Lepton Flavour Universality at LHCb

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on behalf of the LHCb collaboration

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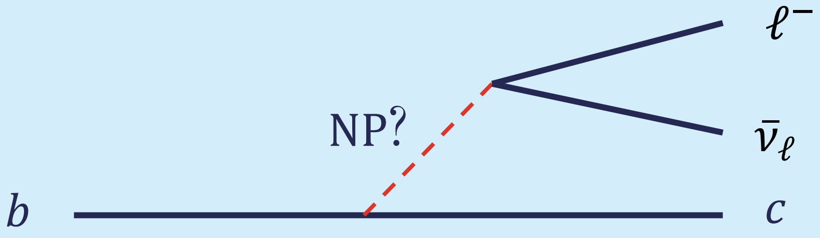
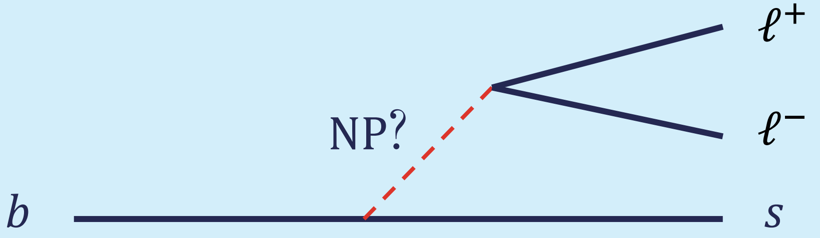
Lepton Flavour Universality

- 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 could imply the existence of new particles outside the SM ($H^\pm$, Z', $W'^\pm$, leptoquarks…).

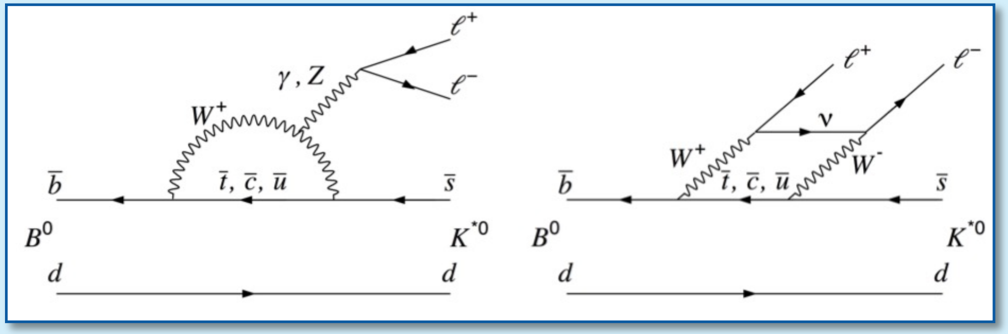


LFU tests at LHCb: neutral currents

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

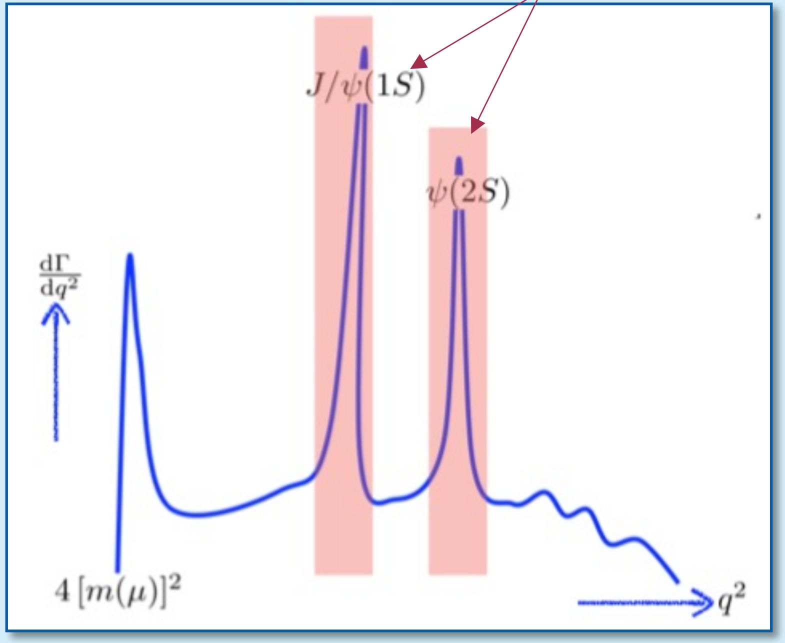
$$R(\mathcal{H}_s)[q^2_{min}, q^2_{max}] \equiv \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\Gamma(\mathcal{H}_b \to \mathcal{H}_s \mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\Gamma(\mathcal{H}_b \to \mathcal{H}_s e^+e^-)}{\mathrm{d}q^2}} \quad , \qquad \text{where} \qquad \begin{array}{c} q^2 = m^2_{\ell\ell} \\ \mathcal{H}_b = B^0, B^+, \ldots \\ \mathcal{H}_s = K, K^*, \ldots \end{array}$$

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

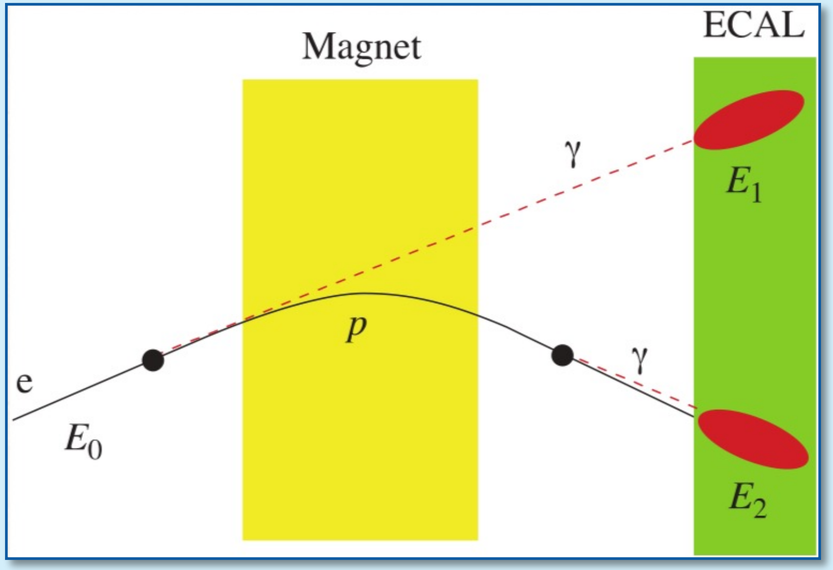


Different q^2 regions → Contributions from different processes.

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:

Nonresonant modes

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

Resonant modes

(Possible since $J/\psi \to \ell^+\ell^-$ is measured to be lepton universal within 0.4% [PDG])

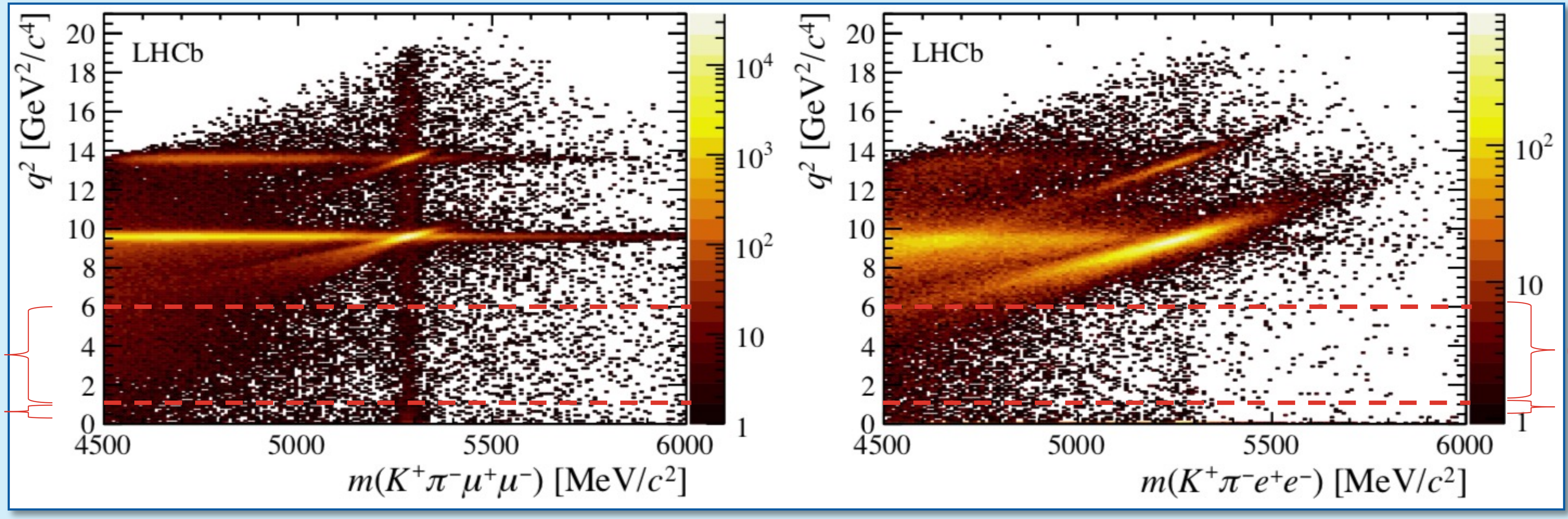
$R(K^{*0})$ measurement at LHCb

(Run1 data, 3 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: $0.045 < q^2 < 1.1 \text{ GeV}^2/c^4$
Central: $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

- e^+e^- data divided into three categories depending on how the event was triggered.
- Neural network classifiers to separate signal from combinatorial background.



