Lepton Flavour Universality Tests at LHCb

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LHCb

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Lepton Universality

- In the Standard Model, the couplings of the gauge bosons to leptons are independent of the lepton flavour
  - Charged Lepton Universality implies that the branching fractions of e, μ and τ differ only by phase space and helicity-suppressed contributions

- The Lepton Flavour Universality (LFU) is enforced in the SM by construction
  - Any violation of lepton universality would be a clear sign of physics beyond the SM.

- Over the years, LFU violation has been searched in several system
  - $Z \rightarrow ll$, $W \rightarrow l\nu$, $J/\psi \rightarrow ll$, $\psi(2S) \rightarrow ll$, $\Upsilon \rightarrow ll$, $\tau \rightarrow l\nu\nu$, $\pi \rightarrow l\nu$, $K \rightarrow \pi l\nu$
  - These measurements provide very strong limit in the non-universality in the SM EW sector
  - More significant tests involve the 1° and 2° quarks and leptons families

- A large class of SM extensions contain new interactions that involve third generation of quarks and leptons
  - Higgs-like charged scalar: $H^{\pm}$, new vectors coupled to SM Higgs doublet, leptoquarks, 2 Higgs doublets model (2HDM type II or III)…

Semileptonic decays

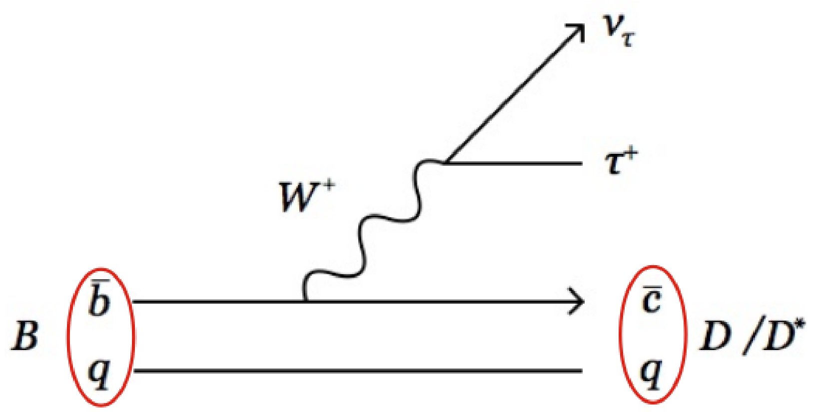
- The products of a semileptonic decay can be grouped in hadrons and leptons.

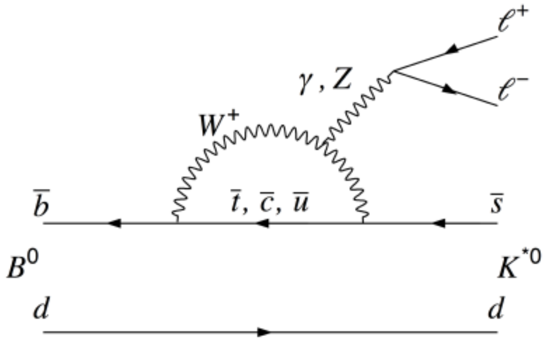
- The contributes to decay rate can be factorized in weak and strong part
  - The theoretical calculation are simplified;
  - The lepton universality ratios cancel the theoretical uncertainties .

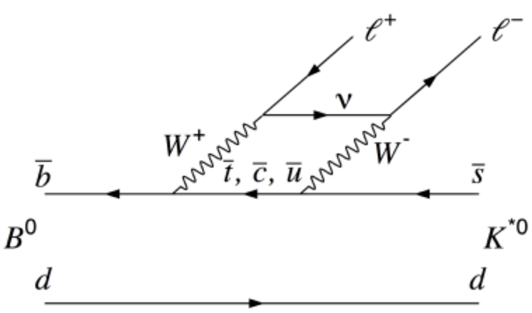
$$\frac{d\Gamma(B \rightarrow X l \nu)}{dq^2} \propto G_F^2 |V_{bq}|^2 |f(q^2)|^2$$

Charged current decays: b → c l ν

Neutral current decays: b → s l l







- Tree level, large BR,
- NP sensitivity up to hundreds of TeV

- FCNC, Loop diagram, low BR

b→sll as probe of NP

- Flavour Changing Neutral Current transitions → proceed only via loop diagrams
- Suppressed in SM → more sensitive to NP
- NP could couple in a non universal way to the different lepton families

- Comparing the rates of B → H μ⁻ μ⁺ and B → H e⁻ e⁺ allows precise test of lepton flavour universality

$$R_{\mathrm{H}}\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B \to He^+e^-)}{\mathrm{d}q^2}}, \quad q^2 = m^2(\ell\ell)$$

$$H = K, K^*, \phi, \ldots$$

- The hadronic uncertainties in the theoretical predictions cancel
- SM expectation: $R_H = 1$, neglecting lepton messes, with QED correction at % level and no QCD effects.

- LHCb measurements:
  - R_K : (Phys. Rev. Lett. 113, 151601 (2014))
  - R_{K^*} : (JHEP 08 (2017) 055)

