Tests of Lepton Flavour Universality and related anomalies at LHCb

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LHCb
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UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
IGFAE
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Today's outline

Introduction

- Lepton Flavour Universality
- The LHCb experiment

Semileptonic decays

- Muonic R(D*)
- Hadronic R(D*)
- R(J/ψ)

Rare *b→sll* decays

- R(K*)
- R(K)

Conclusions

- Conclusions
- Prospects

For very rare decays see Joao Coelho talk (Friday, 10:00h)

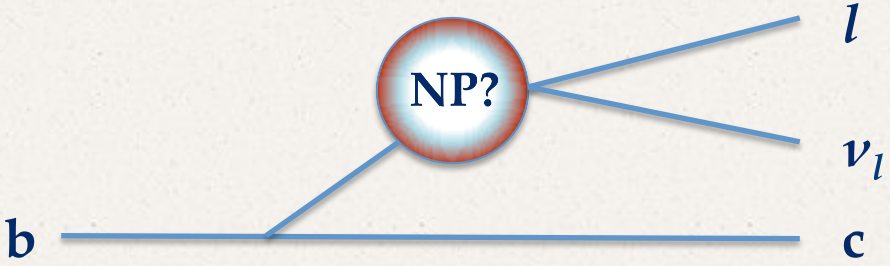
Introduction

Lepton Flavour Universality

- SM predicts **Lepton Flavour Universality** (LFU): equal couplings between gauge bosons and the three lepton families

- Observation of violation of LFU would be sign of **new physics**

- A large class of BSM models contain new interactions that involve third generations of quarks and leptons:
  - Charged Higgs
  - Leptoquarks
  - Z'
  - W'
  - ...



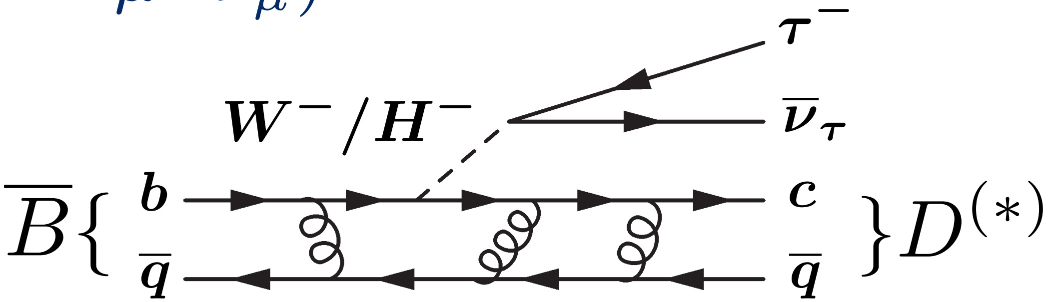
- Tensions between SM expectacion and experimental results:
  - **Charged currents:** $b \rightarrow cl\nu$
  - **Neutral currents:** $b \rightarrow sll$

Searches for LFUV

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

[$b \to cl\nu$]

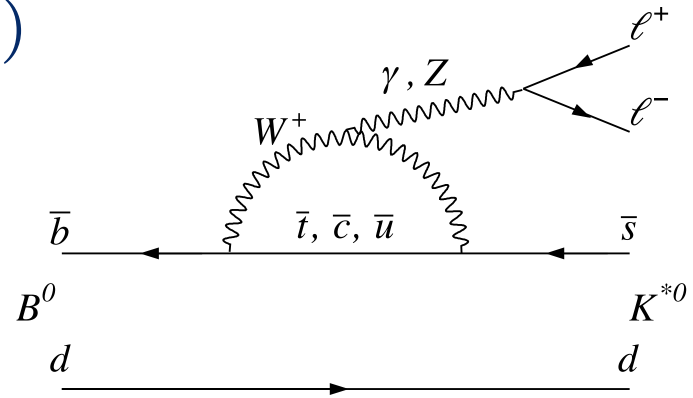
- **Tree Level**
- Potential NP that couple only to the 3rd generation



$$R\left(K^{(*)}\right) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

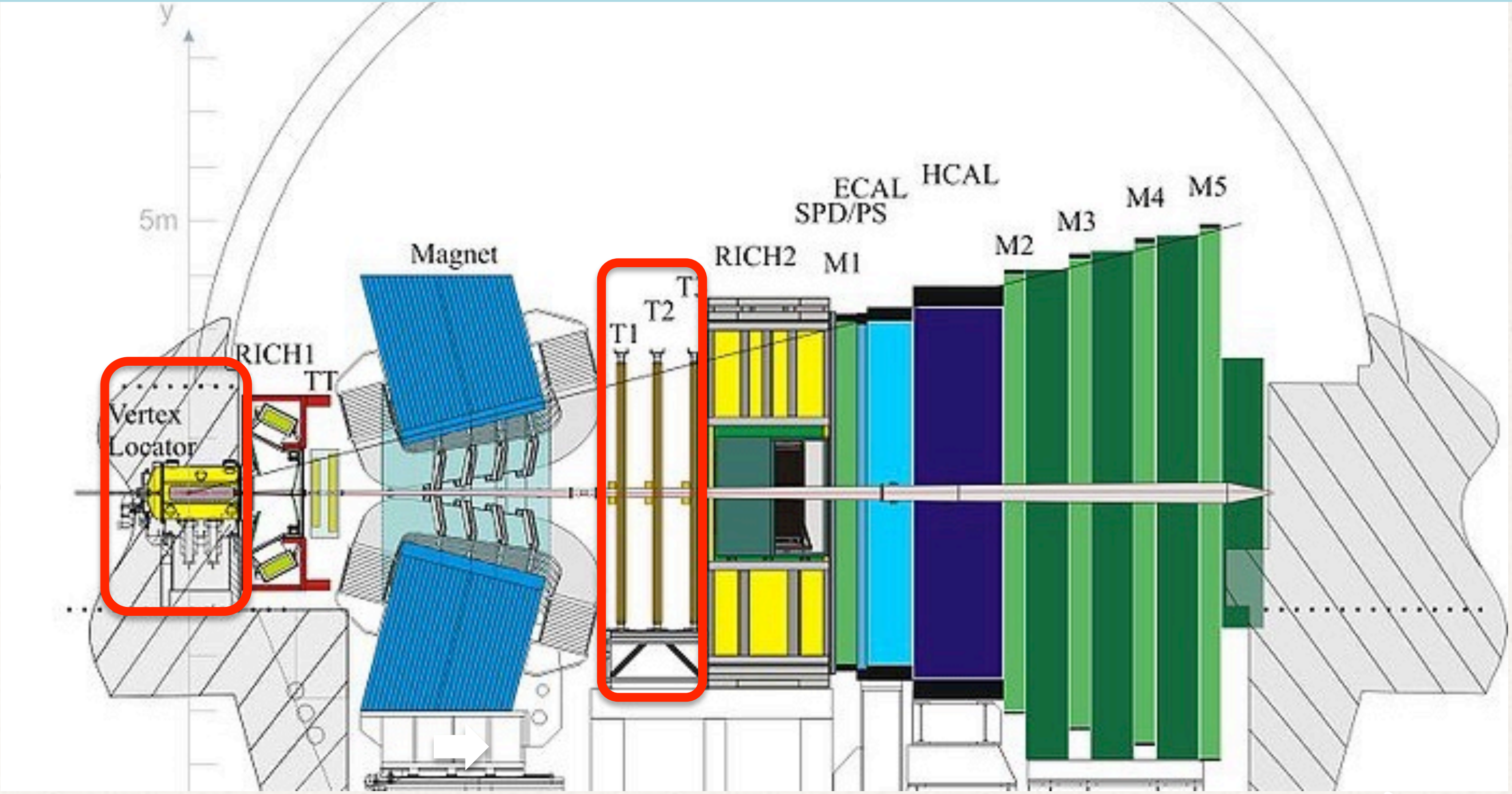
[$b \to sll$]

- **FCNC process.** Forbidden tree level in SM
- Sensitive to either tree or loop NP contributions



