Tests of Lepton Universality at LHCb

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On behalf of the LHCb Collaboration

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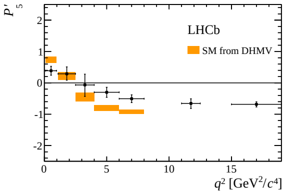
Puzzling Tensions in $b \to s\ell\ell$ Transitions

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

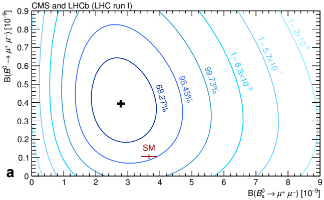
- Angular Observable "P_5'"



LHCb, JHEP 02 (2016) 104, `arxiv:1512.04442`

$B^0_{(s)} \to \mu^+\mu^-$

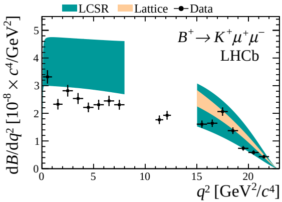
- Ratio of B^0 to B^0_s branching fraction



CMS+LHCb, Nature 522 (2015), `arxiv:1411.4413`

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

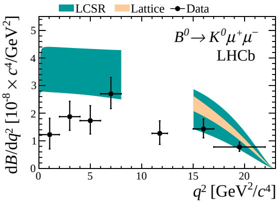
- Differential branching fraction



LHCb, JHEP 06 (2014) 133, `arxiv:1403.8044`

$B^0 \to K^0\mu^+\mu^-$

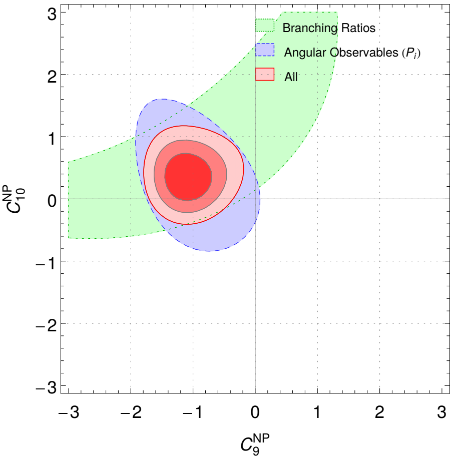
- Differential branching fraction



LHCb, JHEP 06 (2014) 133, `arxiv:1403.8044`

Hints for Lepton Universality Violation?

- Model-independent approach:
  Effective Hamiltonian
- Best fit model has Wilson coefficient
  $C_9^{\text{NP}} \approx -1$ (4 to 5σ)
- What can explain this?
  1. Statistical fluctuations
  2. Not-yet-understood SM effects
  3. New Physics
- Strong case for
  violation of lepton universality

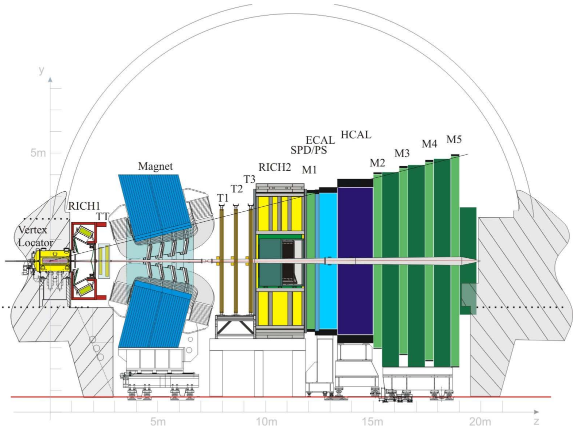


S.Descotes-Genon *et al.*, JHEP 06 (2016) 092
arxiv:1510.04239

This Talk

1. R_K
2. $R(D^*)$
3. $\mathcal{B}(B_s^0 \to \tau^+\tau^-)$ ← **New!**

The LHCb Detector



Forward arm spectrometer to study b- and c-hadron decays

- Pseudo-rapidity coverage: $2 < \eta < 5$

- Good impact parameter resolution to identify secondary vertices: $(15 + 29/p_\mathrm{T})\ \mu\mathrm{m}$
- Invariant mass resolution: $8\ \mathrm{MeV}/c^2$ $(B \to J/\psi X)$ $22\ \mathrm{MeV}/c^2$ $(B \to hh)$
- Excellent particle identification: $95\,\%$ K ID efficiency ($5\,\%$ $\pi \to K$ mis-ID)
- Versatile & efficient trigger for b- and c-hadrons and forward EW signals

