Lepton Flavour Universality tests at LHCb

Pavel Krokovny
on behalf of the LHCb Collaboration

Budker INP & Novosibirsk University

Outline:

- Introduction
- LHCb detector & data taking
- $b \to c\ \ell\ \nu$
- $b \to s\ \ell^+\ell^-$
- Summary

Lepton Flavour Universality

In the Standard Model (SM) quarks and leptons exist in 3 generations of 2 members each. SM assumes Lepton Flavour Universality (LFU):

- the equal gauge couplings for all 3 generations
- difference is only due to mass

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

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

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

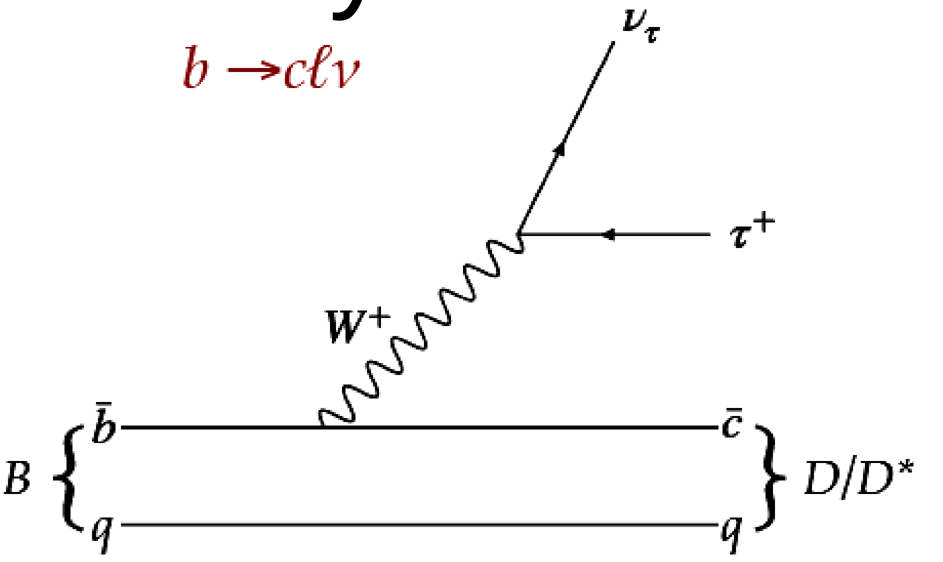
Processes with 3rd generation of quarks and leptons (B and τ) are prominent for LFU violation search:

- Lower experimental constraints
- Stronger couplings to 3rd generation predicted by BSM theories foreseeing LFU violation

LFU in b decays

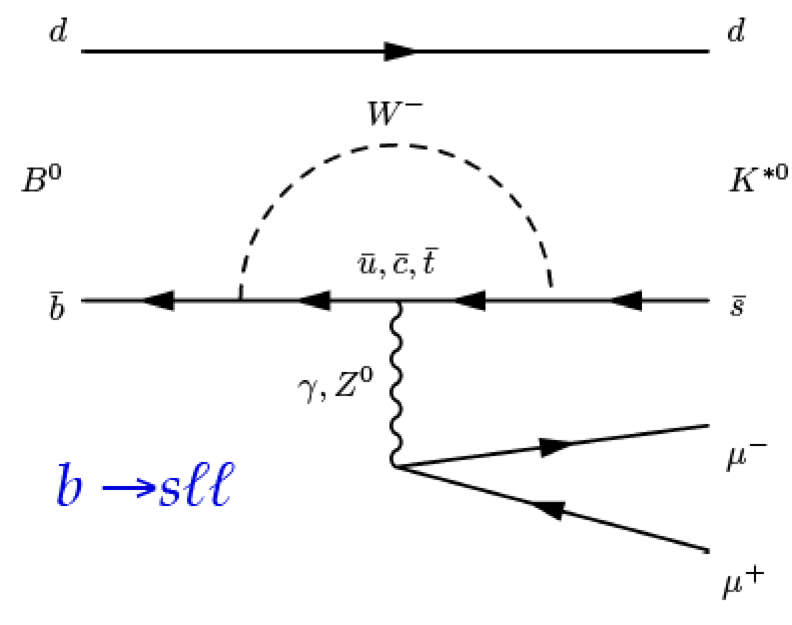
Tree-level decays b → cℓν

- abundant
- very well known in the SM
- BSM theories predict enhanced coupling with 3rd generation → → interested in testing τ against μ / e

