# Tests of Lepton Flavor Universality

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[on behalf of LHCb, CMS and ATLAS collaborations]

10th Large Hadron Collider Physics Conference

# Lepton Flavor Universality in the SM

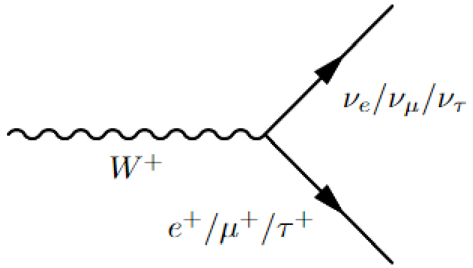
- In the Standard Model couplings of leptons to W,Z,$\gamma$ are independent of flavor by axiom

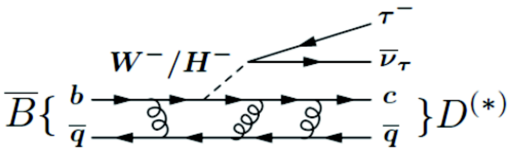
- Different masses generate calculable phase space differences

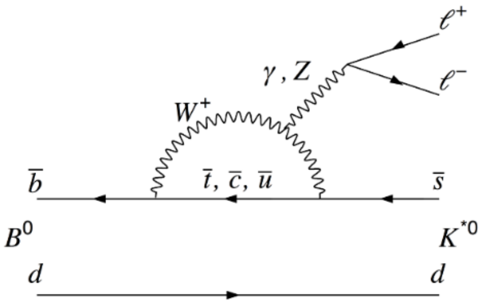
- Hadronic form factors largely cancel out in ratios of branching fractions
  - Measurement of a violation of LFU would be a clear sign of new physics

- Some SM extensions include particles that can cause LFU violation (e.g. LQ, Z')

- Experimental investigation of LFU has been pioneered at LEP ($W \to l^+\nu$) and at the Bfactories ($R(D^{(*)})$)[PRL 109, 101802] showed hints of a tension with the SM

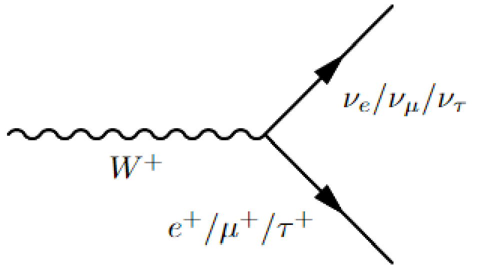


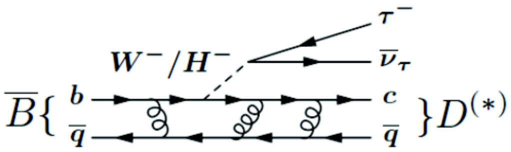



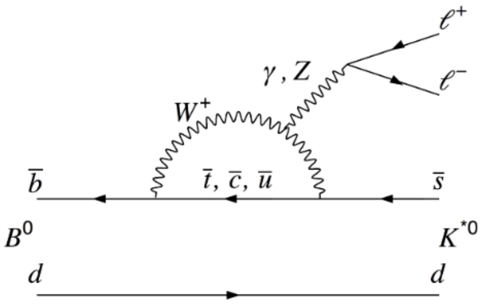



# Overview

- In this report I will present recent results from LHCb, ATLAS and CMS in four different classes of measurements
  - $W \to l\nu$ [ATLAS, CMS]
  - $b \to cl\nu$ [LHCb],
  - $b \to sll$ [LHCb],
  - $q\bar{q} \to l^+l^-$ at high mass [CMS]



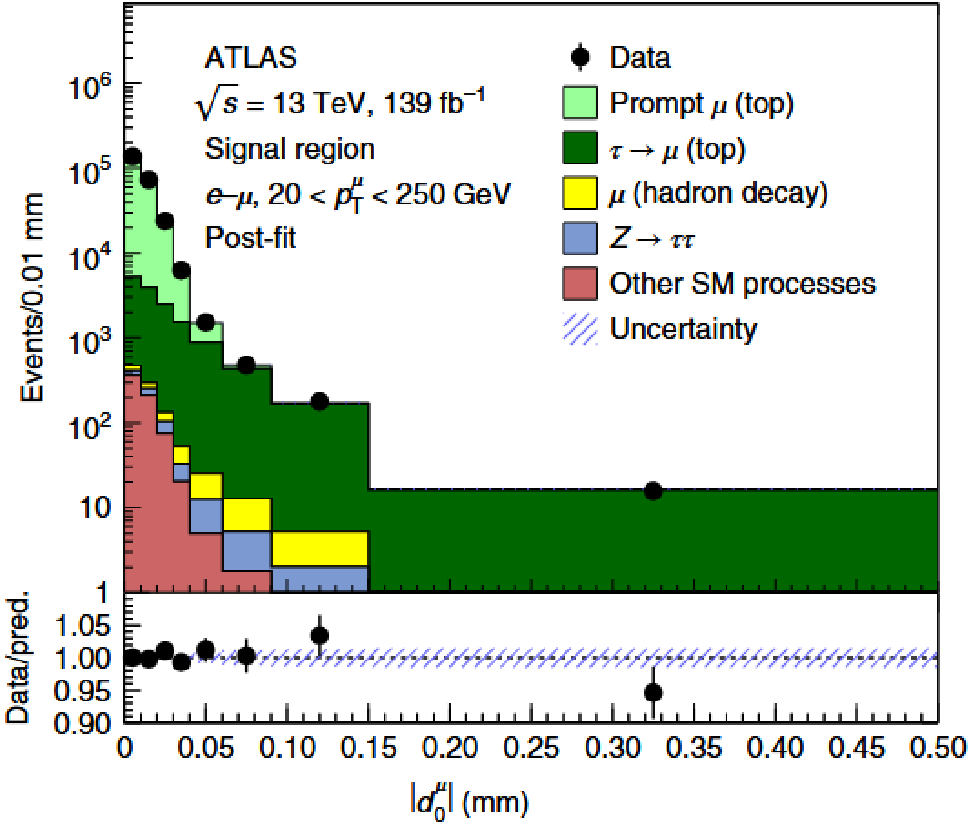



# $W \rightarrow l\nu$

# ATLAS test of LFU in W boson decay

- LEP measured $\mathrm{BF}(W \rightarrow \tau\nu)$ consistently higher w.r.t. $BF(W \rightarrow e\nu, \mu\nu)$ [Phys. Rep. 532 (2013) 119]:
  - $R(\tau/\mu)$=1.070 ± 0.026, 2.7$\sigma$ different from unity
- ATLAS improved this using a pure sample of $W$ (500k) from dileptonic $t\bar{t}$ events where $t \rightarrow Wb$ and $W \rightarrow l\nu$ with tag and probe on lepton (unbiased)
- Background from $Z \rightarrow \mu\mu$ with lost $\mu$ and probe not from $W$: calibrated on control regions
- Muon $P_T$ and impact parameter are used to separate prompt and secondary $\mu$ and to extract yields



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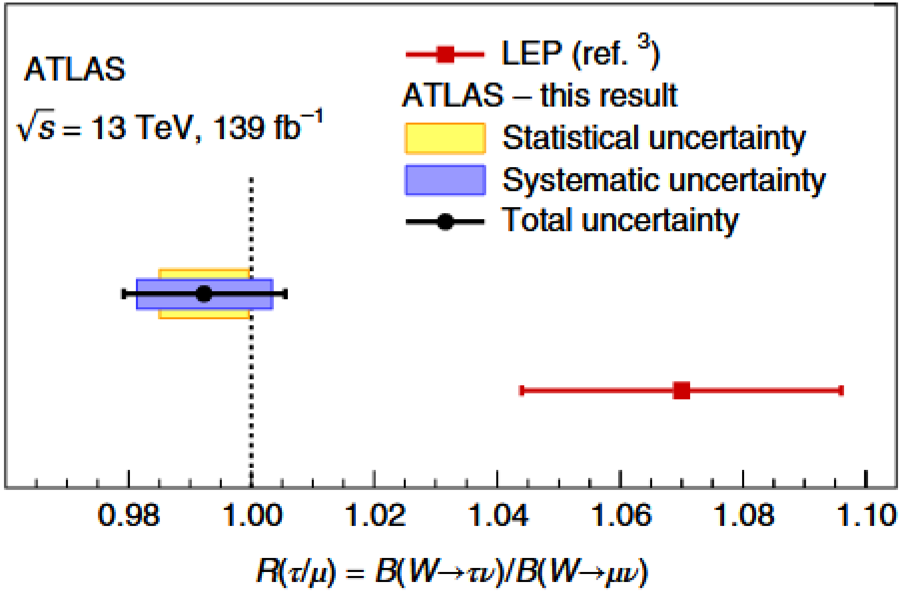
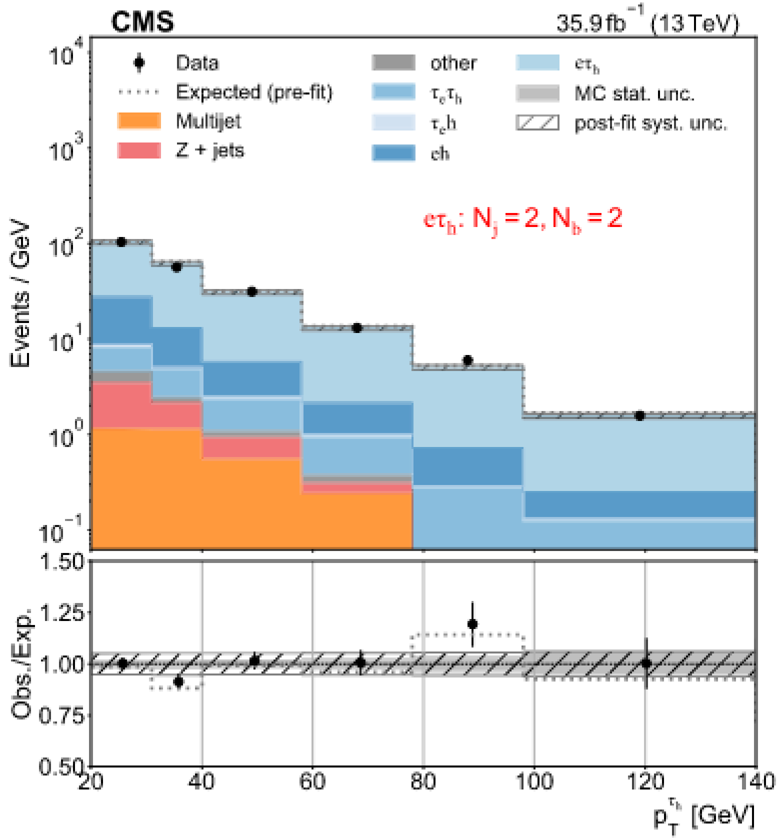
- Muon $P_T$ and impact parameter are used to separate prompt and secondary $\mu$ and to extract yields
- $R(\tau/\mu) = 0.992 \pm 0.013$ agreement with LFU