$\psi(2S)$

J/ψ

Central bin

Lower bin

$\psi(2S)$

J/ψ

Central bin

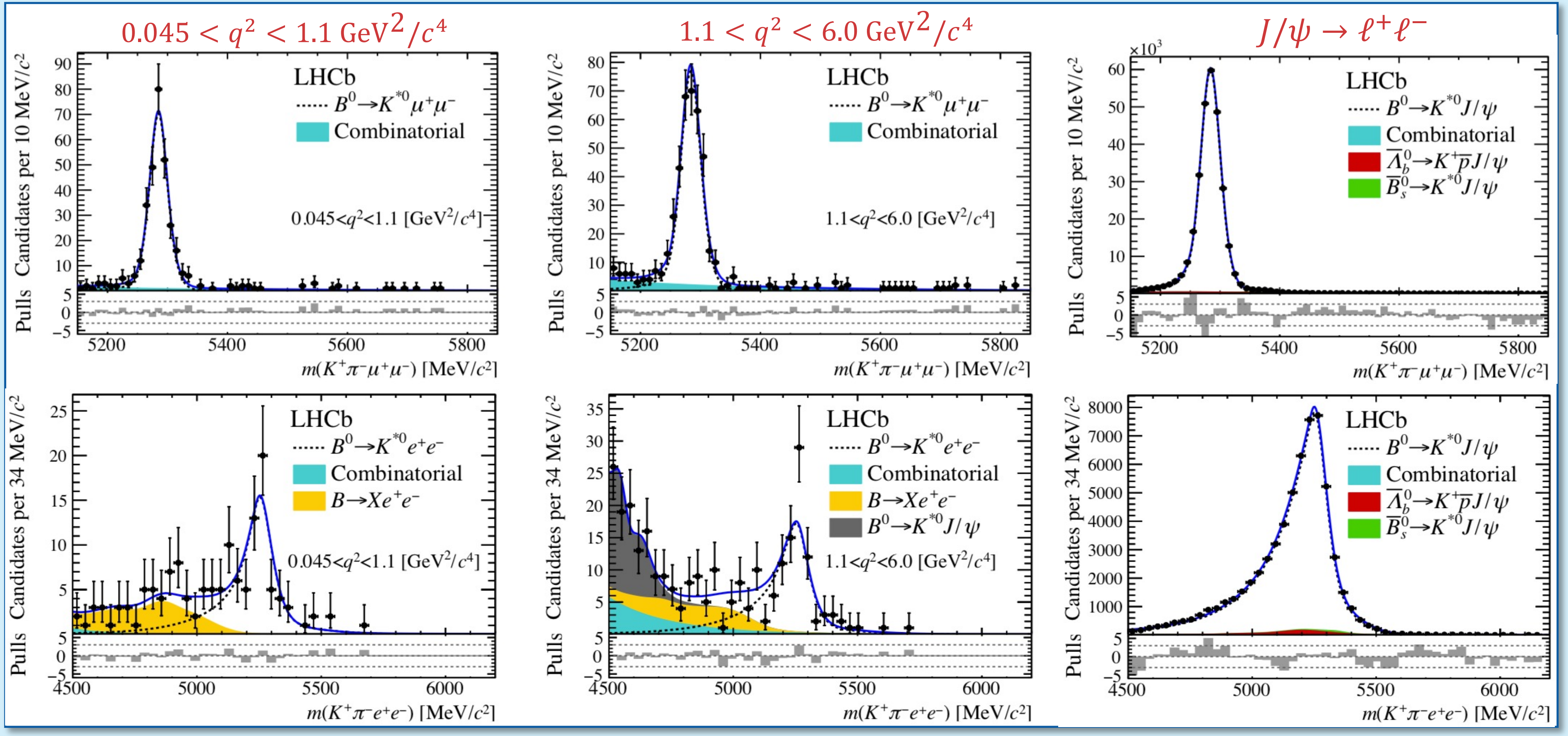
Lower bin

[JHEP 08 055 (2017)]

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

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.

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



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

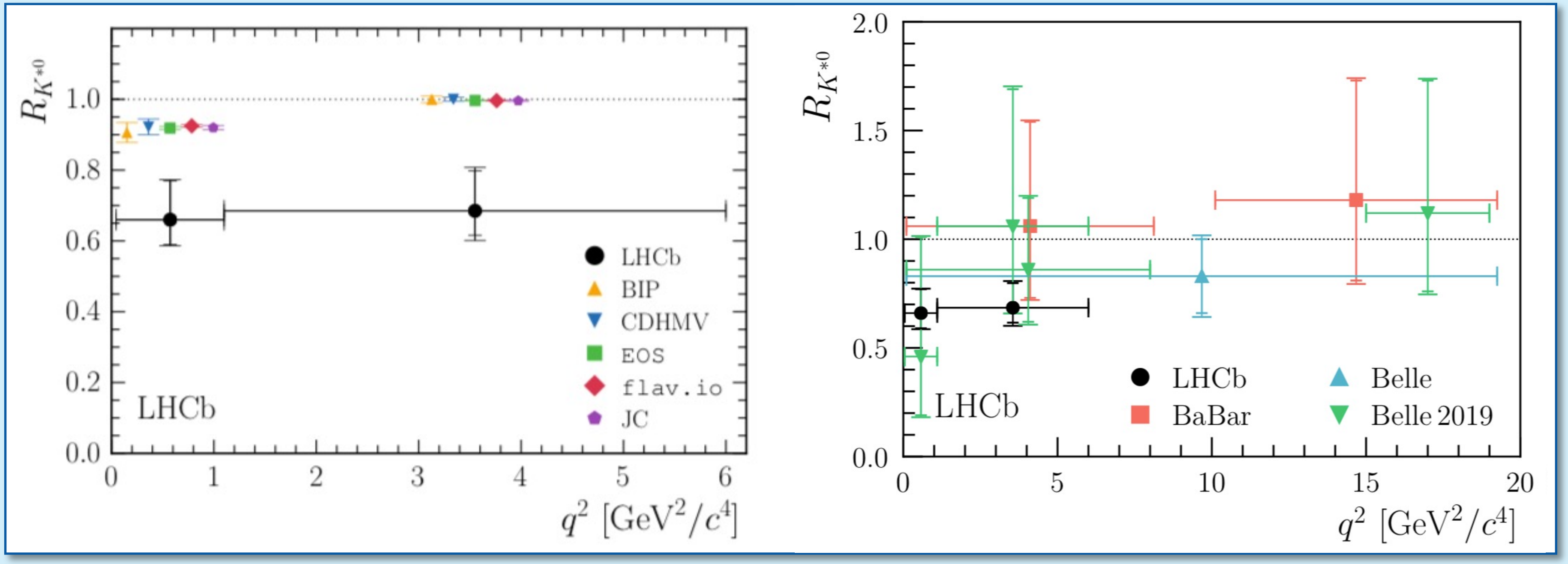
$m(K^+\pi^-e^+e^-)$

[JHEP 08 055 (2017)]

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

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

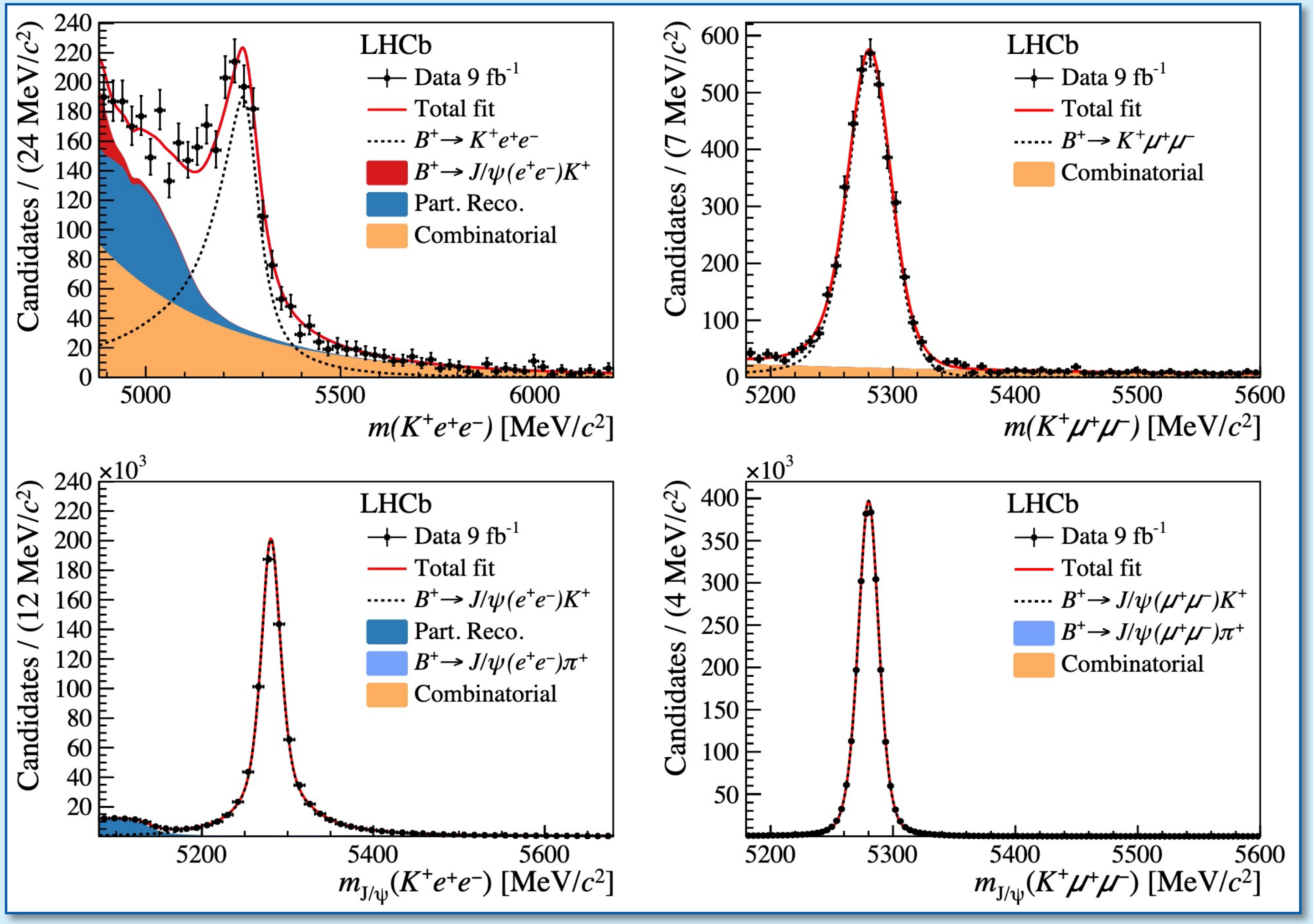
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$: $R(K^{*0}) = 0.69^{+0.11}_{-0.07} \pm 0.05$ ~2.4-2.5σ below SM predictions



BaBar: [PRD 86 (2012) 032012]
Belle: [PRL 103 (2009) 171801]
Belle: [PRL 126 (2021) 161801]

$R(K)$ measurement at LHCb

[arXiv:2103.11769v1]



(Run1+Run2 data, 9 fb^{-1})

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

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

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

[arXiv:2103.11769v1]

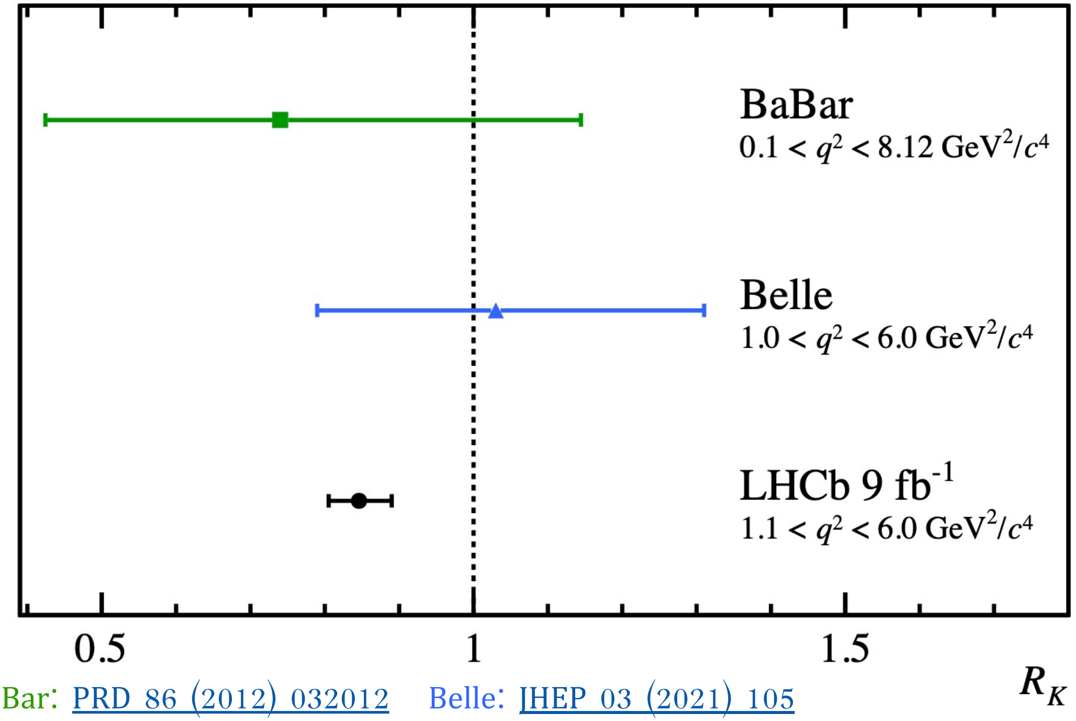
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$: $R(K) = 0.846^{+0.042}_{-0.039}{}^{+0.013}_{-0.012}$

~3.1σ below SM predictions

Most precise $R(K)$ measurement to date!