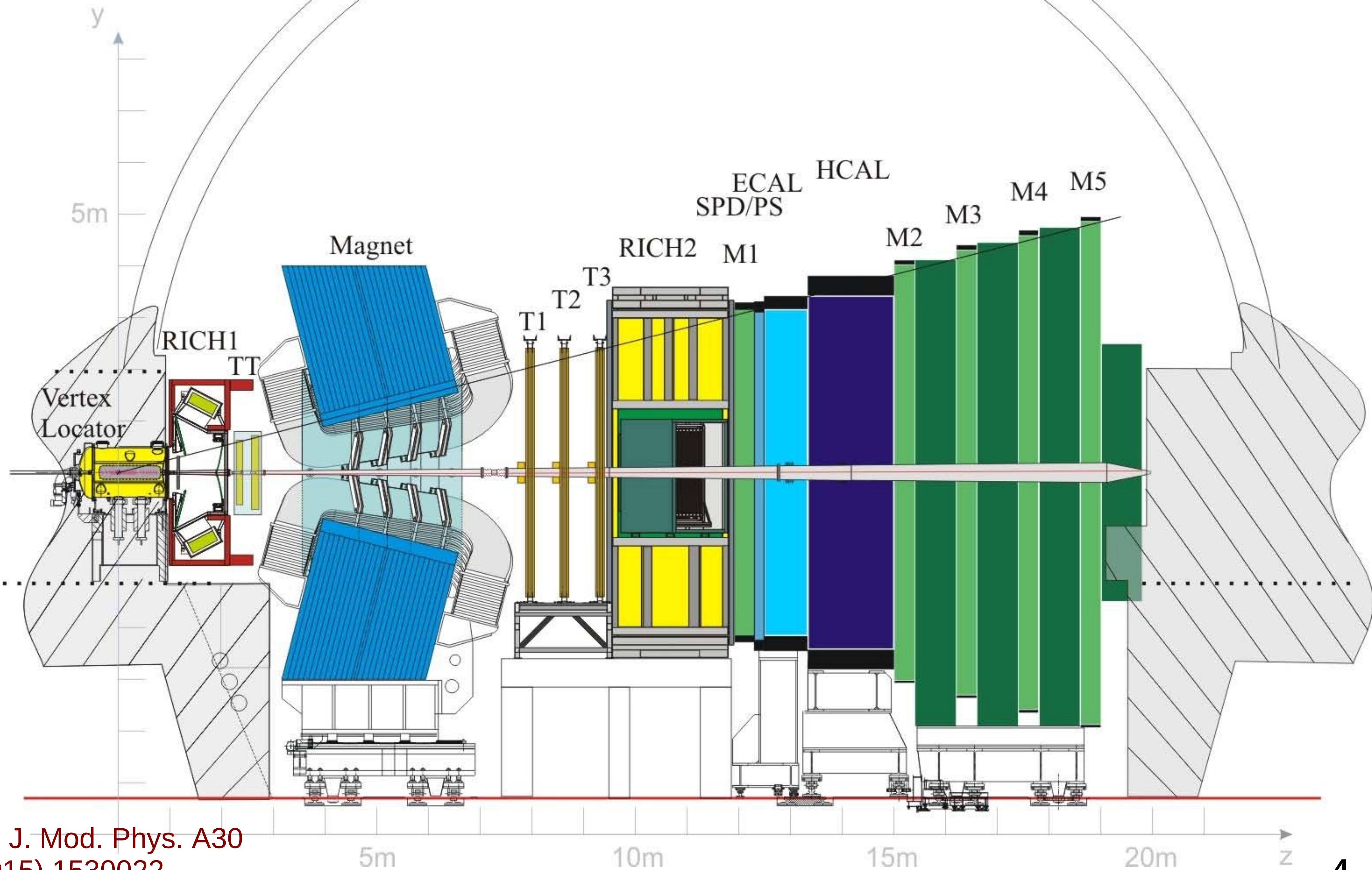


Loop-level decays b → sℓ⁺ℓ⁻

- forbidden at tree-level in SM
- sensitive to NP contributions in loops



LHCb experiment

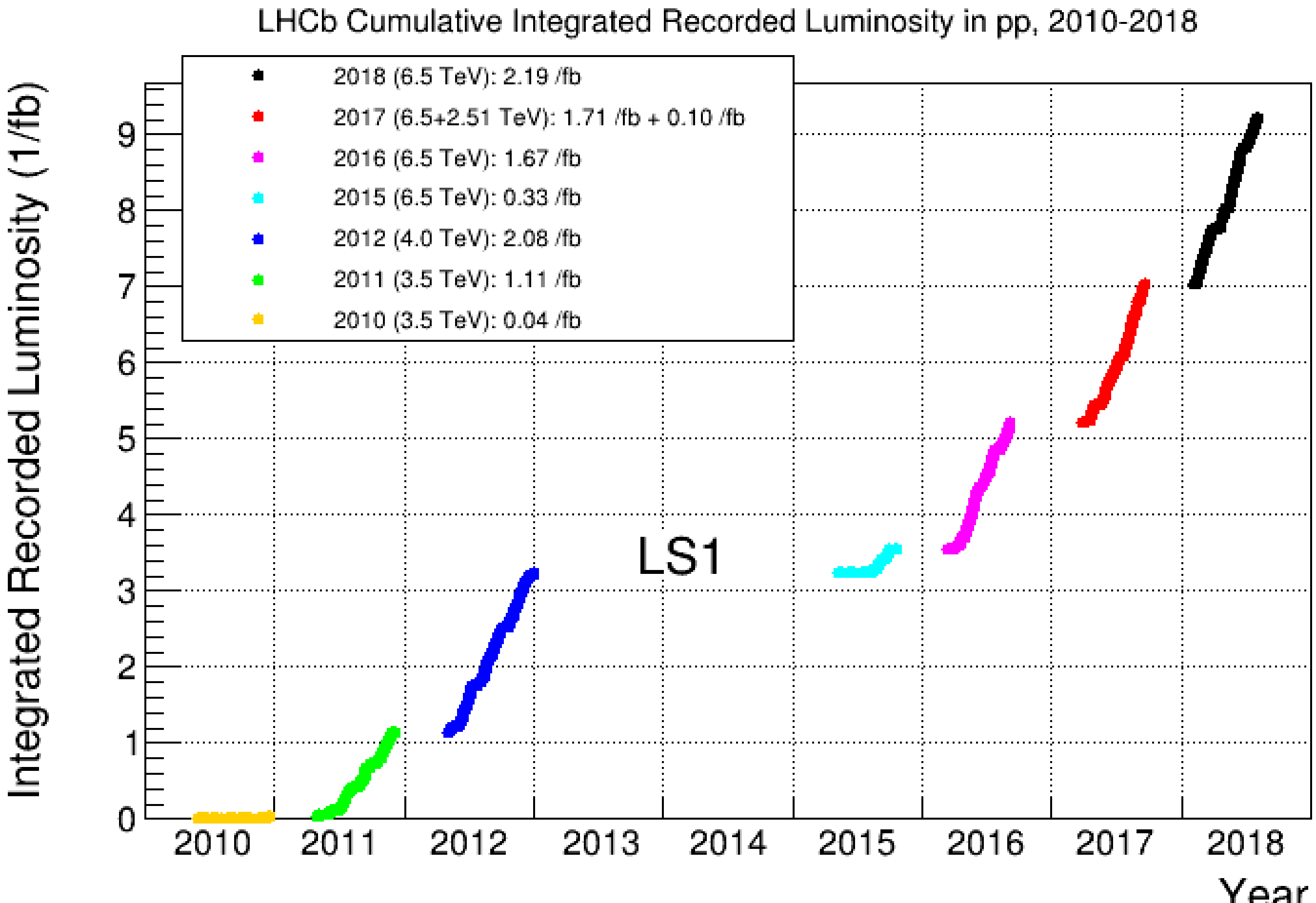


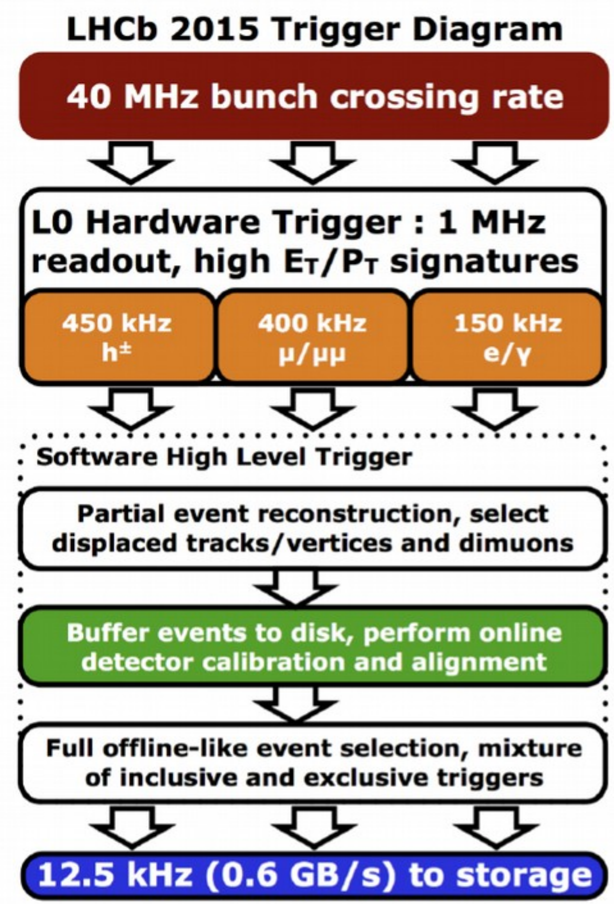
Int. J. Mod. Phys. A30 (2015) 1530022

LHCb performance

Acceptance: $2 < \eta < 5$

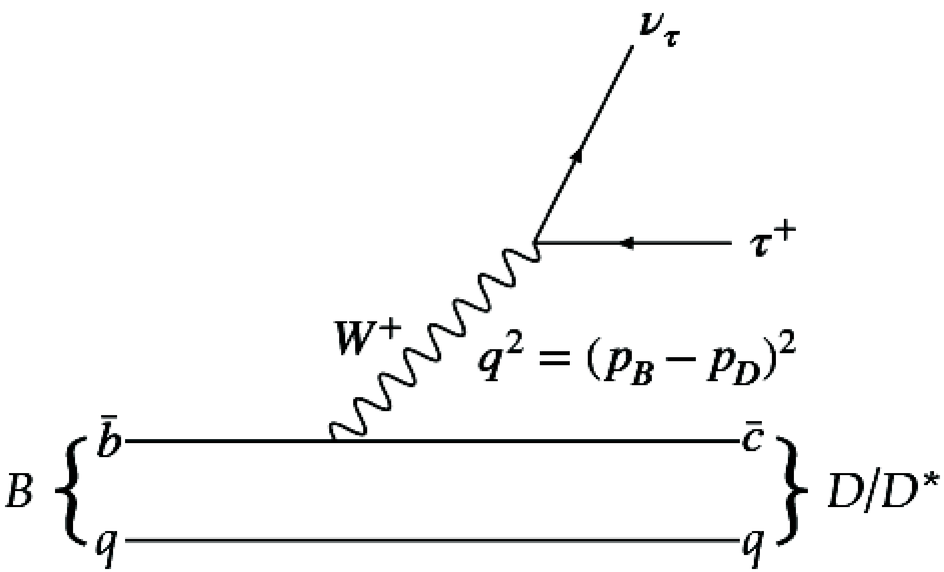
- Momentum resolution: 0.4 – 0.6% at 5 – 100 GeV
- Muon ID efficiency: 97 % with 1-3 % $\pi \to \mu$ mis-ID probability
- Electron ID efficiency: 90% with 4% $h \to e$ mis-ID probability
- Kaon ID efficiency: 95% with 5 % $\pi \to K$ mis-ID probability





Int. J. Mod. Phys. A 30 (2015) 153022

LFU in semileptonic b decays



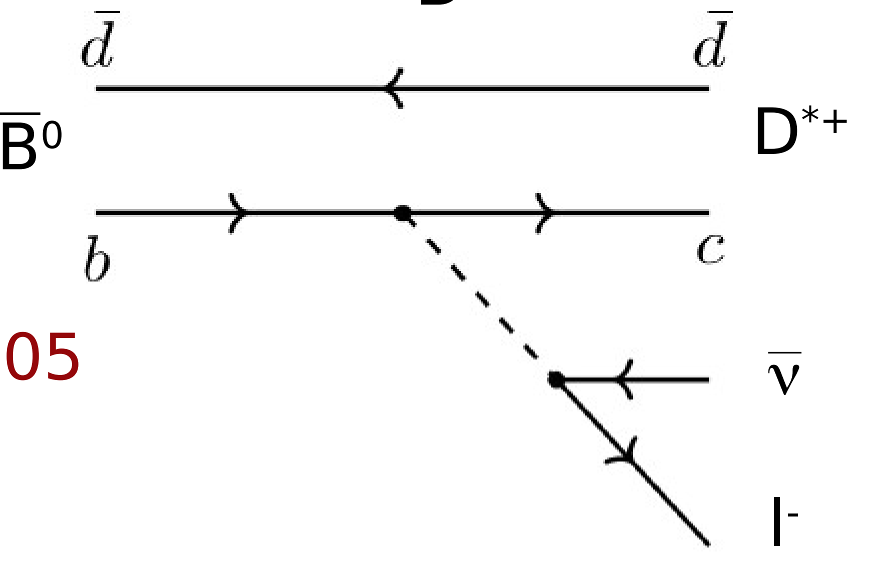
$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto G_F^2 |V_{cb}|^2 f(q^2)^2$$

q^2 = transferred momentum from the W

Measurement of ratios of branching fractions allows to

- cancel $|V_{cb}|$ dependence
- partially cancel out model uncertainties
- reduce experimental systematic uncertanties

SM prediction of R_{D^*}



$$R_{D^*} \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)} \stackrel{\text{SM}}{=} 0.258 \pm 0.005$$

HFLAV average

→ Hadronic uncertainties cancel to large extent in the ratio

→ Difference from unity due to different lepton masses

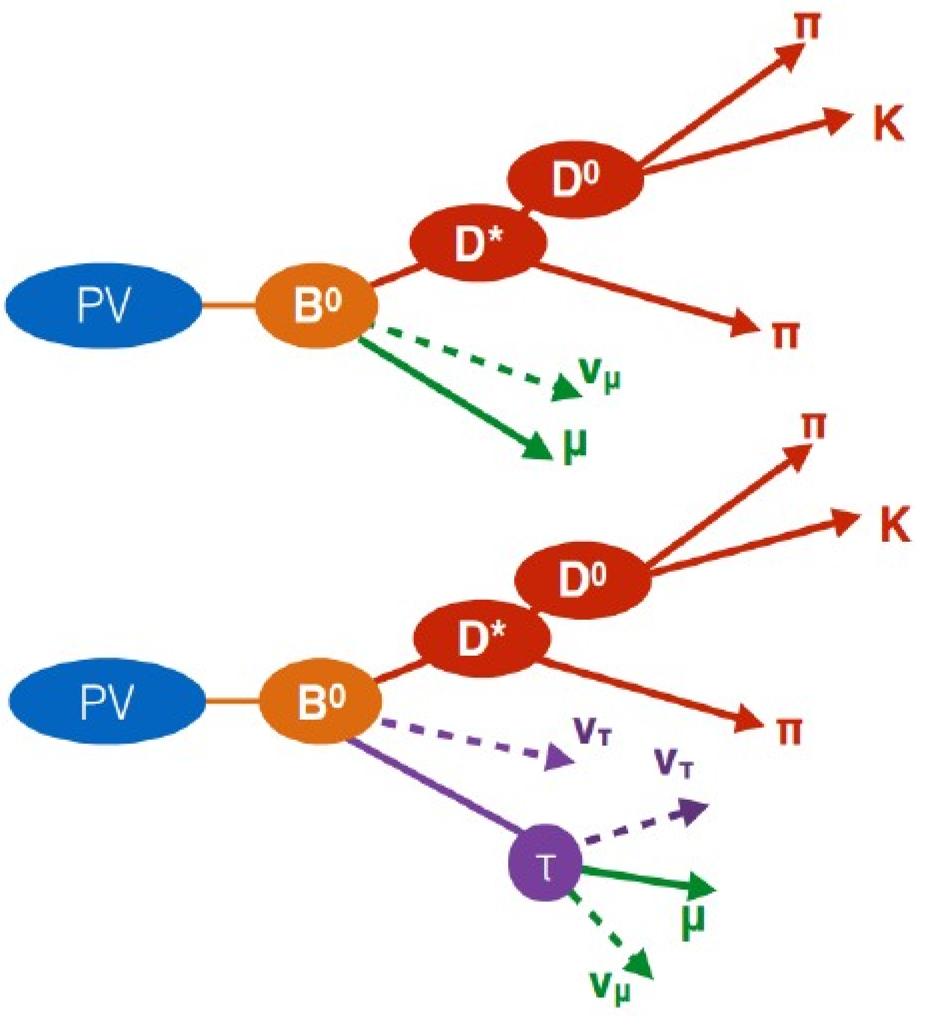
- First deviation from SM was observed by BaBar and Belle
- LHCb performed two independent measurements using
  - $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ [PRL 115 (2015) 111803]
  - $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ [PRD 97 (2018) 072013]

R_{D*} in muonic τ decays

- τ reconstructed by $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$
- Both channels have the same final state (Kππμ)

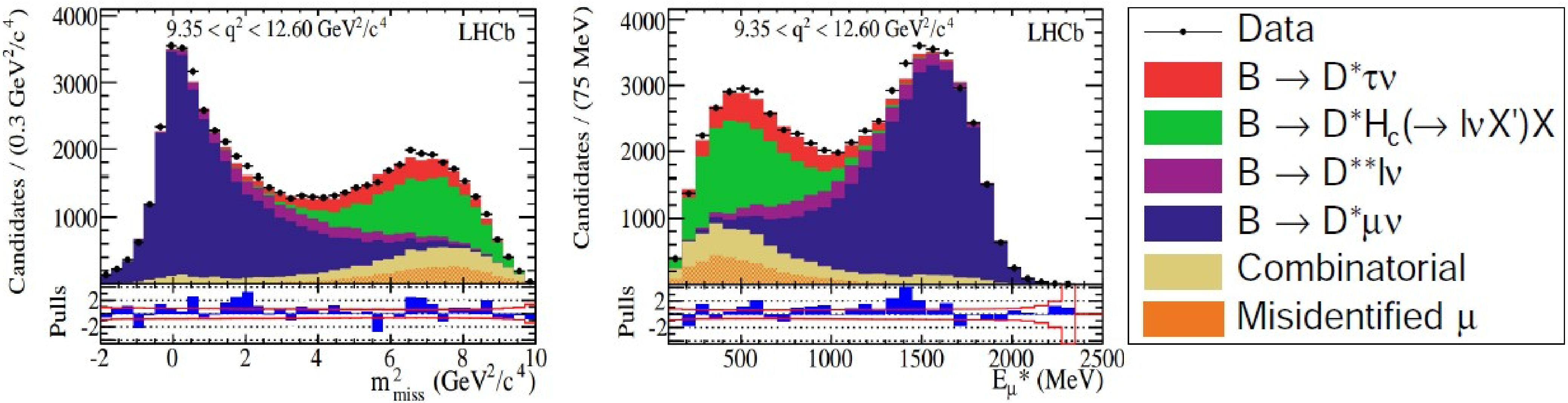
- Separation using three kinematic parameters:
  - $E^*_\mu = E_\mu$ in $\bar{B}^0$ rest frame
  - $m^2_{miss} = (p_{B0}-p_{D*}-p_\mu)^2$
  - $q^2 = (p_{B0}-p_{D*})^2$

- Approximate p_{B0} using
  - $\bar{B}^0$ flight direction
  - $(p_{B0})_z = m_B/m_{reco}\ (p_{reco})_z$



R_{D*} in muonic τ decays

- Yields are extracted with a 3D binned ML fit in E^*_μ, m^2_{miss} , q^2
- Templates for the signal, normalization and backgrounds are obtained on MC and checked against control samples



- R_{D*} = 0.336 ± 0.027 (stat) ± 0.030 (syst) 2σ above SM
- Main background: Partially reconstructed and mis-ID decays
- Main systematic: Size of the simulated sample

Phys. Rev. Lett. 115, 111803 (2015)

Run1: 3.0 fb^{-1}

R_{D^*} in hadronic τ decays

τ reconstructed by $\tau^- \rightarrow \pi^-\pi^-\pi^+ \nu_\tau$ independent from R_{D^*} muonic

$$R_{D^*} = \underbrace{\frac{\mathcal{B}(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-}3\pi)}}_{\text{measured ratio } \mathcal{K}(D^{*-})} \cdot \underbrace{\frac{\mathcal{B}(B^0 \rightarrow D^{*-}3\pi)}{\mathcal{B}(B^0 \rightarrow D^{*-}\mu^+\nu_\mu)}}_{\text{external inputs}}$$