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

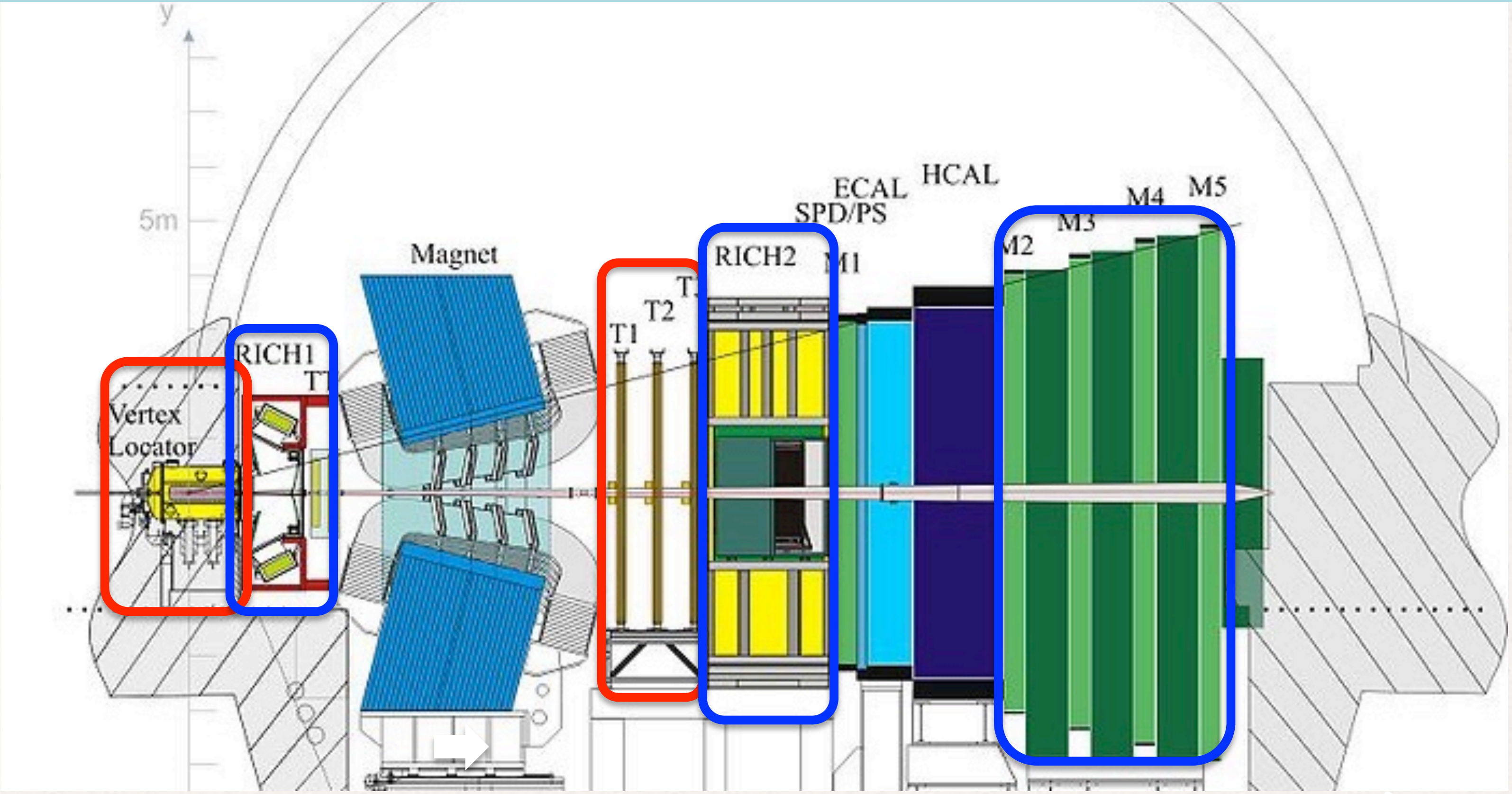
The LHCb detector



- Excellent **vertex and momentum resolution**

The LHCb detector

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



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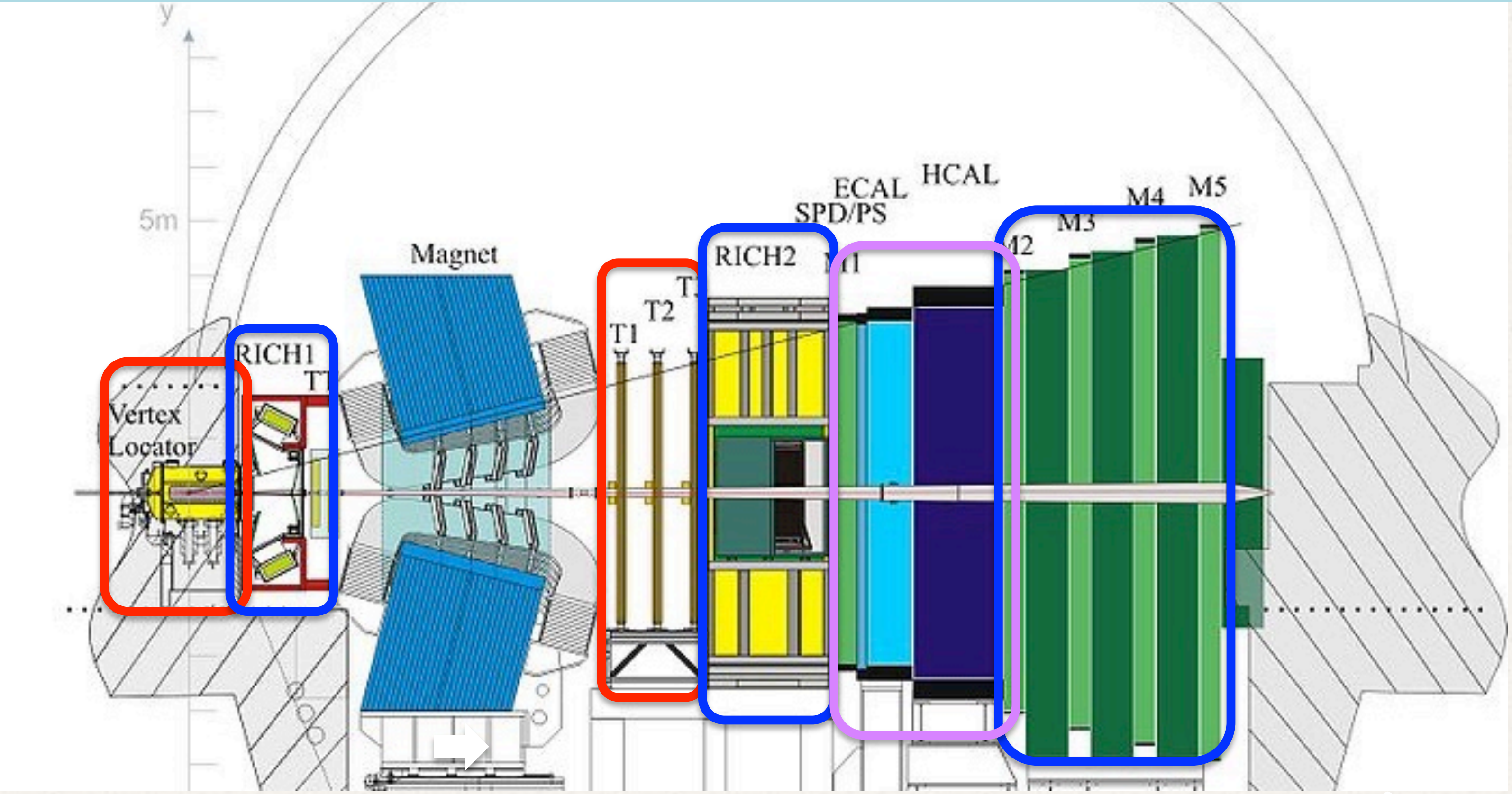
The LHCb detector



- Excellent **vertex and momentum resolution**
- Excellent **charged particle identification**
- Capability for **neutral particle identification**

Semileptonic decays

Why semitauonic decays?

Tree level decays in the SM, mediated by a W boson

$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$

$$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b \ldots$$

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

- **Clean predicion from SM**
    - Partial cancellation of form factors uncertainties in the ratio
    - **Large rate** of charged current decays BR(B→D*$\tau\nu$)~1.2 % in SM
    - Deviation from unity due to different available phase space (τ, μ)
- **Sensitivity to NP** contributions at tree level

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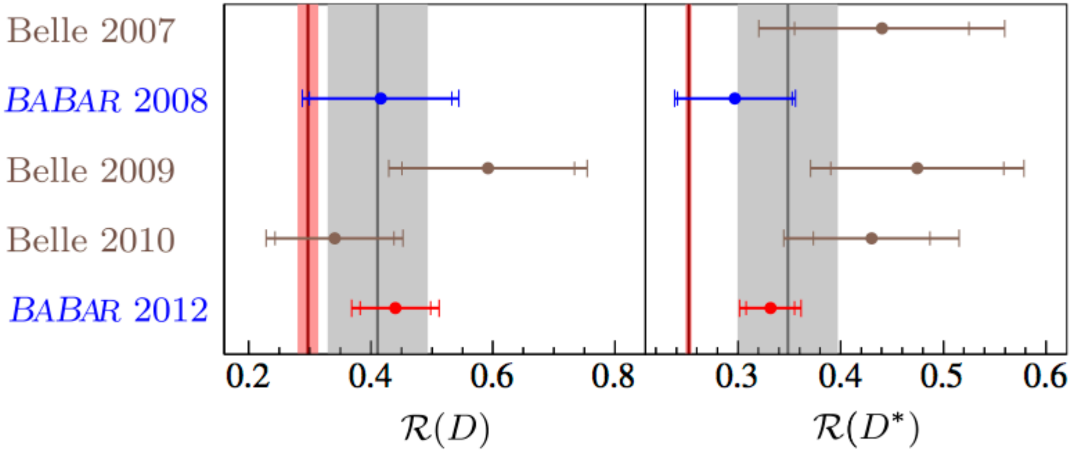
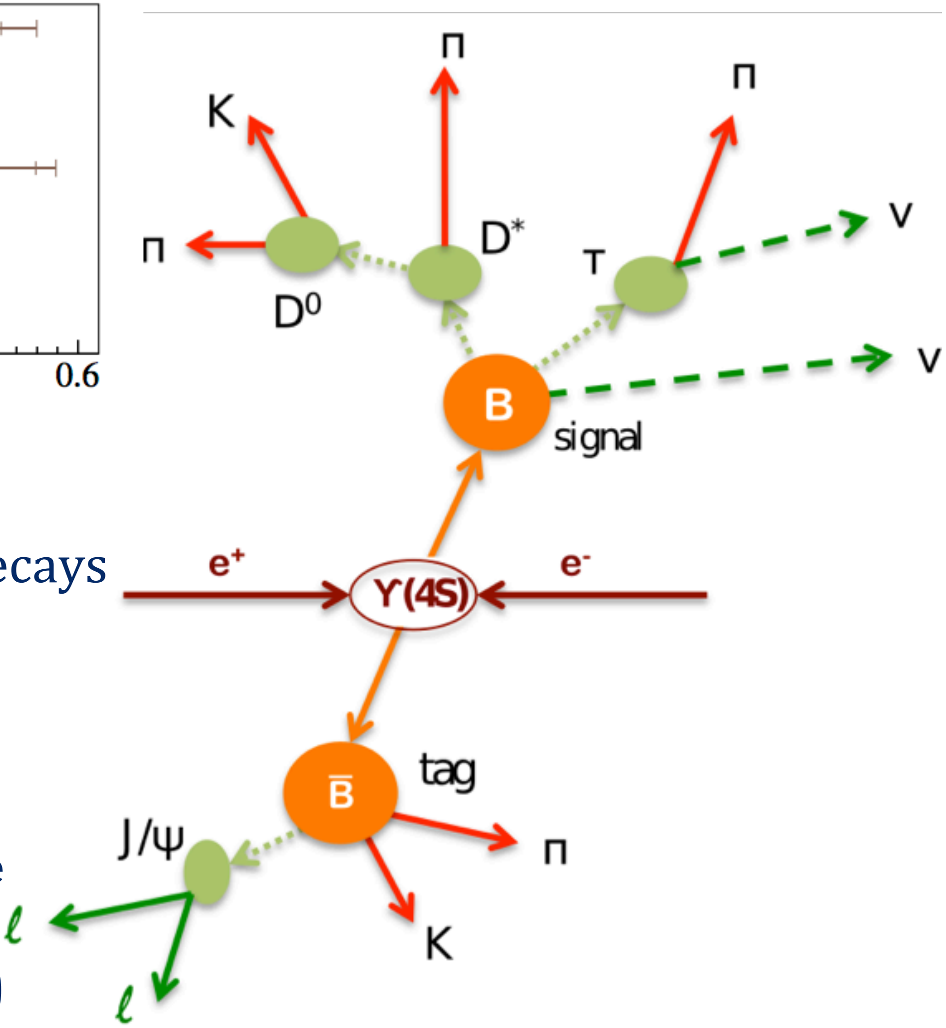
At LHCb...

- Missing momentum of neutrinos not measured: Missing kinematic constraints
- B momentum unknown: approximations
- **Two reconstruction channels for τ**
  - **Muonic mode: $\tau \to \mu \nu_\mu \nu_\tau$**
  - **Hadronic mode: $\tau \to \mu\, \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$**

B-factories

[PRD D88, 072012 (2013)]





Before LHCb...

Belle and BaBar studied semitauonic *B* decays at the **B-factories**

- e^+/e^- collisions producing $\Upsilon(4S) \rightarrow B\bar{B}$
- Measurement of the B-signal using fully reconstructed B-tag and a constraint to the $\Upsilon(4S)$ mass
- Complementary measurement of **R(D)** and **R(D*)** yielded to **3.7σ from SM**

[PRD 115, 111803 (2015)]

R(D*) muonic at LHCb

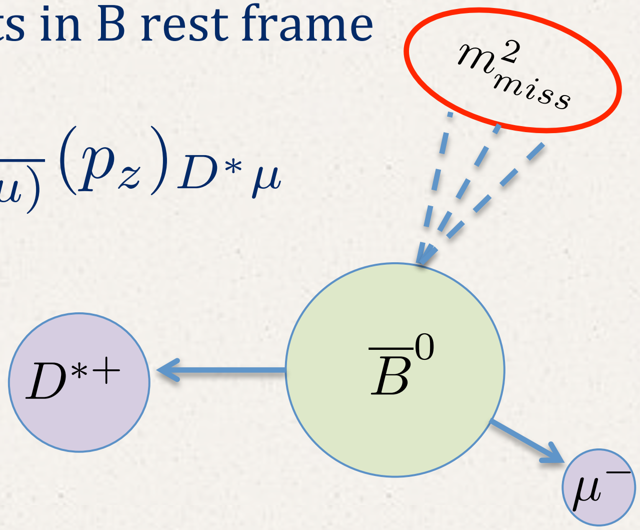
First measurement of R(D*) in a hadron collider, using the muonic decay of τ

$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)} \qquad \text{with } \tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$$

Features of the analysis…

- Missing kinematic constraints. **Rest frame approximation**
- B boost along z axis >> boost of decay products in B rest frame

$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$



18 % resolution on p_B, good enough to preserve signal and background discrimination

[LHCb-PAPER-2015-025]