PHYSICAL REVIEW D 105, 072008 (2022)

# CMS test of LFU in in W boson decay

- Select events with WW, tW, tt and W+jets
- Search for all W decays $W \rightarrow e\bar{\nu}_e, \mu\bar{\nu}_\mu, \tau\bar{\nu}_\tau, hadronic.$
- Split analysis depending on event category
- Does not use impact parameter to separate prompt from secondary muons but only kinematic variables
- Simultaneous extraction of all BF in all event categories by ML fit to $P_T$ distribution



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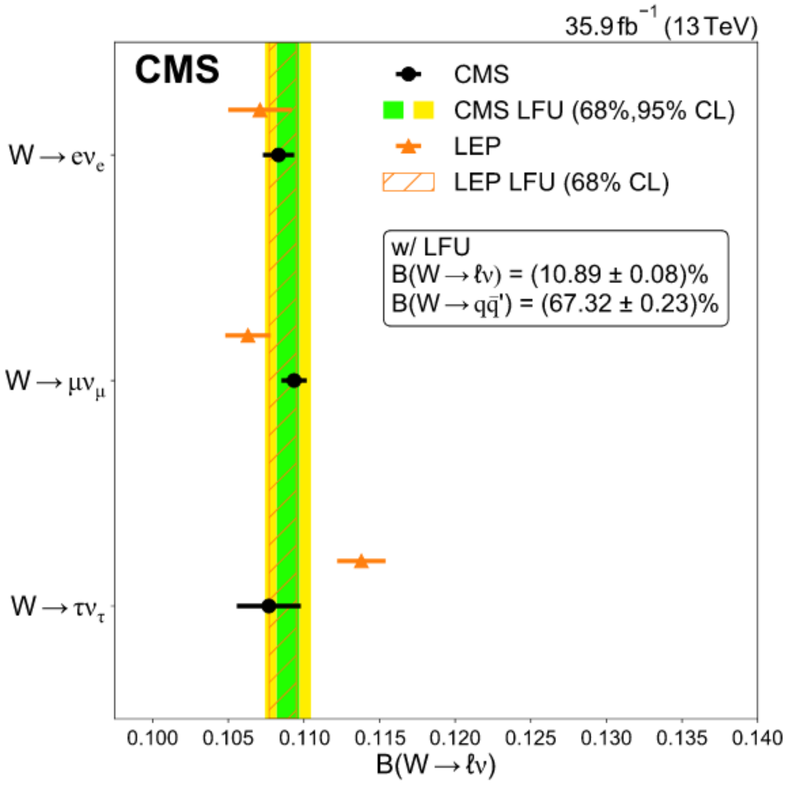
| | CMS | LEP | ATLAS |
|---|---|---|---|
| $R_{\mu/e}$ | $1.009 \pm 0.009$ | $0.993 \pm 0.019$ | $1.003 \pm 0.010$ |
| $R_{\tau/e}$ | $0.994 \pm 0.021$ | $1.063 \pm 0.027$ | ... |
| $R_{\tau/\mu}$ | $0.985 \pm 0.020$ | $1.070 \pm 0.026$ | $0.992 \pm 0.013$ |
| $R_{\tau/\ell}$ | $1.002 \pm 0.019$ | $1.066 \pm 0.025$ | ... |



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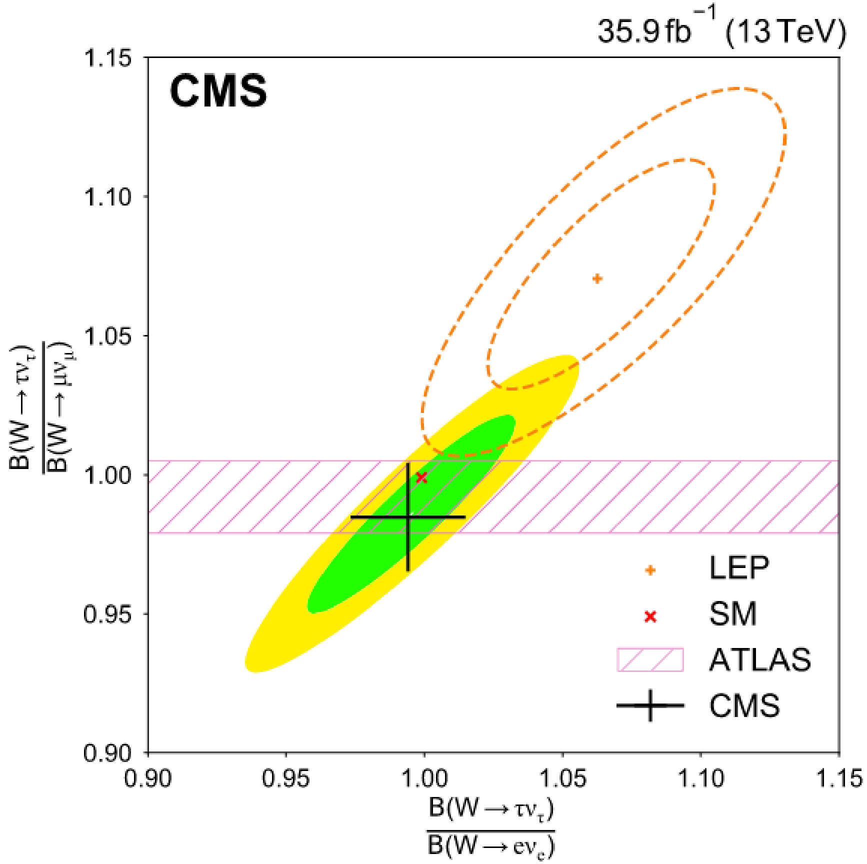


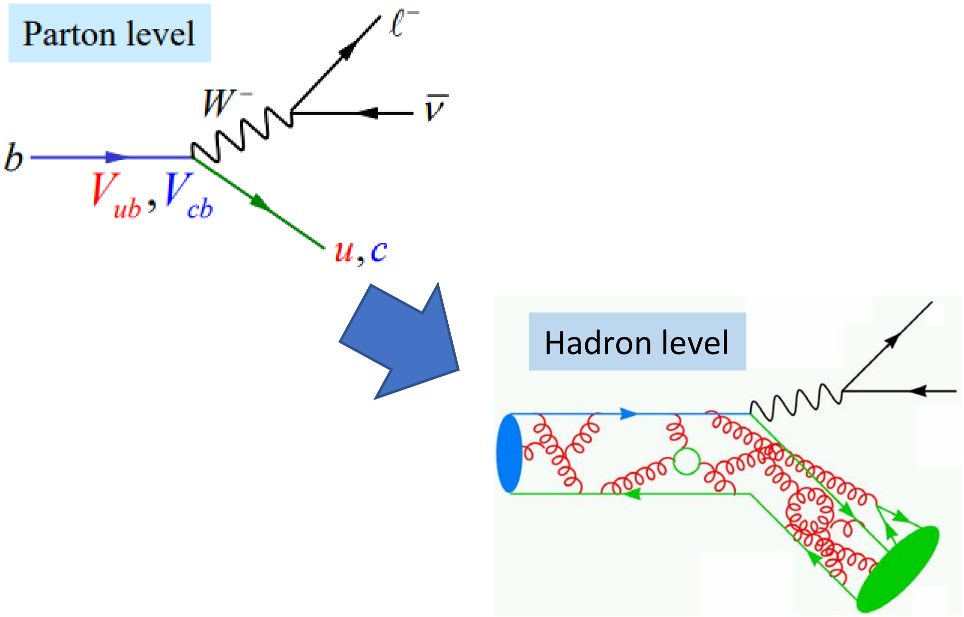
# $b \to cl\nu$

# LFU in semileptonic B-hadron decays

- LFU can be tested comparing BF for different leptons in the final state

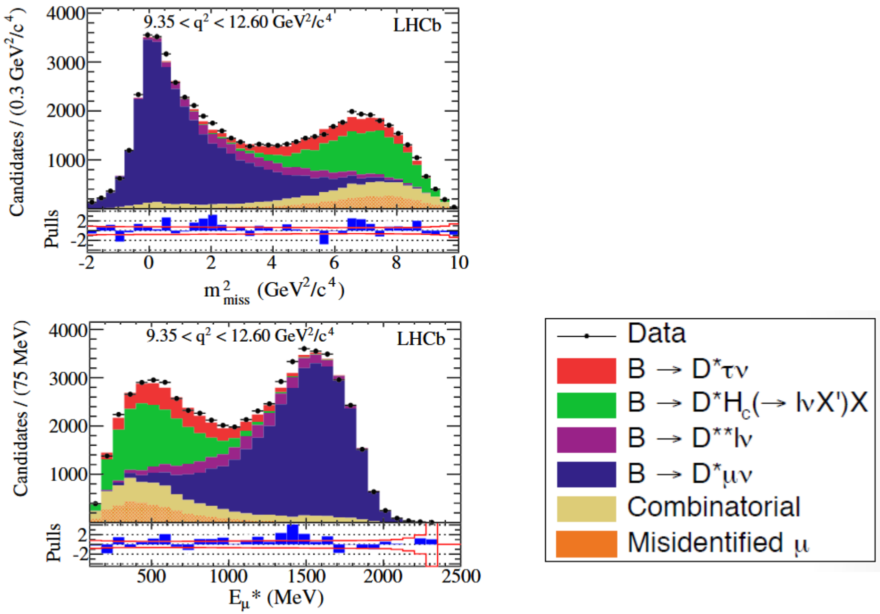
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$$

- Hadronic current
  - form factors from lattice, HQET largely cancel out in the ratio
- For $\tau$ lepton the available space makes $R(H_c) < 1$
- Tree level process
  - large data samples
- Missing neutrino
  - Partially reconstructed decays
  - Background
- Measurements with mesons done by LHCb and B-Factories [PRL 109, 101802 (2012), PRD 88, 072012 (2013), PRD92,072014(2015), [PRL124,161803 (2020)]