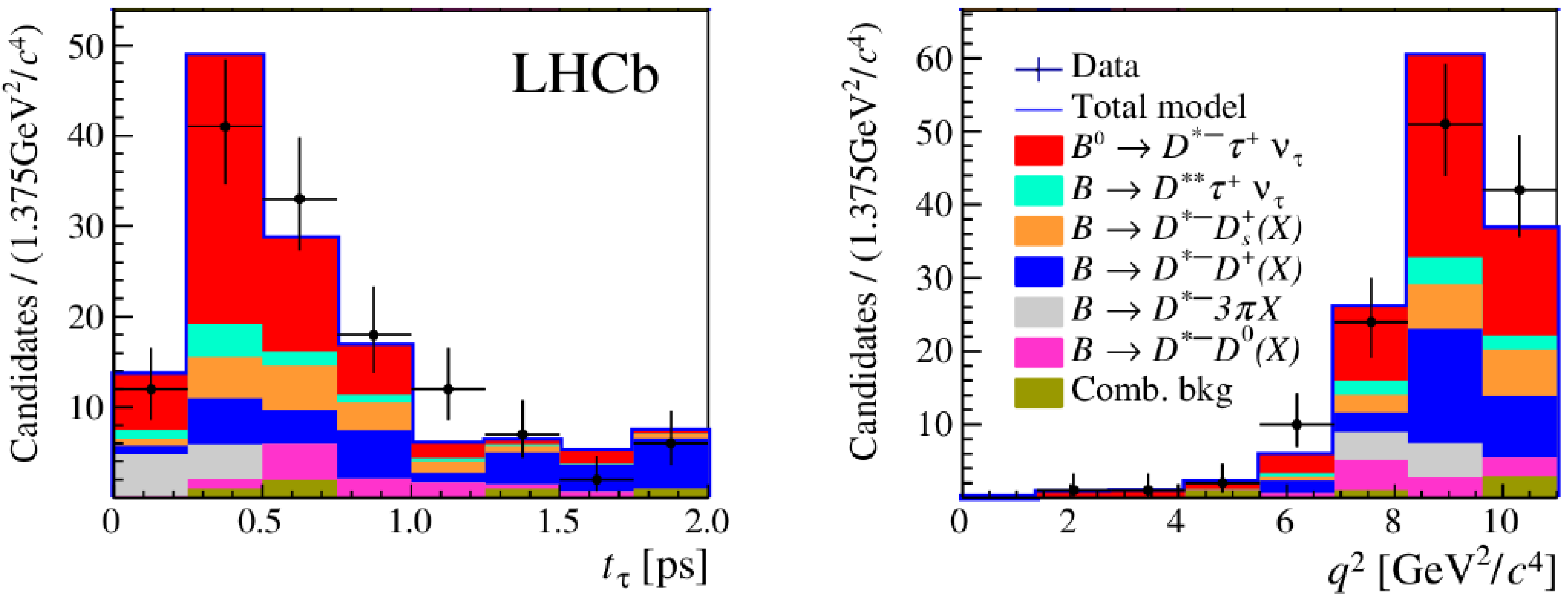
~4% precision
(BABAR, Belle, LHCb)

~2% precision, HFLAV

- Partial cancellation of experimental systematic uncertainties
- Main background:
  - $B^0 \rightarrow D^*\pi\pi\pi X$, suppressed with τ decay time, t_τ
  - $B \rightarrow DD_{(s)}X$, suppressed with BDT

R_{D*} in hadronic τ decays

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



- R_{D*} = 0.291 ± 0.019 (stat) ± 0.026 (syst) ± 0.013 (ext)

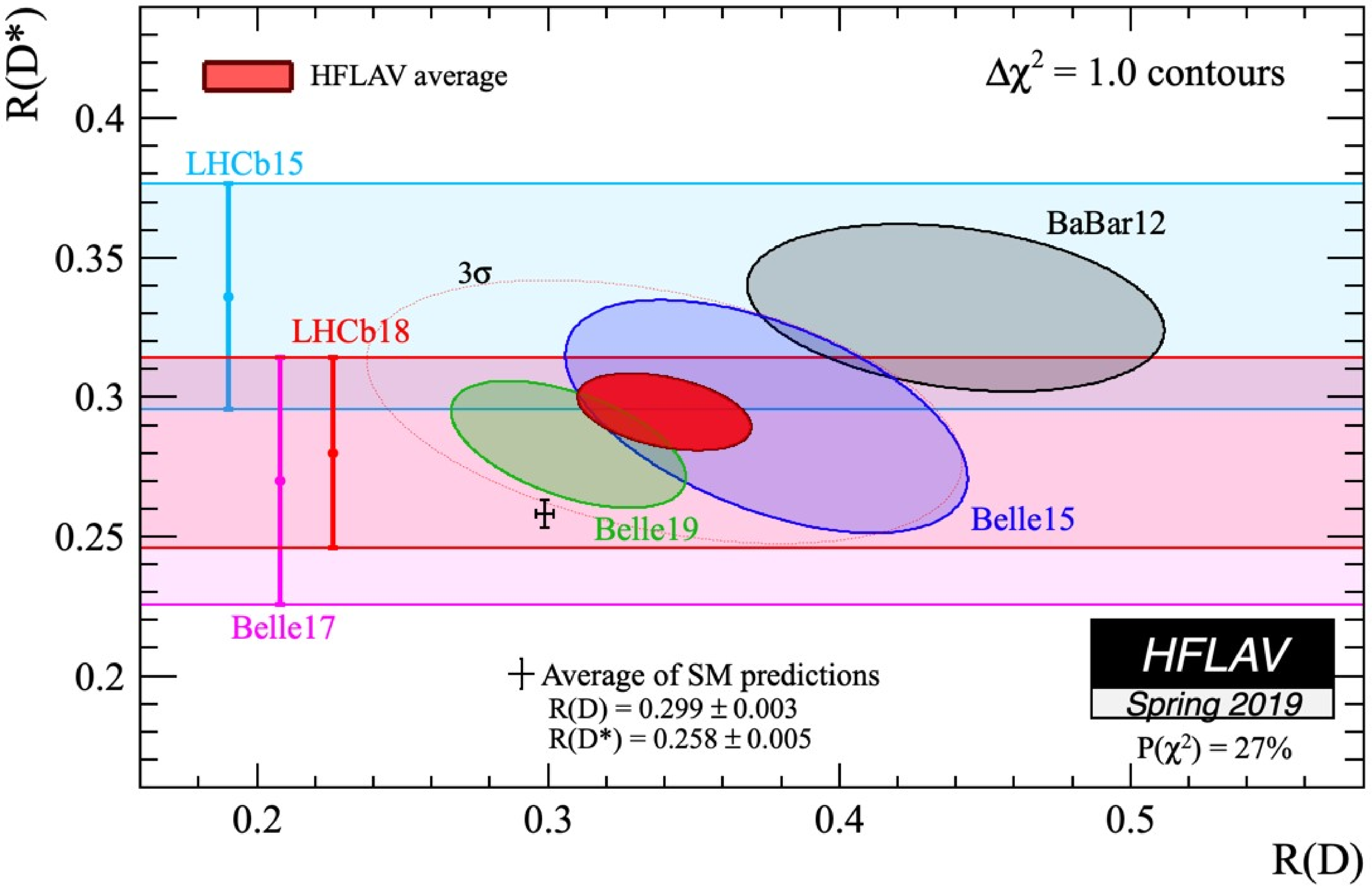
1σ above SM

- Main systematic: Size of the simulated sample

Run1: 3.0 fb^{-1}

Phys. Rev. Lett. 120, 171802 (2018)

R_{D*} results



- LHCb average: $R_{D*} = 0.310 \pm 0.016 \pm 0.022$ 2.2σ above SM
- Measurements of R_D and R_{D*} are consistent with each other
- Combined result is 3.1 σ above SM prediction

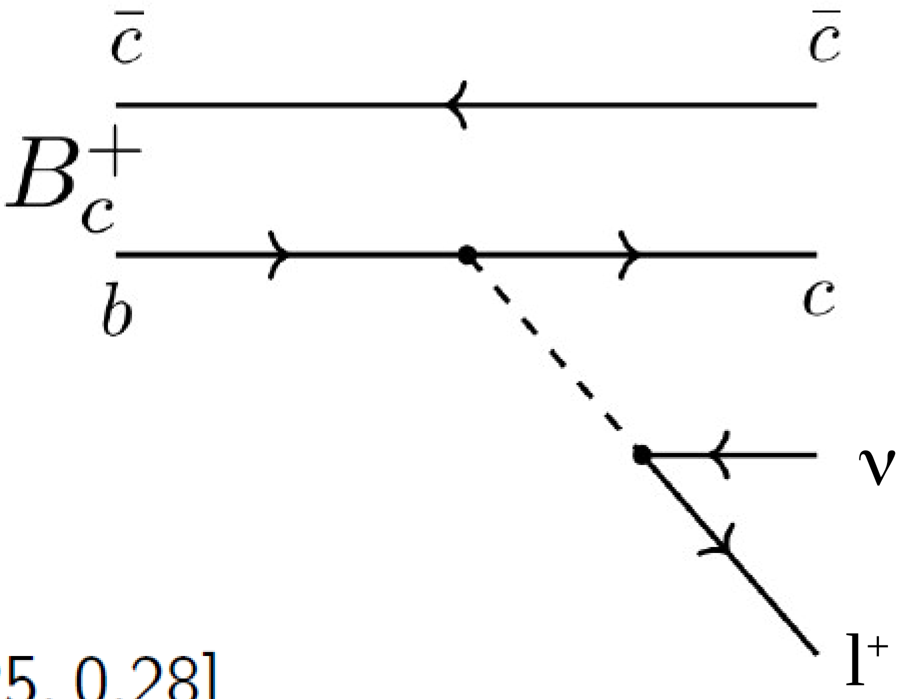
SM prediction of $R_{J/\psi}$

Test of LFU in $b \to c\ell\nu$ decays

with a different spectator quark

using large B^+_c sample available

at LHCb



$$R_{J/\psi} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \overset{\text{SM}}{\in} [0.25, 0.28]$$

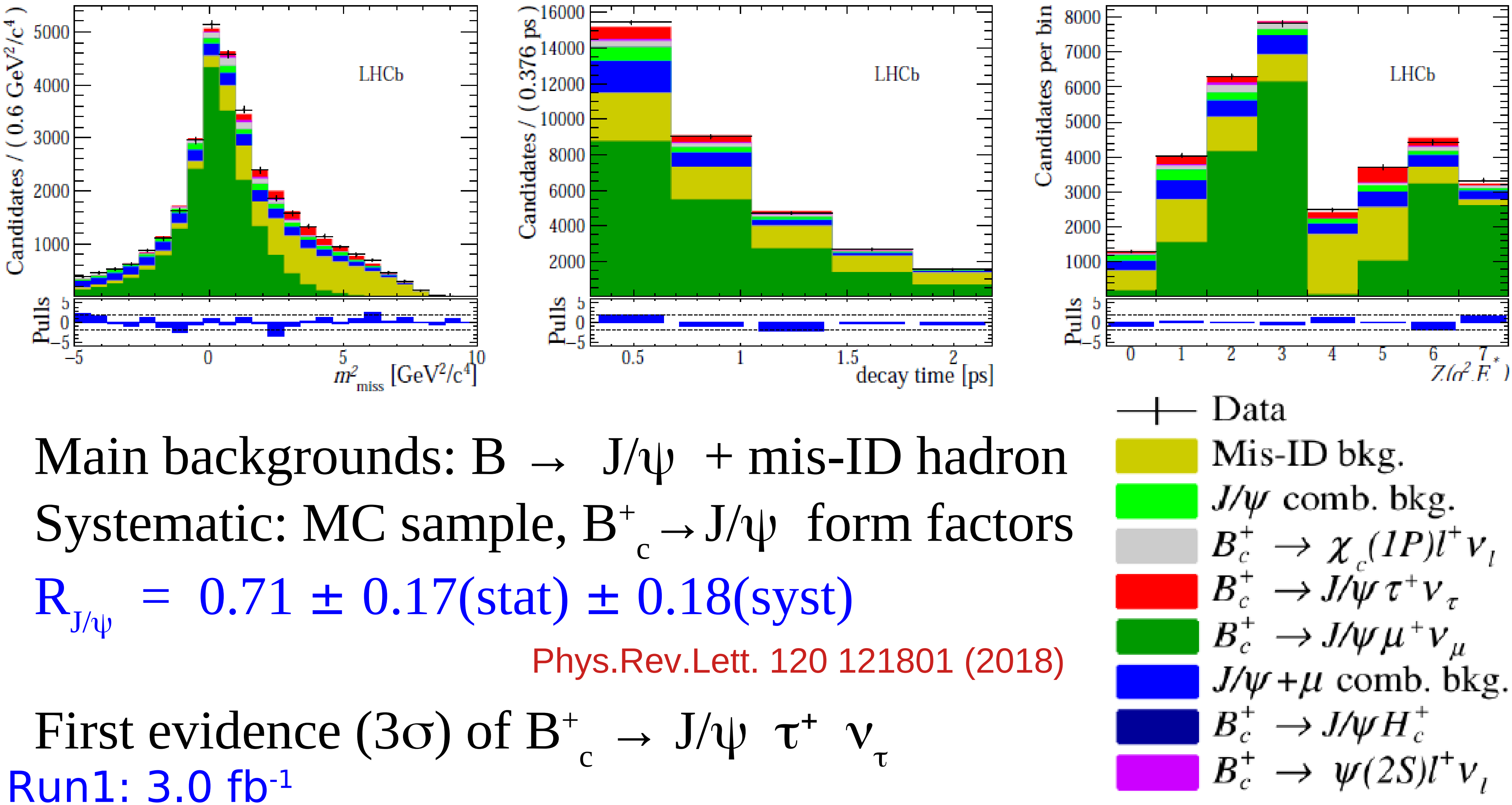
Interval is due to form factor uncertainty [PLB 452 (1999) 129] [arXiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008]

