Flavour results at LHCb

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on behalf of the **LHCb collaboration**

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outline

LHCb have made a significant impact on the flavour physics landscape demonstrating its capability to test the Standard Model (SM) and, potentially, to reveal new physics (NP) effects in the flavour sector

- ✓ huge production of new results ➔ **only in 2017 more than 50 papers**
- ✓ for this talk I selected few analysis between the most recent and intriguing *from my point of view !*

1) CKM physics

- ✓ updated γ combination
- ✓ first measurement of ϕ_s using $B_s \to (K^+\pi^-)(K^-\pi^+)$ decays

2) measurements in specific sectors where anomalies are emerging in recent years

- ✓ lepton-flavour universality in $b \to c\tau\nu_\tau$: $R(D^*)$, $R(J/\psi)$
- ✓ lepton-flavour universality in $b \to sll$: R_K, $R_{K^{*0}}$

the LHCb detector

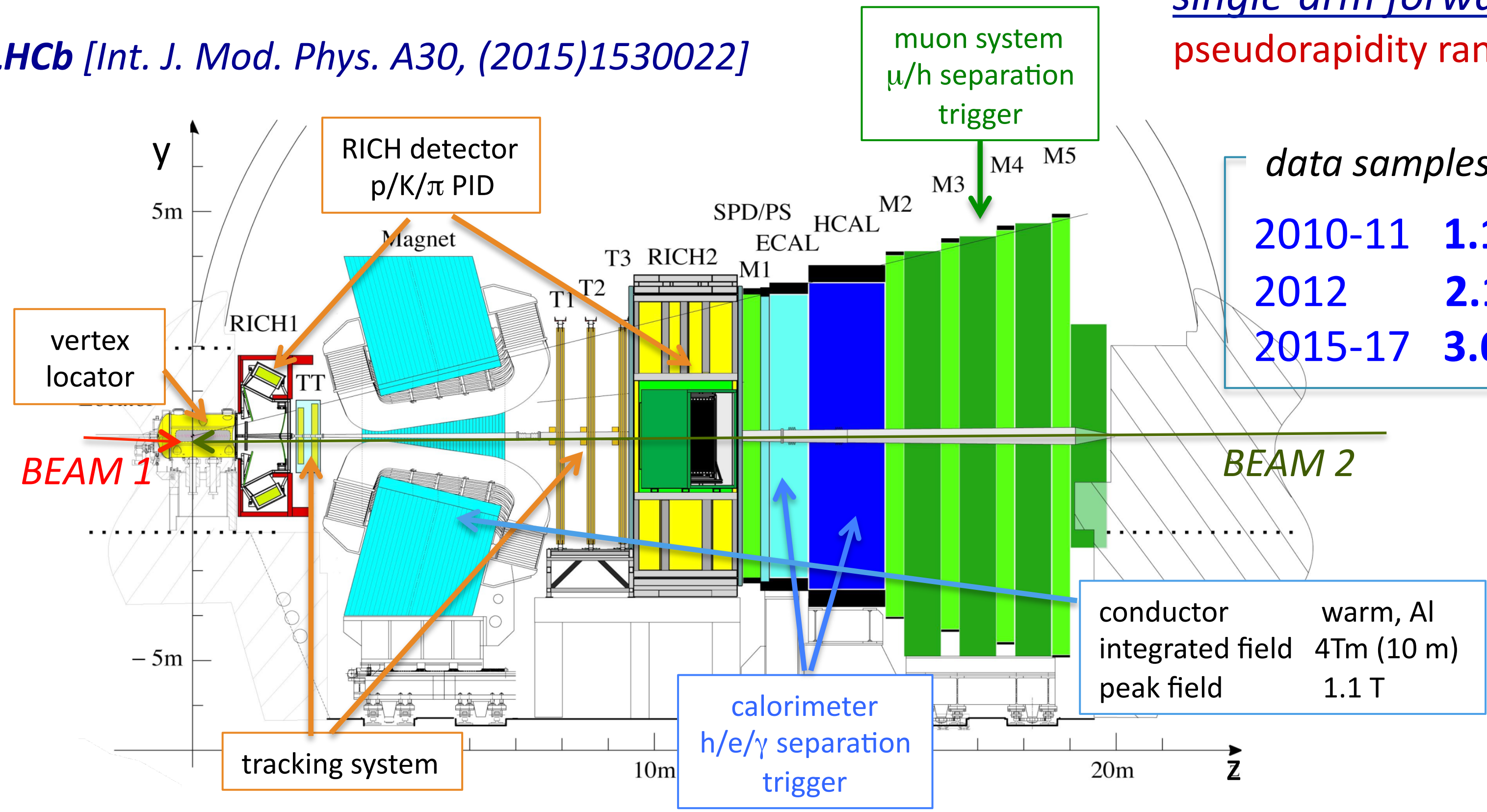
LHCb [Int. J. Mod. Phys. A30, (2015)1530022]

single-arm forward spectrometer

pseudorapidity range ➔ $2 < \eta < 5$

data samples

2010-11	**$1.1\ pb^{-1}$**	at 7 TeV
2012	**$2.1\ fb^{-1}$**	at 8 TeV
2015-17	**$3.6\ fb^{-1}$**	at 13 TeV



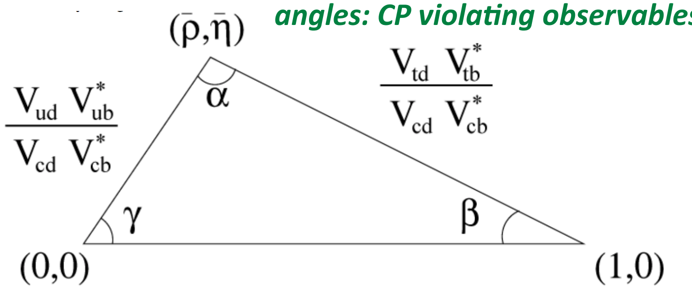
multi-stage trigger first hardware, subsequent two levels are software

- Vertexing proper time resolution 30-50 fs
- Tracking $\Delta p/p = 0.35 - 0.55\ \%$ $\sigma(\text{mass}) = 10 - 25\ \text{MeV}/c^2$
- RICH KaonID $\varepsilon(K \rightarrow K) \approx 95\%$ misID rate $(\pi \rightarrow K) \approx 5\%$
- ECAL $\sigma(E)/E = 10\%/\sqrt{E} \oplus 1.\ \%$ HCAL $\sigma(E)/E = 69\%/\sqrt{E} \oplus 9\%$
- MuonID $\varepsilon(\mu \rightarrow \mu) \approx 97\%$ misID rate $(\pi \rightarrow \mu) = 1\text{-}3\ \%$

updated γ combination

$\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$

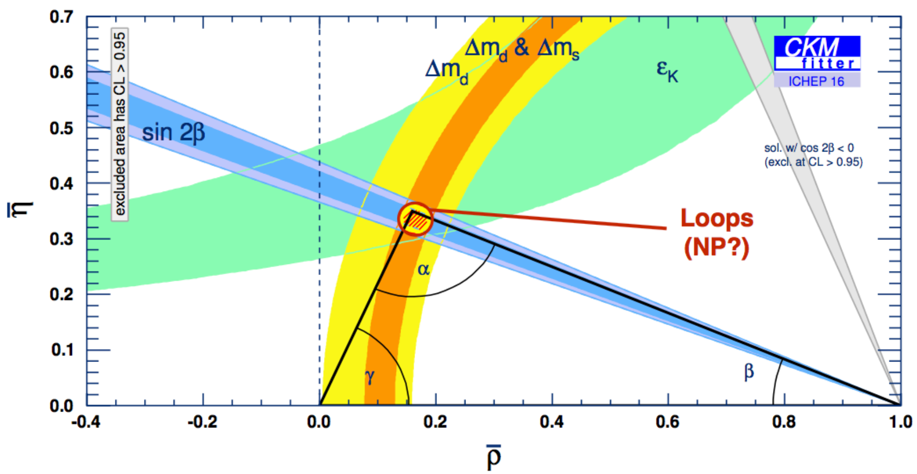
sides: CP conserving observables
angles: CP violating observables

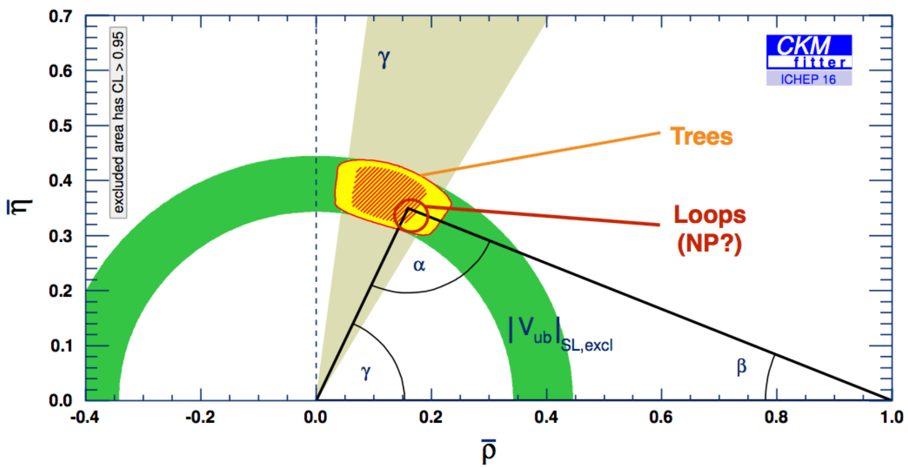


- CKM matrix conveniently represented by Unitarity Triangles (UT)
- consistency of measurements provides test of SM

- γ is still the least well-known angle of the UT, $\delta\gamma \sim 7^o$ ***LHCb****[JHEP 12 (2016) 087]*
- compare with the value inferred from indirect CKM global fits, $\delta\gamma \sim 2^o$

loop processes which give β, Δm_s & Δm_d, are New Physics sensitive

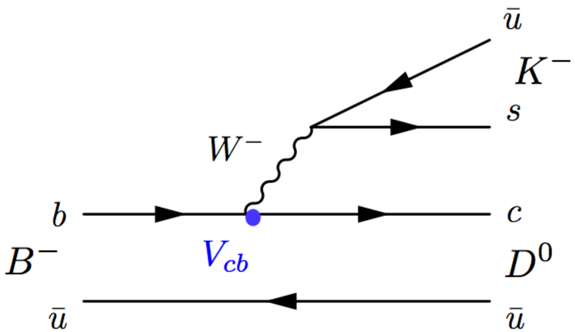




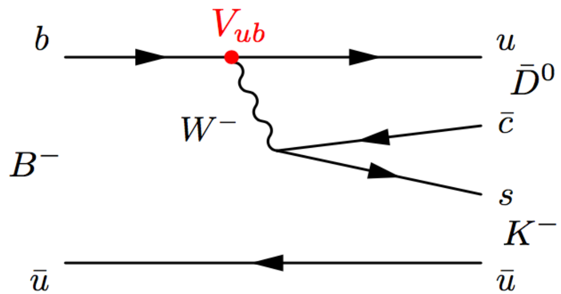
- we must strive to push tree level measurements below 2^o

$\gamma = arg(-V_{ud}V^{*}_{ub}/V_{cd}V^{*}_{cb})$

- γ is still the least well-known angle of the UT, $\delta\gamma{\sim}7^{o}$ ***LHCb****[JHEP 12 (2016) 087]*
- measurements of γ from B decays mediated only by tree level transitions ⟺ theoretically clean $\delta\gamma/\gamma \lesssim O(10^{-7})$ ***[JHEP 1401(2014) 051]***
- γ can be determined exploiting the interference between b→c and b→u transitions, eg: $B^{\pm} \rightarrow Dh^{\pm}$, $B^{0} \rightarrow DK^{*0}$, $B^{0} \rightarrow DK^{+}\pi^{-}$, … where D refers a mixture D^{0} and $\overline{D}^{0}$ flavour eigenstates



Favoured b → c



Suppressed b → u

- small signal yields (BR ~ 10^{-7}), small interference effects (~10%) ⟺ determine γ through a ***combination of measurements from the analyses of a plethora of decay modes***

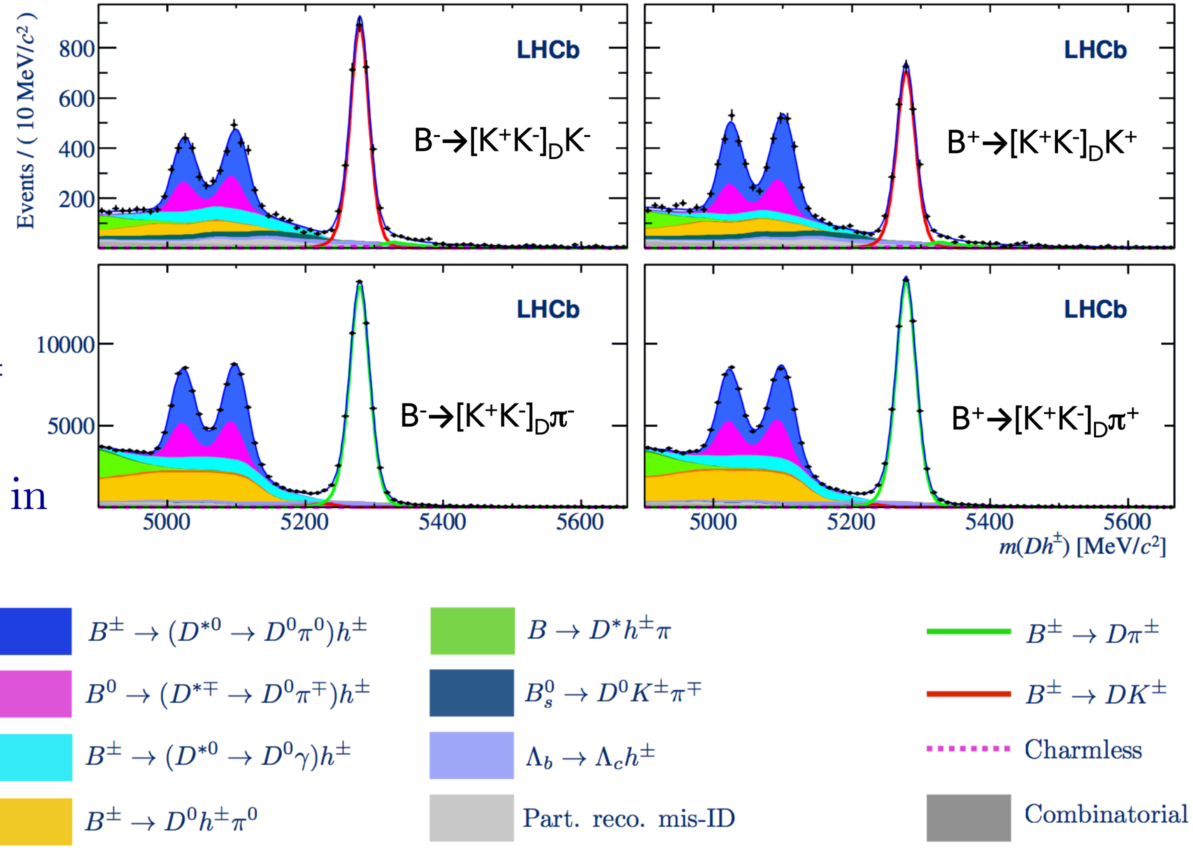
γ using partial reconstruction of $B^{\pm}\rightarrow D^{*}h^{\pm}$ ($h=K,\pi$)

