Flavour Anomalies: What's Cooking in Rare and Semileptonic B Decays?

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IPHC Séminaire Hautes Energies
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The Standard Model . . . and Beyond

Neutrino Masses?

Family Symmetry?

Matter–Anti-Matter Asymmetry?

Standard Model

Strong CP Problem?

Hierarchy Problem?

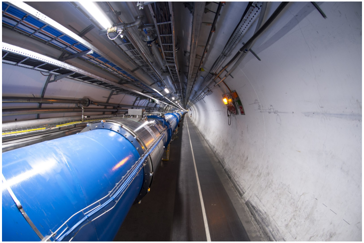
Quantise Gravity & General Relativity?

Neutrinos: Dirac or Majorana?

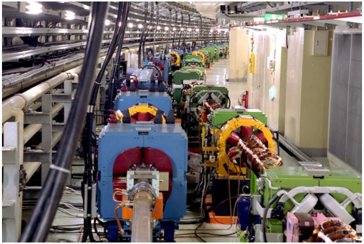
Dark Matter & Dark Energy?

Searching for New Physics

Accelerator-Based High Energy Physics



LHC



SuperKEKB

Two Complementary Strategies:

Direct Searches (Energy Frontier):

Search for new on-shell resonances

- *Bump*-hunting
  - Select x leptons + y jets (= observed decay products)
  - Require some missing energy (= undetected decay products)

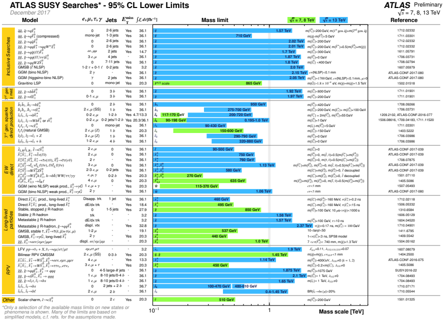
Indirect Searches (Precision Frontier):

Search for anomalies in SM quantities

- Higgs Sector
- (Heavy) Flavour Sector
  - CP Violation & CKM Matrix
  - **Rare & Semileptonic Decays**

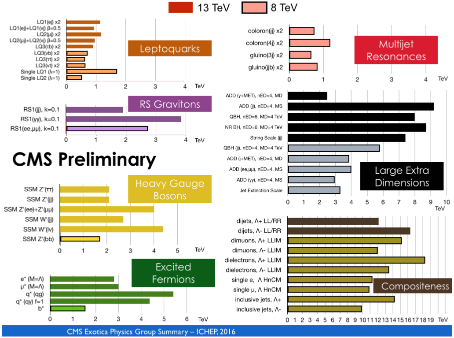
Direct Searches

SUSY Models



ATLAS, December 2017

Other Exotica

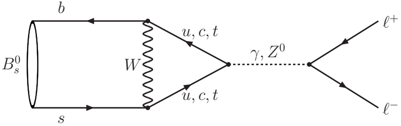


CMS, Summer 2016

- No obvious signals observed yet
- Many limits already surpassing 1 TeV
- Limited by centre-of-mass energy of LHC

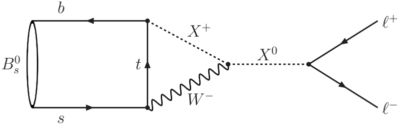
Indirect Searches

Standard Model



? +

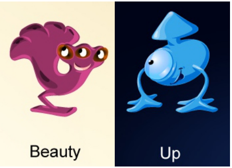
New Physics



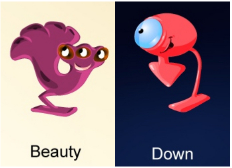
- Sensitive to new virtual contributions
  $\rightarrow$ Both at tree level and in loops
- Can probe energy scales much beyond LHC energy limit
- CP violation effects are largest in transitions involving third generation
- Many NP models predict new heavy particles that prefer coupling to third generation
  $\rightarrow$ Focus on b-hadron decays

B Meson Family

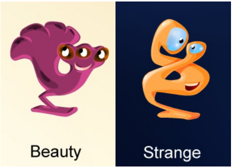
$B^+ = |\bar{b}u\rangle$



$B^0_d = |\bar{b}d\rangle$

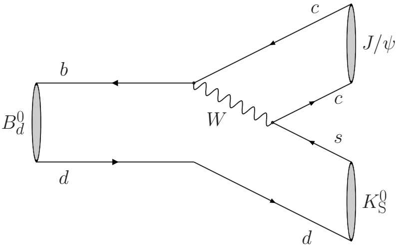


$B^0_s = |\bar{b}s\rangle$



- Unstable particles (lifetime $\approx 1.5 \times 10^{-12}$ seconds)
- More than 250 different decay paths
- Observables: branching fractions, asymmetries, angular correlations, ...
- Allows us to probe many SM parameters

⇒ Perform high precision tests of SM



The Key Players

BaBar

- PEP-II (USA)
- e^+e^- collider
- $\Upsilon(4S) = 10.58$ GeV
- B^+, B_d^0
- 1999 $\to$ 2008

Belle II

- KEKB (Japan)
- e^+e^- collider
- $\Upsilon(4S) = 10.58$ GeV
- $\Upsilon(5S) = 10.89$ GeV
- B^+, B_d^0, (B_s^0)
- 1999 $\to$ 2010
  2018 $\to$ . . .

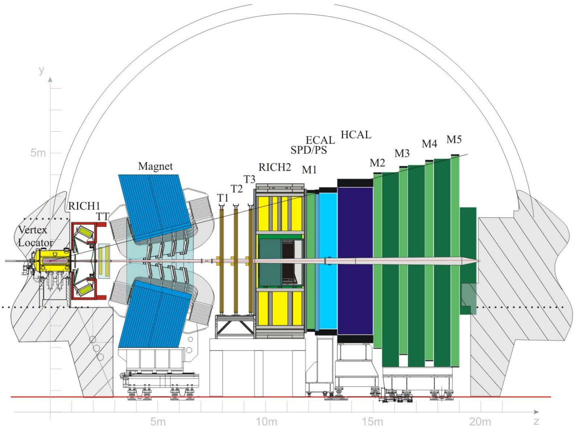
LHCb

- LHC (Switzerland)
- pp collider
- 7,8, & 13 TeV
- B^+, B_d^0, B_s^0, B_c^+, Λ_b
- 2010 $\to$ . . .