Lattice calculation is in progress

$R_{J/\psi}$ results

τ reconstructed by $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$

Analysis strategy as in R_{D*} + t_τ as 4th discriminating variable



Main backgrounds: B → J/ψ + mis-ID hadron

Systematic: MC sample, $B^+_c \rightarrow J/\psi$ form factors

$R_{J/\psi}$ = 0.71 ± 0.17(stat) ± 0.18(syst)

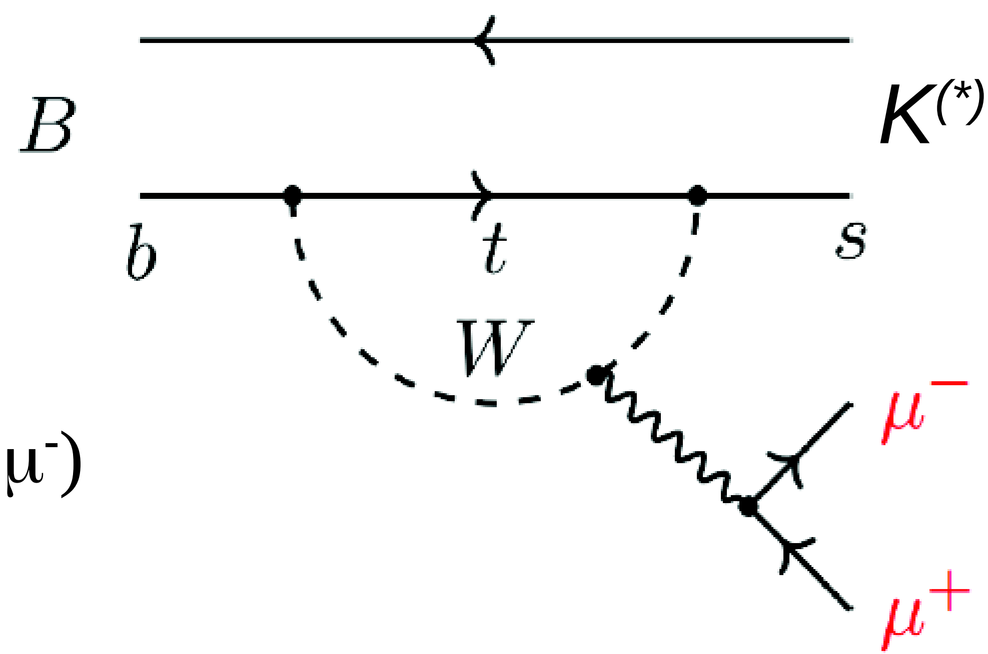
Phys.Rev.Lett. 120 121801 (2018)

First evidence (3σ) of $B^+_c \rightarrow J/\psi\ \tau^+\ \nu_\tau$

Run1: 3.0 fb^{-1}

LFU tests in $b \to s\ell\ell$

$b \to s\ell^+\ell^-$ are FCNC processes that can only occur at loop-level in SM



Measure $R_{K(*)}$ in bins of $q^2 \equiv m^2(\mu^+\mu^-)$

$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \stackrel{\text{SM}}{=} 1 \pm \underbrace{\mathcal{O}(10^{-3})}_{\text{neglect } m_\ell} \pm \underbrace{\mathcal{O}(10^{-2})}_{\text{QED effects}}$$

[EPJC76(2016)8,440]

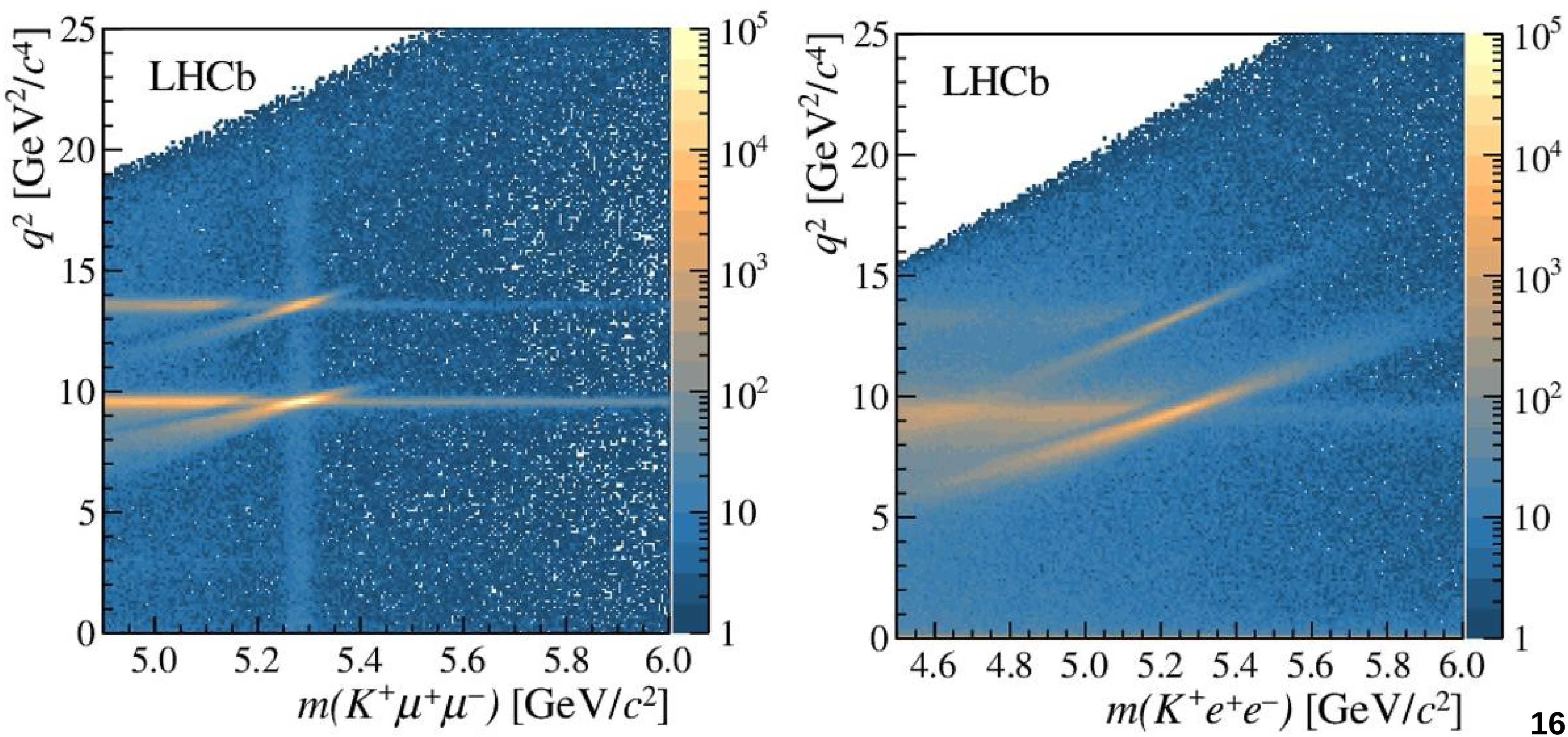
Use double ratio to reduce systematic effects:

$$R_{K(*)} \equiv \frac{\mathcal{B}(B \to K\,\mu^+\mu^-)}{\mathcal{B}(B \to K\,(J/\psi \to \mu^+\mu^-))} \cdot \frac{\mathcal{B}(B \to K\,(J/\psi \to e^+e^-))}{\mathcal{B}(B \to K\,e^+e^-)}$$

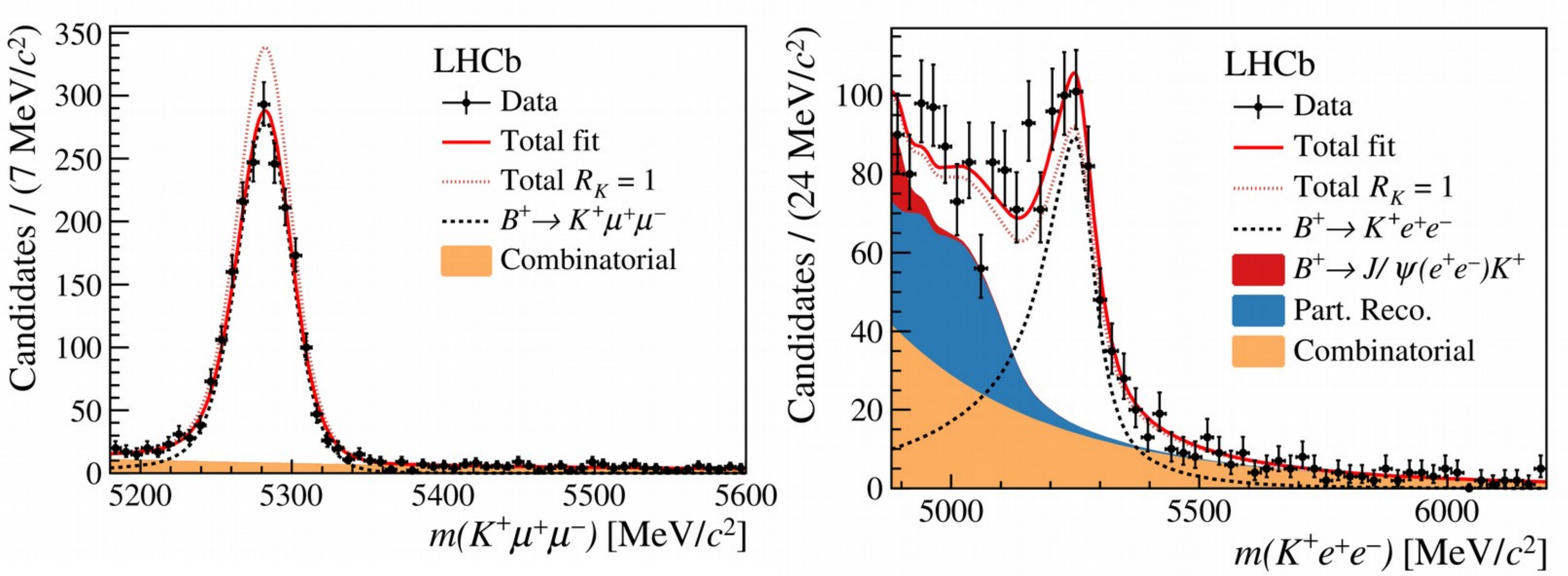
R_K measurement

Phys. Rev. Lett. 122 (2019) 191801

- Combination of K^+ with 2 opposite-sign leptons
- Bremsstrahlung correction for electrons
- Veto b → c by requiring $m(K^+ l^-) > m(D^0)$
- Selection using Boosted Decision Tree with 13 kinematical variables



R_K fit results



Decay Mode	Event Yield
$B^+ \to K^+e^+e^-$	766 ± 48
$B^+ \to K^+\mu^+\mu^-$	$1\,943 \pm 49$
$B^+ \to J/\psi(\to e^+e^-)K^+$	$344\,100 \pm 610$
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$	$1\,161\,800 \pm 1\,100$