✓ the D^0 meson is reconstructed in CP eigenstates KK, $\pi\pi$

✓ $BR(D^{*}\rightarrow D^0\pi^0) = (64.7 \pm 0.9)\%$,
$BR(D^{*}\rightarrow D^0\gamma) = (35.3 \pm 0.9)\%$

5fb^{-1}

LHCb[PLB 777(2018)16]



- limited efficiency reconstruction
  ➔ $\varepsilon(\pi^0)\sim4\%$ and $\varepsilon(\gamma)\sim 20\%$

- **partially reconstruct and select identically to** $B^{\pm}\rightarrow Dh^{\pm}$

- $B^{\pm}\rightarrow Dh^{\pm}$ and $B^{\pm}\rightarrow D^{*}h^{\pm}$ end up in the same selected sample
  ➔ differentiate between them based on their m(Dh) *uniquely related to angular properties of D* decay daughters*

- $B^{\pm}\rightarrow D^{*}h^{\pm}$ modes measured for the first time at LHCb and using a **brand new technique** !
- fully reconstructed $B^{\pm}\rightarrow D^0h^{\pm}$ results are measured with the same fit
- D^0 decays to not-CP eigenstates, eg. $D^0\rightarrow K\pi$, are under investigation

state of art of γ

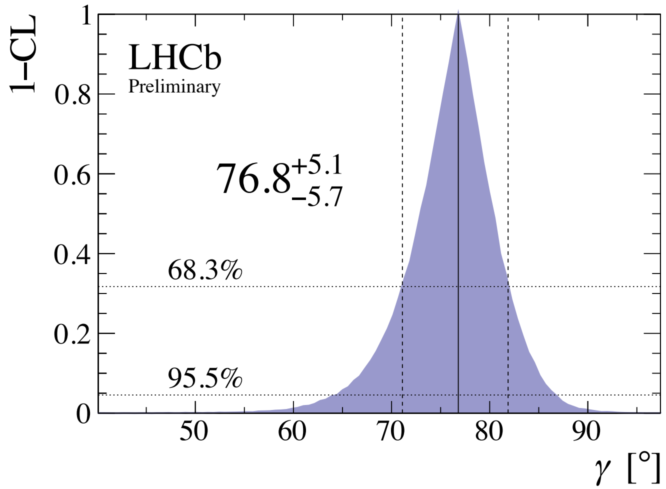
- γ ➔ *obtained with a statistical combination using observables from several LHCb analyses*
- previous combination was entirely based on Run 1 measurements,3 fb^{-1},***LHCb**[JHEP 12 (2016) 087]*
- an update has been performed, which includes the following:

  $B^{\pm} \to DK^{\pm}$ ($5 fb^{-1}$) *$3 fb^{-1} \to 5 fb^{-1}$*

  $B^{\pm} \to D^{*}K^{\pm}$ ($5 fb^{-1}$) *NEW*

  $B^{\pm} \to DK^{*\pm}$ ($5 fb^{-1}$) *NEW*

  time-dependent $B_s^0 \to D_s^- K^+$ ($3 fb^{-1}$) *$1 fb^{-1} \to 3 fb^{-1}$*



- 71 observables and 32 parameters
- frequentist and bayesian interpretations ➔ both show good agreement

uncertainty reduced by ~1.7° relative to previous combination

LHCb combination direct $\gamma = (76.8^{+5.1}_{-5.7})^{o}$ *[LHCb-CONF-2017-004]*

LHCb precision **~5.5°** dominates world average ➔

HFLAV CKM 2017 world average direct $\gamma = (76.2^{+4.7}_{-5.0})^{o}$ *[arXiv:1612.07233]*

CKMfitter 2016 world average indirect $\gamma = (65.3^{+1.0}_{-2.5})^{o}$ *[CKMfitter group]*

strongly motivates the continued pursuit of γ with trees

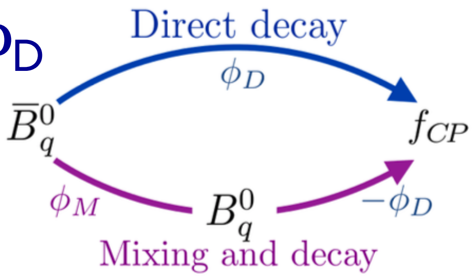
first measurement of $\phi_s^{d\bar{d}}$ using $B_s \rightarrow (K^+\pi^-)(K^-\pi^+)$ decays

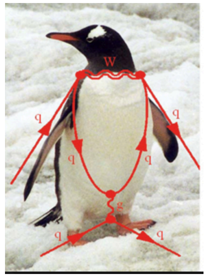
ϕ_s^{dd} using $B_s \rightarrow (K^+\pi^-)(K^-\pi^+)$ decays

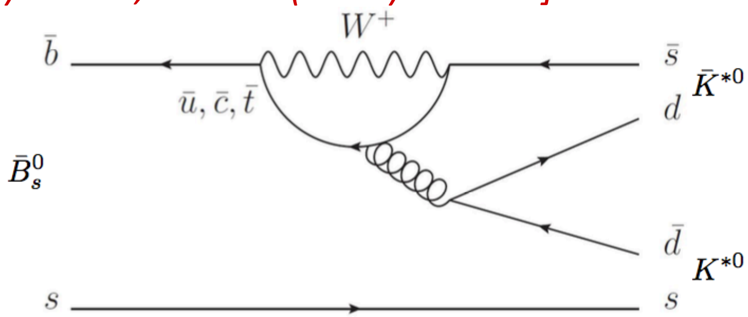
LHCb [arXiv:1712.08683]

- $B_s \rightarrow K^*(892)^0\, \overline{K}^*(892)^0$ (first observation by ***LHCb**[PLB 709(2012) 50]*) penguin dominated mode has been proposed as an excellent probe for NP *[PRL 100 (2008) 03182, PRD 88 (2013) 016007]*

$\phi_q = \phi_M - 2\phi_D$

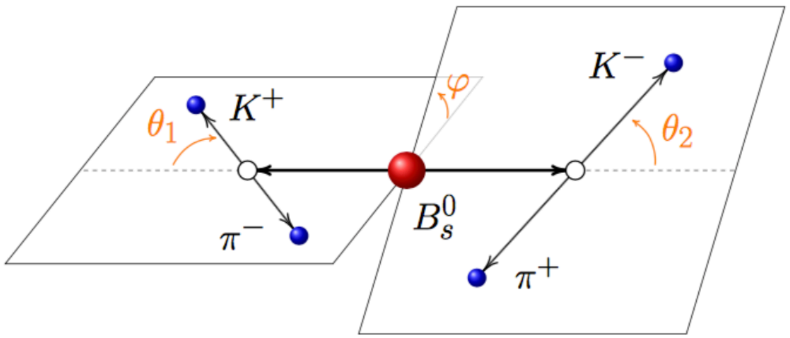






- first decay-time-dependent amplitude analysis of $B_s \rightarrow (K\pi)(K\pi)$ decays using a **$K\pi$ mass window from 750 to 1600 MeV/c^2** ➔ ~ four-fold increase of the signal sample size with respect to a narrow window around the K^{*0} mass
- <u>**3 fb^{-1}** from the Run1 data sample</u>
- 9 different angular analysis of quasi-2-body decay channels ➔ $K\pi$ pairs with spin 0, 1 or 2

assumption: common CP-violating parameters for the contributing amplitudes



Decay	Mode	j_1	j_2	Allowed values of h	Number of amplitudes
$B^0_s \rightarrow (K^+\pi^-)^*_0(K^-\pi^+)^*_0$	scalar-scalar	0	0	0	1
$B^0_s \rightarrow (K^+\pi^-)^*_0\overline{K}^*(892)^0$	scalar-vector	0	1	0	1
$B^0_s \rightarrow K^*(892)^0(K^-\pi^+)^*_0$	vector-scalar	1	0	0	1
$B^0_s \rightarrow (K^+\pi^-)^*_0\overline{K}^*_2(1430)^0$	scalar-tensor	0	2	0	1
$B^0_s \rightarrow K^*_2(1430)^0(K^-\pi^+)^*_0$	tensor-scalar	2	0	0	1
$B^0_s \rightarrow K^*(892)^0\overline{K}^*(892)^0$	vector-vector	1	1	0, $\parallel$, $\perp$	3
$B^0_s \rightarrow K^*(892)^0\overline{K}^*_2(1430)^0$	vector-tensor	1	2	0, $\parallel$, $\perp$	3
$B^0_s \rightarrow K^*_2(1430)^0\overline{K}^*(892)^0$	tensor-vector	2	1	0, $\parallel$, $\perp$	3
$B^0_s \rightarrow K^*_2(1430)^0\overline{K}^*_2(1430)^0$	tensor-tensor	2	2	0, $\parallel_1$, $\perp_1$, $\parallel_2$, $\perp_2$	5

the result

LHCb *[arXiv:1712.08683]*

large computational load due to the complexity of the unbinned maximum likelihood fit ➔ ***parallelization of the calculus on a GPU***

first measurement of the CP-violating phase ϕ_s using $b \rightarrow d\bar{d}s$ transitions

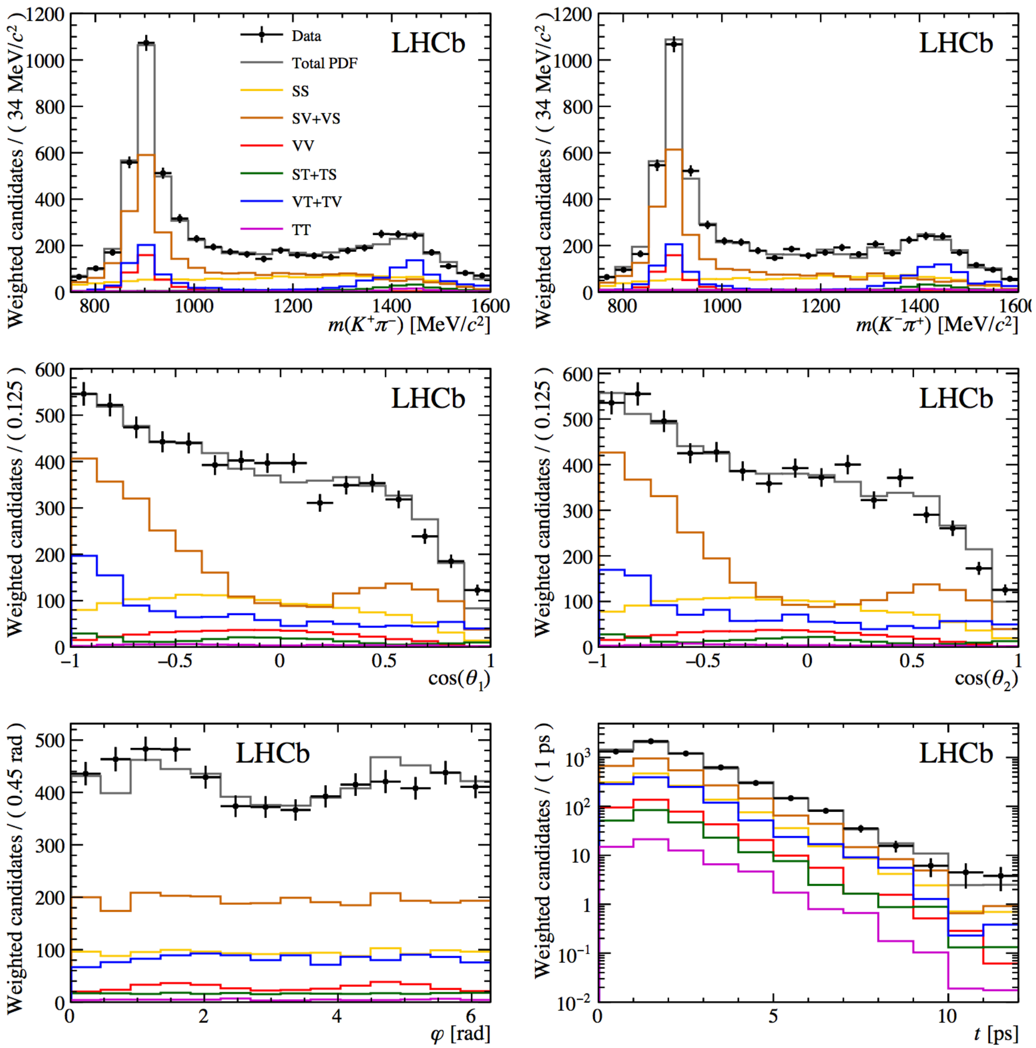
$$\phi_s^{dd} = -0.10 \pm 0.13_{stat} \pm 0.14_{syst} \text{ rad}$$

consistent with:

✓ SM expectation *[PRD 88 (2013) 016007]*

✓ $\phi_s^{ss} = -0.17 \pm 0.15_{stat} \pm 0.03_{syst}$ rad using $B_s \rightarrow \phi\phi$ ***LHCb****[PRD 90 (2014) 50]*

the relatively large systematic uncertainty is mainly due to the treatment of the multi-dimensional acceptance ➔ **will be significantly reduced with larger data sample**



1d projections of the results in six analysis variables shown with the separate components from the contributing decay modes

anomalies about the LFU: what's about ?

- SM features Lepton Flavor Universality (**LFU**) ➔ equal electroweak coupling to all charged leptons, the branching ratios to e, μ and τ differ only due to their mass
any further deviation is a key signature of physics processes beyond the SM

- **recently few deviations from SM emerged in B decays**
  - ✓ tree level semileptonic $b \rightarrow c\tau\nu_\tau$ transitions, high rates O(%), well known in SM ➔ <u>possible NP coupling mainly to the 3rd family</u>
  - ✓ FCNC $b \rightarrow sll$ transitions, rare decays forbidden at the tree level $O(10^{-6})$ in SM ➔ <u>possible NP contributions in the loops</u>

- possible BSM scenarios: leptoquarks, new heavy vector bosons, $H^{\pm}$, ...

