B-flavour anomalies in $b \to s\ell\ell$ and $b \to c\ell\nu$ transitions at LHCb

Julián Lomba Castro
on behalf of the LHCb collaboration

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XUNTA DE GALICIA
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
LHCb
IGFAE Instituto Galego de Física de Altas Enerxías
EXCELENCIA MARÍA DE MAEZTU

Outline

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3. LFU tests in $b \to c\ell\nu$ decays
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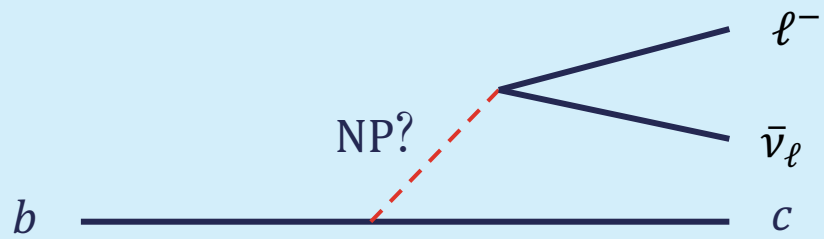
   - $R(J/\psi)$ muonic
   - $R(D^*)$ hadronic
4. Future prospects
5. Conclusions

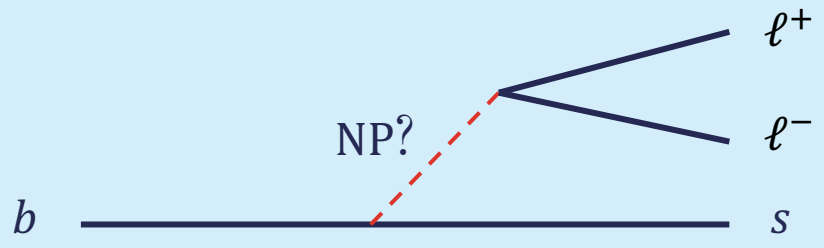
Lepton Flavour Universality

- In the SM, gauge bosons have universal coupling to leptons, independently of their family. This is called Lepton Flavour Universality (LFU).

e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ
u	c	t
d	s	b



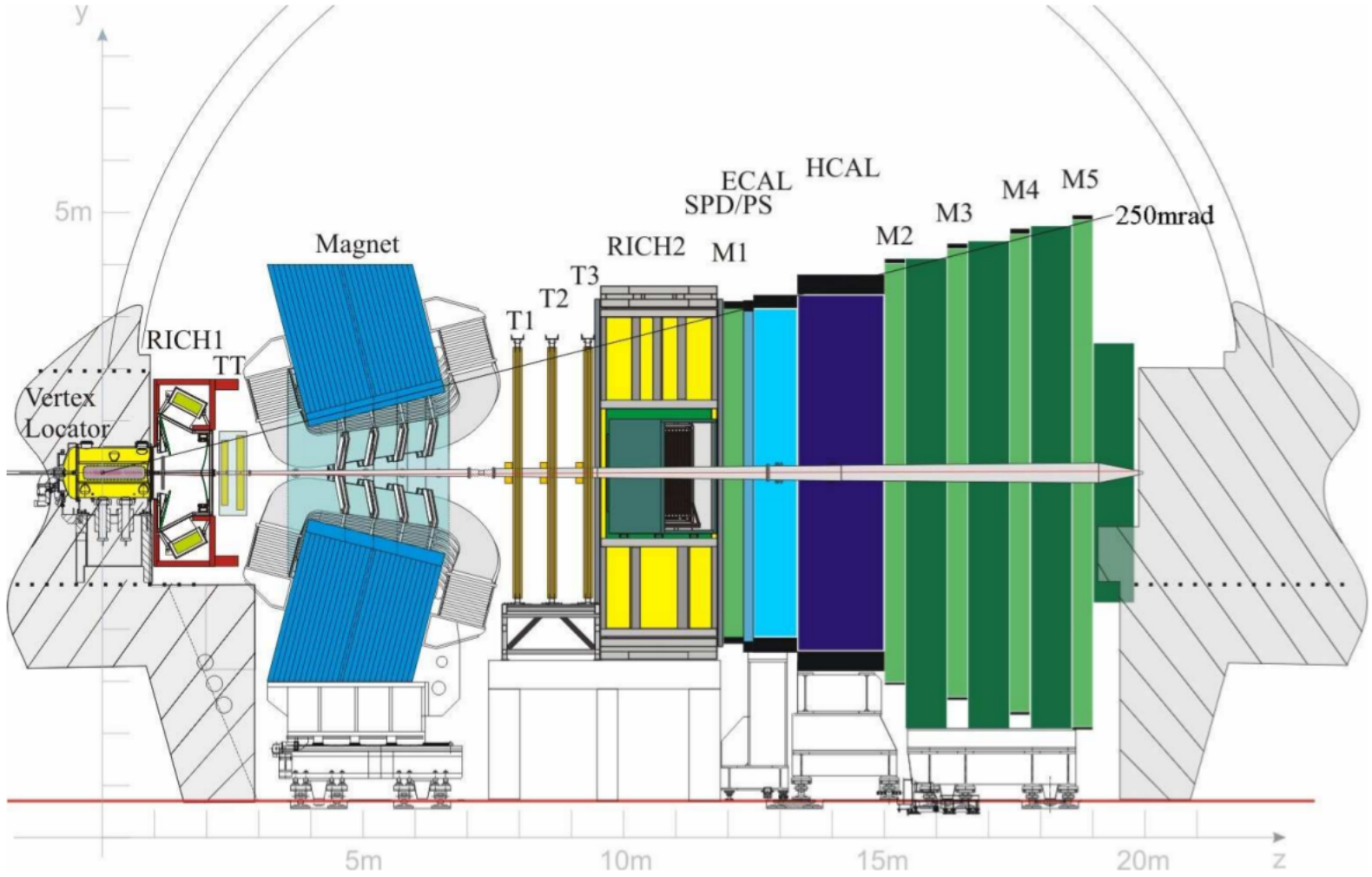
- Tensions between experiments and SM predictions found in:
  - Neutral currents ($b \to s\ell\ell$).
  - Charged currents ($b \to c\ell\nu$).



- A violation of LFU would require the existence of new particles outside the SM ($H^\pm$, Z', $W'^\pm$, leptoquarks...).

LHCb detector

[PRL 119 169901 (2017)]
[Int. J. Mod Phys. A30 1530022 (2015)]



- High b-quark production:
  - Run1 (2011-2012, 7-8 TeV): 3.2 fb^{-1}, $\sigma_{b\bar{b}X} \approx 72$ μb
  - Run2 (2015-2018, 13 TeV): 5.9 fb^{-1}, $\sigma_{b\bar{b}X} \approx 144$ μb
- Excellent vertex and impact parameter resolution (~ 25 μm).
- b-hadrons highly boosted, giving large values of the impact parameter.
- Excellent PID performance for charged particles (muon efficiency of $\sim 97\%$).

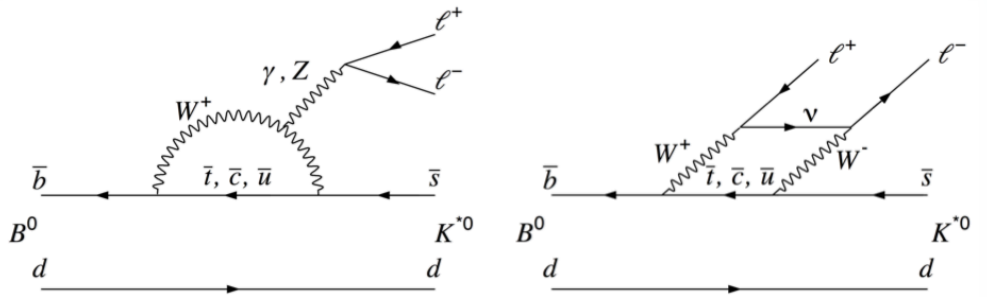
LFU tests at LHCb: neutral currents

- $b \to s\ell^+\ell^-$ decays:

$$R(\mathcal{H}_s)[q^2_{min}, q^2_{max}] \equiv \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(\mathcal{H}_b \to \mathcal{H}_s \mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(\mathcal{H}_b \to \mathcal{H}_s e^+e^-)}{dq^2}} \quad , \qquad \text{where} \quad q^2 = m^2_{\ell\ell}$$

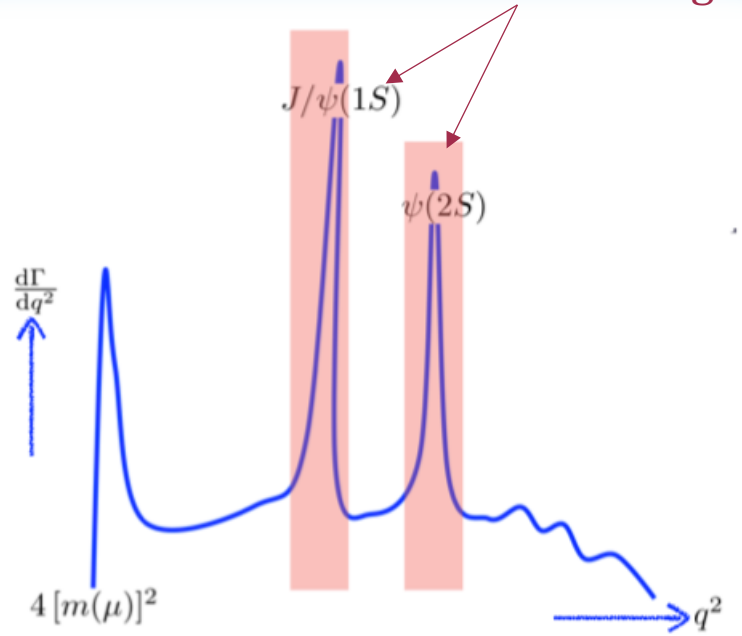
$$\mathcal{H}_b = B^0, B^+, \ldots \qquad \mathcal{H}_s = K, K^*, \ldots$$

  - In SM: strongly suppressed. Can only happen via loops.
  - Sensitivity to NP in branching fractions and in angular distributions.
  - Small theoretical uncertainties.
  - Partial cancelation of hadronic form factor uncertainties.

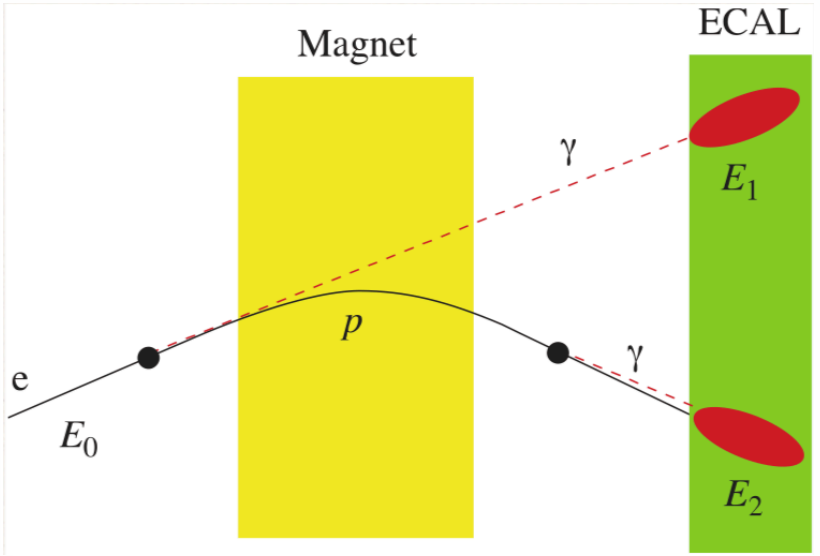


Different q^2 regions → Contributions from different processes

Used as control regions



LFU tests at LHCb: neutral currents



Difficulties due to differences in the detection of electrons and muons:

- Electrons have a lower trigger efficiency.
- Electrons lose a large amount of energy through bremsstrahlung radiation.

  → Bremsstrahlung photons used to improve the reconstruction of the electron energy-momentum.