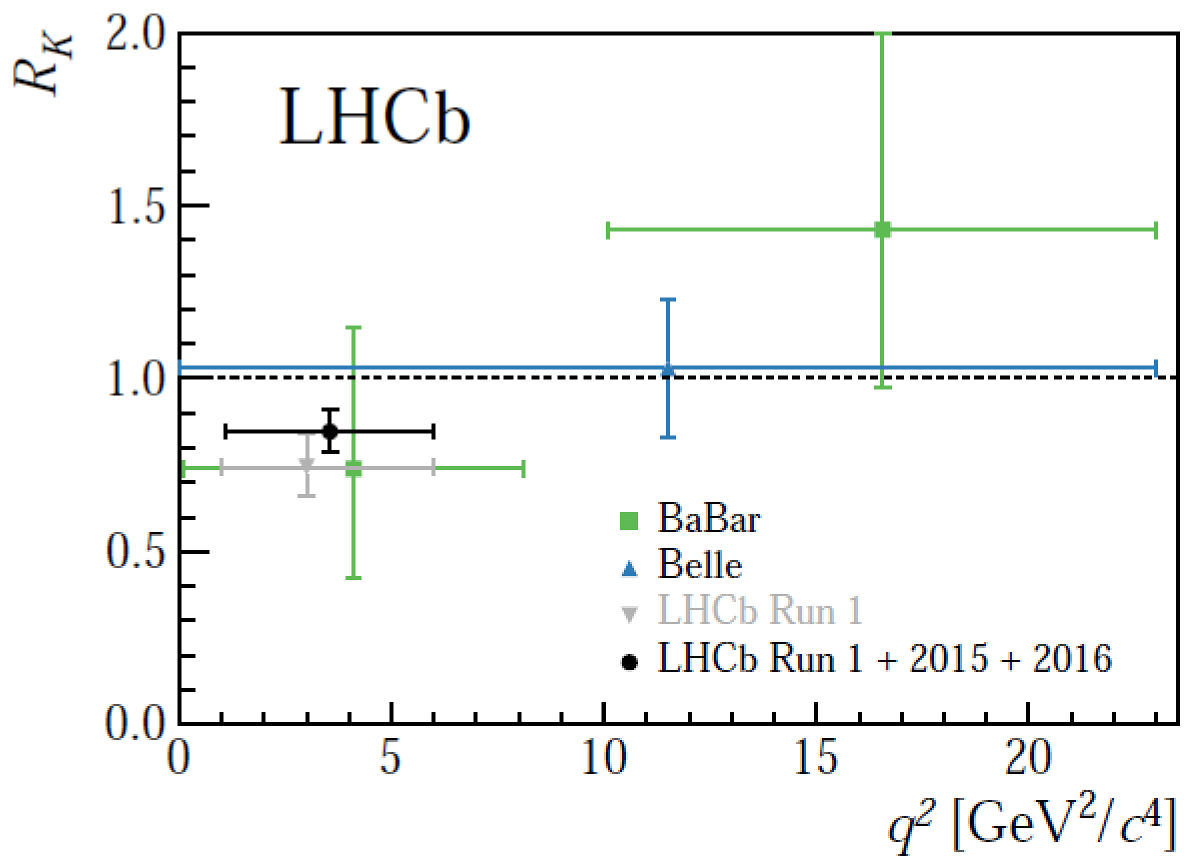
Simultaneous unbinned maximum likelihood fits:

- Signal: Gaussian core with power-law tails
- Combinatorial background: exponential
- Partially reconstructed background from simulated $B \to K^* l^+ l^-$

Run1+Run2: 3.0 + 2.0 fb^{-1}

Phys. Rev. Lett. 122 (2019) 191801

R_K result



Using 2011 and 2012 LHCb data, R_K was:

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

$\sim 2.6\,\sigma$ from SM (PRL113(2014)151601).

$$\boldsymbol{R_K = 0.846\,^{+0.060}_{-0.054}(\text{stat.})\,^{+0.016}_{-0.014}(\text{syst.})}$$

$\sim$ **2.5 σ** from SM.

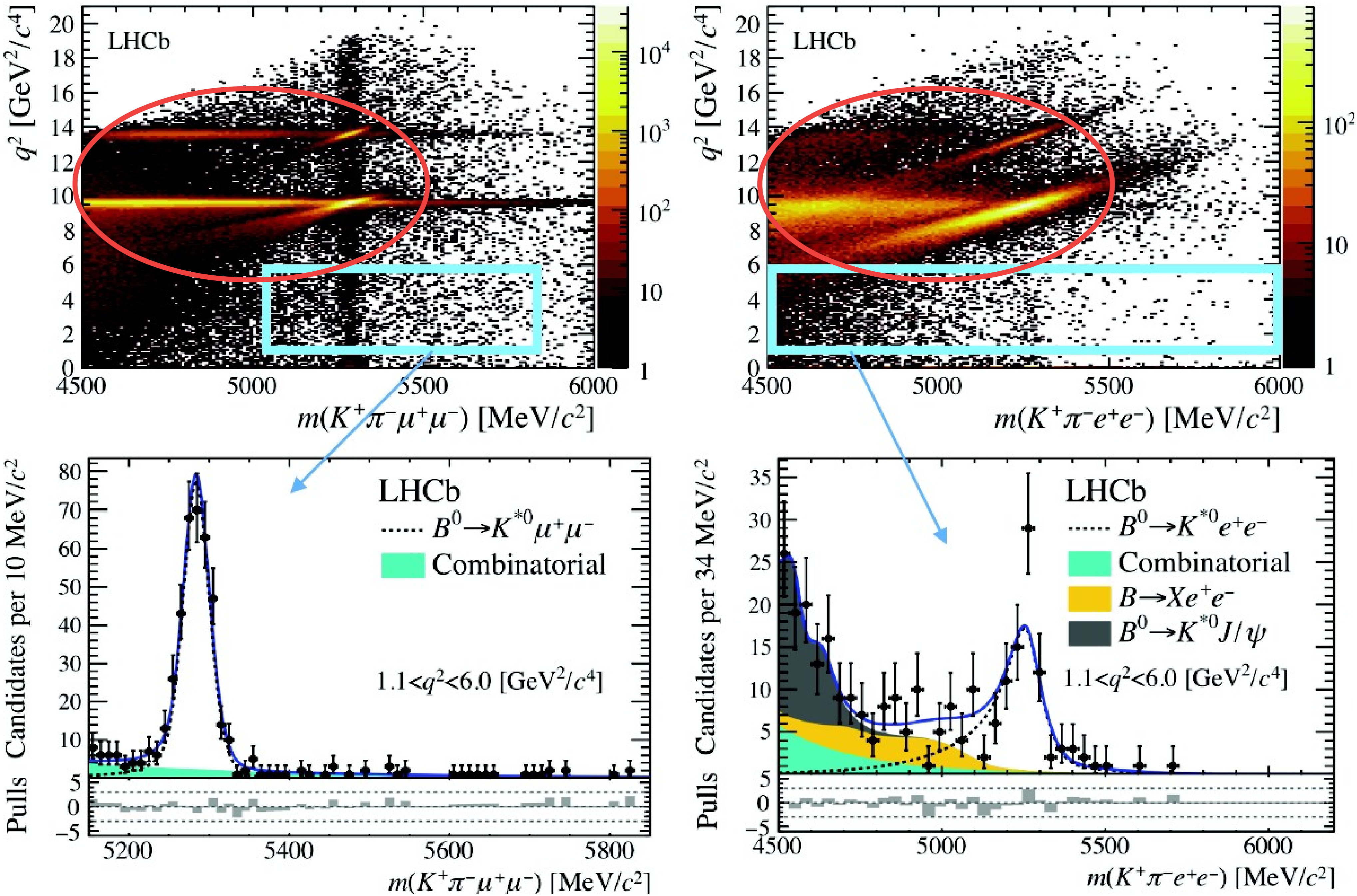
Dominant systematic uncertainties:

Fit shape, trigger calibration, B^+ kinematics.

Run1+Run2: 5.0 fb^{-1}

Phys. Rev. Lett. 122 (2019) 191801

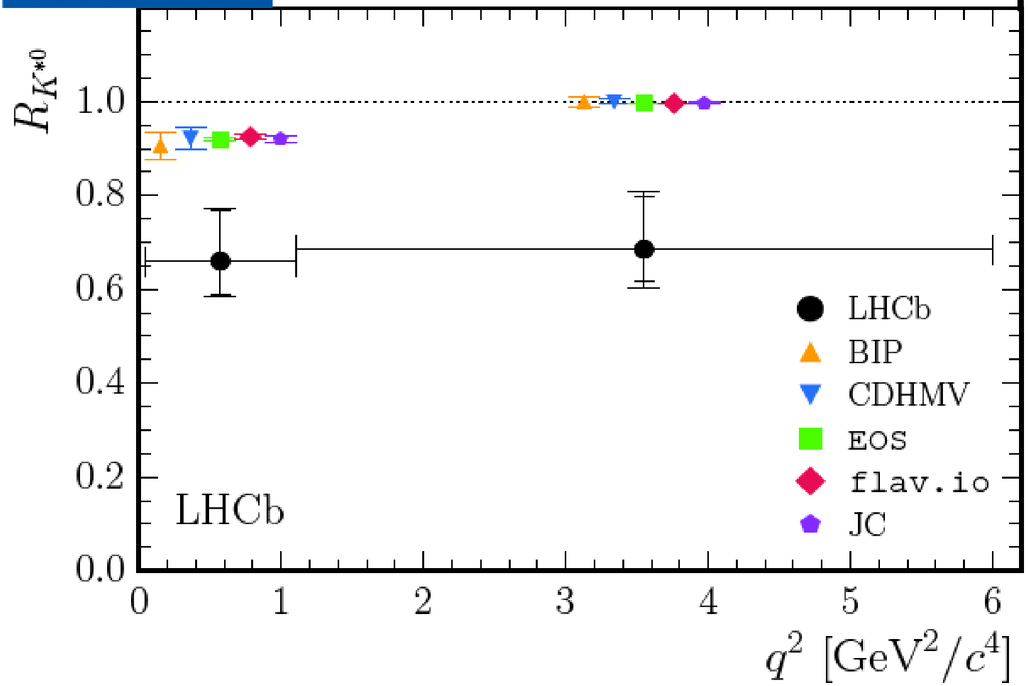
Measurement of R_{K^*}

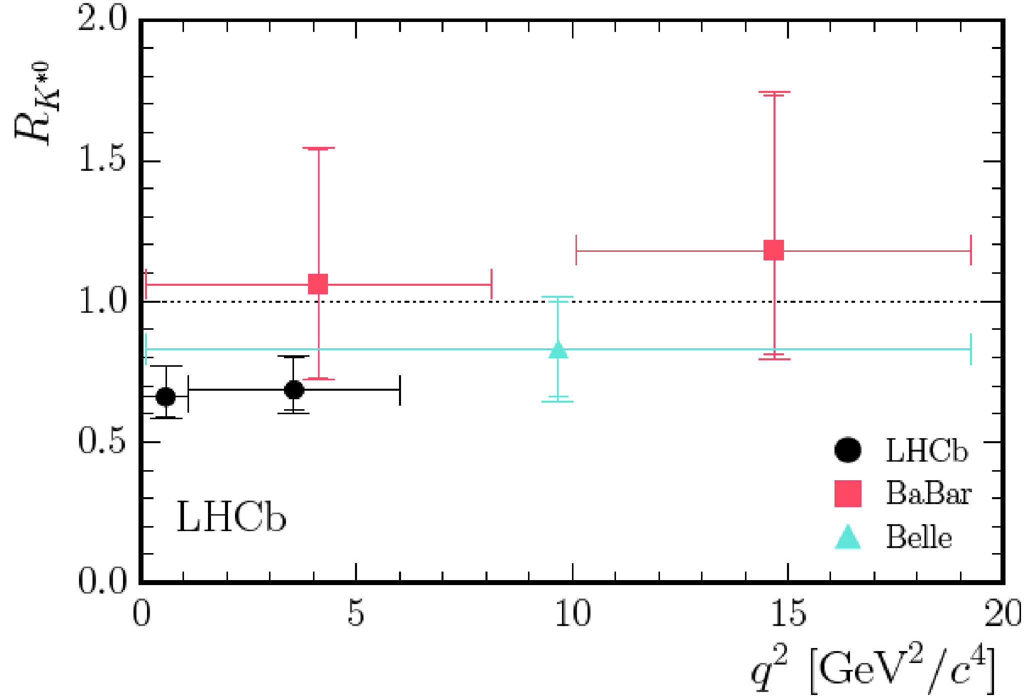


Run1: 3.0 fb^{-1}

JHEP 08 (2017) 055

R_{K^*} results





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

- Most precise measurement to date
- Compatible with BaBar and Belle
- Statistically limited by the electron sample

BIP [EPJC 76 (2016) 440]
CDHMV [JHEP 04 (2017) 016]
EOS [PRD 95 (2017) 035029]
flav.io [EPJC 77 (2017) 377]
JC [PRD 93 (2016) 014028]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

Run1: 3.0 fb^{-1}

JHEP 08 (2017) 055

Prospects for LFU tests at LHCb

LHCb aims to perform complementary LFU tests:

- $b \to c\ell\nu$ transitions:
  - $R_{\Lambda c(*)}$, $R_{D(*)}$, $R_{Ds(*)}$ and others
- $b \to u\ell\nu$ transitions:
  - $R_{p\bar{p}} = B(B^+ \to p\bar{p}\tau\nu) / B(B^+ \to p\bar{p}\mu\nu)$ and others
- $b \to s\ell\ell$ transitions:
  - R_{Ks} , R_{K*+} , $R_{K\pi\pi}$, R_{pK}, R_{φ}, R_{Λ}, direct fit to $\Delta C_9^{\mu,e}$ and others

⇒ Update of R_{K*}, R_{D*} and $R_{J/\psi}$ with Run 2 data is currently on-going. Expected improvement on both statistical and systematic uncertainties.

