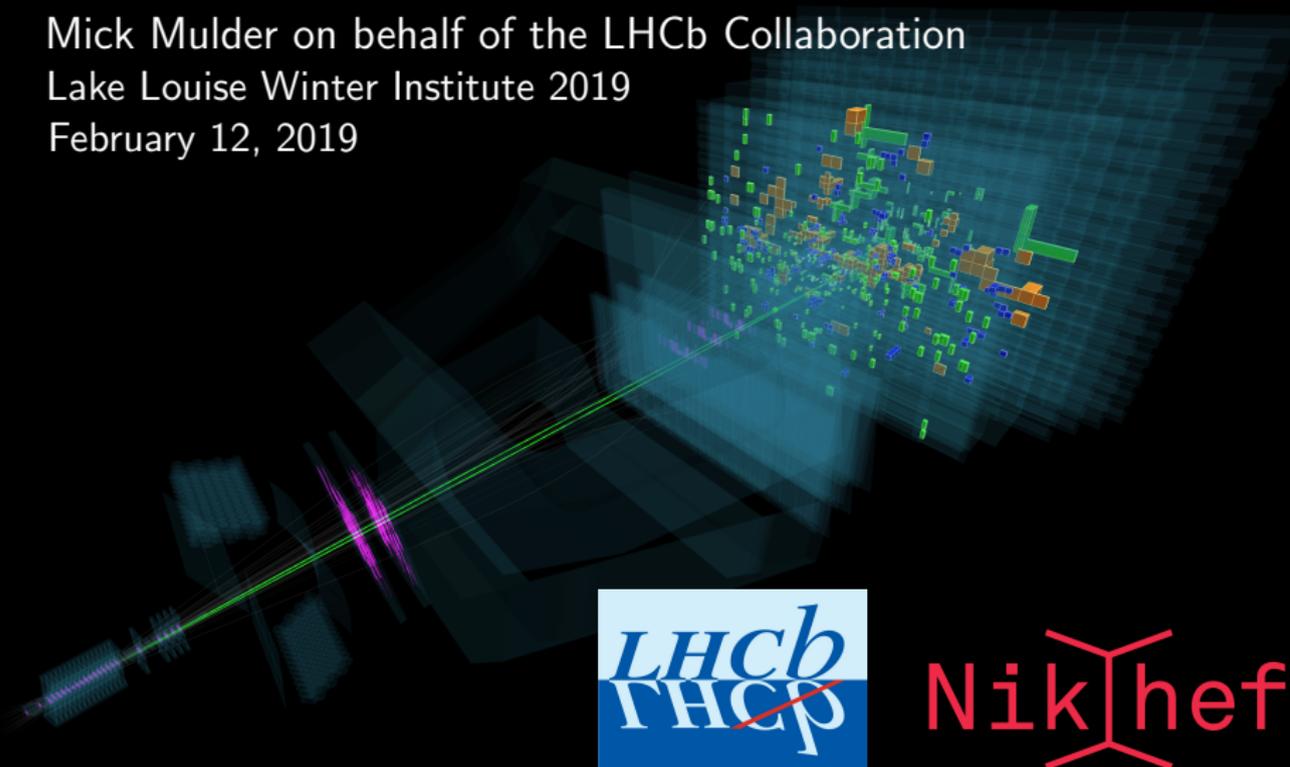


Lepton flavour universality tests at LHCb

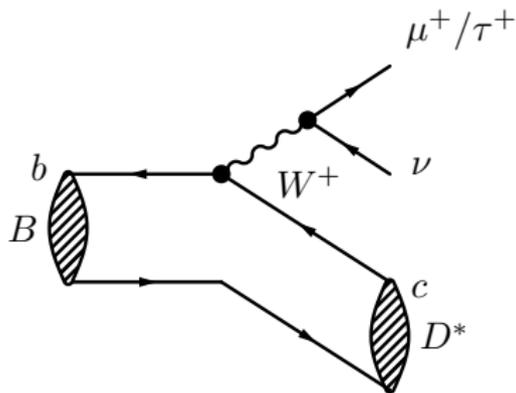
Mick Mulder on behalf of the LHCb Collaboration
Lake Louise Winter Institute 2019
February 12, 2019



LFU in B-decays

Flavour changing charged current:

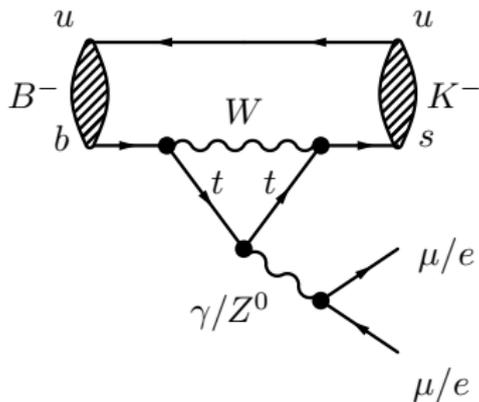
$$b \rightarrow cl\nu_\ell$$



- Tree level decay in SM
- BF $\sim 10^{-2} \rightarrow$ **abundant**
- Compare τ with μ/e mode

Flavour changing neutral current:

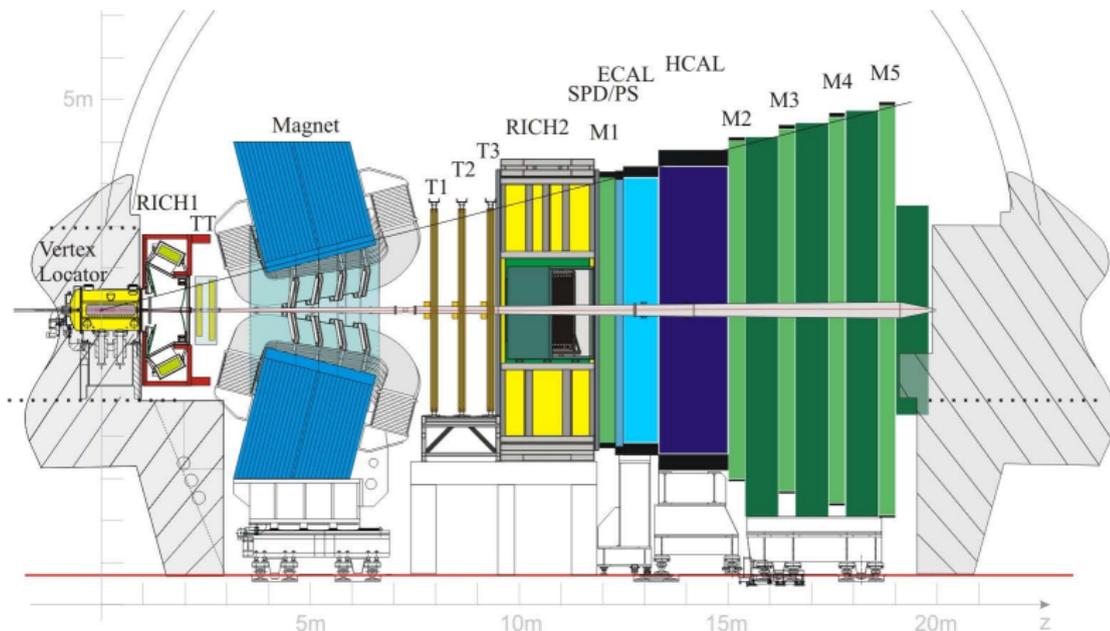
$$b \rightarrow sll$$



- Loop level decay in SM
- BF $\sim 10^{-6} \rightarrow$ **rare**
- Compare μ with e mode