To reduce systematics, $R(\mathcal{H}_s)$ is measured as a double ratio:

$$R(\mathcal{H}_s) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_s \mu^+\mu^-)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_s J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_s e^+e^-)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_s J/\psi(\to e^+e^-))}$$

Nonresonant modes

Resonant modes

(Possible since $J/\psi \to \ell^+\ell^-$ is measured to be lepton universal)

$R(K^{*0})$ measurement at LHCb

[JHEP 08 055 (2017)]

(Run1 data, 3.2 fb^{-1})

Nonresonant modes: $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$

Resonant modes: $B^0 \to K^{*0}(\to K^+\pi^-)J/\psi(\to \ell^+\ell^-)$

Two q^2 bins: Lower: $0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4$; Central: $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$

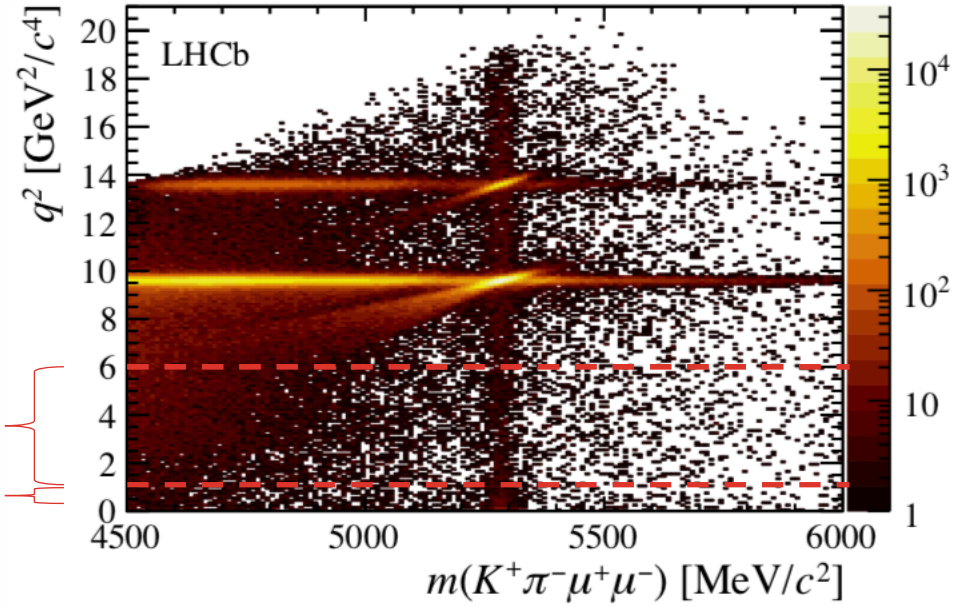
- e^+e^- data divided into three categories depending on how the event was triggered.
- Neural network classifiers to separate signal from combinatorial background.
- Large background from $B^0 \to D^-(\to K^{*0}\ell^-\bar{\nu}_\ell)\ell^+\nu_\ell$ separated using angular distribution of $\ell^+\ell^-$ pair.

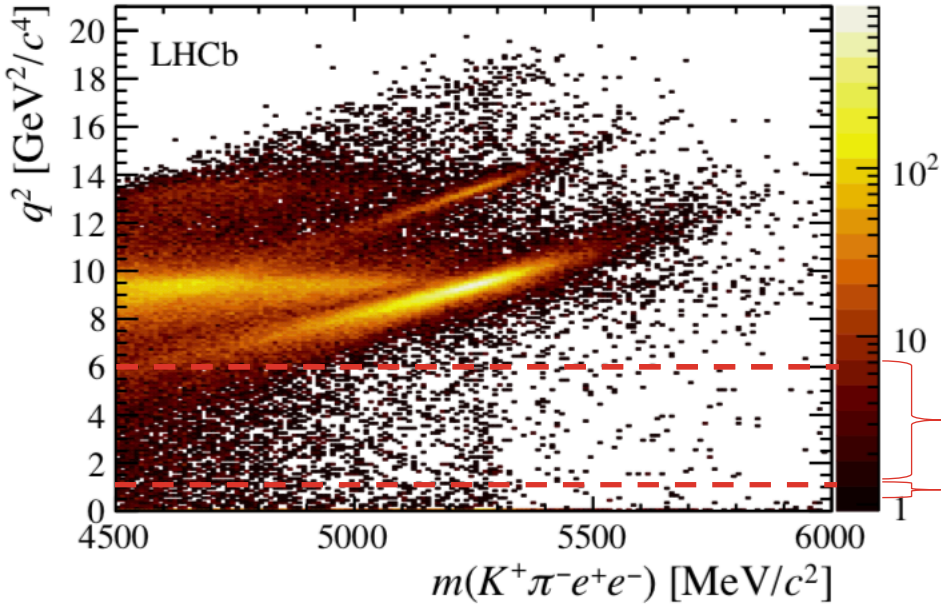
$\psi(2S)$

J/ψ

Central bin

Lower bin





$\psi(2S)$

J/ψ

Central bin

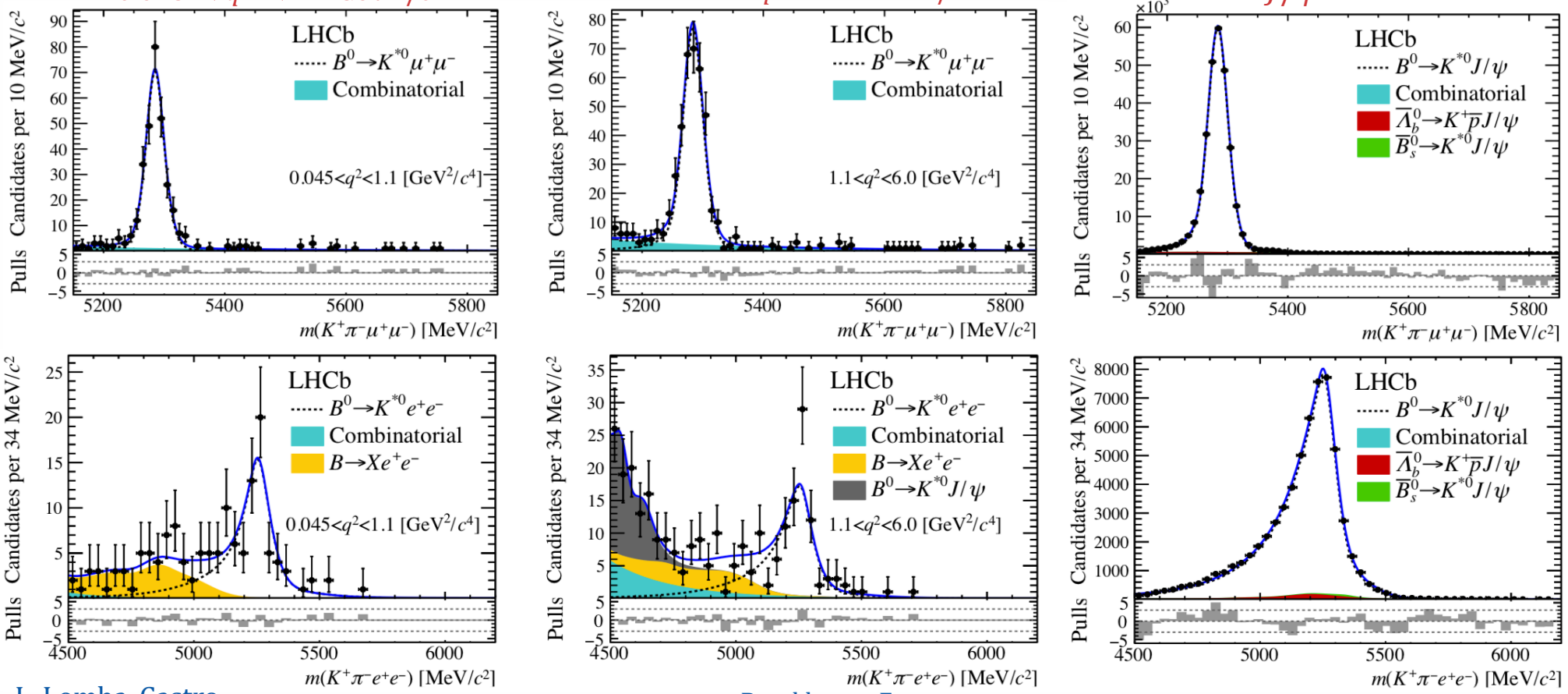
Lower bin

$R(K^{*0})$ measurement at LHCb

[JHEP 08 055 (2017)]

Signal yields obtained from fits to $m(K^+\pi^-\ell^+\ell^-)$ distributions for each q^2 bin and lepton type.
Simultaneous fits on resonant and nonresonant modes, with shared parameters.
In the electron channels, separate model for each trigger category.

$0.045 < q^2 < 1.1\ \text{GeV}^2/c^4$ | $1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$ | $J/\psi \to \ell^+\ell^-$



$m(K^+\pi^-\mu^+\mu^-)$

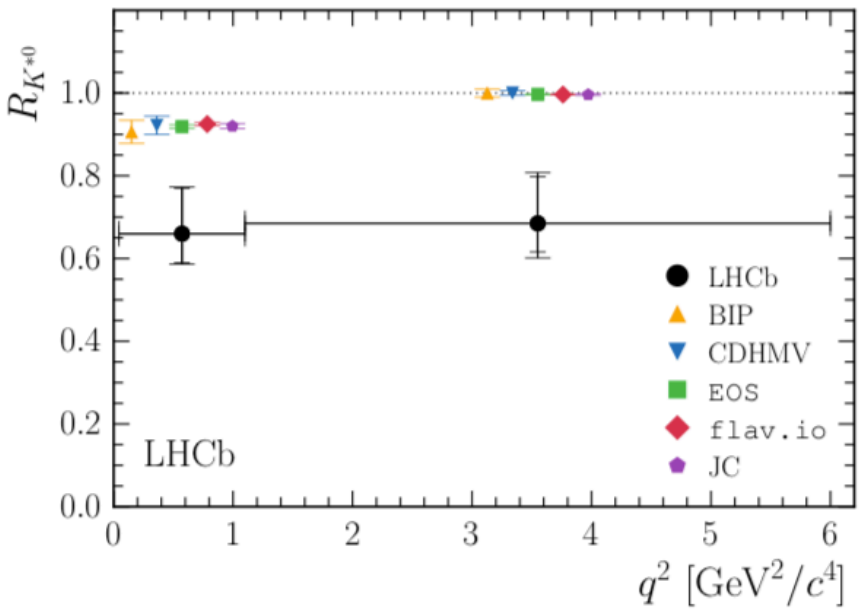
$m(K^+\pi^-e^+e^-)$

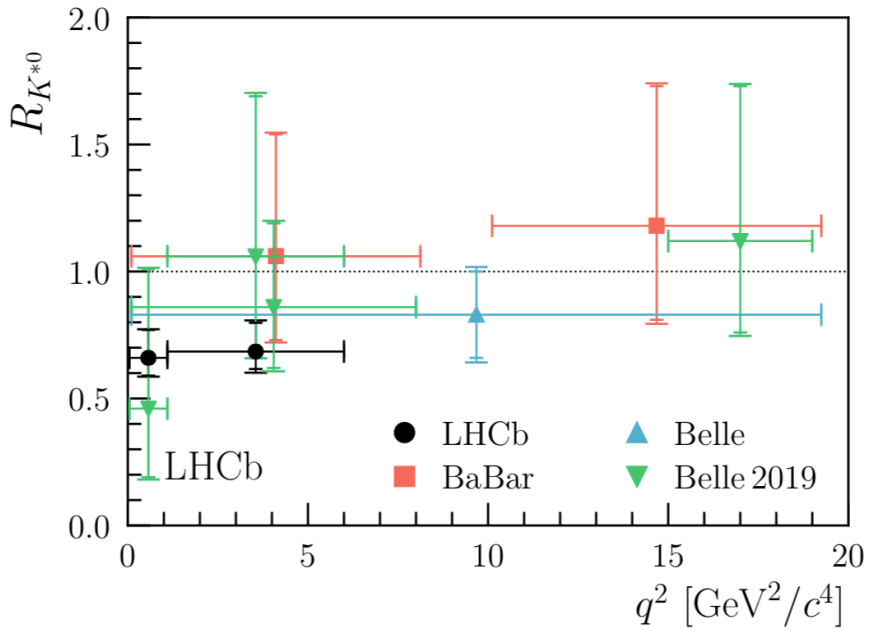
$R(K^{*0})$ measurement at LHCb

[JHEP 08 055 (2017)]