Previous LHCb measurements of $R(K)$:

- With Run1 + 2015+2016 data: PRL 122 (2019) 191801
- With Run1 data: PRL 113 (2014) 151601



BaBar: PRD 86 (2012) 032012 Belle: JHEP 03 (2021) 105

LFU tests at LHCb: charged currents

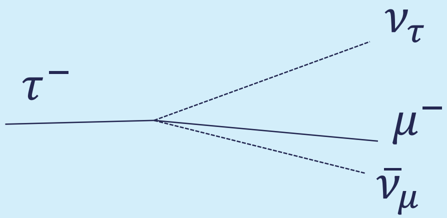
- $b \to c\ell^-\bar{\nu}_\ell$ decays:

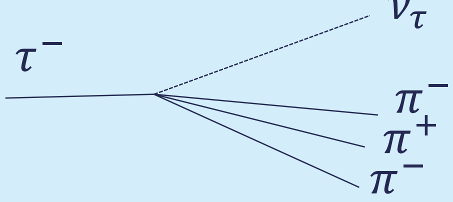
$$R(\mathcal{H}_c) \equiv \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu^- \bar{\nu}_\mu)},$$

where

$$\mathcal{H}_b = B^0, B^+, B_s^0, \Lambda_b^0 \ldots$$
$$\mathcal{H}_c = D^{(*)0}, D^{(*)+}, D_s^+, \Lambda_c^+, J/\psi \ldots$$

  - 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 $\mathcal{H}_b \to \mathcal{H}_c\mu^-\bar{\nu}_\mu\,(\mathrm{X})$ decays.
- Hadronic channel: $\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau) \approx 13.93\%$
  - 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)
- $m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
- $q^2 = (p_B - p_{D^*})^2$

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

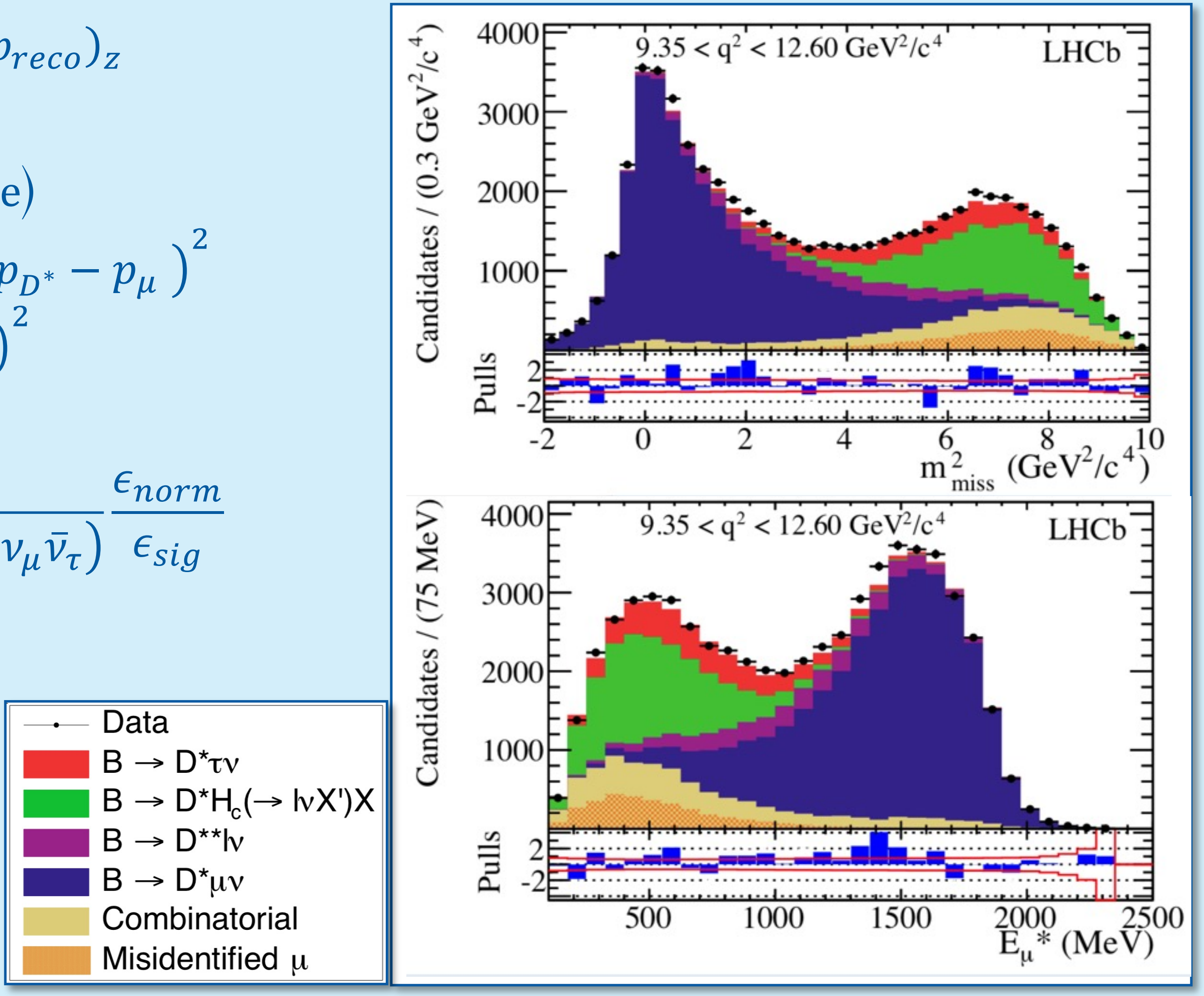
$$R(D^*)_{muonic} = 0.336 \pm 0.027 \pm 0.030$$

2.1σ above SM prediction

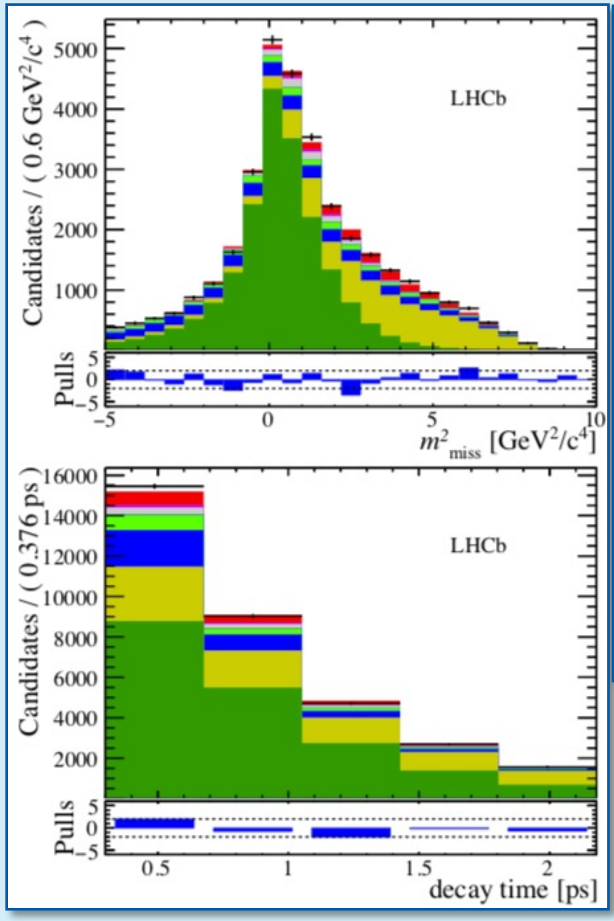
$R(D^*)_{SM} = 0.252 \pm 0.003$

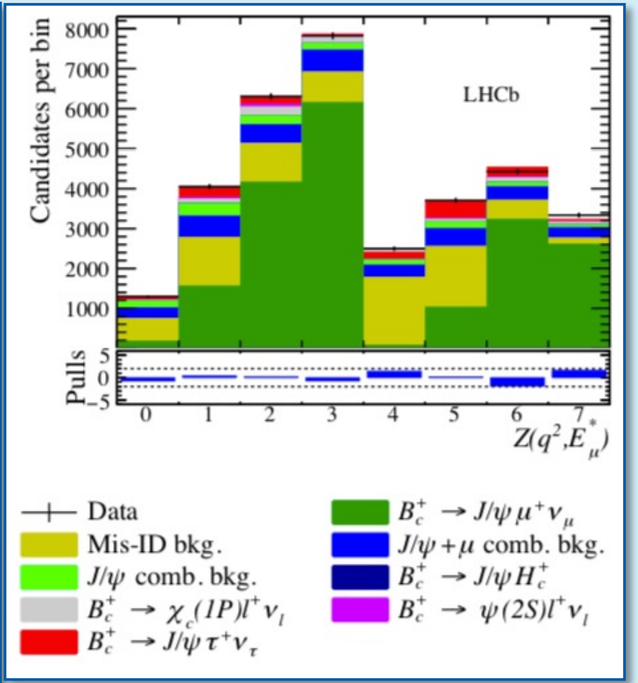
[PRD 85 094025 (2012)]

(Run1 data, 3 fb^{-1})



$R(J/\psi)$ muonic





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

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)
- B_c decay time

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

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

(Run1 data, 3 fb^{-1})

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

<2σ above SM prediction

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

[PLB 452 129 (1999)]
[arXiv:hep-ph/0211021]
[PRD 73 054024 (2006)]
[PRD 74 074008 (2006)]

$R(D^*)$ hadronic

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

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

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

(external inputs)

