Tests of Lepton Flavor Universality at LHCb

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Outline

- Introduction

  - Lepton flavour universality (LFU)

  - LHCb detector

- LFU violation in $b \to cl\nu$ decays

  - R(D), R(D^*) and R(J/ψ)

- LFU violation in $b \to sll$ decays

  - R(K) and R(K^*)

- Outlook and summary

Introduction

Lepton Flavour Universality in the SM

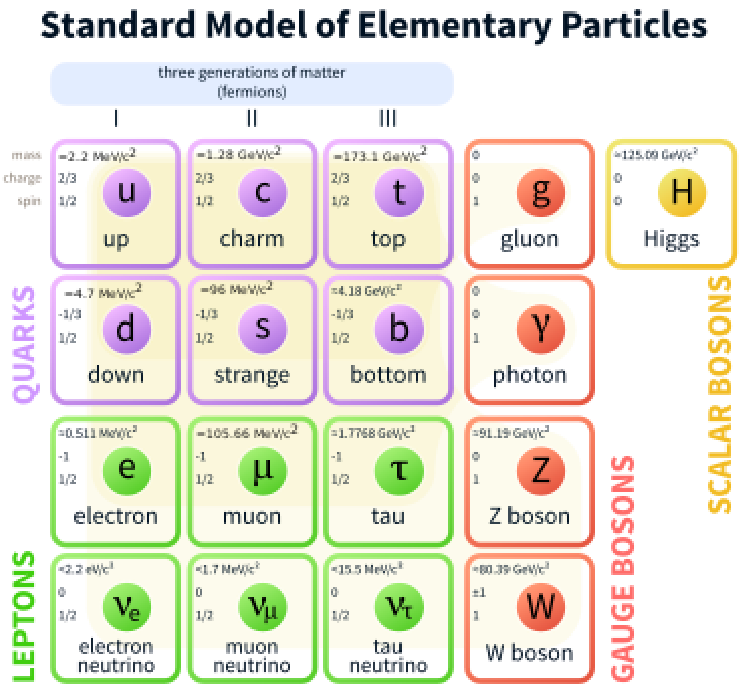
Standard Model (SM):
quarks and leptons exist in three generations with two members each

SM: Lepton Flavour Universality is assumed

→ the gauge couplings are equal for the 3 generations

→ the three generations differ only by the different masses

Tests of LFU probe the validity of the SM



Some SM extensions include particles that can cause LUV or LFV (e.g. LQ, Z′)

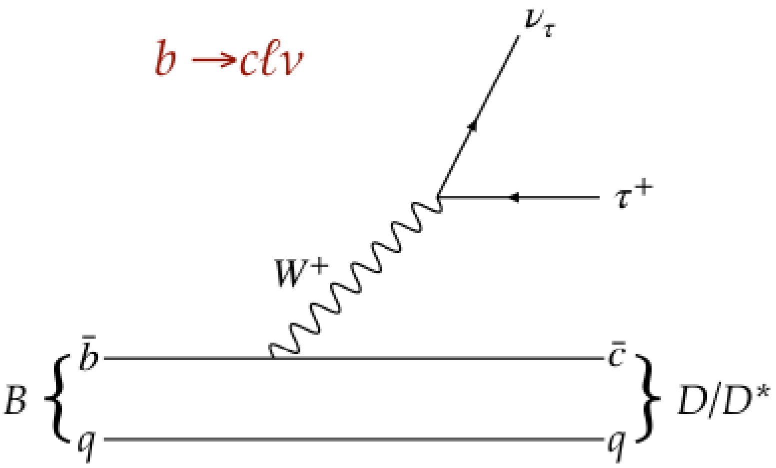
Processes with 3rd generation of quarks and leptons (*B* and *τ*) are well suited for LFU violation search:

- lower experimental constraints
- stronger couplings to 3rd generation predicted by BSM theories with LFU violation

Tests of LFU in *b* decays

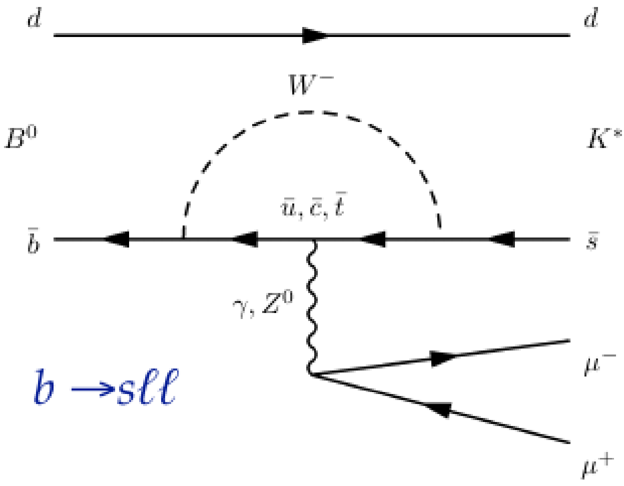
Charged current (Semileptonic decays)
tree-level decays *b* → *clν*

- BR of of few %
- precise prediction in SM
- BSM theories predict enhanced coupling with 3rd generation →
- → interested in testing τ vs μ / e
- NP sensitivity up to ~ 1 TeV



Neutral currents (Rare decays, RD)
b → *sll*

- forbidden at tree-level in the SM
  → FCNC only at loop level
  → BR $10^{-7} \div 10^{-6}$
- sensitive to NP in loops
- NP sensitivity up to ~ 100 TeV



LHCb detector

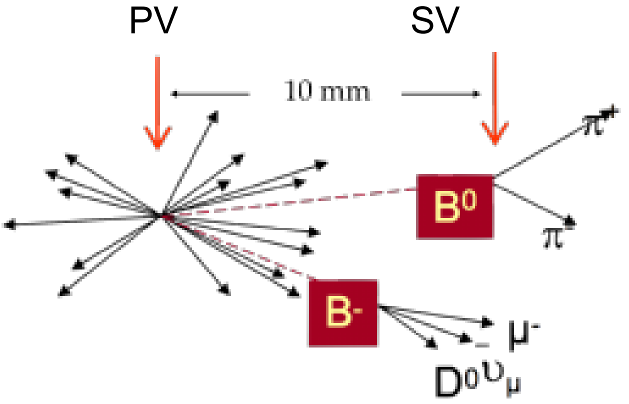
Int. J. Mod. Phys. A 30 (2015) 1530022

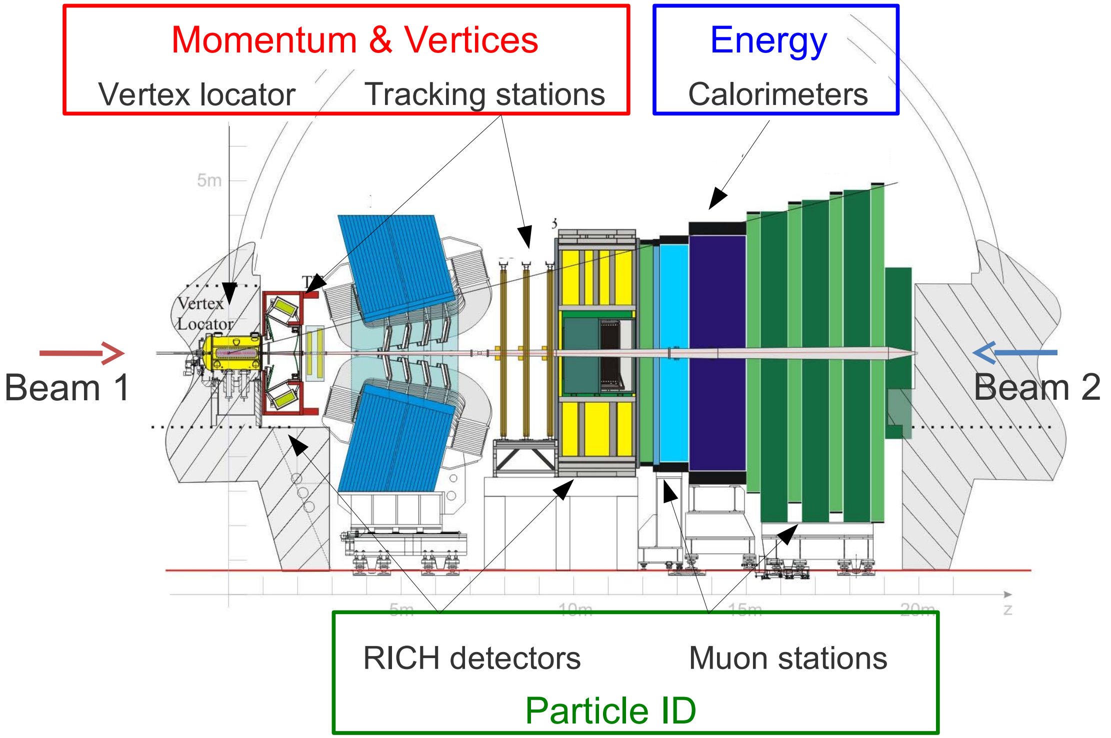
single arm spectrometer – designed for precision measurements in *b* and *c* physics
fully instrumented in the forward region ($2 < \eta < 5$)

25% of *bb*-bar pairs in LHCb acceptance

so far > 10^{12} *bb*-bar pairs

large boost → B mesons fly 1 cm





Momentum & Vertices

Vertex locator

Tracking stations

Energy

Calorimeters

Beam 1

Beam 2

RICH detectors

Muon stations

Particle ID

precise tracking → excellent resolution

- momentum ($\Delta p/p \sim 0.4\%$ at 5GeV)

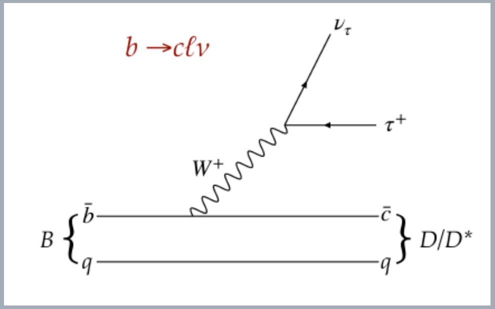
-IP (20μm for high-p_T tracks)

- decay time (~45fs) resolution

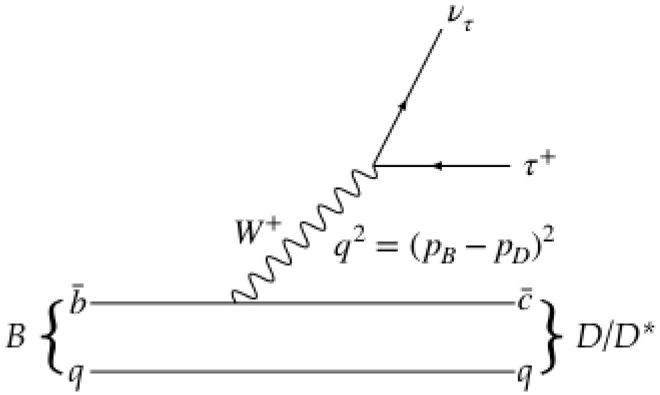
excellent particle identification

- π/K separation over 2-100 GeV
  ($\varepsilon_K \sim 90\%$ for ~5% $\pi \to K$ mis-id)
- powerful muon id
  ($\varepsilon_\mu \sim 97\%$ for ~1–3% $\pi \to \mu$ mis-id)