# $R(D^*) = B(B^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/B(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

- $\tau$ reconstructed in one prong $\tau^- \to \mu^-\nu_\mu\bar{\nu}_\tau$
- B momentum estimated using the visible Pz
- Difficult backgrounds from partially reconstructed semileptonic decays $B \to D^{**+}\mu^-\nu$ modeled using a control sample $B \to D^{*+}\mu^-\pi^+\pi^-$
- Corrections for double charm from simulation corrected with control sample $D^{*+}\mu^-K^\pm$
- Prompt and secondary muons from ML fit to $m^2_{miss}$, $E_\mu$, $q^2$ distributions with 3D templates representing signal, normalization and background sources




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

2.1 $\sigma$ from theoretical prediction

Physical Review Letters 115, 111803 (2015) ($3fb^{-1}$)

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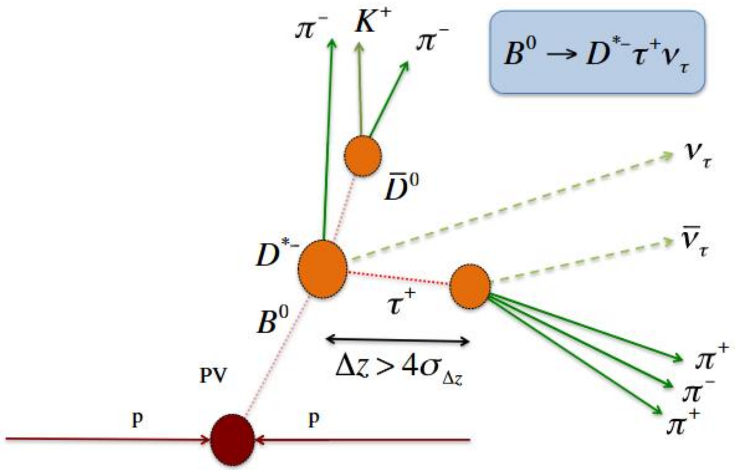
Result also obtained using hadronic $\tau$ decays [PRL 120, 171802 (2018)] ($3fb^{-1}$)




$$R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

Physical Review Letters 115, 111803 (2015) ($3fb^{-1}$)

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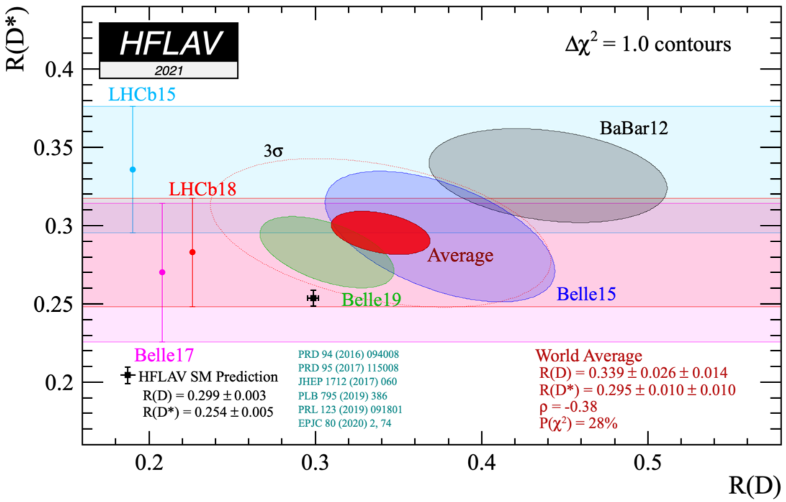



Combined with hadronic tau reco and other measurements: 3.4 $\sigma$ from theo.

# LHCb Test of LFU in B Baryon decays

- Measurement of $\mathcal{R}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)$

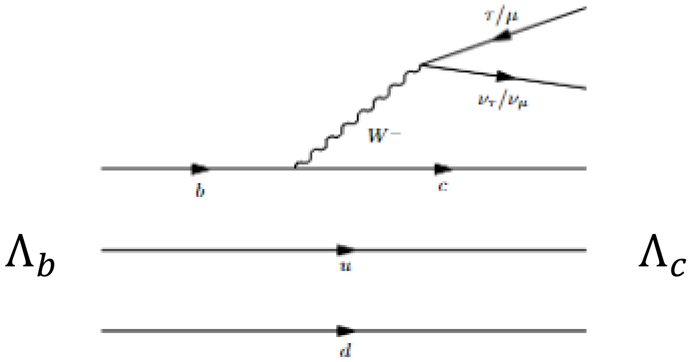
  First LFU test in semi-lept. baryon decays

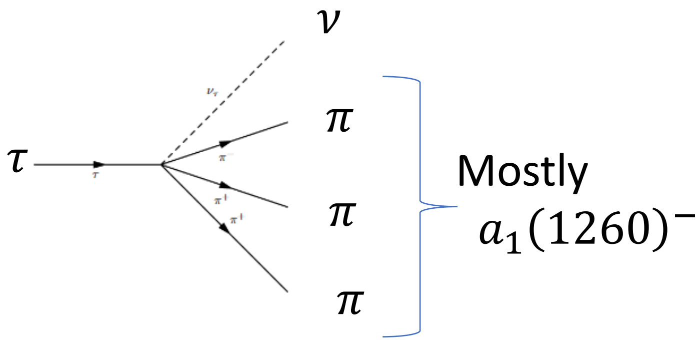
- Precise SM prediction $R(\Lambda_c) = 0.324 \pm 0.004$ [PRD 99 (2019) 055008]

- Different form factors involved w.r.t $B \to D$ transitions
  - Complementary constraints on NP

- Half integer spin → can help in distinguishing different NP operators [PRD 99 (2019) 055008, JHEP 08 (2017) 131]

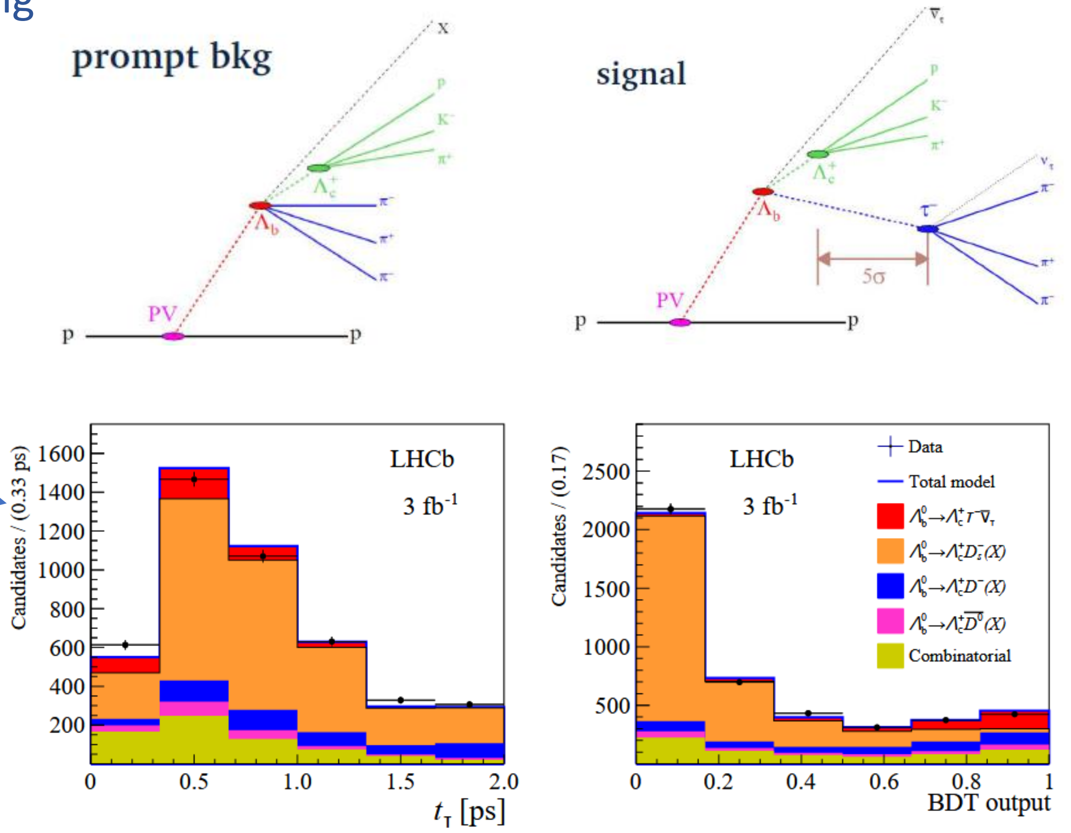
- $\tau$ reconstructed using hadronic decays $\tau^+ \to \pi^+\pi^+\pi^-(\pi^0)$



# $R(\Lambda_c)$ Analysis method

- Background from $\Lambda_b \to \Lambda_c D_s^{(*)}$ suppressed using resonant structure of $\tau$ decay
- Reconstruction of $\tau$ decay vertex allows suppression of prompt background
  - $\Delta z = z(3\pi) - z(\Lambda_c) > 5\sigma_{VTX}$
- Only one neutrino missing
  - $q^2 = (p_\tau + p_\nu)^2$ of the $\tau l$ pair can be reconstructed
  - Used to suppress background and extract signal yield
- Signal extracted from 3D ML fit to BDT, $t_\tau, q^2$