$0.045 < q^2 < 1.1\ \text{GeV}^2/c^4$: $R(K^{*0}) = 0.66^{+0.11}_{-0.07} \pm 0.03$ ~2.1-2.3σ below SM predictions

$1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$: $R(K^{*0}) = 0.69^{+0.11}_{-0.07} \pm 0.05$ ~2.4-2.5σ below SM predictions

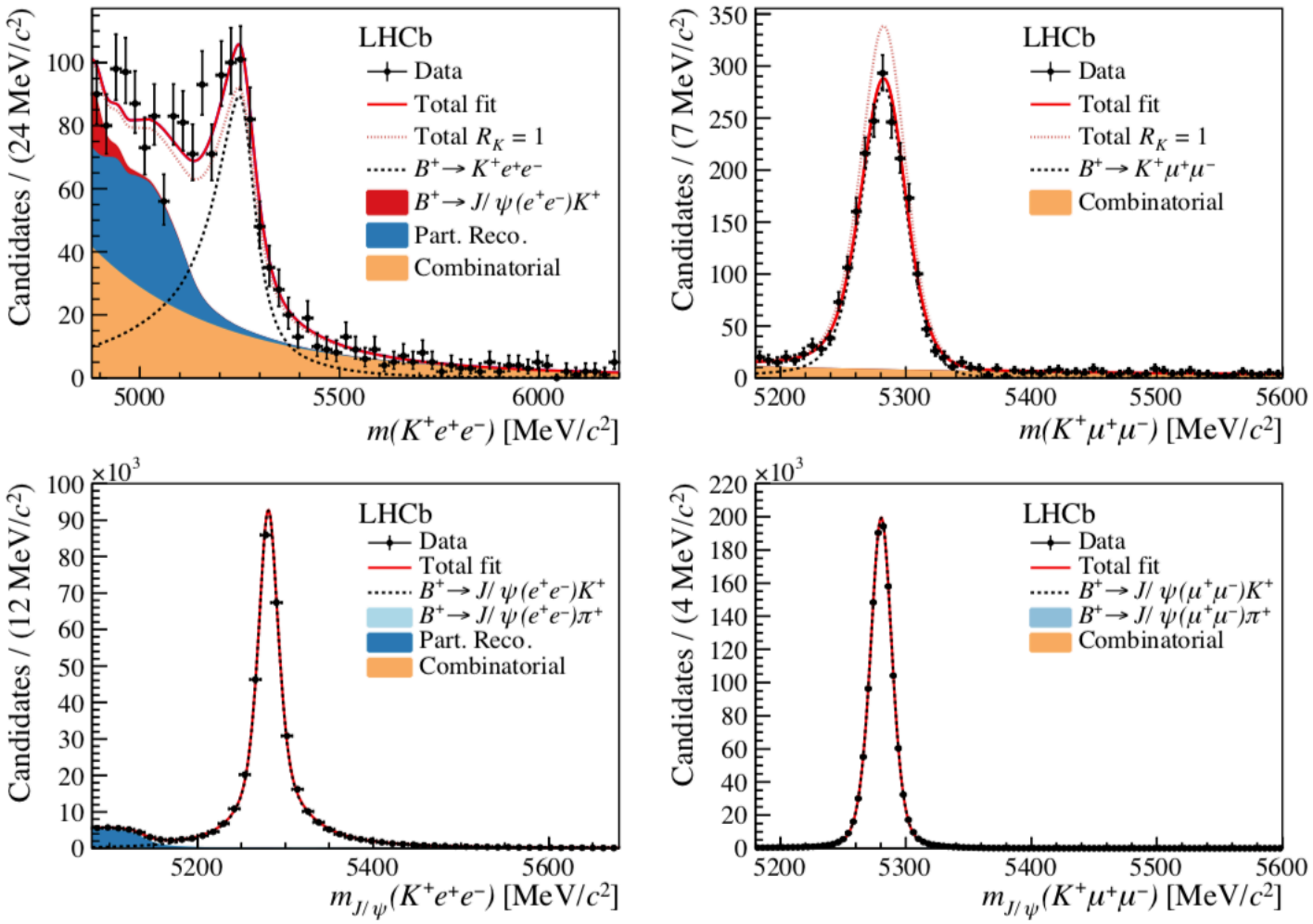




BaBar: [PRD 86 (2012) 032012]
Belle: [PRL 103 (2009) 171801]
Belle 2019: [arXiv:1904.02440]

$R(K)$ measurement at LHCb

[PRL 122 (2019) 191801]



(Run1 + 2015+2016 data, 5.2 fb^{-1})

Nonresonant modes: $B^+ \to K^+\ell^+\ell^-$

Resonant modes: $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$

q^2 range: $1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$

BDTs reduce combinatorial background and select resonant decays.

Resonant mode yields obtained from separate fits to $m_{J/\psi}\,(K^+\ell^+\ell^-)$, and used as constraints in the fit to $m(K^+\ell^+\ell^-)$, with $R(K)$ as a free parameter.

$R(K)$ measurement at LHCb

[PRL 122 (2019) 191801]

$1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$: $R(K) = 0.846^{+0.060\ +0.016}_{-0.054\ -0.014}$

~2.5σ below SM predictions

Separate fits just to Run1 and Run2 data:

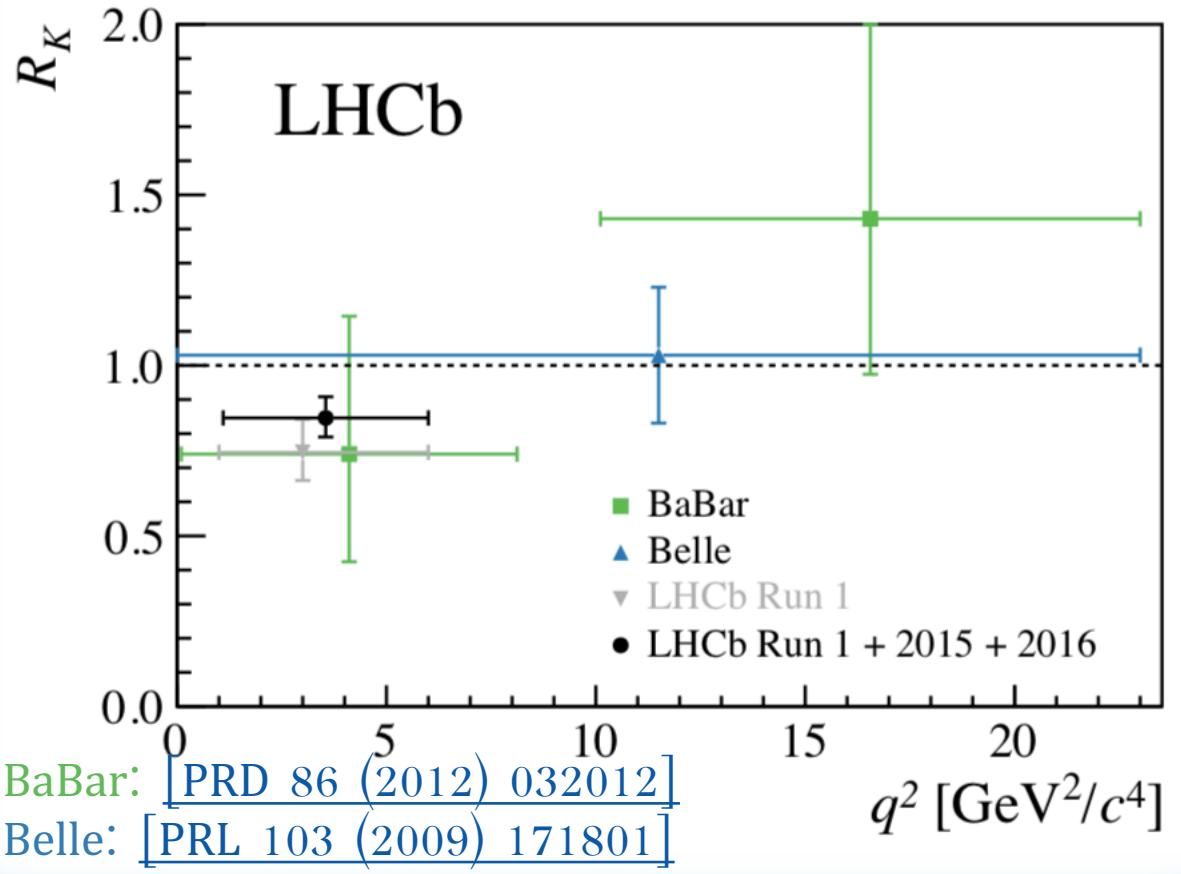
$$R(K)_{7-8\,\text{TeV}} = 0.717^{+0.083\ +0.017}_{-0.071\ -0.016}$$
$$R(K)_{13\,\text{TeV}} = 0.928^{+0.089\ +0.020}_{-0.076\ -0.017}$$

Previous LHCb measurement with Run1 data:

$1.0 < q^2 < 6.0\ \text{GeV}^2/c^4$: $R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$

[PRL 113,151601 (2014)] ~2.6σ below SM predictions

Both measurements compatible within 1σ.



BaBar: [PRD 86 (2012) 032012]

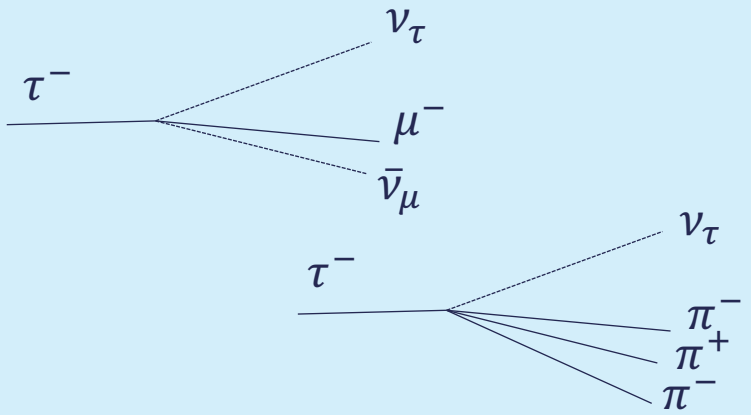
Belle: [PRL 103 (2009) 171801]

LFU tests at LHCb: charged currents

- $b \to c\ell^-\bar{\nu}_\ell$ decays:

$$R(\mathcal{H}_c) \equiv \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu^- \bar{\nu}_\mu)}\,, \qquad \text{where} \qquad \begin{matrix} \mathcal{H}_b = B^0, B^+, B_s^0, \Lambda_b^0 \ldots \\ \mathcal{H}_c = D^{(*)0}, D^{(*)+}, D_s^+, \Lambda_c^+, J/\psi \ldots \end{matrix}$$

  - In SM: tree-level decays mediated by a W boson.
  - Sensitivity to NP contributions at tree level.
  - Partial cancelation of hadronic form factor uncertainties.
  - High rate of charged current decays: $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau) \approx 1.2\%$.



- Muonic channel: $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) \approx 17.39\%$
  - Systematic uncertainties cancel in the ratio $R(\mathcal{H}_c)$.
  - Presence of inclusive $\mathcal{H}_b \to \mathcal{H}_c\mu^-\bar{\nu}_\mu$ (X) decays.
- Hadronic channel: $\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau) \approx 13.81\%$
  - Only one neutrino.
  - τ vertex reconstruction.