LFU violation in $b \to clv$ decays



Semileptonic b-decays – R(D^*)



q^2= transferred 4 momentum by the W to the lepton system

final state with leptons and hadrons

measure ratio of branching fractions (BF)

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)} \tau \bar{\nu}_\tau)}{BR(B \to D^{(*)} \mu \bar{\nu}_\mu)} \begin{matrix} \leftarrow \text{signal} \\ \leftarrow \text{normalization} \end{matrix}$$

→ reduced experimental uncertainties
→ theoretically clean:
dependence from |V_{cb}| cancelled
partially cancel model uncertainties

SM: R(D*) = 0.252 ± 0.003

Phys.Rev.D85(2012) 094025

tau reconstruction: $\tau \to \mu\nu_\tau\nu_\mu$ or: $\tau \to 3h\nu_\tau$
main experimental challenge: neutrino(s) in the final state → no narrow peak to fit

main backgrounds:
- partially reconstructed B-decays
- combinatorial background
- mis-identification background

R(D^*) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs)

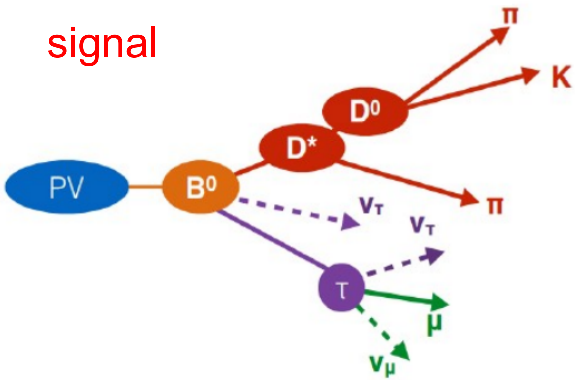
R(D^*) in muonic τ decays

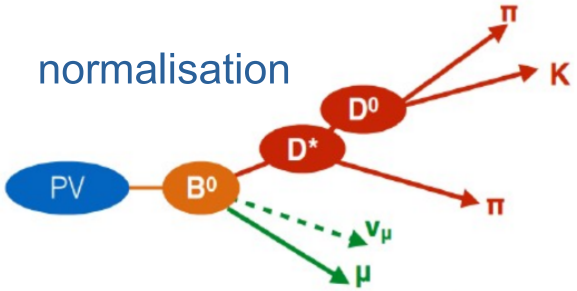
$$R(D^*) = \frac{BR(B \to D^* \tau \bar{\nu}_\tau)}{BR(B \to D^* \mu \bar{\nu}_\mu)}$$

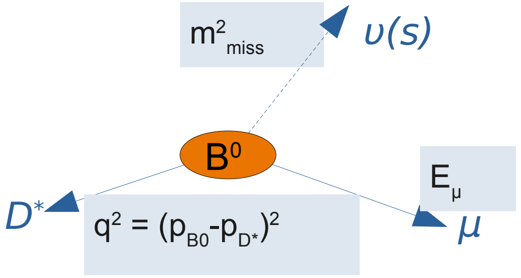
τ reconstruction: $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$

→ signal and normalisation channel have the same visible final state ($K\pi\pi + \mu$)

separation signal-normalisation using three kinematic variables sensitive to
- μ-τ mass difference
- presence of extra neutrinos


signal


normalisation



- $E^*_\mu = E_\mu$ in B^0 rest frame
- $m^2_{miss} = (p_{B0} - p_{D^*} - p_\mu)^2$
- $q^2 = (p_{B0} - p_{D^*})^2$ = squared 4-momentum transfer to the lepton system

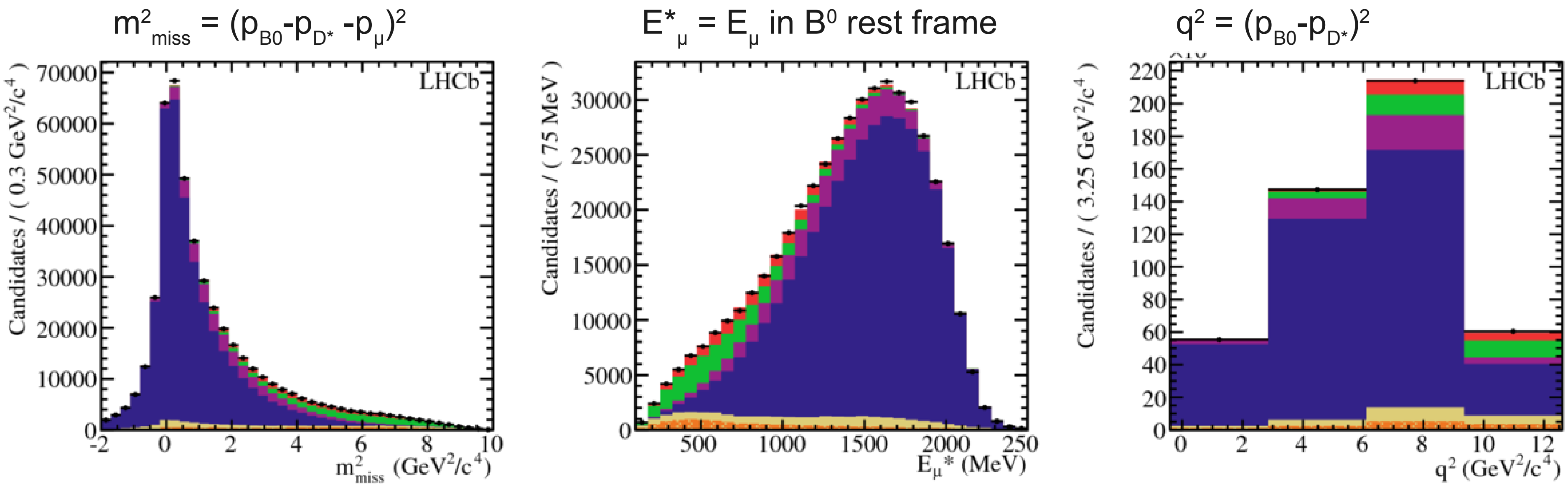
R(D^*) in muonic τ decays

[PRL115(2015)111803]

Separate τ signal from μ normalisation with 3D binned template fit
Background and signal shapes extracted from control samples and simulations

τ signal
normalisation
Backgrounds:
feed-down from excited D states, double charm (DD), combinatorial, muon mis-ID

R(D^*) =0.336±0.027±0.030, 1.9σ above the SM



$m^2_{miss} = (p_{B0}-p_{D^*}-p_\mu)^2$

$E^*_\mu = E_\mu$ in B^0 rest frame

$q^2 = (p_{B0}-p_{D^*})^2$

R(D*) in hadronic τ decays

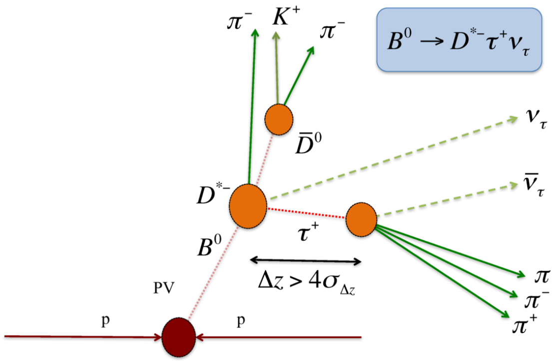
$$R(D^*)=\frac{BR(B\to D^*\tau\bar{\nu}_\tau)}{BR(B\to D^*\mu\bar{\nu}_\mu)}$$

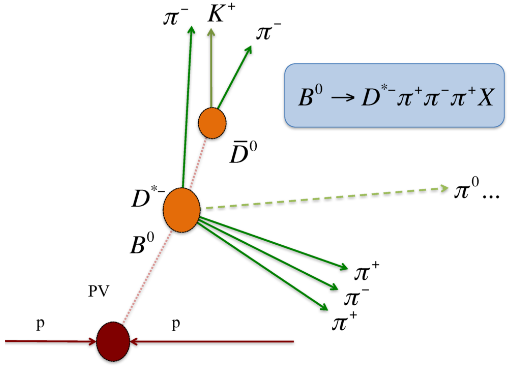
τ reconstruction: $\tau^-\to\pi^-\pi^+\pi^-\nu_\tau$

normalisation channel with same visible final state $B^0\to D^*\pi\pi\pi$
→ reduce systematic uncertainties

measure $\kappa=\frac{BR(B\to D^*\tau\bar{\nu}_\tau)}{BR(B\to D^*3\pi)}=$

$$\frac{N(D^*\tau\bar{\nu}_\tau)}{N(D^*3\pi)}\times\frac{\epsilon_{D^*3\pi}}{\epsilon_{D*\tau\bar{\nu}_\tau}}\times\frac{1}{BR(\tau\to3\pi(\pi^0)\nu)}$$





$$R(D^*)=\underbrace{\frac{BR(B\to D^*\tau\bar{\nu}_\tau)}{BR(B\to D^*3\pi)}}_{\text{measured ratio }\kappa}\underbrace{\frac{BR(B\to D^*3\pi)}{BR(B\to D^*\mu\nu_\mu)}}_{\text{external inputs}}$$