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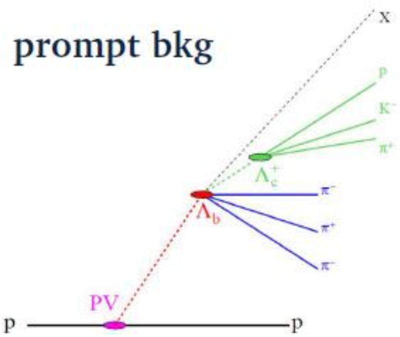
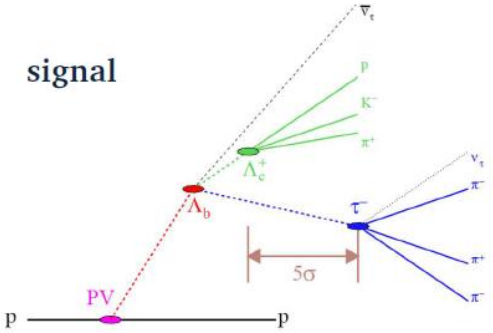
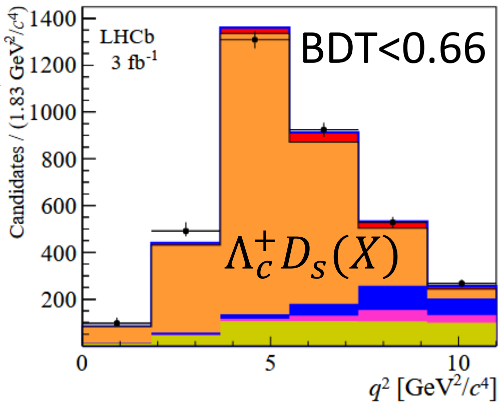
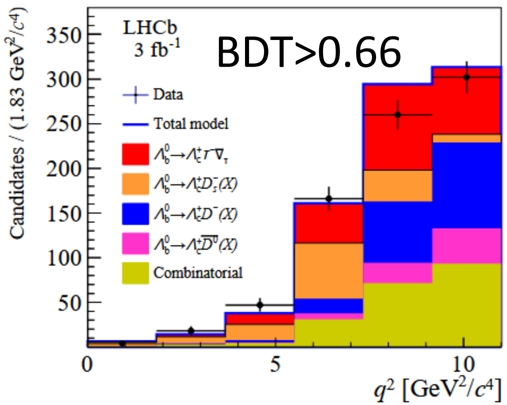


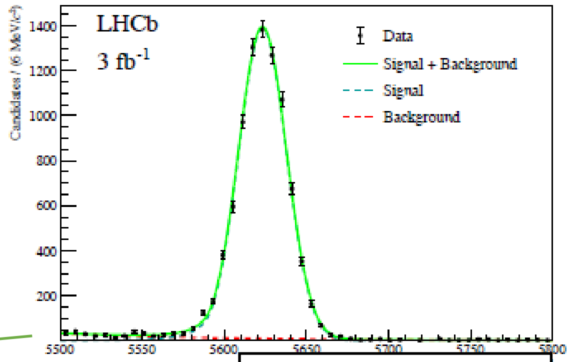



# Normalization and result on $R(\Lambda_c)$

- Normalization to $\Lambda_c^+ 3\pi$ to reduce systematics
  - $R(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \nu_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c 3\pi)} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu_\mu)}$

$K(\Lambda_c^+)$ measured

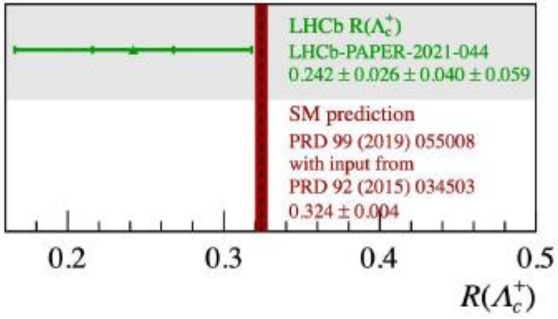
external




$M(\Lambda_b^0 \to \Lambda_c 3\pi)$

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

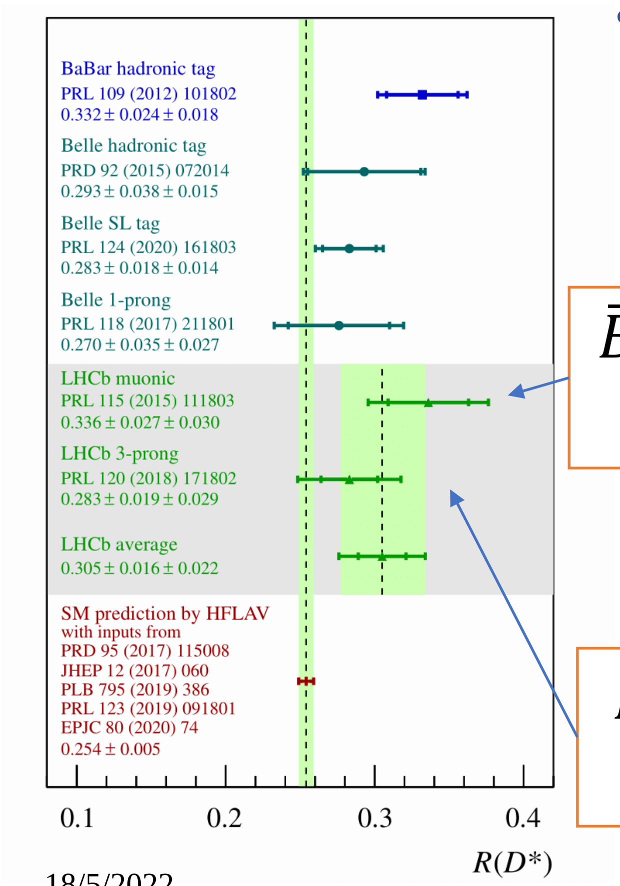
Simulation




- $K(\Lambda_c^+)$= 2.46 $\pm$ 0.27(stat) $\pm$ 0.40(sys)
- $R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{sys}) \pm 0.059(\text{ext})$

# Pattern of LFU in $b \to cl\nu$ at LHCb

- $R(H_c) = \frac{B(H_b \to H_c \tau \bar{\nu}_\tau)}{B(H_b \to H_c l \bar{\nu}_l)}$




$B_c^+ \to J/\psi \tau^+ \nu_\tau$

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

$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$
$\tau \to 3\pi(\pi^0)$

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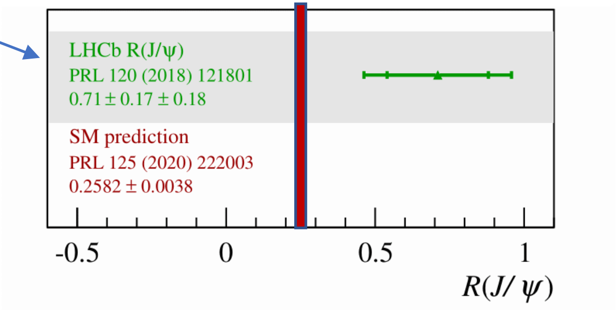


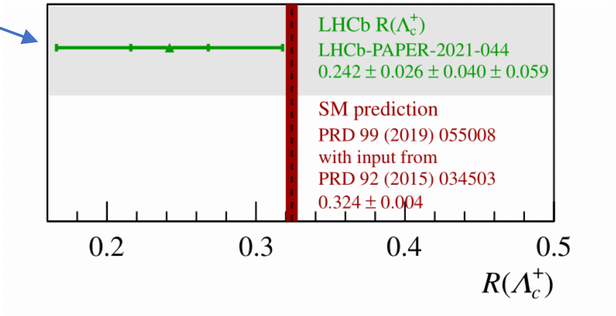

# Prospects for $b \to cl\nu$

- Combined measurement of $R_{D^0}, R_{D^*}$ with leptonic tag and on run1 data (3 fb$^{-1}$)
  - Extension of 2015 analysis
- Updated $R_{D^*}$ with hadronic tag of $\tau$ and $D^{*+} \to D^0\pi^+$ on 2015-2016 data
  - Update
- New combined $R_{D^+}, R_{D^*}$ measurement with leptonic tag on run2 data
  - New

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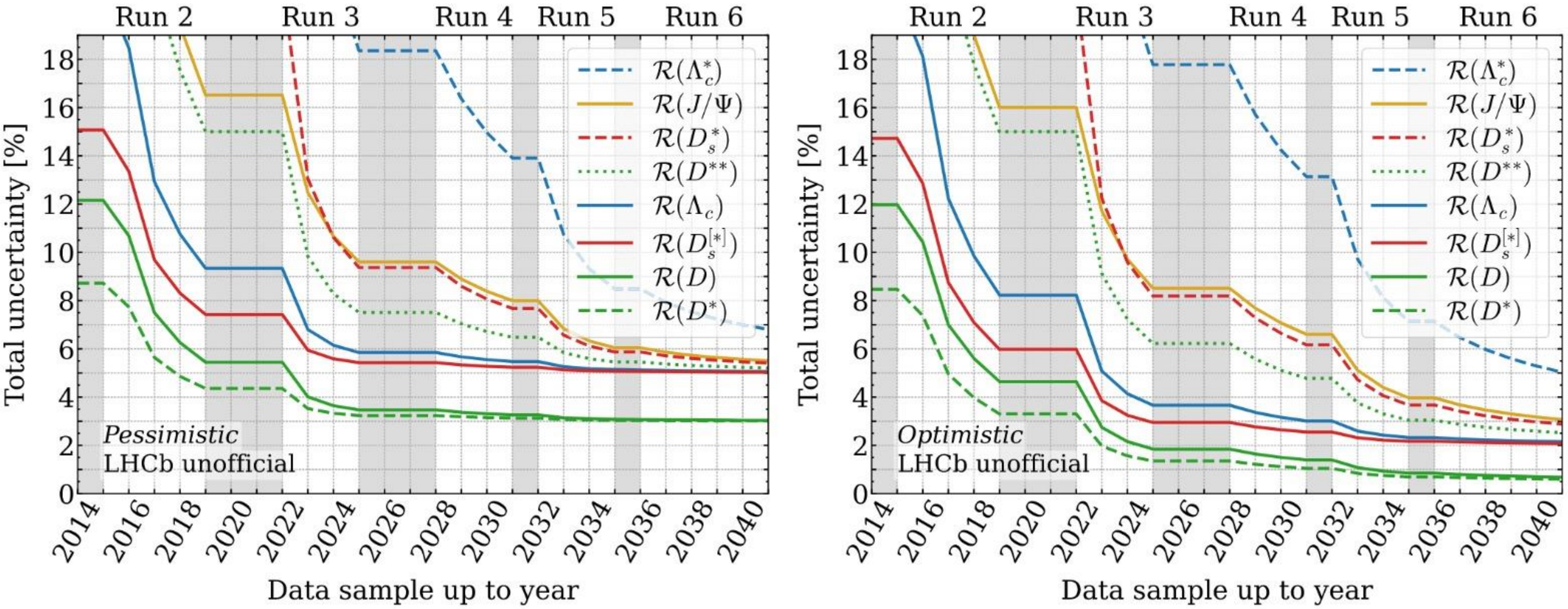
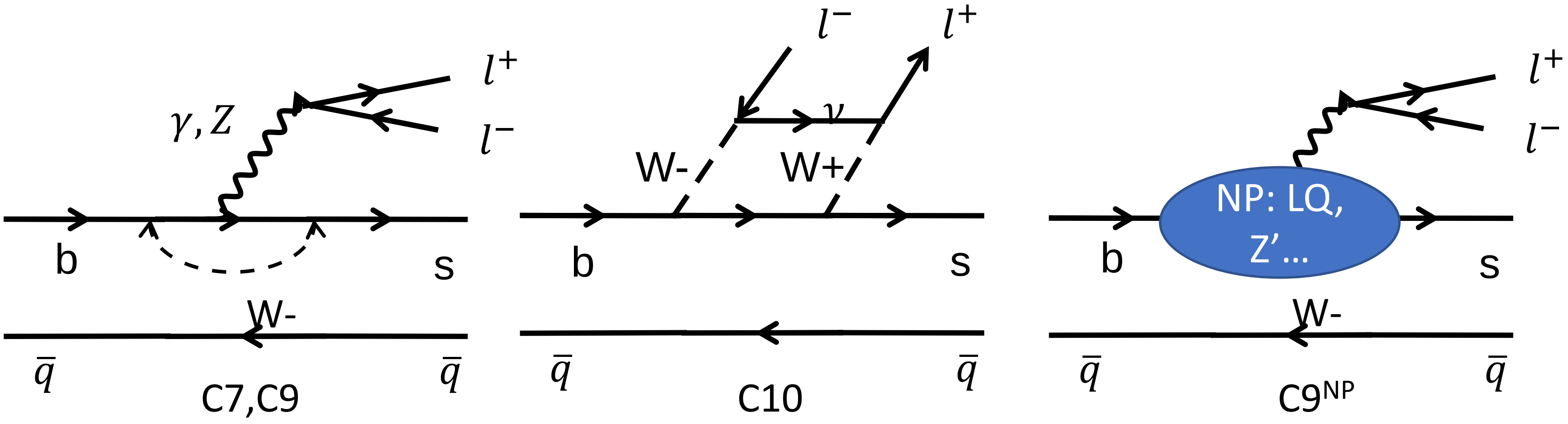
# Summary of evolution of $R_H$