R(D*) muonic at LHCb

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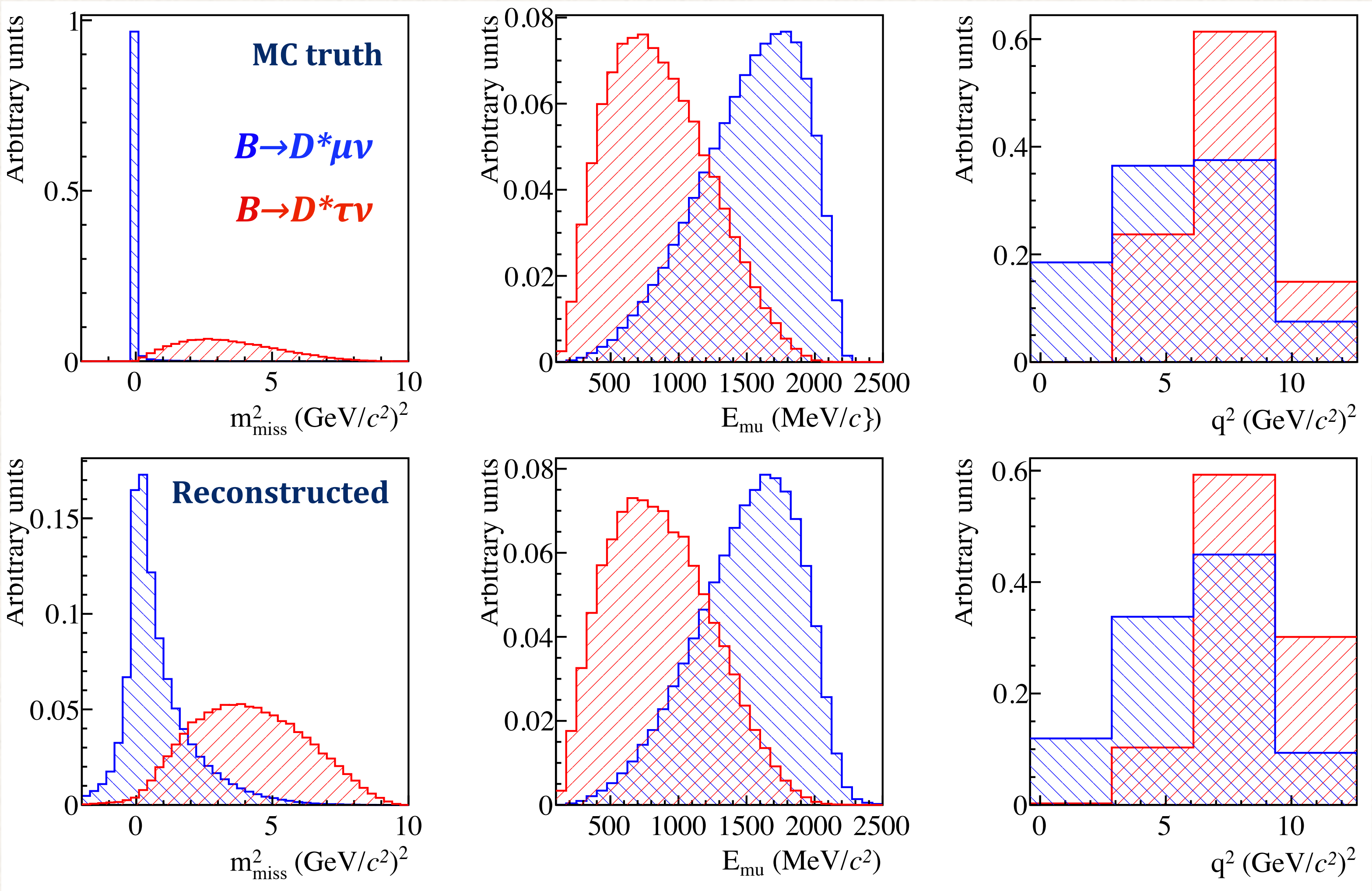
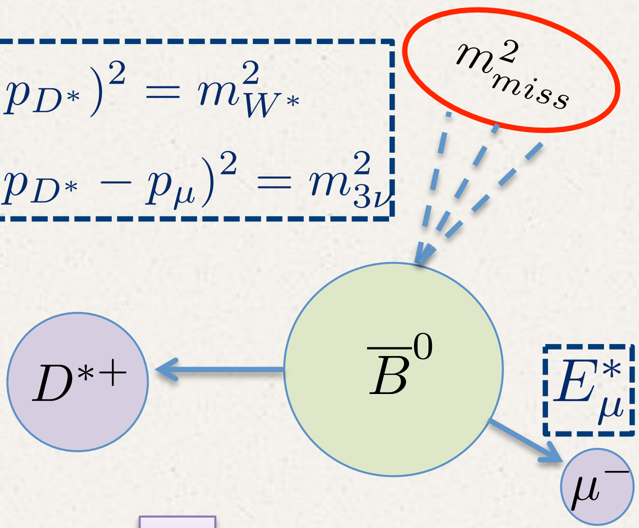


[PRD 115, 111803 (2015)]

R(D*) muonic at LHCb

Result: separate τ and μ components via a **3D binned template fit** to the q^2, m^2_{miss} and E^*_μ distributions

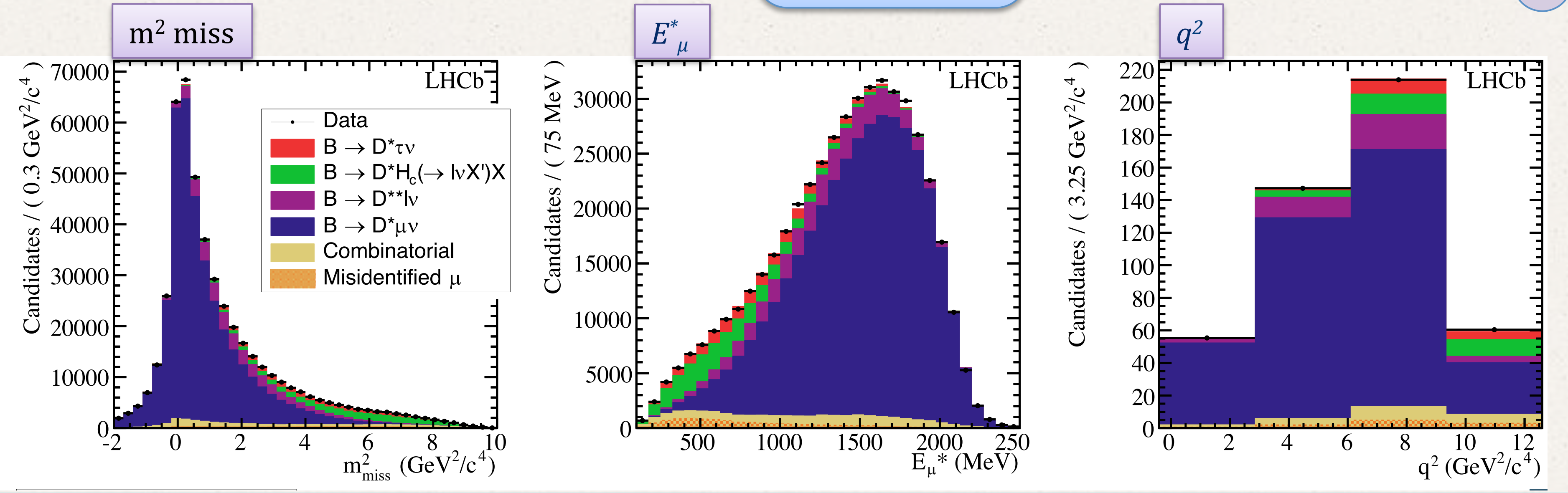
$$q^2 = (p_B - p_{D^*})^2 = m^2_{W^*}$$
$$m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2 = m^2_{3\nu}$$



[Run 1 data]

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

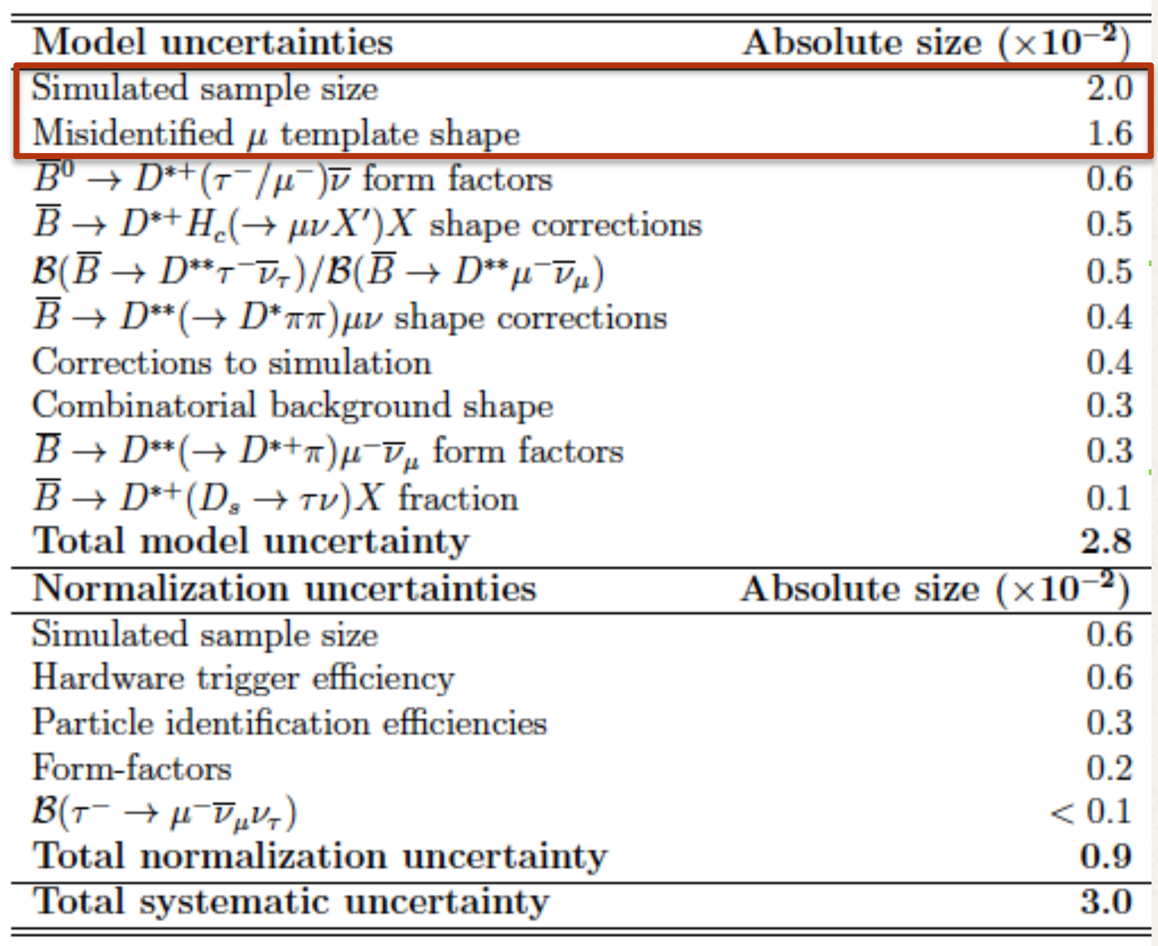
~2.1 σ from SM



[PRD 115, 111803 (2015)]

R(D*) muonic at LHCb

Systematics:



Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

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

R(D*) hadronic at LHCb

- First measurement of R(D*) using the hadronic τ decay with $\tau^-\to\pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
- What is measured:

$$\boxed{R_{had}(D^{*-}) = \frac{\mathcal{B}(B^0\to D^{*-}\tau^+\nu_\mu)}{\mathcal{B}(B^0\to D^{*-}\pi^+\pi^-\pi^+)}} = \frac{\mathbf{N_{sig}}}{\mathbf{N_{norm}}}\times\frac{\epsilon_{norm}}{\epsilon_{sig}}\times\frac{1}{\mathcal{B}(\tau^+\to\pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau)}$$

Overlapping signal decay mode

τ decay mode	BR (%) [PDG-2017]
$\tau\to\mu\nu_\mu\nu_\tau$	17.39 ± 0.04
$\tau\to e\nu_\mu\nu_\tau$	17.82 ± 0.04
$\boldsymbol{\tau\to\pi^-\pi^+\pi^-\nu_\tau}$	**9.31 ± 0.05**
$\boldsymbol{\tau\to\pi^-\pi^+\pi^-\pi^0\nu_\tau}$	**4.62 ± 0.05**
$\tau\to\pi^-\nu_\tau$	10.82 ± 0.05
$\tau\to\rho^-\nu_\tau$	25.49 ± 0.09

- Approximations are done to reconstruct the B and τ momentum. Good precision obtained
- Signal and normalization same visible state: $D^{*-}\pi^-\pi^+\pi^-$
- Most of the theoretical and experimental uncertainties on cancel out in the ratio
- **R(D^{*-})** obtained from:

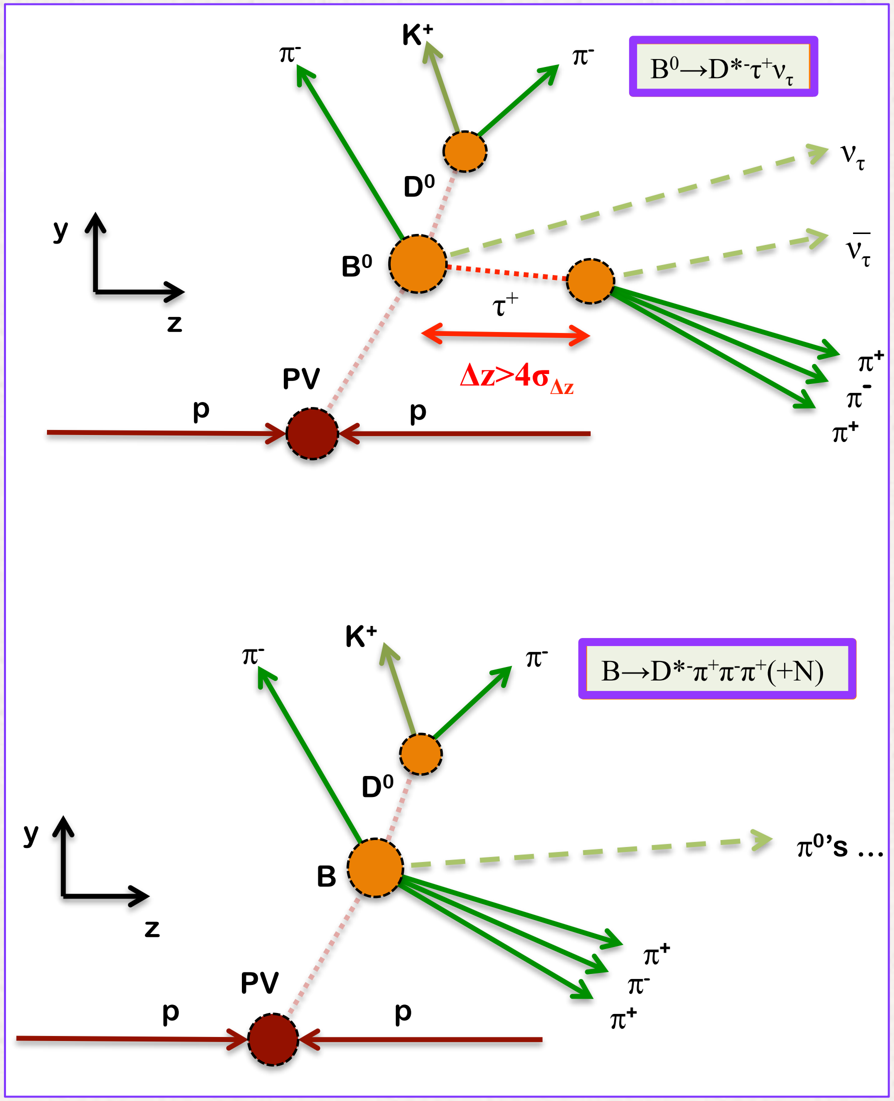
$$\boxed{R(D^{*-}) = R_{had}(D^{*-})\times\frac{\mathcal{B}(B^0\to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0\to D^{*-}\mu^+\nu_\mu)}}$$

[4.0 % precision]

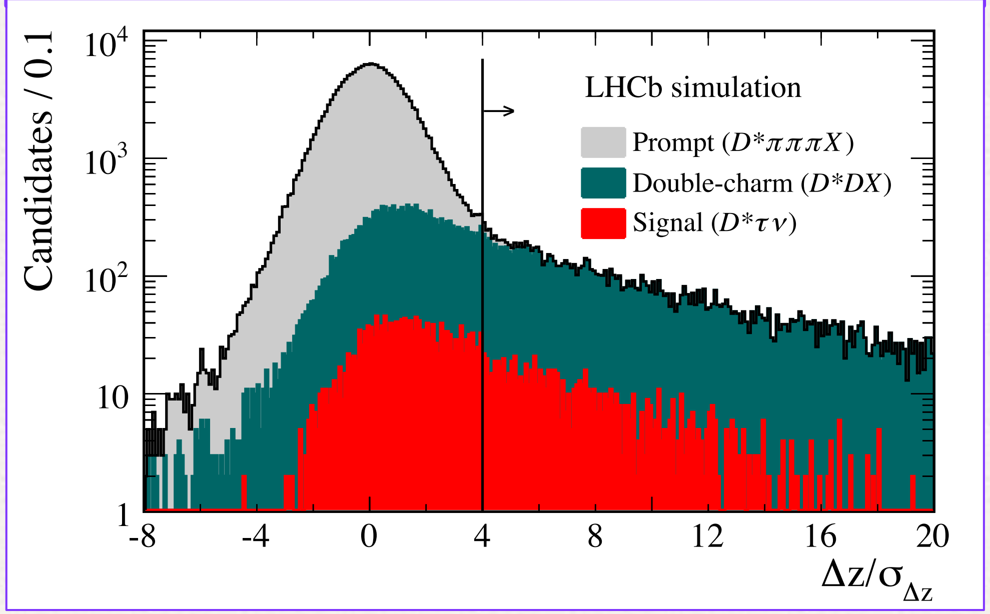
[2.2 % precision]

[PRD 97, 072013 (2018)]

R(D*) hadronic at LHCb



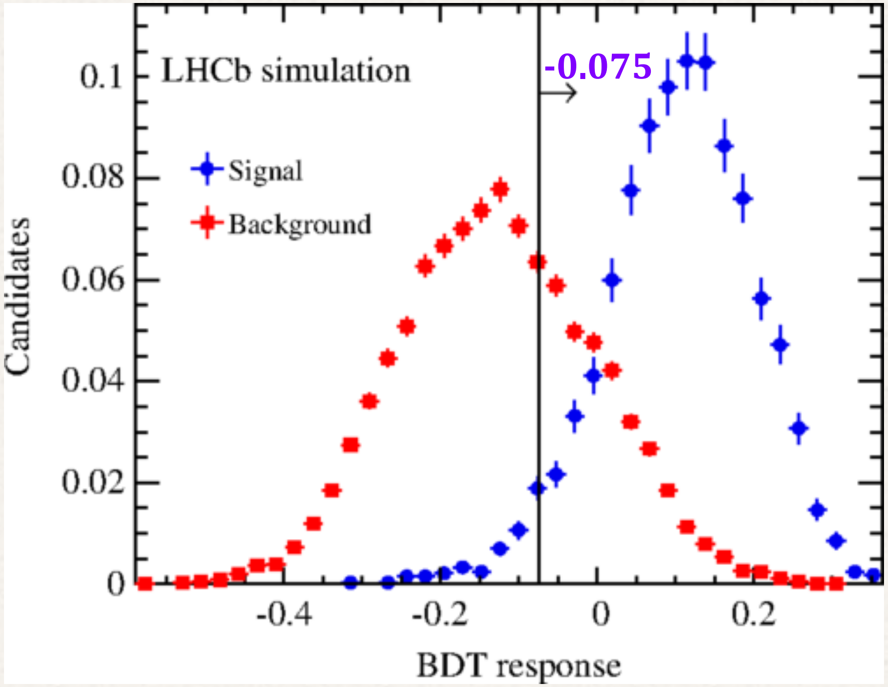
- ○ Largest background due to ***$B \to D^{*-}\pi^+\pi^-\pi^+X$*** (neutrals), where 3 pions come from the *B* vertex (100 higher than the signal)
  - Requirement: decay topology with minimum distance between *B* and *τ* vertices: $\Delta z > 4\,\sigma_{\Delta z}$
  - **Suppressed by 3 orders of magnitude**
- ○ 2nd largest background is the double charm ***$B \to D^{*-}D_s^+X$* : Multivariate Analysis**

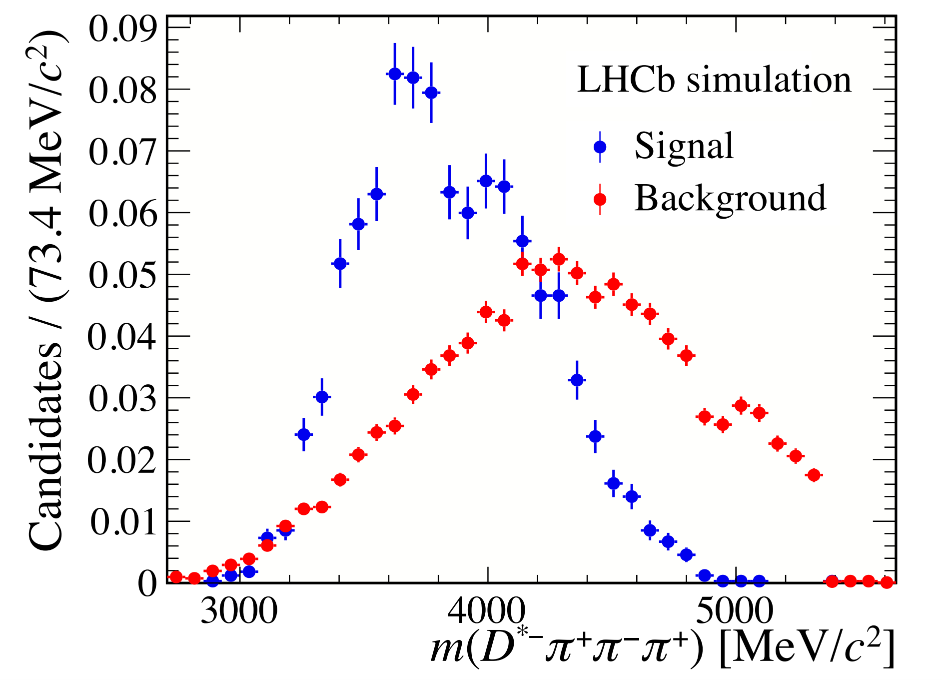


[PRD 97, 072013 (2018)], [PRL 120,171802 (2018)]

R(D*) hadronic at LHCb

- Most important background after the inversion cut comes from $B \rightarrow D^{*-} D_s^{+} X$
- Multivariate Analysis: 18 variables combined in a **BDT**:
  - 3 π variables
  - $D^{*-} 3\pi$ dynamics
  - Neutral isolation variables

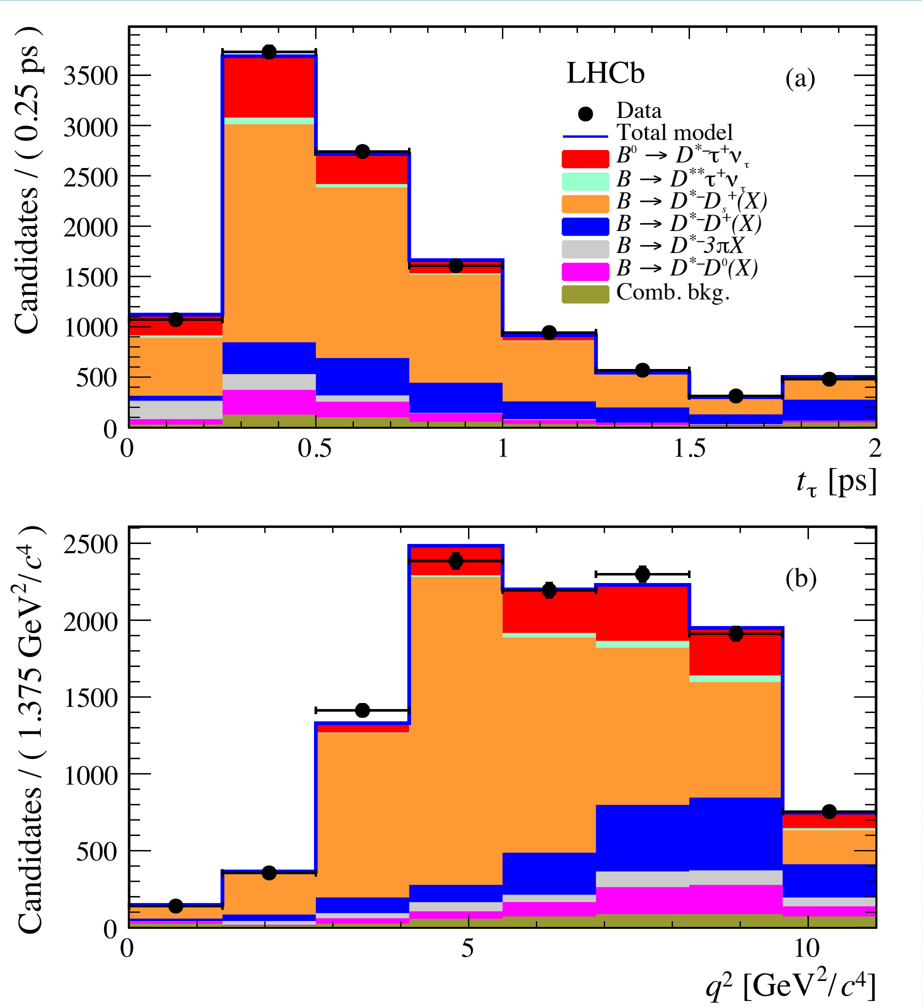


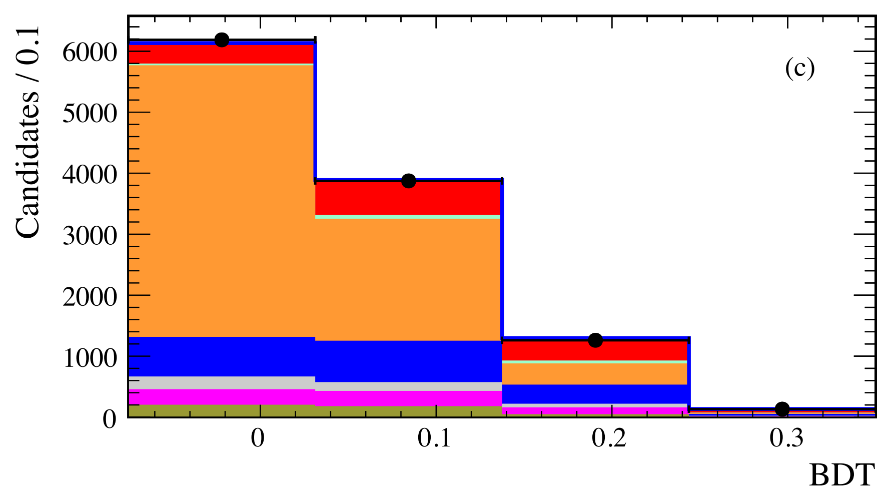


BDT used as variable in the fit to extract signal yield

[PRD 97, 072013 (2018)]