$\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau) = (13.93 \pm 0.07)\%$

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

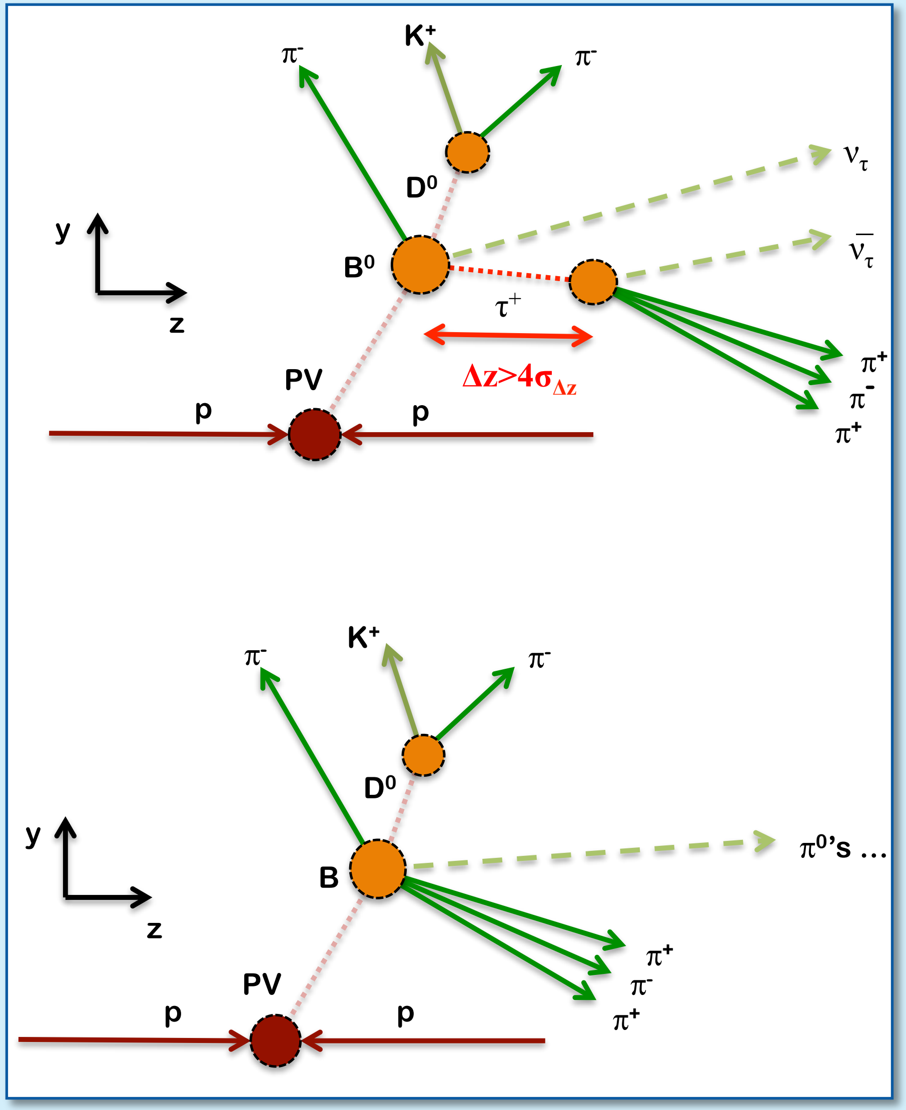
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10)\times 10^{-2}$

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:

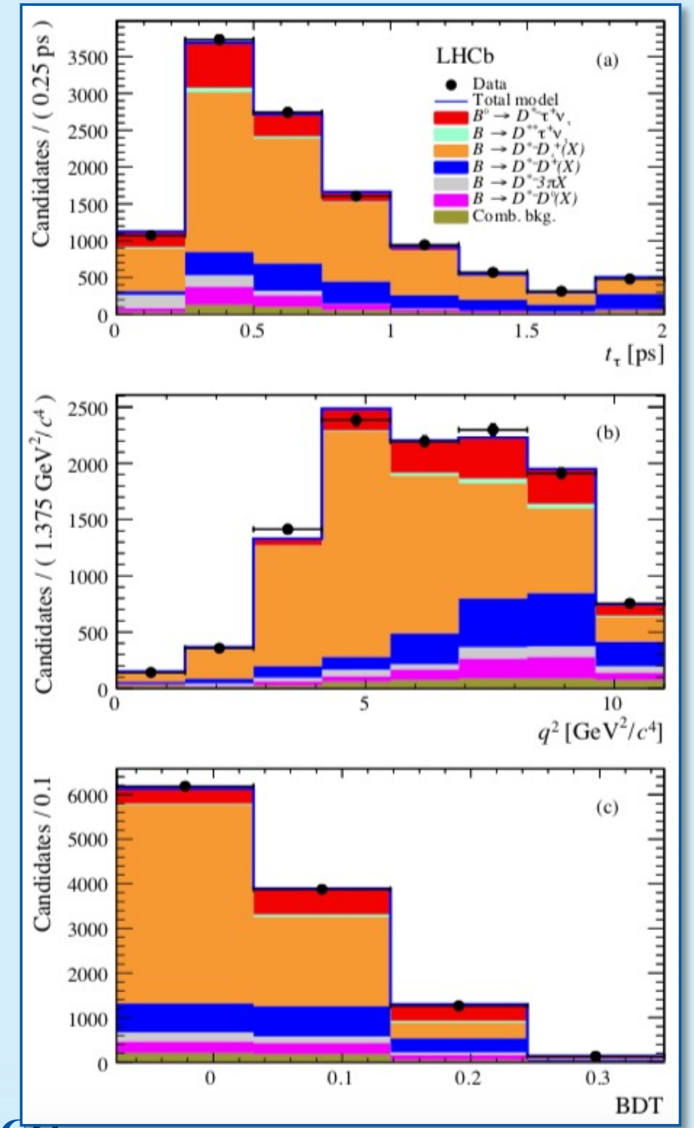
- Squared transferred momentum, q^2.
- τ decay time, t_τ.
- Output of a BDT, which takes as input 18 variables (kinematic variables of the decay chain and neutral isolation properties).

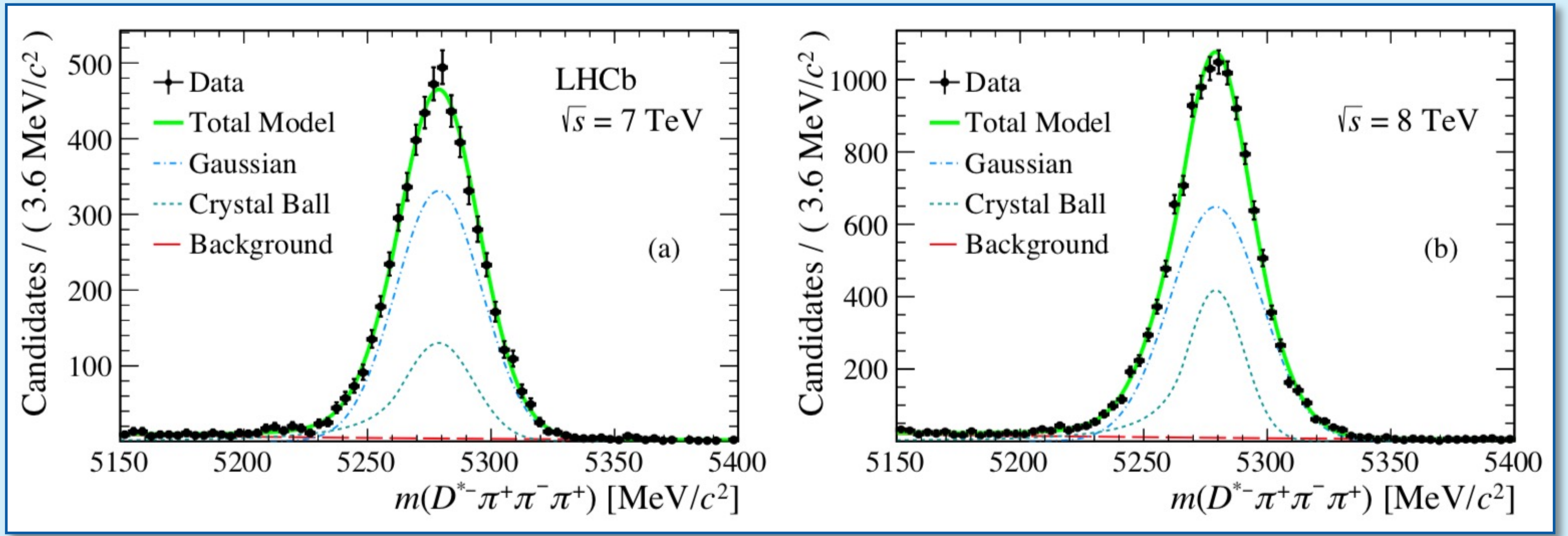
N_{norm} obtained by fitting the invariant mass distribution of the $D^{*-}3\pi$ system around the B^0 mass.



$R(D^*)$ hadronic

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





(Run1 data, 3 fb^{-1})

$$N_{norm} = 17808 \pm 143$$

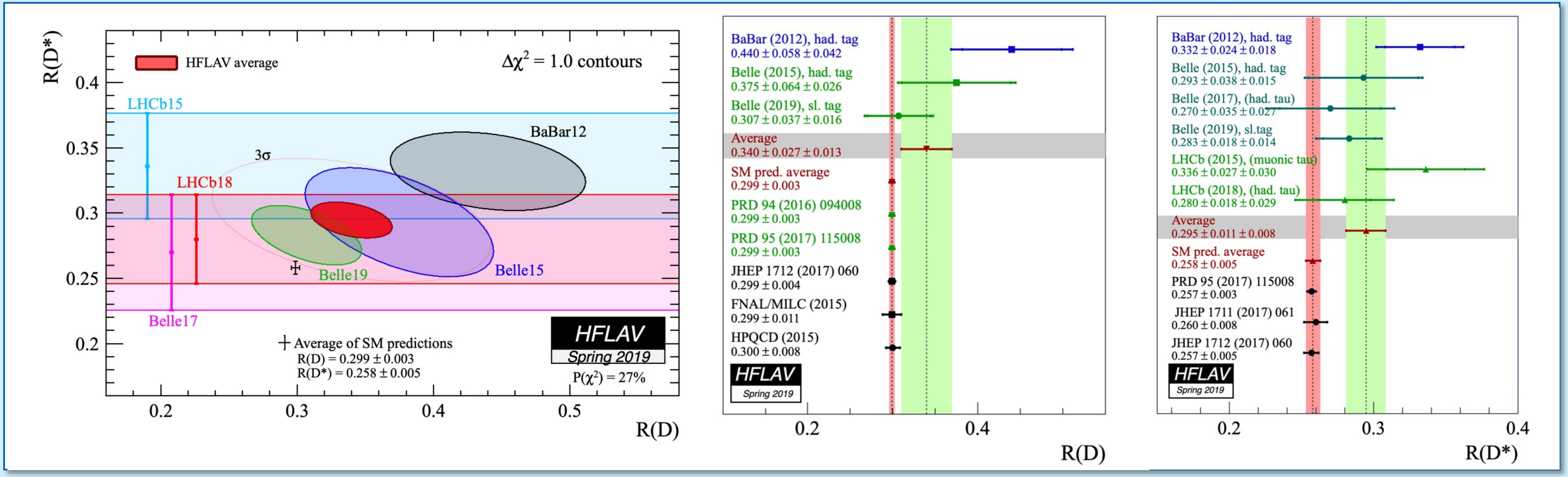
$$N_{sig} = 1296 \pm 86 \longrightarrow \mathcal{K}(D^{*-}) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$$

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

1.1σ higher than SM prediction
$R(D^*)_{SM} = 0.252 \pm 0.003$
[PRD 85 094025 (2012)]

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

Global status of $R(D^{(*)})$



Global averages are at 1.4σ from SM predictions in $R(D)$, 2.5σ in $R(D^*)$, and 3.08σ combined.