Focus on the LHCb results

The LHCb Detector

JINST 3 (2008) S08005

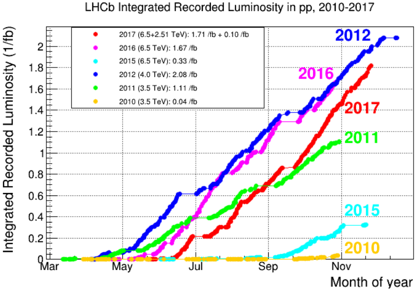


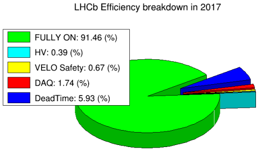
Forward arm spectrometer to study b- and c-hadron decays

- 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

The LHCb Detector Performance



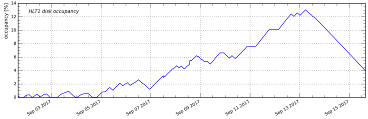


Innovative Run 2 Trigger Strategy:

- During Fill:
  - Run Trigger Stage 1
  - Temporarily buffer events to disk
  - Real-time detector alignment and calibration
- Interfill: Run Trigger Stage 2

⇒ Remove online ↔ offline differences

- **Run 1:** 2010 → 2012
  3.23 fb^{-1} collected at 7+8 TeV
- **Run 2:** 2015 → 2018
  3.71 fb^{-1} collected at 13 TeV
- Most results shown are Run 1 only.
- Run 2 updates are still work in progress



- Example: Disk usage (early September 2017)

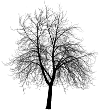
Today's Menu

- **Semileptonic $b \to c\ell^- \bar{\nu}_\ell$ Decays**
  - $R(D^*)$: $B_d^0 \to D^{*-}\tau^+\nu_\tau$ Muonic Mode
  - $R(D^*)$: $B_d^0 \to D^{*-}\tau^+\nu_\tau$ Hadronic Mode
  - $R(J/\psi)$: $B_c^+ \to J/\psi\tau^+\nu_\tau$
- **Rare $b \to s\ell^+\ell^-$ Transitions**
  - $B \to \mu^+\mu^-$
  - R_K & R_{K^*}: $B^+ \to K^+\ell^+\ell^-$ and $B_d^0 \to K^{*0}\ell^+\ell^-$
  - $b \to s\mu^+\mu^-$ differential branching ratios
  - P_5': $B_d^0 \to K^{*0}\mu^+\mu^-$
  - Global Fits

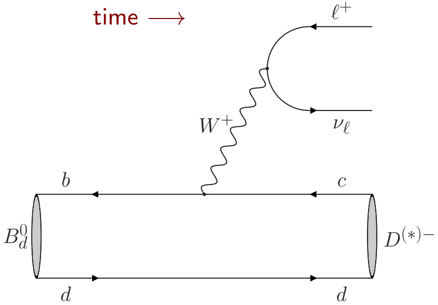
Semileptonic $b \to c\ell^- \bar{\nu}_\ell$ Decays

Semileptonic $b \to c\ell^-\bar{\nu}_\ell$ Decays

Tree-Level Transitions



1. $B_d^0 \to D^{(*)-} e^+ \nu_e$
2. $B_d^0 \to D^{(*)-} \mu^+ \nu_\mu$
3. $B_d^0 \to D^{(*)-} \tau^+ \nu_\tau$



Standard Model Decays

- Relatively simple final state
- Theoretically well understood
- No difference in behaviour between the lepton families $\ell^+ \in \{e^+, \mu^+, \tau^+\}$

Lepton Flavour Universality

Semileptonic $b \to c\ell^-\bar{\nu}_\ell$ Decays

Lepton Flavour Universality

- Accurate predictions for the $B_d^0 \to D^{(*)-}\ell^+\nu_\ell$ branching ratios
- **Only** difference is the lepton mass
- Allows us to test Lepton Flavour Universality

→ Ratio of branching fractions ($\ell^+ \in \{e^+, \mu^+\}$)

$$R(D) \equiv \frac{\mathcal{B}(B_d^0 \to D^-\tau^+\nu_\tau)}{\mathcal{B}(B_D^0 \to D^-\ell^+\nu_\ell)} \stackrel{\text{SM}}{=} 0.300 \pm 0.008 \,, \qquad R(D^*) \equiv \frac{\mathcal{B}(B_d^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B_d^0 \to D^{*-}\ell^+\nu_\ell)} \stackrel{\text{SM}}{=} 0.252 \pm 0.003$$

FLAG, EPJC77 (2017) 112, `arxiv:1607.00299`

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

Challenging Measurements for LHCb:

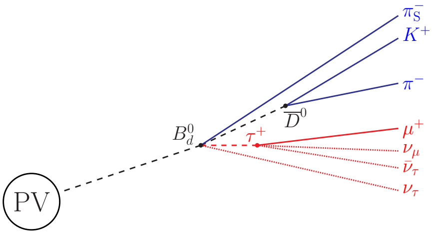
1. Missing energy due to neutrino(s) in the final state
   - No narrow (mass) peak to fit
2. Feed down from higher D^* resonances
   - Need large MC samples to control the background distributions
3. Large combinatorial background
   - Use isolation variables to suppress or enrich background

→ $B_d^0 \to D^{*-}\ell^+\nu_\ell$ is experimentally easier than $B_d^0 \to D^-\ell^+\nu_\ell$

$R(D^*)$ – Muonic Mode

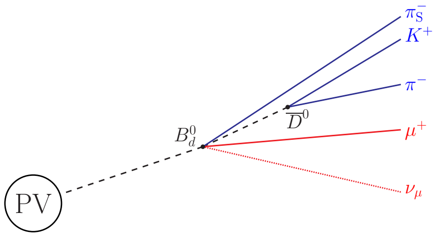
- $\approx 2/3$ of the times D^{*-} decays into $D^0\pi_S^-$
- The presence of this slow pion (π_S^-) is very useful to suppress background

$B_d^0 \to D^{*-}\tau^+\nu_\tau$



- Reconstructed $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$

$B_d^0 \to D^{*-}\mu^+\nu_\mu$

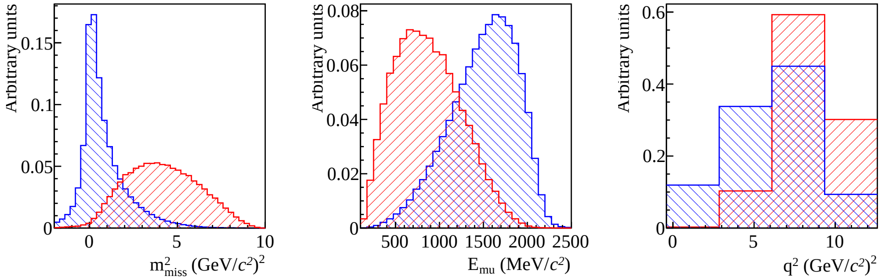


- Normalisation Mode
- ...and largest background
- But difference in kinematic distributions

$R(D^*)$ – Muonic Mode: 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.