$R(K^*)$

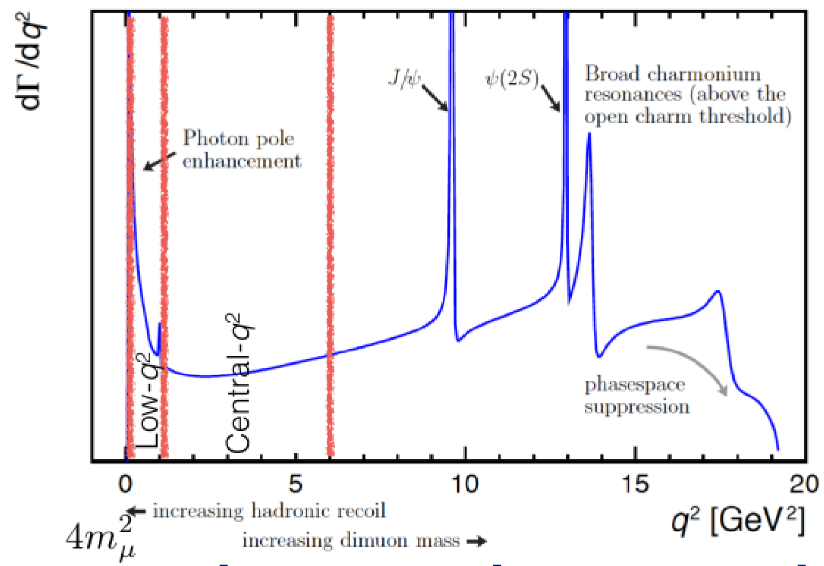
JHEP 08 (2017) 055

$$R_{\mathrm{K}^{*0}}\left[q^2_{\mathrm{min}}, q^2_{\mathrm{max}}\right] = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0 \to K^{*0}e^+e^-)}{\mathrm{d}q^2}}, \quad K^*(892)^0 \to K^+\pi^-$$

- The double ratio of rare to J/psi channel is used to reduce the systematic uncertainties:

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

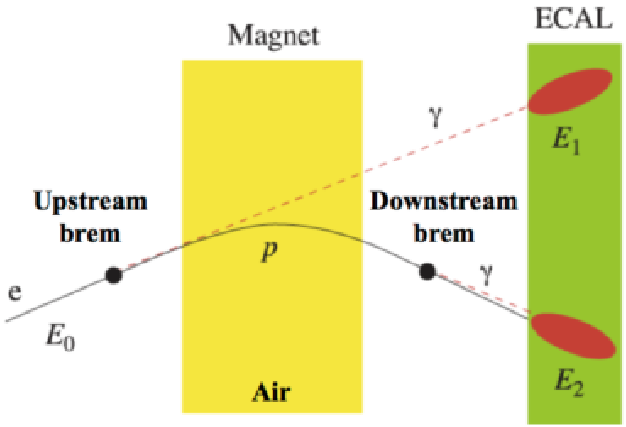
- run1 data, 3 fb^{-1} of data
- The measurement is performed in two bins:
  - Low q^2 bin: [0.0045, 1.1] GeV^2
  - central q^2 bin: [1.1, 6] GeV^2



- Extremely challenging due to significant differences in the way μ and e interact with the detector:
  - bremsstrahlung
  - trigger

Bremsstrahlung and Trigger

- Electron reconstruction is more difficult than muon due to bremsstrahlung
- The electrons emits a large amount of bremsstrahlung that results in a degraded momentum and mass resolution
- Recovery momentum procedure: extrapolation of the electron track upstream and addition of the bremsstrahlung calorimeter cluster to electron momentum.
- Limits:
  - Energy Threshold of bremsstrahlung photon (E_T>75 MeV)
  - Calorimeter acceptance
  - Energy deposits mistaken identified as bremsstrahlung clusters



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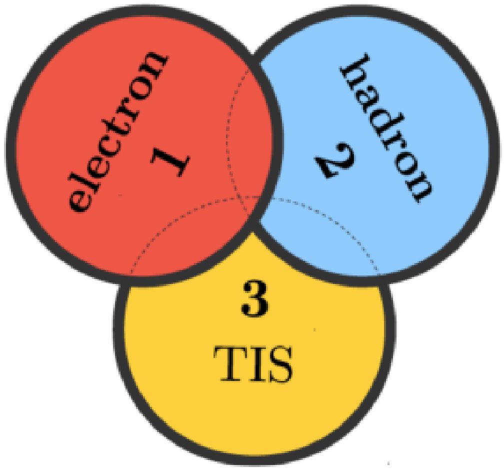
Bremsstrahlung and Trigger

- Due to higher occupancy of the calorimeters compared to the muon stations, hardware thresholds on the electron E_T are higher than on the muon p_T (L0 Muon, p_T >1.5,1.8 GeV)
  - → partial loss of electron signal
  - → to partially mitigate this effect 3 exclusive trigger categories are defined



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R(K*)

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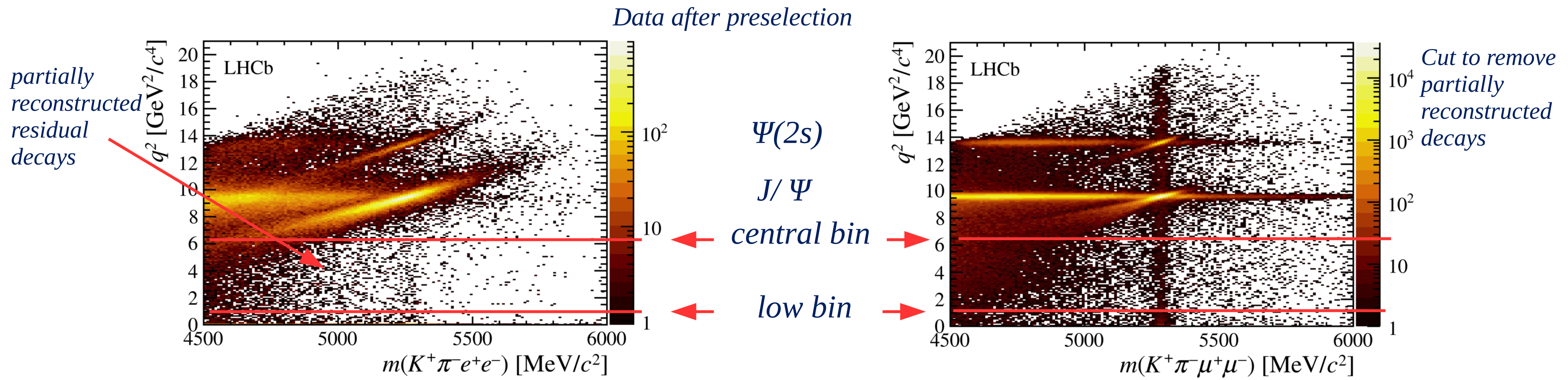

- Due to bremsstrahlung the reconstructed B mass is shifted towards lower values and events leak into the central-q bins