4% precision, BaBar, Belle, LHCb
2% precision, HFLAV 2016

partial cancellation of experimental systematic uncertainties

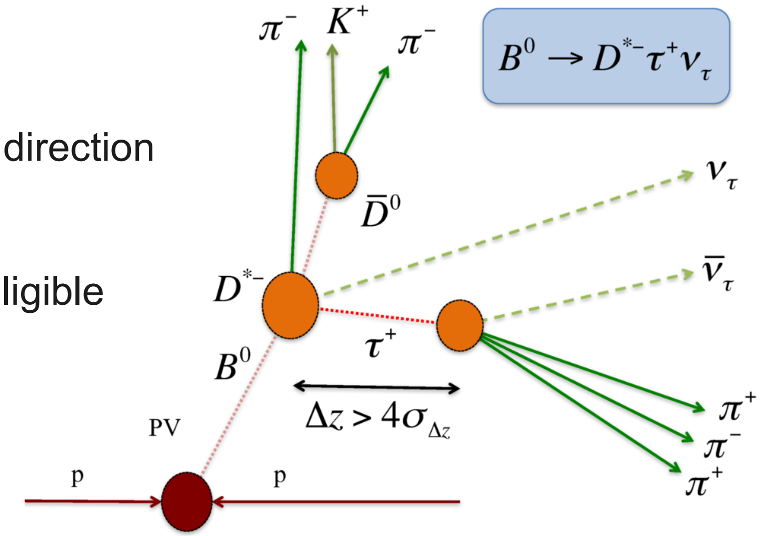
R(D*) in hadronic τ decays

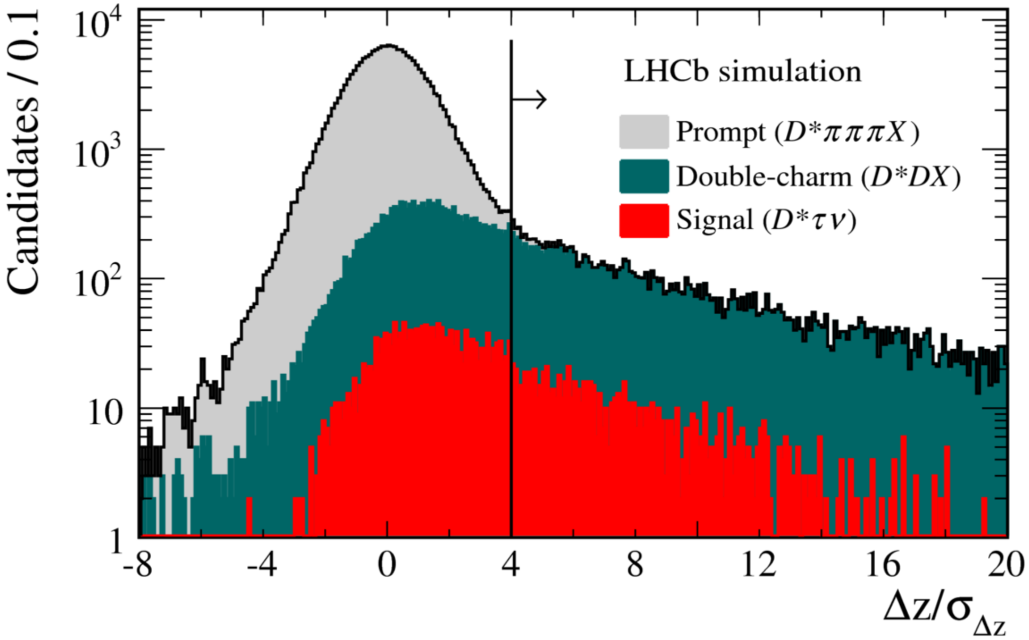
[PRL 120,171802, 2018], [PRD 97,072013 2018]

most abundant background
partially reconstructed B → $D^*3\pi X$ (BR ~ 100× signal)
suppressed with cut on τ decay time, t_τ

require τ vertex to be downstream wrt B vertex along beam direction
Δz > 4σΔz improves S/B by 160

remaining background: doubly charmed decay with non-negligible lifetime, estimated with BDT
B → D^*D_sX, D^*D^+X, D^*D^0X ~ 10× signal





R(D*) in hadronic τ decays

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

Yields:
N($D^*3\pi$) from an un-binned likelihood fit to $m(D^*3\pi)$

N($D^*\tau\nu$) yield extracted by a binned ML fit

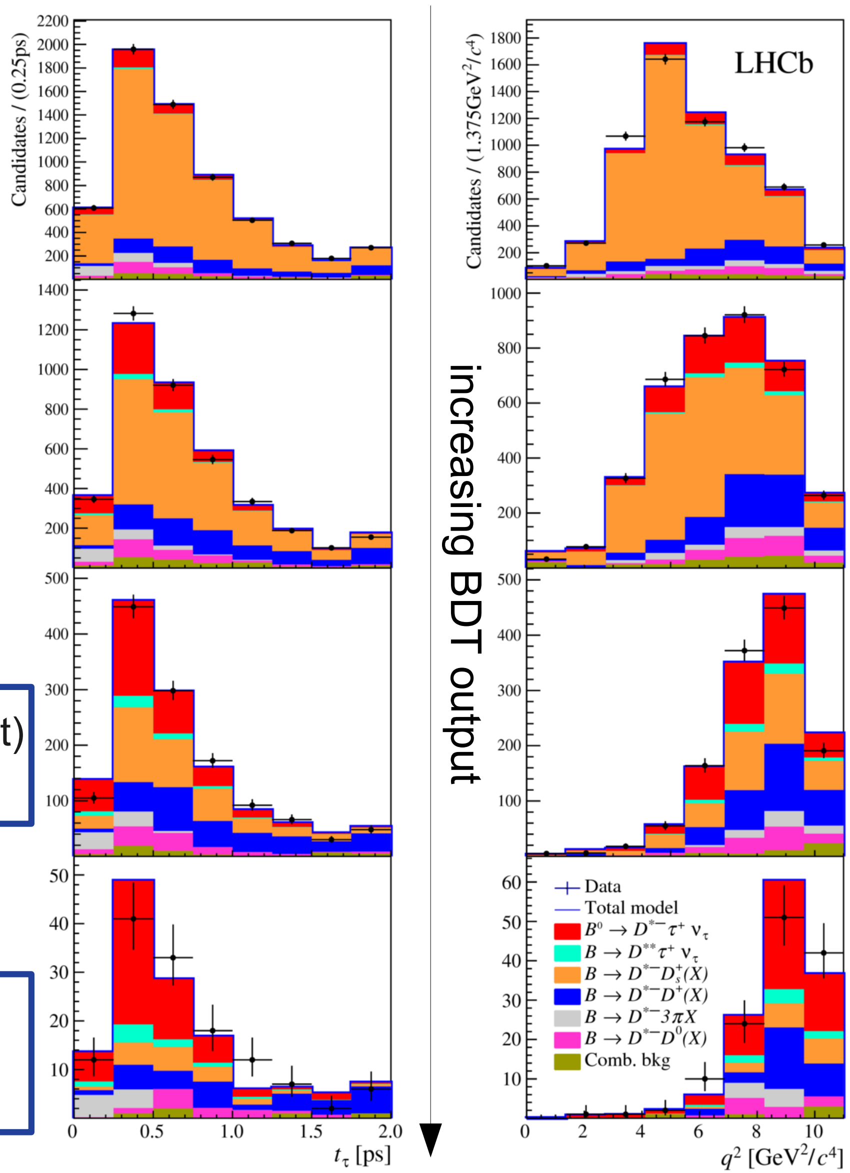
- q^2 transferred momentum to the lepton system
- BDT against double charm background
- t_τ against D^*D^+X

with increasing BDT output
→ increase in signal purity
→ decrease of D^*D_s component
high BDT D^*D^+ background dominant

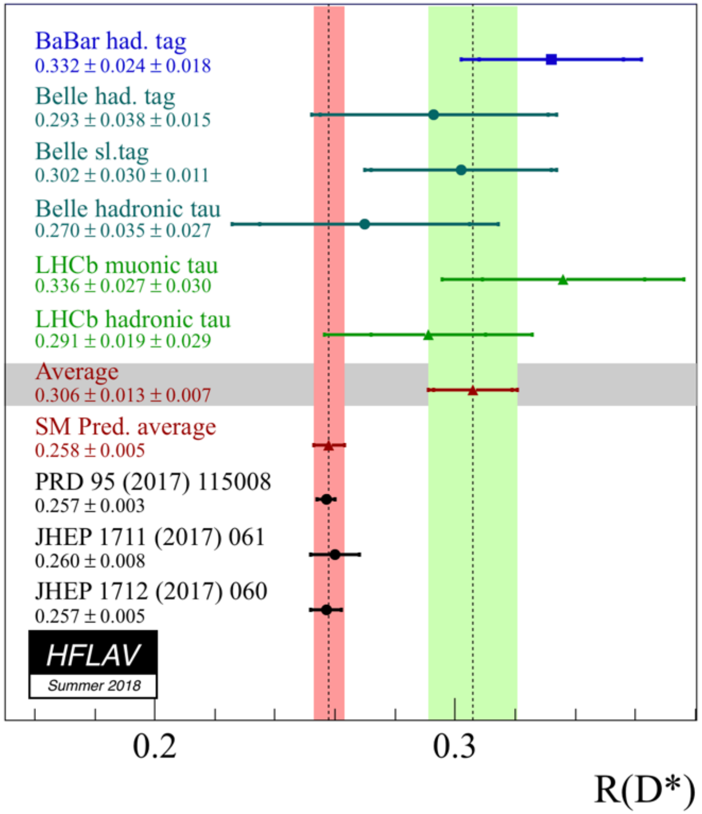
R(D^*) = 0.291 ± 0.019(stat) ± 0.026 (syst) ± 0.013 (ext)
1σ above SM

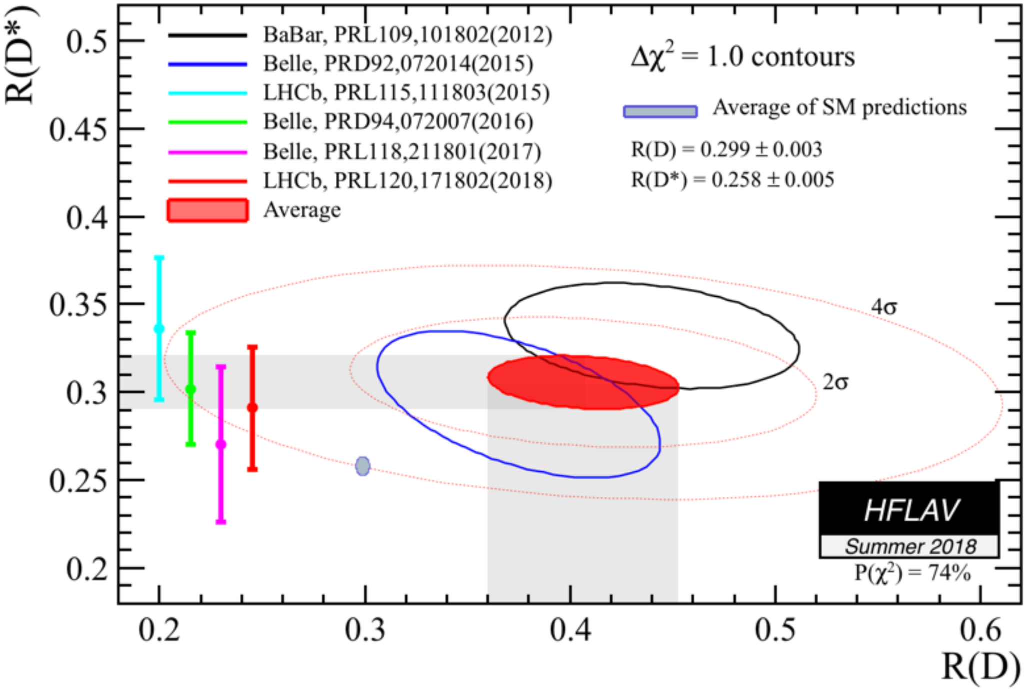
main systematic uncertainty:
size of the simulated sample