Future prospects

[arXiv:2101.08326v1]

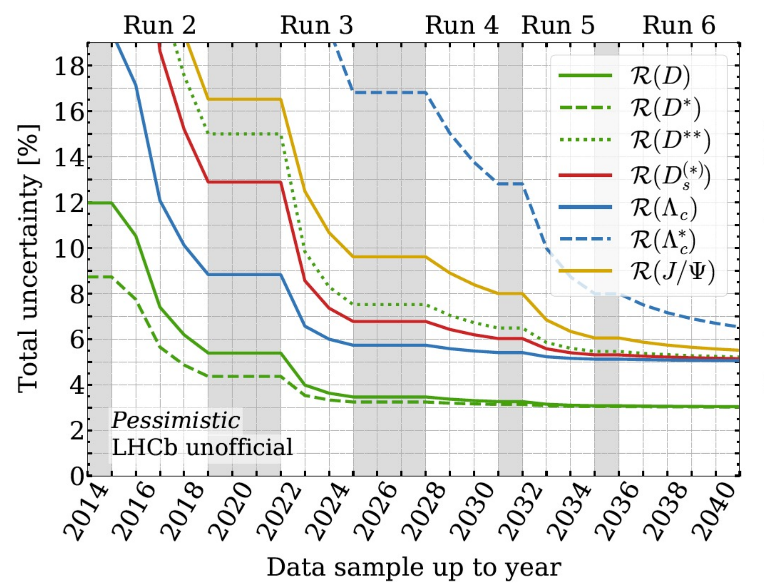
Run1+Run2: ~4 times as many $b\bar{b}$ pairs as in Run1.
→ Significant reduction in statistical uncertainties.

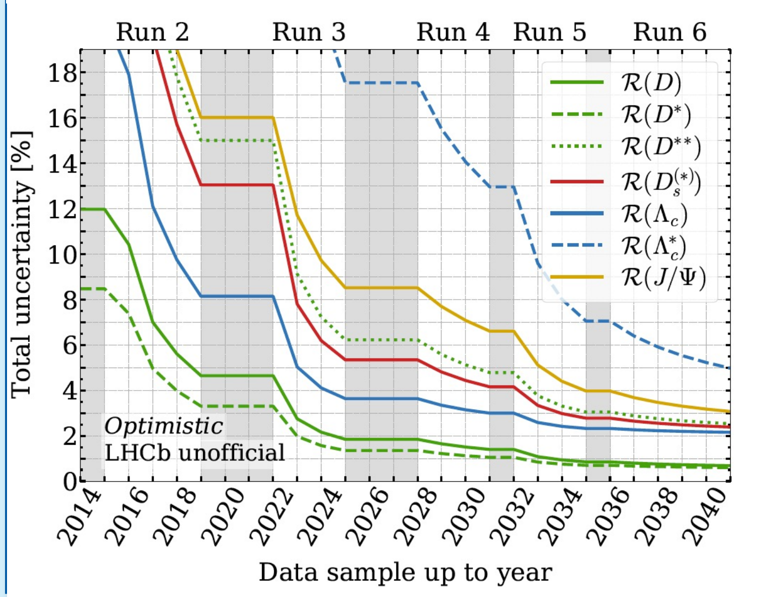
Systematic uncertainties will be reduced thanks to:

- Improvements in simulation techniques and hardware.
- Better knowledge of background channels.
- Improved external uncertainties thanks to new measurements.

Ongoing and future analyses:

- Updated results for $R(K^*)$, $R(D^*)$, $R(J/\psi)$...
- 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).
- Measurement of new ratios $R(\phi)$, $R(\Lambda_c)$, $R(D_s)$...





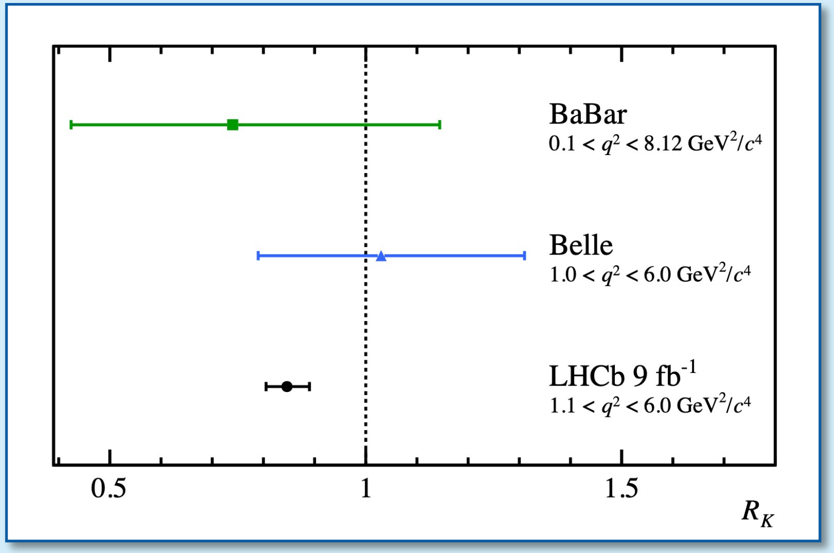
Conclusions

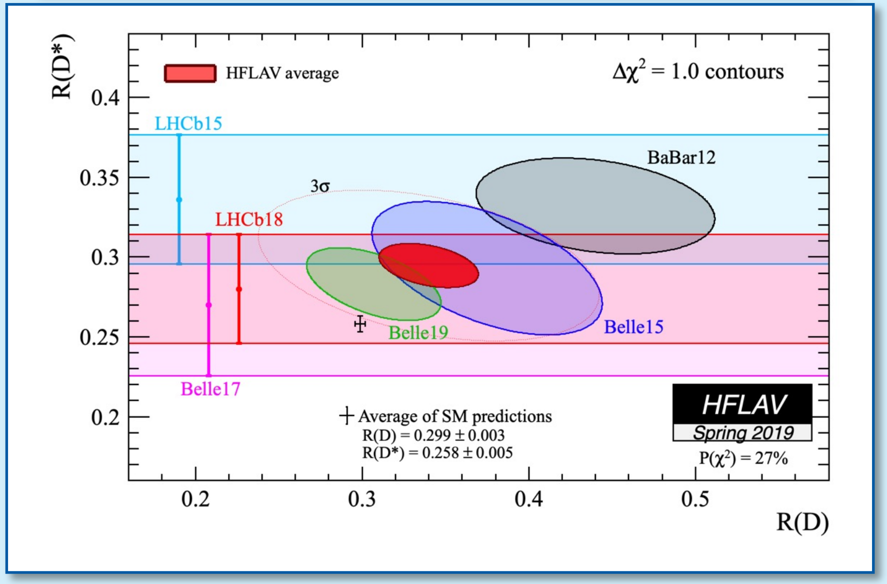
[arXiv:2103.11769v1]

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

- 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 is working on analyses that will provide significant improvements and new measurements.

Stay tuned!



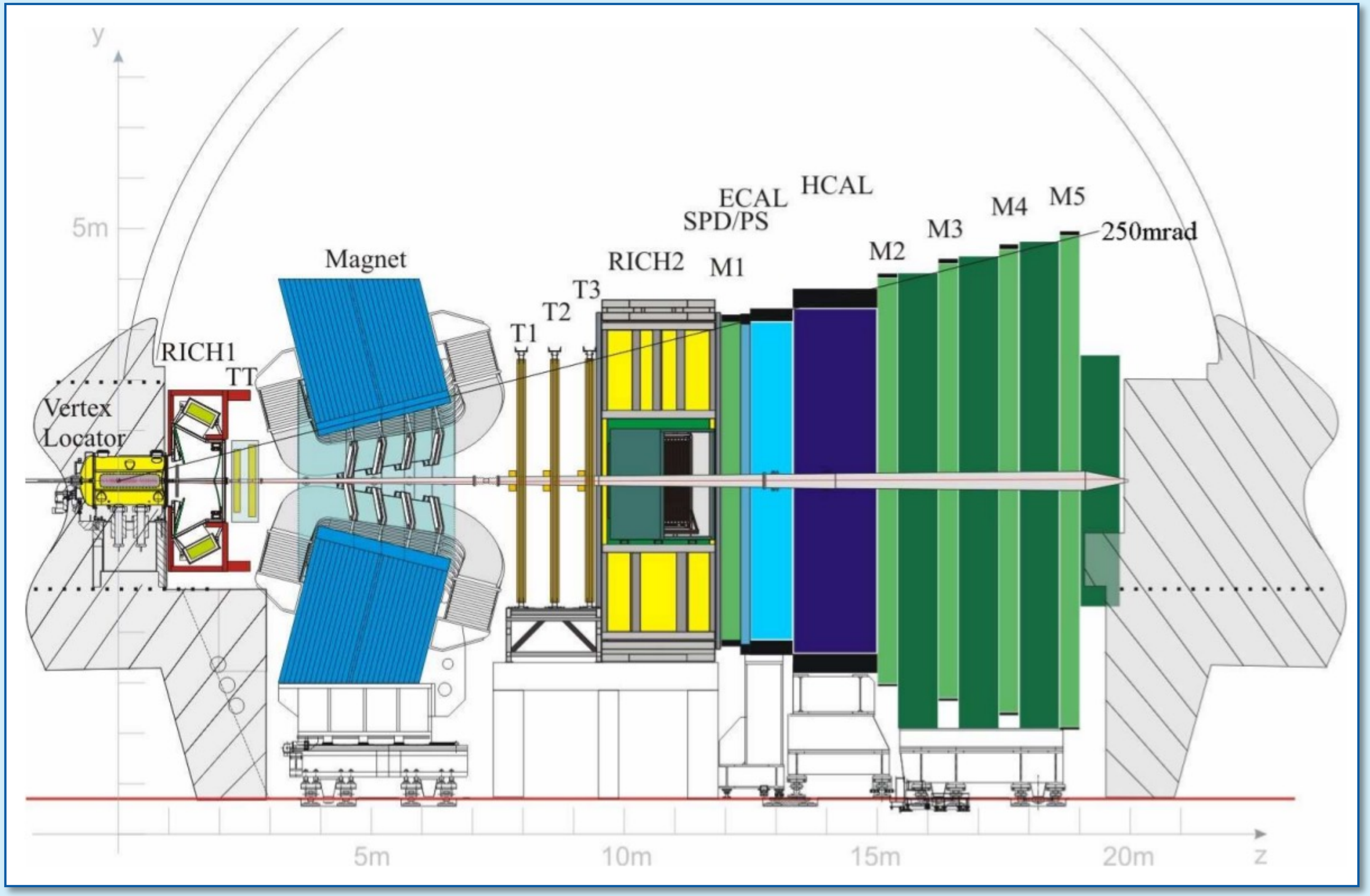


Thank you!

Backup Slides

The (old) LHCb detector

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



- High b-quark production:
  - Run1 (2011-2012, 7-8 TeV): $3\ \mathrm{fb}^{-1}$, $\sigma_{b\bar{b}X} \approx 72\ \mu\mathrm{b}$
  - Run2 (2015-2018, 13 TeV): $5.9\ \mathrm{fb}^{-1}$, $\sigma_{b\bar{b}X} \approx 144\ \mu\mathrm{b}$

- b-hadrons highly boosted, giving large values of the impact parameter.