- main test variables are ratios of decay rates
  - ✓ theoretically clean: cancellation of QCD effects
  - ✓ experimentally clean: cancellation of efficiency and reconstruction effects

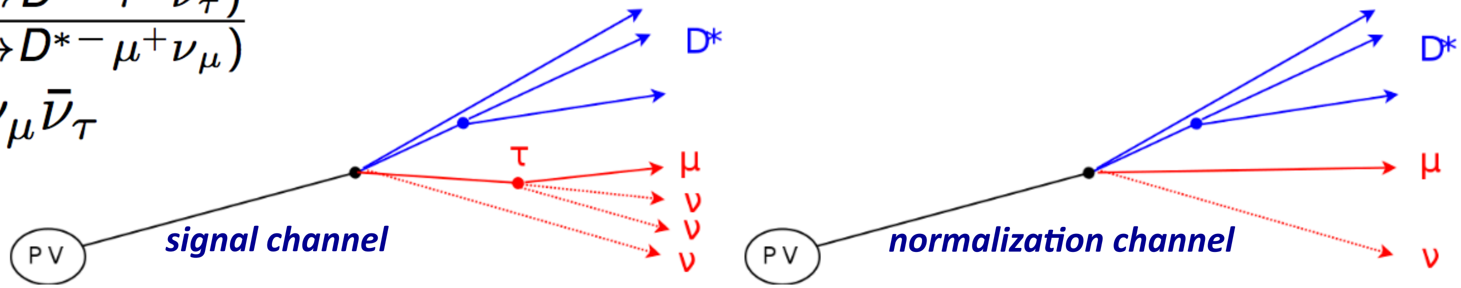
lepton-flavour universality in $b \rightarrow c\tau\nu_\tau$: $R(D^*)$, $R(J/\psi)$

R(D*) from $\tau \to \mu\nu_\mu\nu_\tau$

***LHCb** [PRL (2015) 111803]*

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

with $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$



precise SM prediction: $R(D^*) = 0.252 \pm 0.003$ *[PRD85 (2012) 094025]*

$BR(\tau \to \mu\, \nu_\mu\nu_\tau) = (17.39 \pm 0.04)\%$

signal and normalization decay chain with identical visible final state ➔ $(\pi(K\pi))\mu$

at LHCb ➔

- ✓ B momentum unknown in production from pp collisions at LHC
- ✓ 3 missing neutrinos ➔ no narrow peak to fit
- ✓ large backgrounds from part-reco B decays: $B \to D^{**}\mu\nu$, $B \to (D \to X\mu)D^*X$

- ✓ statistics from high $pp \to bb$ cross section at LHC
- ✓ use B flight direction to measure transverse component of missing momentum
- ✓ B boost along beam direction approximated with boost of the visible final state
- ✓ can then calculate rest frame quantities ➔ m^2_{miss} , E^*_μ , $q^2 = (p_B - p_{D^*})^2$

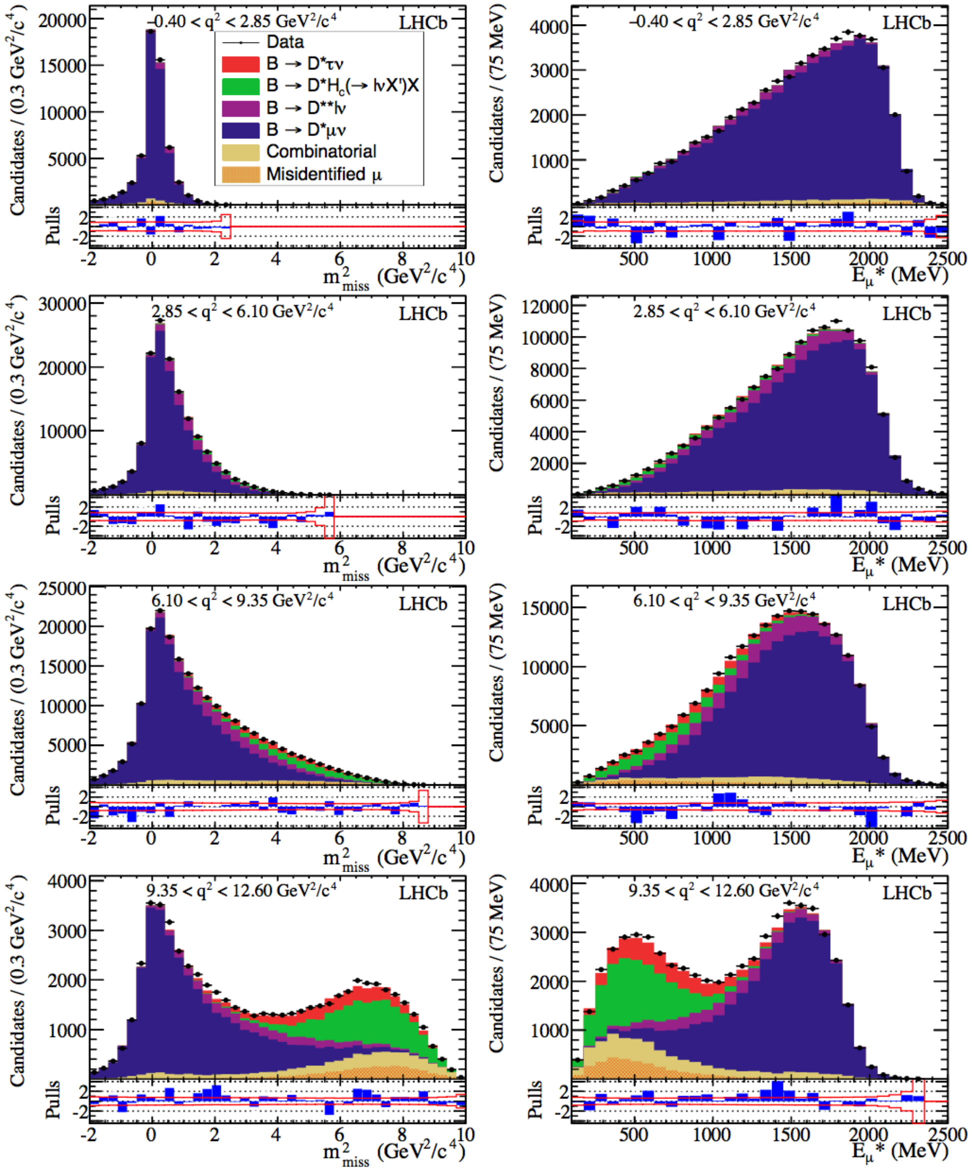
R(D^*) from $\tau \rightarrow \mu\nu_\mu\nu_\tau$

***LHCb** [PRL (2015) 111803]*

analysis based on Run 1 dataset, **3 fb^{-1}**

maximum likelihood fit to m^2_{miss}, E^*_μ, q^2 distributions with 3D templates representing $B^0 \rightarrow D^*\tau\nu$, $B^0 \rightarrow D^*\mu\nu$, and background sources

- ✓ *background and signal shapes extracted from control samples and simulations validated against data*



$$R(D^*) = 0.336 \pm 0.027_{stat} \pm 0.030_{syst}$$

2.1σ above Standard Model

$R(D^*)^{SM} = 0.252 \pm 0.003$

dominant systematics ➔
size of the simulation sample

this is the first measurement of a b hadron decay with a τ lepton in the final state at a hadron collider

R(D*) from $\tau \to \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$

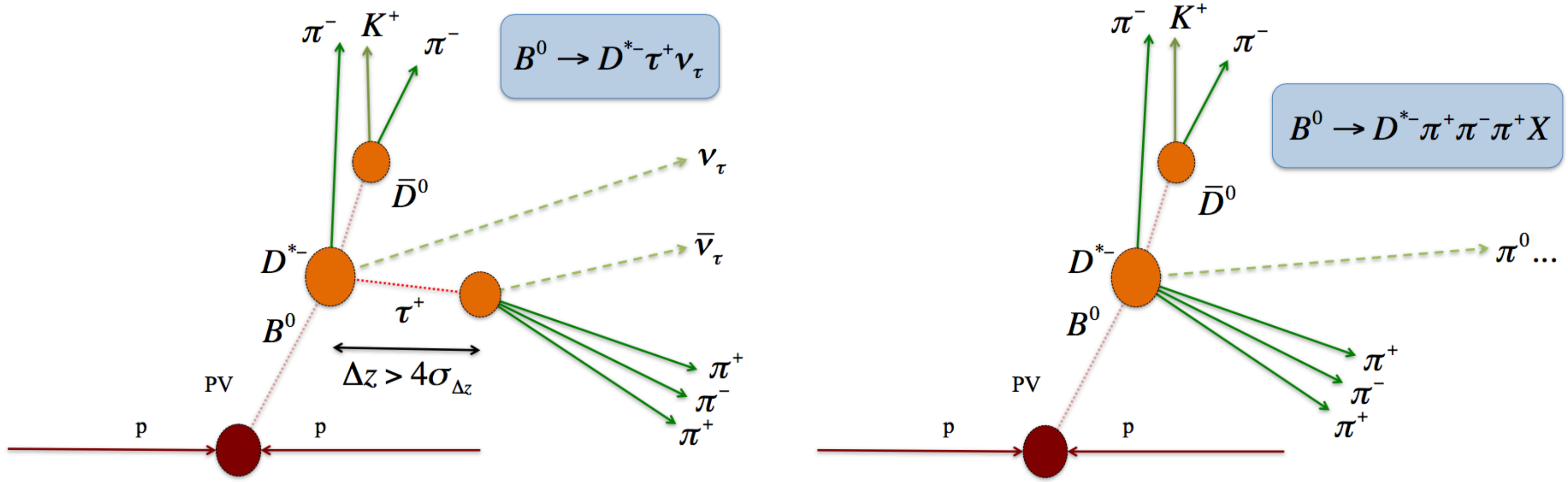
***LHCb** [arXiv:1708.08856]*

✓ BR($\tau \to 3\pi(\pi^0)\nu_\tau$) ~ 13.9% (was ~ 17% for the muonic case)

✓ no charged leptons in the final state ➔ no backgrond from semileptonic decays

✓ the 3-prong topology enables the precise reconstruction of τ vertex

the requirement of a 3π vertex detached from B vertex suppresses $D^{*-}3\pi X$ background by 3 orders of magnitudes retaining ~ 40% of the signal



✓ BDT technique to suppress the remaining background, that is due to $B \to D^{*-}D_{(s)}(X)$, double-charm decays (~ 10 × signal)

R(D*) from $\tau \to \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$

***LHCb** [arXiv:1708.08856]*

- experimental systematic uncertainty reduced normalizing to a decay with a very similar final state: $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

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

- derive R(D*) by dividing by known semimuonic $B^0 \to D^*\mu\nu$ branching fraction

$$\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-}) \times \mathcal{B}(B^0 \to D^{*-}3\pi)/\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$$

- measure
  - ✓ $B^0 \to D^*\tau\nu$ and $B^0 \to D^*3\pi$ event yields
  - ✓ efficiencies from MC, validated using data control samples
- external inputs are

$\mathcal{B}(B^0 \to D^*\mu\nu) = (4.88 \pm 0.10) \times 10^{-2}$

***HFLAV** [arXiv:1612.07233]*

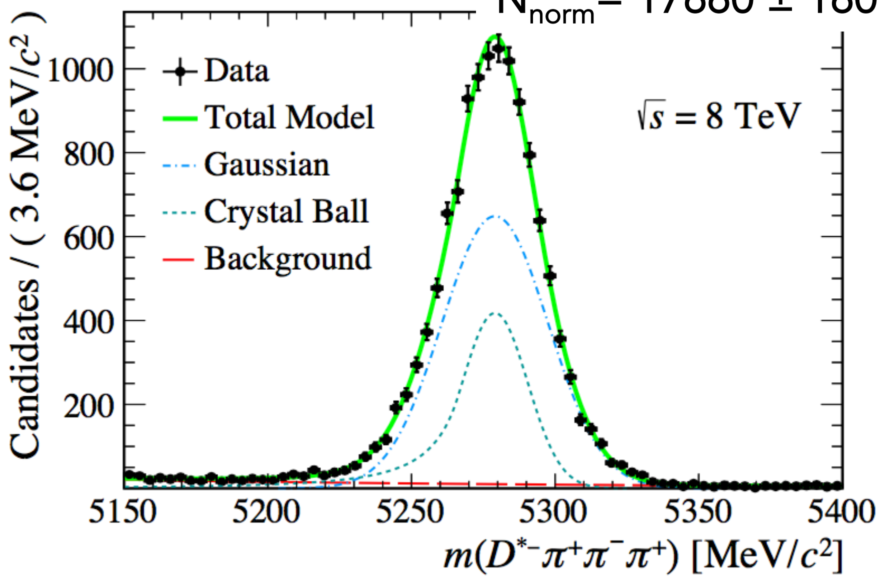
$\mathcal{B}(B^0 \to D^*3\pi) = (7.21 \pm 0.29) \times 10^{-3}$

***LHCb** [PRD 87 (2013) 092001]*

$\mathcal{B}(\tau \to 3\pi(\pi^0)\nu_\tau) = (13.81 \pm 0.07)\%$

***PDG** [Review of particle physics (2016)]*

$N_{\text{norm}} = 17660 \pm 160$



R(D*) from $\tau \rightarrow \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$