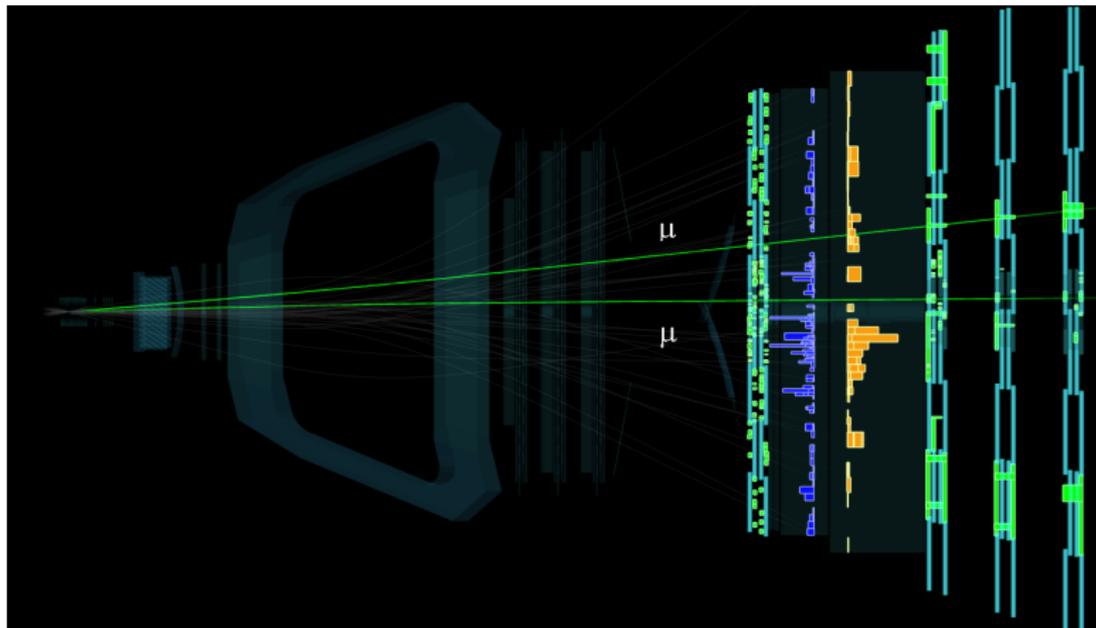
The LHCb detector [JINST 3 (2008) S08005]

- Very good momentum resolution ($\delta p/p \sim 0.1\%$)
- Excellent identification of stable charged particles (π, K, p, μ, e)
- Clear separation of B meson decay vertex from pp collision



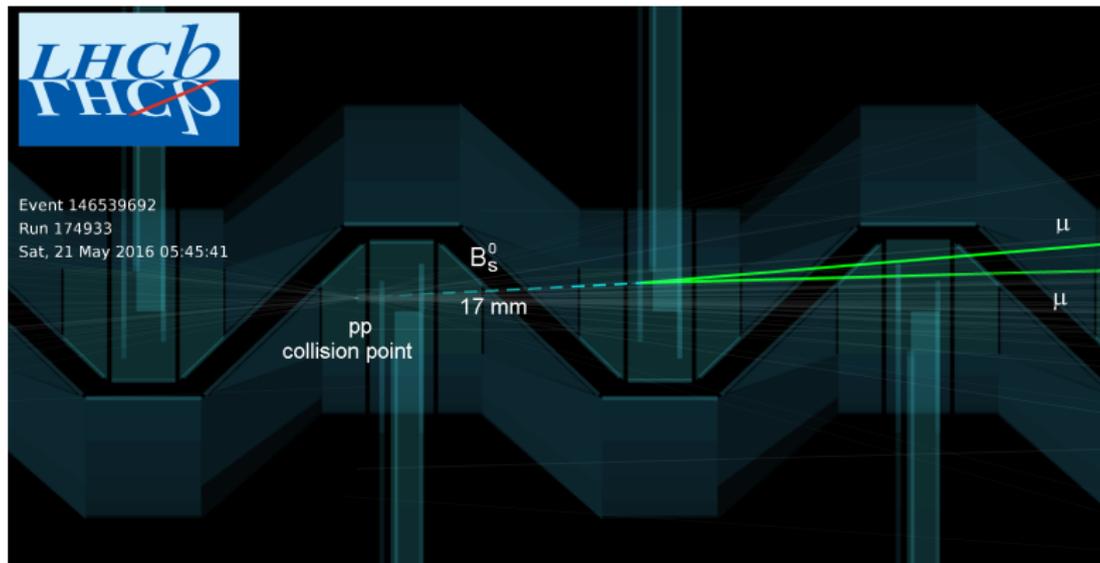
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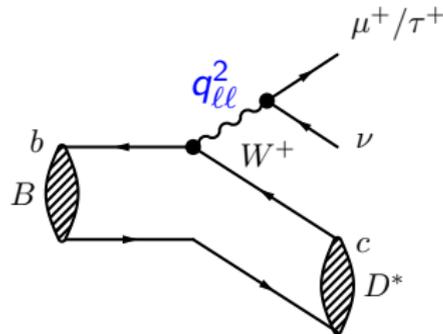
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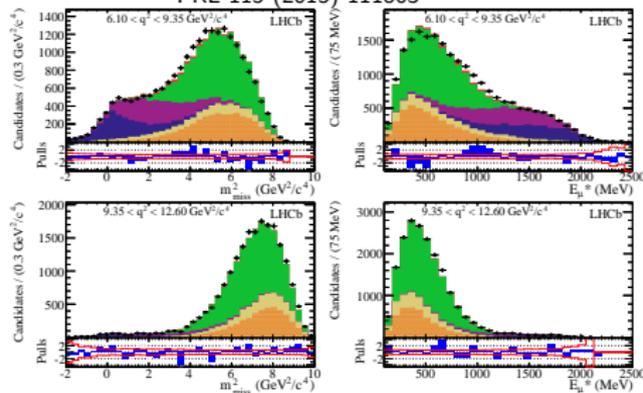
Semi-leptonic $b \rightarrow c l \nu_l$ decays

- $R(X_c^{(*)}) = \frac{\mathcal{B}(B \rightarrow X_c^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow X_c^{(*)} \mu \nu_\mu)}$
- Reconstruct $\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$ (muonic), $\tau \rightarrow 3\pi \nu_\tau$ (hadronic)
- Neutrino in final state \rightarrow no clear mass peak
- Significant backgrounds, checked with control samples (enriched in background)
- Use different topological variables per analysis in template fit (e.g. $q_{\ell\ell}^2$)



