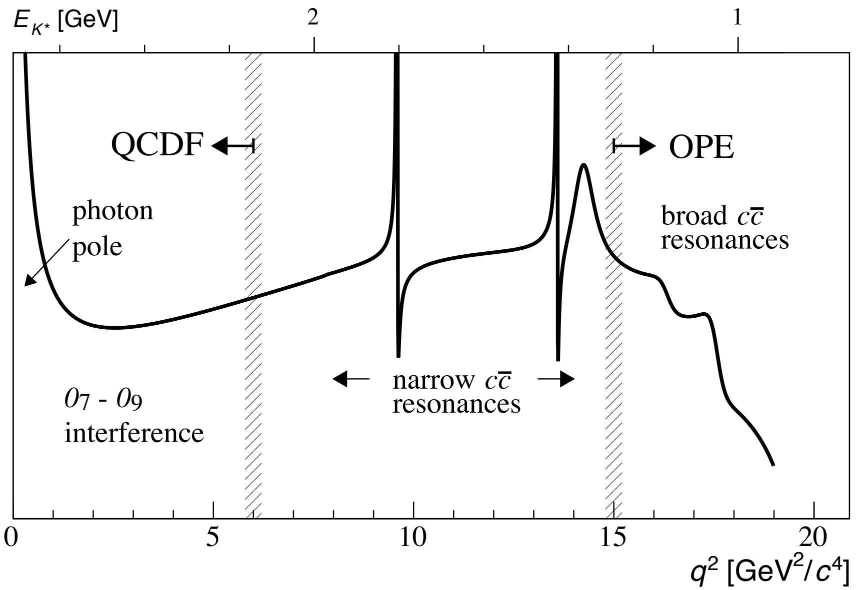
$$\mathscr{L} = \mathscr{L}_{SM} + \sum C_i O_i$$

Effective Hamiltonian

  - C_i **(Wilson Coefficients)** describe interactions at high energy (possible NP sources)
  - operators O_i describe low energy effects

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

Annu. Rev. Nucl. Part. Sci. 65 (2015) 113



Parametrisation of $B^0 \to K^{*0} \mu^+\mu^-$ decay width

- The differential decay width of $B^0 \to K^{*0} \mu^+\mu^-$ can be parametrised in terms of

$$
\begin{aligned}
\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = \; & \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k \\
& +\tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell \\
& +S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi \\
& +\sqrt{F_L(1-F_L)}P_5'\sin 2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell \\
& +S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + S_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi \\
& +S_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi\Big]
\end{aligned}
$$

with **F_L, A_{FB}, S_i =f($C^{(\prime)}_7$,$C^{(\prime)}_9$,$C^{(\prime)}_{10}$)** combinations of K^*_0 decay amplitudes

- Theoretical uncertainty on hadronic form factors ⇒ reduced by moving to optimised observables, e.g.

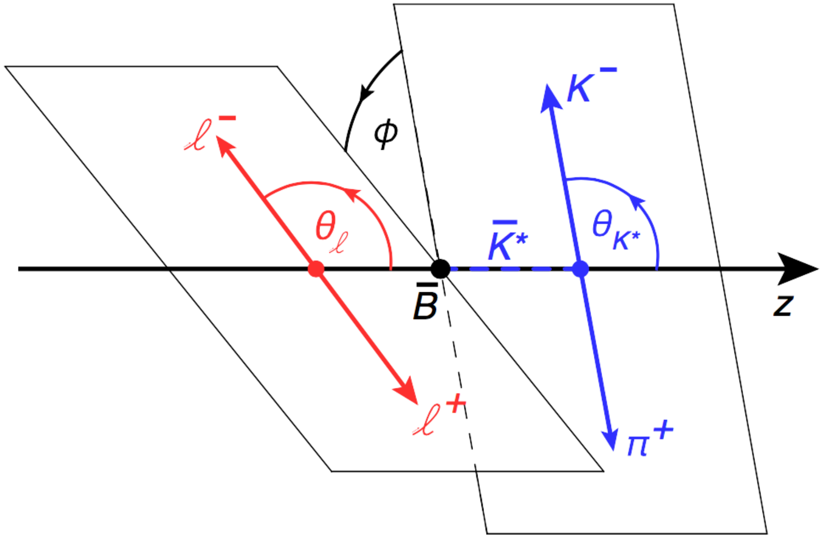
$$
P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2+|A_\parallel|^2)}} = \frac{S_5}{\sqrt{F_L(1-F_L)}}
$$