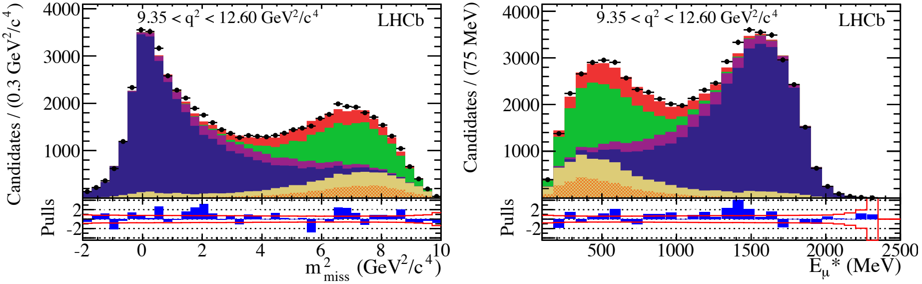


- Legend: $B^0_d \to D^{*-}\mu^+\nu_\mu$ $B^0_d \to D^{*-}\tau^+\nu_\tau$

$R(D^*)$ – Muonic Mode: Fit Result

LHCb, arxiv:1506.08614

- Form factor dependence included in the fit
- Data-driven systematic uncertainties on template shapes
- Fit result for most significant q^2 bin

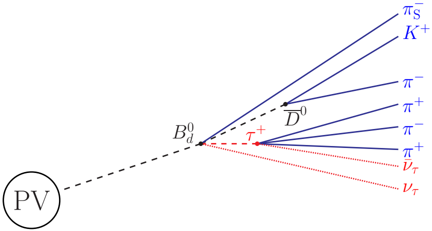


Legend

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

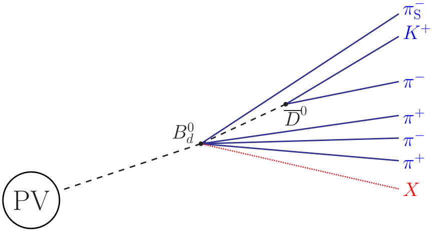
$R(D^*)$ – Hadronic Mode

$B_d^0 \to D^{*-}\tau^+\nu_\tau$



- Reconstructed $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- Exploit flight distance of τ:
  Require $\Delta z > 4\sigma_{\Delta z}$

$B_d^0 \to D^{*-}\pi^+\pi^-\pi^+X$



- Normalisation $= B_d^0 \to D^{*-}\pi^+\pi^-\pi^+$
- $D^{*-}3\pi(+X)$ background $\approx$ 100 signal
- $D^{*-}D$ background $\approx$ 10 signal
  with contribution from $D_s^0 > D^+ > D^0$

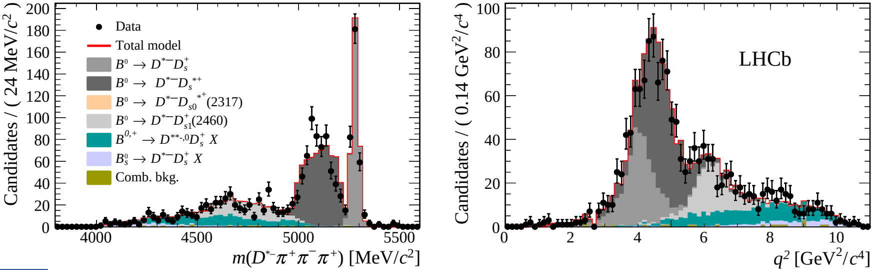
- Different normalisation mode requires slightly different tactic

$$R(D^*) = \frac{\mathcal{B}(B_d^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B_d^0 \to D^{*-}\pi^+\pi^-\pi^+)} \times \frac{\mathcal{B}(B_d^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B_d^0 \to D^{*-}\ell^+\nu_\ell)}$$

$R(D^*)$ – Hadronic Mode: Fit Strategy

LHCb, arxiv:1708.08856

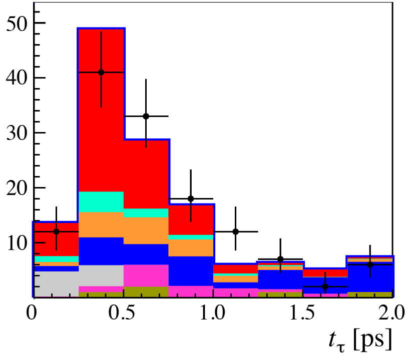
- Perform a 3-dimensional histogram fit to
  1. Four-momentum transfer $q^2 = (p^\mu_B - p^\mu_{D^*})^2$
  2. τ lifetime t_τ
  3. BDT classifier output
- Classifier validated using $B \to D^{*-}\{D_s^+, D^0, D^+\}X$ data samples
- Background templates are constrained from dedicated fits to control samples
- Example: $D^{*-} D_s^+ X$ control mode

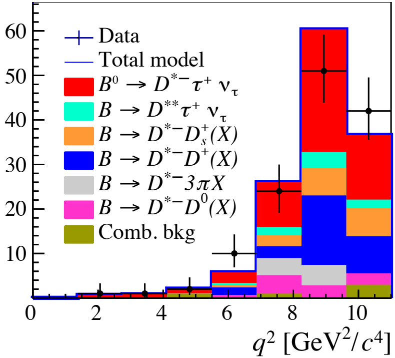


$R(D^*)$ – Hadronic Mode: Fit Result

LHCb, arxiv:1708.08856

- Fit result for the most significant BDT bin





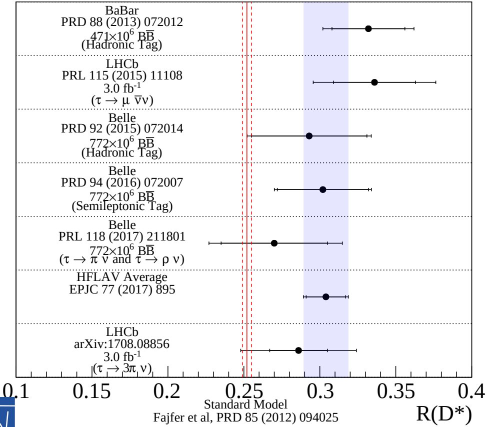
- Form factor and τ polarisation dependence treated as systematic uncertainties
- Dominant systematic uncertainty comes from limited sample size in simulation

$\to$ Description of signal and background templates, efficiencies

Summary on $R(D^*)$

LHCb Contribution

$$R(D^*)_{\text{Muonic}} = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$
$$R(D^*)_{\text{Hadronic}} = 0.286 \pm 0.019\,(\text{stat}) \pm 0.025\,(\text{syst}) \pm 0.021\,(\text{ext})$$

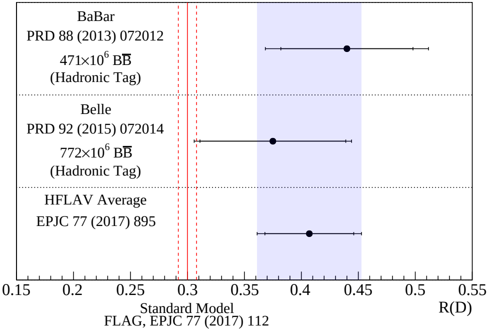


Overview

- 3 different experiments: BaBar, Belle & LHCb
- Different decay channels
- Different techniques
- **All** above the SM prediction
- Significance: $3.4\,\sigma$

Summary on $R(D)$

- More challenging due to feed down from excited D^{**} resonances
- Final state entwined with $B_d^0 \to D^{*-}\ell^+\nu_\ell \Rightarrow$ large correlation