***LHCb** [arXiv:1708.08856]*

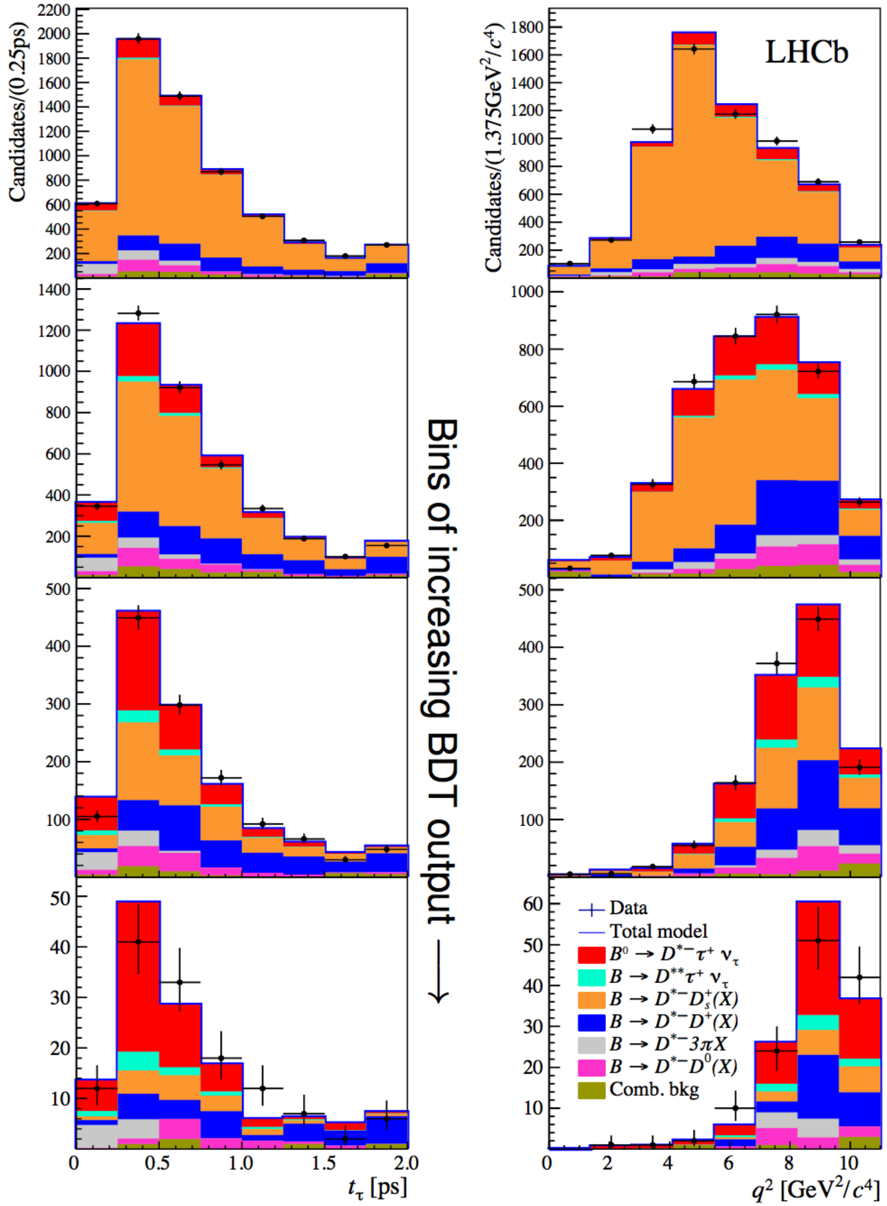
analysis based on Run 1 dataset, **3 fb^{-1}**

- signal yield from a 3D binned maximum likelihood fit to q^2, decay time, and BDT output
  - ✓ *background and signal shapes extracted from control samples and simulations validated against data*

- $N(B^0 \rightarrow D^*\tau\nu) = 1273 \pm 85$

$R(D^*) = 0.286 \pm 0.019_{stat} \pm 0.025_{syst} \pm 0.021_{ext}$

~ 1. σ higher than Standard Model



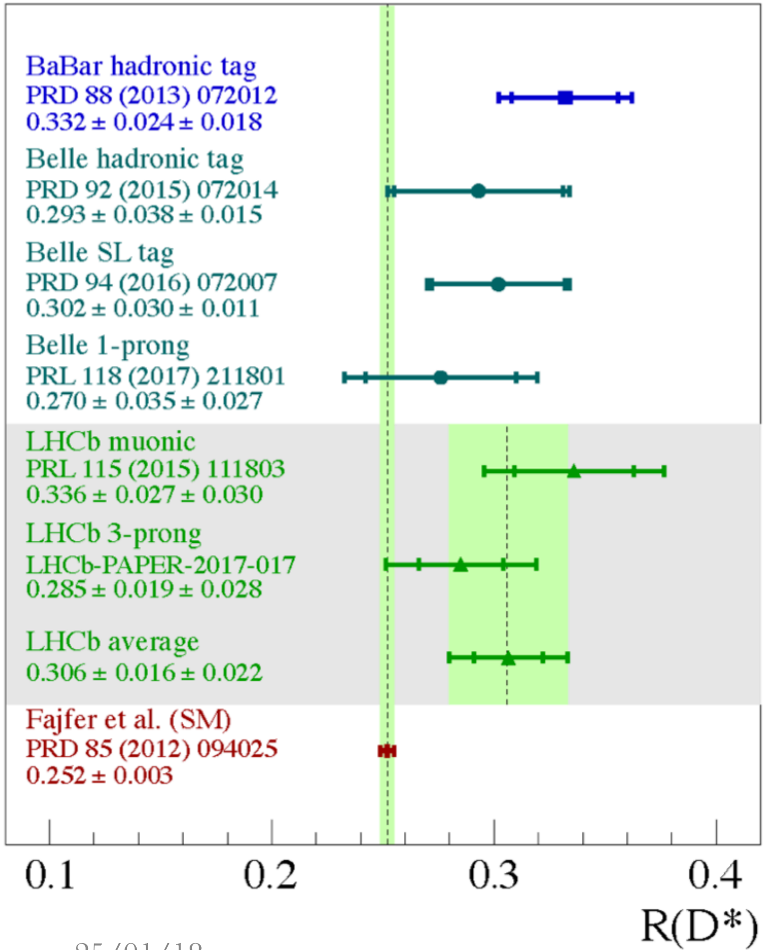
- compatible with the muonic channel
- dominant systematics ➔ size of the simulation samples and external BRs

R(D*) combination

LHCb combination

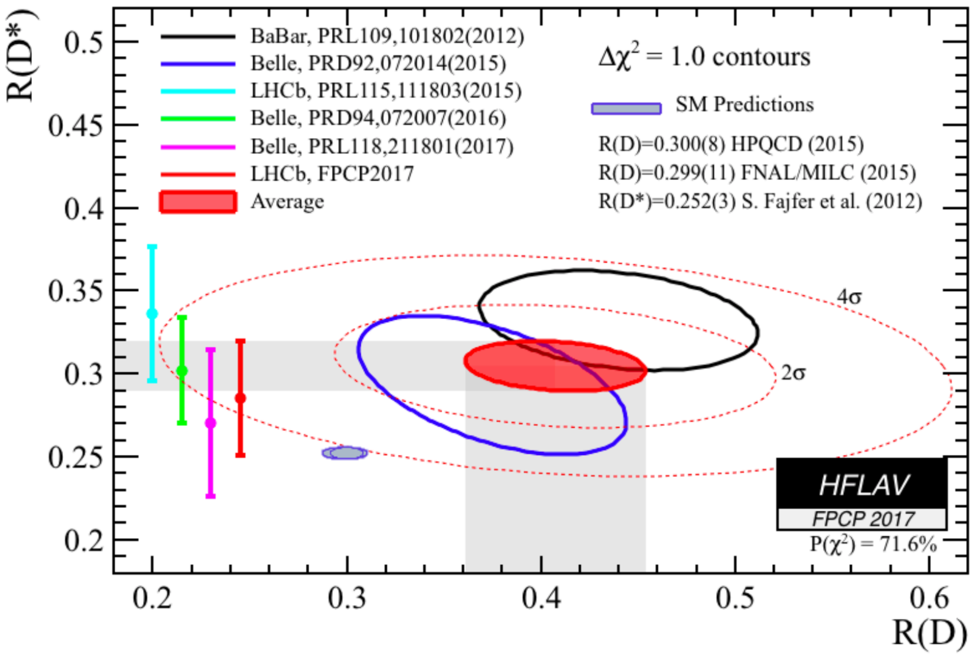
$R(D^*) = 0.306 \pm 0.016 \pm 0.022$

2.1 σ above Standard Model



combination with R(D)

R(D) and R(D) exceed the SM predictions by 2.3 σ and 3.4 σ respectively*

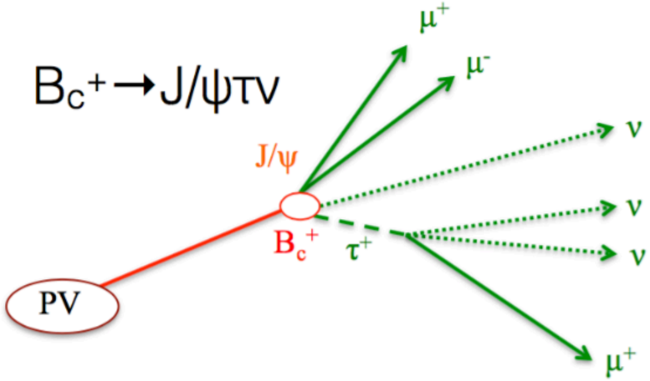


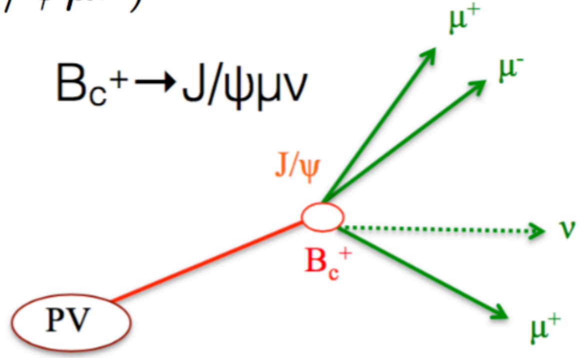
R(D) and R(D*) combination is about 4.1 σ above the SM prediction

R(J/ψ), LFU with B_c decays

***LHCb** [arXiv:1711.05623]*

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau \nu)}{\mathcal{B}(B_c^+ \to J/\psi \mu \nu)}$$ with $\tau \to \mu \nu_\tau \nu_\mu$, $J/\psi \to \mu\mu$





✓ SM predictions are in the range of 0.25 to 0.28 ➔ the spread is due to the modeling of form factors *[PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]*

✓ form factor parameters are fitted on a data sample enriched in normalization decays

✓ signal and normalization decay chain with identical visible final state ➔ (μμ)μ

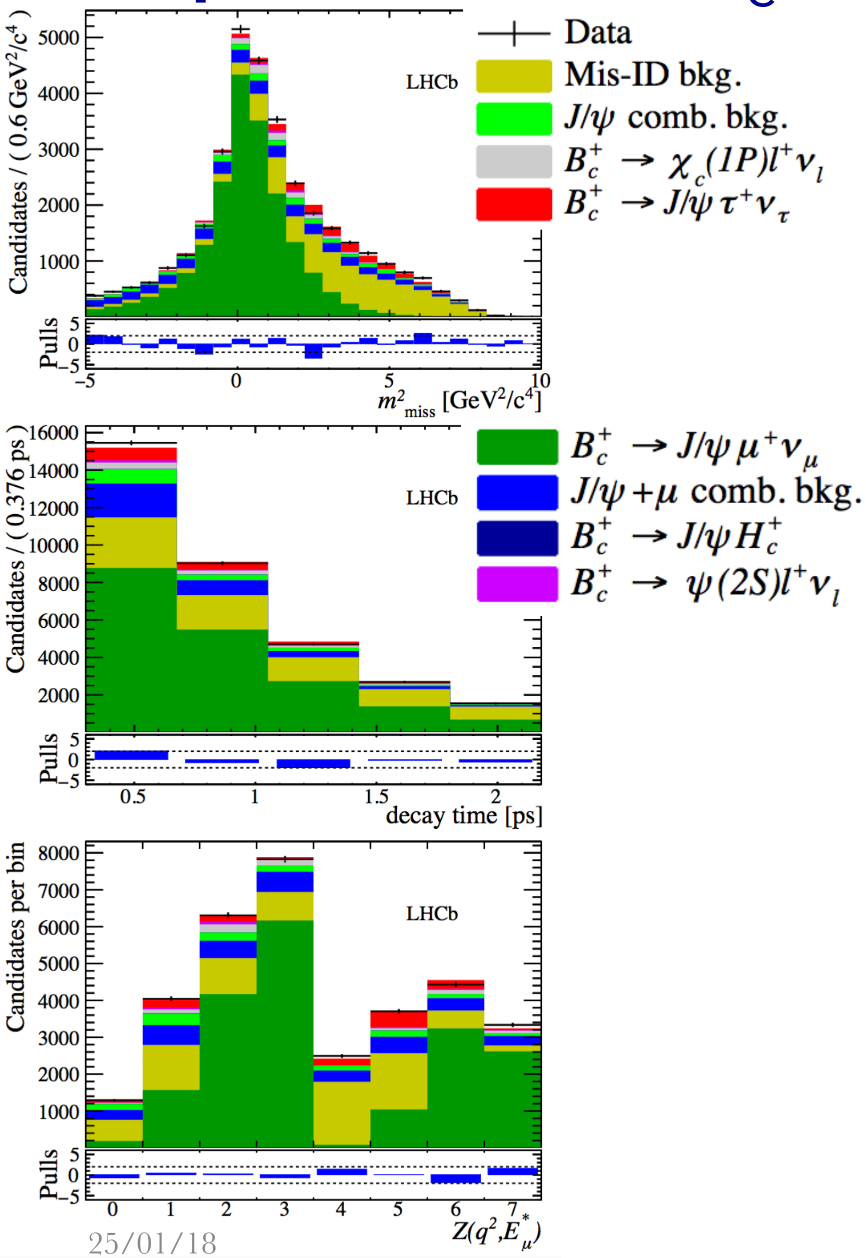
✓ **like in the muonic R(D*) analysis ➔**

1. use m^2_{miss}, E^*(unpaired muon), and q^2 to disantagle between signal and normalization mode
2. B_c boost along beam direction approximated with boost of the visible system

✓ B_c decay time (~ 3 times shorter than other b hadrons) helps to discriminate the large background from lighter b hadrons

R(J/ψ) LFU with B_c decays

***LHCb** [arXiv:1711.05623]*



analysis based on Run 1 dataset, **3 fb^{-1}**

- signal yield from a 3D binned maximum likelihood fit to $m^2_{\rm miss}$, decay time, and a discrete quantity Z representing 8 bins in (E^*_μ, q^2)
  - ✓ *background and signal shapes extracted from control samples and simulations validated against data*

- main background due to misidentified hadrons and combinatorial muons
- first evidence of the decay $B_c \to J/\psi \tau \nu_\tau$ (3σ)