R(D*) hadronic at LHCb





Result Run 1 data:

- **N($B^0 \to D^{*-}\pi^+\pi^-\pi^+$) unbinned likelihood fit to M($D^{*-}\pi^-\pi^+\pi^-$)**
- **N($B^0 \to D^{*-}\tau^+\nu_\tau$) three dimensional binned fit to data**

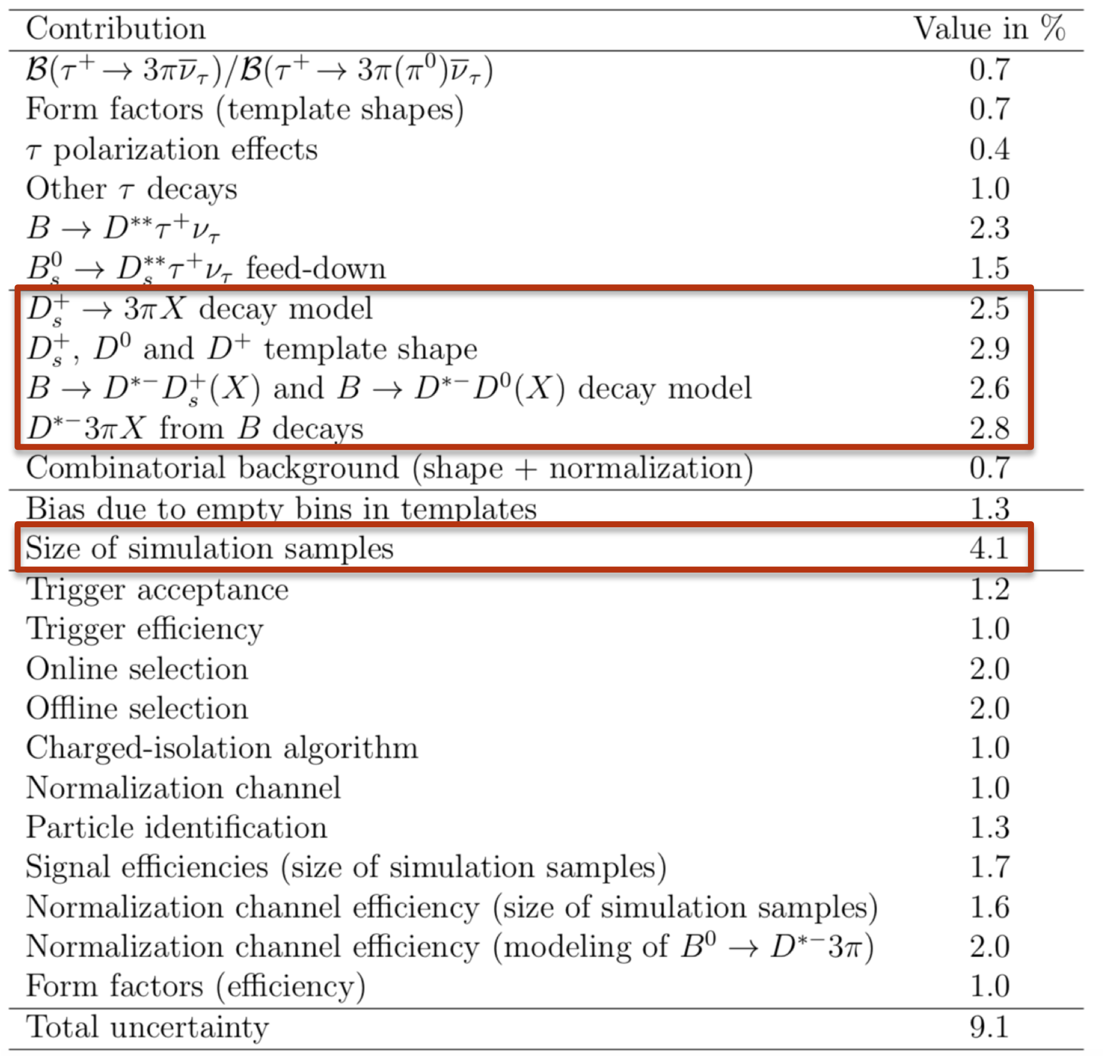
  Variables: τ decay time, q^2, BDT output

$$\boxed{R(D^*) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(ext)}$$

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

R(D*) hadronic at LHCb

Systematics:



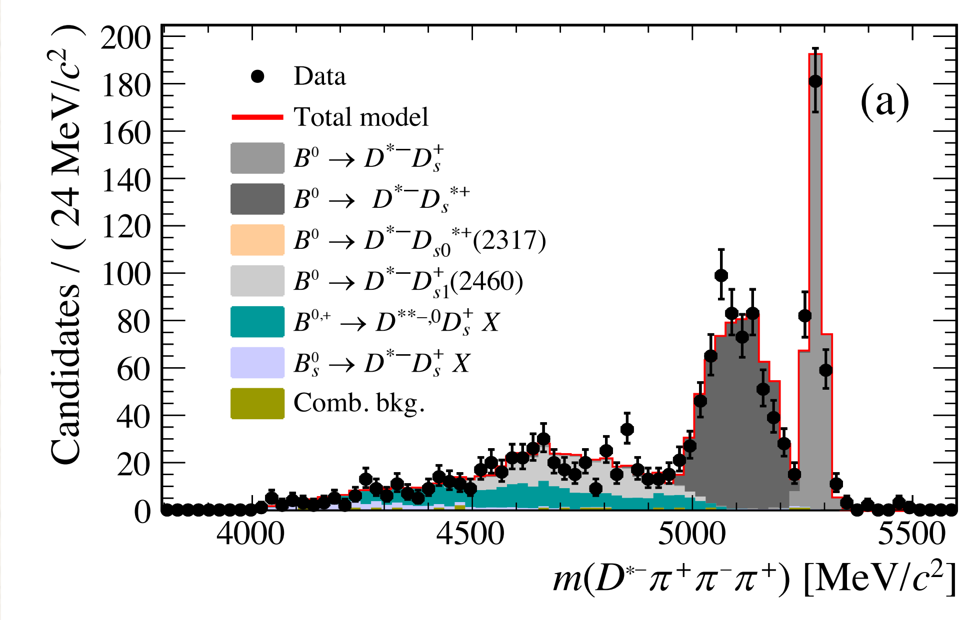
Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Normalization channel	1.0
Particle identification	1.3
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Form factors (efficiency)	1.0
Total uncertainty	9.1

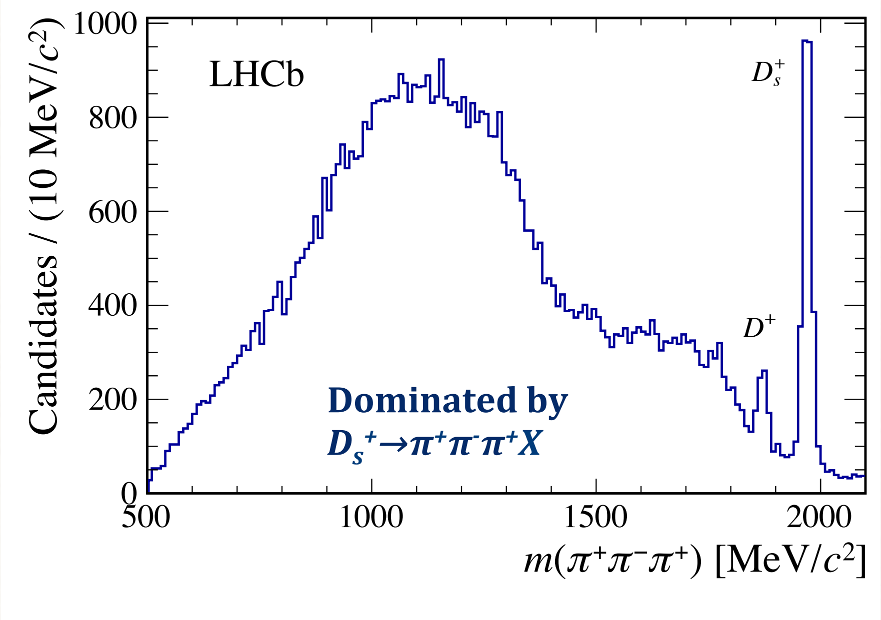
[PRD 97, 072013 (2018)], [PRL 120,171802 (2018)]

R(D*) hadronic at LHCb

Main systematic uncertainties due to:

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



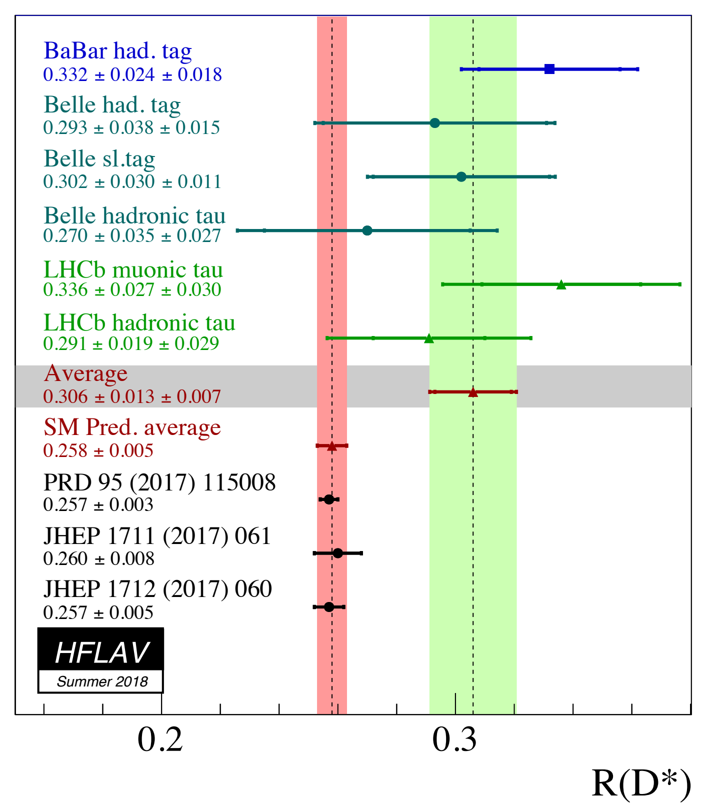


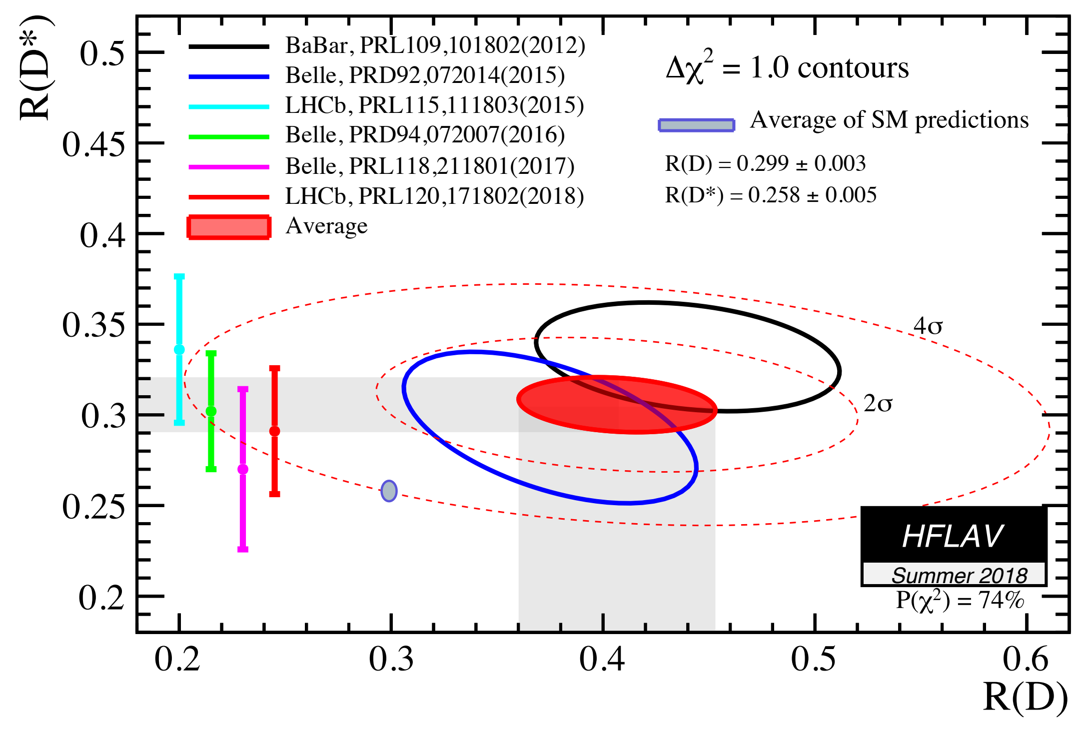
Dominated by
$\boldsymbol{D_s^+ \to \pi^+\pi^-\pi^+ X}$