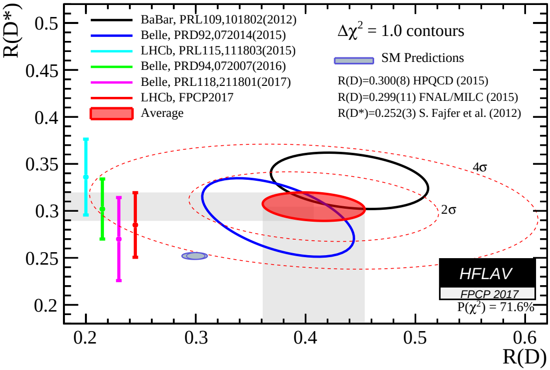


Overview

- 2 different experiments: BaBar & Belle
- **Both** above the SM prediction
- Significance: $2.3\,\sigma$
- LHCb is also planning a measurement

Combined $R(D^*)$–$R(D)$ Fit

4.1 σ deviation from SM



SM Expectation:	Experimental Average:	Sig.
$R(D^*) = 0.252 \pm 0.003$	$R(D^*) = 0.304 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})$	$3.4\,\sigma$
$R(D) = 0.300 \pm 0.008$	$R(D) = 0.407 \pm 0.039\,(\text{stat}) \pm 0.024\,(\text{syst})$	$2.3\,\sigma$
FLAG, arxiv:1607.00299	HFLAV, arxiv:1612.07233	
S. Fajfer *et al.*, arxiv:1203.2654		

$R(J/\psi)$: $B_c^+ \to J/\psi\tau^+\nu_\tau$

LHCb, arxiv:1711.05623

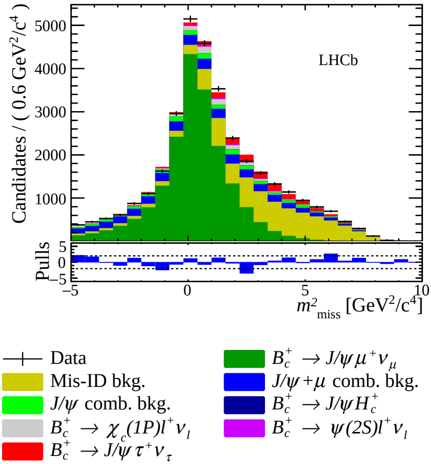
- What about other semileptonic ratios?
- Try

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

- Analysis follows same procedure as $R(D^*)$ – muonic mode
- We observe $B_c^+ \to J/\psi\tau^+\nu_\tau$ with 3σ significance
- Result:

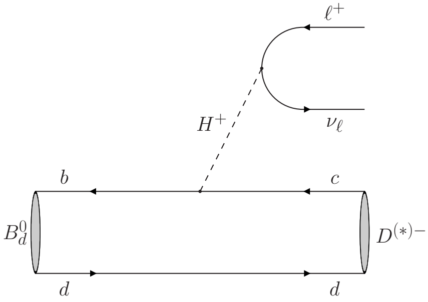
$$R(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

- Standard Model predictions in the range $[0.25, 0.28]$
- Significance: $< 2\sigma$



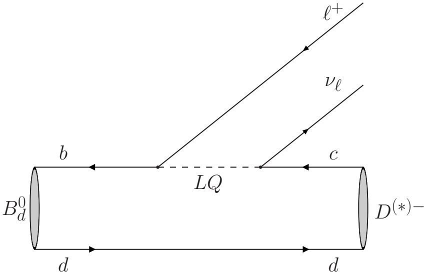
Possible New Physics Explanations

2 Higgs Doublet Models



- Model now contains 5 Higgs particles
- Charged Higgs interaction

LeptoQuark Models



- Model allows direct interaction between quarks and leptons

Rare $b \to s\ell^+\ell^-$ Transitions

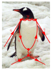
Rare $b \to s\ell^+\ell^-$ Transitions

Flavour Changing Neutral Current

- Forbidden at Tree level in the Standard Model

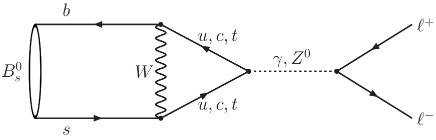
$\Rightarrow$ Loop suppressed

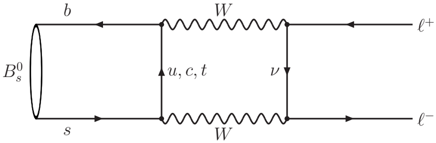
- Sensitive to new physics contributions



Penguin Topologies

Box Topologies

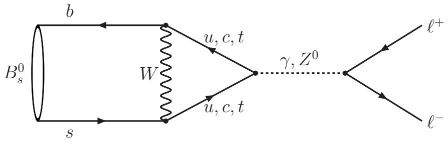




The Decay $B \to \mu^+\mu^-$

Theory Calculations

- Only leptons in the final state
- Theoretically well understood
- Accurate SM predictions



$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) \overset{\text{SM}}{=} (1.06 \pm 0.09) \times 10^{-10}\,, \qquad \mathcal{B}(B_s^0 \to \mu^+\mu^-) \overset{\text{SM}}{=} (3.65 \pm 0.23) \times 10^{-9}$$

Bobeth *et al.*, PRL 112 (2014) 101801, arxiv:1311.0903

- Special interest: the ratio $\mathcal{B}(B_d^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
  (Is there New Physics? Is it *minimal flavour violating* or not?)

Experimental Status

- Active search since '80s
- 2014: First observation of $B_s^0 \to \mu^+\mu^-$ using LHC Run 1 data
  CMS+LHCb, Nature 522 (2015) 68, arxiv:1412.6433
- Latest update from LHCb: 3 fb^{-1} Run 1 + 1.4 fb^{-1} of Run 2

$B \to \mu^+\mu^-$: In a Nutshell

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747

Overview

- Selection based on: BDT + particle identification (PID)
  - → BDT output is flat for signal, calibrated on $B_d^0 \to K^+\pi^-$
  - → BDT output peaks towards zero for background, calibrated on mass sidebands
  - → PID requirements suppress peaking $B \to h^+h^-$ background
- Fit the $m_{\mu^+\mu^-}$ mass in bins of BDT output
- Normalisation based on control channels: $B^+ \to J/\psi K^+$ and $B_d^0 \to K^+\pi^-$
- (= Same strategy as for the Run 1 CMS+LHCb analysis)

Exclusive Backgrounds

- Decays with two real muons
  - $B_c^+ \to J/\psi\mu^+\nu_\mu$
  - $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
- Decays with hadrons misidentified as muons
  - $B \to h^+h^-$ (peaking in signal region)
  - $B_d^0 \to \pi^-\mu^+\nu_\mu$
  - $B_s^0 \to K^-\mu^+\nu_\mu$
  - $\Lambda_b^0 \to p\mu^+\nu_\mu$

$B \to \mu^+\mu^-$: Fit Strategy

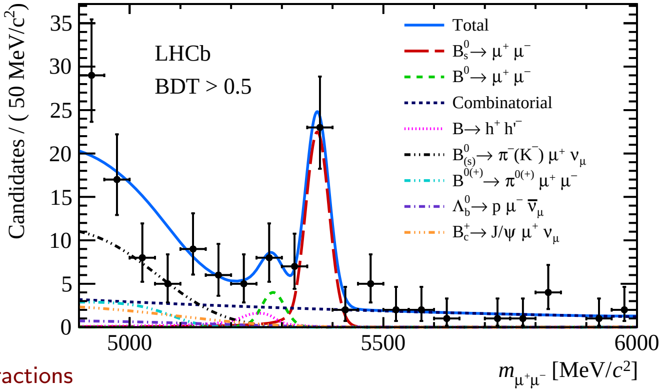
LHCb, PRL 118 (2017) 191801, arxiv:1703.05747

Mass Fit

- Unbinned maximum likelihood fit in 4 bins of BDT output
- $m_{\mu^+\mu^-} \in [4900, 6000]$ MeV$/c^2$
- Exclude BDT$<$ 0.25 (background dominated)
- Simultaneous fit of Run 1 and Run 2 data
- Free parameters: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, $\mathcal{B}(B_d^0 \to \mu^+\mu^-)$ and comb. bkg.
  - LHCb's excellent mass resolution allows to separate B_d^0 and B_s^0 signals
- Exclusive background are all individually included, with constrained yields.