# $b \to sll$

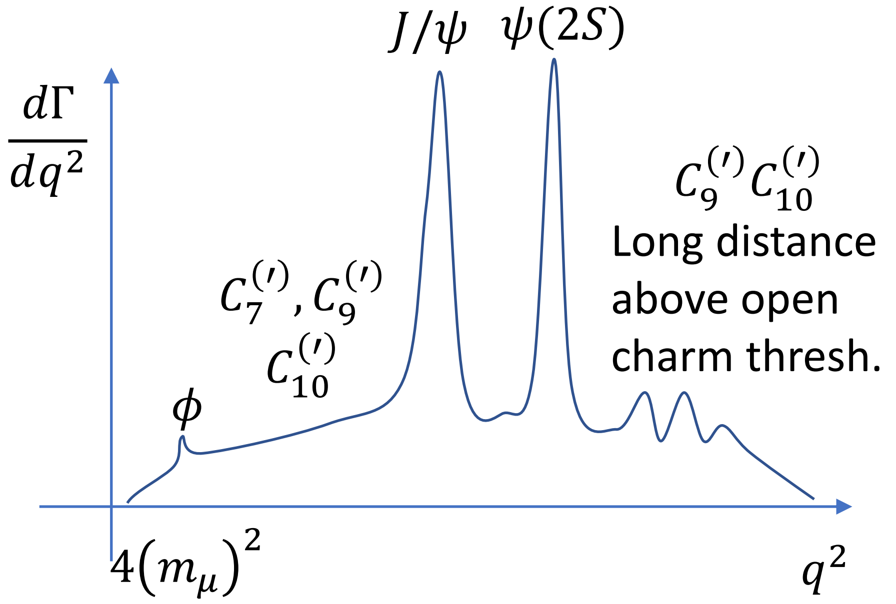
# LFU in $b \to sll$

- $b \to sll$ are FCNC, forbidden at tree level and therefore very rare
- NP contributions can be significant with small SM "background"
- Loop dominated diagrams: sensitive to the effect of virtual unobserved particles above reach of direct searches, affect short distance physics C7,C9,C10 Wilson coefficients
- It is possible to reconstruct the $q^2$ of the lepton pair and study angular observables



# Choice of $q^2$

- Different bins in $q^2$ are sensitive to different diagrams and Wilson coefficients
- $B \to K^* ll$ decays have a pole at low $q^2$ due to the photon propagator
  - Low $q^2$region gives a significant increase in statistics



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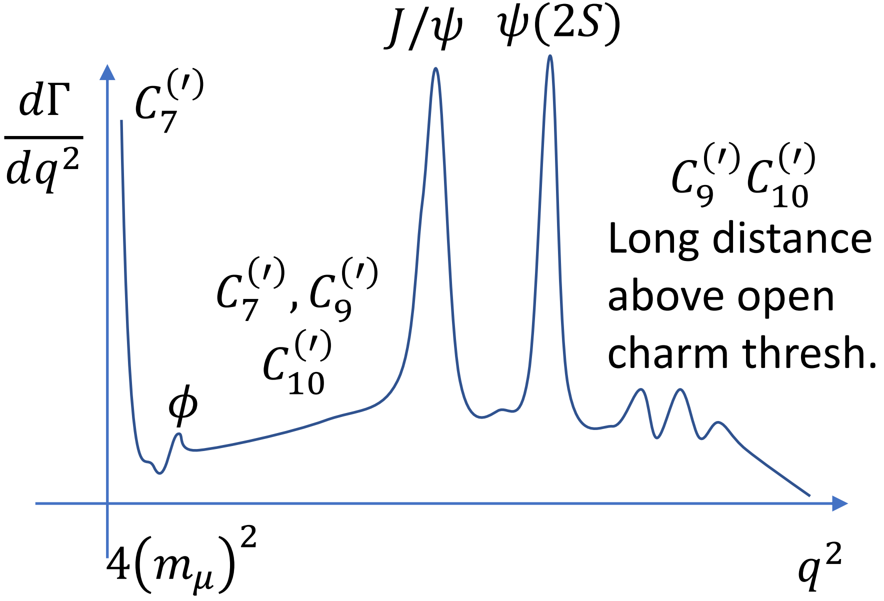
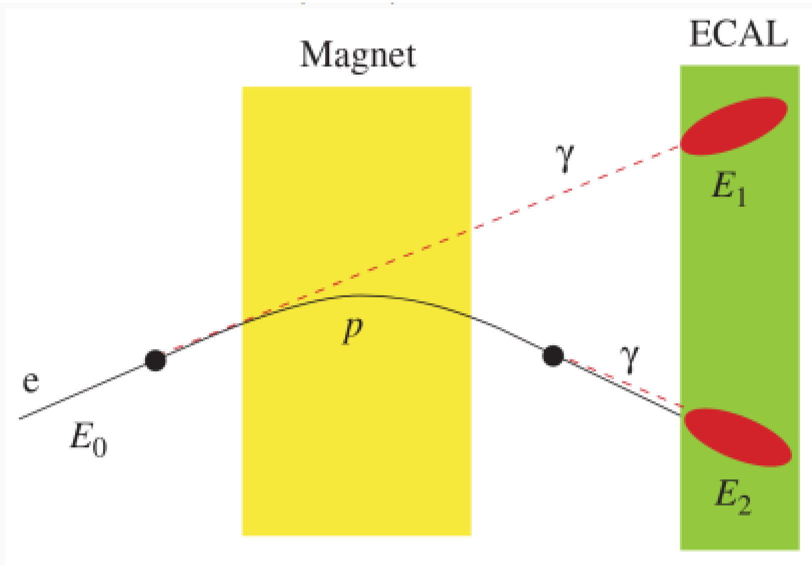


# Testing LFU in $b \to sll$

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2} \cong 1$$

- Measure the ratio $R_H$
- Theoretically very clean
- Electron reconstruction different w.r.t to muons due to bremsstrahlung
  - Energy and momentum resolution is degraded due to bremsstrahlung
- Bremsstrahlung recovery by adding photons compatible with the direction of the electron track



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- Theoretically very clean
- Electron reconstruction different w.r.t to muons due to bremsstrahlung
  - Bremsstrahlung recovery

To a good approximation

$$\frac{\mathcal{B}(B \to HJ/\psi(e^+e^-)}{\mathcal{B}(B \to HJ/\psi(e^+e^-)} = 1$$

- Double ratio to reduce systematic uncertainty on efficiencies
  - Normalization channel $B \to HJ/\psi(l^+l^-)$
  - Does not account for background differences

$$R_H(q^2_{Bin}) = \frac{\int_{q^2_{Bin}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{Bin}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2} \cdot \frac{\mathcal{B}(B \to HJ/\psi(e^+e^-))}{\mathcal{B}(B \to HJ/\psi(\mu^+\mu^-))}$$

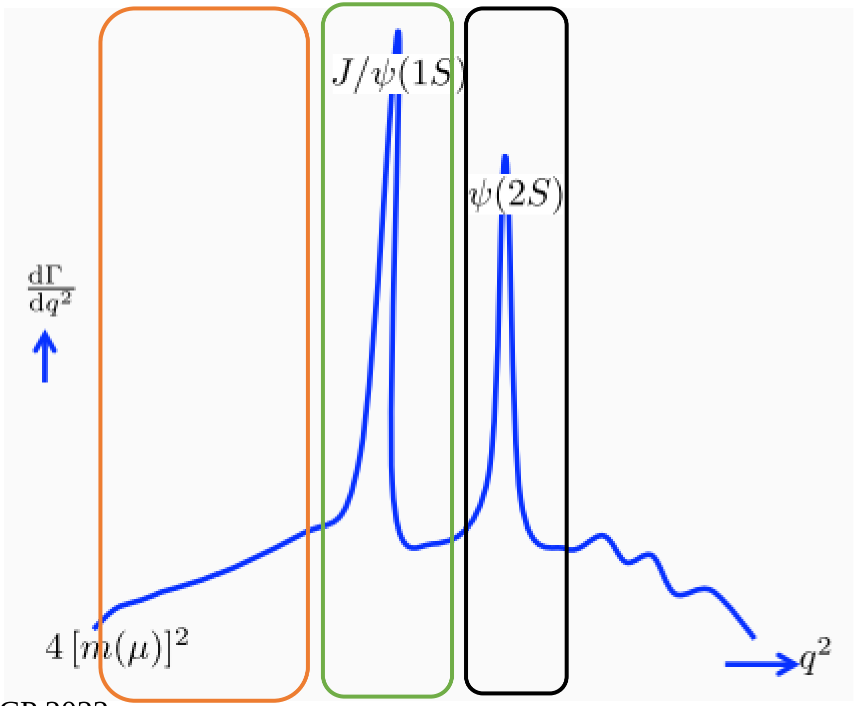
$$= \left( \frac{N^{\mu\mu}_{\mathrm{sig}}}{\epsilon^{\mu\mu}_{\mathrm{sig}}} \cdot \frac{\epsilon^{\mu\mu}_{\mathrm{con}}}{N^{\mu\mu}_{\mathrm{con}}} \right) \Big/ \left( \frac{N^{ee}_{\mathrm{sig}}}{\epsilon^{ee}_{\mathrm{sig}}} \cdot \frac{\epsilon^{ee}_{\mathrm{con}}}{N^{ee}_{\mathrm{con}}} \right)$$