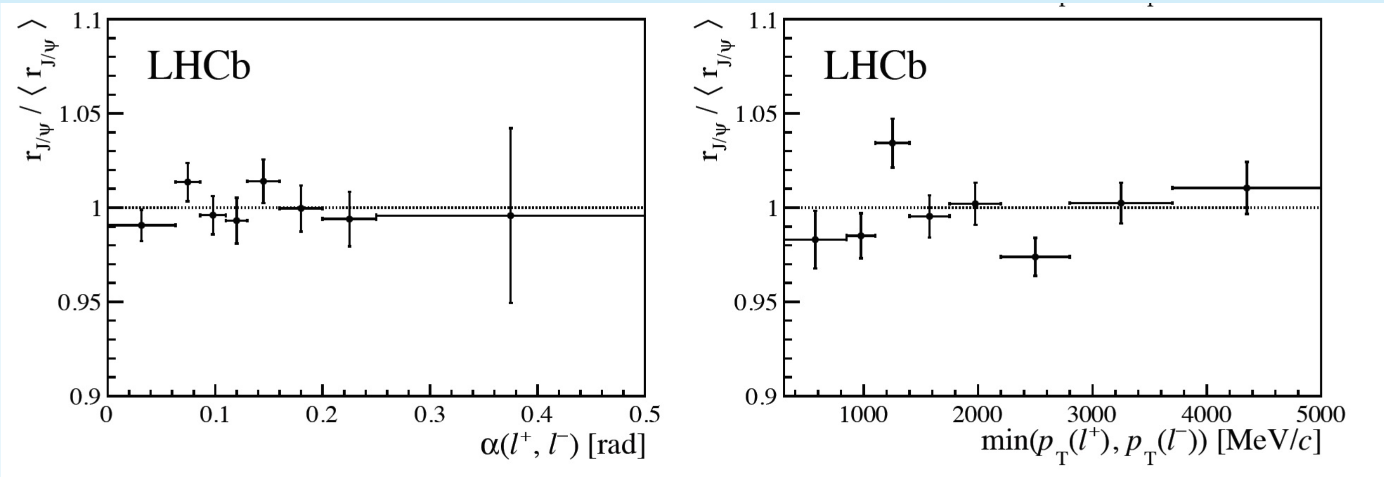
- Excellent vertex and impact parameter resolution ($\sim 25\ \mu$m).

- Excellent PID performance for charged particles (muon efficiency of $\sim 97\%$).

$R(K)$ cross-checks

[arXiv:2103.11769v1]

$$r_{J/\psi} = \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(J/\psi \to e^+e^-)} = 0.981 \pm 0.020$$



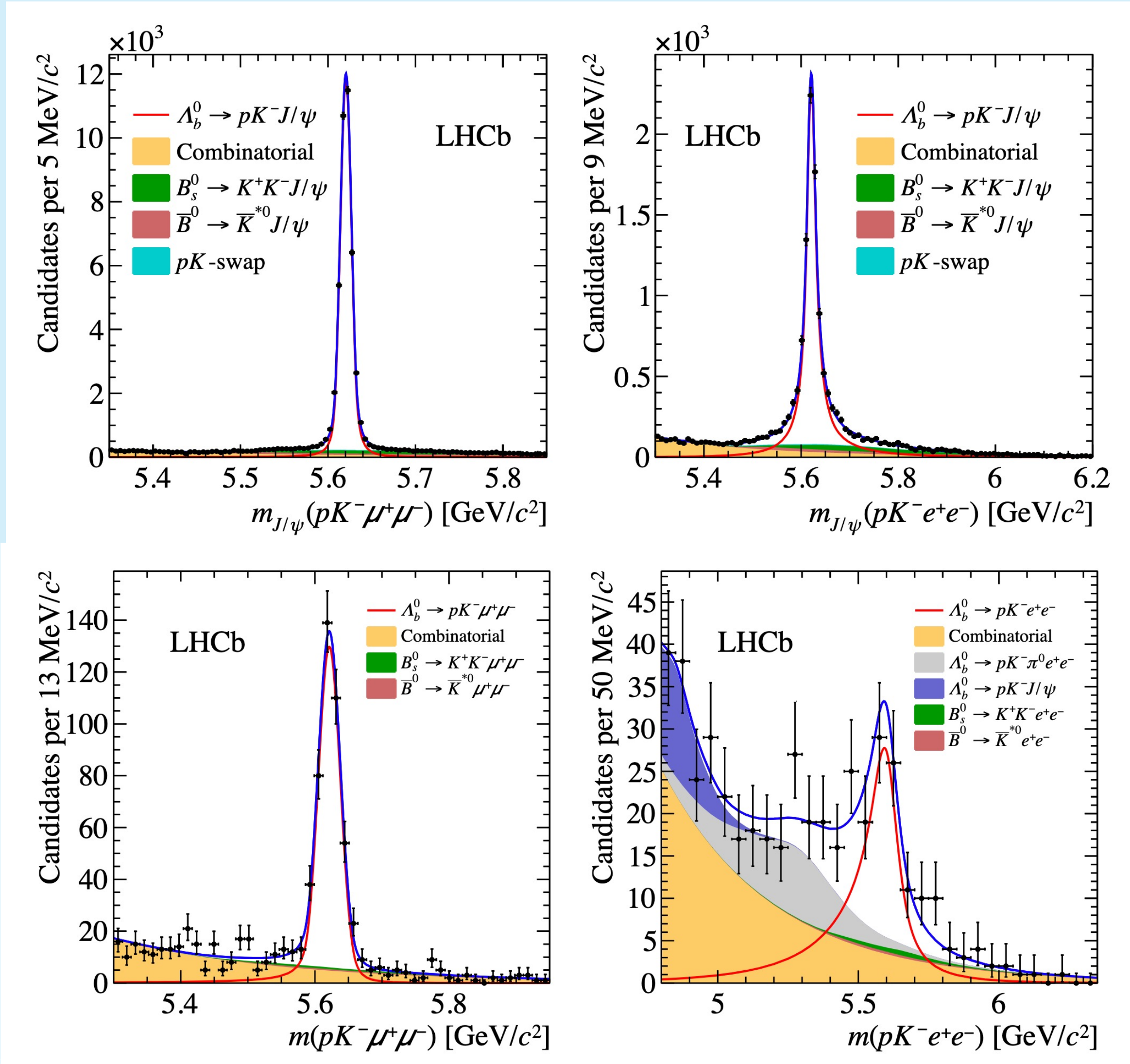
$r_{J/\psi}$ compatible with unity and does not depend on kinematic variables.

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))} = 0.997 \pm 0.011$$

$R_{\psi(2S)}$ compatible with unity as expected, validating the analysis procedure.

[JHEP 05 (2020) 040]

$R(pK)$ measurement at LHCb



(Run1+2016 data, 4.7 fb^{-1})

Nonresonant modes: $\Lambda_b^0 \to pK^+\ell^+\ell^-$
Resonant modes: $\Lambda_b^0 \to pK^+J/\psi(\to \ell^+\ell^-)$

q^2 range: $0.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$

Very similar strategy to the $R(K)$ analysis.

$0.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$: $R(pK) = 0.86^{+0.14}_{-0.11} \pm 0.05$

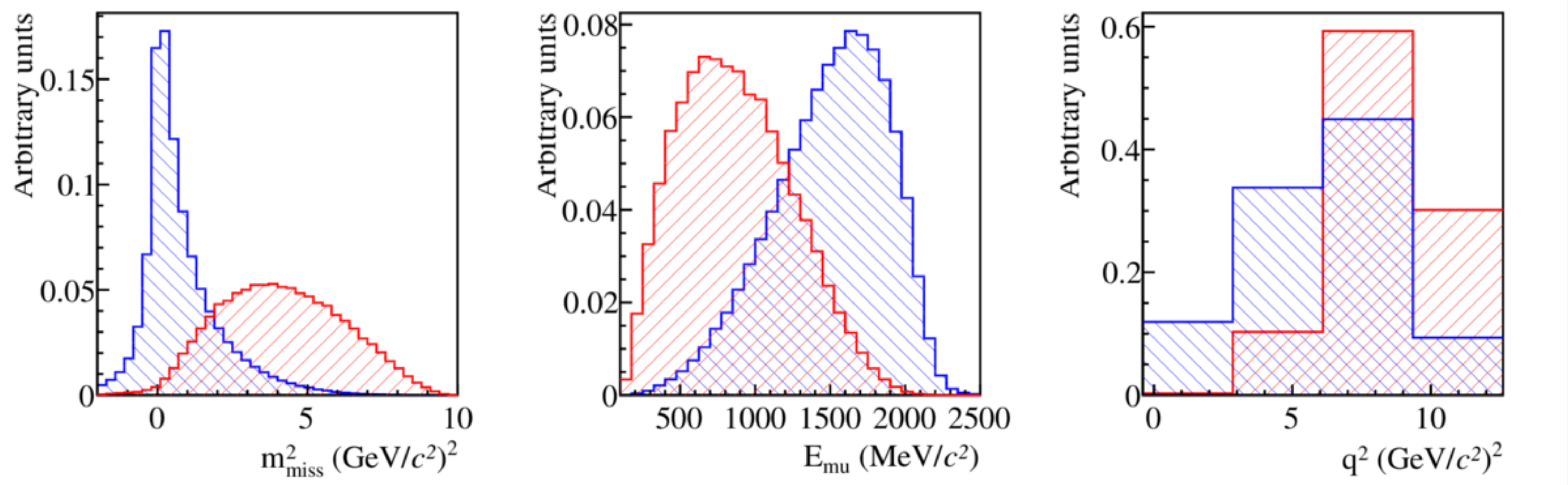
Compatible with SM prediction within 1σ

- First LFU test with b-baryons
- Different experimental uncertainties due to spin effects and different kind of backgrounds.

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

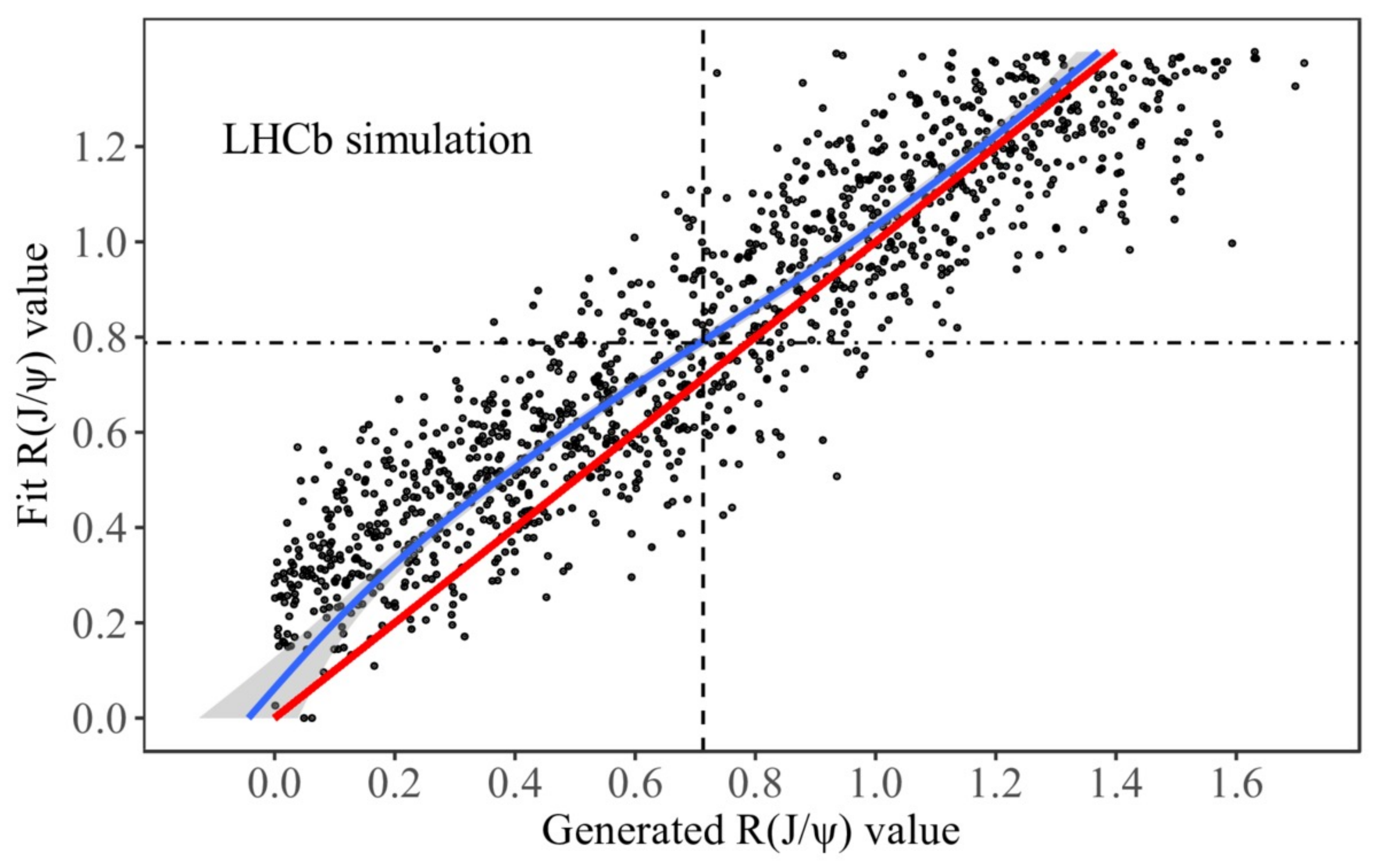
🟦 $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$