$B \to \mu^+\mu^-$: Mass Fit

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747



Branching Fractions

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,(\text{stat})\,^{+0.2}_{-0.1}\,(\text{syst})) \times 10^{-10} \qquad (1.6\sigma)$$

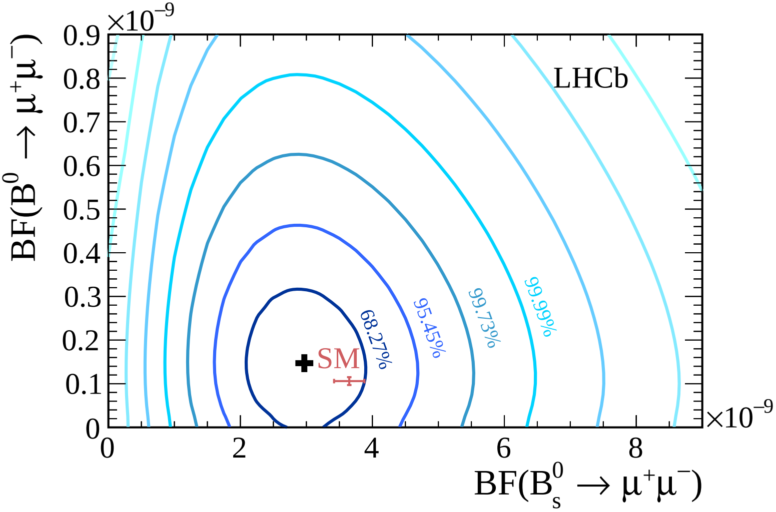
Branching Fraction Limit (CL_s Method)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \quad @\,95\,\%\text{ C.L.}$$

$B \to \mu^+\mu^-$: 2D Contours

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747

- Good agreement with the SM expectation
- But better precision is needed regarding $\mathcal{B}(B_d^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$



$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

- Even if $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM}$, NP can still hide in this decay
- Need a second, complementary observable to find it:

  either CP asymmetry parameter $\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}$ or effective lifetime $\tau_{\mu^+\mu^-}$

- Defined as

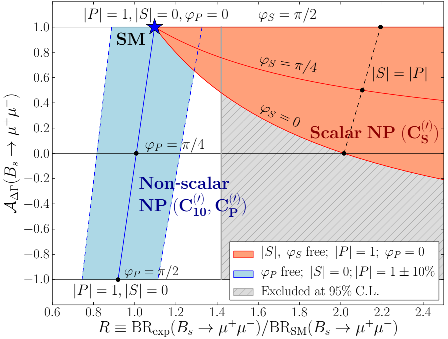
$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\langle\Gamma(B_s(t) \to \mu^+\mu^-)\rangle \mathrm{d}t}{\int_0^\infty \langle\Gamma(B_s(t) \to \mu^+\mu^-)\rangle \mathrm{d}t}$$

- They are related

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2\,\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}y_s + y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right]$$

- where

$$y_s \equiv \tau_{B_s}\Delta\Gamma_s/2 = 0.062 \pm 0.006$$



K. De Bruyn *et al.*, PRL 109 (2012) 041801

arxiv:1204.1737

$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747

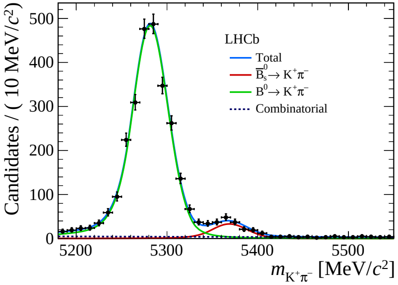
Analysis Strategy

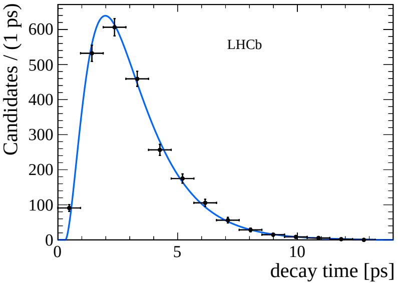
- Apply same selection, but looser cuts
- Reduces mass window $m_{\mu^+\mu^-} \in [5320, 6000]$ MeV/c^2
- Step 1: Mass fit to derive weights (sPlot technique)
- Step 2: Fit to weighted decay time distribution
- Strategy validated on $B_d^0 \to K^+\pi^-$

$$\tau_{B_d^0} = 1.52 \pm 0.03\,(\text{stat})\ \text{ps}$$

- Compare to

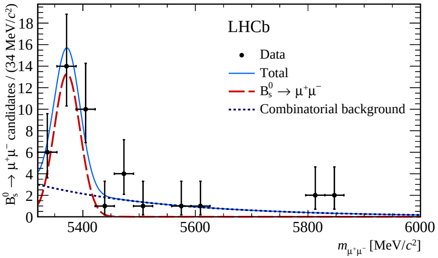
$$\tau_{B_d^0}^{\text{PDG}} = 1.520 \pm 0.004\ \text{ps}$$

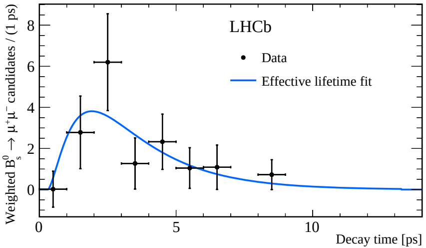




$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

LHCb, PRL 118 (2017) 191801, arxiv:1703.05747





Results

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44\,(\text{stat}) \pm 0.05\,(\text{syst})\text{ ps}$$

- Consistent with both $\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} = 1$ (1σ) and $\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} = -1$ (1.4σ)
- Does not yet constrain any NP models

The Decays $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$

Testing Lepton Flavour Universality

- Compare the branching ratios for electrons and muons
- Theoretically very precisely known

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{\to} 1, \qquad R_{K^*} = \frac{\mathcal{B}(B_d^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B_d^0 \to K^{*0}e^+e^-)} \overset{\text{SM}}{\to} 1$$

- Measured in bins of q^2, where q^2 = mass of the $\ell^+\ell^-$ system
- Measured as a double ratio ($J/\psi \to \ell^+\ell^-$ is lepton flavour universal)