- Selection chosen as similar as possible between μ μ and ee:
  - Multivariate classifier to reject the combinatorial background
  - Kinematic requirements to reduce partial reconstructed background

- Use normalization channel to correct simulation and signal mass shapes.
- Efficiencies evaluated from simulation, tuned to data using dedicated control samples

Fit Procedure

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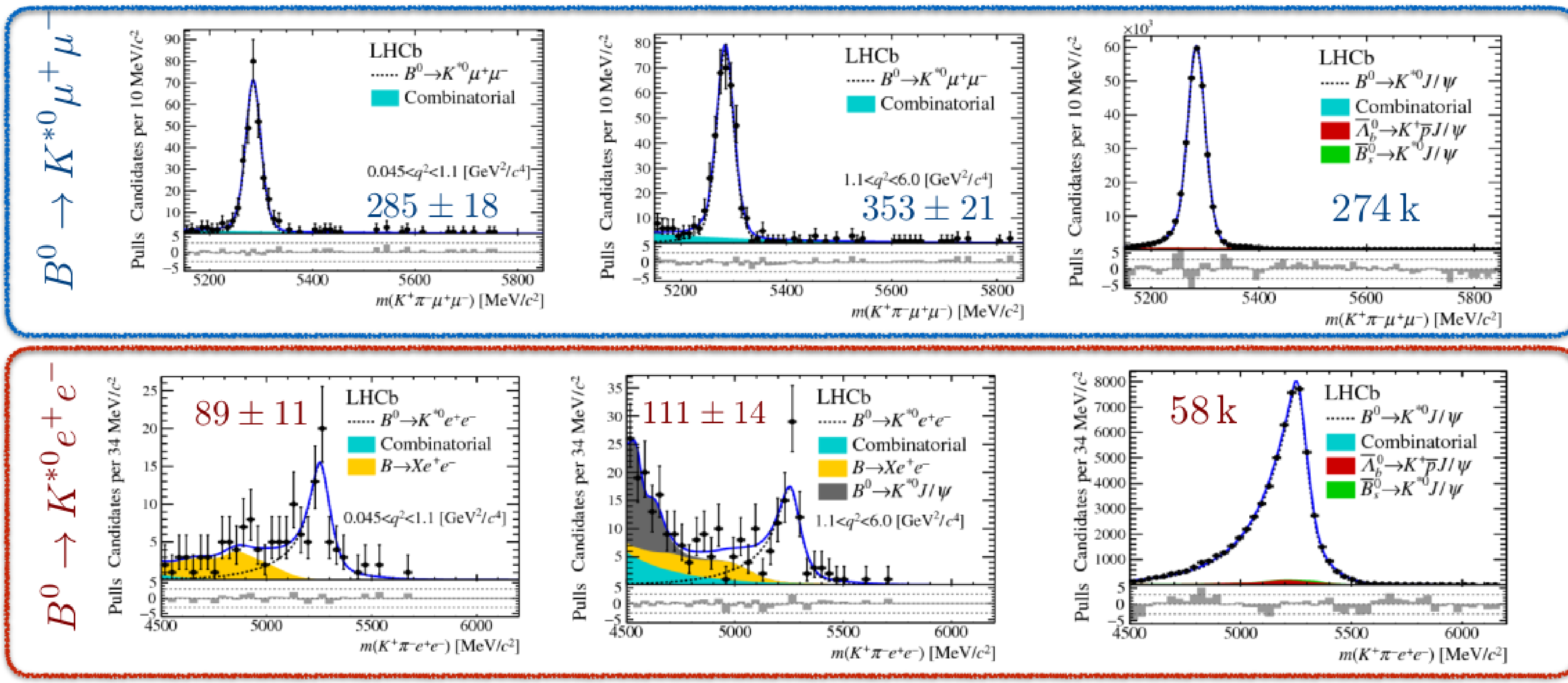
- Fit to B mass in lower and central dilepton transferred momentum region.
- Simultaneous fit to resonant and not resonant data, particularly for the electron decays splitted in 3 trigger categories.

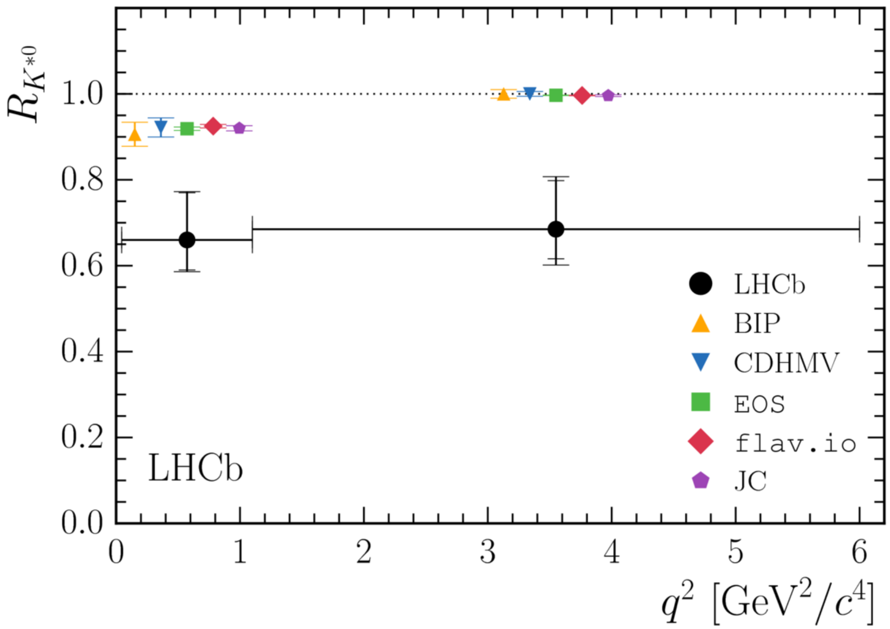
low q^2 bin | central q^2 bin | normalization channel