R(D*) global picture

[HFLAV 2018]

- ○ R(D*) world average is in tension with the SM at the level of 3.0 σ





- ○ WA combination of R(D) and R(D*) is in tension with SM at the **3.8 σ level**

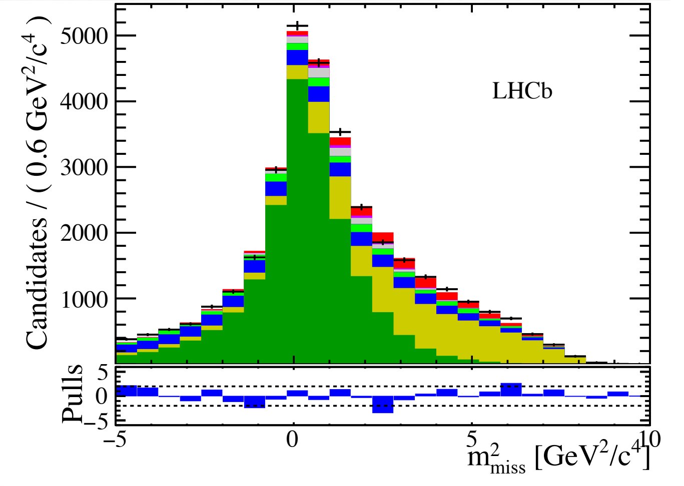
[PRL 120 (2018) 121801]

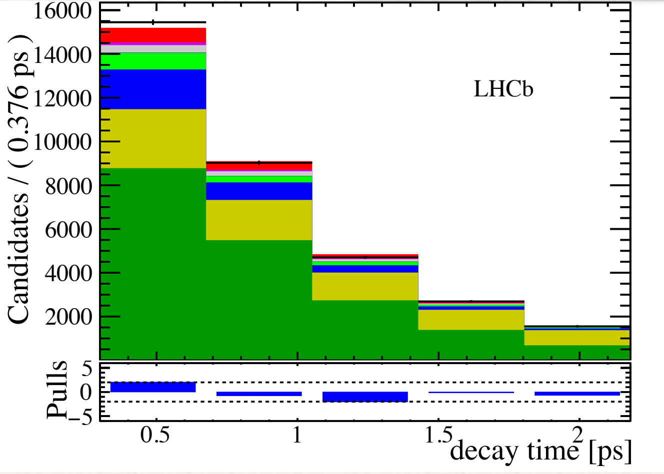
$R(J/\psi)$ in LHCb

Generalization of R(D*) in the B_c sector

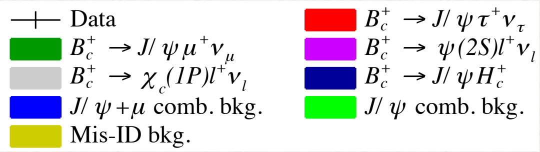
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

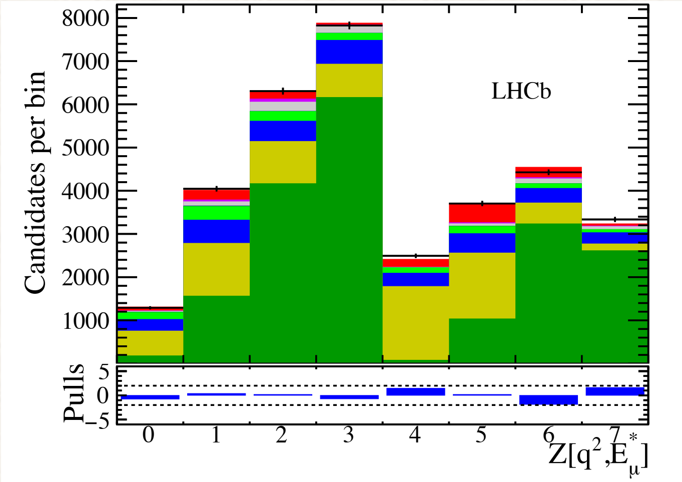
with $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$





[Run 1 data]





- Form factors unconstrained experimentally. Poorly calculated from theory

Result: **3D binned maximum likelihood fit** to data.

Variables: decay time, m^2_{miss}, $Z(E^*_\mu, q^2)$

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

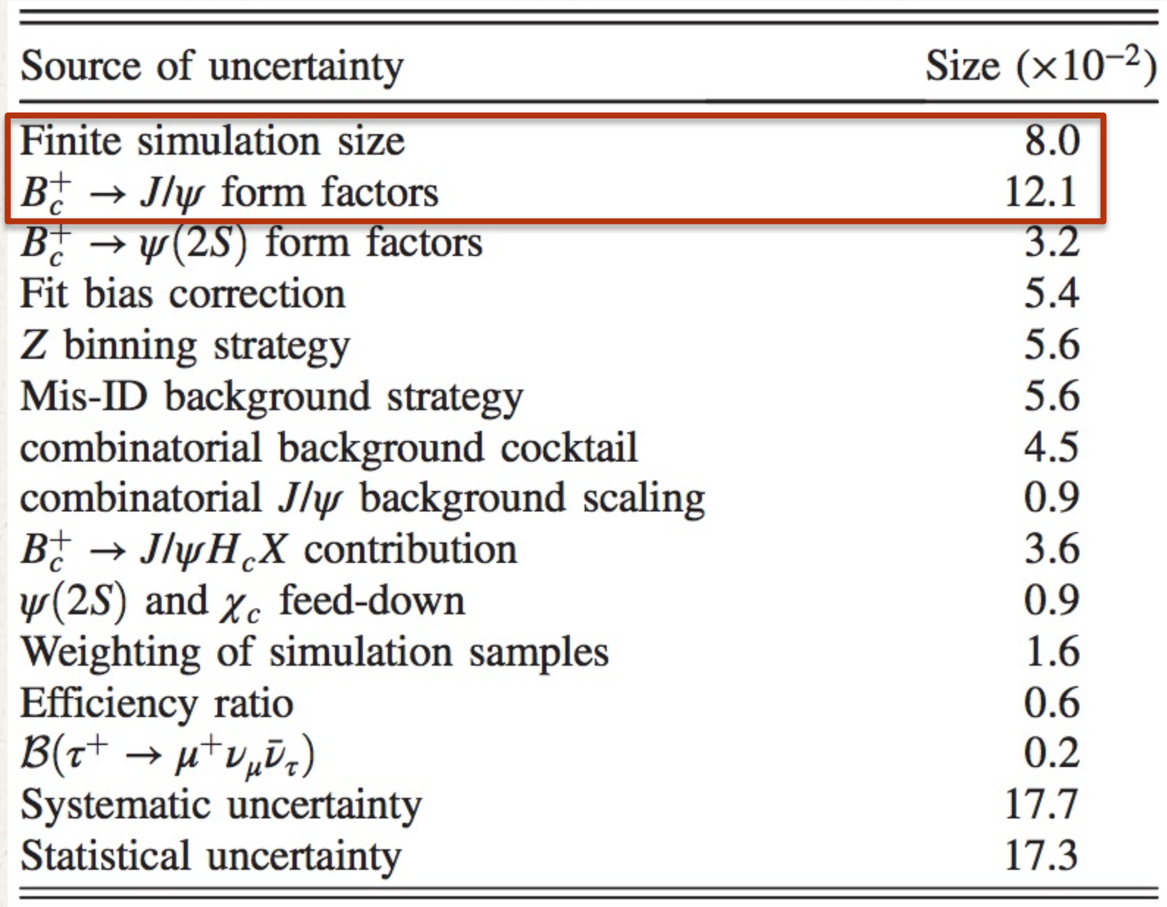
$$R_{SM}(J/\psi) \in [0.25, 0.28]$$

~2σ from SM

[PRL 120 (2018) 121801]

R(J/ψ) in LHCb

Systematics:



Source of uncertainty	Size ($\times 10^{-2}$)
Finite simulation size	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
Mis-ID background strategy	5.6
combinatorial background cocktail	4.5
combinatorial J/ψ background scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
$\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$	0.2
Systematic uncertainty	17.7
Statistical uncertainty	17.3

Rare b→sll decays

Rare *b→sll* decays

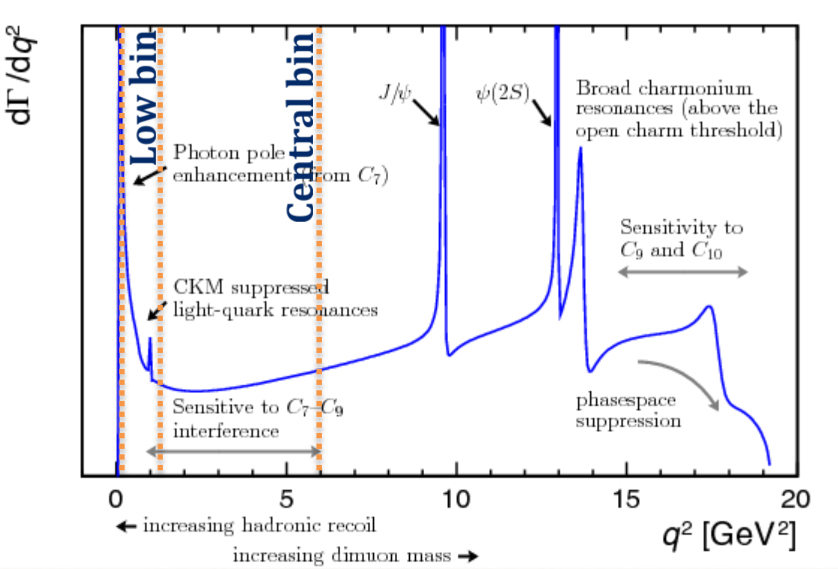
Flavour Changing Neutral Current transitions. Proceed via loop diagrams. Within a given range of the dilepton mass squared, q^2:

$$R_X[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to X\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B \to Xe^+e^-)}{dq^2}} \quad \text{with} \quad X = K, K^*, \phi ...$$

- ○ **SM expectation R_x=1**, neglecting lepton masses
  - Partial cancellation of hadronic uncertainties in theoretical predictions
- ○ **Suppressed in SM**: more sensitive to NP

At LHCb…

- ○ Extremely challenging due to significant differentes in the way *μ* and *e* interact with the detector: Bremsstrahlung, trigger
- ○ **LHCb published measurements:**
  - **R_K**
  - **$R_K{}^*$**



[JHEP 08 (2017) 55]