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

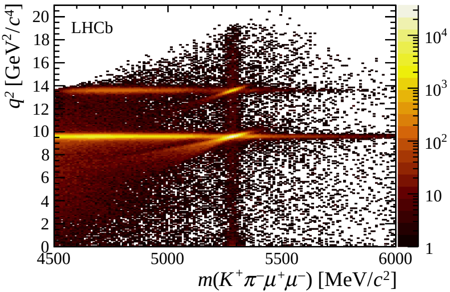
- This substantially reduces the systematic uncertainties
- And allows the cross check

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} \to 1$$

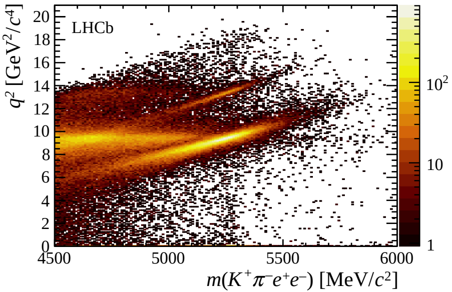
$B_d^0 \to K^{*0}\ell^+\ell^-$: Reconstructing Electrons

LHCb, arxiv:1406.6482

Muon Final State



Electron Final State

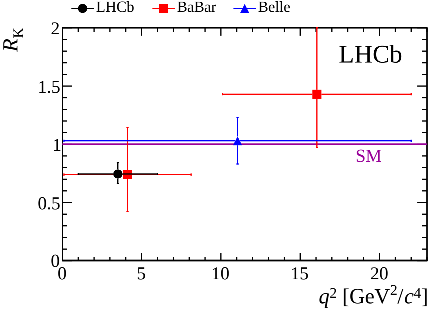


1. Trigger: Muon Stations ($\mu^\pm$) $\leftrightarrow$ Calorimeter ($e^\pm$)
   - Tighter constraints on electron E_T than on muon p_T
   - Also trigger on the K^{*0} or independent of signal
2. Electrons more affected by bremsstrahlung
   - Search for associated photons in the calorimeter
   - More background contamination
   - Worse mass resolution

$\rightarrow$ $\epsilon_{ff}(B_d^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}) \approx 5 \times \epsilon_{ff}(B_d^0 \to J/\psi(\to e^+e^-)K^{*0})$

$B^+ \to K^+\ell^+\ell^-$ and $B^0_d \to K^{*0}\ell^+\ell^-$: Results

R_K : $B^+ \to K^+\ell^+\ell^-$

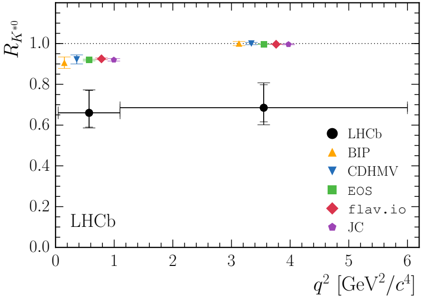


LHCb, PRL 113 (2014) 151601, `arxiv:1406.6482`

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

- Significance: 2.6σ

R_{K^*} : $B^0_d \to K^{*0}\ell^+\ell^-$



LHCb, JHEP 08 (2017) 055, `arxiv:1705.05802`

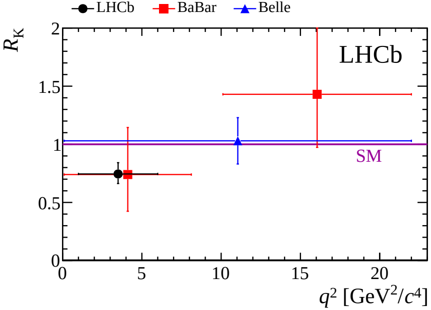
$$R_{K^*}|_{[0.045,1.1]} = 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

$$R_{K^*}|_{[1.1,6.0]} = 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

- Significance: 2.2σ + 2.5σ

$B^+ \to K^+\ell^+\ell^-$ and $B_d^0 \to K^{*0}\ell^+\ell^-$: Results

R_K : $B^+ \to K^+\ell^+\ell^-$

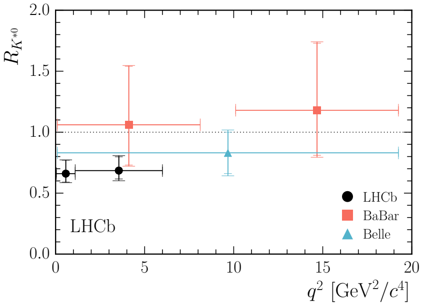


LHCb, PRL 113 (2014) 151601, arxiv:1406.6482

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

- Significance: 2.6σ

R_{K^*} : $B_d^0 \to K^{*0}\ell^+\ell^-$



LHCb, JHEP 08 (2017) 055, arxiv:1705.05802

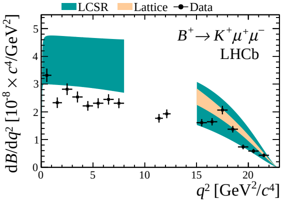
$$R_{K^*}|_{[0.045,1.1]} = 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

$$R_{K^*}|_{[1.1,6.0]} = 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

- Significance: $2.2\sigma + 2.5\sigma$

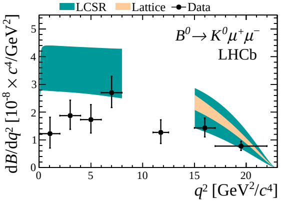
Other $b \to s\mu^+\mu^-$ Branching Fractions

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



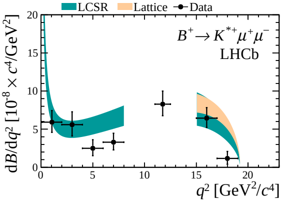
- Also used for R_K

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



- Also used for R_{K^*}

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



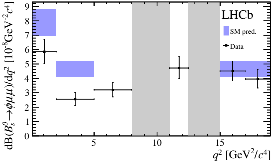
LHCb, JHEP 06 (2014) 133, arxiv:1403.8044

- Measure branching fractions as a function of q^2
- All are below the theory predictions

$\Rightarrow$ Same trend as for R_K and R_{K^*}

- For $B_s^0 \to \phi\mu^+\mu^-$ in bin $1 < q^2 < 6$ GeV^2:
- Significance: $> 3\sigma$

$B_s^0 \to \phi\mu^+\mu^-$

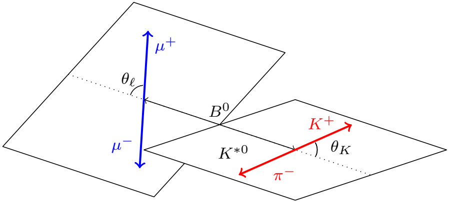


LHCb, JHEP 09 (2015) 179, arxiv:1506.08777

The Decay $B_d^0 \to K^{*0}\mu^+\mu^-$ (yet again)

Angular Observables

- K^{*0} is a Spin 1 particle
- Angular correlations between the decay products



- Many additional observables to look at, complementing the branching fraction
- Of interest here: the one named "P_5'" (optimised for NP searches)