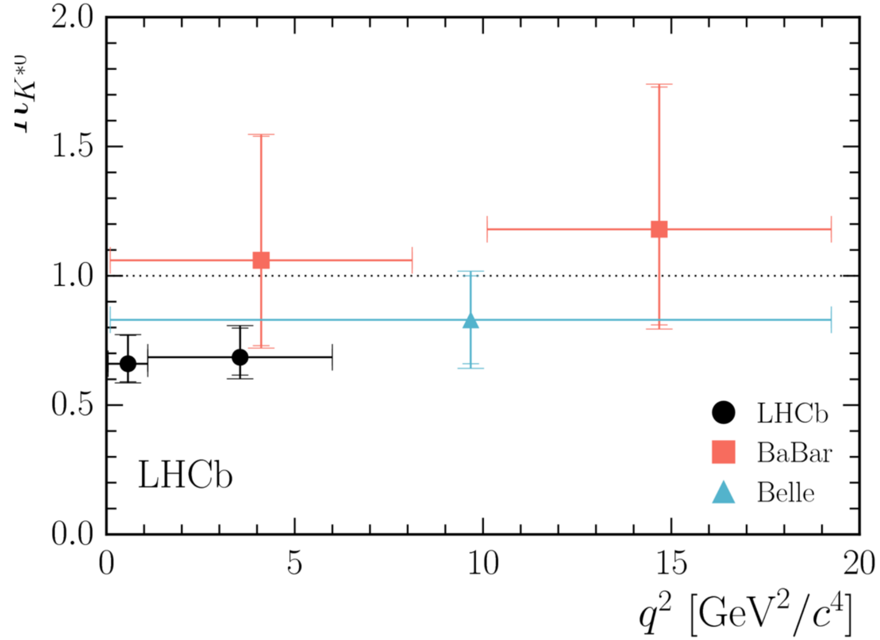


R(K*) result

- Precision of the measurement driven by statistics of electron samples

- Compatibility with the SM
  - low q^2 bin: 2.1-2.3 standard deviation
  - central q^2 bin: 2.4-2.5 standard deviation



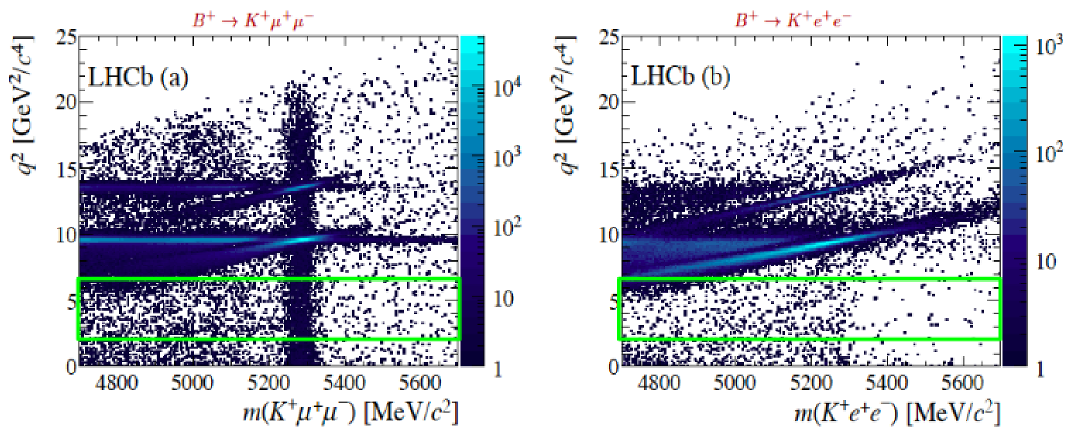


- BaBar: PRD 86 (2012) 032012
- Belle: PRL 103 (2009) 171801
- LHCb: JHEP 08 (2017) 055

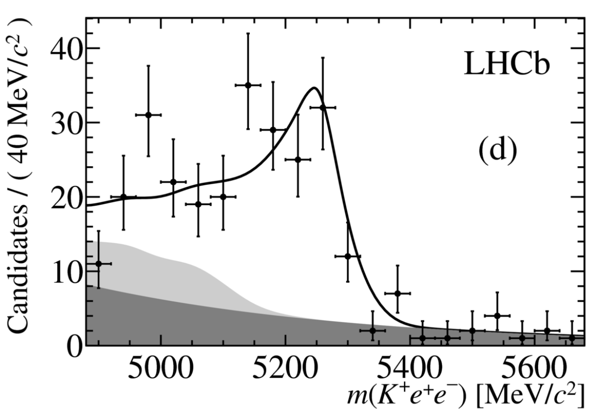
R(K)

(Phys. Rev. Lett. 113, 151601 (2014))

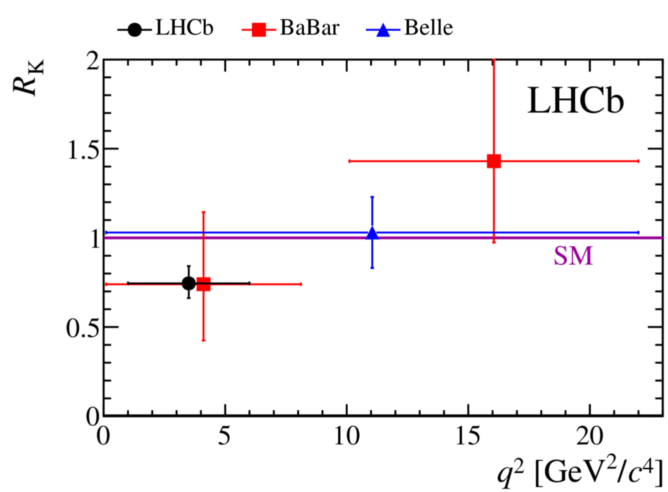
- Double ratio with respect the $B^+ \rightarrow J/psi\ K^+$ resonant decay mode
- Signal extracted in the $1 < q^2 < 6\ GeV^2$
- SM expectation: $R_K \approx 1 + 0\ (10^{-2})$ (arXiv:1605.07633v3)
- Distributions affected by bremsstrahlung and trigger