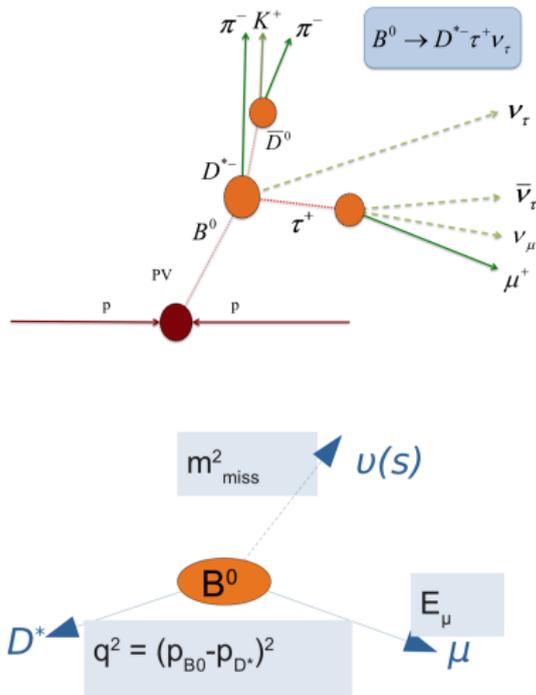
Control sample for $B \rightarrow D(D \rightarrow \ell X)$:

PRL 115 (2015) 111803

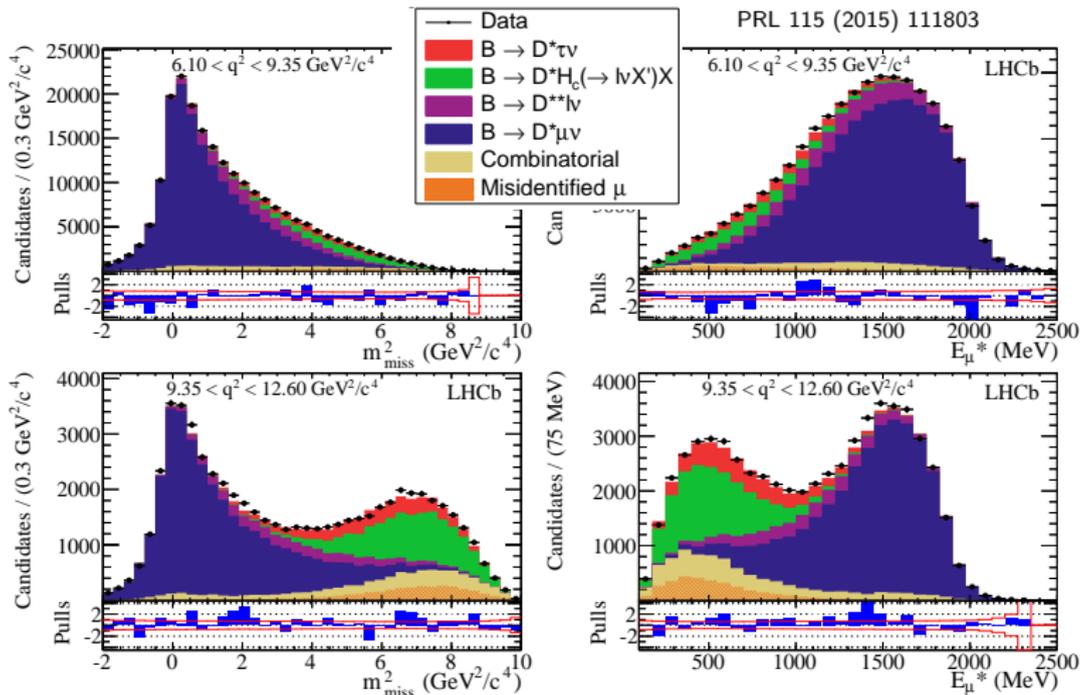


$R(D^*)$ muonic

- SM expectation:
 $R(D^*) = 0.256 \pm 0.005$
- $R(D^{(*)})$ with $\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$
- Separate τ from μ by using extra neutrinos in final state
- Fit to:
 - $q^2 =$ energy in W transfer
 - $E_\mu^* =$ energy muon
 - $m_{miss}^2 =$ energy neutrino's
- Main backgrounds:
 $B \rightarrow D^{**} \ell \nu, B \rightarrow DD$
- Main current systematic:
 size of simulation sample



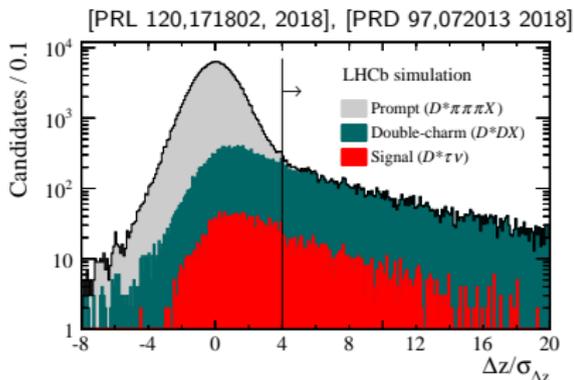
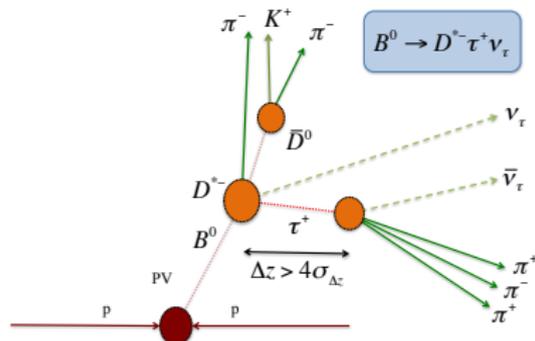
Fit result in most sensitive q^2 bins with τ mode and μ mode:



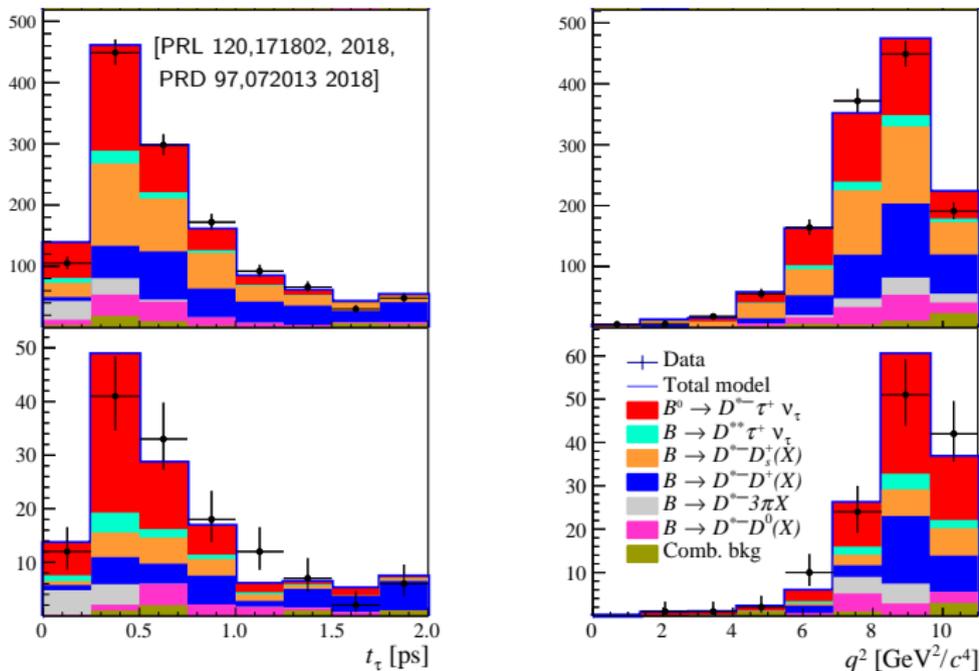
$$R(D^*) = 0.336 \pm 0.027(\text{stat.}) \pm 0.030(\text{syst.}) \text{ at } 2\sigma \text{ from SM}$$

$R(D^*)$ hadronic

- $R(D^*)$ with $\tau \rightarrow 3\pi\nu_\tau$
 - Extra vertex to reject background
 - Need to reject $B \rightarrow D^*3\pi, D^*(D \rightarrow 3\pi)$ backgrounds even more
- Measure $\frac{\mathcal{B}(B \rightarrow D^* \tau \bar{\nu}_\tau)}{\mathcal{B}(B \rightarrow D^* 3\pi)}$ to reduce experimental uncertainties
- Fit variables:
 - q^2
 - BDT to separate τ and D
 - t_τ to reject $B \rightarrow D^* 3\pi$
- Main current systematic: size of simulation sample



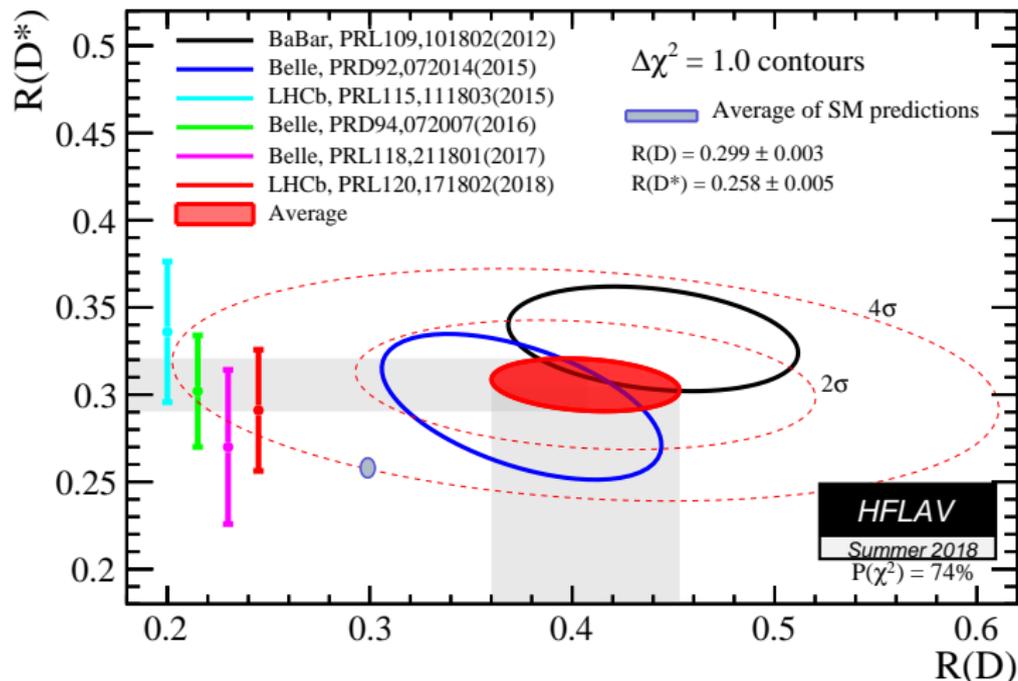
Fit result in most sensitive BDT bins with **signal in red**:



$$R(D^*) = 0.291 \pm 0.019(\text{stat.}) \pm 0.026(\text{syst.}) \pm 0.013(\text{ext}) \text{ at } 1\sigma \text{ from SM}$$

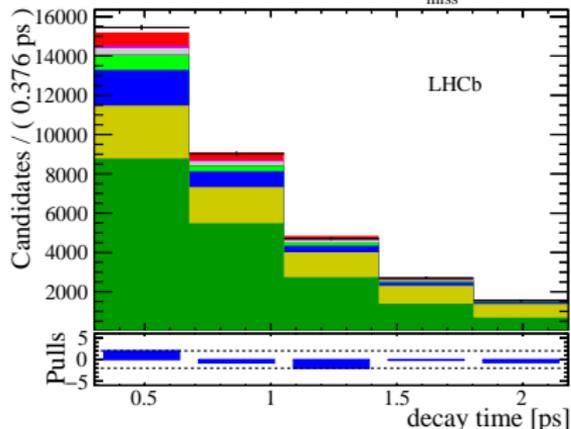
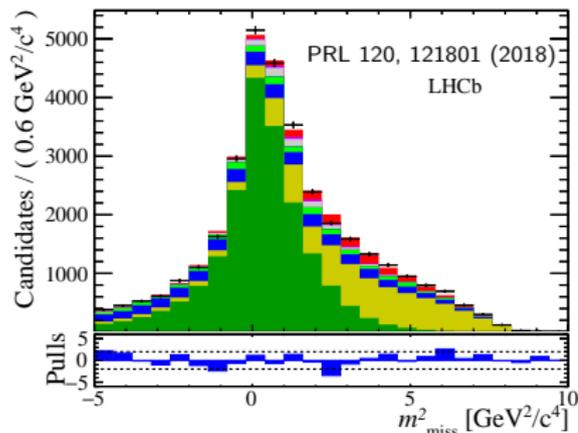
Status of $R(D^{(*)})$

- Many measurements of $R(D)$, $R(D^*)$ at B-factories
- Combining all, HFLAV finds tension with SM at level of 3.8σ