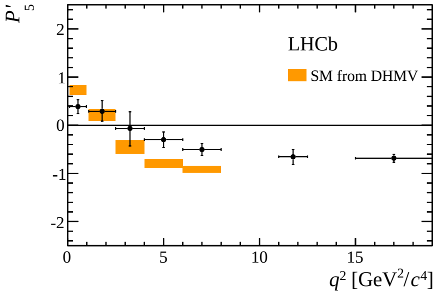
$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

- F_L = fraction of longitudinal polarisation K^*
- S_5 = q^2-dependent CP average associated with 5th spherical harmonic

The Decay $B^0 \to K^{*0}\mu^+\mu^-$ (yet again)

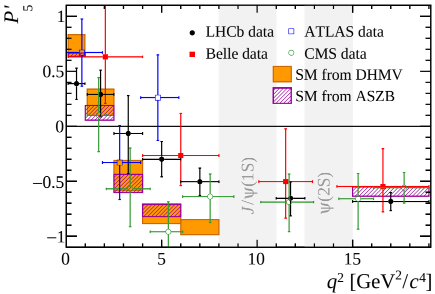
- Measured by 4 different experiments: Belle, LHCb, ATLAS, CMS
- Most precise measurement from LHCb

LHCb Only



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

All Together



Belle, arxiv:1604.04042

ATLAS, ATLAS-CONF-2017-023

CMS, CMS-PAS-BPH-15-008

- Significance: 3.4 σ
  - Ongoing discussion about the interpretation and theory predictions
  - Situation is not as clear cut as for the R-measurements
  - See also LHCb, EPJC 77 (2017) 161, arxiv:1612.06764

Puzzling Tensions in $b \to s\ell^+\ell^-$ Transitions

The Pieces

- R_K, R_{K^*}, Branching fractions, P_5'

The Puzzle

- Individual "discrepancies" only have significance between 2 and 3 σ
- Can simply be statistical fluctuations

⇒ Why the excitement?

- They do seem to point in the same direction ...
- So what if ... we put all the pieces together?

Effective Field Theory Framework

- Describe all decays in a model-independent way: Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \frac{\overbrace{G_F}^{\text{Fermi Constant}}}{\sqrt{2}} \sum_{j=u,c} \underbrace{V_{jd}^* V_{jb}}_{\text{CKM Elements}} \left[\sum_k \underbrace{(C_k^{\text{SM}} + C_k^{\text{NP}})}_{\text{Wilson Coefficients}} \overbrace{\mathcal{O}_k}^{\text{Operator}} + C_k' \mathcal{O}_k' \right]$$

G. Buchalla *et al.*, RMP 68 (1996) 1125, `arxiv:9512380[hep-ph]`

- Does not favour any particular New Physics model
- Matching to specific NP models can be done later

Ingredients:

- Coupling constants & CKM elements
- Wilson coefficients contain all perturbative short-distance effects
  - ⇒ For specific models: Can be calculated within perturbation theory
  - ⇒ C_k^{NP} **Free parameters** in the fit to the data
- Operators contain all non-perturbative long-distance effects
  - Electromagnetic operator: $\mathcal{O}_7$ ($b \to s\gamma$ transitions)
  - Semileptonic operators: $\mathcal{O}_9$ (vector) and $\mathcal{O}_{10}$ (axial-vector)
  - Primed operators have mirrored (L ↔ R) chirality

Global Fit of $b \to s\ell^+\ell^-$ and $b \to s\gamma$ Transitions

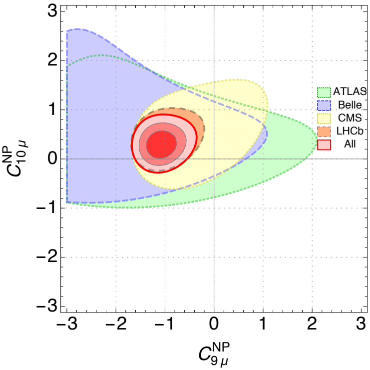
- Performed by many groups

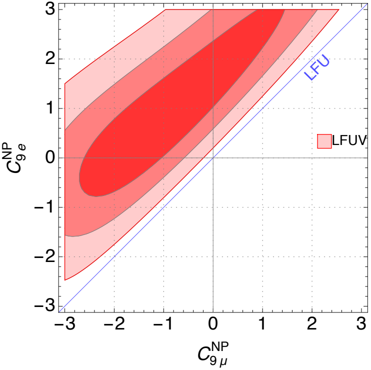
See for example overview here

- All obtain the same best fit model:

$$C_9^{\text{NP}} = -1$$

- Significance: $\approx 5\,\sigma$ (depending on group)
- And suggests lepton universality violation

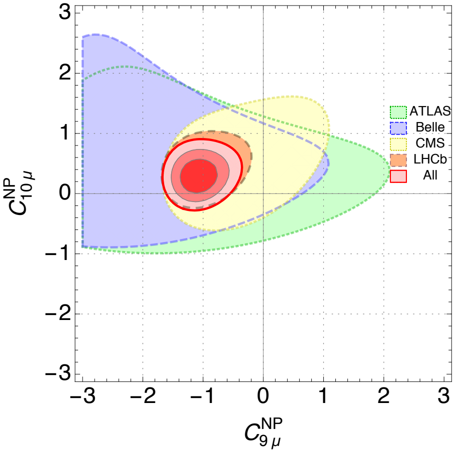




B. Capdevila *et al.*, JHEP 01 (2018) 093, arxiv:1704.05340

Hints for New Physics?

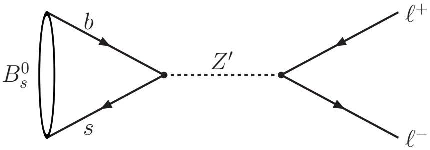
- What can explain this?
  1. Statistical fluctuations
  2. Not-yet-understood SM effects
  3. New Physics
- Way forward?
  - Increase the statistics
  - Additional observables
  - Additional decay channels



B. Capdevila *et al.*, JHEP 01 (2018) 093, `arxiv:1704.05340`

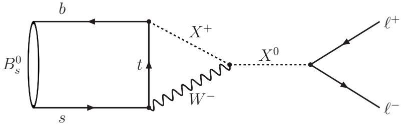
Possible New Physics Explanations

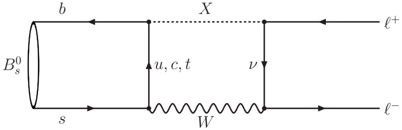
Z'-Models



- New tree level processes

2HDM or LeptoQuarks





- Additional loop contributions

The Real Challenge

- Simultaneously explain the tensions in $R(D^*)$–$R(D)$ and $b \to s\ell^+\ell^-$ transitions
  - New physics at tree-level and at loop-level

$\Rightarrow$ Required NP contributions differ orders of magnitude

Conclusion

- Possible first hints for beyond the SM physics
- Discrepancy in $R(D^*)$–$R(D)$
- Puzzling tensions in $b \to s\ell^+\ell^-$ transitions
- Somethings is cooking ... hopefully it's New Physics!