R_K

Test of Lepton Univserality: R_K

LHCb, PRL 113 (2014) 151601, arxiv:1406.6482

- Definition

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \quad \xrightarrow{SM} \quad 1 \pm \mathcal{O}\left(10^{-4}\right)$$

C. Bobeth *et al.*, JHEP 07 (2007) 040, arxiv:0709.4174

- Measured relative to their $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$ counterparts
- Determined for the range

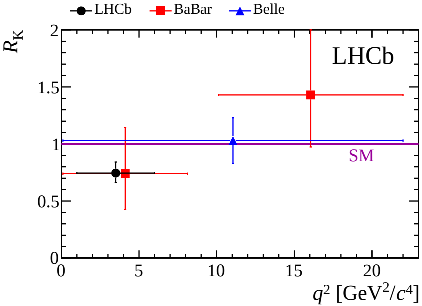
$$1 < q^2 < 6\mathrm{GeV}^2/c^4$$

in momentum transfer q^2 to lepton system

- Using the full Run 1 data

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

- 2.6σ deviation from the SM



$R(D^*)$

Test of Lepton Universality: $R(D^*)$

- Definition

$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

- In the SM, only difference between $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ and $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ is due to dependence on the lepton mass
- Theoretically clean quantity $\to$ accurate SM prediction

$$R(D^*) \overset{\text{SM}}{=} 0.252 \pm 0.003$$

S.Fajfer *et al.*, PRD85 (2012) 094025, arxiv:1203.2654

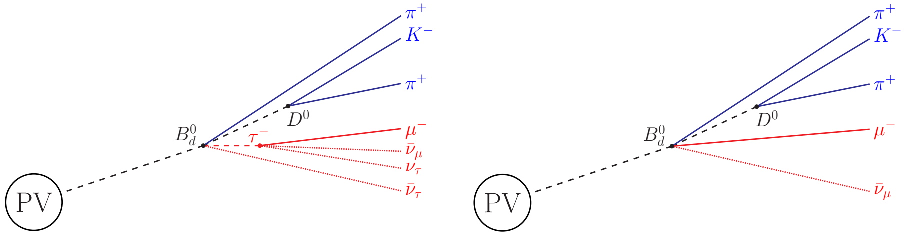
LHCb Analysis for $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$

- Reconstructed in $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ mode
- Reconstructed in leptonic $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ mode

$\to$ Similar to the normalisation mode $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

Experimental Signature

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



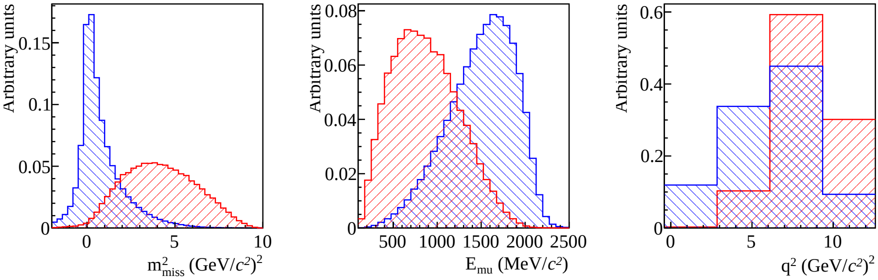
Challenges

1. 3 missing neutrinos
   - No narrow (mass) peak to fit
2. Feeddown from higher D^* resonances
   - Need large MC samples to control the background distributions
3. Large combinatorial background
   - Use isolation variables to suppress or enrich background

Fit Strategy

LHCb, PRL 115 (2015) 111803, arxiv:1506.08614

- Exploit the kinematic differences between the signal and background.
- Perform a 3-dimensional histogram fit to
  1. Missing mass $m^2_{\text{miss}} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$
  2. Muon energy E^*_μ
  3. Four-momentum transfer $q^2 = (p^\mu_B - p^\mu_{D^*})^2$
- Rest-frame quantities calculated using the B's flight direction to estimate the transverse component of missing momentum.