LHCb average:
R(D^*) = 0.310 ± 0.016 (stat) ± 0.022 (syst)
2.2σ above SM



R(D) and R(D*) results



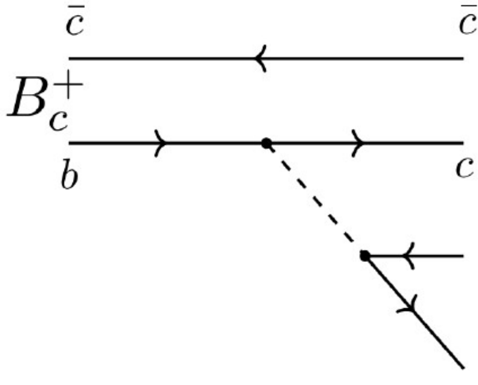


3 experiments, six measurements → all R(D^*) measurements lie above the SM expectation (0.258 ± 0.005)
[PRD95, 115008 (2017)], [JHEP 1711 (2017) 061], [JHEP 1712 (2017) 060]

R(D^*) world average: 3.0 σ above SM prediction

combining R(D) + R(D^*) measurements: overall tension with SM of 3.8σ

$R(J/\psi)$ - $B_c \rightarrow J/\psi\, l\nu$



R(J/ψ) results

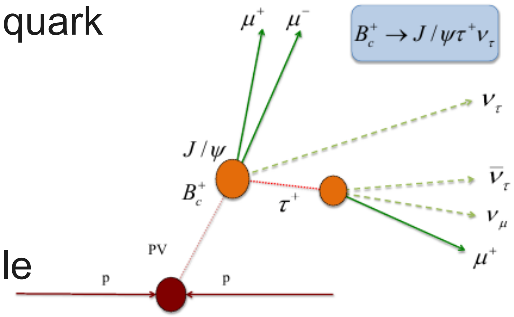
$$R(J/\psi) = \frac{BR(B_c^+ \to J/\psi\, \tau \bar{\nu}_\tau)}{BR(B_c^+ \to J/\psi\, \mu \bar{\nu}_\mu)}$$

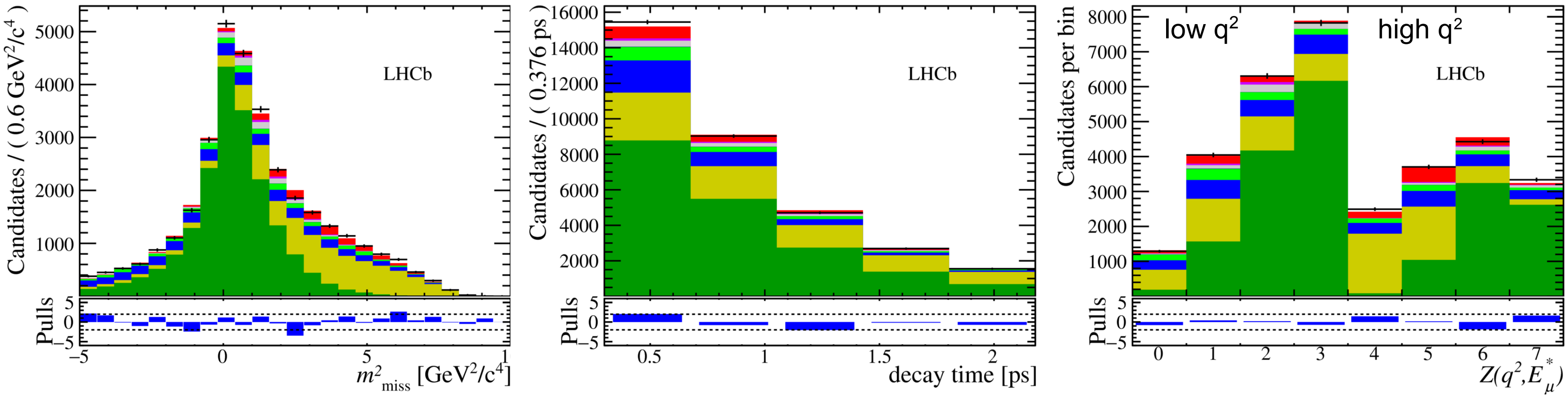
PRL 120, 121801 (2018)

R(J/ψ) : test of LFU in semileptonic decays with a different spectator quark

τ reconstruction: $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$
final state with three visible muons
→ first study of the semitauonic decay of B_c

analysis strategy as in R(D^*) decay time as 4th discriminating variable





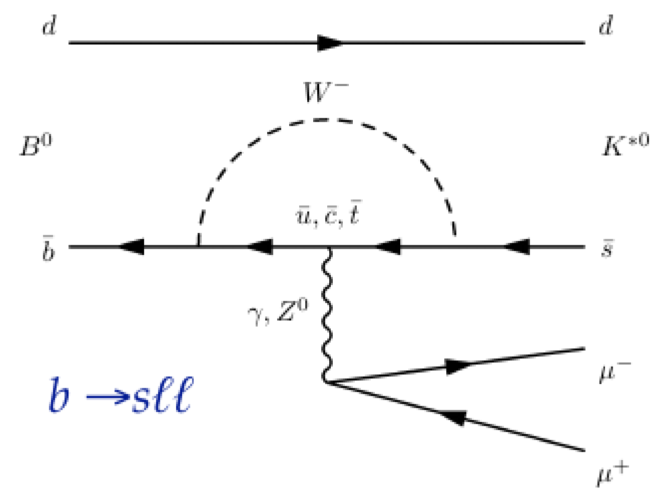
main backgrounds: $B \to J/\psi$ + mis-ID hadron
systematic: MC sample, $B^+_c \to J/\psi$ form factors

R(J/ψ) = 0.71 ± 0.17(stat) ± 0.18(syst)

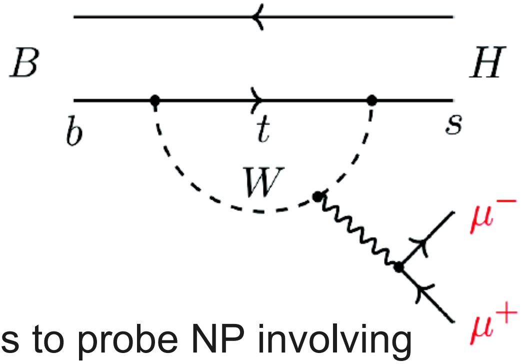
→ first evidence (3σ) of $B^+_c \to J/\psi\ \tau\ \nu_\tau$

SM prediction 0.25-0.28 (form factor uncertainty)

LFU violation in *b*→*sll* decays



LFU tests in *b*→ *sll* transition



decay not allowed at tree level
→ highly sensitive to virtual particles and interactions
- NP effects can be sizeable compared to the *b*→*sll* SM amplitude
- probe models with e.g. charged Higgs, Z' bosons or leptoquarks

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

$$R(K^{(*)}) = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)} = 1 \pm \underbrace{O(10^{-3})}_{\text{neglect lepton mass}} \pm \underbrace{O(10^{-2})}_{\text{QED}}$$

EPJ C76 (2016) 8, 440

measure R as a double ratio to reduce systematic effects
due to differences between electrons and muons

$$R(K^{(*)}) = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}J/\psi(\to \mu\mu))} \frac{BR(B \to K^{(*)}J/\psi(\to ee))}{BR(B \to K^{(*)}ee)}$$

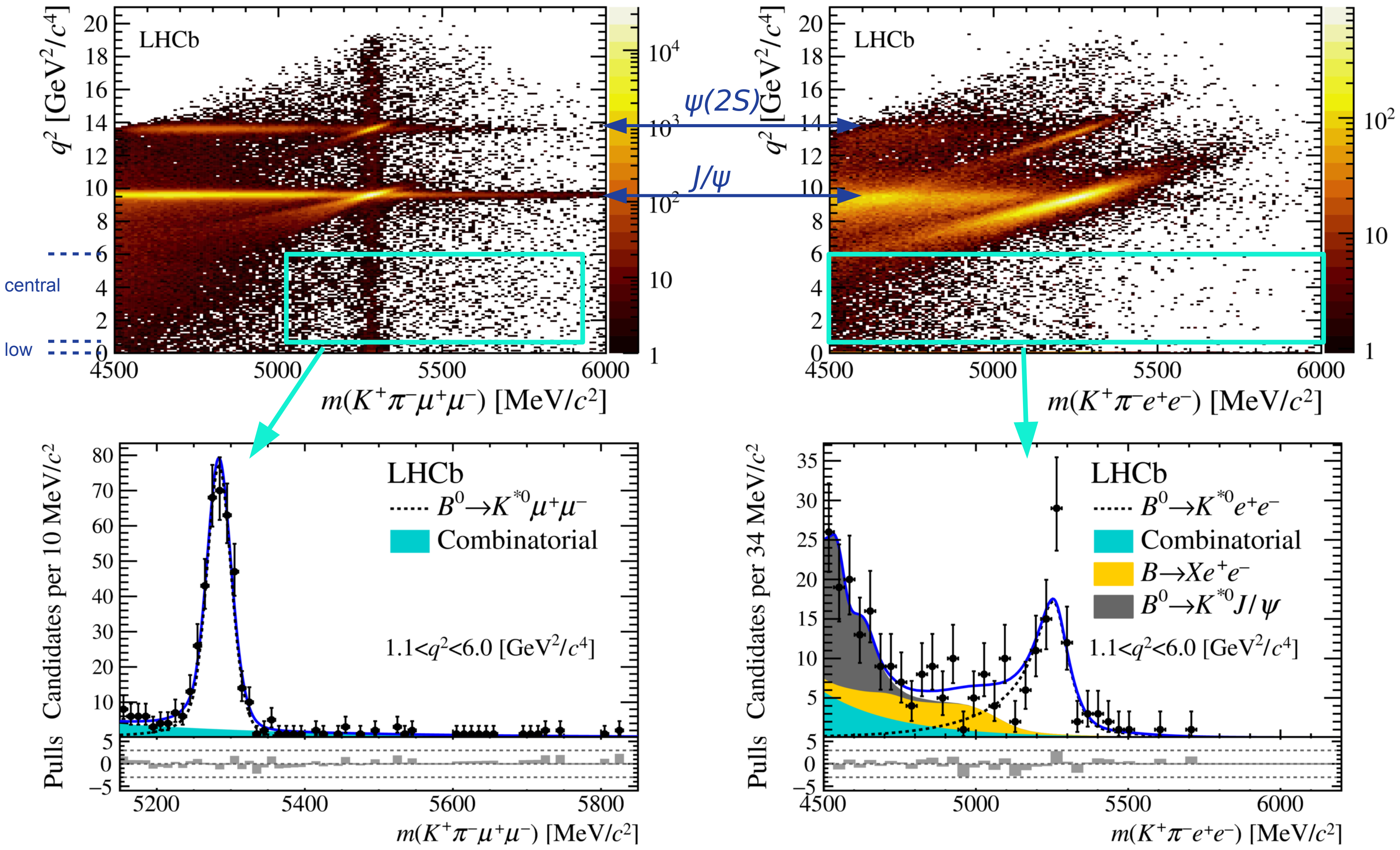
but electrons are difficult to measure at LHCb: trigger, Bremsstrahlung ...