$R(J/\psi) = 0.71 \pm 0.17_{stat} \pm 0.18_{syst}$

~ 2. σ above Standard Model

- dominant systematics ➔ size of the simulation samples and form factors

lepton-flavour universality in $b \to sll$: R_K, $R_{K^{*0}}$

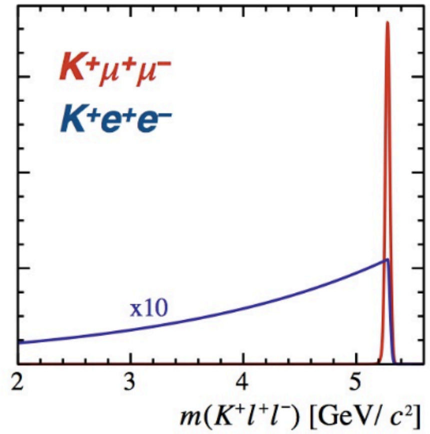
test of LFU using $B \rightarrow K^{(*)}ll$ decays @ LHCb

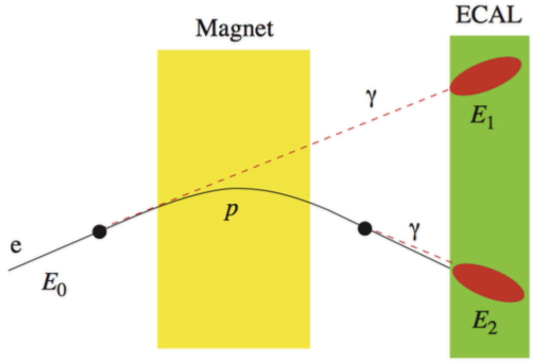
- ✓ FCNC transitions forbidden at tree level in SM ➔ expected BR < 10^{-6}
- ✓ *test of LFU measuring the ratio between the decay rates of $B \rightarrow K^{(*)}ll$, cancellation of hadronic form-factors uncertainties in predictions*
- ✓ $R_{K(*)}$ is close to unity in SM, with very small uncertainties

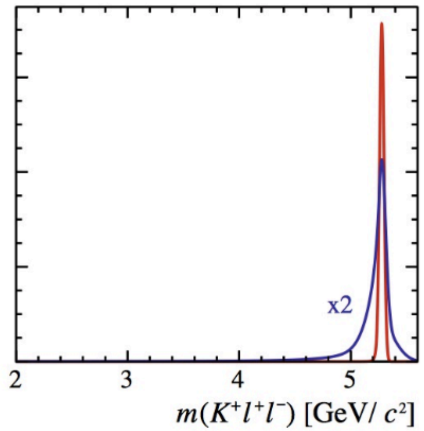
$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

the ee channel is the challenge of these analyses

- **Bremsstrahlung** affects the e momentum ➔ energy recovered looking at calorimeter hits







- **low trigger efficiency**
  - ✓ trigger by the electron, hadron and other particles in the event
  - ✓ final result comes from likelihoods combination

the R_K measurement

***LHCb** [PRL 113 (2014) 151601]*

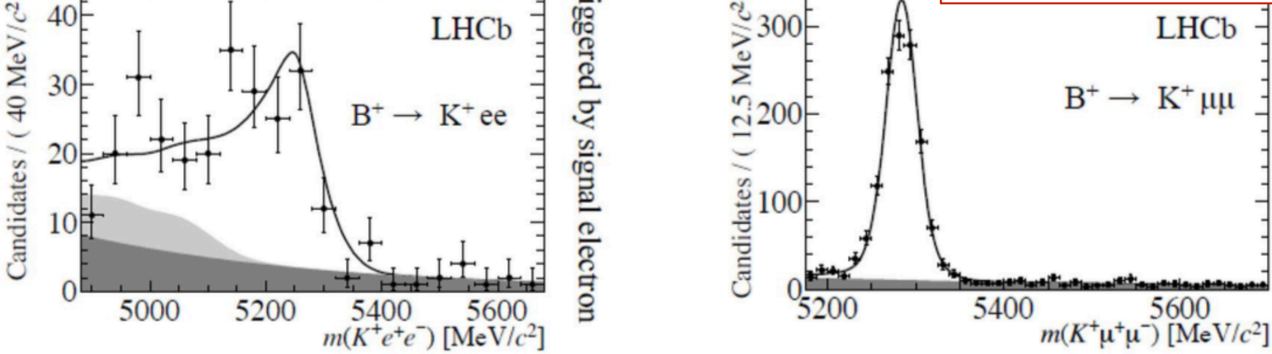
✓ measure using **double ratio** to minimize uncertainties

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

✓ B mass fit in $q^2 = m^2_{ll} \in [1, 6]$ GeV^2/c^4 to avoid resonance regions

✓ **signals extracted via invariant mass fits**

Run 1 dataset, **3 fb^{-1}**



grey: partially reconstructed *b*-hadron decays; dark: combinatorial

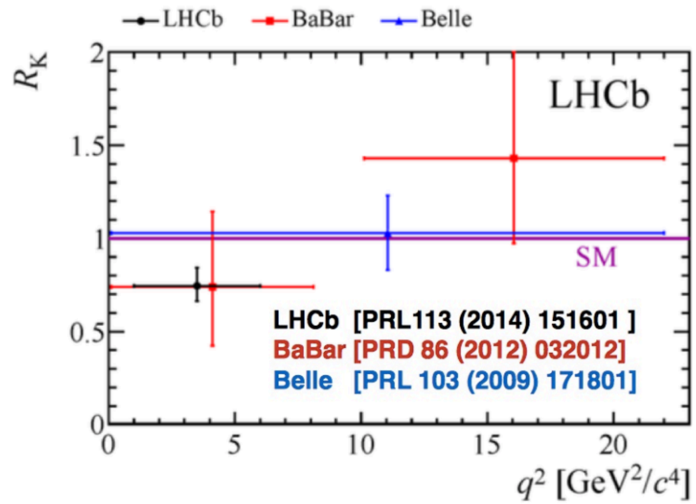
$R_K = 0.745^{+0.090}_{-0.074}$(stat) ± 0.036(syst)

most precise measurement to date

2.6 σ from Standard Model prediction

$R_K^{SM} = 1 \pm O(10^{-3})$

[JHEP12(2007)040, PRL111,162002(2013)]

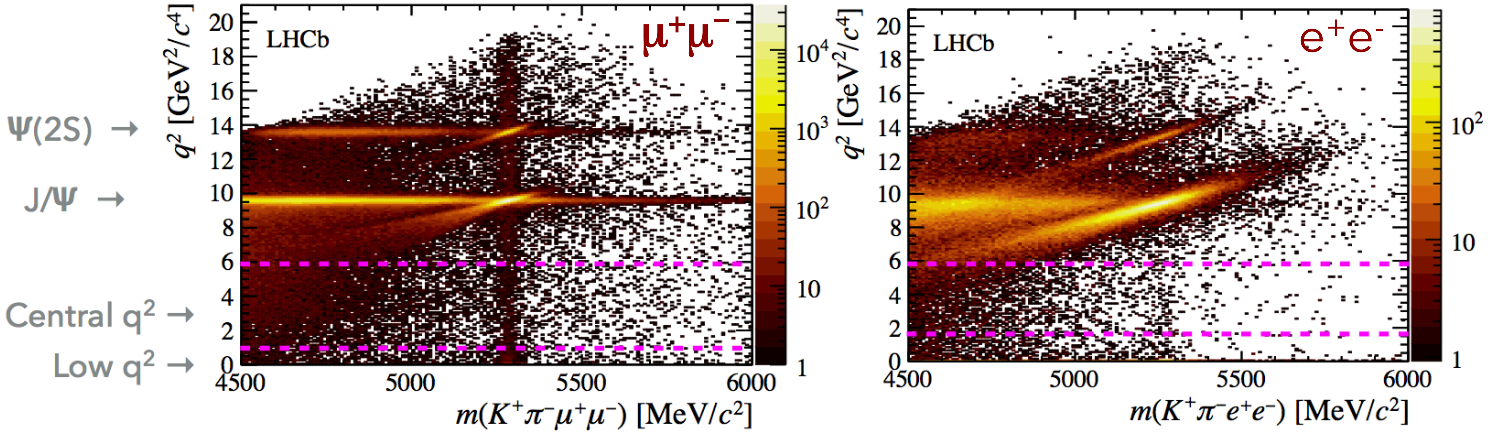


the $R_{K^{*0}}$ measurement

***LHCb** [JHEP 08 (2017) 055]*

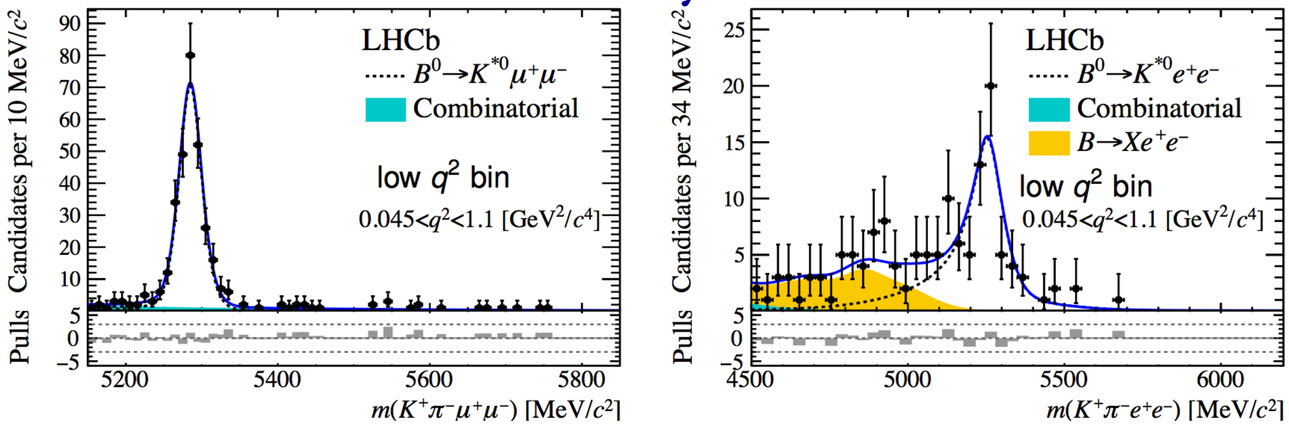
✓ measure using **double ratio** $R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$ to minimize uncertainties

✓ B mass fit in $q^2 = m^2_{ll} \in [.045, 1.1]$ and $[1.1, 6.]$ GeV^2/c^4 to avoid resonance regions



✓ **signals from invariant mass fits simultaneously on the nonresonant and resonant modes**

Run 1 dataset **3 fb⁻¹**



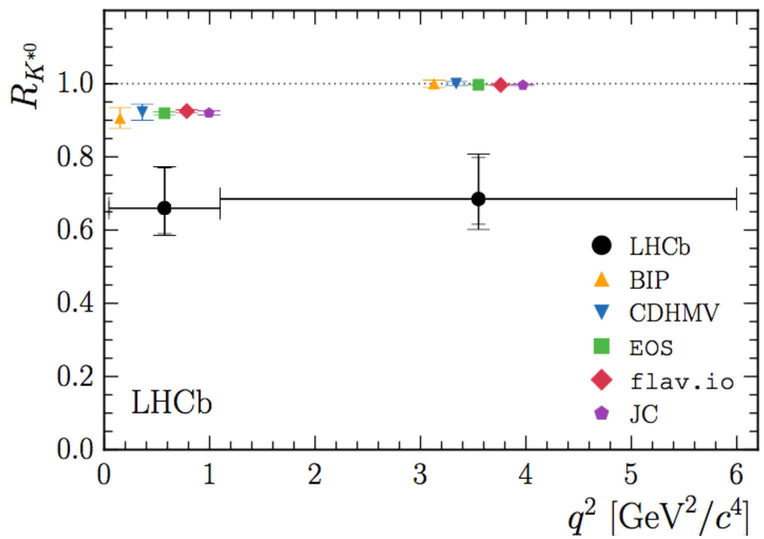
• **test** ratio of BRs of the μ and e resonant channels is measured to be 1.043 ± 0.006 ± 0.045, consistent with unity

the $R_{K^{*0}}$ measurement

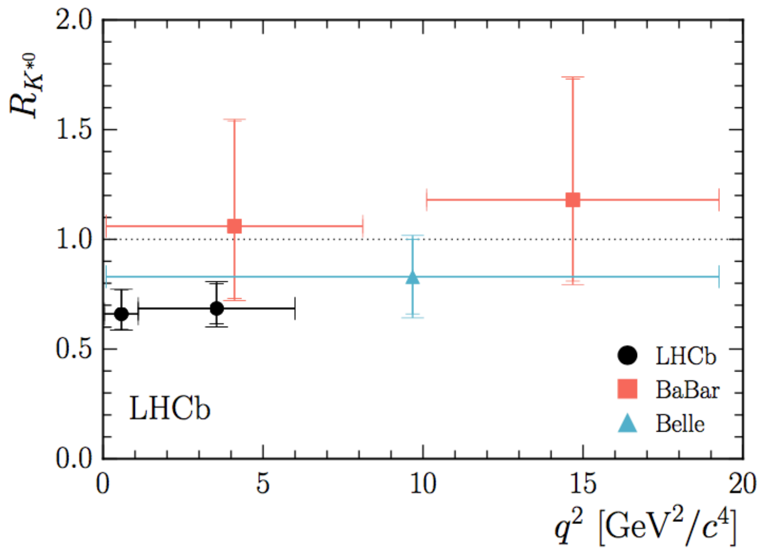
***LHCb** [JHEP 08 (2017) 055]*

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

- ✓ most precise measurement to date
- ✓ below the SM at 2.1-2.3σ in the low q^2 and 2.4-2.5σ in the central q^2
- ✓ larger data set will allow for more precise tests



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

conclusions and outlook

LHCb has a wide physics program in heavy flavour and beyond

for this talk I tried to select only few between the most recent and hot results ➔

- LHCb keeps making world-best measurements of γ across a range of interesting modes, a brand new technique to select $B^{\pm} \rightarrow D^{*}h^{\pm}$ modes has been used
- first measurement of the CP-violating phase ϕ_s using $b \rightarrow d\bar{d}s$ transitions
  - ✓ *many updates to come as we approach the end of Run 2*

- several deviations from LFU observed in ratios of decay rates ➔ while individually not that large, consistently shows a tension with the SM
  - ✓ *all ratios will be updated using the whole data sample collected so far*
  - ✓ *new analysis already ongoing are:* $B_s \rightarrow D_s^{(*)}\tau\nu$, $\Lambda_b \rightarrow \Lambda_c^{(*)}\tau\nu$

entering an exciting phase of precision measurements !

Thank you !