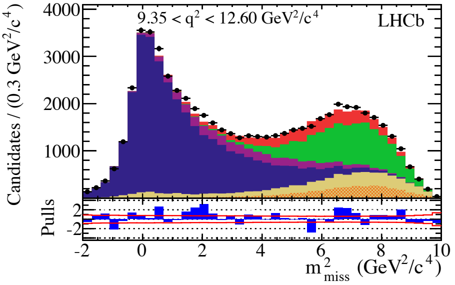
- Legend: $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$

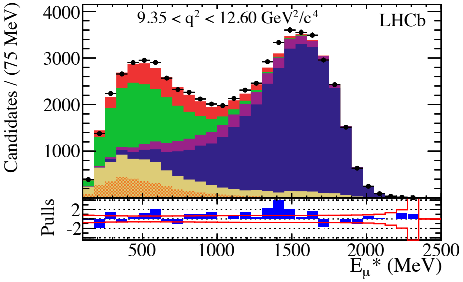
Background Sources

LHCb, PRL 115 (2015) 111803, arxiv:1506.08614

Templates

- $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ Signal [MC]
- $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ Normalisation [MC]
- Combinatorial Background [Data]
- Misidentified μ background [Data]
- Double charm hadrons [MC]
- $B \to D^{**}\ell\nu$ [MC]





- Form factor dependence included in the fit
- Data-driven systematic uncertainties on template shapes

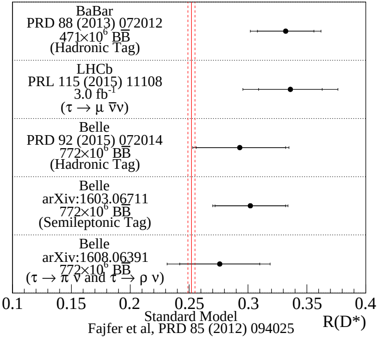
Results

LHCb, PRL 115 (2015) 111803, arxiv:1506.08614

- We measure

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

- 2.1σ deviation from SM
- Good agreement with other measurements

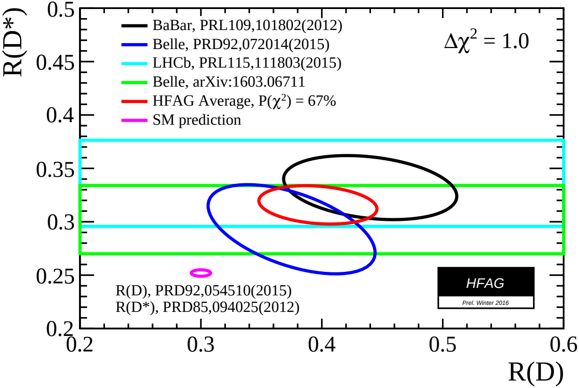


Still to come ...

- Update including $R(D)$
- Measurement of $R(D^*)$ using hadronic $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ decay

Experimental Picture

Heavy Flavour Averaging Group



SM Expectation:

$$R(D^*) = 0.252 \pm 0.003$$
$$R(D) = 0.300 \pm 0.008$$

- 4σ deviation from SM

Experimental Average:

$$R(D^*) = 0.316 \pm 0.016\,(\text{stat}) \pm 0.010\,(\text{syst})$$
$$R(D) = 0.397 \pm 0.040\,(\text{stat}) \pm 0.028\,(\text{syst})$$

*Does not yet include latests result from Belle

Belle, (2016), arxiv:1608.06391

NEW

$\mathcal{B}(B_s^0 \to \tau^+\tau^-)$

Test of Lepton Universality: $\mathcal{B}(B_s^0 \to \tau^+\tau^-)$

- In the SM, only difference between $B_s^0 \to \tau^+\tau^-$ and $B_s^0 \to \mu^+\mu^-$ is due to helicity suppression (lepton mass)
- Theoretically clean quantity $\to$ accurate SM prediction

$$\mathcal{B}(B^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8} \quad (1)$$

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7} \quad (2)$$

Bobeth *et al.*, PRL 96 (2006) 241802, `arxiv:hep-ex/0511015`

- Branching ratio enhanced in many new physics models (leptoquarks, Z', ...)
- Current best limit:

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \quad @\,90\%\ \text{C.L.}$$

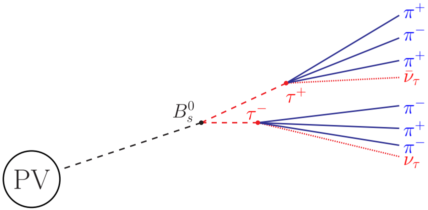
BaBar, PLB 687 (2010) 139, `arxiv:1001.3221`