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

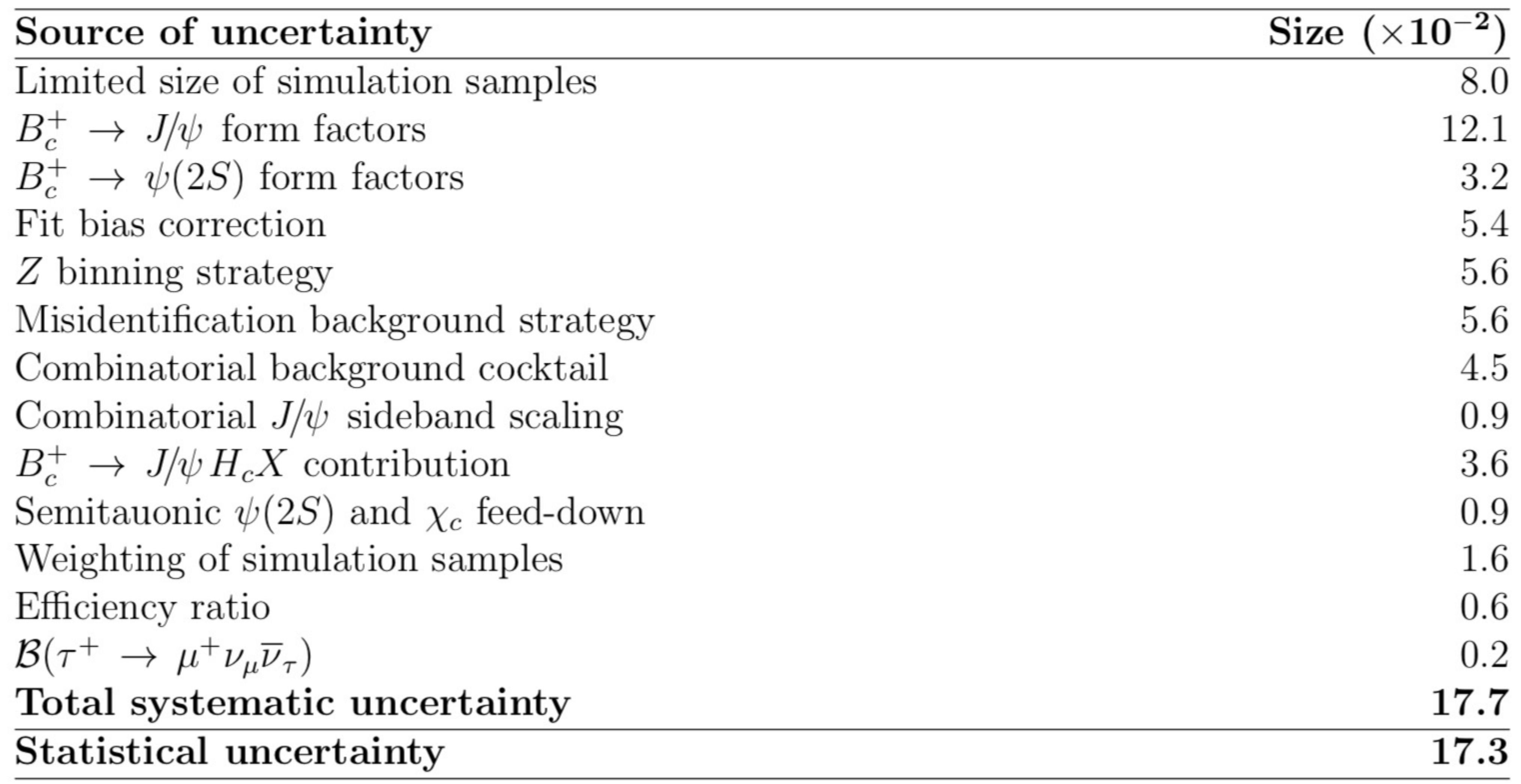


$R(J/\psi)$ muonic: systematic uncertainties

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

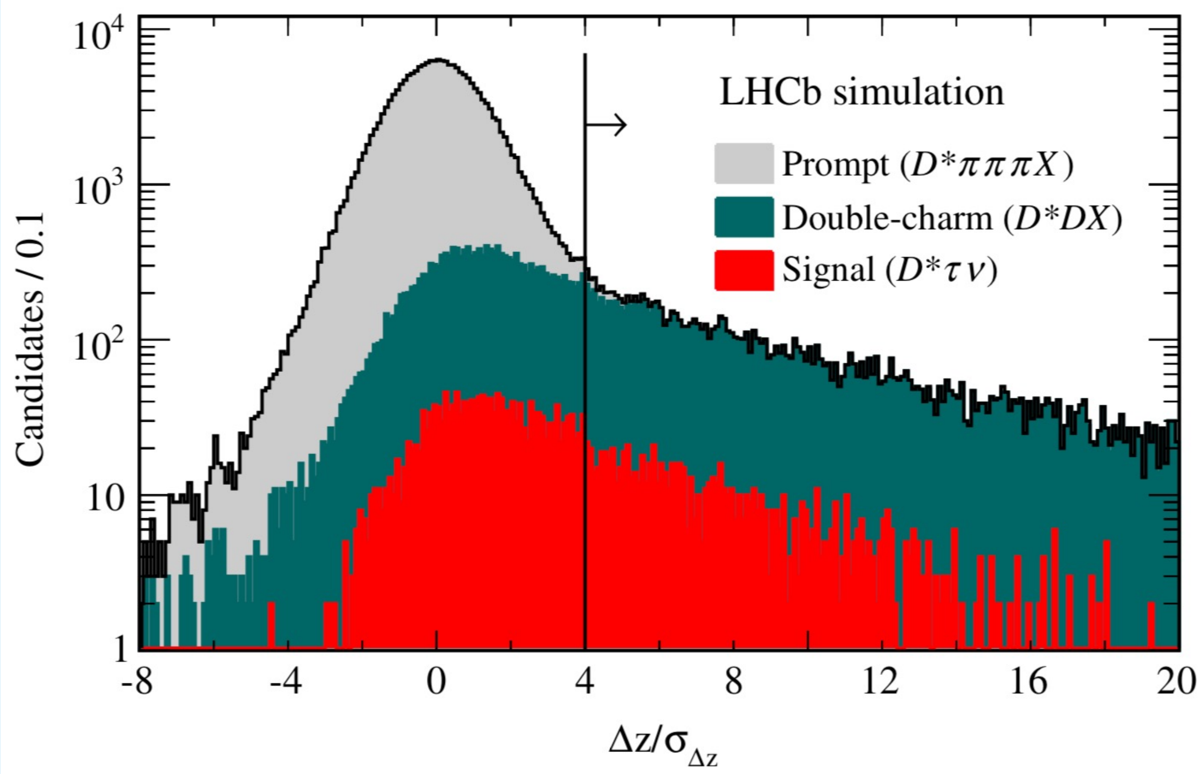


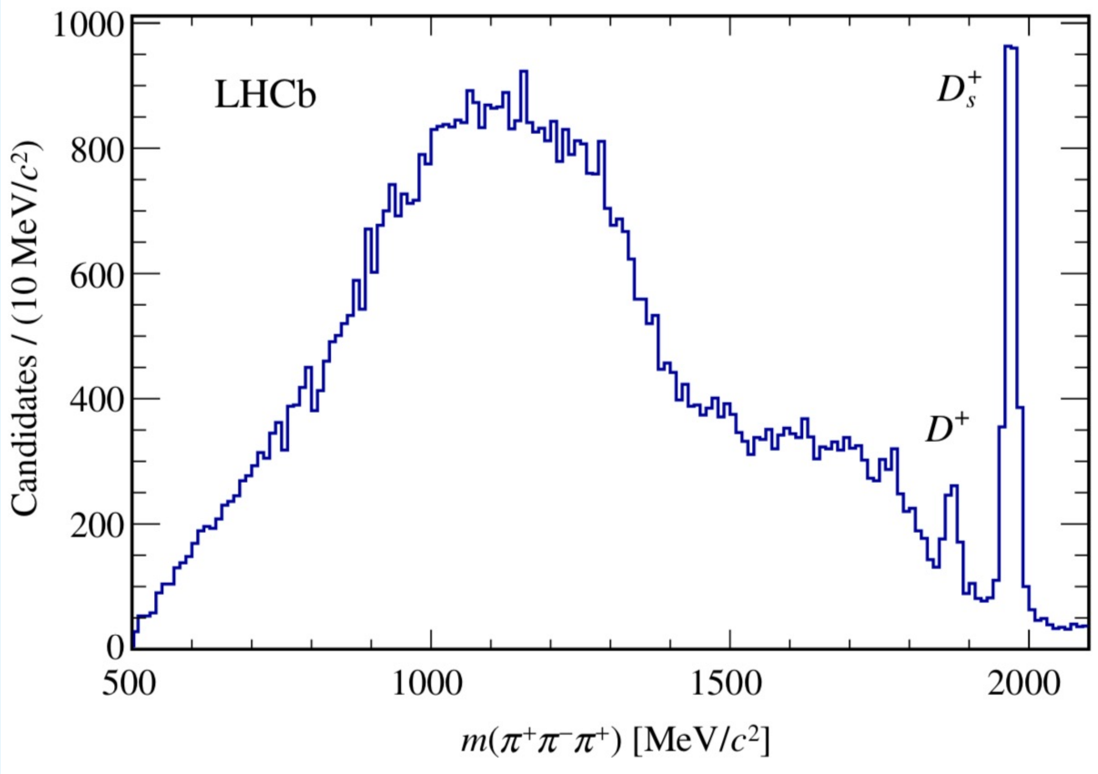
$R(J/\psi)$ muonic: systematic uncertainties