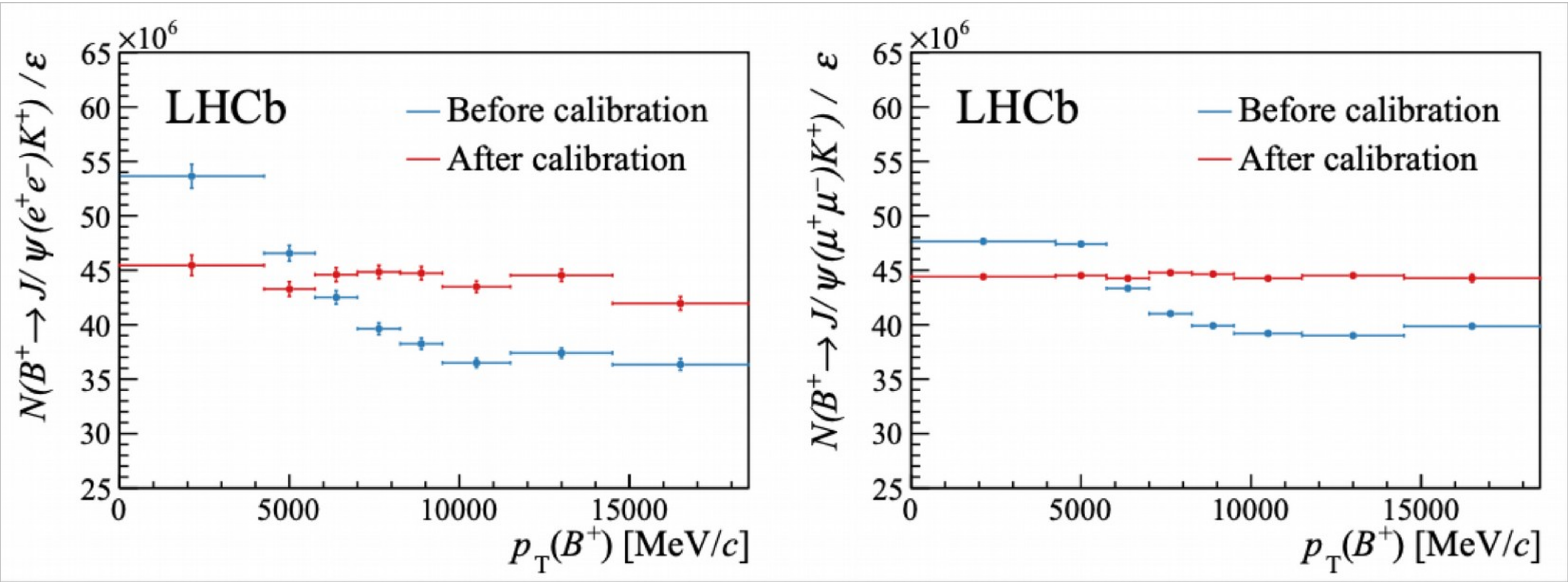
Conclusion

- Tests of LFU in heavy flavour physics present a tension with the SM predictions on ratios of branching fractions in both $b \to c\ell\nu$ and $b \to s\ell^+\ell^-$
  - 3.1σ tension in R_D and R_{D*} when combining BaBar, Belle and LHCb
  - 2.5σ below SM prediction in $R_{K(*)}$ at central q^2
- Anomalies in both $b \to c\ell\nu$ and $b \to s\ell^+\ell^-$ decays could be described with same New Physics models.
- Looking forward for contribution from theory community.
- LHCb continue testing the LFU hypothesis. Please stay tuned!

Backup

Efficiencies and corrections

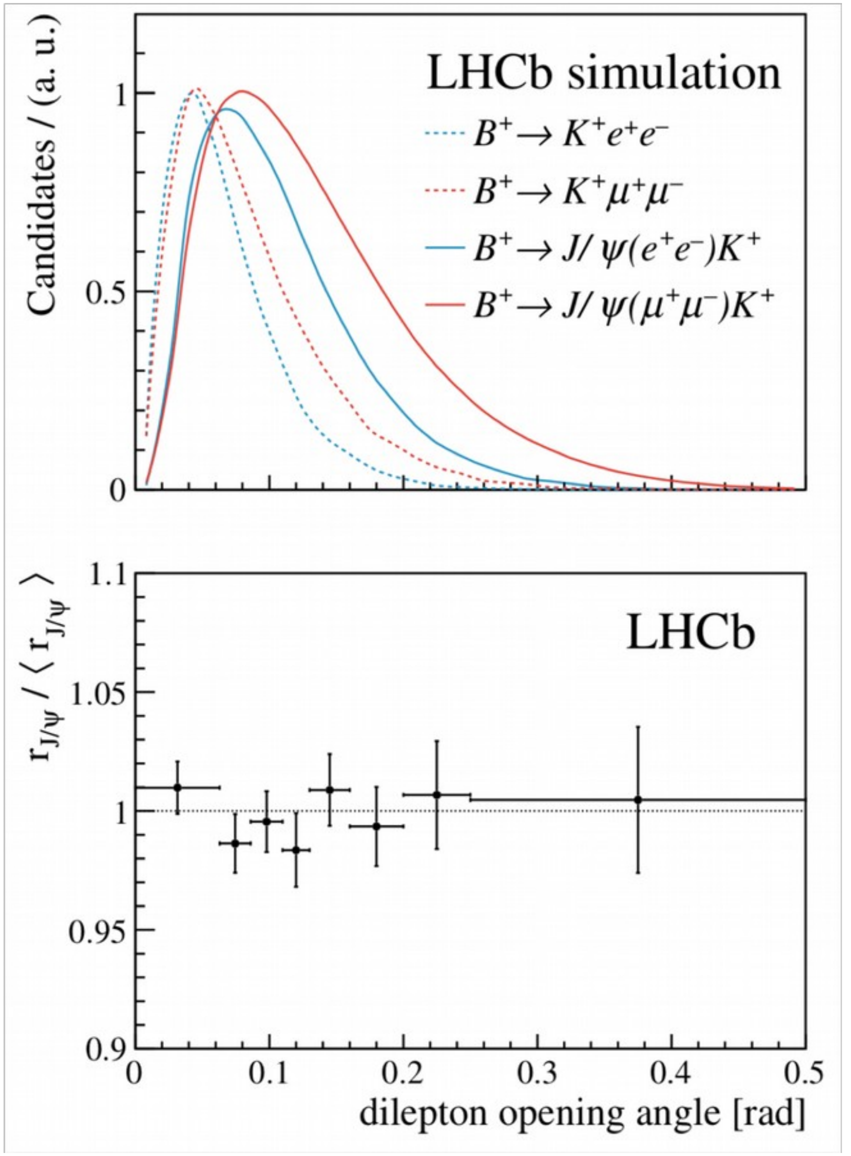
- Efficiencies calculated from simulation corrected with data:
- B^+ kinematics corrected with $B^+ \to J/\psi[\mu^+\mu^-] K^+$
- Trigger efficiency corrected with tag-and-probe $B^+ \to J/\psi[\ell^+\ell^-] K^+$
- Particle identification calibrated with data [EPJ TI (2019)6:1]
- q^2 resolution corrected based on $m(\ell^+\ell^-)$ of the J/ψ peak

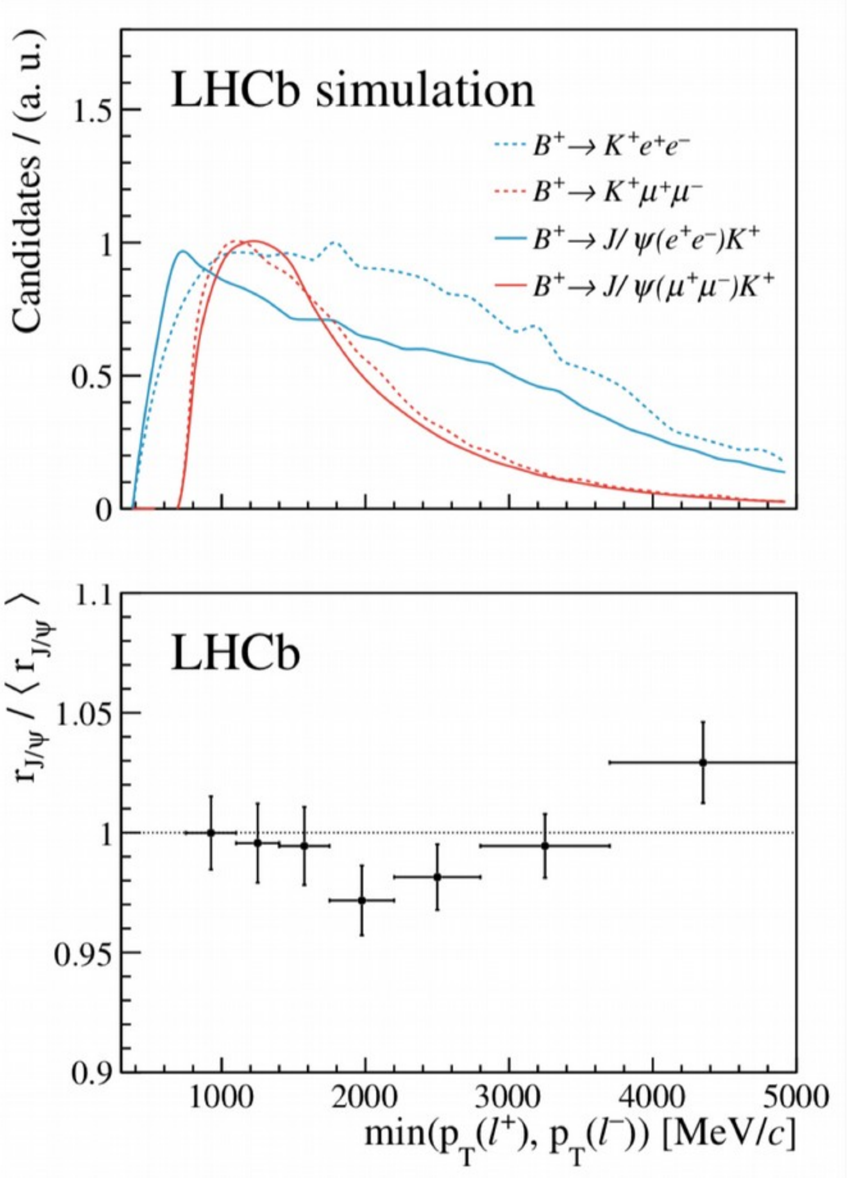


Overall effect of corrections on R_K ~0.02

Cross checks

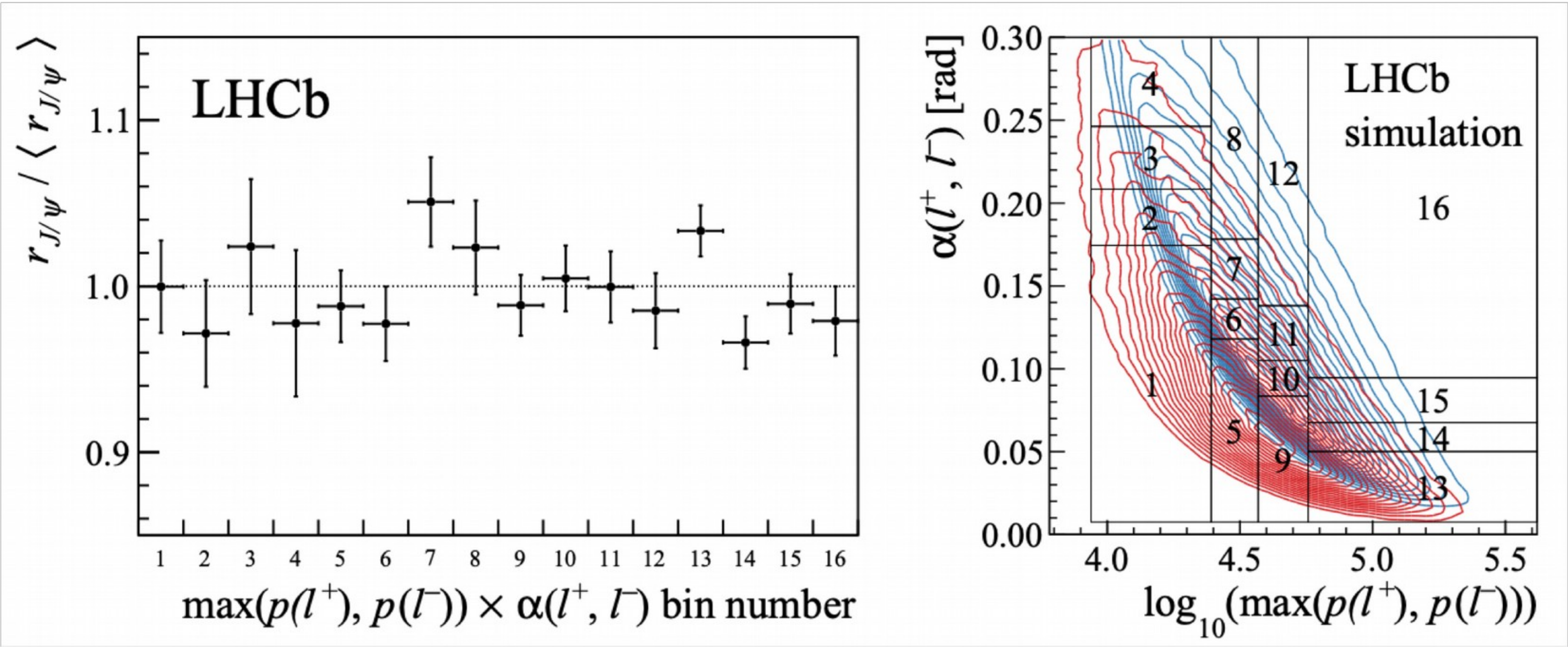
$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 1.014 \pm 0.035\ (\text{stat} + \text{syst})$$