$R(K^*)$ - B→ $K^*(\rightarrow K^+\pi^-)$ *ll*

JHEP 08 (2017) 055

muons

electrons

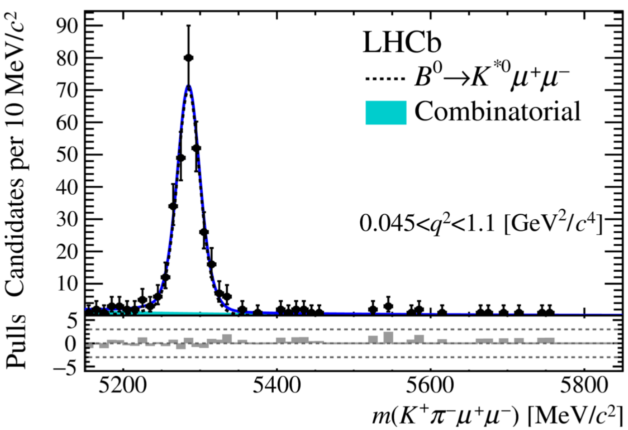


LHCb R(K^*) - $B\to K^*(\to K^+\pi^-)\ ll$

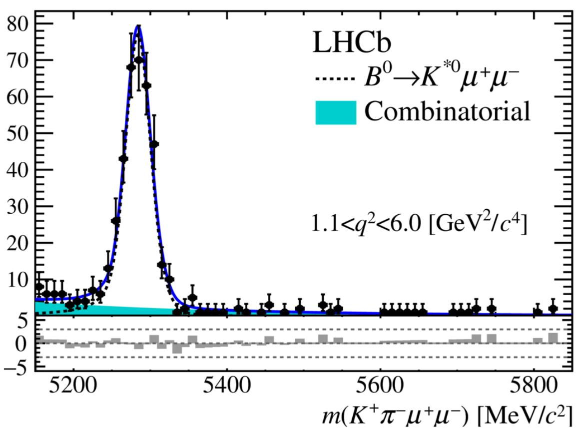
JHEP 08 (2017) 055

Event yield obtained from simultaneous fit of M($K\pi ll$) to the J/ψ and non-resonant channels in two regions of q²: [0.045-1.1], [1.1-6.0]

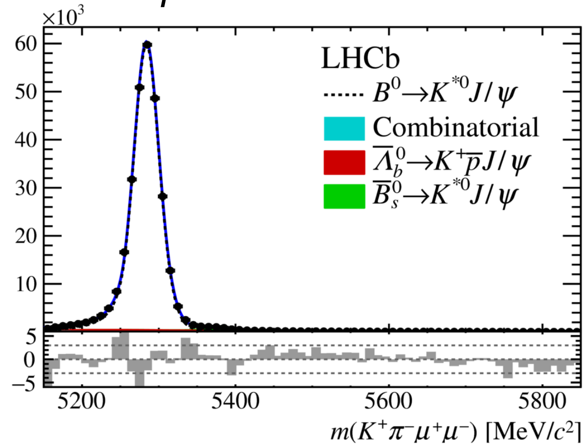
Muons low q² 285±18



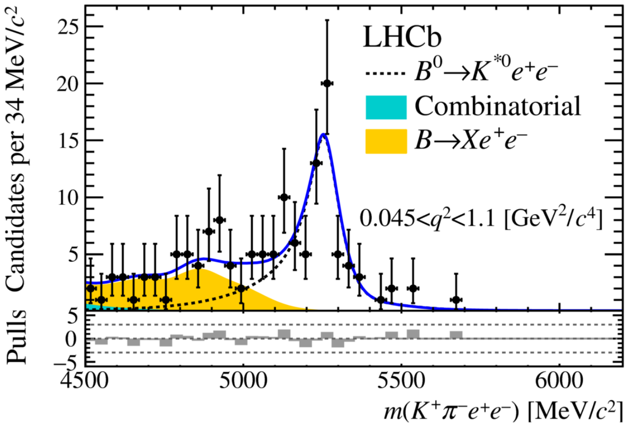
central q² 353±21



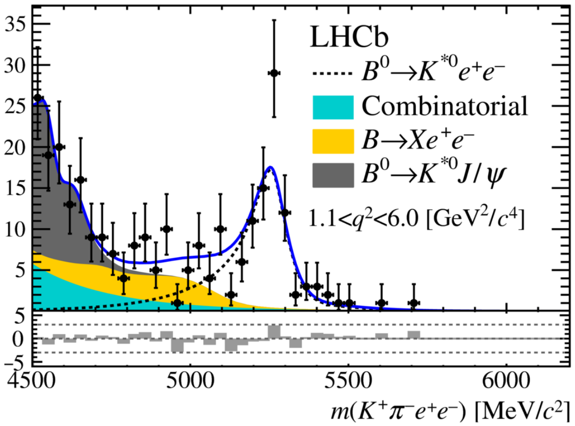
J/ψ 274000



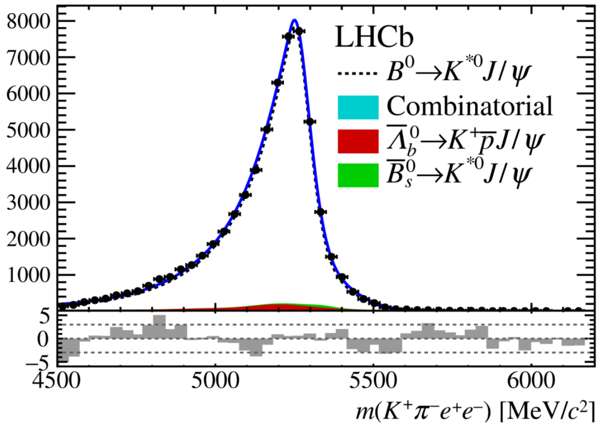
Electrons low q² 89±11



central q² 111±14

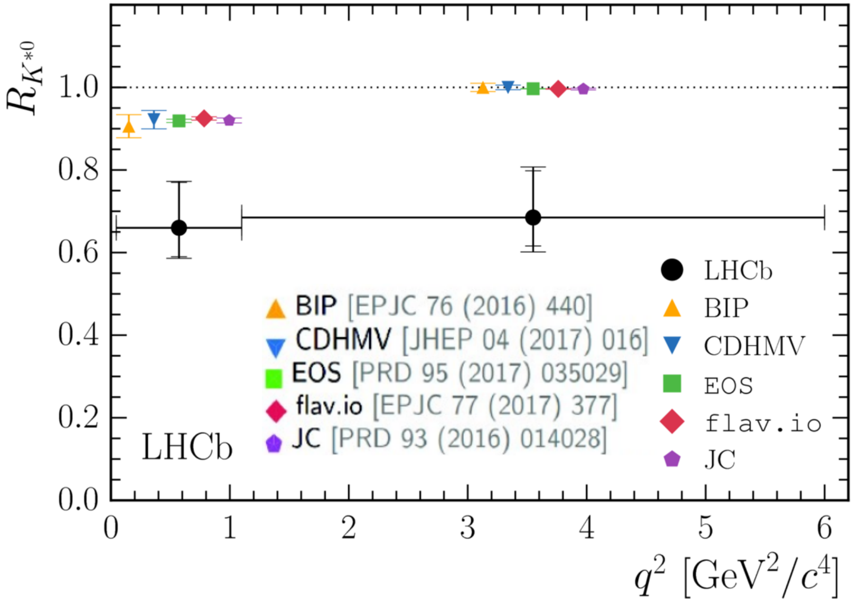


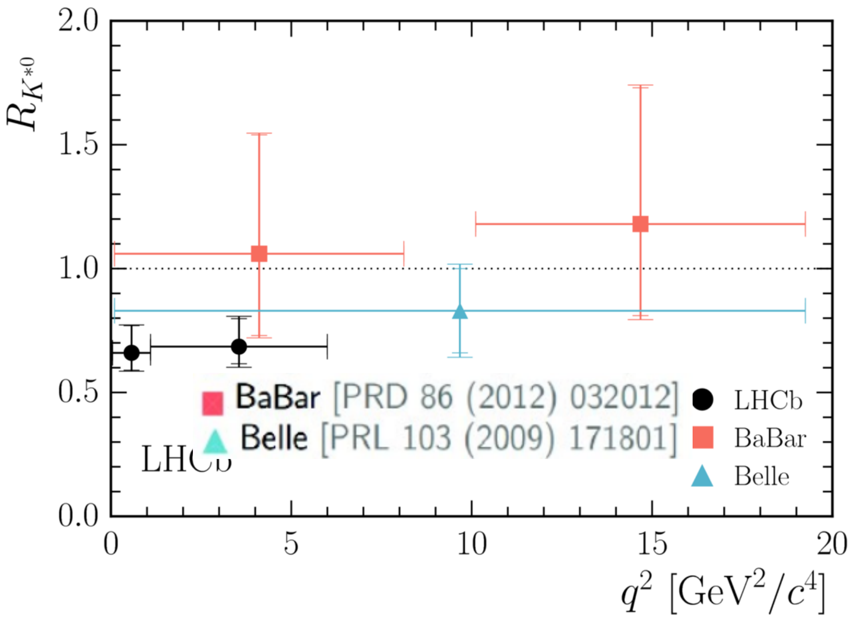
J/ψ 58000



R(*K**) results

JHEP 08 (2017) 055





$$\boxed{R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}), & \text{at low } q^2 \ (\sim 2.2\sigma \text{ below SM}) \\ 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}), & \text{at central } q^2 \ (\sim 2.4\sigma \text{ below SM}) \end{cases}}$$