LHCb Analysis for $B_s^0 \to \tau^+\tau^-$

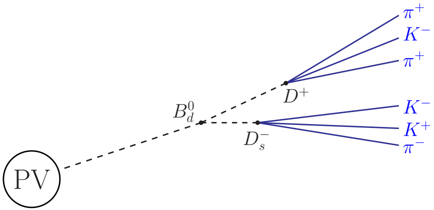
- Reconstructed in hadronic $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ mode (both τs)
- Normalisation mode: $B^0 \to D^+(\to \pi^+K^-\pi^+)D_s^-(\to K^-K^+\pi^-)$

Experimental Signature

$B_s^0 \to \tau^+\tau^-$



$B^0 \to D^+ D_s^-$



Challenges

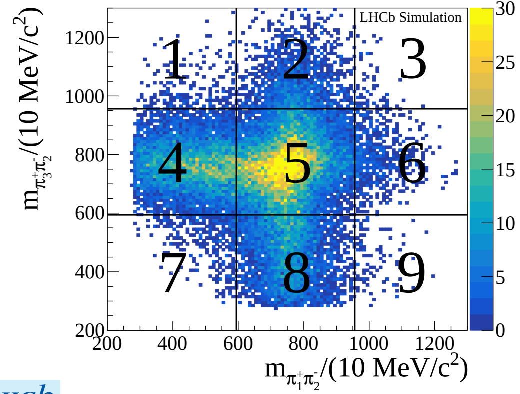
1. 2 missing neutrinos
   - No narrow (mass) peak to fit
   - Cannot differentiate B_s^0 from B^0
2. 6 pions = large combinatorial background
   - Use isolation variables to suppress background
   - Use decay geometry to approximately reconstruct the B and τ properties

Intermediate Resonances

- Predominantly proceeds through

$$\tau^- \to a_1^-(1260)\nu_\tau \to \rho^0(770)\pi^-\nu_\tau \ .$$

- Exploit this in analysis



Subsamples:

- Signal Region [SR]: $(\tau^+ \in 5)\ \&\ (\tau^- \in 5)$
- Background Region [BR]: $(\tau^+ \in 1,3,7,9)\,||\,(\tau^- \in 1,3,7,9)$
- Control Region [CR]: $(\tau^\pm \in 4,5,8)\ \&\ (\tau^\mp \in 4,8)$

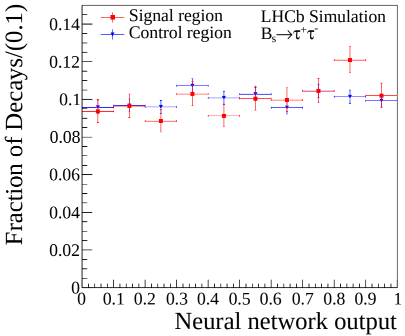
Selection:

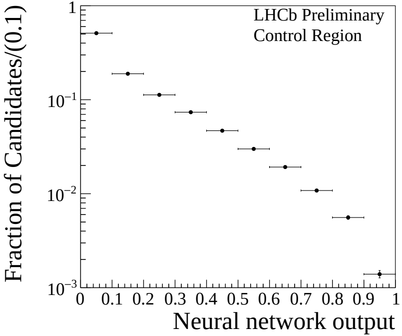
- Cut-based loose selection
- Two-stage neural network

Fit Strategy

LHCb, LHCb-CONF-2016-011

- Perform a 1-dimensional histogram fit to the output of a neural network
- Output is remapped such that signal is flat
- The Signal templates are taken from simulation
- The Background template is taken from data control region





Fit Model

LHCb, LHCb-CONF-2016-011

Events:

Signal: 17% $B_s^0 \to \tau^+\tau^-$ Simulation versus 4.8% data

Background: 11% $B_s^0 \to \tau^+\tau^-$ Simulation versus 44% data

Control: 55% $B_s^0 \to \tau^+\tau^-$ Simulation versus 41% data

- . . . so the data control region might also contain signal.