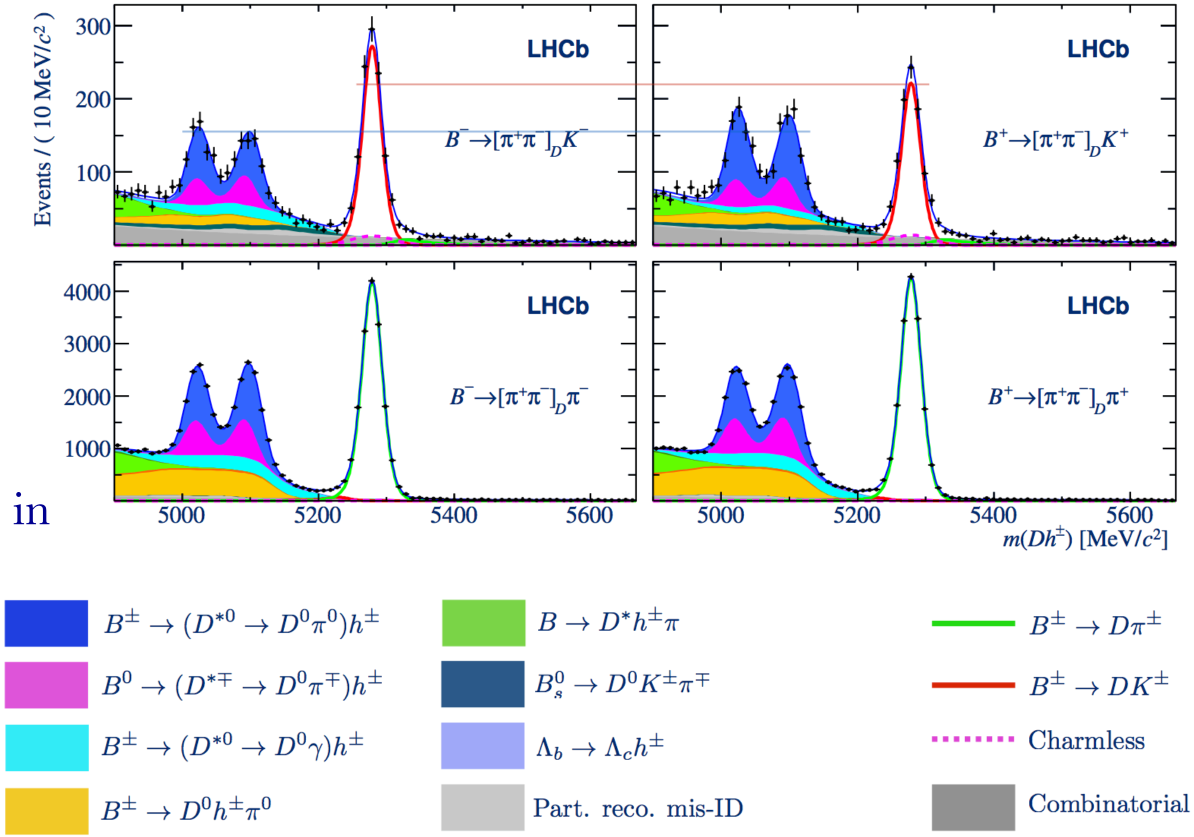
spares

γ using partial reconstruction of $B^{\pm} \to D^{*}h^{\pm}$ ($h=K,\pi$)

✓ the D meson is reconstructed in CP eigenstates KK, ππ

✓ strong phase δ_D difference of 180° between $D^{*} \to D\pi^0$ and $D^{*} \to D\gamma$ *[PRD 70 (2004) 091503]*

5fb^{-1} ***LHCb*** *[PLB 777(2018)16]*



- limited efficiency reconstruction
  ➔ $\varepsilon(\pi^0)$~4% and $\varepsilon(\gamma)$~ 20%

- <u>partially reconstruct and select identically to</u> $B^{\pm} \to Dh^{\pm}$

- $B^{\pm} \to Dh^{\pm}$ and $B^{\pm} \to D^{*}h^{\pm}$ end up in the same selected sample
  ➔ differentiate between them based on their m(Dh)

- $B^{\pm} \to D^{*}h^{\pm}$ modes measured for the first time at LHCb and using a **brand new technique** !
- fully reconstructed $B^{\pm} \to D^0h^{\pm}$ results are measured with the same fit
- D^0 decays to not-CP eigenstates, eg. $D^0 \to K\pi$ are under investigation

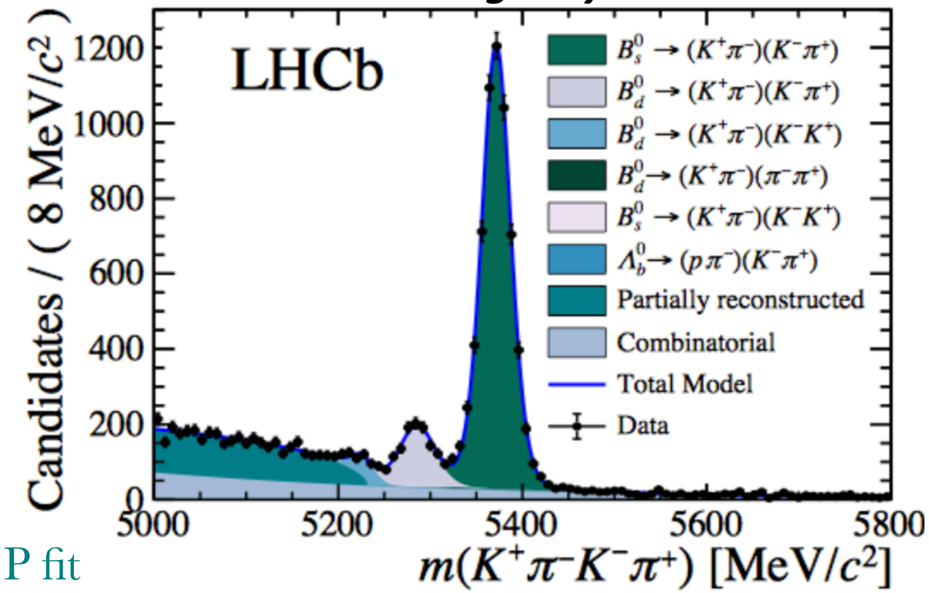
few hints about the analysis

***LHCb** [arXiv:1712.08683]*

- ✓ fit quality of the B_s decay vertex
- ✓ p_T and Impact Parameter of each track
- ✓ PID info from RICH
- ✓ $750 \leqslant m(K\pi) \leqslant 1600$ MeV/c^2
- ✓ $5000 \leqslant m(K^+\pi^-K^-\pi^+) \leqslant 5800$ MeV/c^2
- ✓ BDT trained with simulated $B_s \to K^{*0}\overline{K}^{*0}$ and invariant mass sideband $5600 \leqslant m(K^+\pi^-K^-\pi^+) \leqslant 5800$ MeV/c^2

signal weights fitting the $m(K^+\pi^-K^-\pi^+)$ distribution
➔ allows to perform the decay time-dependent CP fit

signal yield 6080 ± 83



the PDF used for the fitting, incorporates the relevant flavour-tagging and production-asymmetry parameters, and the acceptance and resolution factors

◎ tagging algorithms ***LHCb**[JINST 11 (2016) P05010, EPJ C72 (2012) 2022]* provide for each event a tagging decision, and an estimated mistag probability ➔ tagging power $\varepsilon_{eff} = \varepsilon_{tag}(1 - 2\langle\omega\rangle)^2 = (5.15 \pm 0.14)\%$

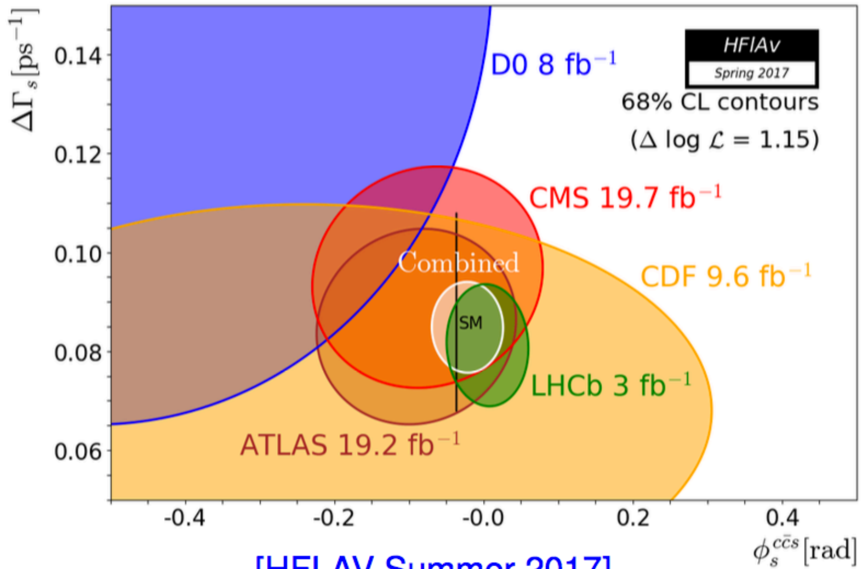
◎ $A_p = [\sigma(\overline{B}^0_s) - \sigma(B^0_s)]/[\sigma(\overline{B}^0_s) + \sigma(B^0_s)]$, measured by LHCb by means of a decay-time-dependent analysis of $B^0_s \to D^-_s\pi^+$ ***LHCb**[PLB 39 (2014) 218]* ➔ $A_p = -.005 \pm .019$ corrected for the different kinematics

◎ both acceptance and decay-time resolution effects are studied using samples of simulated events weighted to match the data distributions

state of art of ϕ_s^{cc}

◎ $\phi_s^{SM} = -2\arg(-V_{cs}V^*_{cs}/V_{ts}V^*_{ts}) = -37.6^{+0.7}_{-0.8}$ *mrad* ignoring contribution from penguin diagrams *[CKM fitter]* prediction very precise !

◎ although there as been impressive progress since the initial measurements at CDF/D0, **the uncertainty needs to be further reduced**



[HFLAV Summer 2017]

LHCb:

- $J/\psi\phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^-$ above $\phi(1020)$[arXiv:1704.08217 (2017)]
- $J/\psi\pi^+\pi^-$ [Phys. Lett. B736, (2014) 186]
- $\psi(2S)\phi$ [Phys. Lett. B762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

◎ **world average (dominated by LHCb) is consistent with SM**

$\phi_s^{cc} = -21 \pm 31$ mrad *HFLAV Summer 2017*

Δm_s and Δm_d

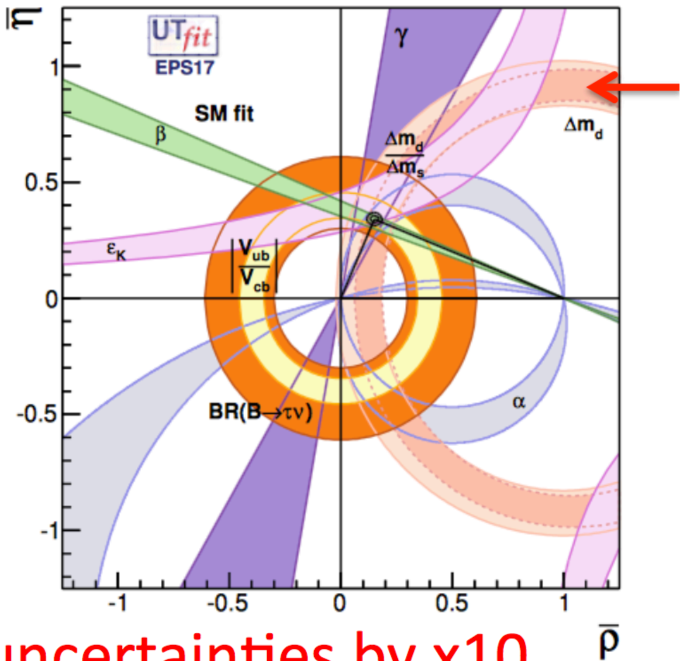
- Experimental precision has reached a remarkable level at the per mille level, dominated by LHCb
  - $\Delta m_d = 0.5065 \pm 0.0019\ ps^{-1}$
  - $\Delta m_s = 17.757 \pm 0.021\ ps^{-1}$
- However, the interpretation requires inputs from LQCD

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar\rho)^2+\bar\eta^2]\ m_{B_d} f_{B_d}^2 \hat B_{B_d}$$

~7%

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat B_{B_d}}{m_{B_s} f_{B_s}^2 \hat B_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar\rho)^2+\bar\eta^2]$$

~4%



- The quest for precision with these constraints is now on LQCD
  - Need to sustain efforts from the LQCD community to reduce the theoretical uncertainties by x10

direct CP violation in charm

Charmed hadrons provide the only way to probe *CP* violation with up-type quarks.
In the SM *CP* violation in charm is expected to be $< \mathcal{O}(10^{-3})$ [Phys. Rev. D, 85, 079901 (2012)]

$$A_{raw}(D \to X) = \frac{N(D \to X) - N(\overline{D} \to \overline{X})}{N(D \to X) + N(\overline{D} \to \overline{X})} \qquad A_{raw} \approx A_{CP} + A_P + A_D$$

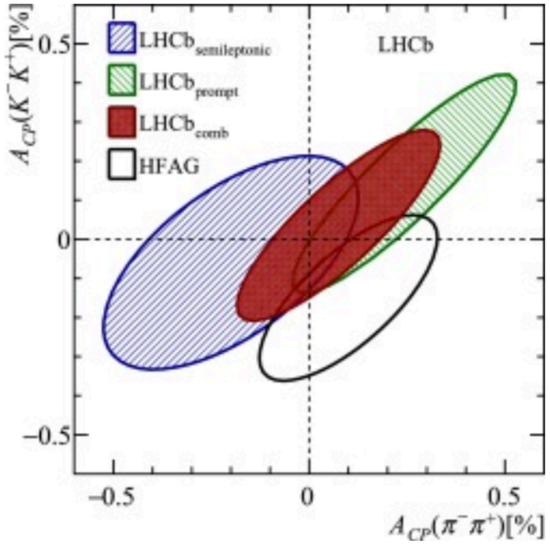
LHCb studied *CP* asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$:

$$\boxed{A_{CP}(K^+K^-) = (0.04 \pm 0.12(\mathrm{stat}) \pm 0.10(\mathrm{syst}))\%}$$

$$\boxed{A_{CP}(\pi^+\pi^-) = (0.07 \pm 0.14(\mathrm{stat}) \pm 0.11(\mathrm{syst}))\%}$$

- Main syst: statistics available in control samples, e.g. $D^+ \to K^0_S\pi^+$

[Phys.Lett. B 03 (2017) 62]



anomalies about the LFU: what's about ?