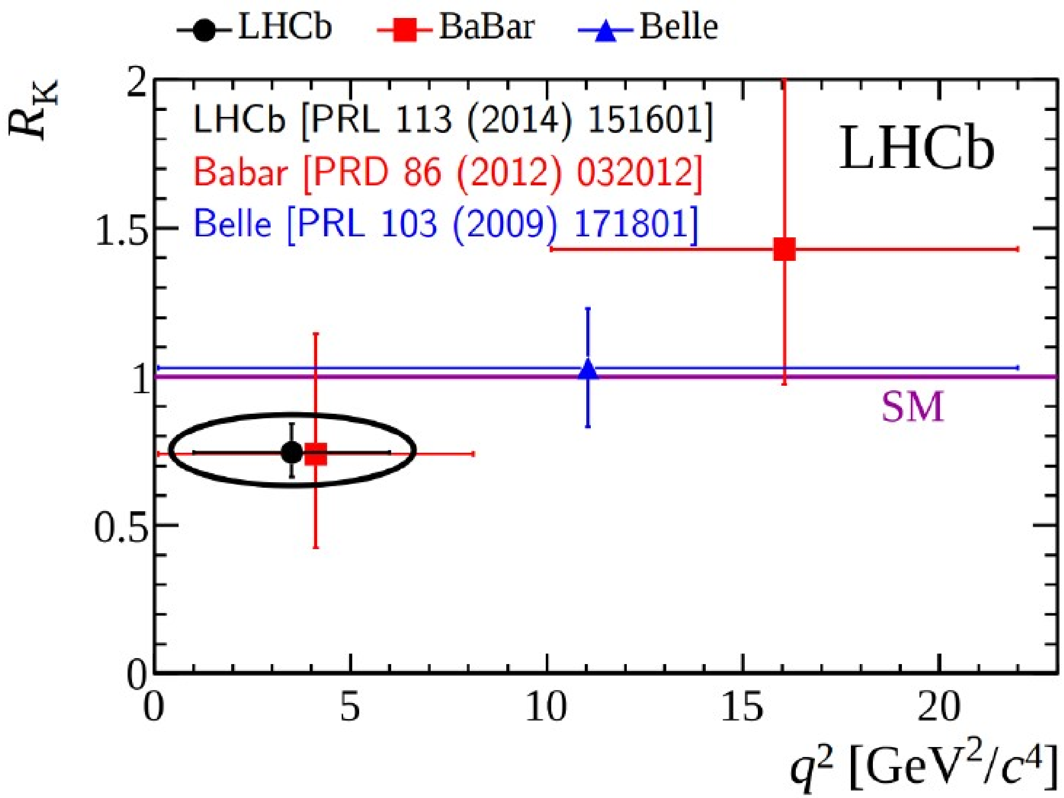
Most precise measurement to date, compatible with BaBar and Belle
statistically limited by the electron sample

R(*K*) results

$$R(K) = \frac{BR(B^+ \to K^+ \mu\mu)}{BR(B^+ \to K^+ e\, e)}$$

PRL 113, 151601 (2014)

measurement in central q^2 bin 1-6 GeV^2/c^4
3 fb, dominated by statistical uncertainty of electon mode (172 events)



$R(K) = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ ~ 2.6 σ below SM prediction

SM prediction for R(K) = 1.00 ± 0.01
[Bordone, Isidori Eur.Phys.J. C76 (2016) no.8, 440]

Prospects for LFU measurements at LHCb

aim to perform complementary LFU tests:

- *b* → *clν* transitions:
  R(*Λ**), R(D_s), R(D_s*) and others

- *b* → *ulν* transitions:
  R(*ππ*) = B($B^+ \to \pi\pi\tau\nu$) /B($B^+ \to \pi\pi\mu\nu$) and others

- *b* → *sll* transitions:
  R(*Kππ*), R(*pK*) , R(*φ*) , R(Λ_b) are analysed
  direct fit to $\Delta C_9^{\mu,e}$ and others

→ update of R(*K*), R(*K**), R(*D**) and R(*J/ψ*) with Run 2 data is currently on-going with four times more statistics
→ expected improvement on statistical and systematic uncertainties

Conclusions

Tests of LFU are excellent ways to look for new physics in a complementary way w.r.t. direct searches

Tests of LFU in heavy flavour physics show a tension with the SM predictions that seem to form a coherent pattern:

ratios of branching fractions in $b\to c l\nu$ and $b\to s l l$

- 3.8σ tension in R(D) and R(D^*) when combining BaBar, Belle and LHCb

  PRL115(2015)111803, [PRL 120,171802, 2018], [PRD 97,072013 2018]

- ~2.5σ below SM prediction in R($K^{(*)}$) at central q^2

  JHEP 08 (2017) 055, PRL 113, 151601 (2014)

- 3.4σ from angular distributions of $B^0\to K^{*0}\mu\mu$

  JHEP 02 (2016) 104

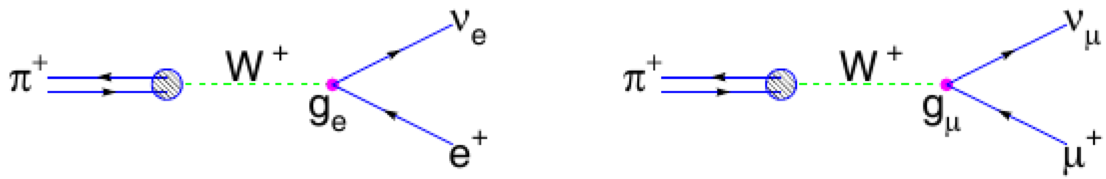
→ anomalies in both $b\to c l\nu$ and $b\to s l l$ decays could be described with same New Physics models

many more new or updated measurements in the pipeline

Backup

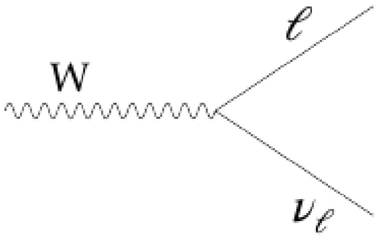
Tests of LFU

LFU is established in the decay of light mesons, e.g.
$\pi \to l\nu$, $K \to \pi ll$, $J/\psi \to ll$, $\psi \to ll$



$g_\mu/g_e = 1.0023 \pm 0.0016$

LEP measurements of decays $W \to l\nu$ and $Z \to ll$ confirm LU, however there is some tension in $W \to \tau\nu$



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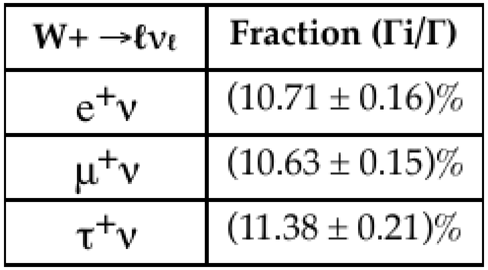
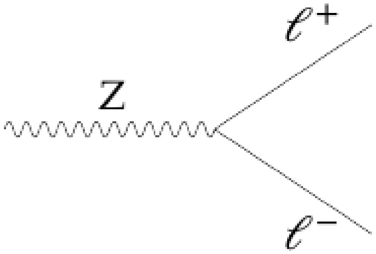


$W+ \to \ell\nu_\ell$	Fraction ($\Gamma i/\Gamma$)
$e^+\nu$	$(10.71 \pm 0.16)\%$
$\mu^+\nu$	$(10.63 \pm 0.15)\%$
$\tau^+\nu$	$(11.38 \pm 0.21)\%$



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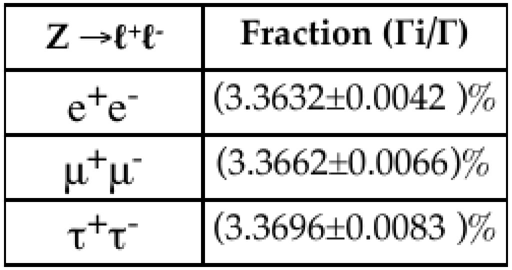
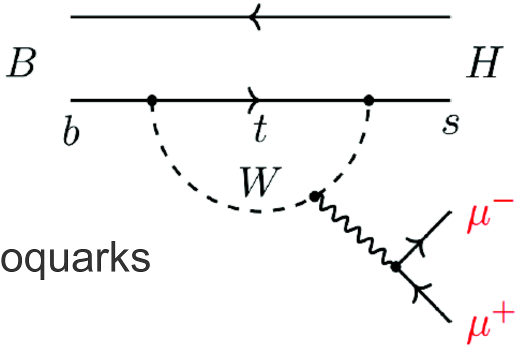


$Z \to \ell^+\ell^-$	Fraction ($\Gamma i/\Gamma$)
e^+e^-	$(3.3632 \pm 0.0042)\%$
$\mu^+\mu^-$	$(3.3662 \pm 0.0066)\%$
$\tau^+\tau^-$	$(3.3696 \pm 0.0083)\%$

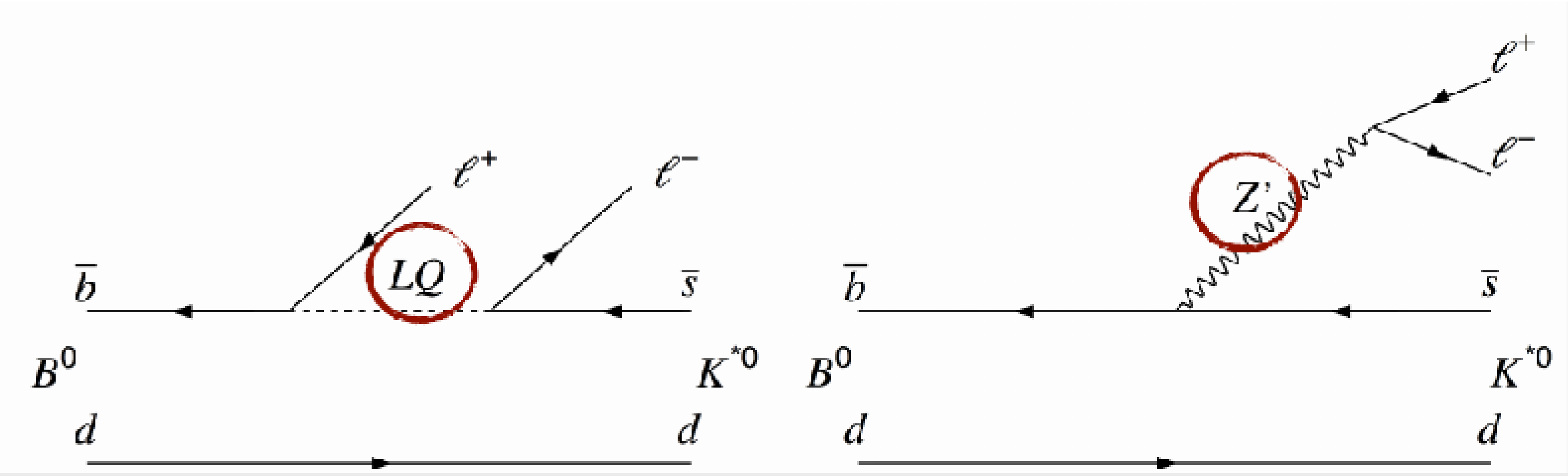
any violation of LFU → hint for New Physics

LHCb: search for LFU violation in processes including third generation of quarks and all lepton generations