Cross checks

Dependence of $R_{J/\psi}$ on kinematical variables (2D)



Double ratio of Branching fractions:

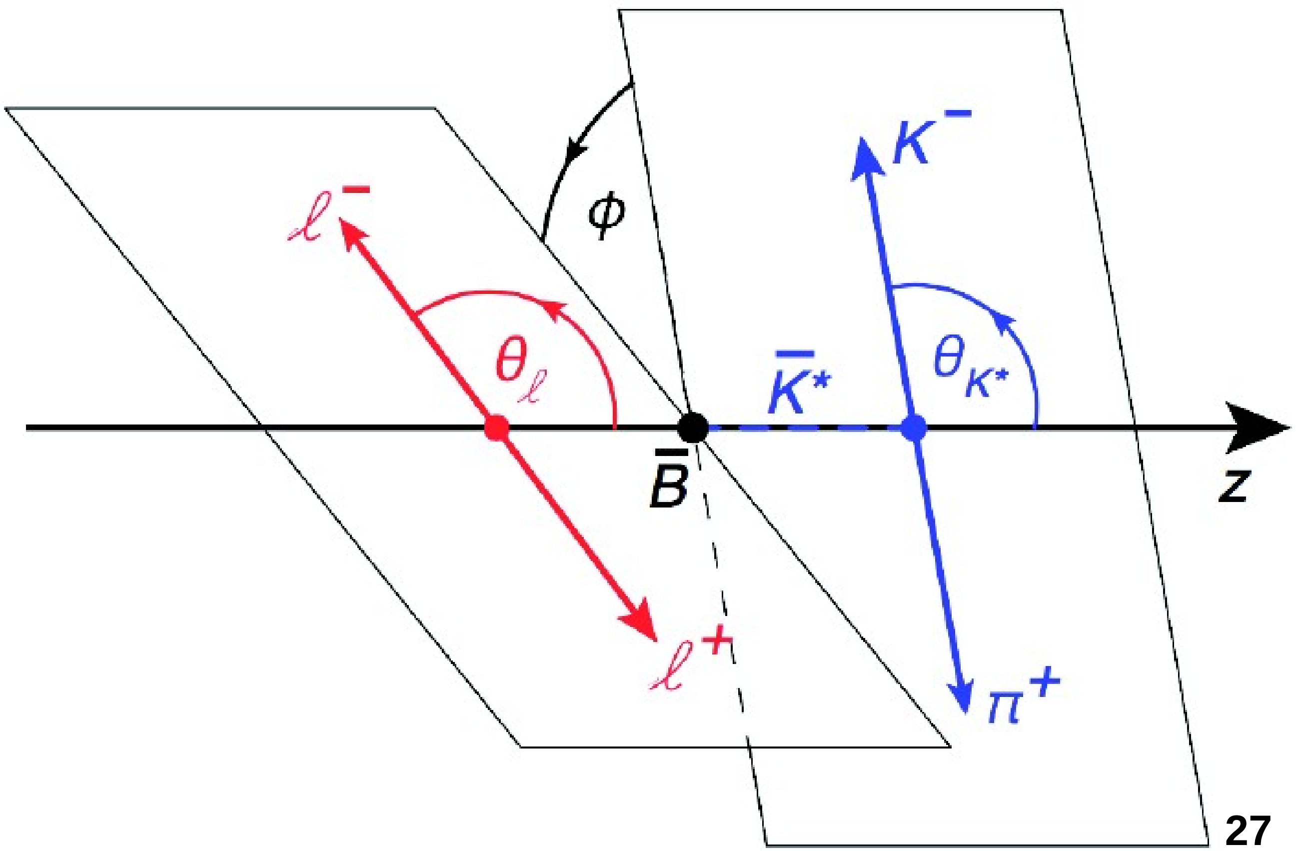
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.996 \pm 0.013$$

(stat+syst)

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

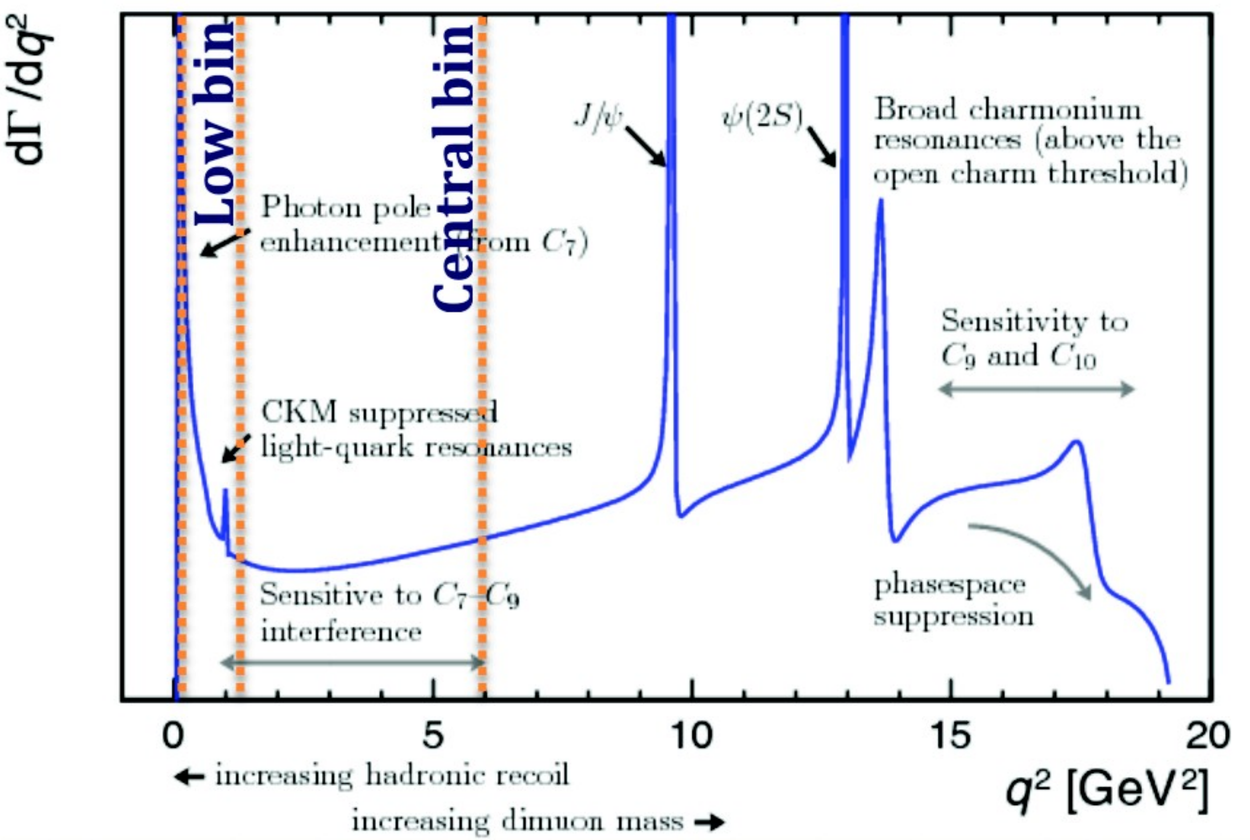
NP models which explain the observed discrepancies in the measurement of R(K(*)) w.r.t SM predictions, foresee anomalous behaviors also in the angular distribution of the decay $B^0 \to K^{*0}\mu^+\mu^-$

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



Decay amplitude of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

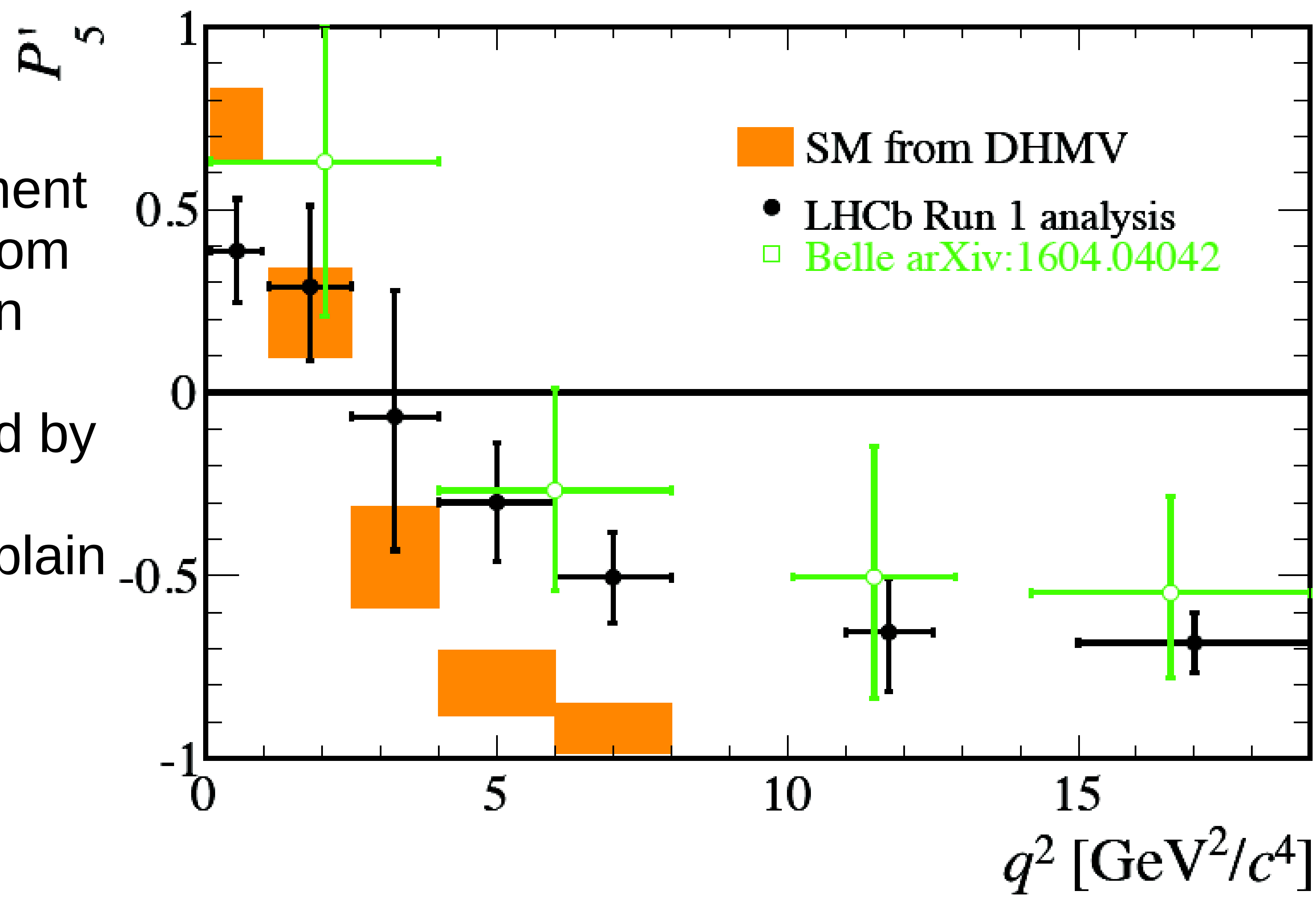
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \frac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell + S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_k\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell + S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + S_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi\Big],$$