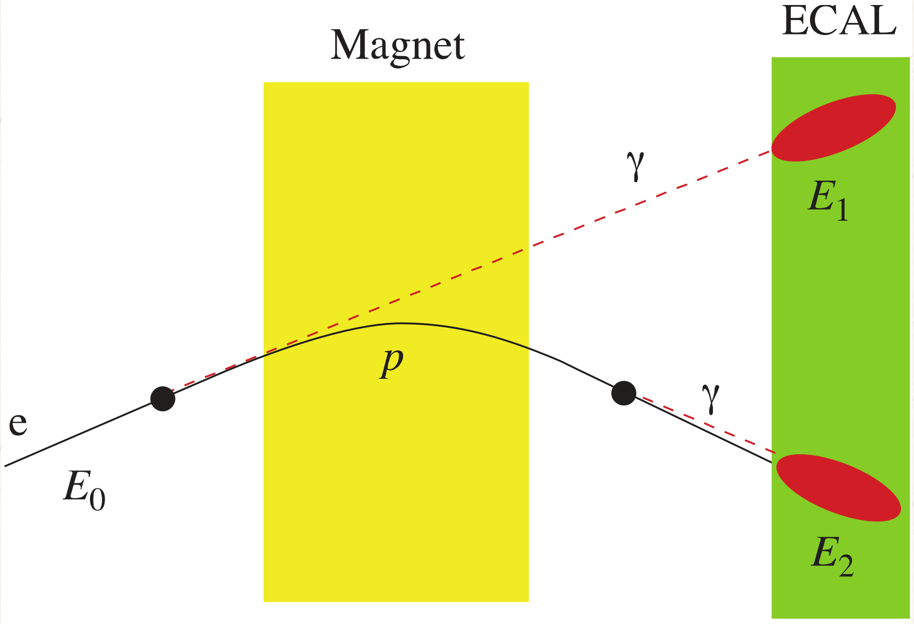
R(K*) at LHCb

LHCb measured **R(K*)** for $q^2 \in [0.045, 1.1]$ and $[1.1, 6.0]$ GeV^2/c^4, with $K^{*0} \to K^+ \pi^-$
Double ratio to reduce systematics:

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

Bremsstrahlung effects:
two reconstruction strategies

- Downstream of the magnet: Photon energy is likely to be in the same calorimeter cell as the electron
- Upstream of the magnet: Photon energy is likely to be in different calorimeter cell than electron



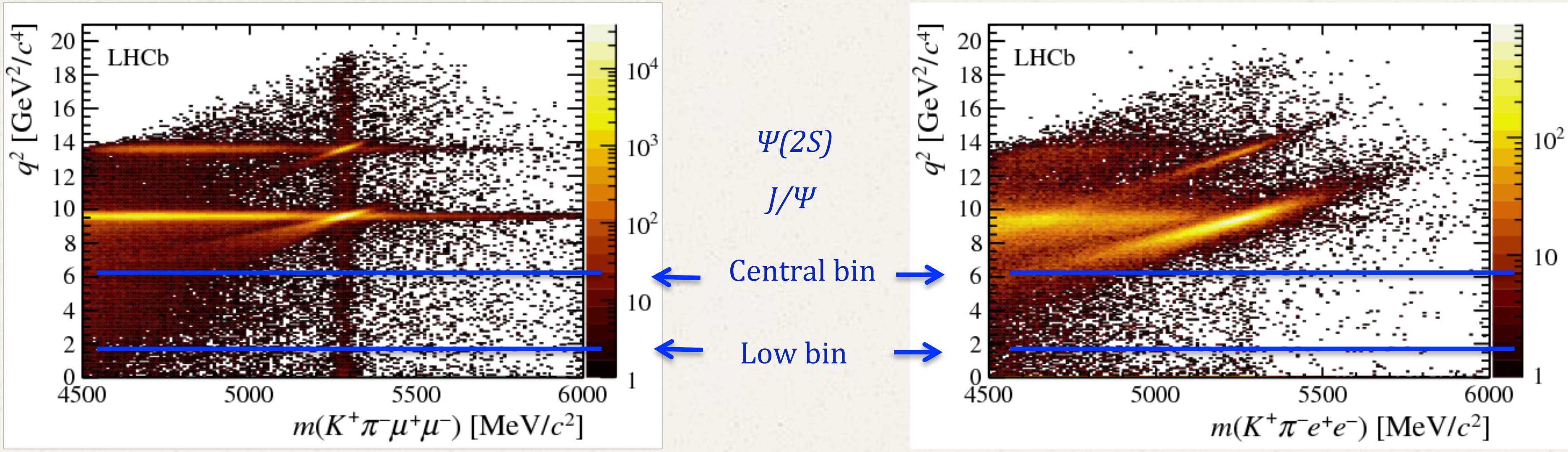
[JHEP 08 (2017) 55]

R(K*) at LHCb

Bremsstrahlung effects

- Recovery procedure → improvement momentum resolution, B mass resolution
- Worse separation of partially reconstructed backgrounds
- Background from the *J/ψ* and *ψ(2S)* contaminate the signal region

[Run 1 data]



- ○ Electron sample is separated in **3 Bremsstrahlung categories** (0γ, 1γ, ≥2γ*)*
- ○ **3 types of trigger**: electrons (L0E), hadrons (L0H) and signal independence (L0I)

↓

Maximize the electron sample size

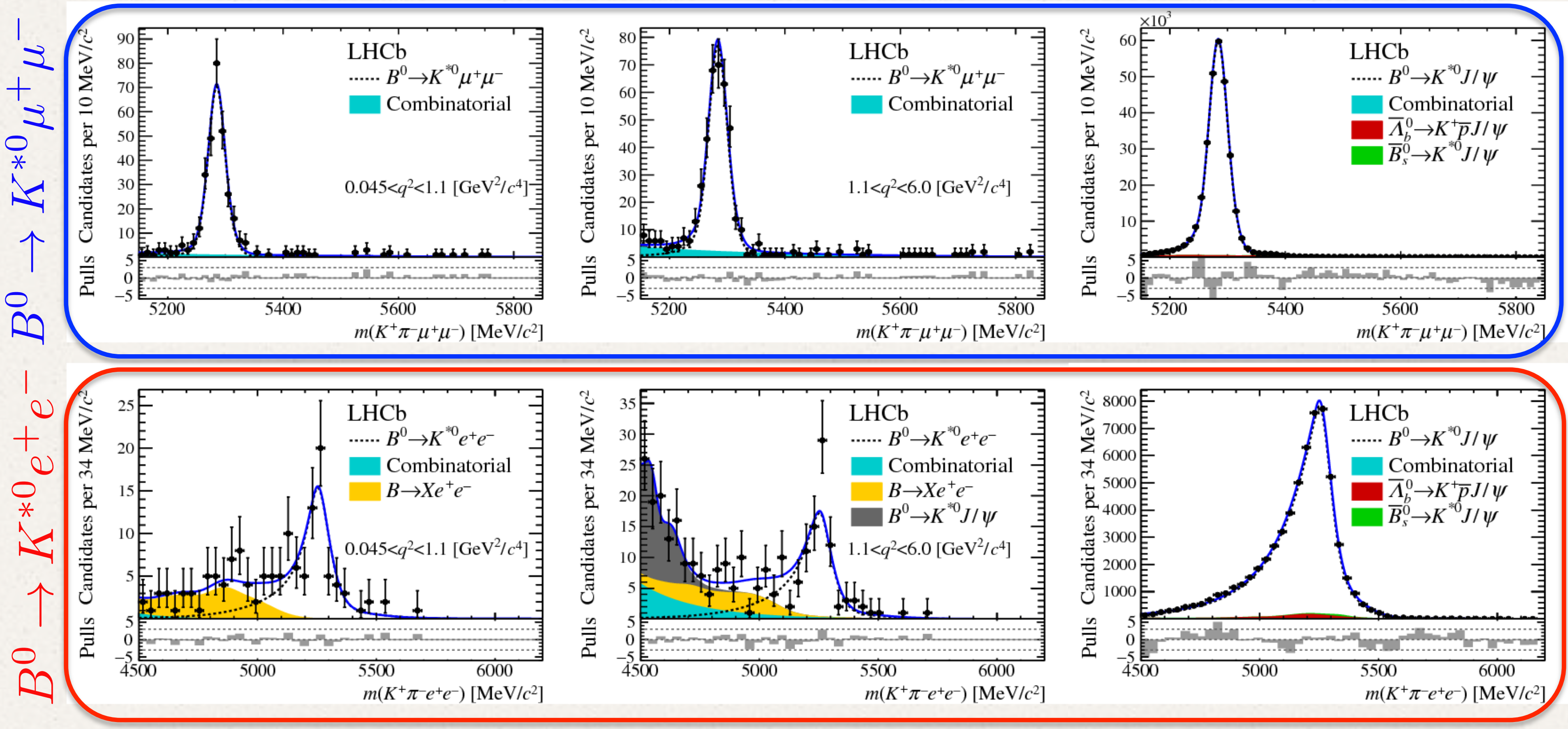
R(K*) at LHCb

[Run 1 data]

Result: Fit to B mass distribution in lower and central q² bin

Simultaneous fit $M(K^+\pi^- l^+ l^-)$ to the J/ψ and non-resonant channels

Low q² bin *Central q² bin* *Normalization channel*

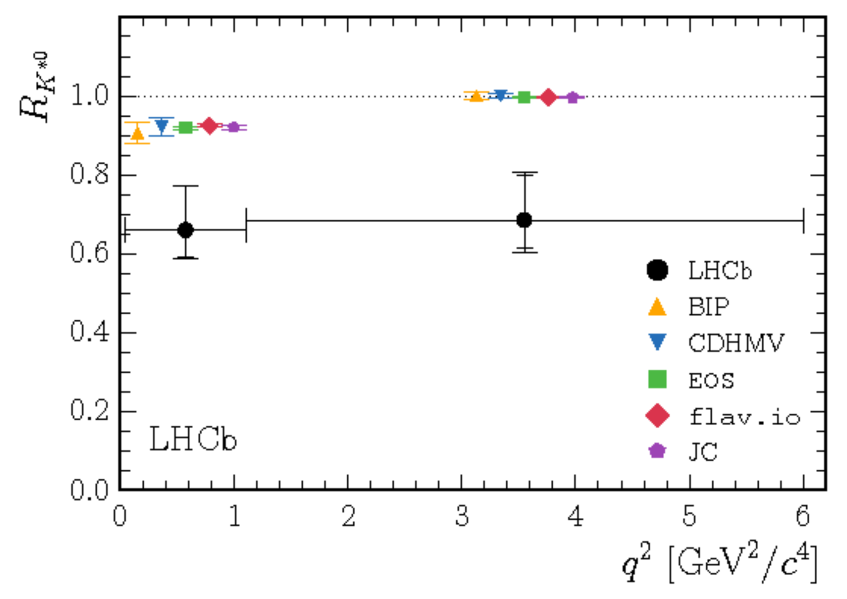


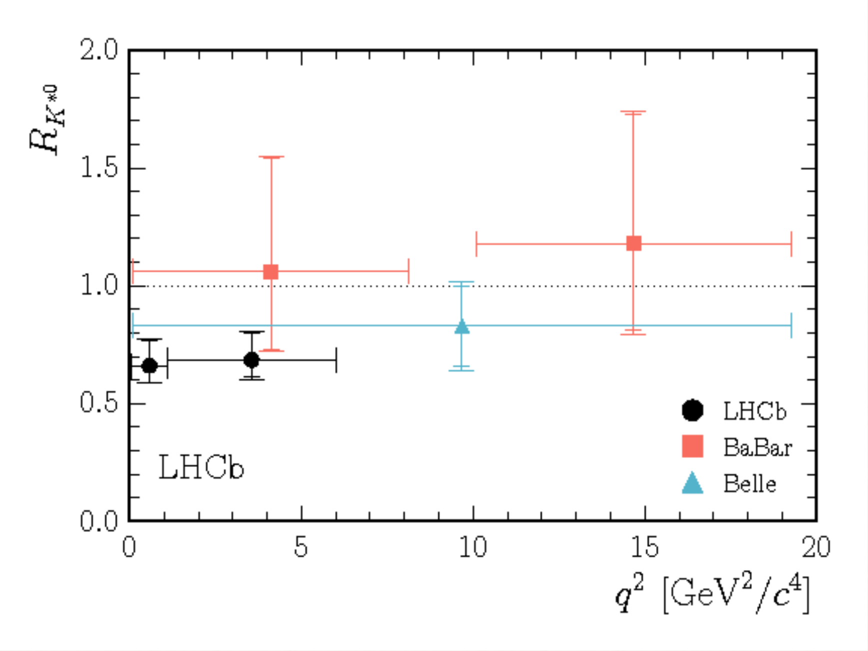
R(K*) at LHCb

LHCb: JHEP 08 (2017) 55
Babar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

LHCb: [Run 1 data]

q^2 bin	R(K*)	σ from SM
Low	$0.66^{+0.11}_{-0.07} \pm 0.03$	~ 2.2
Central	$0.69^{+0.11}_{-0.07} \pm 0.05$	~ 2.4