$R(D^*)$ muonic

[PRL 115 111803 (2015)]

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

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

Both channels selected, and then disentangled using a multidimensional fit to:

- E_μ^* (B rest frame)
- $m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2$
- $q^2 = (p_B - p_{D^*})^2$

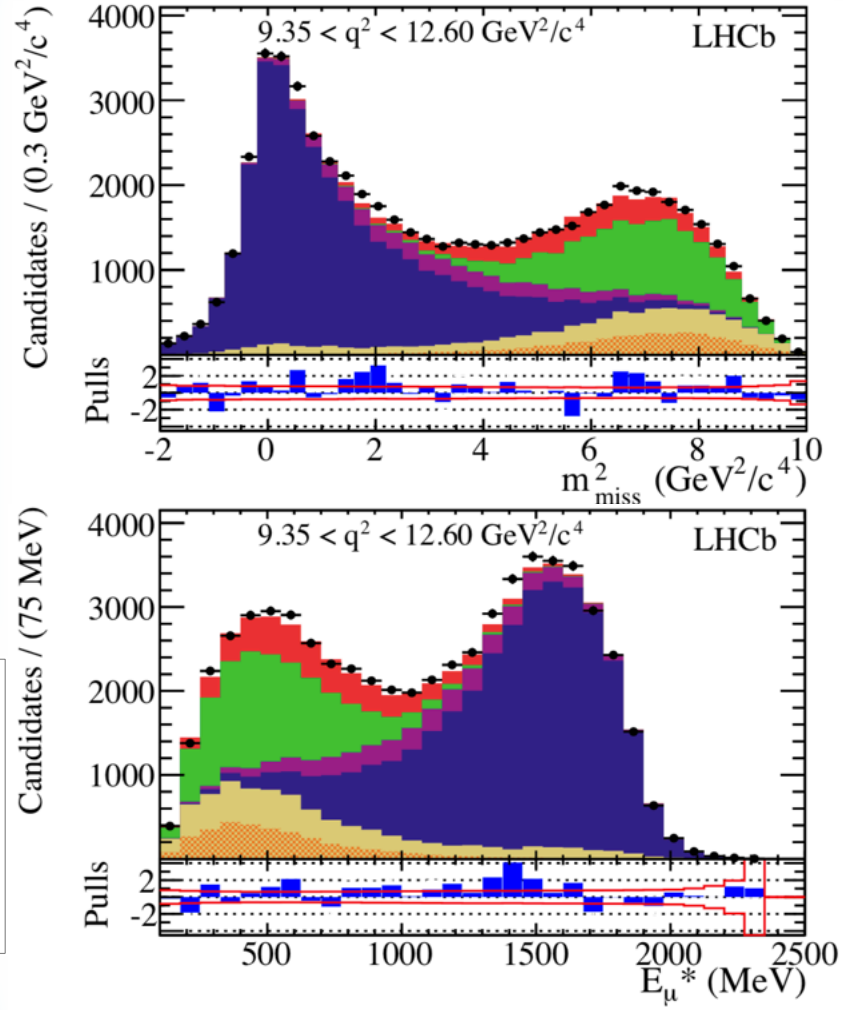
$$R(D^*)_{muonic} = \frac{N(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \frac{1}{\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)} \frac{\epsilon_{norm}}{\epsilon_{sig}}$$

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

2.1σ above SM prediction

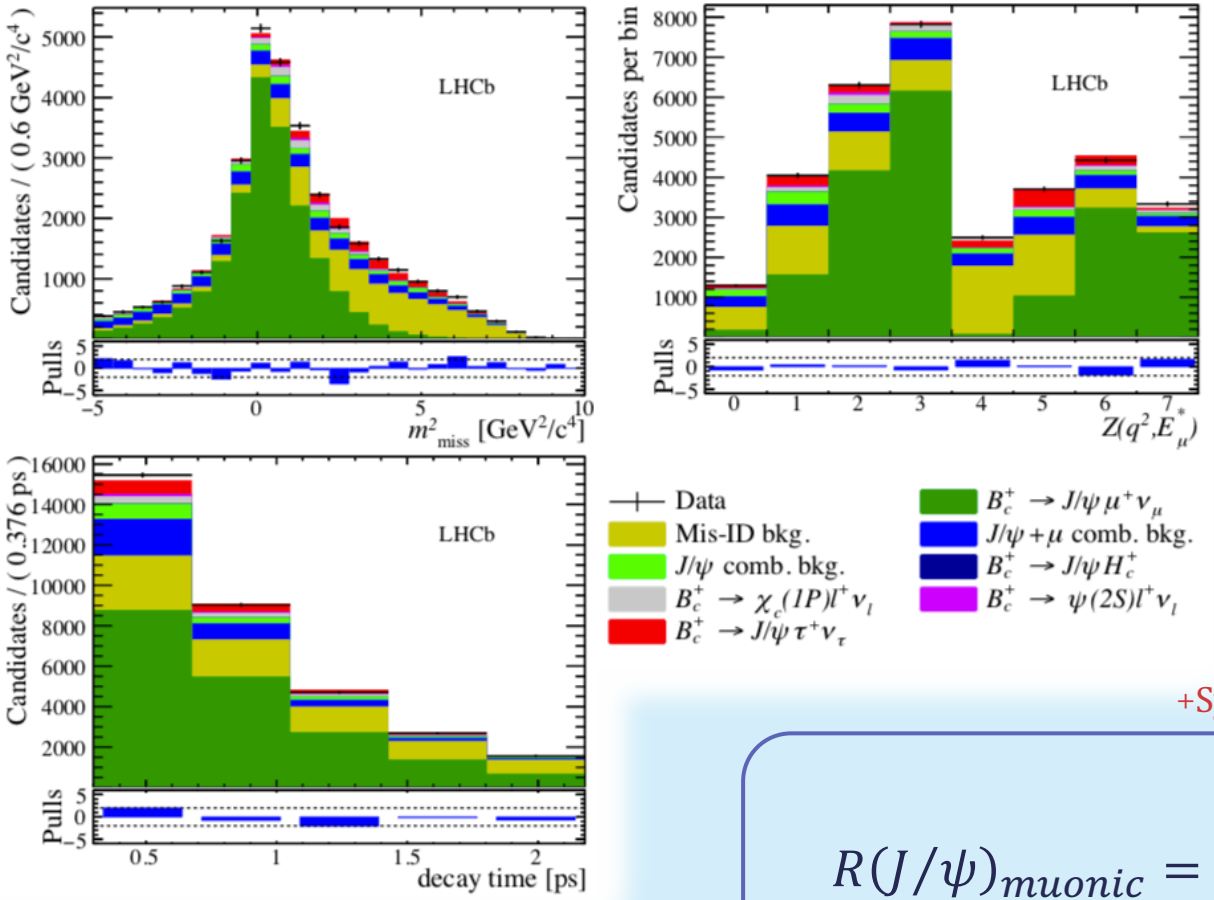
$R(D^*)_{SM} = 0.252 \pm 0.003$

(Run1 data, 3.2 fb^{-1})



[PRL 120 121801 (2018)]

$R(J/\psi)$ muonic



(Run1 data, 3.2 fb^{-1})

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

Similar to $R(D^*)$ analysis, fit using:

- $m^2_{miss} = (p_B - p_{J/\psi} - p_\mu)^2$
- $q^2 = (p_B - p_{J/\psi})^2$
- E^*_μ (B rest frame)

} $Z(q^2, E^*_\mu)$

- B_c decay time

$$R(J/\psi)^{(raw)}_{muonic} = \frac{N(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{N(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)} \frac{1}{\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)} \frac{\epsilon_{norm}}{\epsilon_{sig}}$$

+Systematic bias in the fit

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

2σ above SM prediction
$R(J/\psi)_{SM} \in [0.25, 0.28]$

$R(D^*)$ hadronic

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]

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

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

(external inputs)

$\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau) = (13.81 \pm 0.07)\%$

$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.21 \pm 0.28)\times 10^{-3}$

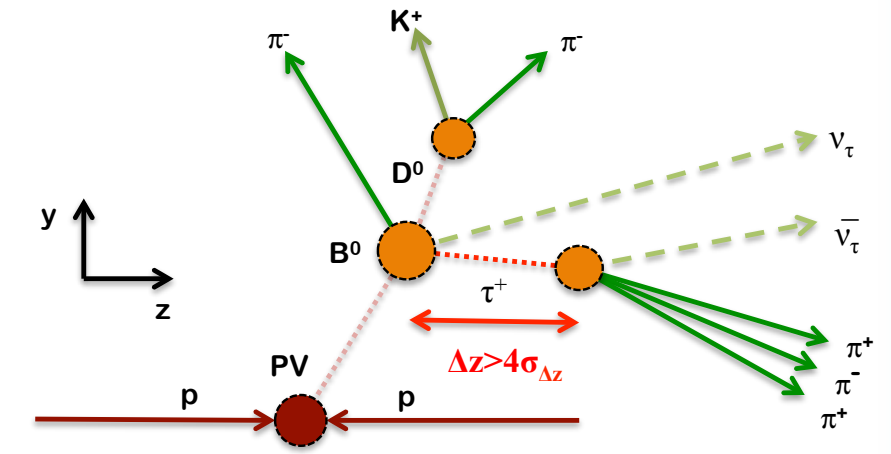
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10)\times 10^{-2}$

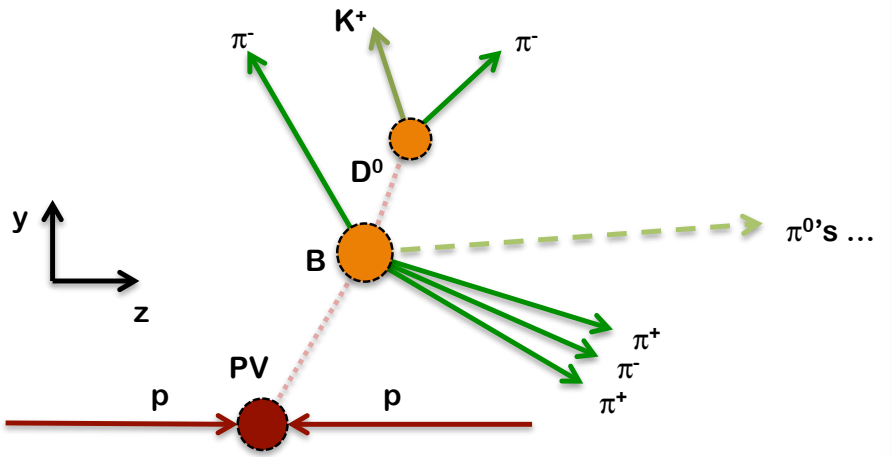
The presence of only one neutrino allows the τ and B^0 momenta to be determined up to a two-fold ambiguity.

N_{sig} obtained from a binned fit in these variables:

- Squared transferred momentum, q^2.
- τ decay time, t_τ.
- Output of a BDT, which takes as input 18 variables (kinematic variables of the decay chain and neutral isolation properties).

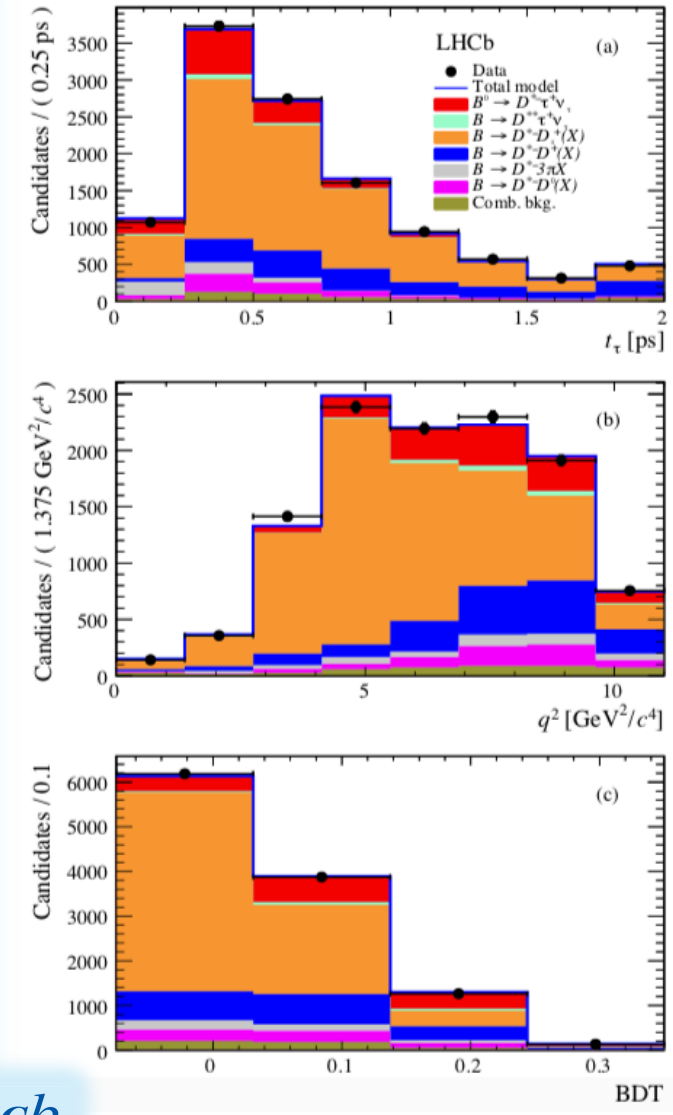
N_{norm} obtained by fitting the invariant mass distribution of the $D^{*-}3\pi$ system around the B^0 mass.