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



Events triggered by one of electrons only



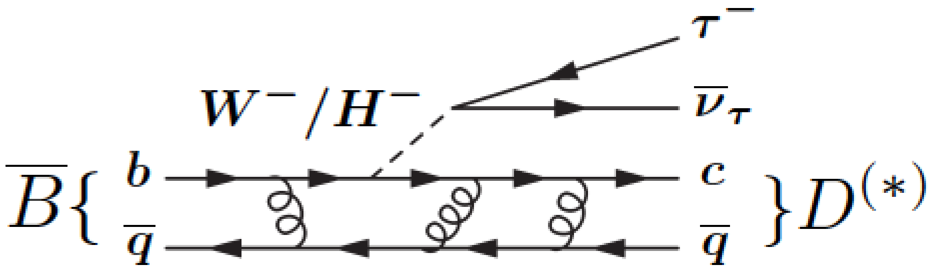
→ with respect to SM 2.6 σ

- BaBar:PRD 86 (2012) 032012
- Belle: PRL 103 (2009) 171801
- LHCb:Phys. Rev. Lett. 113, 151601 (2014)

b→clν: R(D*)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- Large rate of charged current decays
- Cancel QCD uncertainties
- Precisely prediction: R(D*) = 0.252 ± 0.003 (PRD85 (2012) 094025)
- R(D*) sensitive to any physics model favoring 3rd generation leptons for ex leptoquarks or charged Higgs



- LHCb measurement:
  - R(D*) where $\tau \to \mu\nu_\mu\nu_\tau$ (PRL115,111803 (2015))
  - R(D*) where $\tau \to \pi\pi\pi(\pi^0)\nu_\tau$ (LHCb-PAPER-2017-017, arXiv:1708.08856)

R(D*) with hadronic τ decays

arXiv:1708.08856

- Final states: $D^{*-} \rightarrow \overline{D}^0 (\rightarrow K^+ \pi^-) \pi^-$ $\tau \rightarrow \pi\pi\pi(\pi^0)\nu_\tau$
- \+ no charged lepton in the final states → zero background from $B \rightarrow D^*\mu\nu X$
- \+ good tau vertex reconstruction
- \- large hadronic backgrounds:
  - $B \rightarrow D^* 3\pi X$ (BF ~ 100x signal)
  - $B \rightarrow D^* D_s X$ (BF ~10x signal)
- R(D*) is obtained by

$$\mathrm{R}(D^*) = \mathrm{K}(D^*) \times \frac{Br(B^0 \rightarrow D^{*-} 3\pi)}{Br(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

[~4% precision, PDG2017]

[~2% precision, HFLAV 2016]

- the measured ratio is K(D*):

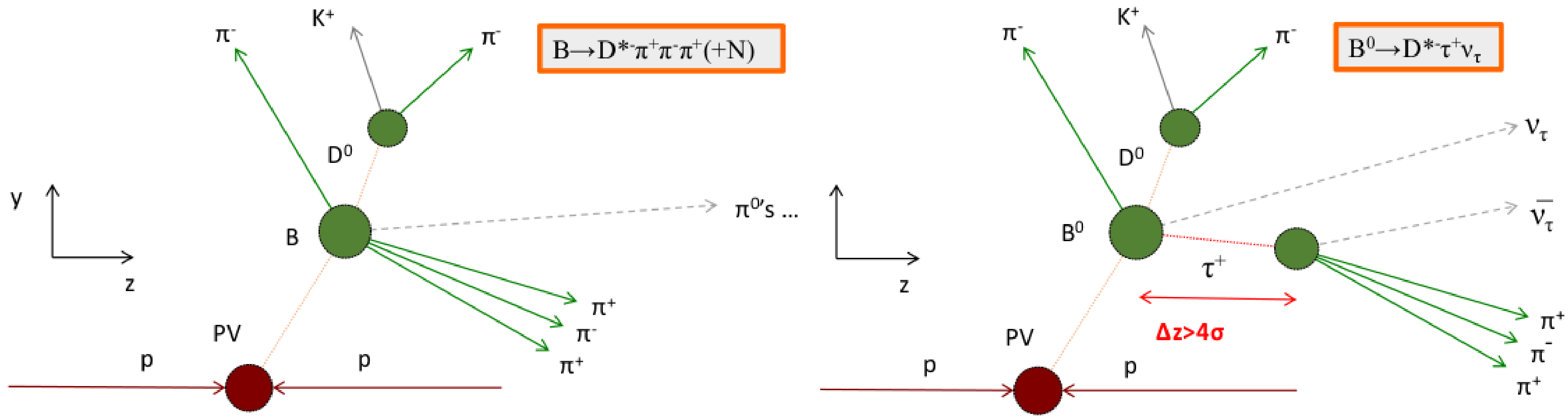
$$\mathrm{K}(D^*) \equiv \frac{Br(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{Br(B^0 \rightarrow D^{*-} 3\pi)} = \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{Br(\tau^+ \rightarrow 3\pi(\pi^0)\overline{\nu}_\tau)}$$

- Signal and normalization have the same visible final states → most of the systematic uncertainties cancel in the ratio (PID, trigger and selection).
- $N_{D^*3\pi}$ from a unbinned likelihood fit to m(D* πππ).
- $N_{D^*\tau\nu}$

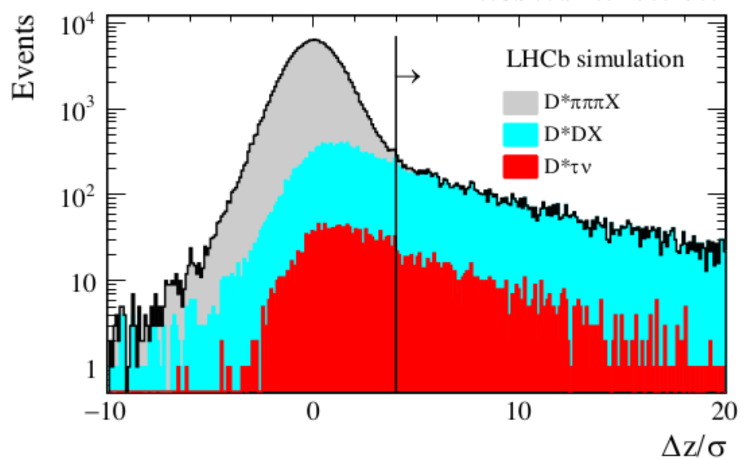
$H_b \to D^*3\pi X$

arXiv:1708.08856

- The main background is due to $H_b \to D^*3\pi X$ (BF ~ 100x signal)