LFU tests in *b*→ *sll* transition



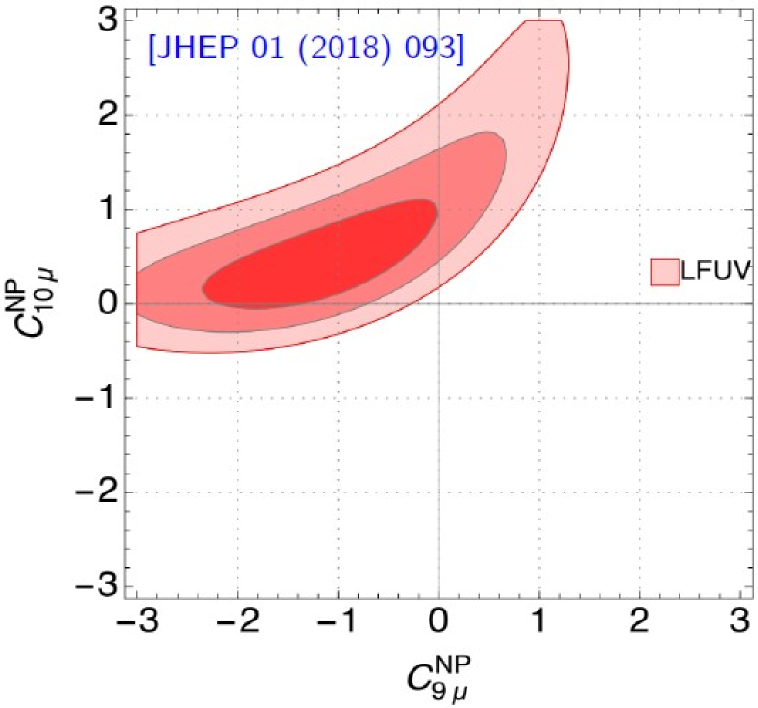
decay not allowed at tree level
→ highly sensitive to virtual particles and interactions
- NP effects can be sizeable compared to the *b*→*sll* SM amplitude
- Can probe models with e.g. charged Higgs, Z' bosons or leptoquarks

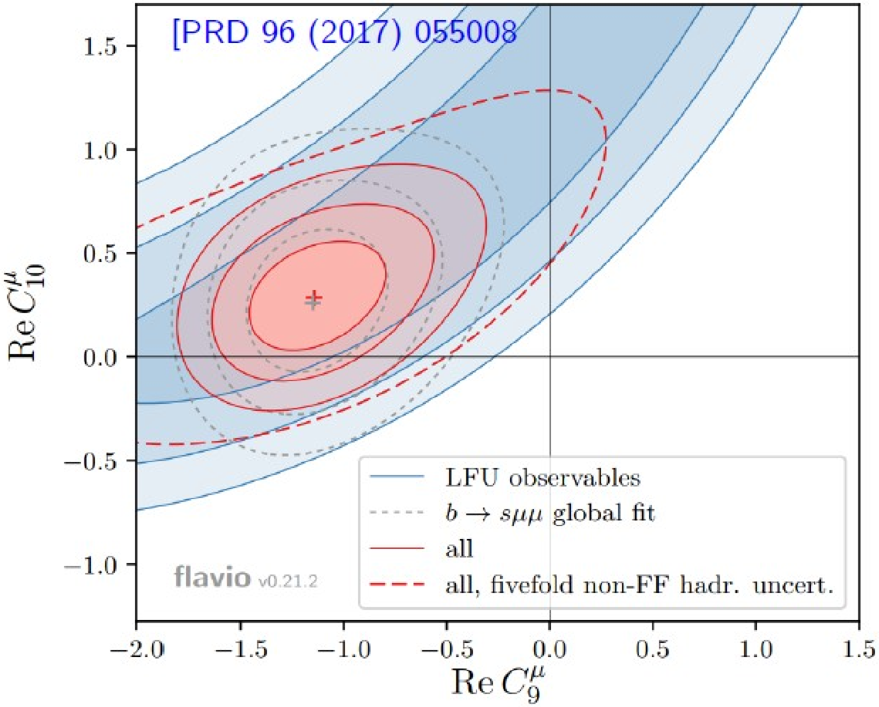


R(K$^{(*)}$) global fit

PRL 113, 151601 (2014)

Global fits combine all *b→sll* observables and suggest a coherent NP pattern with a shift in C_9 (C_9&C_{10})





combination of R(*K**) , R(*K*) is ~4σ from SM

b→sμμ BR and angular observables are in agreement with LFU tests
→ considered together the tension with SM further increases

$R(D^{(*)})$ in hadronic τ decays

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

τ reconstruction: $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$

main background:

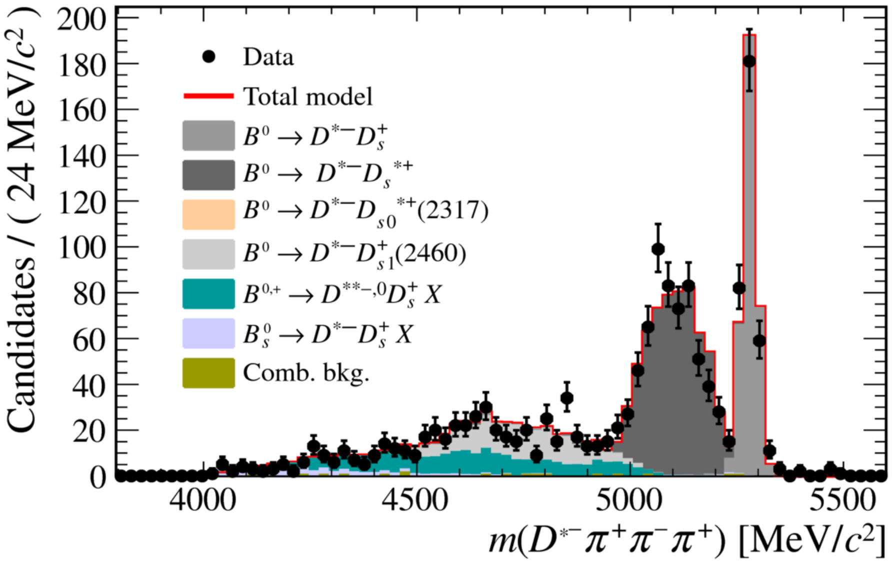
$B^0 \to D^*\pi\pi\pi X$, suppressed with τ decay time, t_τ

$B \to DD_{(s)}X$, suppressed with BDT

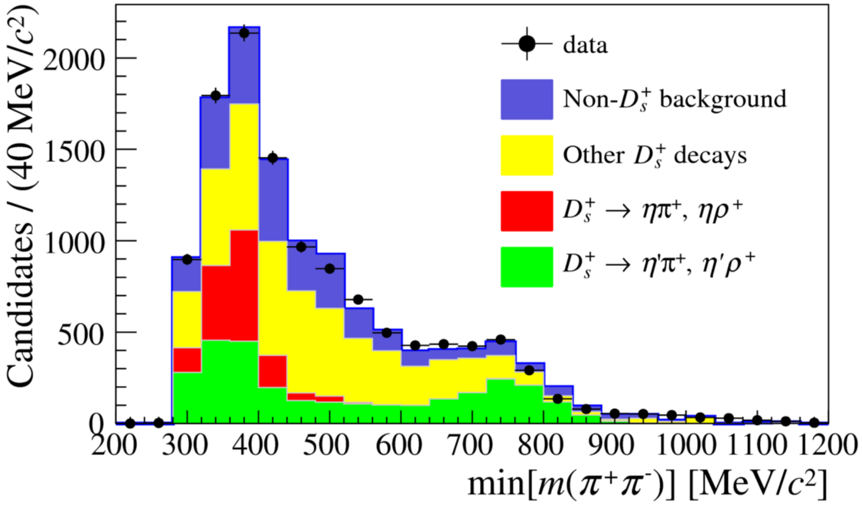
yields are extracted by a binned ML fit on q^2, BDT and t_τ

$$R(D^*) = \frac{BR(B \to D^* \tau \bar{\nu}_\tau)}{BR(B \to D^* \mu \bar{\nu}_\mu)}$$

fit to the invariant mass of the $D^*D^+_s$ pair for the $D^*D^+_s(X)$ data control sample, with $D^+_s \to 3\pi$



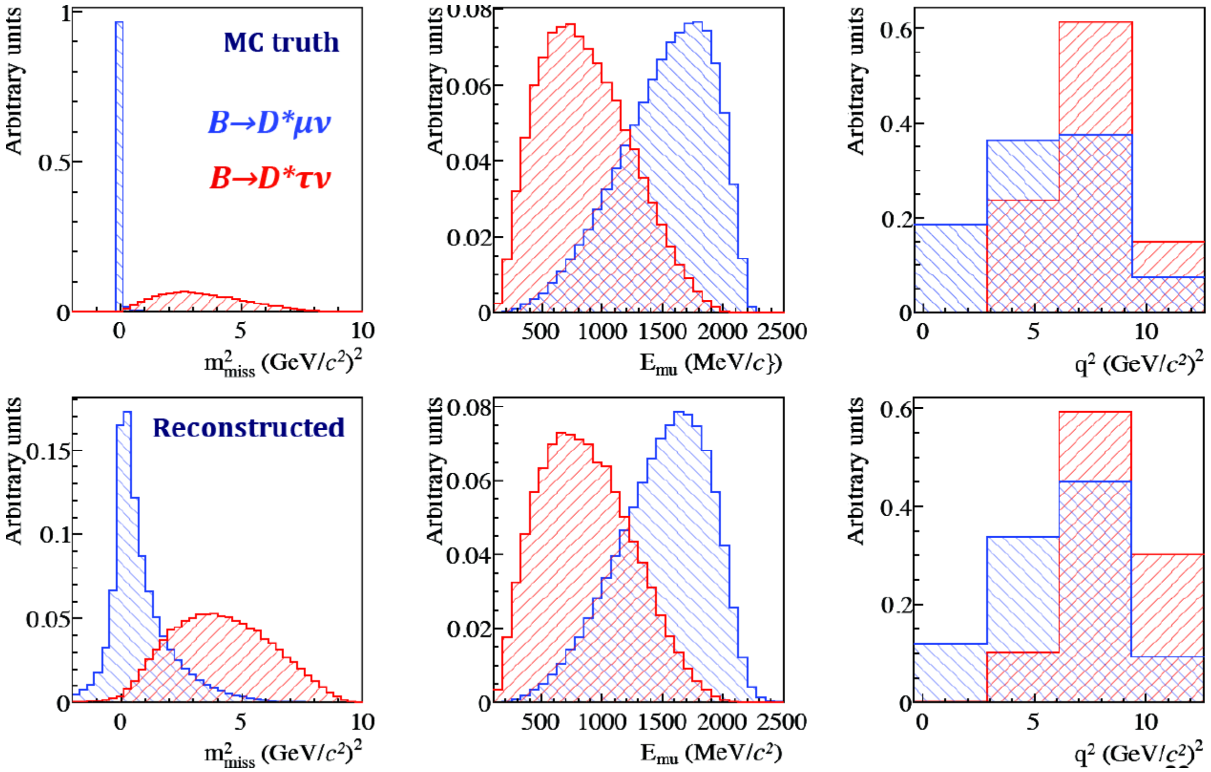
sample enriched in $B \to D^{*-}D^+_s(X)$



R(D$^{(*)}$) in muonic τ decays

$$R(D^*) = \frac{BR(B \rightarrow D^* \tau \bar{\nu}_\tau)}{BR(B \rightarrow D^* \mu \bar{\nu}_\mu)}$$

[PRL115(2015)111803]