The P_5' anomaly

- Angular observable: $P_5' \equiv S_5/\sqrt{F_L(1-F_L)}$

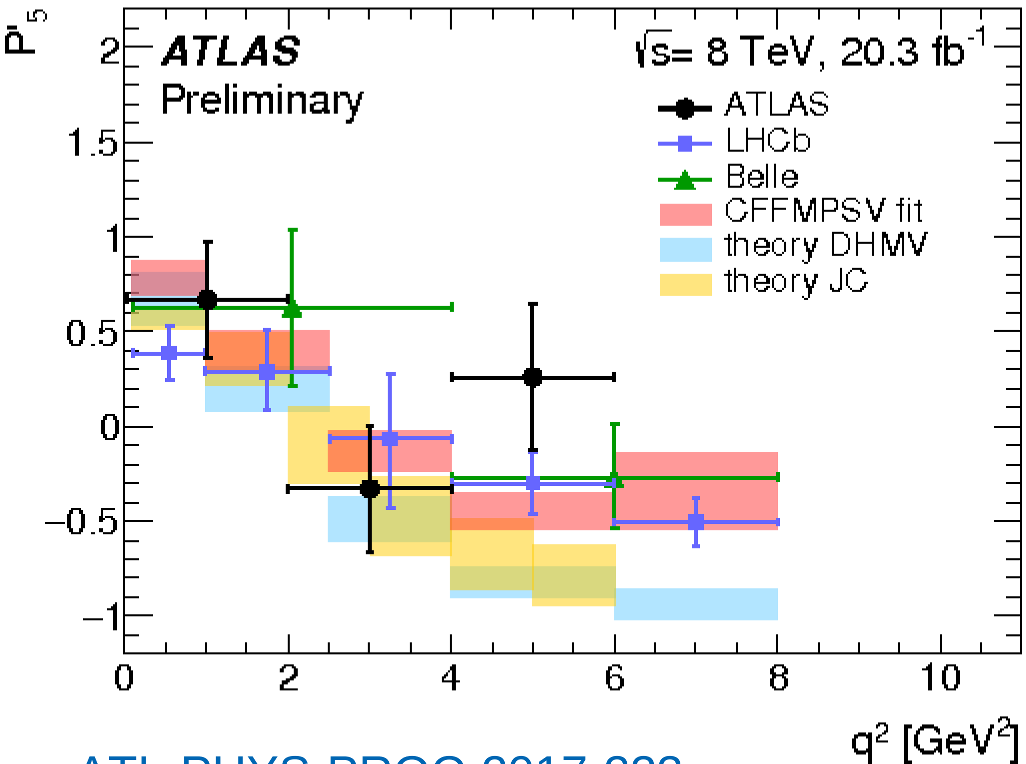
JHEP 02 (2016) 104



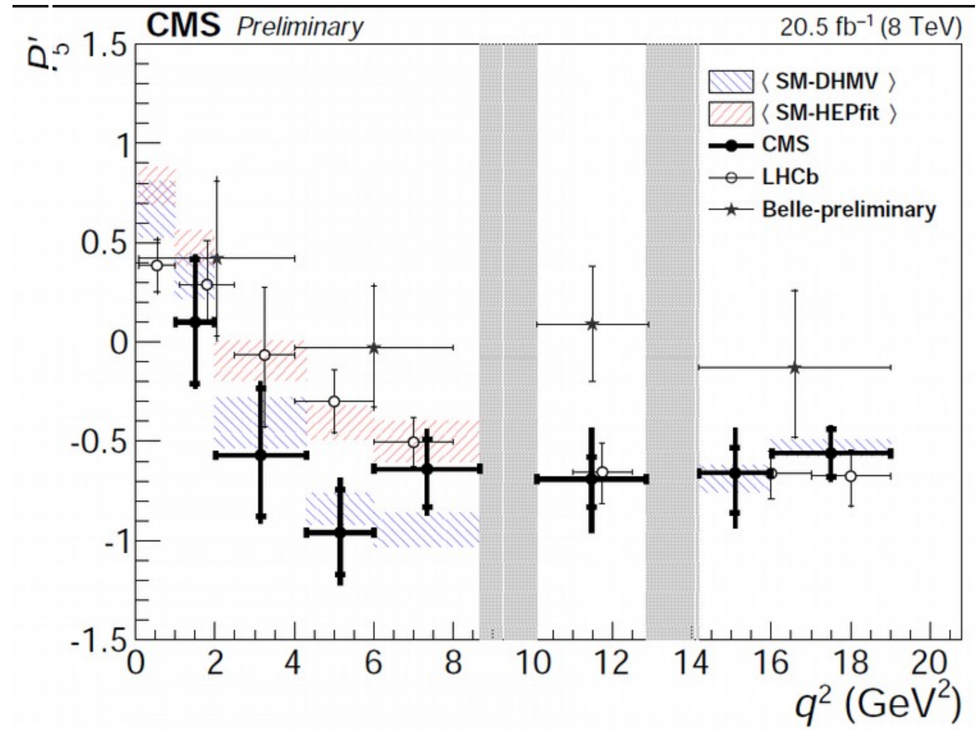
- LHCb measurement differs by 3.4σ from the SM prediction

- Can be explained by
  - SM charm-loop effects (cannot explain tension in R_{K^*})
  - New Physics

ATLAS and CMS results on P_5'



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



CMS-PAS-BPH-15-008

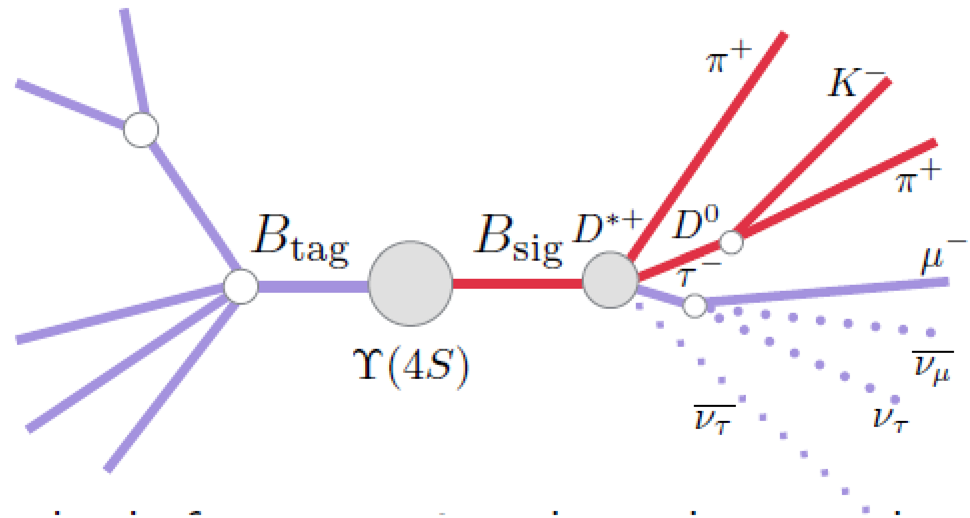
ATLAS measurement differs by 2.7σ from the SM prediction
CMS results are consistent with SM prediction and other measurements

Measurement of R_{D^*}

B factories

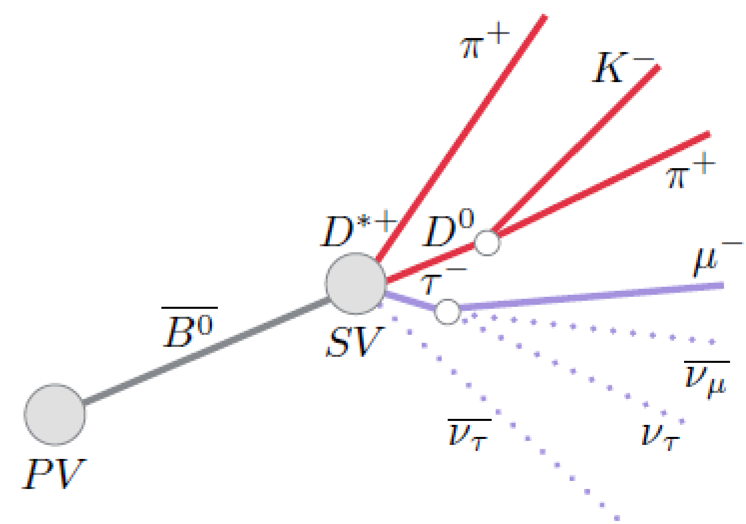
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-(B^0\overline{B}^0)$

- Reconstruction of other B
- Clean signal but low efficiency



LHCb

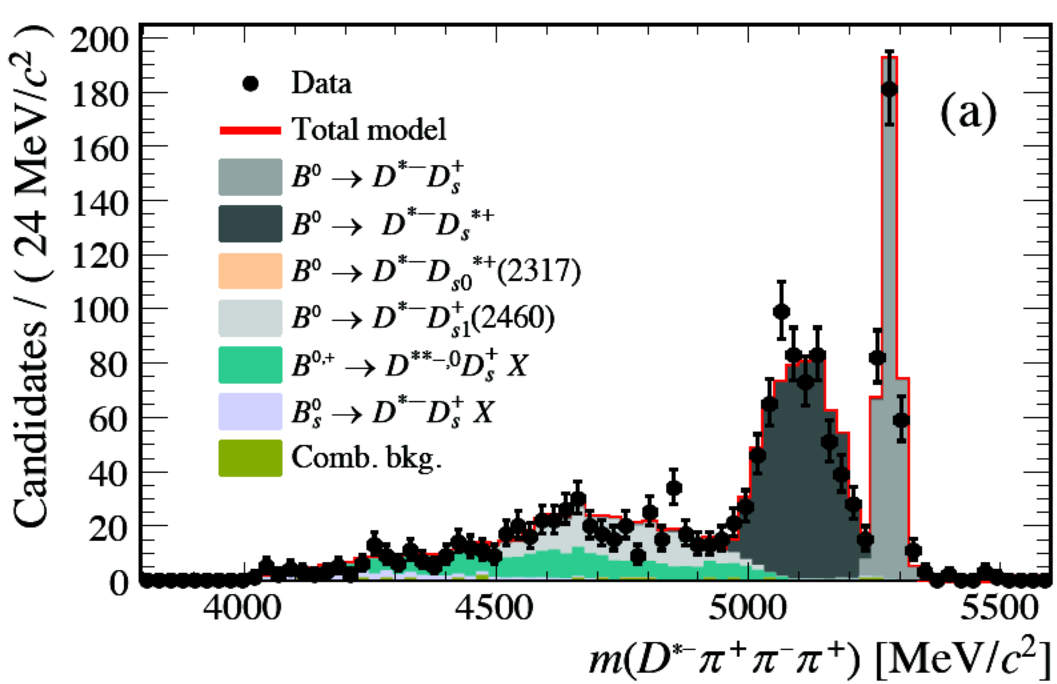
- Large boost, flight direction determined by PV & SV
- Huge B production

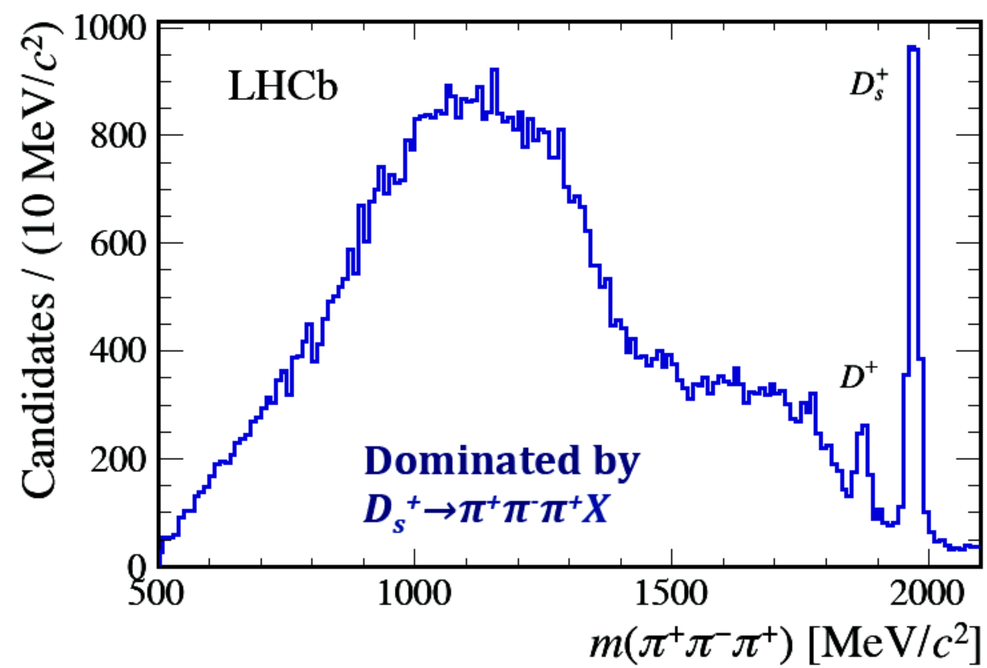


R_{D^*} in hadronic τ decays

Main systematic uncertainties due to:

- Size of simulated sample
- Shape of the background $B \rightarrow D^{*-} D_s^+ X$
- $D_{(s)}^+ \rightarrow \pi^+\pi^-\pi^+ X$ decay mode. BESII future measurement will reduce it. Improvement as well of the upgraded ECAL
- Branching fraction of normalisation mode $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$ known with ~4% precision. Belle II can measure it precisely





Phys. Rev. Lett. 120, 181802 (2018)

R_{D^*} in muonic channels