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**

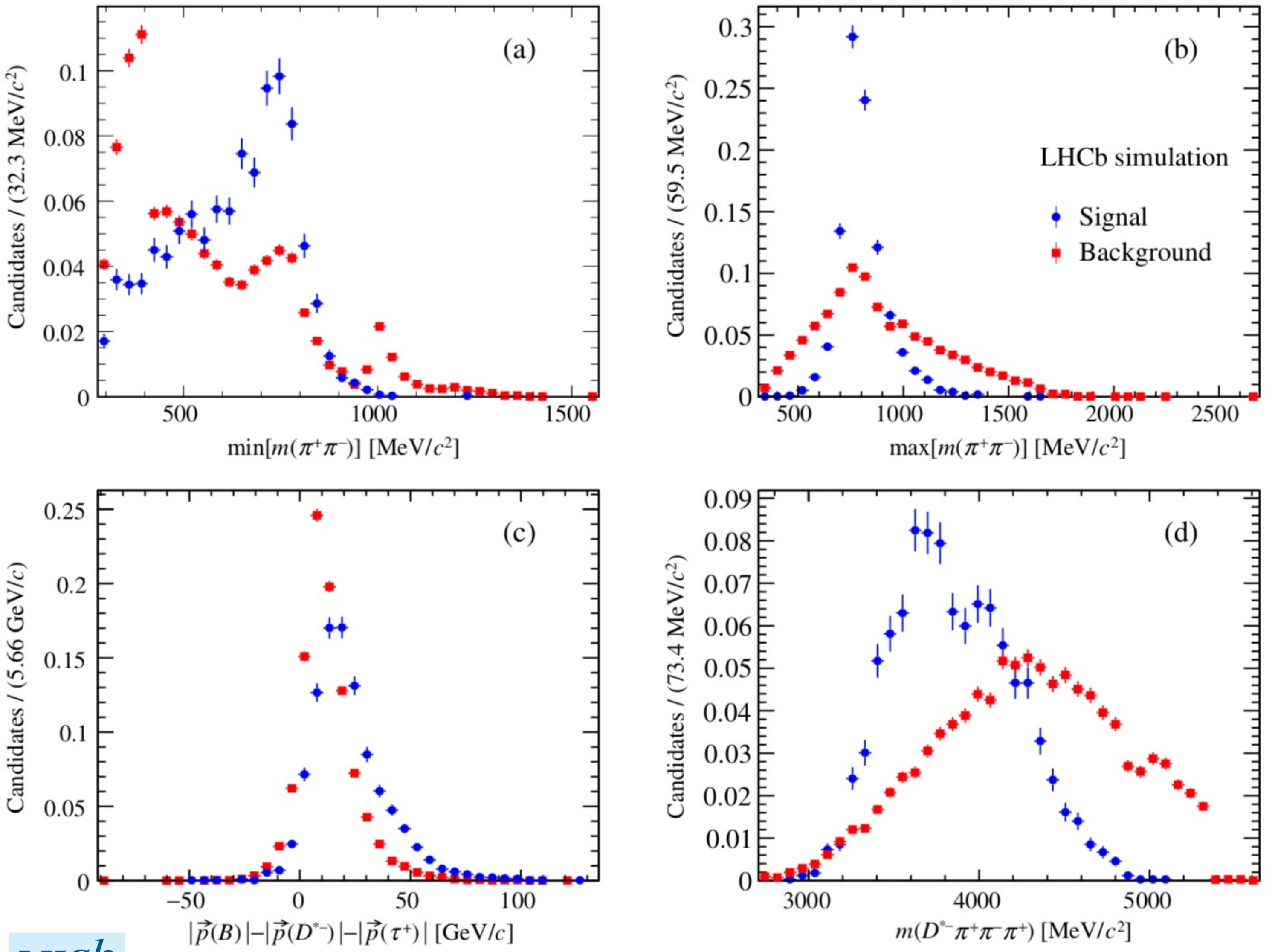
$R(D^*)$ hadronic: detached vertex cut

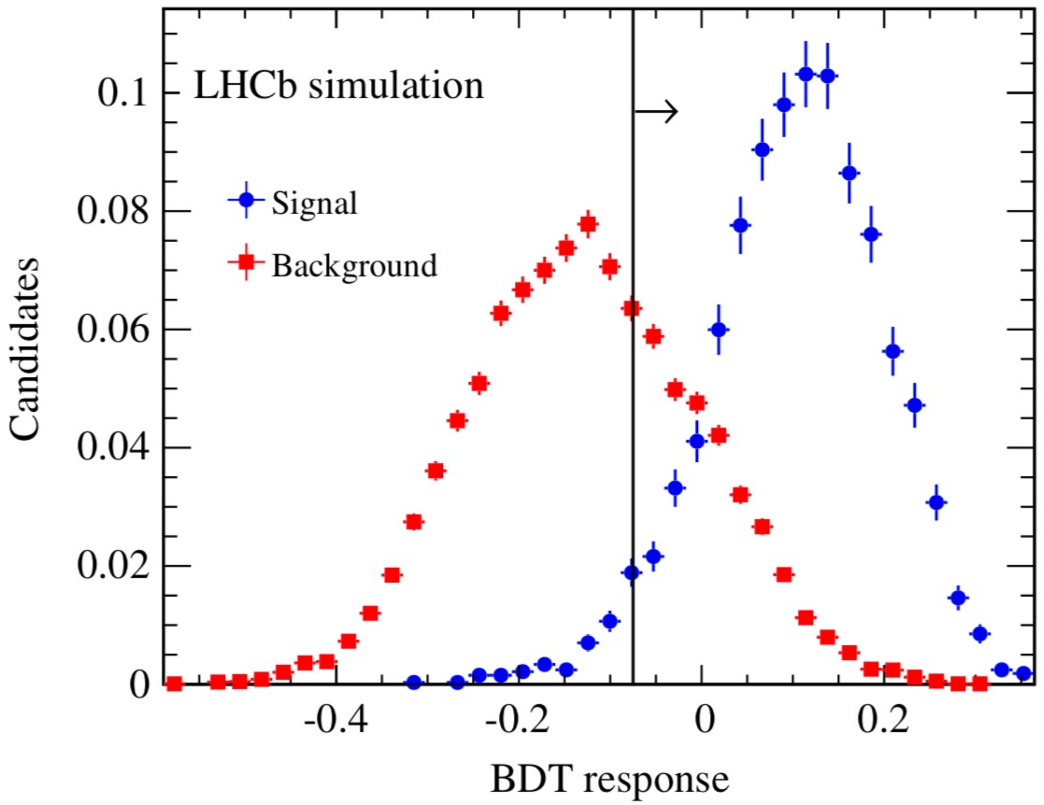




Prompt background reduced by three orders of magnitude
40% of signal retained

$R(D^*)$ hadronic: BDT

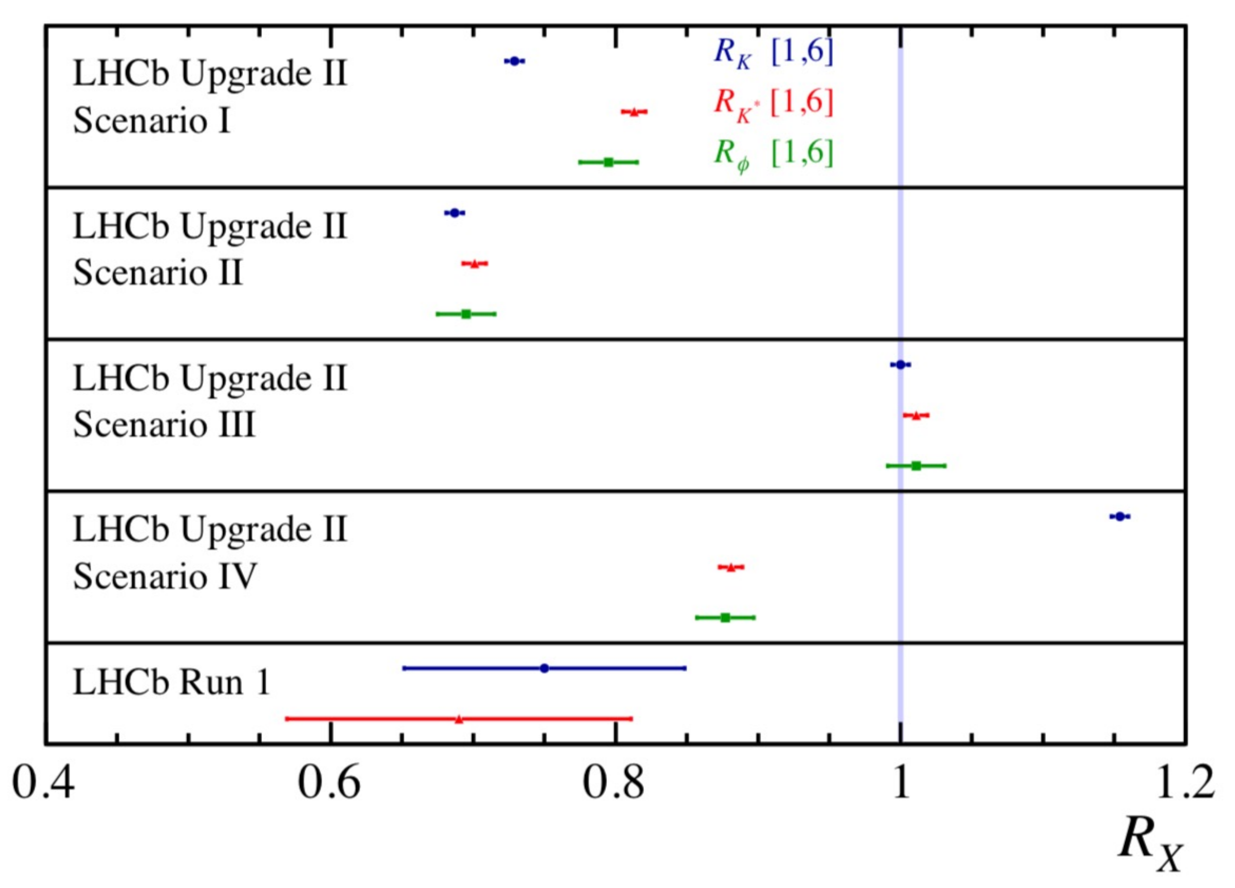


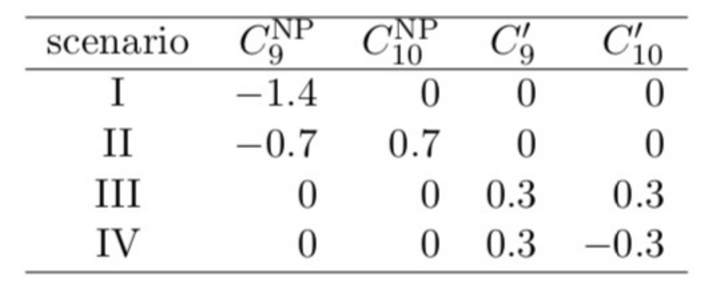


arXiv:1808.08865 [hep-ex]

Upgrade II

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





scenario	C_9^{NP}	C_{10}^{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