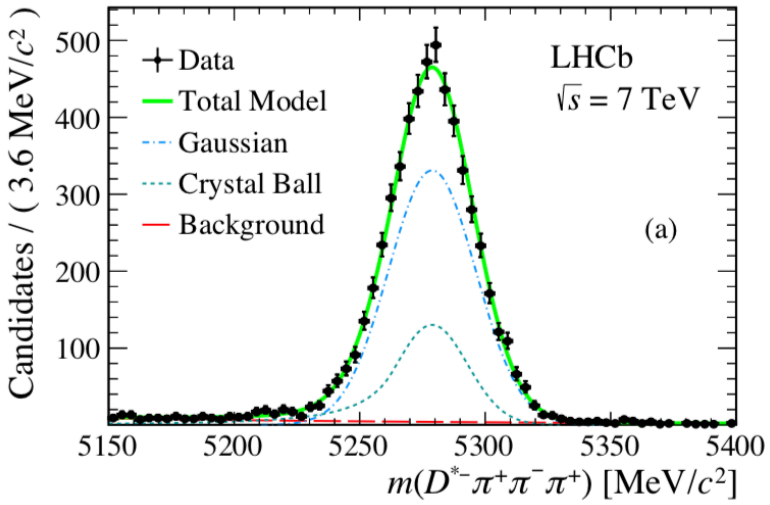


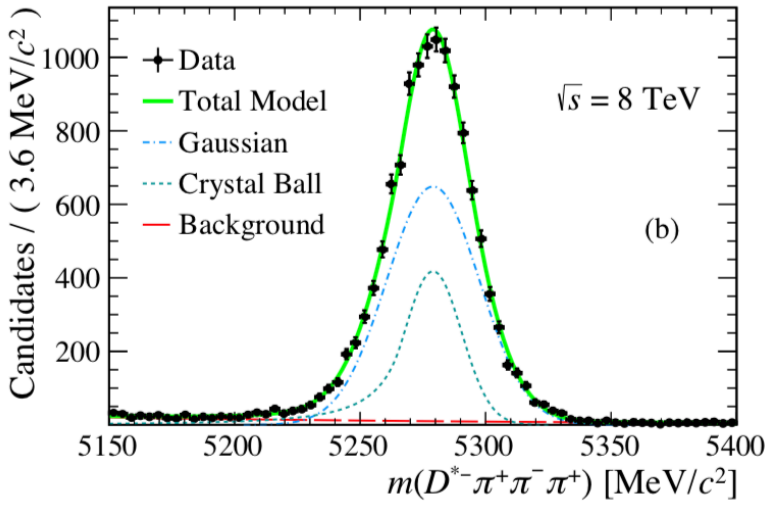


$R(D^*)$ hadronic

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]







(Run1 data, 3.2 fb^{-1})

$N_{norm} = 17808 \pm 143$

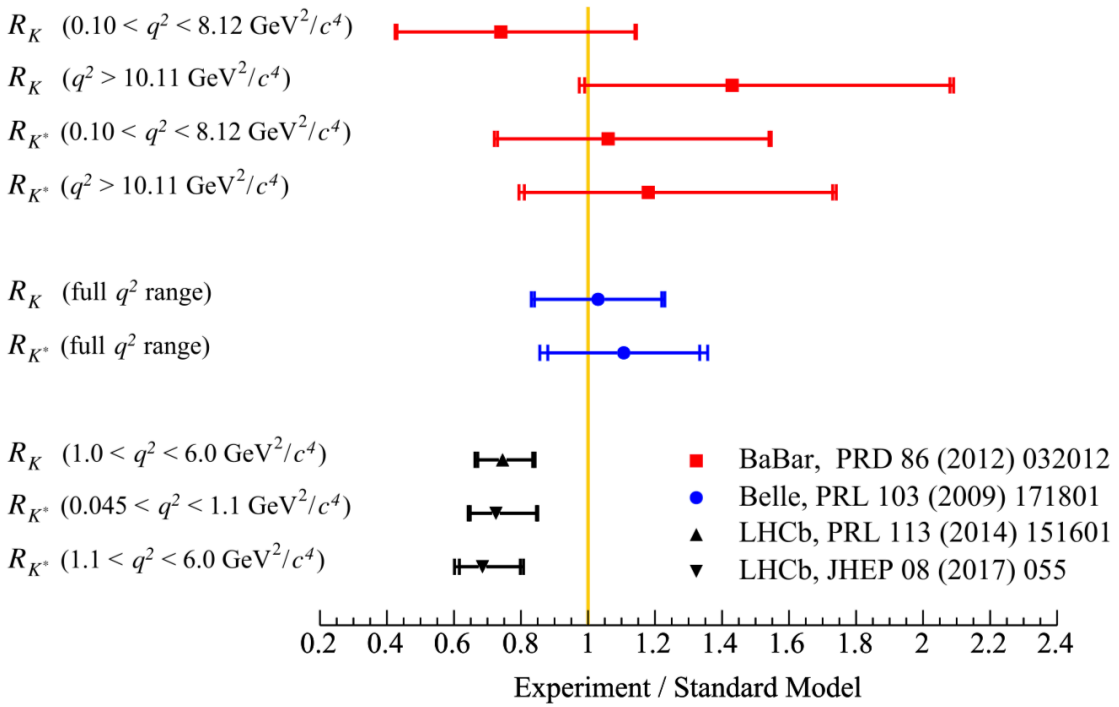
$N_{sig} = 1296 \pm 86$ → $\mathcal{K}(D^{*-}) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$

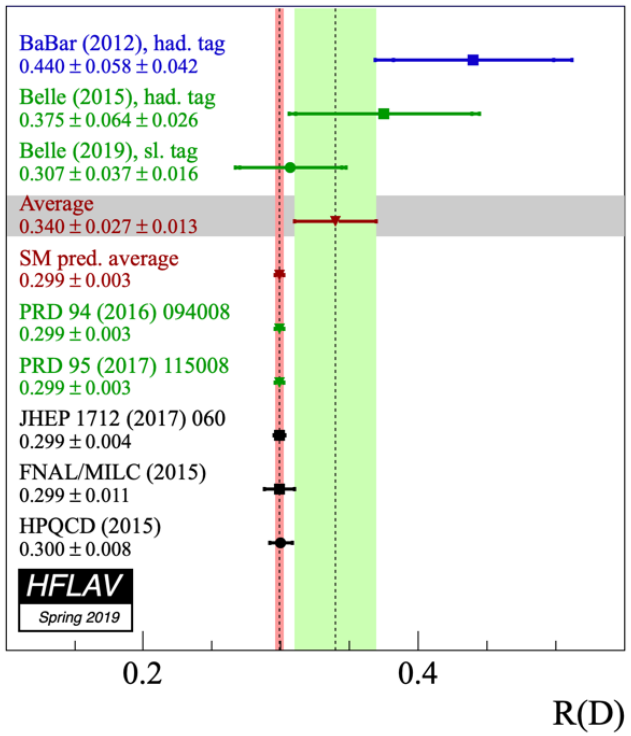
$$R(D^{*-})_{had} = 0.291 \pm 0.019 \pm 0.029$$

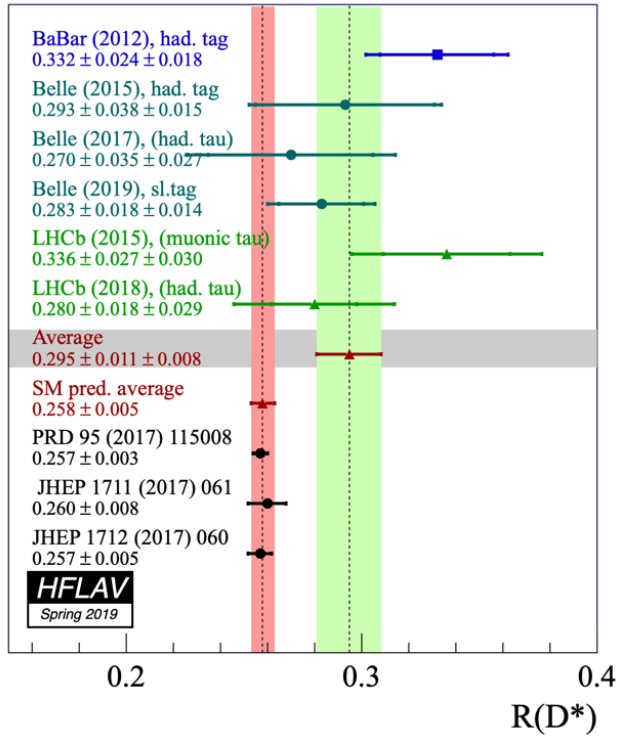
1.1σ higher than SM prediction
$R(D^*)_{SM} = 0.252 \pm 0.003$

Status

[HFLAV R(D) and R(D*) averages]

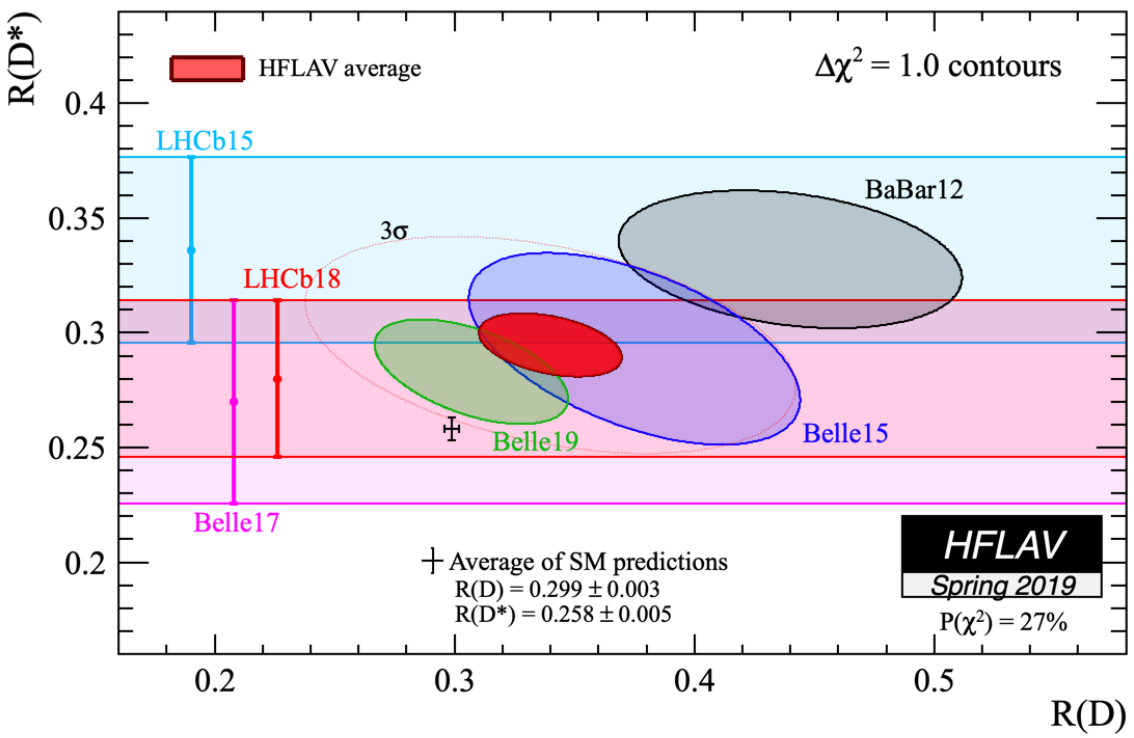






Status

[HFLAV R(D) and R(D*) averages]



With the new Belle preliminary result, global averages are at 1.4σ difference in $R(D)$, 2.5σ in $R(D^*)$ and 3.08σ combined.