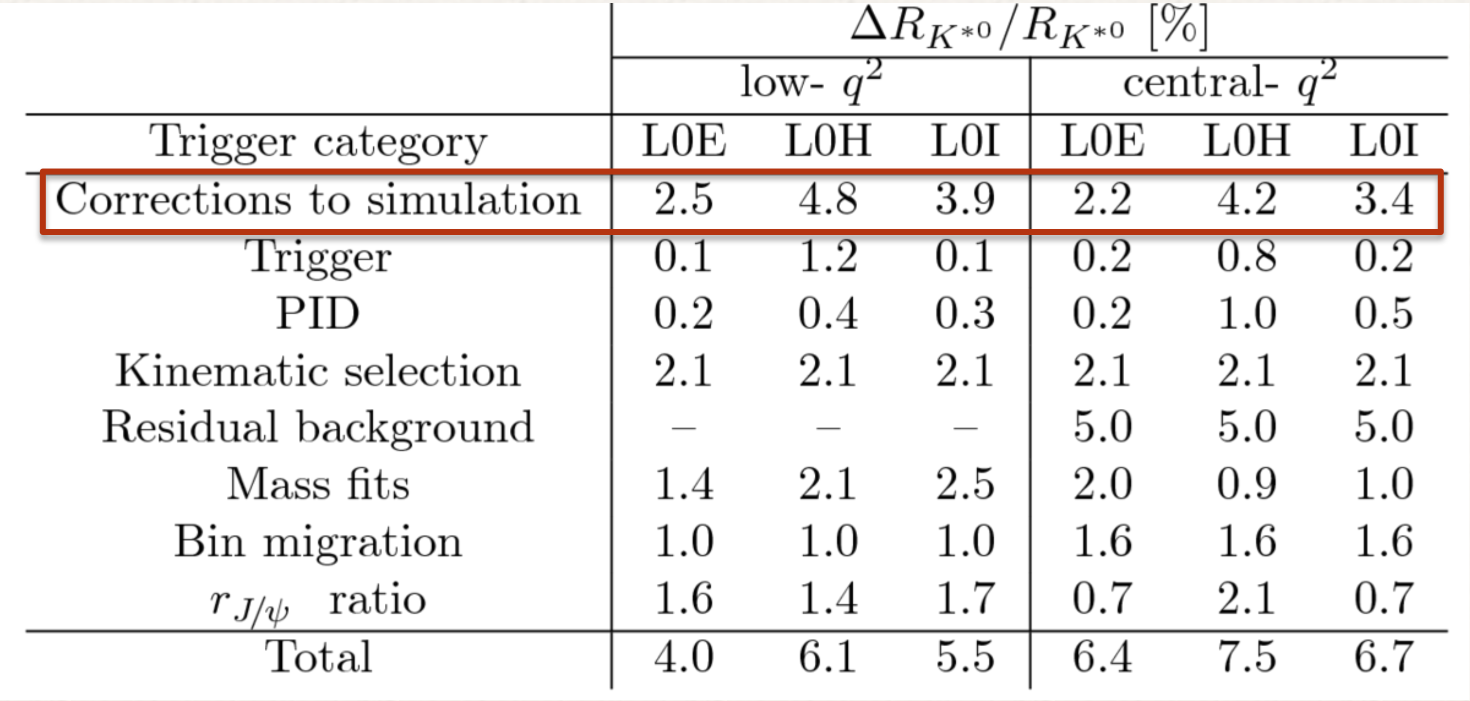


- LHCb result most precise measurement to date
- Statistically limited by the electron sample size

R(K*) at LHCb

[JHEP 08 (2017) 55]

Systematics:



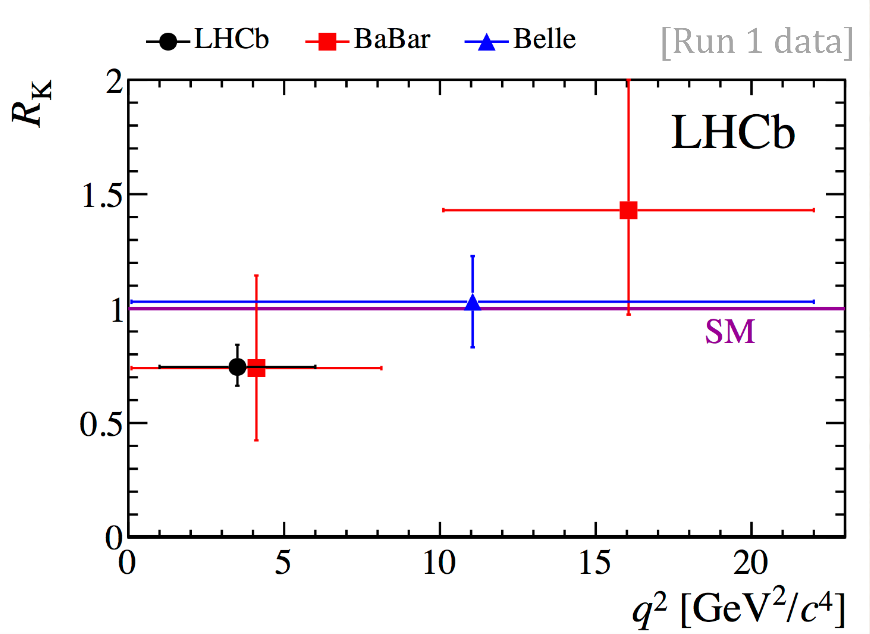
	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low- q^2			central- q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass 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(K) at LHCb

LHCb: PRL 113, 151601 (2014)
BaBar: PRD 86, 032012
Belle: PRL 103, 171801

In 2014, LHCb measured **R(K)** for $q^2 \in [1, 6]$ GeV^2/c^4

- Double ratio of rare J/ψ channel used to reduce the systematic uncertainties
- Low efficiency for electrons: Bremsstrahlung effects
- Signal extracted via **invariant mass fits**
- Dominant source of systematic uncertainty are due to the parametrization $B^+ \to J/\psi\ (\to e^+e^-)K^+$ mass distribution and trigger efficencies. Both contribute ~3% to the value of R(K)

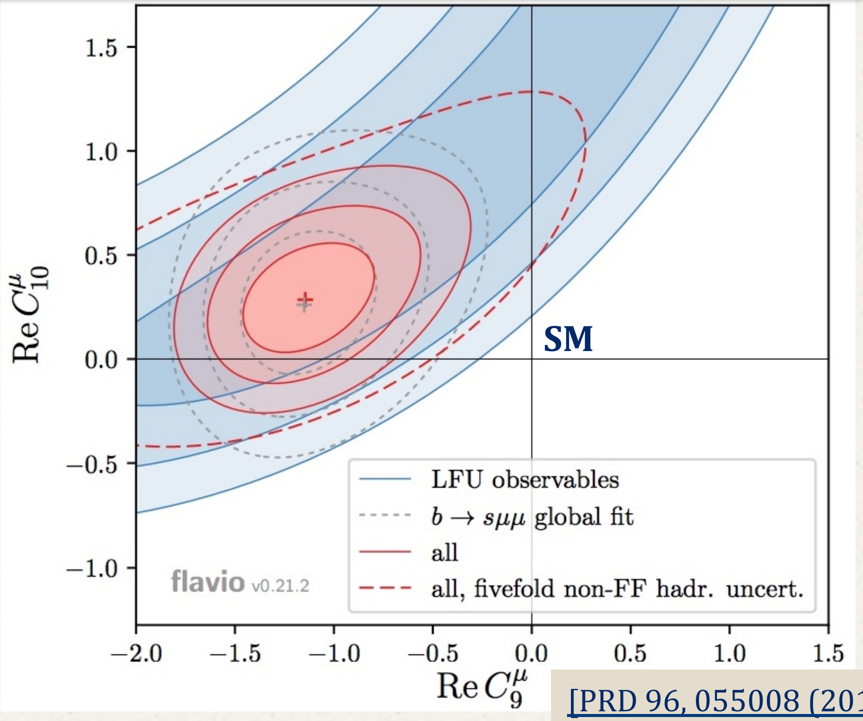


$$R(K) = 0.755^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$$

$$R_{SM}(K) = 1 \pm \mathcal{O}(10^{-2})$$

2.6 σ from SM

Global fit. NP preferred over SM by **~4σ**



[PRD 96, 055008 (2017)]

Conclusions

Conclusions

LFUV road to new physics!

Semileptonic B decays hint anomalies with respect to the SM at both tree and loop levels

- All measurements presented were performed using Run 1 data and are dominated by statistical uncertainties
- ~9fb^{-1} expected at the end of Run 2
- Run 2 LHCb data: Exciting program ahead! Updates and new analysis: Statistical and systematic uncertainties will be reduced

Ongoing and planned

$R(D^0)$, $R(D^+)$, $R(D_s)$, $R(\Lambda^{(*)}_c)$…

$R(\psi)$, $R(K_s)$, $R(\Lambda)$…

Conclusions

STAY TUNED!

LFUV road to new physics!

Semileptonic B decays hint anomalies with respect to the SM at both tree and loop levels

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Ongoing and planned

$R(D^0)$, $R(D^+)$, $R(D_s)$, $R(\Lambda^{(*)}_c)$…

$R(\psi)$, $R(K_s)$, $R(\Lambda)$…

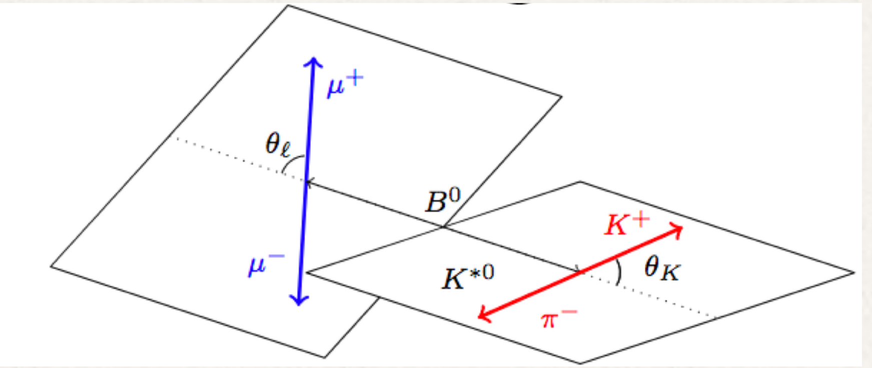
Thank you for your attention

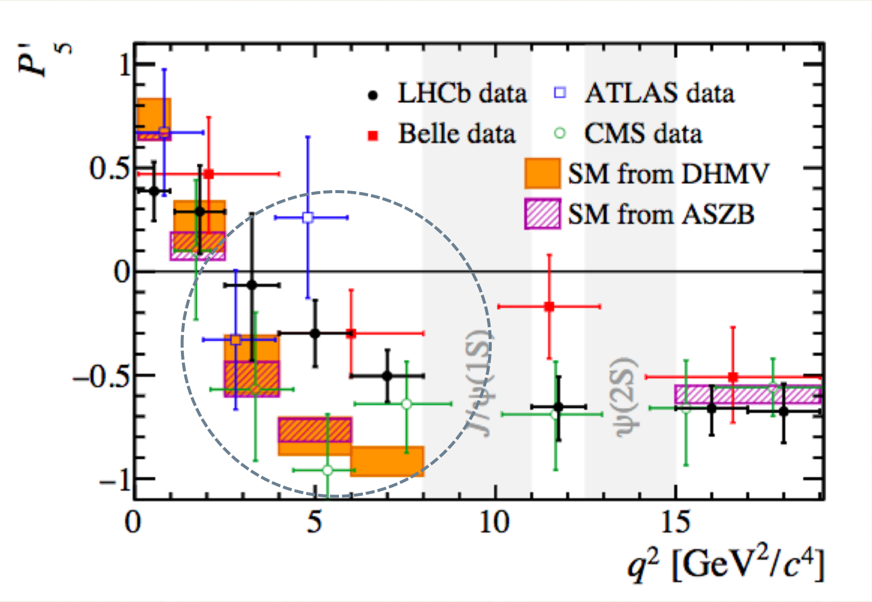
Any question?

Backup slides

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

- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ exhibits rich angular structure
- Optimized angular observable P'_5
  - The differential decay width can be parametrised in terms of this observable
  - Aim to reduce dependence on hadronic form factors





- LHCb measurement is in tension at the 3.4 σ
- Global picture at q^2 bins [4,6] and [6,8] GeV^2/c^4 is in tension with the SM at the level of 2.8 σ and 3 σ

LHCb: JHEP02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: arXiv:1805.04000
CMS: CMS-PAS-BPH-15-008