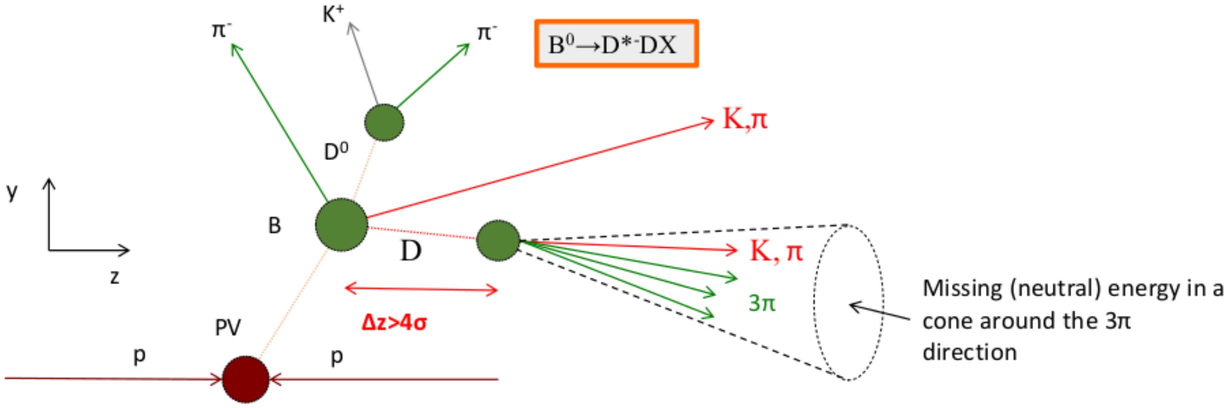
- Suppressed by requiring the τ vertex to be downstream wrt B vertex along beam direction with a 4σ significance



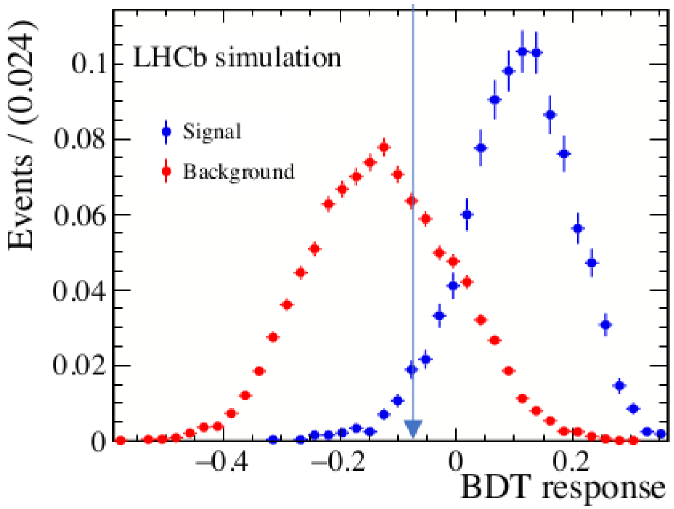
- Reduction of 3 order of magnitude
- Signal efficiency = 35 %

Double charmed background

- Remaining B meson double charmed decays are of type $B \to D^* D(3\pi Y)X$
- Veto on candidates with extra charged particles compatible with B and 3π vertices
- BDT is based on
  - Isolation variables;
  - Neutral isolation BDT;
  - Different resonant structure of $D^*3\pi$ system;