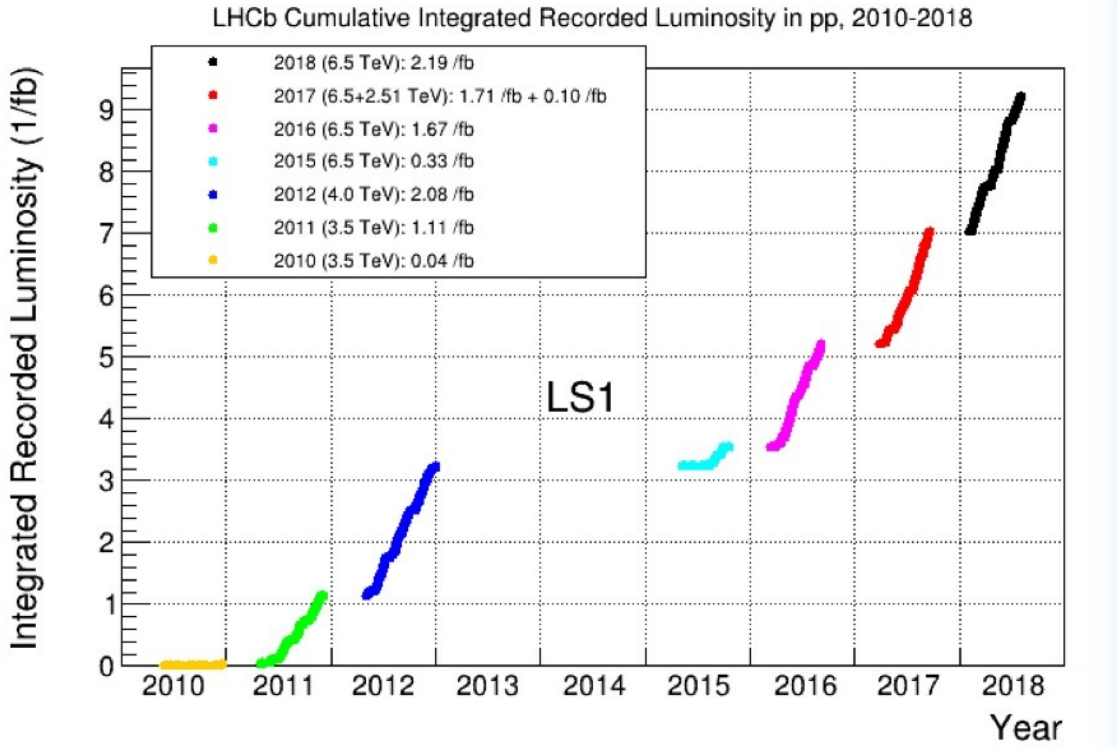
Prospects

[J. Phys. G 46 2 (2018)]

Run1+Run2: ~4 times as many $b\bar{b}$ pairs as in Run1

Ongoing and future analyses:

- Simultaneous measurement of $R(D^0)$ and $R(D^*)$ via three-prong and muonic tau decays (Run2).
- Simultaneous measurement of $R(D^+)$ and $R(D^*)$ via three-prong and muonic tau decays (Run2).
- Updated results for $R(K)$, $R(K^*)$, $R(D^*)$, $R(J/\psi)$...
- Measurement of new ratios $R(\phi)$, $R(\Lambda_c)$, $R(D_s)$...

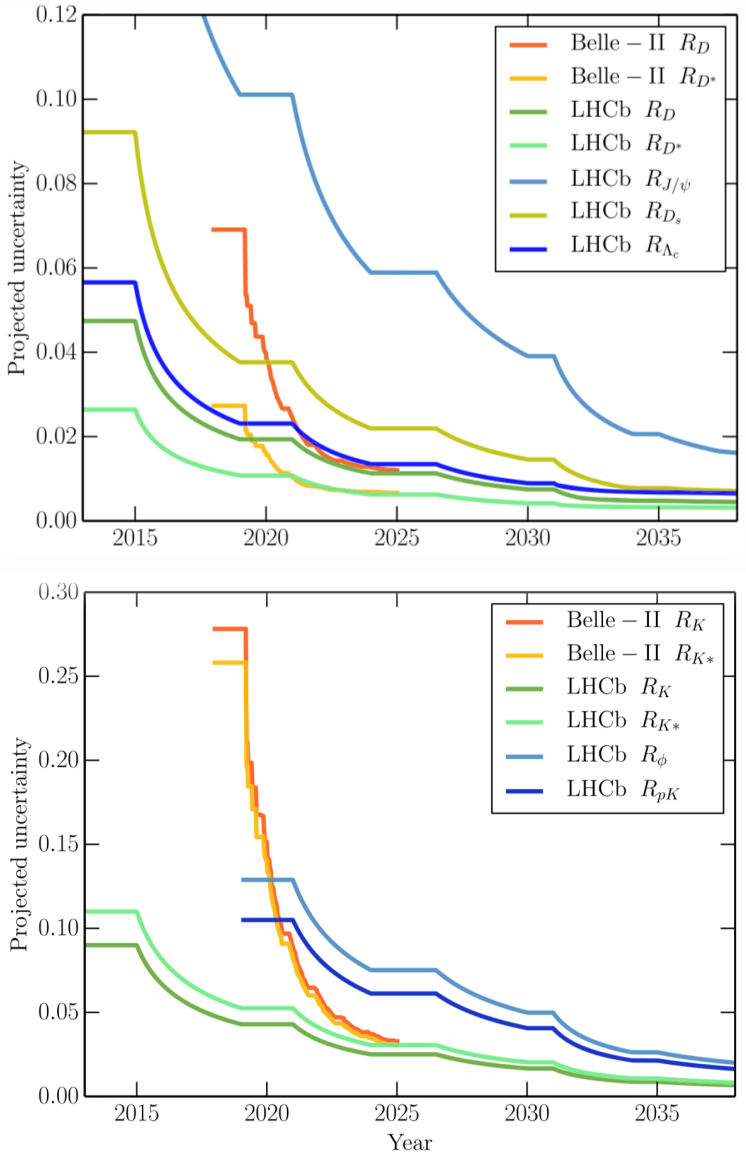


Conclusions

[HFLAV R(D) and R(D*) averages]
[arXiv:1904.08794 (2019)]
[J. Phys. G 46 2 (2018)]

- Intriguing tensions with SM in ratios of branching fractions in
  - $b \to s\ell\ell$ decays
  - $b \to c\ell\nu$ decays
- Potential for NP? We need smaller uncertainties!
- LHCb Run2 data will provide significant improvements and new measurements.

Stay tuned!



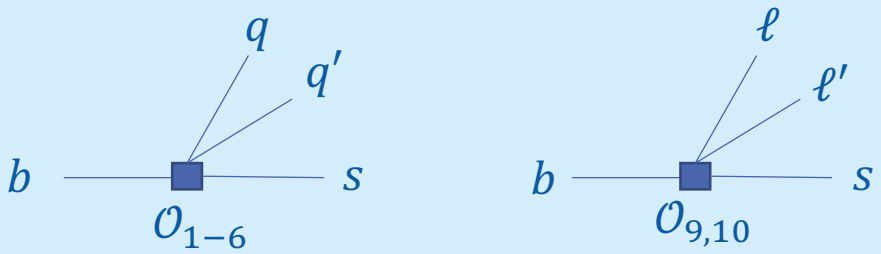
Thank you!

Backup Slides

Effective Hamiltonian

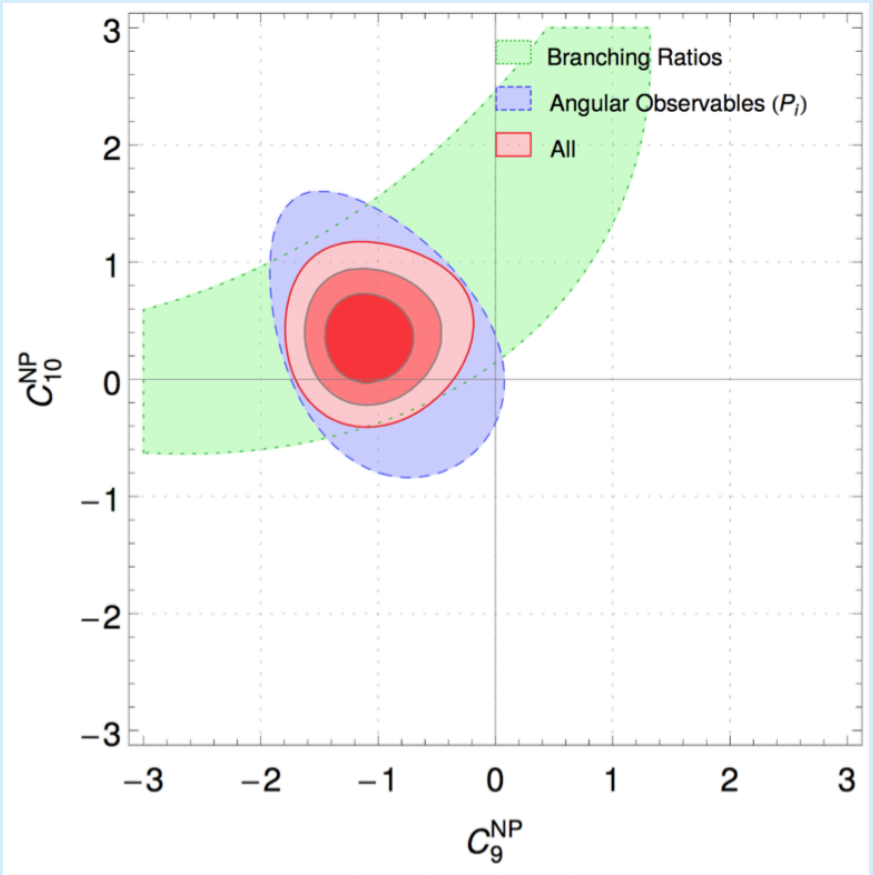
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{\mathrm{tb}} V_{\mathrm{ts}}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

$\mathcal{C}_i$: Wilson coefficients, effective coupling (short-distance).
$\mathcal{O}_i$: Local operators (long-distance).



$$\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$$

Global fits performed to constrain the value of $\mathcal{C}_i^{NP}$



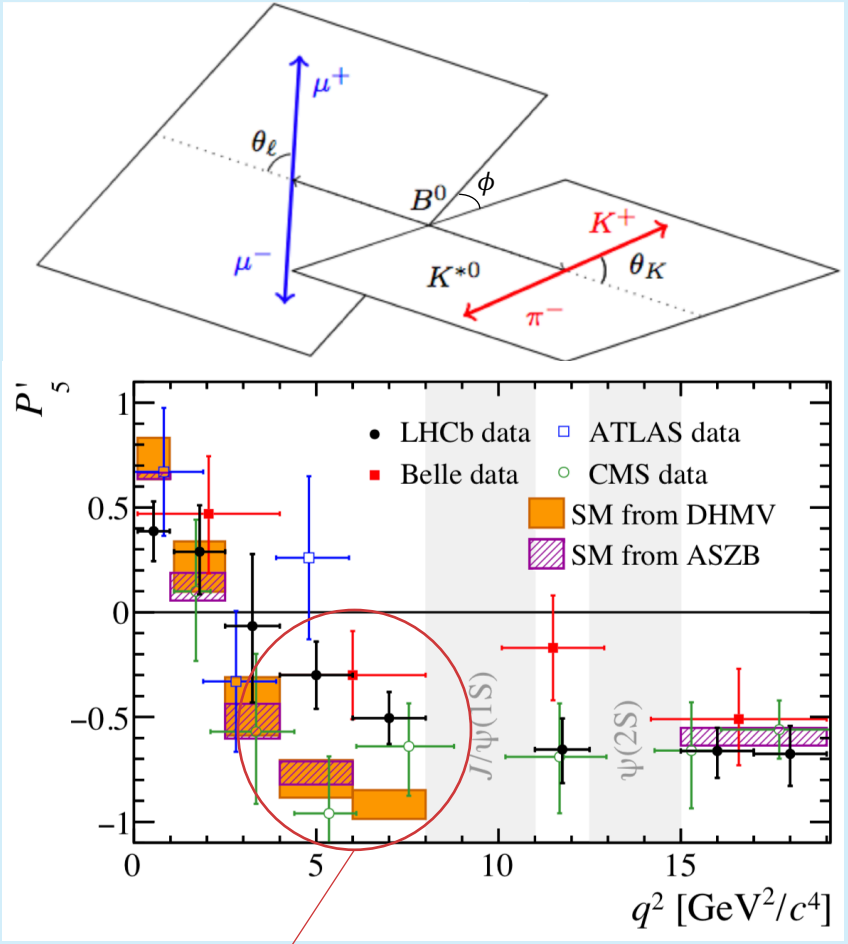
Angular analysis in $B^0 \to K^{*0}\mu^+\mu^-$

LHCb: [JHEP 02 (2016) 104]
Belle: [PRL 118 (2017) 111801]
Atlas: [JHEP 10 (2018) 047]
CMS: [PLB 781 (2018) 517541]

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

F_L, A_{FB}, S_i are combinations of angular amplitudes and depend on Wilson coefficients and on form factors.