- SM features Lepton Flavor Universality (**LFU**) ➔ equal electroweak coupling to all charged leptons, the branching ratios to e, μ and τ differ only due to their mass
any further deviation is a key signature of physics processes beyond the SM

- measurements of the Z and W couplings to leptons, mainly constrained by LEP and SLC experiments, are all compatible with LFU
  - ✓ except for a 2.8 σ difference between the measurement of the branching fraction of the $W \to \tau\nu_\tau$ decay with respect to $W \to \mu\nu_\mu$ and $W \to e\nu_e$ decays

- **recently few deviations from SM emerged in B decays**
  - ✓ tree level semileptonic $b \to c\tau\nu_\tau$ transitions, high rates O(%), well known in SM ➔ <u>possible NP coupling mainly to the 3rd family</u>
  - ✓ FCNC $b \to sll$ transitions, rare decays forbidden at the tree level $O(10^{-6})$ in SM ➔ <u>possible NP contributions in the loops</u>
- possible BSM scenarios: leptoquarks, new heavy vector bosons, $H^{\pm}$, ...

- main test variables are ratios of decay rates
  - ✓ theoretically clean: cancellation of QCD effects
  - ✓ experimentally clean: cancellation of efficiency and reconstruction effects

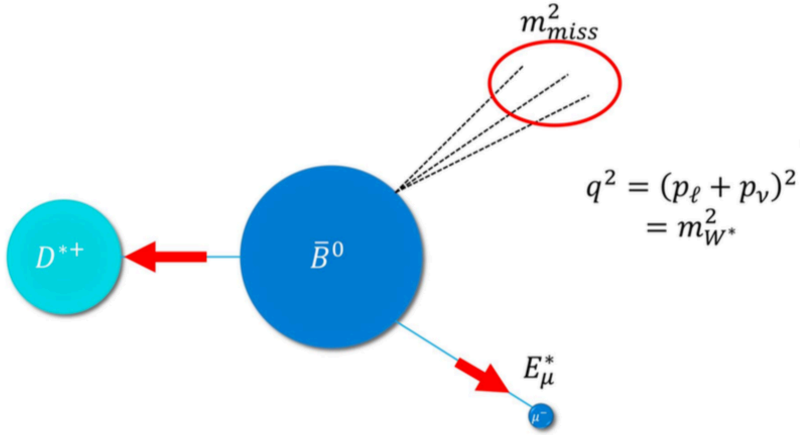
- <u>the following analysis are based on Run 1 dataset, **3 fb^{-1}**</u>

R(D*) from $\tau \to \mu\nu_\mu\nu_\tau$

LHCb [PRL (2015) 111803]

separation of the signal from the normalization channel exploiting distribution of 3 kinematic variables computed in the B rest frame

1. $m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2$
2. E^*_μ
3. $q^2 = (p_B - p_{D^*})^2$



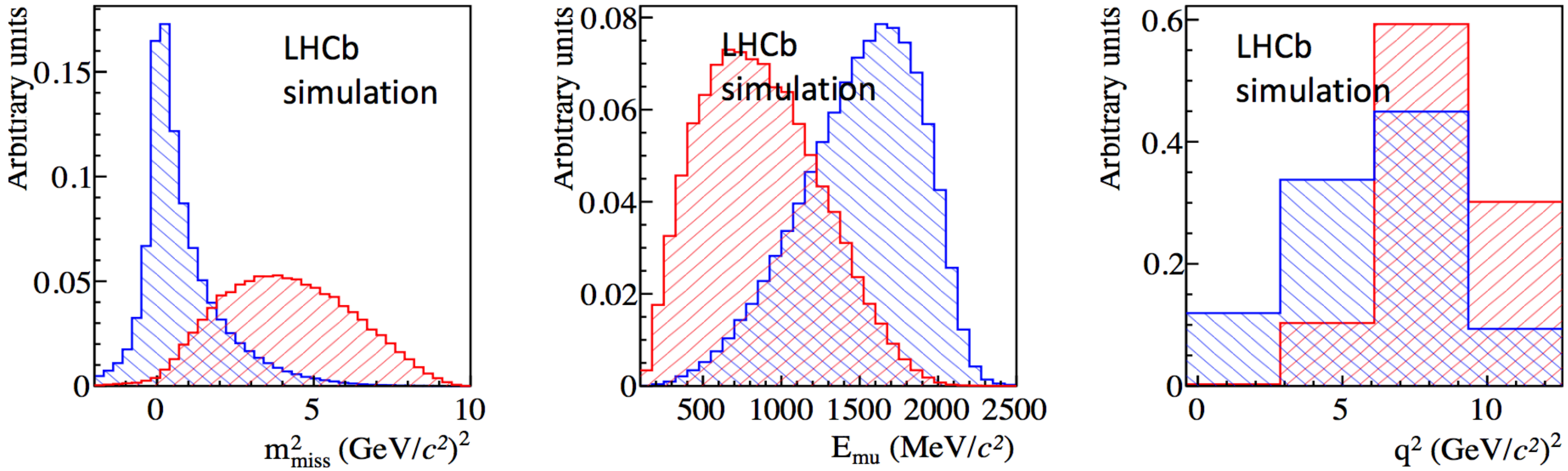
the component of p_B along the beam axis is approximated with

$(p_B)_z = (m_B/m_{reco})(p_{reco})_z$

~18% resolution sufficient to retain discriminating power

$B \to D^*\tau\nu_\tau$

$B \to D^*\mu\nu_\mu$

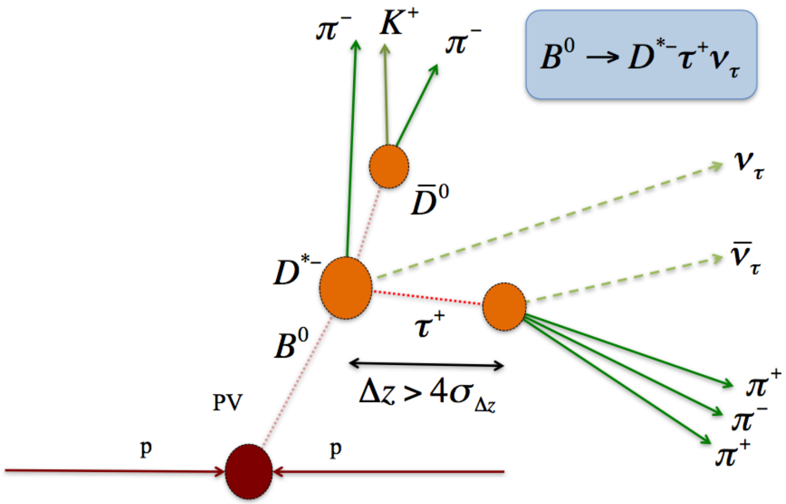


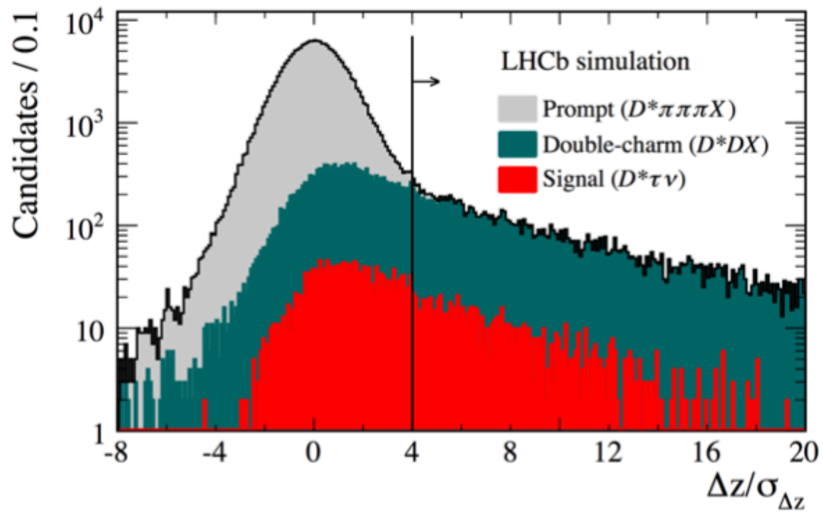
R(D*) from $\tau \rightarrow \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$

***LHCb** [arXiv:1708.08856]*

✓ BR($\tau \rightarrow 3\pi(\pi^0)\nu_\tau$) ~ 13.9% (was ~ 17% for the muonic case)
✓ no charged leptons in the final state ➔ no backgrond from semileptonic decays
✓ the 3-prong topology enables the precise reconstruction of τ vertex

the requirement of a 3π vertex detached from B vertex suppresses $D^{*-}3\pi X$ background by 3 orders of magnitudes retaining ~ 40% of the signal

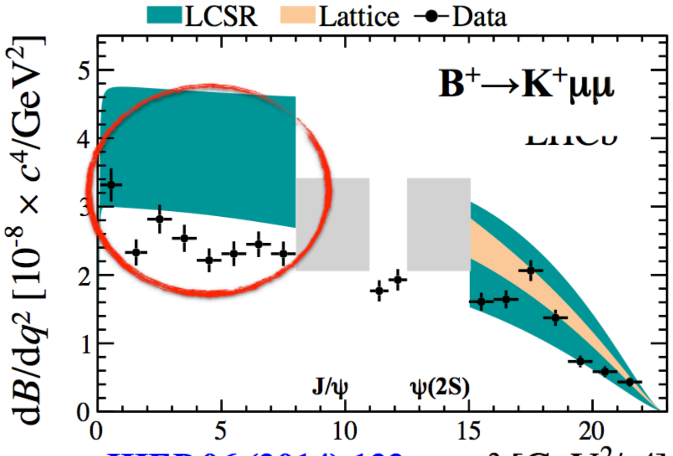




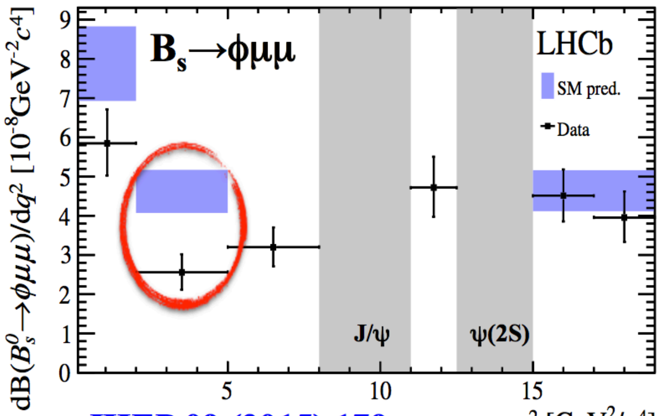
✓ BDT technique to suppress the remaining background, that is due to $B \rightarrow D^{*-}D_{(s)}(X)$, double-charm decays (~ 10 × signal)
✓ extensive studies performed in data control samples

other anomalies in the $b \to s l^+ l^-$ sector

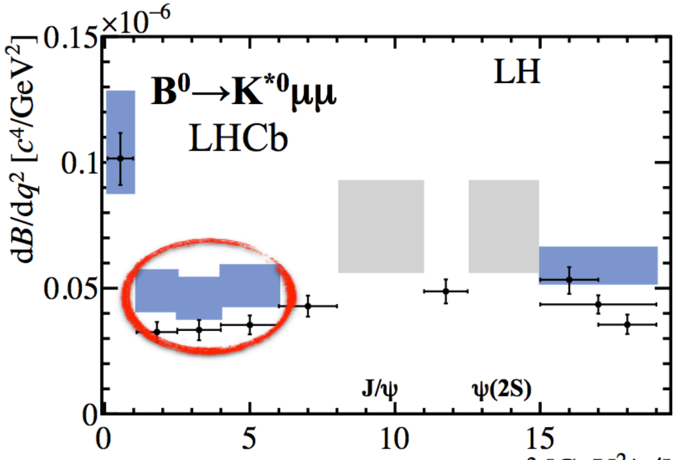
- Differential branching fractions consistently lower than SM expectations, although predictions are still matter of discussion



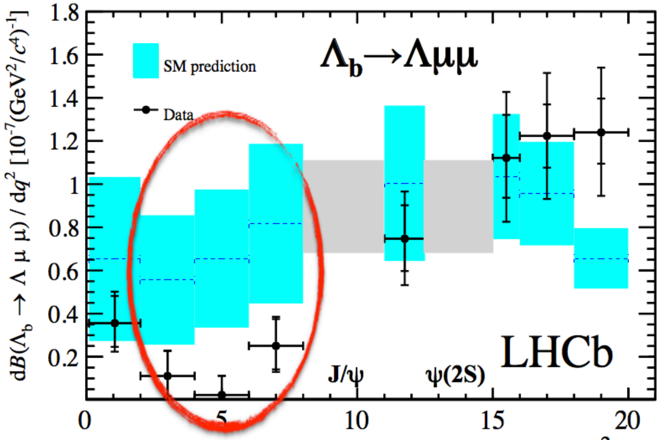
JHEP 06 (2014) 133



JHEP 09 (2015) 179



JHEP 11 (2016) 047
JHEP 04 (2017) 142



JHEP 06 (2015) 115

other anomalies in the $b \to s l^+ l^-$ sector

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

Consider ratios of observables where leading form-factor uncertainties cancel, *e.g.*:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

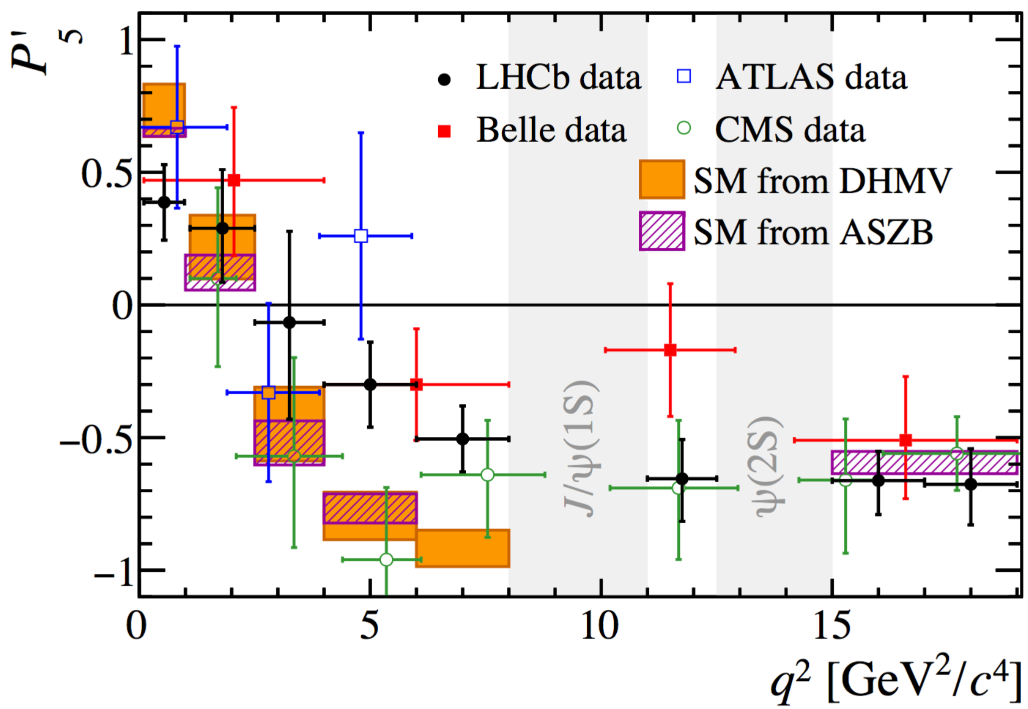
[S. Descotes-Genon et al. JHEP 1204 (2012) 104]