- Numerous checks can be performed
- LHCb has investigated $R_{K^+}, R_{K^{*0}}, R_{pK}, R_{K^{*+}}, R_{K_S}$

# Testing LFU in $b \to sll$

- Signal extracted in bins of $q^2$
- $J/\psi$ resonance control sample used in the double ratio to reduce sys effects in electron reconstruction efficiency
- $\psi_{2S}$ resonance control sample used to check efficiency corrections
- Precise calculation of reconstruction efficiencies crucial point of the analysis
  - Simulation is corrected using data-driven approach including
    - PID, Tracking, kinematics, multiplicity, fraction of $K_S$ downstream, trigger , BDT, $q^2$

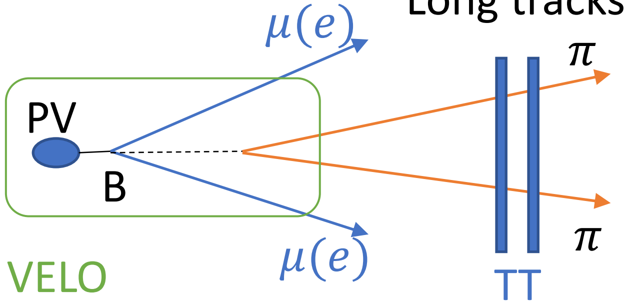
$$R_H(q^2_{Bin}) = \left(\frac{N^{\mu\mu}_{\rm sig}}{\epsilon^{\mu\mu}_{\rm sig}} \cdot \frac{\epsilon^{\mu\mu}_{\rm con}}{N^{\mu\mu}_{\rm con}}\right) \Bigg/ \left(\frac{N^{ee}_{\rm sig}}{\epsilon^{ee}_{\rm sig}} \cdot \frac{\epsilon^{ee}_{\rm con}}{N^{ee}_{\rm con}}\right)$$

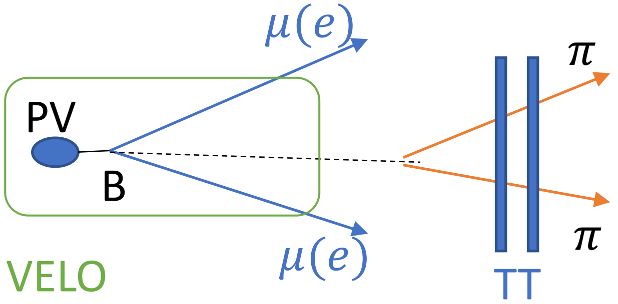


# Testing LFU in $B^0 \to K_S^0 ll$, $B^+ \to K^{*+} ll$

- Ks reconstruction
  - Reduced efficiency due decays after the VELO, PID cuts, trigger thresholds
- $K^{*+} \to K_S \pi^+$

Long tracks




Downstream tracks

*Phys.Rev.Lett.* 128 (2022) 9fb$^{-1}$

# Yield extraction and Control checks

- Ks reconstruction
  - Reduced efficiency due decays after the VELO, PID cuts, trigger thresholds
- $K^{*+} \to K_S \pi^+$
- Yield extraction
  - ML Fit to B meson invariant mass distribution
- Various Checks using $J/\psi$ control sample

$$r^{-1}_{J/\psi K^{(*)}} = \frac{\mathcal{B}\left(B \to J/\psi\left(e^+e^-\right)K^{(*)}\right)}{\mathcal{B}\left(B \to J/\psi\left(\mu^+\mu^-\right)K^{(*)}\right)} = \frac{N^{ee}_{\rm con}}{N^{\mu\mu}_{\rm con}}\frac{\epsilon^{\mu\mu}_{\rm con}}{\epsilon^{ee}_{\rm con}},$$

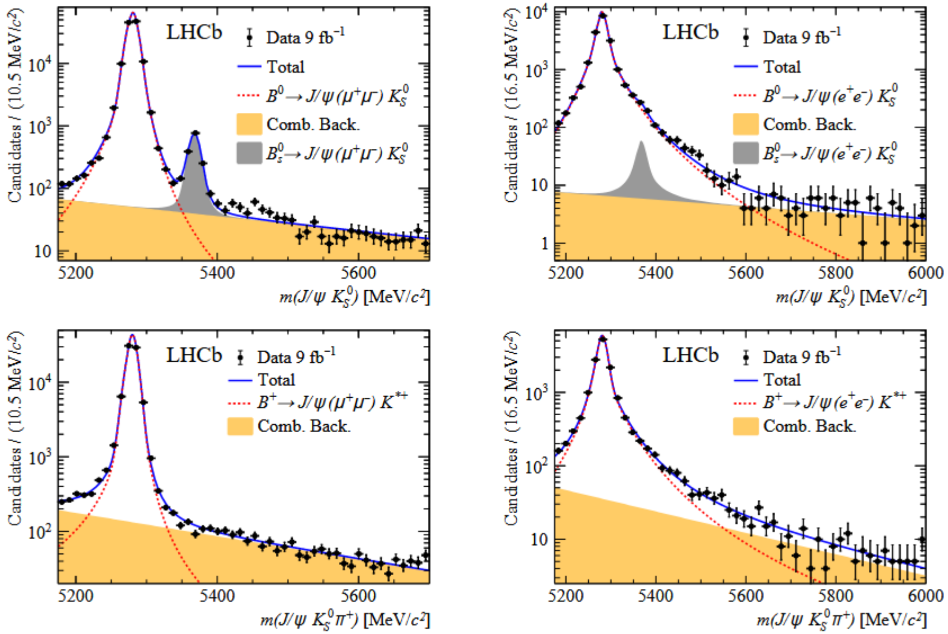
$$r^{-1}_{J/\psi K^0_S} = 0.977 \pm 0.008\,(\text{stat.}) \pm 0.027\,(\text{syst.})$$

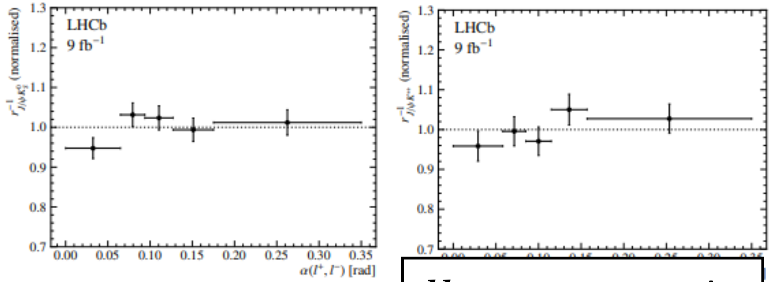
$$r^{-1}_{J/\psi K^{*+}} = 0.965 \pm 0.011\,(\text{stat.}) \pm 0.034\,(\text{syst.})$$

Stringent test

$$R^{-1}_{\psi(2S)K^0_S} = 1.014 \pm 0.030\,(\text{stat.}) \pm 0.020\,(\text{syst.})$$

$$R^{-1}_{\psi(2S)K^{*+}} = 1.017 \pm 0.045\,(\text{stat.}) \pm 0.023\,(\text{syst.})$$

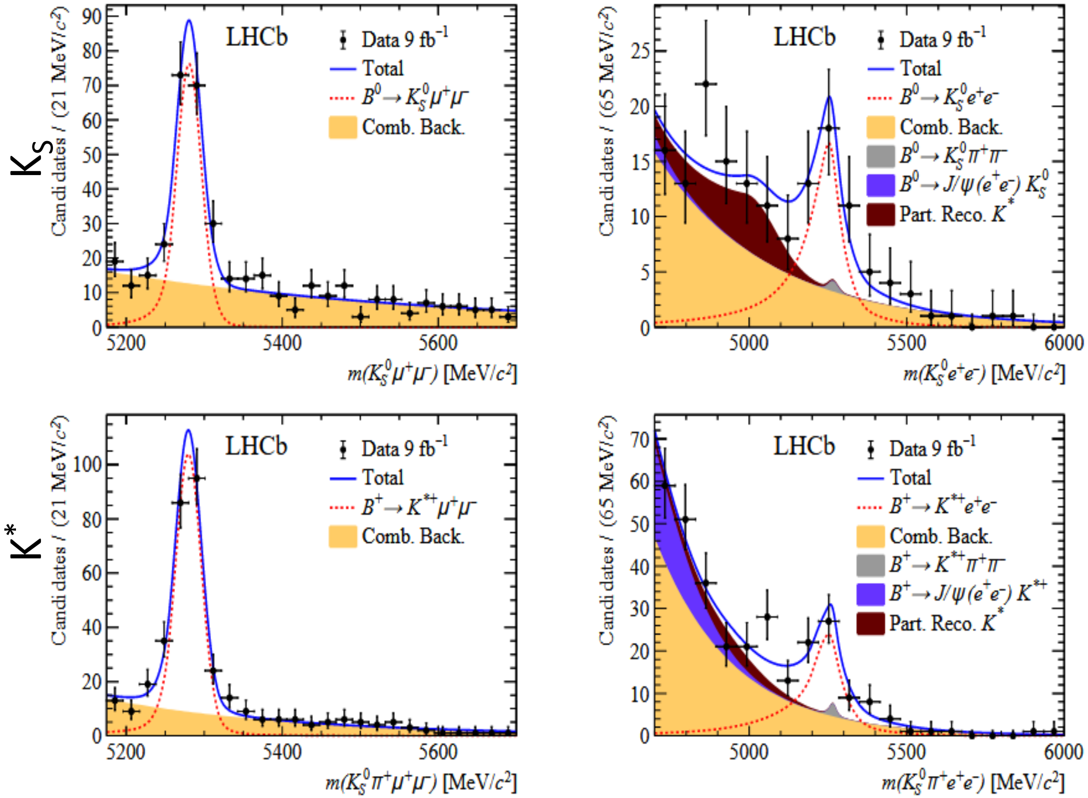



$ll$ opening angle

# Results

muons electrons




- First observation of $B^0 \to K_S e^+ e^-$ (5.3$\sigma$) and $B^+ \to K^+ e^+ e^-$(6.0$\sigma$)

$$\frac{d\mathcal{B}(B^0 \to K^0 e^+ e^-)}{dq^2} = (2.6 \pm 0.6\,(\text{stat.}) \pm 0.1\,(\text{syst.})) \times 10^{-8}\ \text{GeV}^{-2}c^4,$$

$$\frac{d\mathcal{B}(B^+ \to K^{*+} e^+ e^-)}{dq^2} = (9.2\,^{+1.9}_{-1.8}\,(\text{stat.})\,^{+0.8}_{-0.6}\,(\text{syst.})) \times 10^{-8}\ \text{GeV}^{-2}c^4,$$