Optimised observables where form factor uncertainties cancel, like $P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$



3.4σ difference with SM

Trigger categories

B^0 mass resolution and signal/background contributions depend on the way the event is triggered.

Data sample divided in three categories, by order of precedence:

- L0E: one of the electrons satisfies the hardware electron trigger.
- L0H: one of the hadrons satisfies the hardware hadron trigger.
- L0I: candidates triggered by non-signal particles.

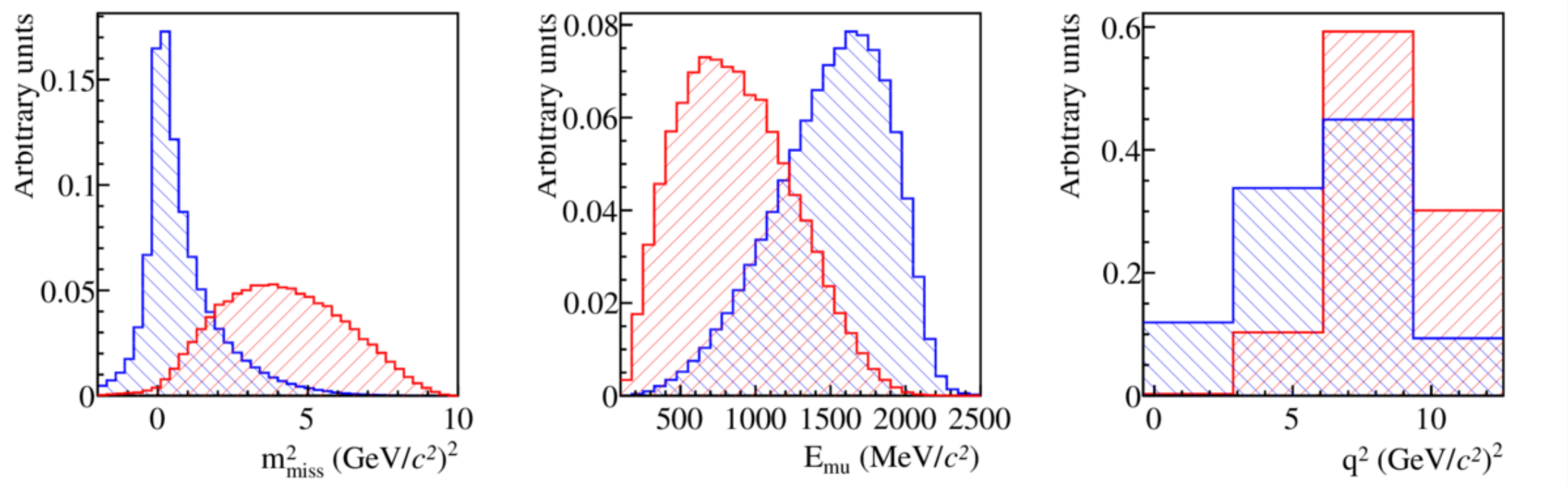
$B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

$R(D^*)$ muonic: signal discrimination

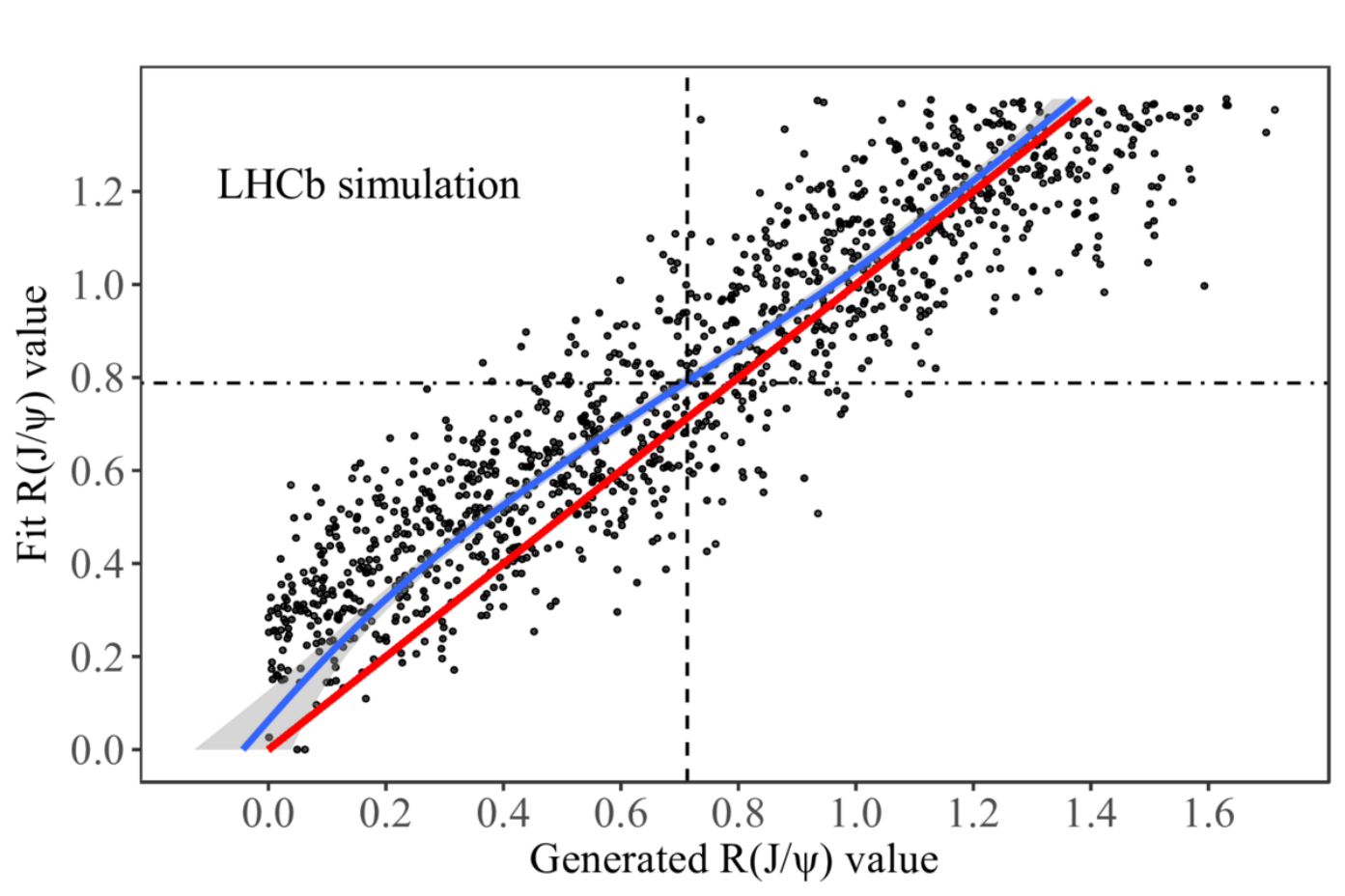
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$

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



$R(J/\psi)$ muonic: systematic uncertainties

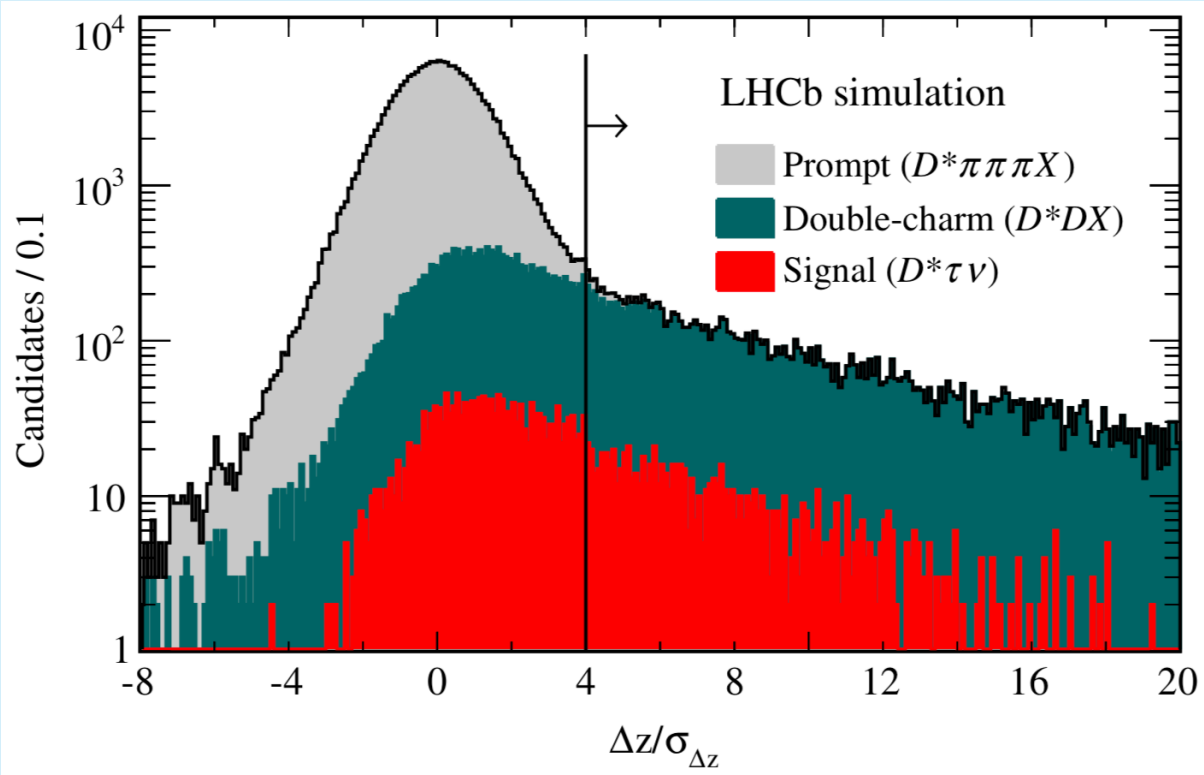
Fits to simulated data reveal a systematic bias, thus the raw $R(J/\psi)$ result needs to be corrected:

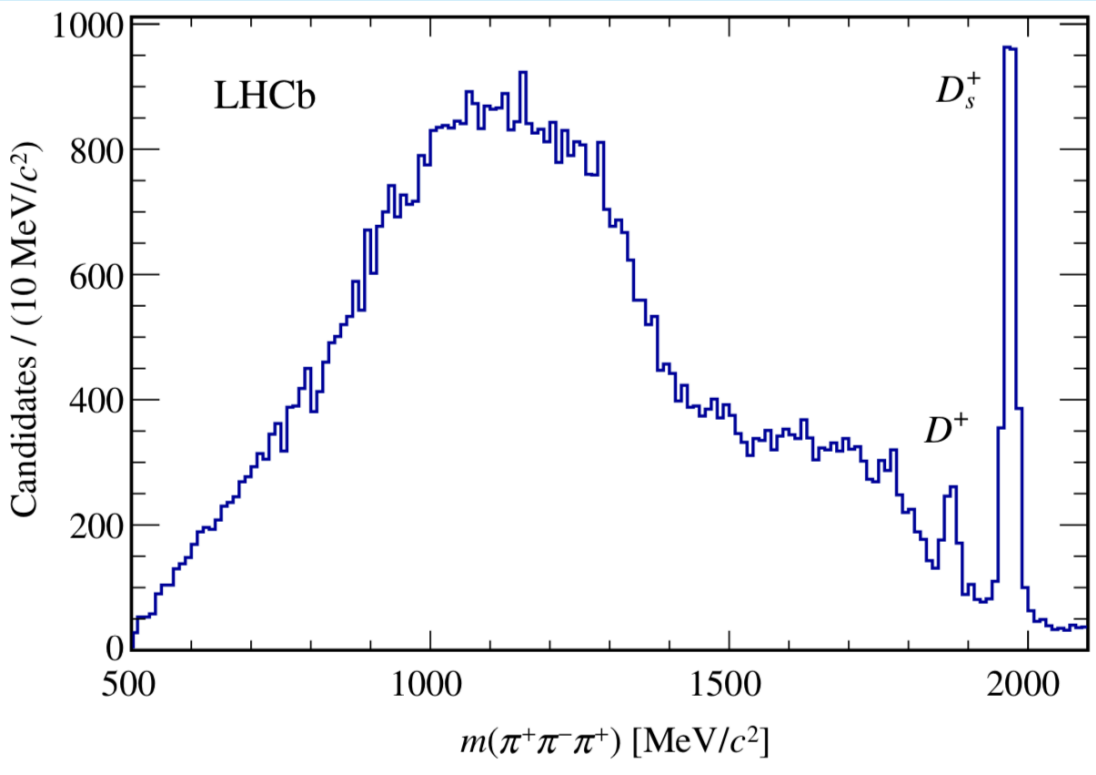


$R(J/\psi)$ muonic: systematic uncertainties

Source of uncertainty	Size ($\times 10^{-2}$)
Limited size of simulation samples	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau)$	0.2
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

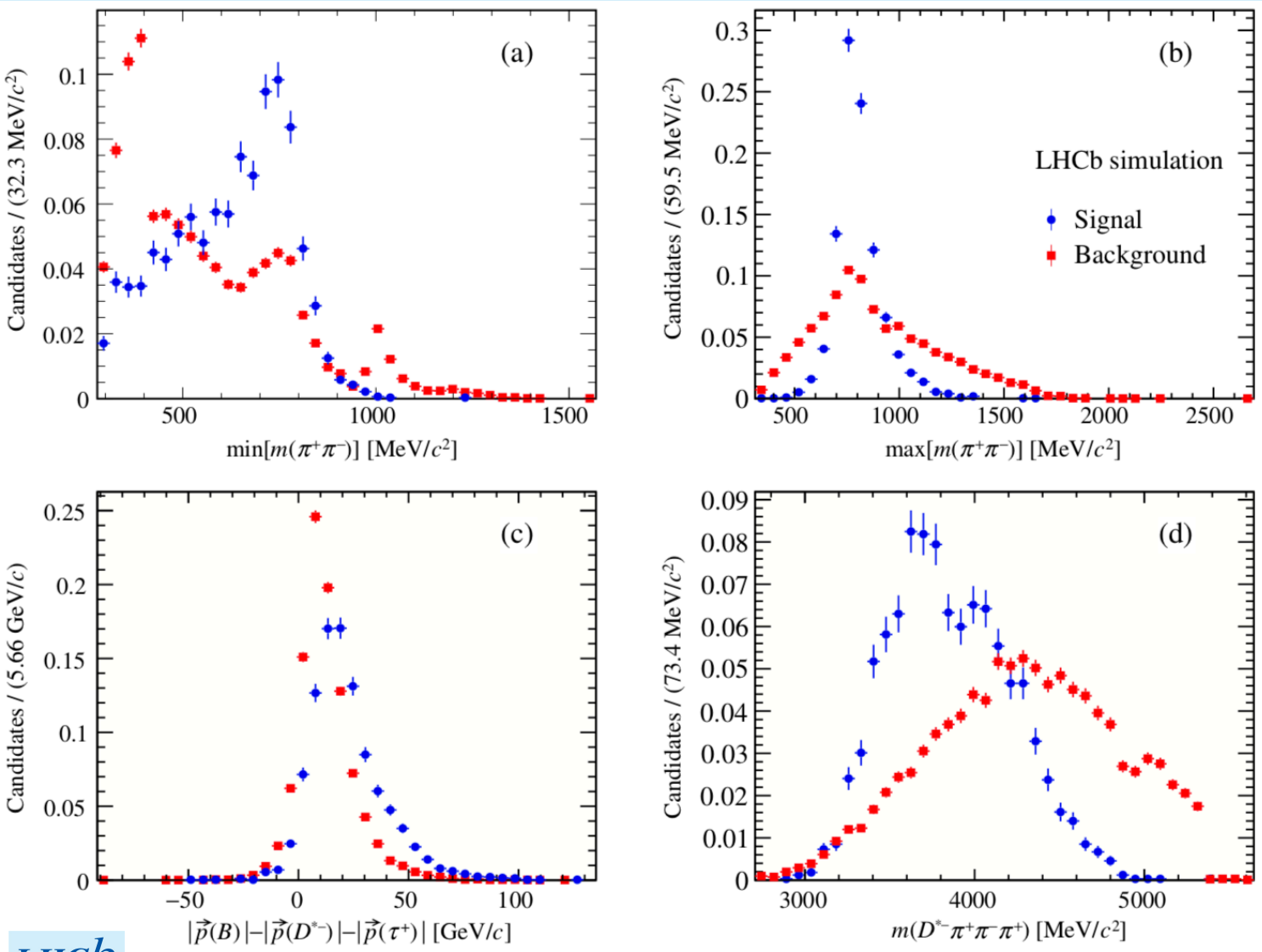
$R(D^*)$ hadronic: detached vertex cut

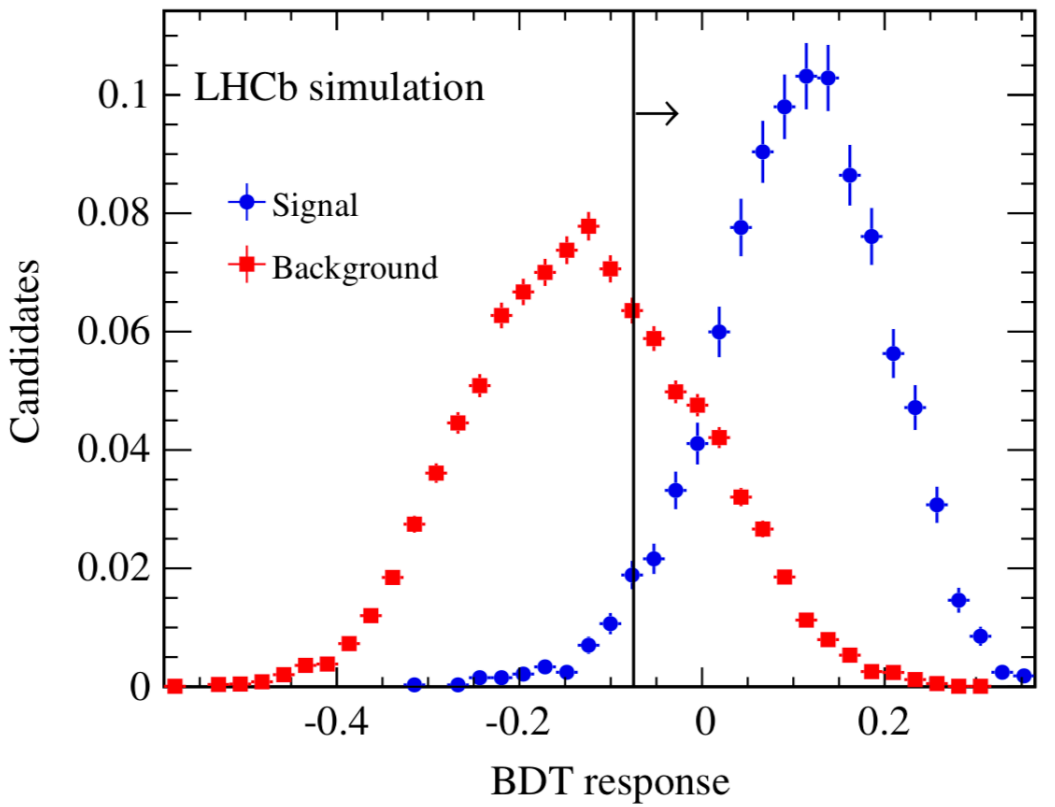




Prompt background reduced by three orders of magnitude
40% of signal retained

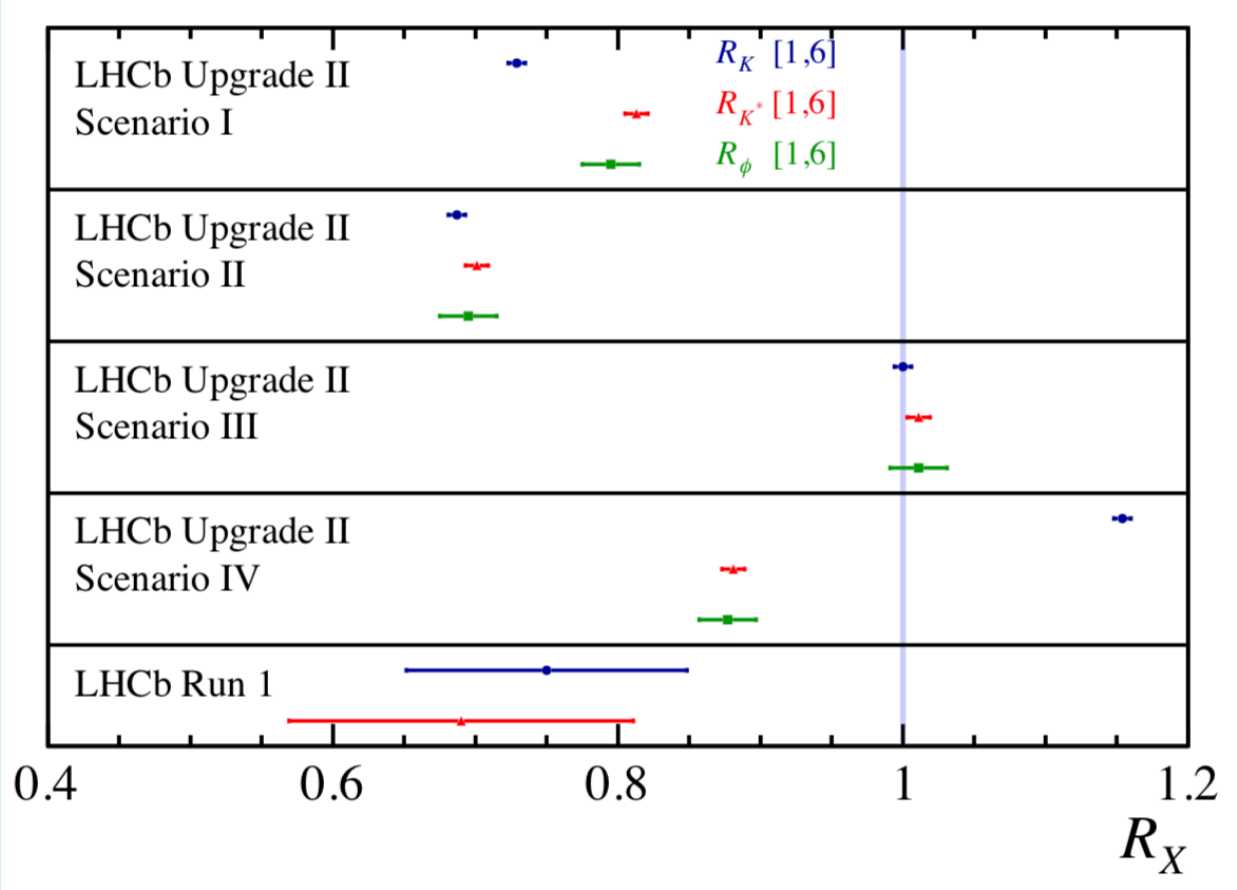
$R(D^*)$ hadronic: BDT





Upgrade II

With LHC Upgrade II, we will be able to discriminate between different NP scenarios:



scenario	$C_9^{\rm NP}$	$C_{10}^{\rm NP}$	C_9'	C_{10}'
I	−1.4	0	0	0
II	−0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	−0.3