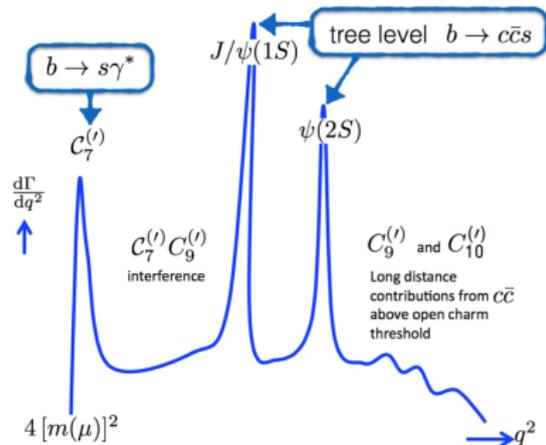
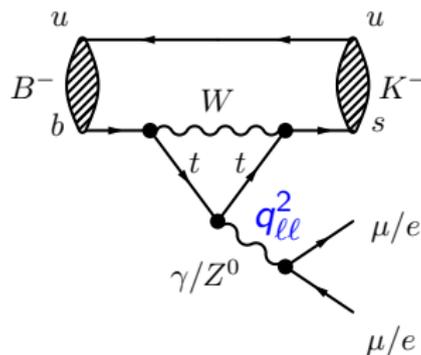
$R(J/\psi)$ muonic

- In SM, $R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = [0.25, 0.28]$
- Fit form factors from data
- Use same fit variables as in $R(D^*)$ muonic + B_c^+ candidate lifetime
- Main background: $B \rightarrow J/\psi h^+ X$
- First evidence for $B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau$
- $R(J/\psi) = 0.71 \pm 0.17(\text{stat.}) \pm 0.18(\text{syst.})$ at 2σ above SM
- Main current systematics: form factors, size of simulation sample

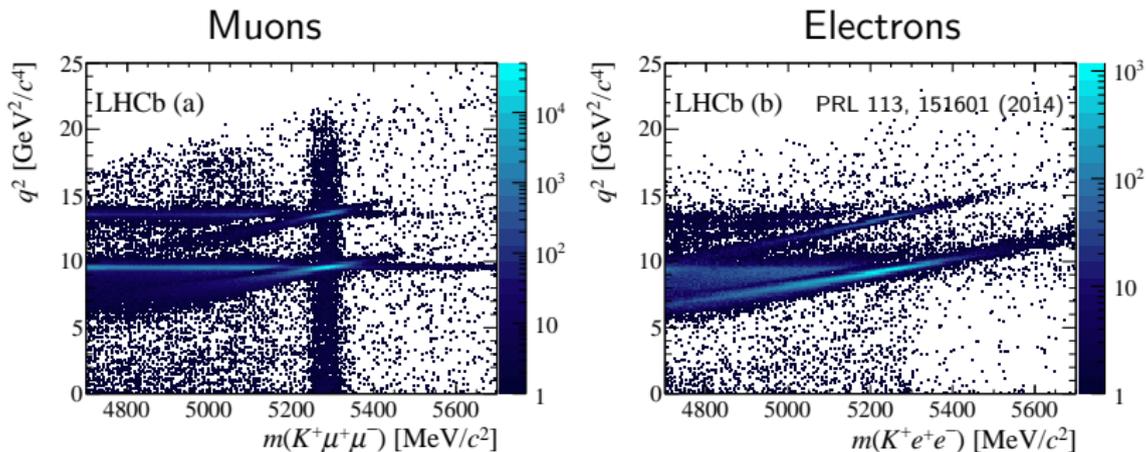


Semi-leptonic $b \rightarrow s \ell \ell$ decays

- $R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}$
- Three body decay: bins of $q_{\ell\ell}^2$
- Measure $R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-) \mathcal{B}(B \rightarrow J/\psi(\rightarrow e^+ e^-) K^{(*)})}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-) \mathcal{B}(B \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^{(*)})}$ to reduce systematics
- Rare decay: statistics limited
- Experimental challenges:
 - Hardware trigger: muon vs. electron/hadron/rest of event
 - Electron reconstruction



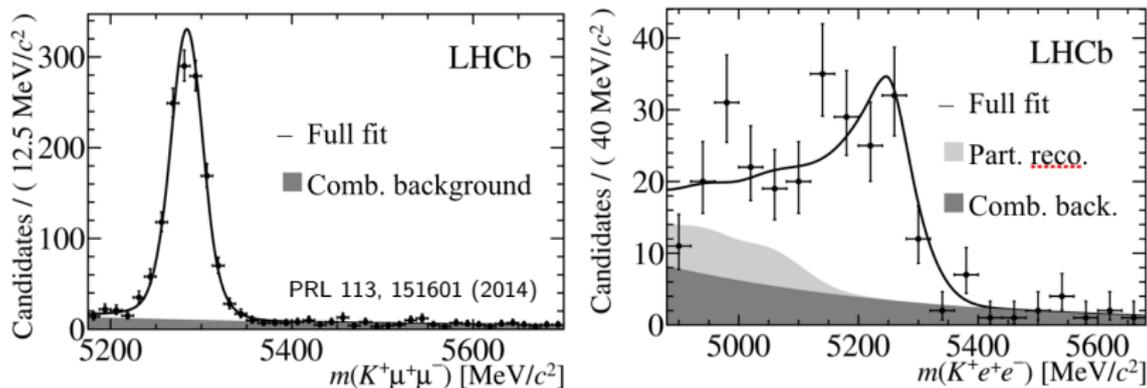
Electron reconstruction



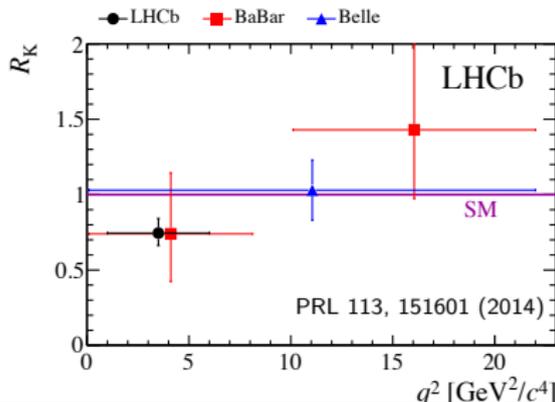
- Bremsstrahlung reduces efficiency and mass resolution
- More background from partially reconstructed decays
- Lower trigger efficiency because of higher p_T threshold needed for electrons and hadrons
- In total reconstruct about 1 electron pair per 10 muon pairs

Measurement of R_K

Fits for $R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}$, for $q^2 \in [1, 6] \text{ GeV}^2$:

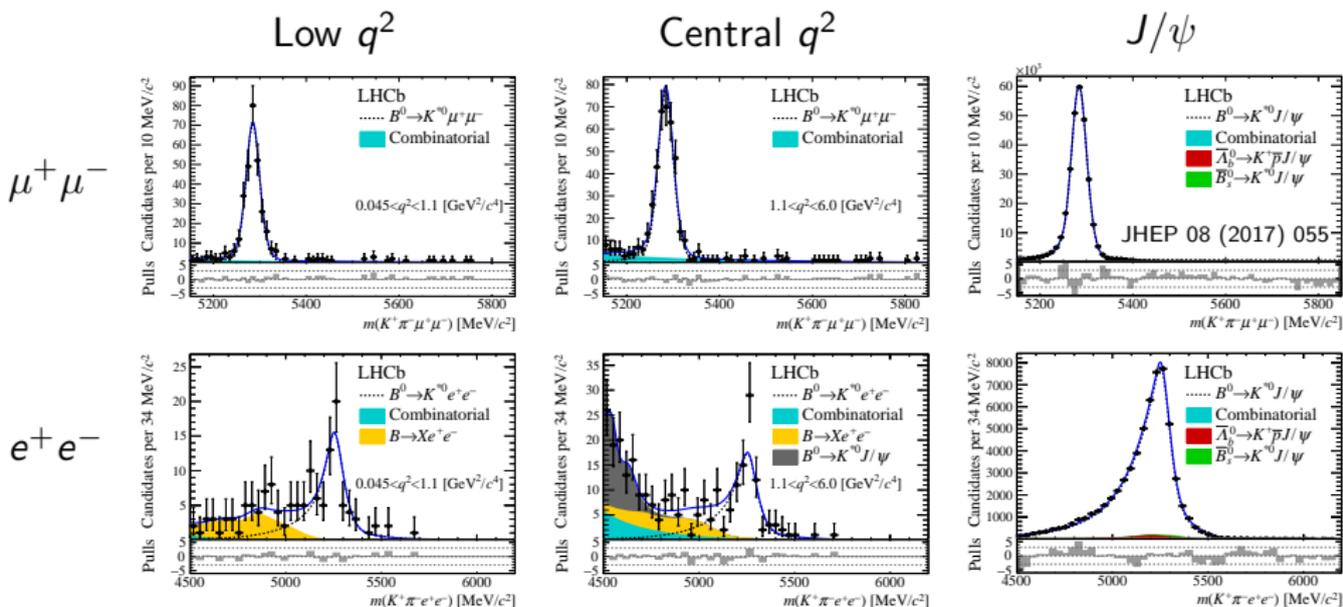


- $R_K = 0.745_{-0.074}^{+0.090}(\text{stat.}) \pm 0.036(\text{syst.})$
- Tension with SM at 2.6σ
- Consistent with New Physics only coupling to muons



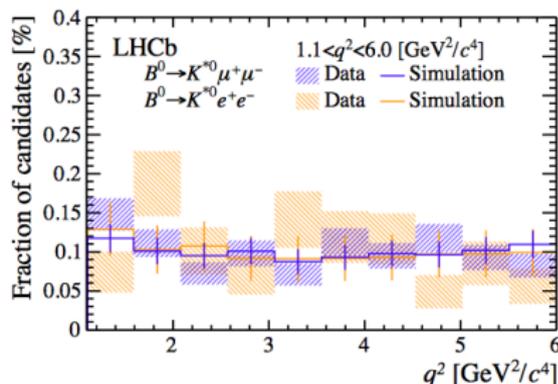
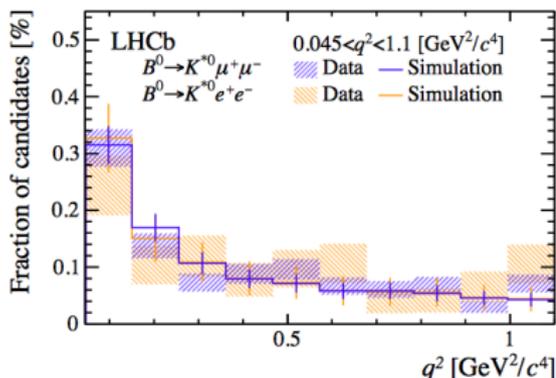
Measurement of $R_{K^{*0}}$

- Main difference with R_K : photon penguin at low q^2
- Therefore, measure in two bins in q^2 :
 - Low ($q^2 \in [0.045, 1.1] \text{ GeV}^2$)
 - Central ($q^2 \in [1.1, 6] \text{ GeV}^2$)

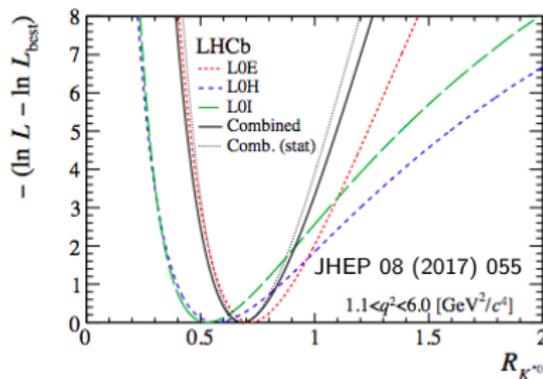
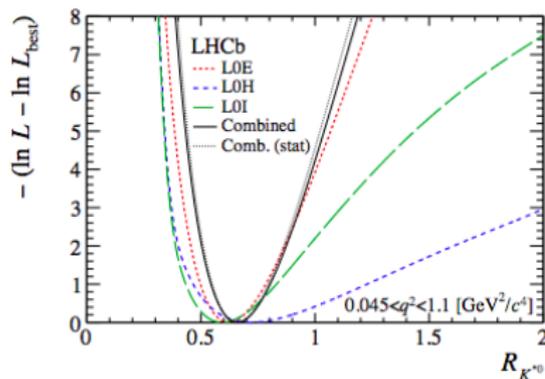


Measurement of $R_{K^{*0}}$: cross-checks

- To control absolute efficiencies, measure $R_{J/\psi} = \frac{\mathcal{B}(B_d^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^{*0})}{\mathcal{B}(B_d^0 \rightarrow J/\psi(\rightarrow e^+ e^-) K^{*0})} = 1.043 \pm 0.006(\text{stat.}) \pm 0.045(\text{syst.})$
(flat ratio in various event, kinematical variables)
- Double ratio of J/ψ and $\psi(2S)$ modes:
measured with $\sim 2\%$ precision, consistent within 1σ
- Data and simulation agree in q^2 distributions:



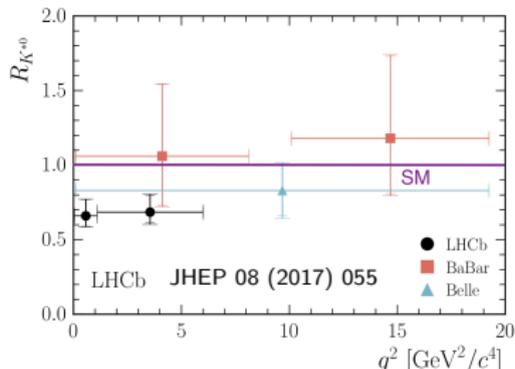
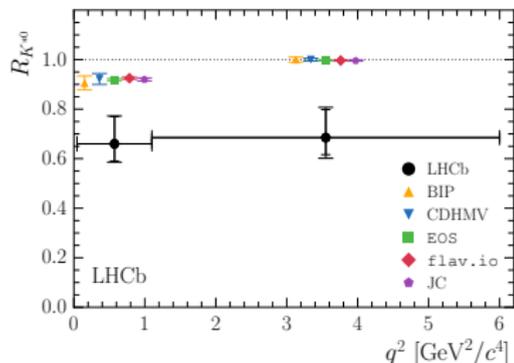
Measurement of $R_{K^{*0}}$: results