- $R_{K_S}$ and $R_{K^{*+}}$

$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})\,,$$
$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})\,.$$

- Consistency with SM 1.5$\sigma$ and 1.4$\sigma$ respectively
- Systematics: statistical error on efficiency (2-3%), MC model for background (1-2%)
- NP: fit for $C_9^{NP} = -C_{10}^{NP}$ with “Flavio” yields 2$\sigma$ significance

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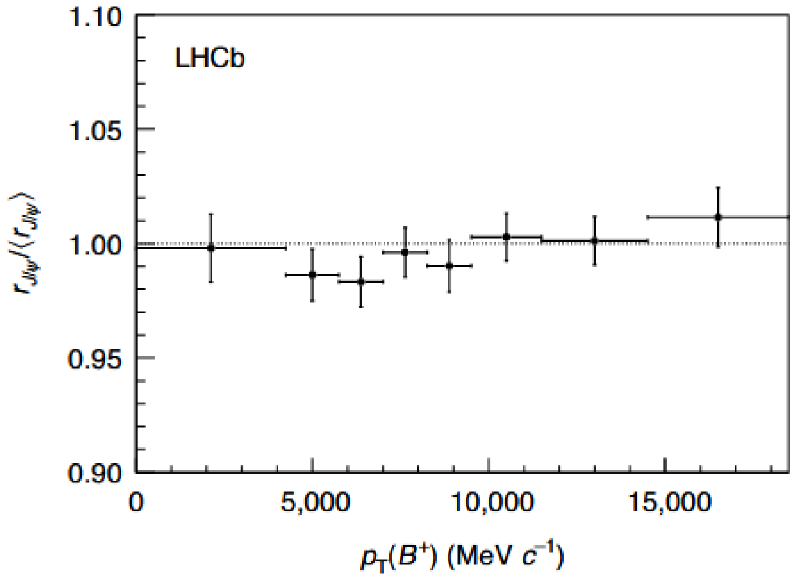
# Testing LFU in $B^+ \to K^+ll$

- Very similar analysis and reconstruction technique
  - $R_{K^+}$ extracted from a double ratio of resonant and non resonant decays
- Yield extraction
  - ML Fit to B meson invariant mass distribution
- Various Checks using $J/\psi$ and $\psi(2S)$ control samples
  - $R_{J/\psi} = 0.981 \pm 0.020$ (single ratio)
  - $R_{\psi(2S)} = 0.997 \pm 0.011$ (double ratio)

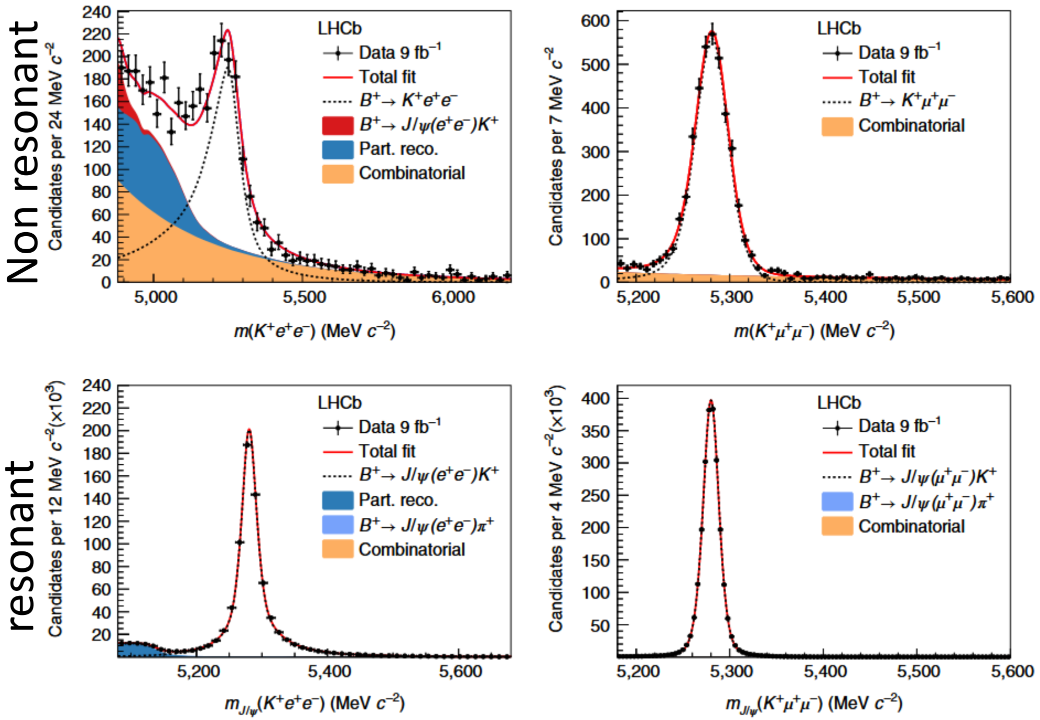



$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

Nat. Phys. 18, 277 282 (2022) $9\,\mathrm{fb}^{-1}$

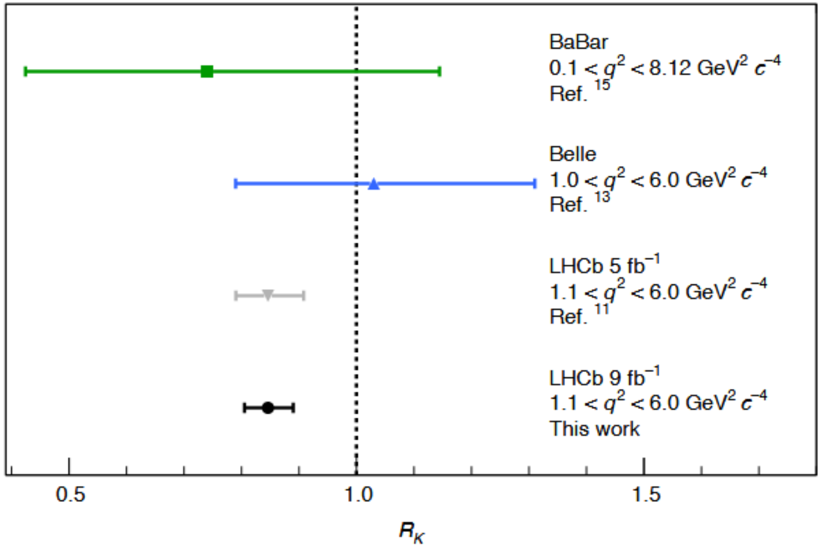
# Results of LFU in $B^+ \to K^+ll$

electrons muons




- Combined ML fit to invariant mass
- LFU violation at $3.1\sigma$
- Comparison between $R_K$ measurements

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




$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2\,c^{-4}) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

# LFU tests in $b \to sll$

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2},$$

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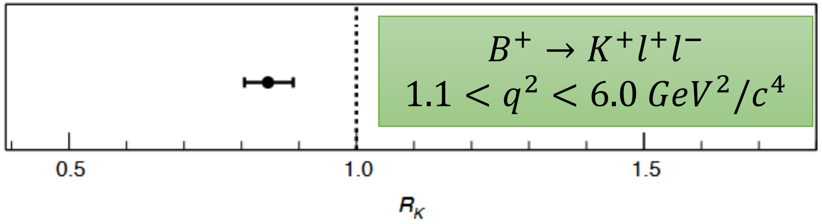


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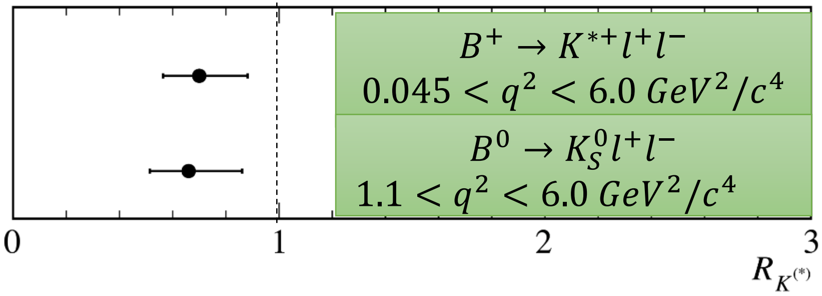
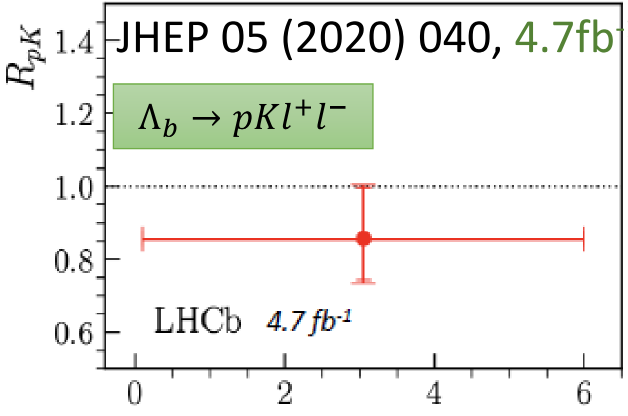
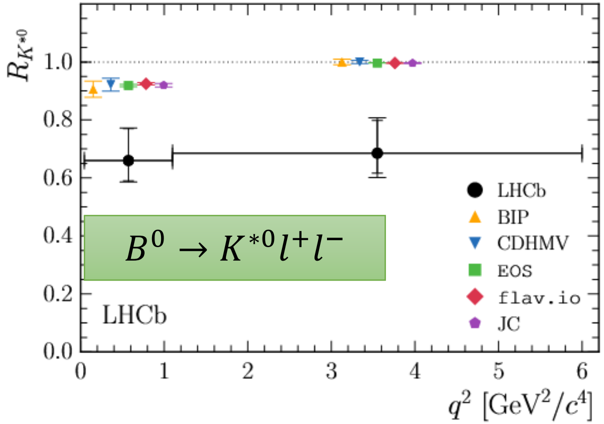