Model:

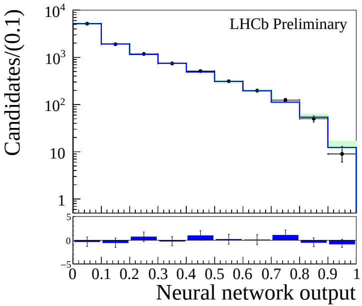
$$\text{NN}_{\text{data}}^{\text{SR}} = s \times \widehat{\text{NN}}_{\text{sim}}^{\text{SR}} + f_b \times \left(\text{NN}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon_{\text{CR}}}{\epsilon_{\text{SR}}} \times \widehat{\text{NN}}_{\text{sim}}^{\text{CR}} \right)$$

- s: signal yield (free parameter)
- f_b: scale factor for background template (free parameter)
- ϵ_i: efficiencies, taken from simulation
- $\widehat{\ }$: indicates normalised distributions

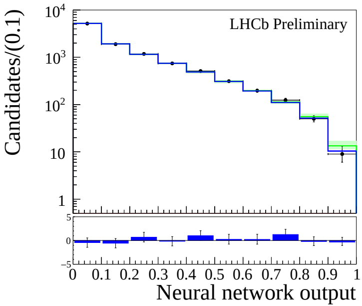
Fit to Data

LHCb, LHCb-CONF-2016-011

Background-Only Model



Nominal Fit Model



$$N^{\text{obs}}_{\tau^+\tau^-} = s = -46 \pm 51$$

- Compatible with the background-only hypothesis

$\rightarrow$ Set an upper limit

From Yield to Branching Ratio

LHCb, LHCb-CONF-2016-011

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = \alpha_s \cdot N^{\text{obs}}_{\tau^+\tau^-} \ ,$$

- Assume all signal comes from $B_s^0 \to \tau^+\tau^-$, i.e. ignore $B^0 \to \tau^+\tau^-$ completely
- Determine α_s using $B^0 \to D^- D_s^+$ normalisation mode

$$\alpha_s = \frac{\epsilon^{D^- D_s^+} \cdot \mathcal{B}(B^0 \to D^- D_s^+) \cdot \mathcal{B}(D^+ \to \pi^+ K^- \pi^+) \cdot \mathcal{B}(D_s^+ \to K^+ K^- \pi^+)}{N^{\text{obs}}_{D^- D_s^+} \cdot \epsilon^{\tau^+\tau^-} \cdot [\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)]^2} \cdot \frac{f_d}{f_s}$$

- Fit to data, Efficiencies from simulation, External Input

$$\alpha_s = (3.16 \pm 0.43) \times 10^{-5} \qquad \to \qquad N^{\text{SM}}_{\tau^+\tau^-} = 0.0245 \pm 0.0037 \qquad (3)$$

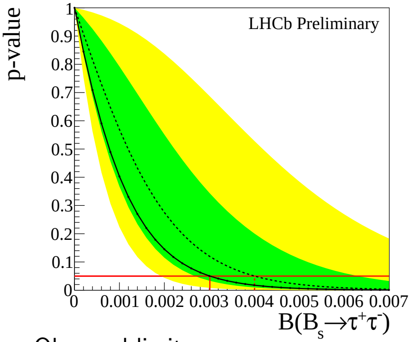
$$\alpha_d = (0.94 \pm 0.16) \times 10^{-5} \qquad \to \qquad N^{\text{SM}}_{\tau^+\tau^-} = 0.0024 \pm 0.0004 \qquad (4)$$

- Model-dependent result based on `EvtGen` simulation of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

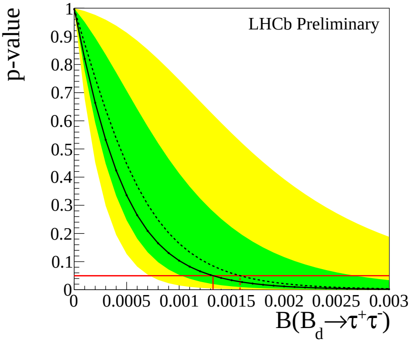
Branching Fraction Limit

LHCb, LHCb-CONF-2016-011

$B_s^0 \to \tau^+\tau^-$



$B^0 \to \tau^+\tau^-$



- Observed limit

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 3.0 \times 10^{-3} \quad @\, 95\,\%\ \text{C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.3 \times 10^{-3} \quad @\, 95\,\%\ \text{C.L.}$$

- Model-dependent result based on `EvtGen` simulation of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

Conclusion

- Ratio of branching fraction involving $B^+ \to K^+\ell^+\ell^-$

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

$\rightarrow$ 2.6σ deviation from the SM

- Ratio of branching fraction involving $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$

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

$\rightarrow$ 2.1σ deviation from the SM

- First limit on the $B_s^0 \to \tau^+\tau^-$ branching ratio **New!**

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 3.0 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.3 \times 10^{-4} \quad @\,95\,\%\ \text{C.L.}$$

- Decays involving τ's play an important role in tests of lepton universality