- Results are consistent for each trigger category

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

Measurement of $R_{K^{*0}}$: results



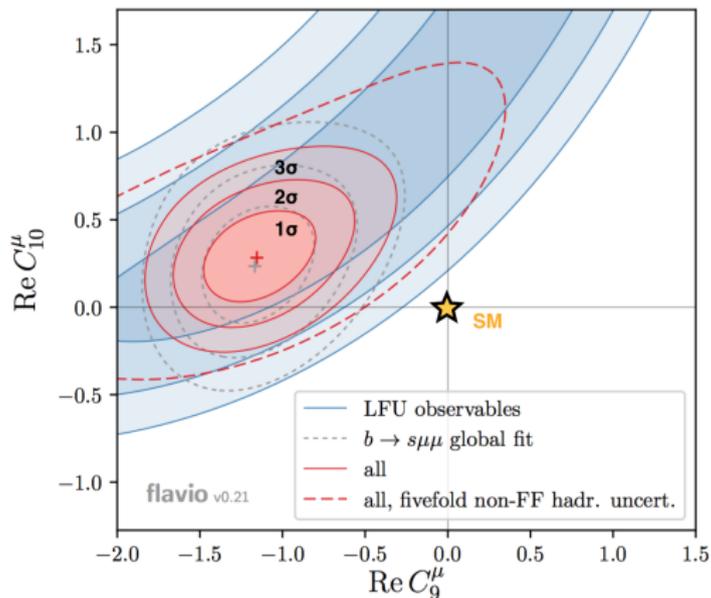
- ▲ BIP arXiv:1605.07633
- ▼ CDHMV arXiv:1510.04239, 1605.03156, 1701.08672
- EOS arXiv:1610.08761, <https://eos.github.io>
- ◆ flav.io arXiv:1503.05534, 1703.09189, flav-io/flavio
- JC arXiv:1412.3183

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

- Most precise measurement
- Uncertainty dominated by yield of electron modes
- Tension with SM at 2.2, 2.5 σ for low, central q^2
- Also consistent with NP only in muons

R_K and R_{K^*0} : the bigger picture

Look at global fit combining $b \rightarrow sll$ results: [PRD 96 (2017) 055008]



R_K, R_{K^*} together deviate 4σ from SM
LFU consistent with other $b \rightarrow sll$ anomalies! (see talk by Davide)

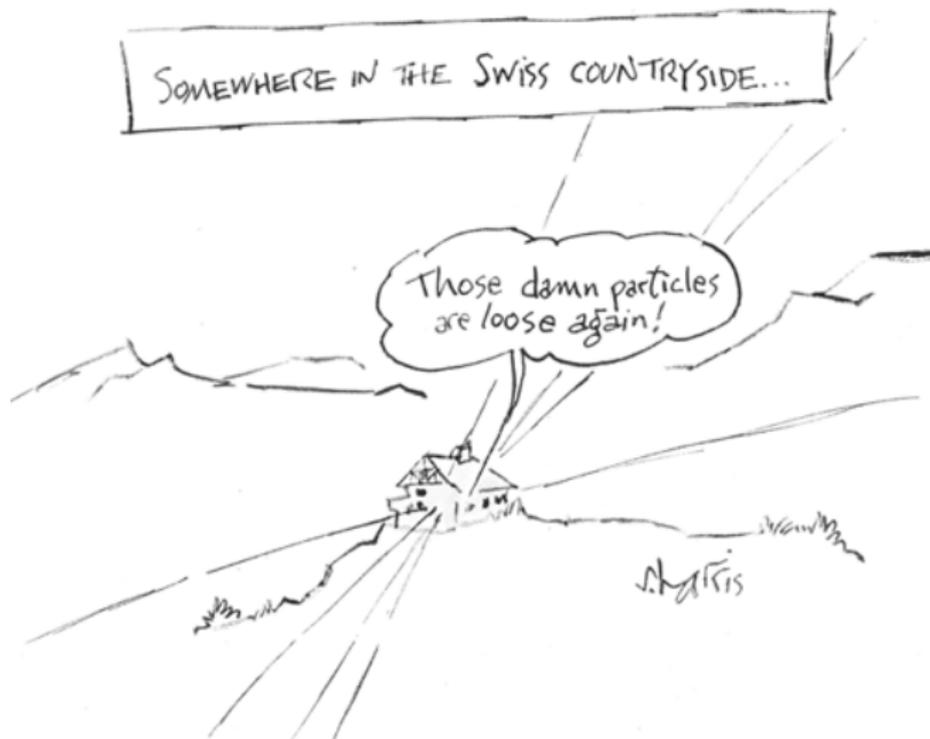
Many other global fits:

JHEP 1801 (2018) 093, arXiv:1704.05447, PRD 96 (2017) 093006, ...

Conclusions

- Intriguing deviations found in lepton universality tests at LHCb
- In $b \rightarrow c l \nu_l$ transitions, $R(D^{(*)})$ measured 3.8σ above SM by LHCb and B-factories
- In $b \rightarrow s l l$ transitions, $R_{K^{(*)}}$ measured 4σ below SM by LHCb in EFT interpretation
- Both might be described with same New Physics model (see previous talk)
- LHCb is investigating!
 - These results were with Run 1, now analysing our Run 2 data ($\sim 4 \times$ Run 1!)
 - New decay modes: $R(D^{(*)0}), R(D^+), R(\Lambda_c^{(*)}), R_\phi, R_{\Lambda^{(*)}}, \dots$
- Exciting times in flavour physics!

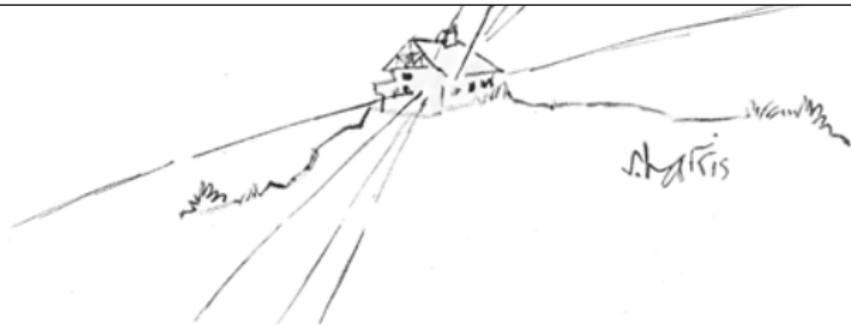
Conclusions



SOMEWHERE IN THE SWISS COUNTRYSIDE...

Those damn particles
are loose again!

Thanks for your attention!