JHEP 05 (2020) 040, 4.7fb$^{-1}$




JHEP 08 (2017) 055, 3fb$^{-1}$

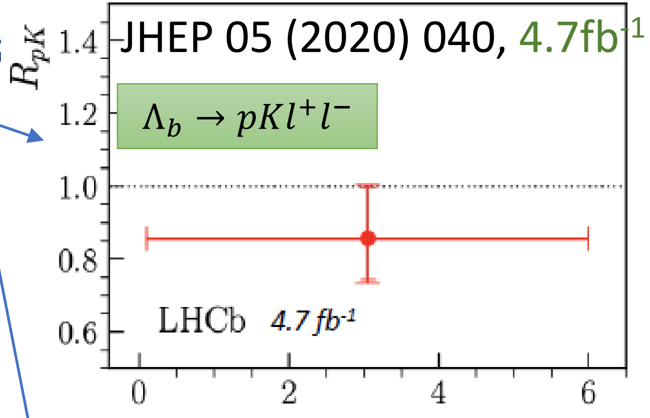



- Intriguing hints of a pattern of suppression of muons vs electrons
- Difficult measurements yet statistically limited
- More data and more measurements will help in clarifying the situation
- Improved analyses and more control checks

# LFU tests in $b \to sll$

$$R_H \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2},$$

- An update to the full run2 statistics is in preparation
- Measurement of $D_s \to \phi(l^+l^-)\pi$
  - a stringent test of the control on electron reconstruction at low $q^2$
- Run3 will be crucial to clarify the picture on $b \to sll$ anomalies

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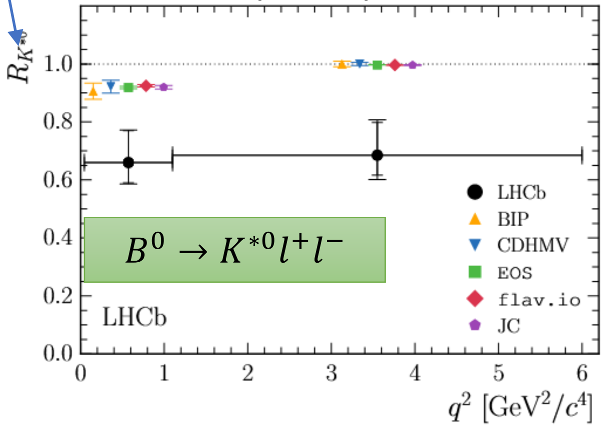
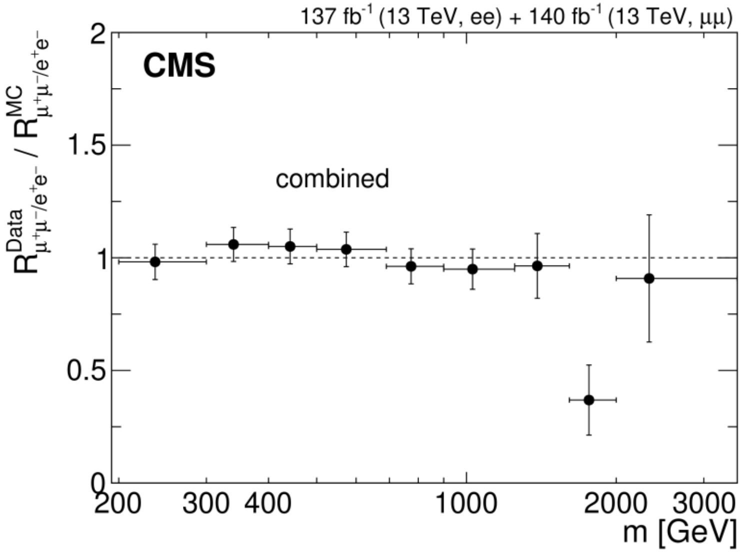


# LFU test with di-leptons at high mass

- The hits of LFU violation presented have sparked interest in models that could explain them
  - E.g. leptoquarks[JHEP 11 (2016) 035], heavy neutral gauge bosons [Rev. Mod. Phys. 81 (2009) 1199]

- Some models result in $R_{\mu^+\mu^-/e^+e^-} = \frac{\frac{d\sigma(q\bar{q}\to\mu^+\mu^-)}{dm_{ll}}}{\frac{d\sigma(q\bar{q}\to e^+e^-)}{dm_{ll}}}$ being different form 1 at high $m_{ll}$

- CMS tested LFU by measuring $R_{\mu^+\mu^-/e^+e^-}$ with 137(140) fb$^{-1}$ in the $e^+e^-(\mu^+\mu^-)$ channel
  - First test of LFU in these final states at CMS



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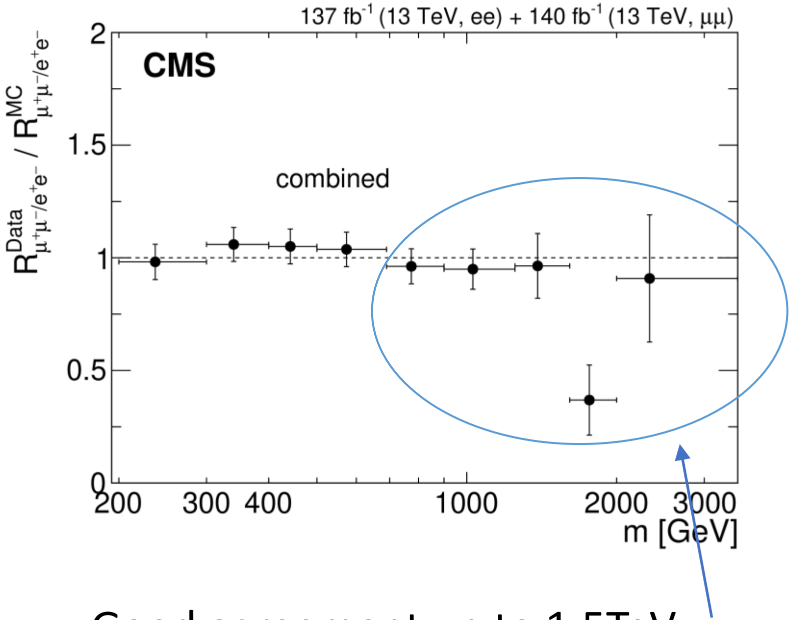
# LFU test with di-leptons at high mass

- $R_{\mu^+\mu^-/e^+e^-} = \dfrac{\frac{d\sigma(q\bar{q}\to\mu^+\mu^-)}{dm_{ll}}}{\frac{d\sigma(q\bar{q}\to e^+e^-)}{dm_{ll}}}$
- Subtract all background except for DY
- Correct for resolution, acceptance and efficiency
- To correct for differences between electrons and muons
  - Normalize R to 1 in the mass region 200–400 GeV, assuming departures from 1 are negligible in this region [EPJC 77 (2017) 548]
  - Correct for remaining differences using simulated DY events (up to 20% for forward leptons)
  - Uncertainties from PDF cancel out in the ratio




Good agreement up to 1.5TeV
Some deviations at high masses point to an excess of electrons w.r.t. muons (stat limited)

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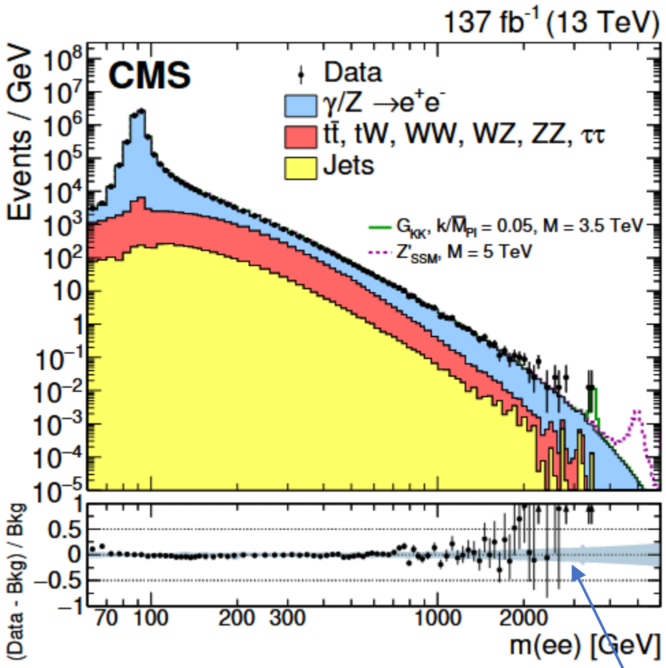


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# Conclusions, Summary, Outlook

- ATLAS and CMS tested LFU in W boson decays addressing a long-standing tension observed at LEP
  - Found results consistent with the SM.
- LHCb tested LFU in semi-leptonic decays of baryons for the first time.
  - Found a result consistent with the SM at the $1\sigma$ level, with decay involving $\tau$ suppressed w.r.t $\mu$
  - Could give complementary information w.r.t. mesons
- LHCb tested LFU in $B^0 \to K_S ll$ and $B^+ \to K^{*+} ll$ with the full dataset
  - Consistent with SM at $1.5\sigma$ and $1.4\sigma$ level
  - Most precise single measurement
- LHCb tested LFU $B^+ \to K^+ ll$ with the full dataset
  - Observed a tension in LFU with SM at 3.1 $\sigma$ level
  - Same pattern as other $b \to sll$ tests: muons are suppressed w.r.t electrons
- More $R_H$ measurements ongoing, including angular analysis
- CMS Tested LFU with dileptons at high mass for the first time
  - found hints of excess of electrons w.r.t. muons at high masses
- More data coming soon with upgraded detectors in run3
- Look forward also at Belle II results

# Backup