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

- NP models which explain the observed discrepancies in the measurement of $R(K^{(*)})$ w.r.t SM predictions, foresee anomalous behaviours also in the angular distribution of the decay $B^0 \rightarrow K^{*0} \mu^+\mu^-$

- Vector meson in final state

  ⇨ differential decay width expressed in terms of q^2 + 3 decay angles (θ_l, θ_k, ϕ)



The P_5' anomaly

- One of the angular observables in which the differential decay width can be parametrised is P5′
  - designed to reduce dependence on hadronic form-factors using optimised observables

- Global fit at **3.4 σ** from the SM prediction
- Explainable in terms of:
  - SM charm-loop effects (cannot explain tension in R(K(*))) *
  - New Physics

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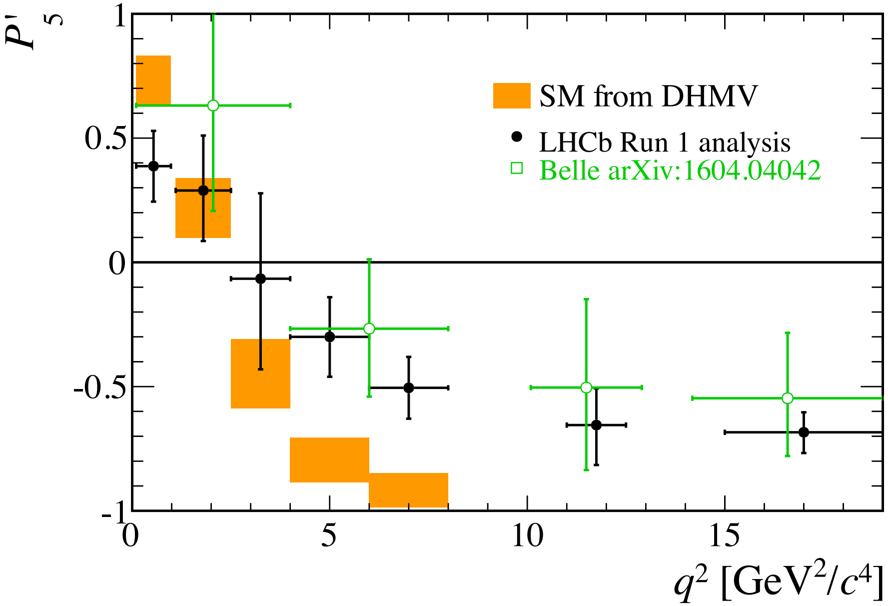
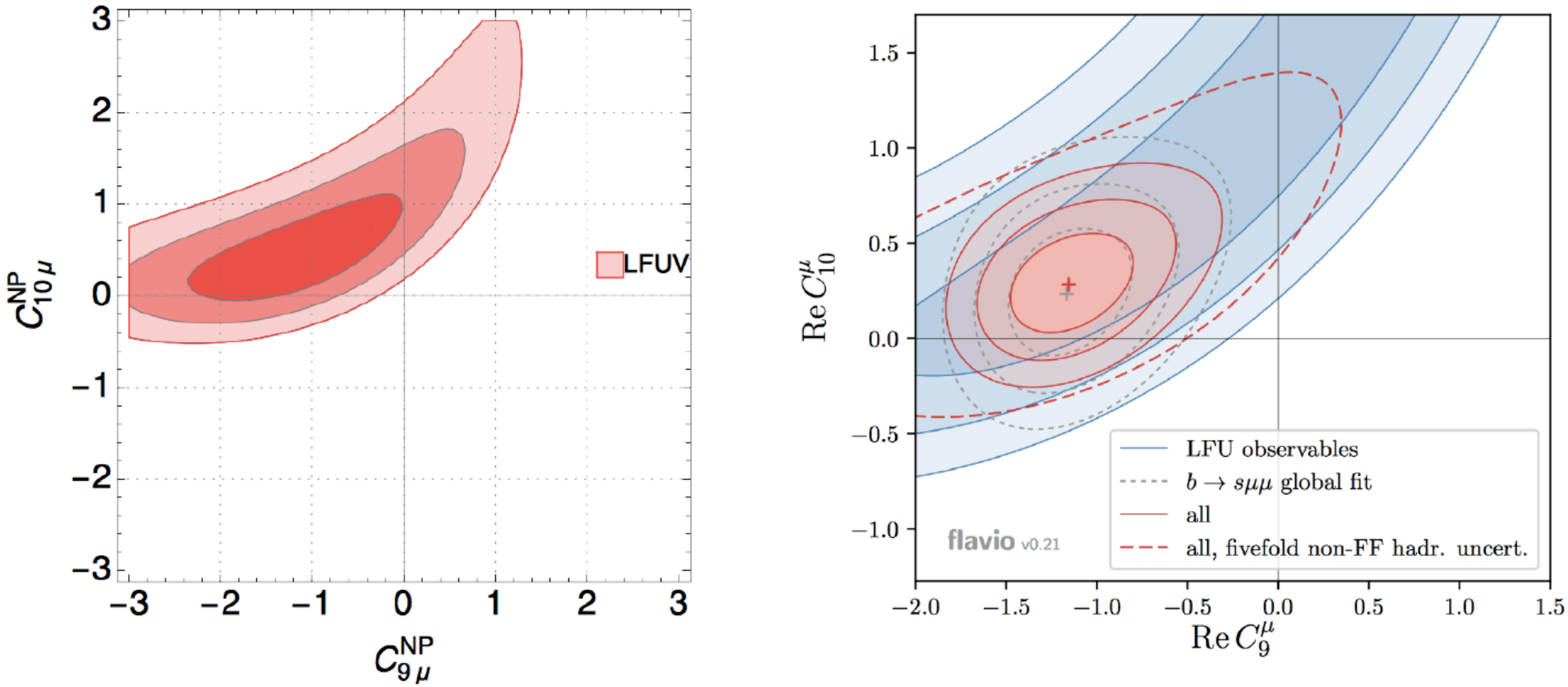