No information on initial B momentum

B momentum direction: unit vector to the B decay vertex from the PV

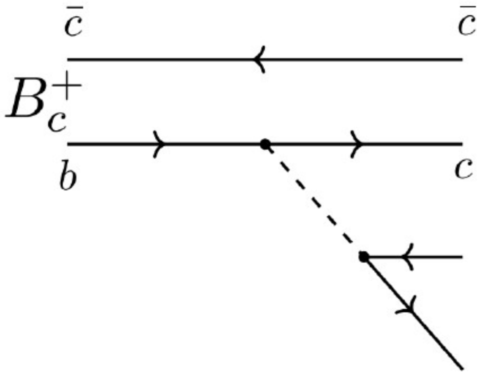
component of the B momentum along the beam axis: $(p_B)z = m_b/m_{reco}(p_{reco})_z$

m_{reco} and p_{reco} from system of reconstructed particles

→ simulation: approximation still preserves differences between signal, normalization and backgrounds

Theoretical predictions

Test of LFU in $b \rightarrow c l \nu$ decays with a different spectator quark using large B^+_c sample available at LHCb



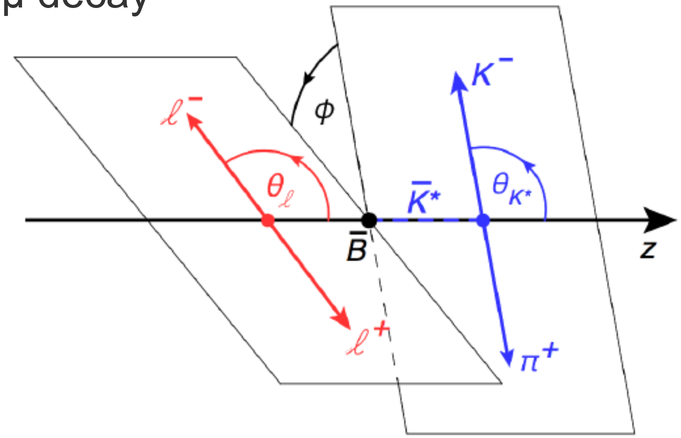
$$R(J/\psi) = \frac{BR(B_c^+ \rightarrow J/\psi\, \tau\, \bar{\nu}_\tau)}{BR(B \rightarrow J/\psi\, \mu\, \bar{\nu}_\mu)} = 0.25 - 0.28(\mathrm{SM})$$

Interval is due to form factor uncertainty
[PLB 452 (1999) 129][arXiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008
Lattice calculation is in progress

Angular analysis of $B^0\to K^{*0}\mu\mu$

NP models which explain observed discrepancies in R(K(*)) predict anomalous behavior in the angular distribution of $B^0 \rightarrow K^{*0}\mu\mu$ decay

Decay amplitude can be described using q^2 and three angles θ_l, θ_K and Φ



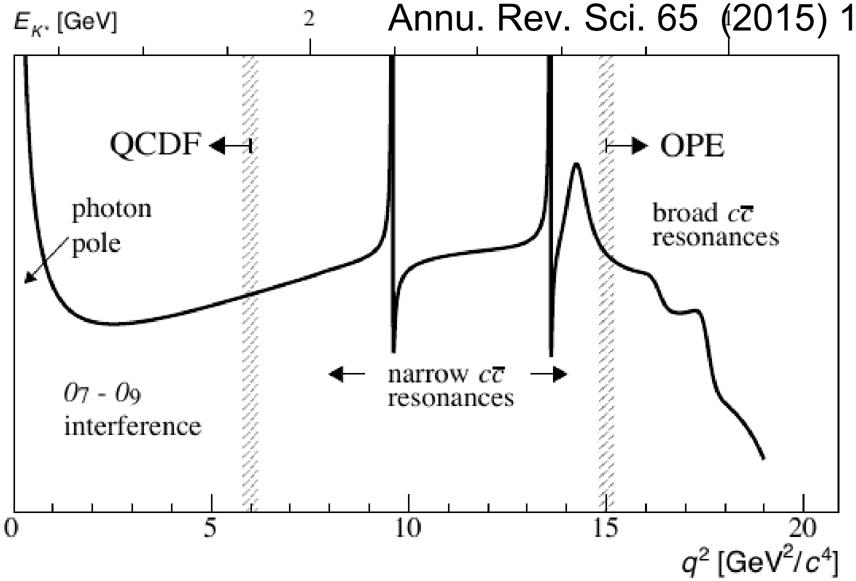
Model independent parametrization of NP

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

Effective Hamiltonian

C_i: Wilson coefficients describe interaction at high energies

O_i: operators describe low energy effects



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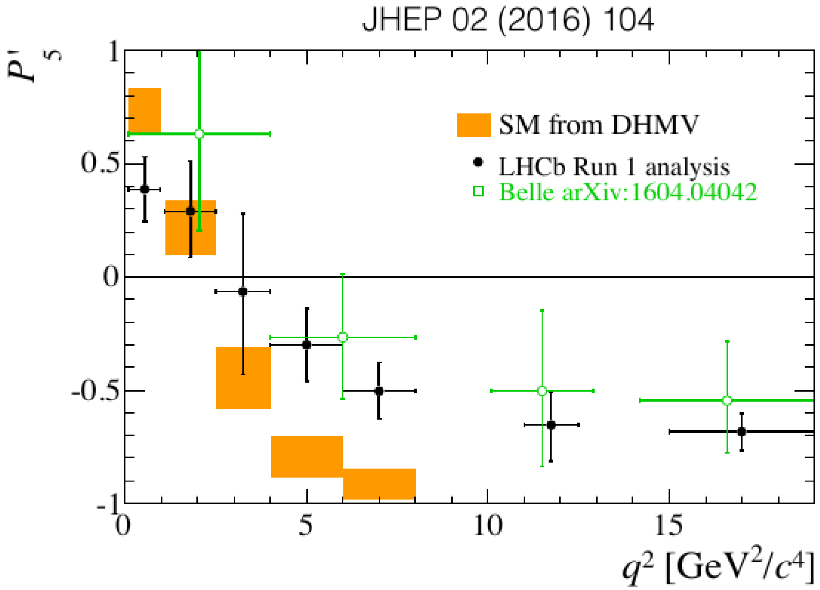
The P_5' anomaly

P_5' is one of the variables the differential decay width can be parametrized
it is designed to reduce dependencies on hadronic form-factors



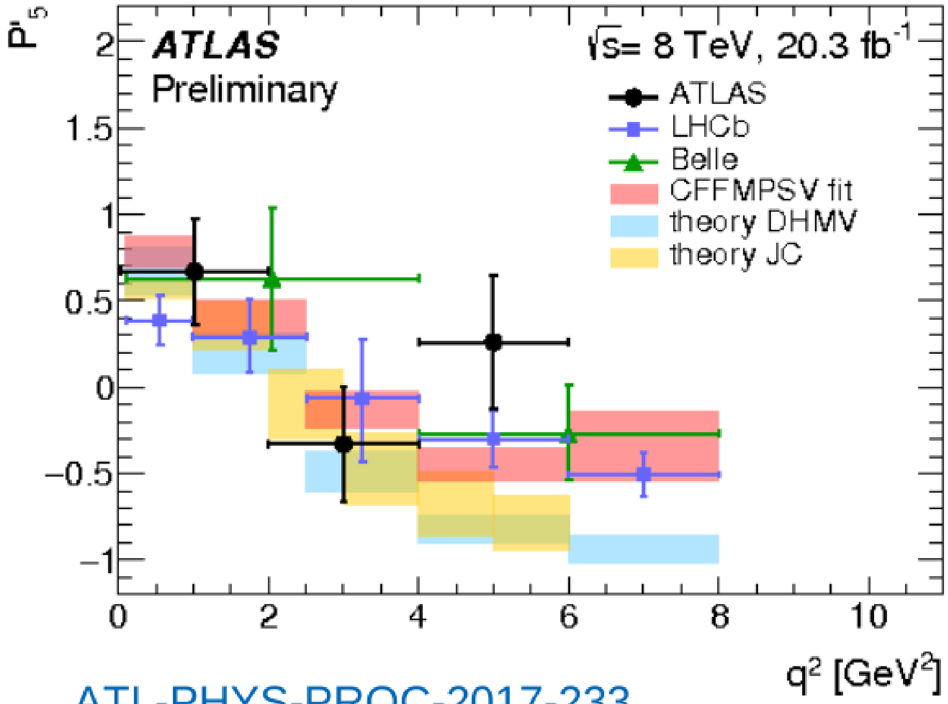
Global fit at 3.4 σ from the SM prediction

explainable in terms of:
- SM charm-loop effects
- New Physics

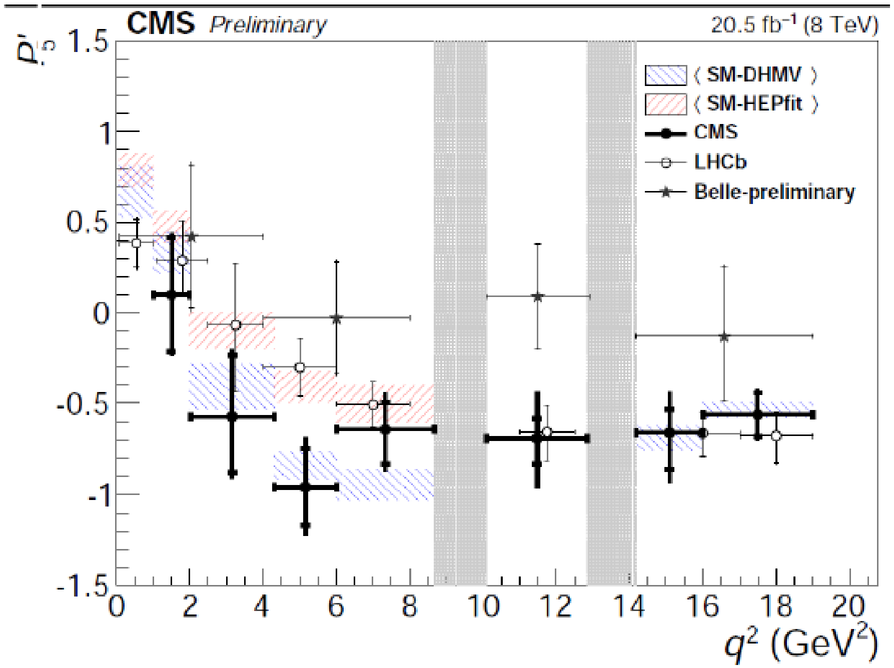
The P_5' anomaly

JHEP 02 (2016) 104

P_5' is one of the variables the differential decay width can be parametrized
it is designed to reduce dependencies on hadronic form-factors



ATL-PHYS-PROC-2017-233
arXiv:1710.11000 [hep-ex]



CMS-PAS-BPH-15-008

Angular analysis of $B^0\to K^{*0}\mu\mu$

Parametrization of decay width:

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

with F_L, A_{FB}, S_i $=f(C^{(\prime)}_7,C^{(\prime)}_9,C^{(\prime)}_{10})$ combinations of K^{*0} decay amplitudes

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

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