Preliminary results from Belle confirmed tension seen in LHCb

NB: results from Belle combine bc
electron and muon final states

CMS/ATLAS also started to measure the same angular observables, *e.g.* P'$_5$

[LHCb, JHEP 02 (2016) 104]



Local tension with SM predictions (2.8 and 3.0σ)

Global analysis finds deviation corresponding to 3.4σ

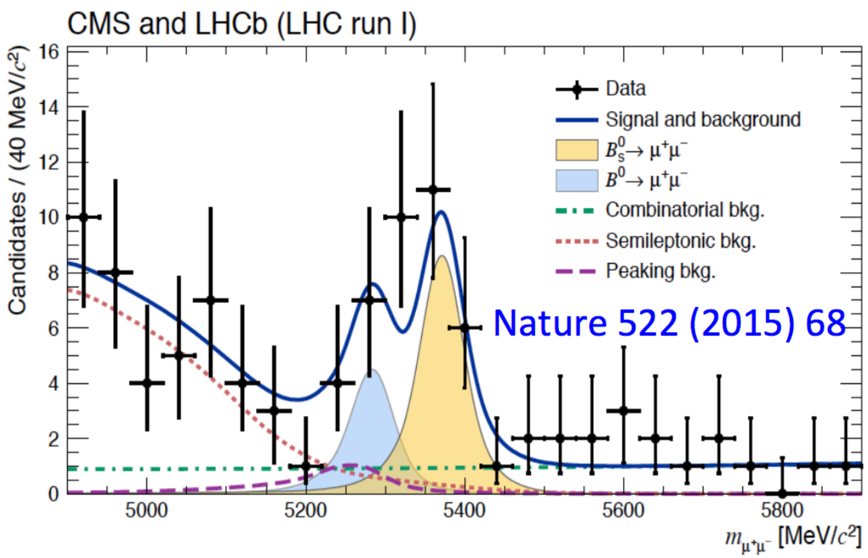
$B^0 \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$

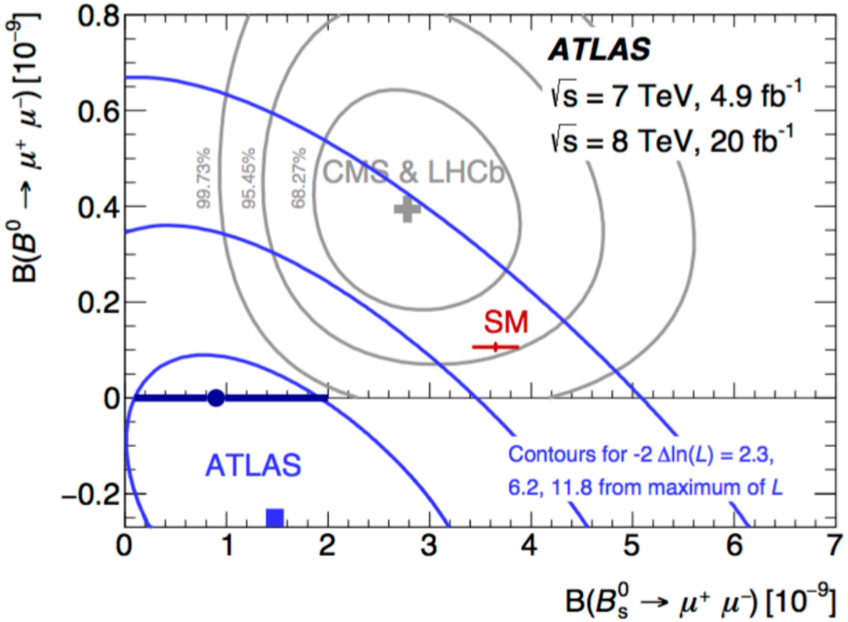
- CMS and LHCb have performed a combined fit to their full Run-1 data sets

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

- $B_s \to \mu\mu$ 6.2σ significance was first observation
  - Compatibility with the SM at 1.2σ
- Excess of events at the 3σ level for $B^0 \to \mu\mu$
  - Compatible with SM at 2.2σ
- More recently, also ATLAS published a measurement with Run-1 data





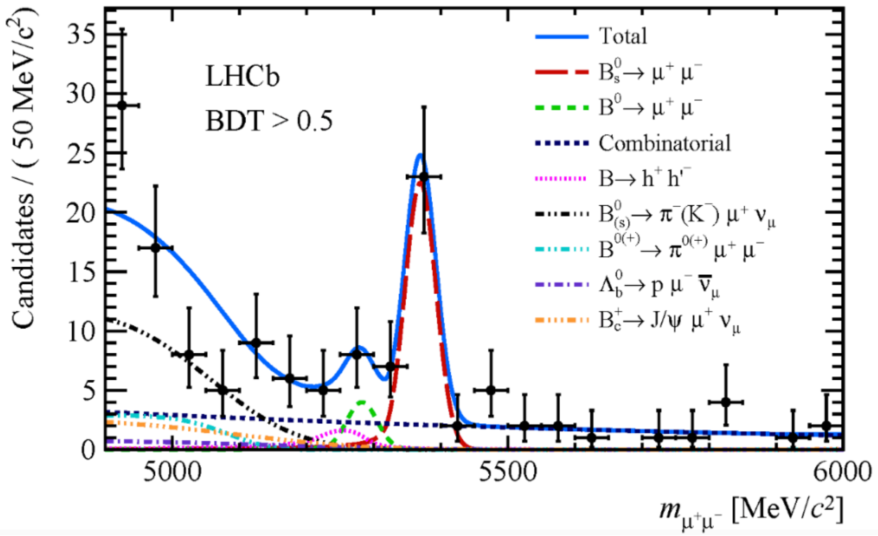
update on $B \to \mu^+\mu^-$ by LHCb

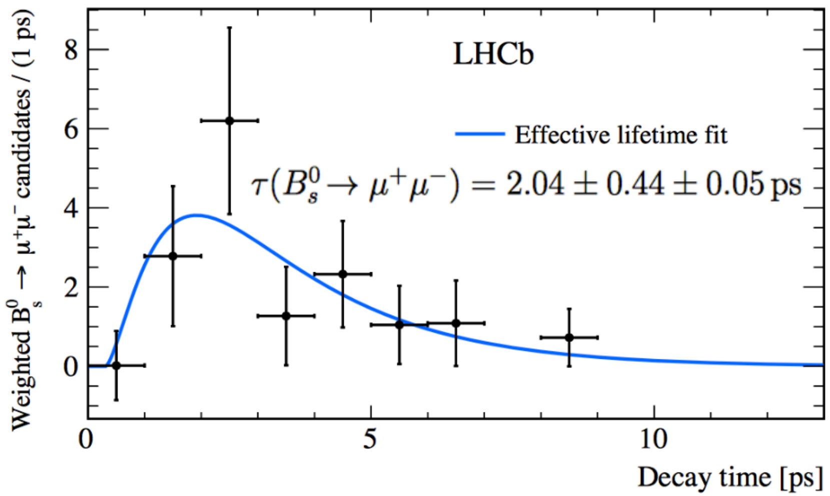
- New measurement from LHCb using Run-2 data has led this year to the first observation of the $B_s \to \mu\mu$ decay from a single experiment

  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$

- Moreover, it starts to be possible to measure other properties, such as the effective lifetime, that will be useful for discriminating between NP models
  - Experimental precision not yet in the interesting range, but important proof of concept

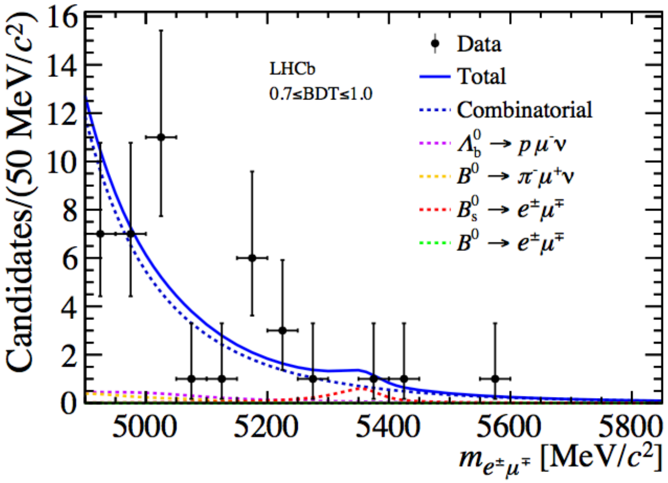
Phys. Rev. Lett. 118, 191801 (2017)



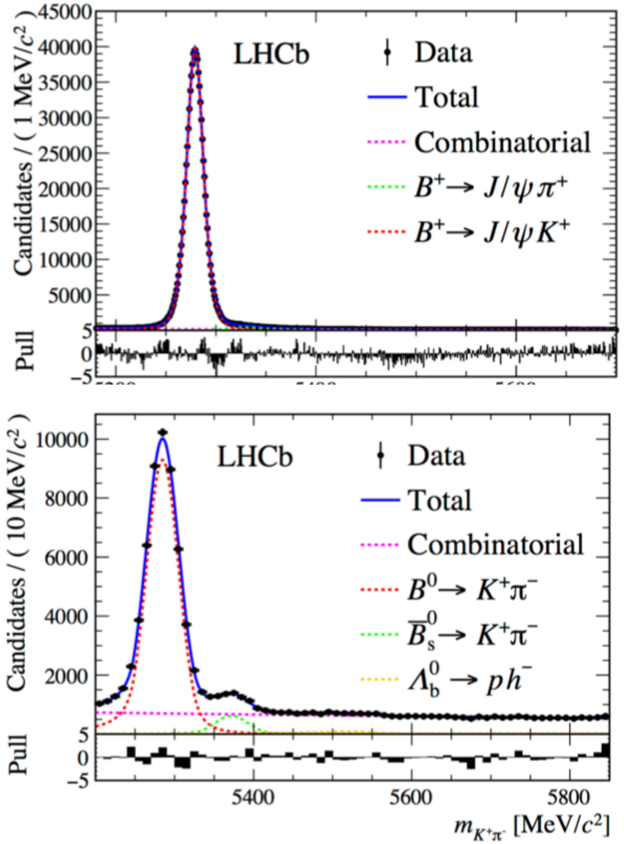


LFV at LHCb: $B_{(s)} \rightarrow e\mu$

- $B^0 \rightarrow e\mu$ on full Run I: $3fb^{-1}$
- Normalisation:
  - ✓ $B^+ \rightarrow J/\psi\, K^+$ (clean final state)
  - ✓ $B^0 \rightarrow K^+\pi^-$ (same topology as signal)
- Primary background: $B^0 \rightarrow h^+h'^-$ with both hadrons misidentified
- Fit to m(eμ): no excess → limits with CLs



arXiv:1710.04111

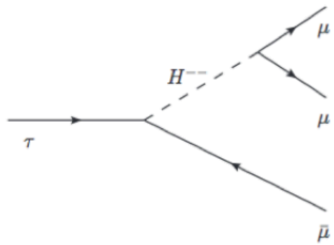


$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.0\,(1.3) \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 5.4\,(6.3) \times 10^{-9}$$

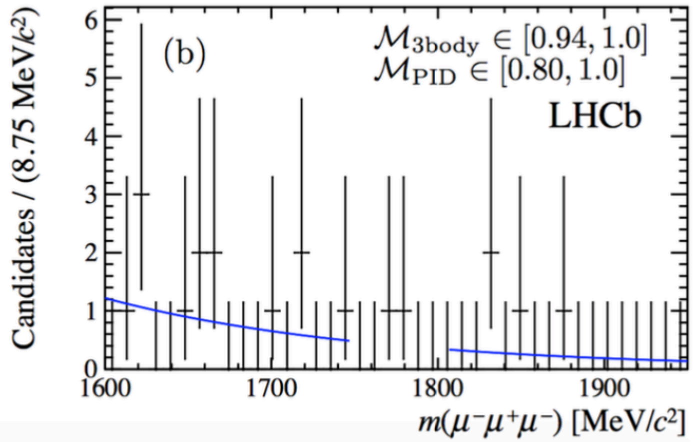
@ 95(90)% CL

LFV at LHCb: τ→μμμ

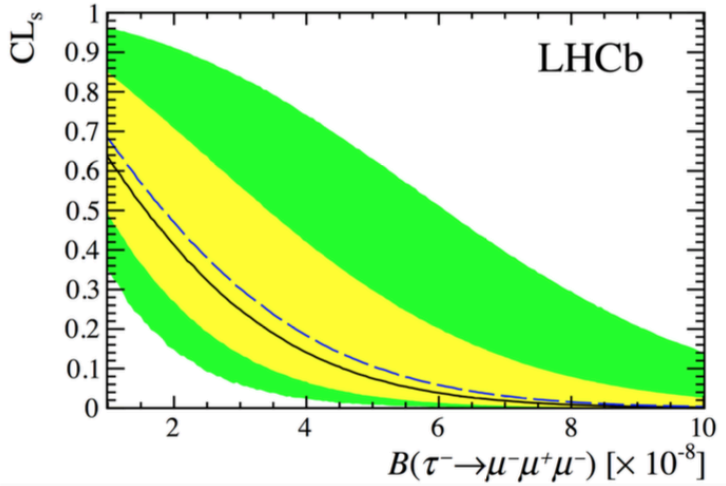
- Possible contribution from doubly charged Higgs
- Using full Run 1: 3fb^{-1}



[JHEP 02 (2015) 121]



- Events studied in a 3D binned space:
  - Invariant mass of τ candidate
  - Output of a MVA based on topological information: vertex quality, displacement
  - Output of a MVA based on PID



$$\mathcal{B}(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

Compatible with best limit from Belle.