* JHEP 06 (2016) 116

Global fits to $b \to s\ell^+\ell^-$

- Global fits combine all $b \to s\ell^+\ell^-$ observables and suggest a coherent NP pattern as a shift in C_9 (C_9&C_{10})



Future prospects: study of R(Λc)

$$R(\Lambda_c) = \frac{BR(\Lambda_b^0 \to \Lambda_c \tau \nu)}{BR(\Lambda_b^0 \to \Lambda_c \mu \nu)}$$

- First lepton universality measurement with baryons.
- Baryons are spin 1/2 particles → sensitive in different ways to new particles compared to the existing measurements.
- Experimental issues are different if compared to the meson case → independent measurement.
- Two important advantages in using the Λb channel:
  - Branching fraction of muonic decay three times larger than the mesonic case:

$$BR(\Lambda_b^0 \to \Lambda_c \mu \nu) \approx 6\% \qquad BR(B \to \bar{D}^0 \mu \nu) \approx 2\%$$

    - Assuming a similar ratio between τ and μ between the two channels, then:

$$BR(\Lambda_b^0 \to \Lambda_c \tau \nu) \approx 2\% \qquad BR(B \to \bar{D}^0 \tau \nu) \approx (7.7 \pm 2.5) \times 10^{-3}$$

  - The conservation of the baryon number reduces the combination of double charmed hadron production Λ_b decays: only from $\Lambda^0_b \to \Lambda^+_c D_s^-$.