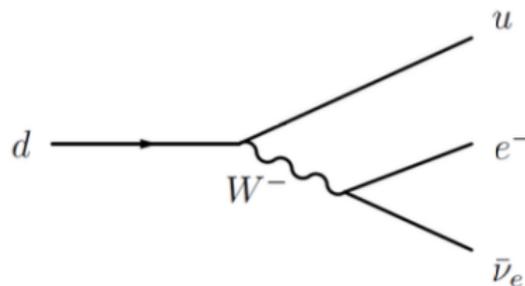
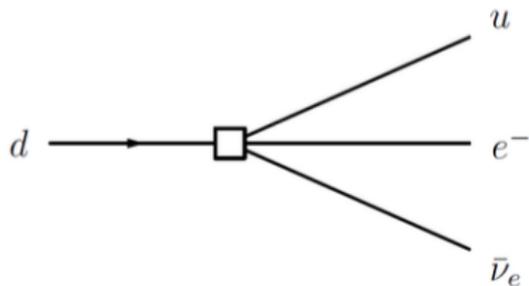
Backups are often required



How to interpret $b \rightarrow sll$ measurements

Effective Field Theory!

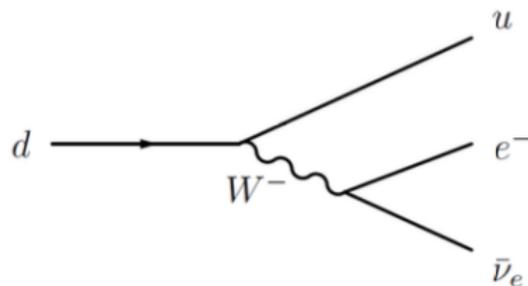
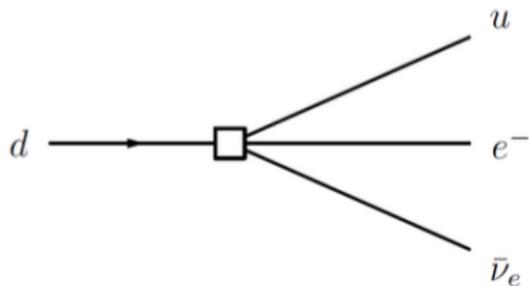
Most famous example: Fermi interaction



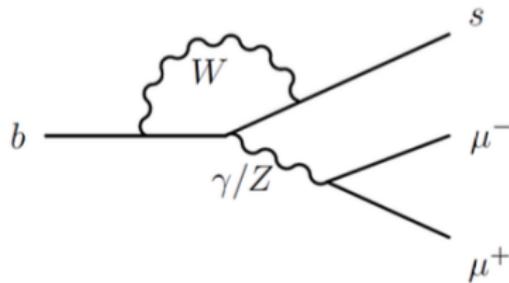
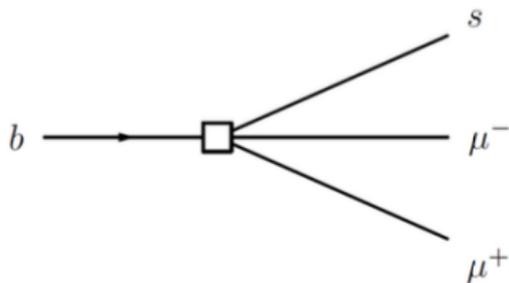
How to interpret $b \rightarrow sll$ measurements

Effective Field Theory!

Most famous example: Fermi interaction



Similar approach for $b \rightarrow sll$:

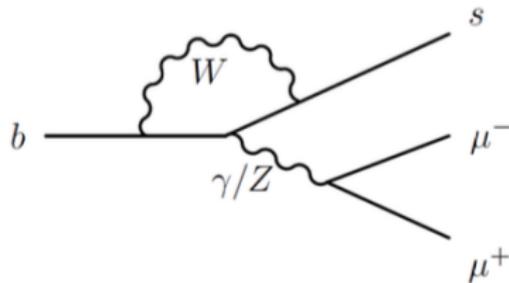
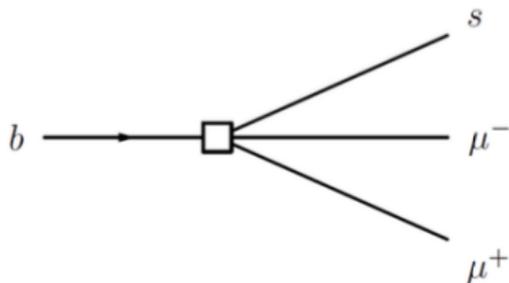


How to interpret $b \rightarrow sll$ measurements

An EFT probes different couplings:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\text{right-handed part}}]$$

- Photon penguin (C_7)
- Vector (C_9)
- Axial vector (C_{10})
- Left-handed ($V - A = C_9 - C_{10}$)

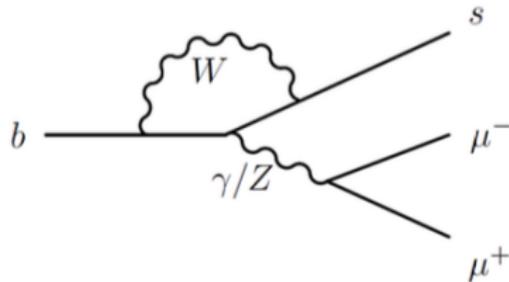
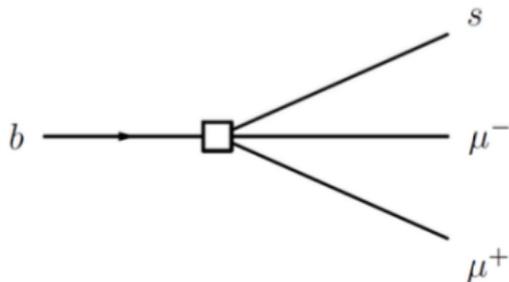
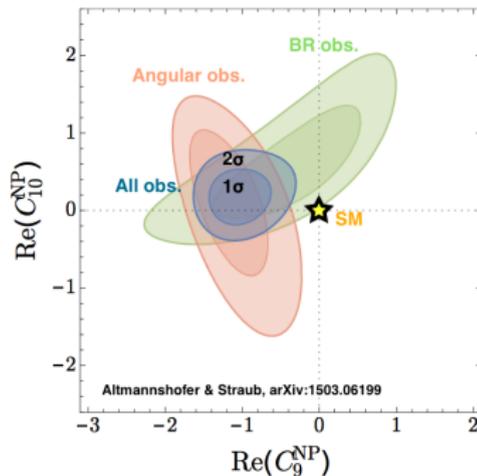


How to interpret $b \rightarrow sll$ measurements

An EFT probes different couplings:

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- Photon penguin (C_7)
- Vector (C_9)
- Axial vector (C_{10})
- Left-handed ($V - A = C_9 - C_{10}$)



Possible models

- Many papers discussing these anomalies
 - **My favorite model: vector leptoquarks!** (arXiv:1706.07808)
 - Couples mainly to 3rd generation, so main signatures:
 - 100x enhancement of $b \rightarrow s\tau\tau$, for example $B_s^0 \rightarrow \tau^+\tau^-$
 - ATLAS, CMS: $pp \rightarrow \tau^+\tau^-$ or direct searches ($t\bar{t}\nu\nu$)
 - Possible relation with Standard Model Higgs couplings?
- Extensions of these models can explain hierarchy in generations** [PLB 779 (2018) 317-323]