- High BDT region is used to extract the signal: BDT > −0.075

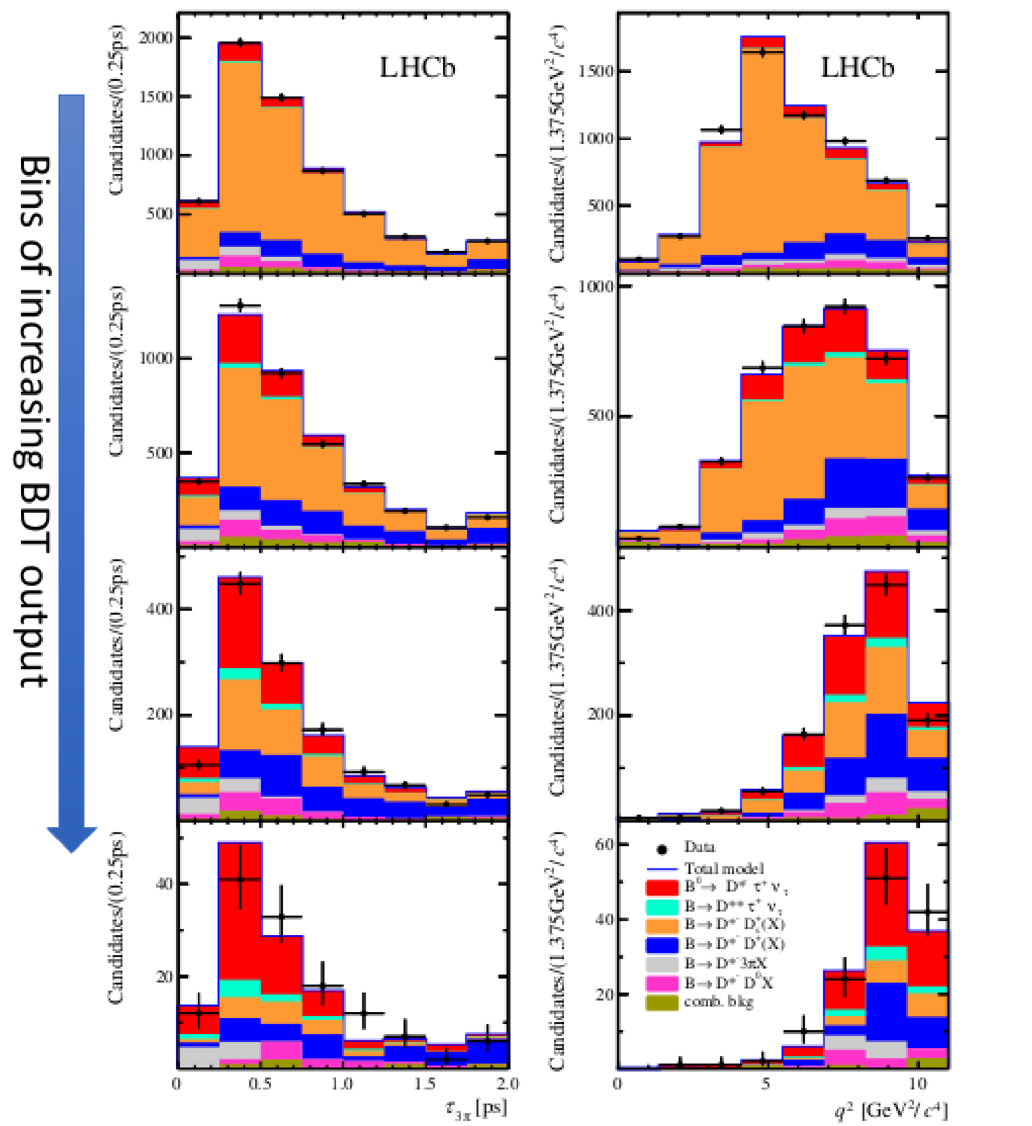


arXiv:1708.08856

Fit procedure

arXiv:1708.08856

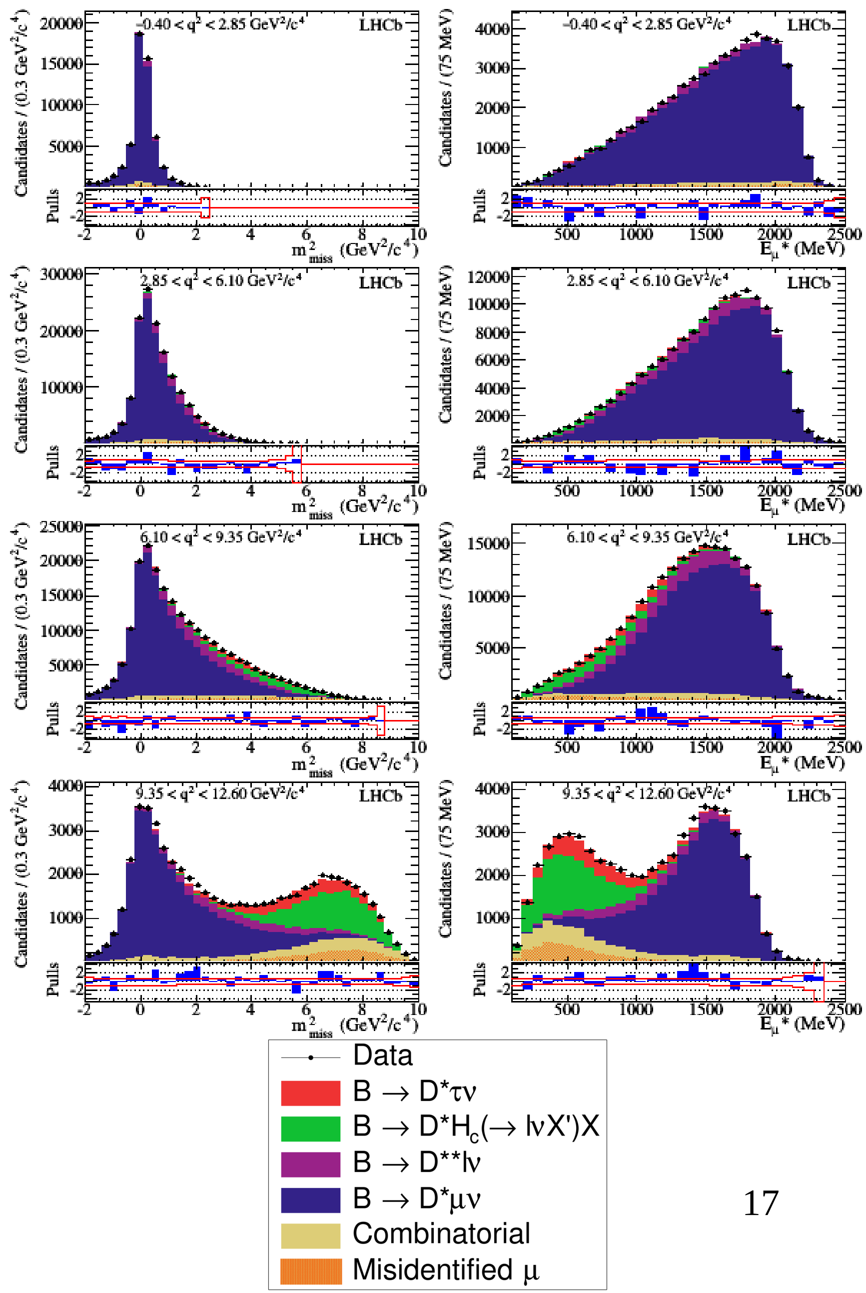
- A 3D extended maximum likelihood template fit is performed on data to extract signal yield:
  - BDT output
  - tau decay time
  - q^2
- Templates are extracted from simulated and control samples with represent the contributions to the data



- $N_{D^*\tau\nu} = 1300 \pm 85$
- $K(D^*) = 1.93 \pm 0.13(\text{stat}) \pm 0.13(\text{sys})$
- $R(D^*) = 0.285 \pm 0.019(\text{stat}) \pm 0.025(\text{sys})$
  $\pm 0.014(\text{ext})$