Additional Slides

Search for the Rare Decays $B \to \tau^+\tau^-$

- 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

$$\mathcal{B}(B_d^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7}$$

Bobeth *et al.*, PRL 112 (2014) 101801, `arxiv:1311.0903`

- Current best limit:

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

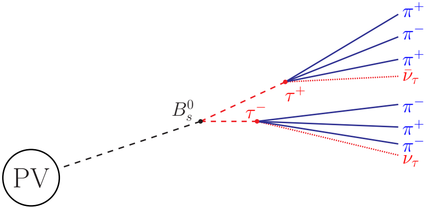
BaBar, PRL 96 (2006) 241802, `arxiv:hep-ex/0511015`

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

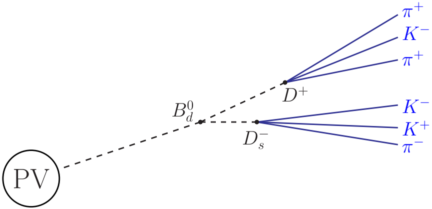
- Reconstructed in hadronic $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ mode (both τs)
  $\to$ Low efficiency: $\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau) = (9.31 \pm 0.05)\%$
- Normalisation mode: $B_d^0 \to D^+(\to \pi^+K^-\pi^+)D_s^-(\to K^-K^+\pi^-)$

$B \to \tau^+\tau^-$: Experimental Signature

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



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



Challenges

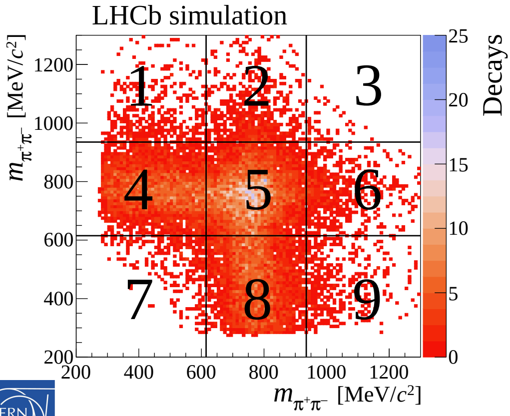
1. 2 missing neutrinos
   - No narrow (mass) peak to fit
   - Cannot differentiate B_s^0 from B_d^0
2. 6 pions = large combinatorial background
   - Use isolation variables to suppress background
   - Use decay geometry to approximately reconstruct the B and τ properties

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

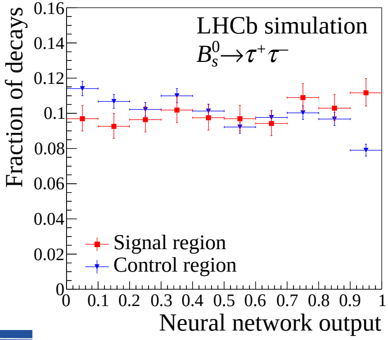
Selection:

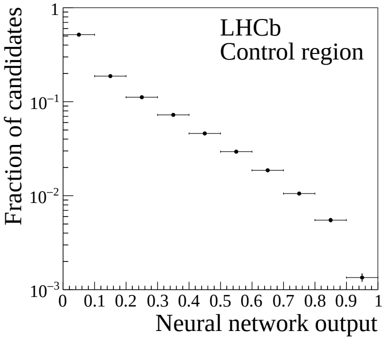
- Cut-based loose selection
- Two-stage neural network

$B \to \tau^+\tau^-$: Fit Strategy

LHCb, PRL 118 (2017) 251802, arxiv:1703.02508

- 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





$B \to \tau^+\tau^-$: Fit Model

LHCb, PRL 118 (2017) 251802, arxiv:1703.02508

Events:

Signal: 16% $B_s^0 \to \tau^+\tau^-$ Simulation versus 7% data

Sig.-Depleted: 13% $B_s^0 \to \tau^+\tau^-$ Simulation versus 37% data

Control: 58% $B_s^0 \to \tau^+\tau^-$ Simulation versus 47% data

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

Model:

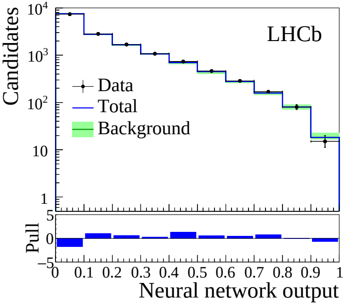
$$\mathcal{N}_{\text{data}}^{\text{SR}} = s \times \widehat{\mathcal{N}}_{\text{sim}}^{\text{SR}} + f_b \times \left(\mathcal{N}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon_{\text{CR}}}{\epsilon_{\text{SR}}} \times \widehat{\mathcal{N}}_{\text{sim}}^{\text{CR}} \right)$$

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

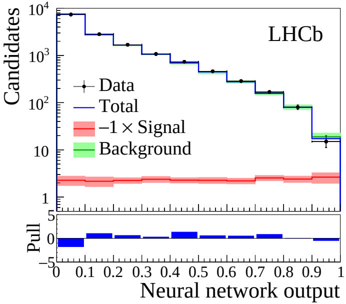
$B \to \tau^+\tau^-$: Fit to Data

LHCb, PRL 118 (2017) 251802, arxiv:1703.02508

Background-Only Model



Nominal Fit Model



$$N^{\text{obs}}_{\tau^+\tau^-} = s = -23 \pm 71$$

- Compatible with the background-only hypothesis

→ Set an upper limit

$B \to \tau^+\tau^-$: From Yield to Branching Ratio

LHCb, arxiv:1703.02508

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

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

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

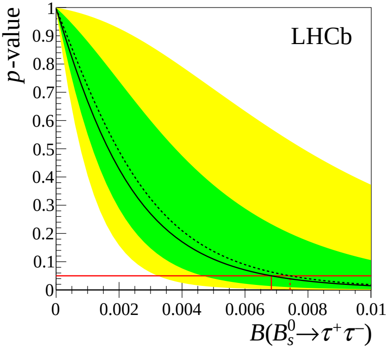
- Fit to data, Efficiencies from simulation, External Input

$$\alpha^s = (4.07 \pm 0.70) \times 10^{-5} \quad \to \quad N^{\text{SM}}_{\tau^+\tau^-} = 0.019$$

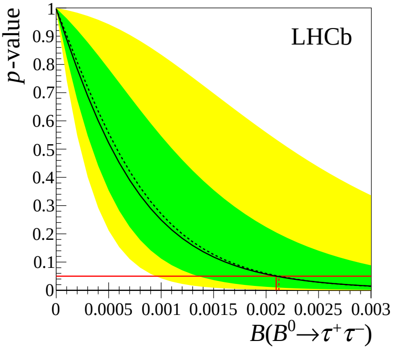
$$\alpha^d = (1.16 \pm 0.19) \times 10^{-5} \quad \to \quad N^{\text{SM}}_{\tau^+\tau^-} = 0.002$$

$B \to \tau^+\tau^-$: Branching Fraction Limit LHCb, PRL 118 (2017) 251802, arxiv:1703.02508

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



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



Branching Fraction Limit (CL$_s$ Method)

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$

$$\mathcal{B}(B_d^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$