R(D*) with leptonic τ decays

- Final states: $D^{*-} \rightarrow D^0 (\rightarrow K^+ \pi^-) \pi^-$ $\tau \rightarrow \mu \nu_\mu \nu_\tau$
- Neutrinos → no narrow peak to fit in any distribution
- Multivariate approach (isolation BDT) to reject the backgrounds $B \rightarrow D^{**} \mu \nu_\mu$ with additional charged track around the B vertex with respect to signal
- In the B rest frame, three kinematics variables allow to distinguish $B^0 \rightarrow D^* \tau \nu$ and $B^0 \rightarrow D^* \mu \nu$:
  - $m^2_{miss} = (p_B - p_{D^*\mu})^2$
  - $q^2 = (p_B - p_{D^*})^2$
  - E^*_l: energy of lepton in the B centre of mass frame
- Maximum Likelihood Fit to binned m^2_{miss}, E^*_l and q^2 distributions with 3D templates



R(D*) = 0.336 ± 0.027(stat) ±0.030(syst)

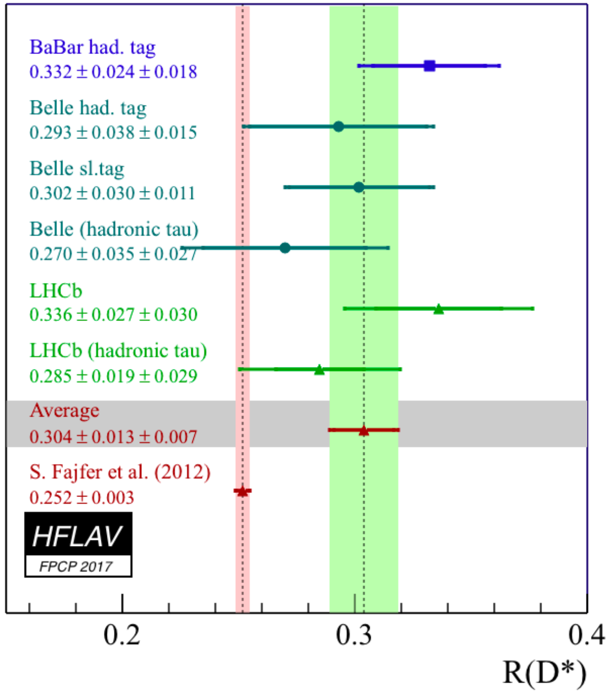
→ 2.1σ from SM prediction

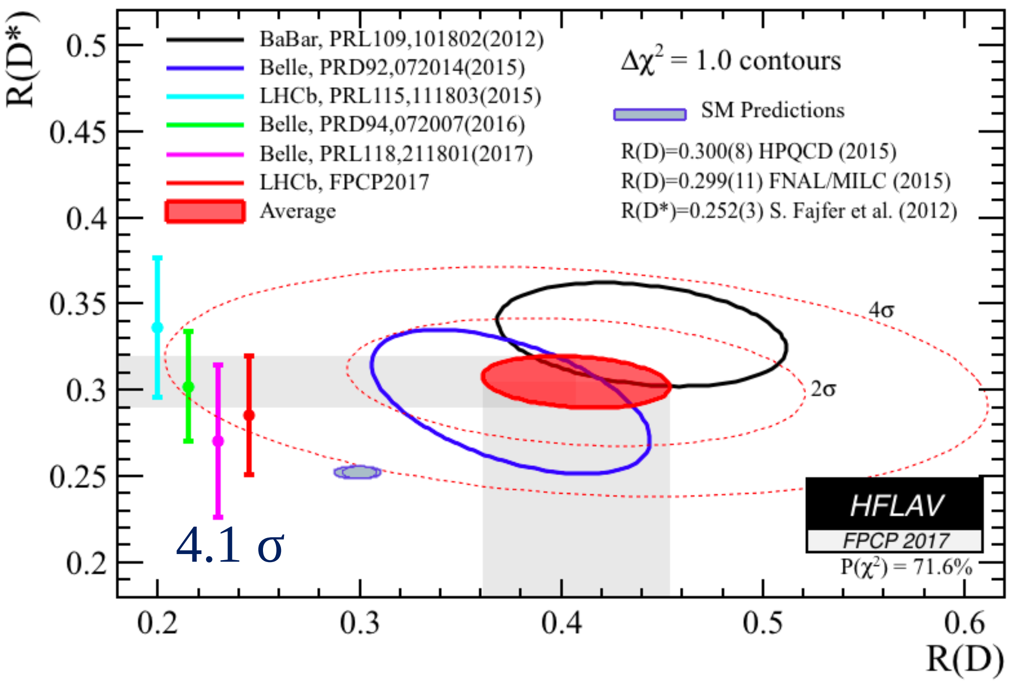
Phys.Rev.Lett. 115, 111803 (2015)

R(D*) mesaurements combintion

- $R(D^*)_{\text{HADRONIC LHCb}}$ = 0.285 ± 0.019 (stat) ± 0.025 (syst) ± 0.014 (ext)
- $R(D^*)_{\text{MUONIC LHCb}}$ = 0.336 ± 0.027(stat) ±0.030(syst)
- LHCb average: R(D*) = 0.306 ± 0.027 → 2.1σ above the SM prediction
- HFLAV world average: R(D*) = 0.304 ± 0.015 → 3.4 σ above the SM

- HFAG average of R(D) and R(D*) is 4.1 σ from the SM prevision





Conclusion

- Lepton Flavour Universality test are a clean probe to NP, completing the direct researches;
- Both in tree and loop level semileptonic B decays present anomalies with respect the SM;

- All measurements presented are performed using run 1 data and are dominated by statistical error → run 2 LHC data

- The compatibility of R(K*) result with respect to the SM predictions is of 2.2-2.5 standard deviations in each q^2 bins. It is particularly interesting given a similar behavior in R(K).

  The hadronic LHCb R(D*) measurement is one of the best single measurements having the smallest statistical error. It is compatible with SM and with the World Average. It slightly increases the discrepancy of WA with SM.

- Other ongoing R measurement at LHCb:
  - Tree: R(D), R(Λ_c*),...
  - Loop: R(K_S), R(Φ),...

Thank you for your attention