Recent results about lepton flavour universality violation at LHCb

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On behalf of the LHCb Collaboration

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Outline

- LFUV and semitauonic Beauty decays
- The LHCb detector
- Recent results from LHCb:
  - First observation of $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ and measurement of R(Λ_c^+) with hadronic tau decays [PRL 128(2021)191803]
  - Simultaneous measurement of $R(D^*)$ and $R(D)$ with muonic tau decays [LHCb-PAPER-2022-039 in preparation]
- Prospects and summary

Lepton flavour universality (LFU)

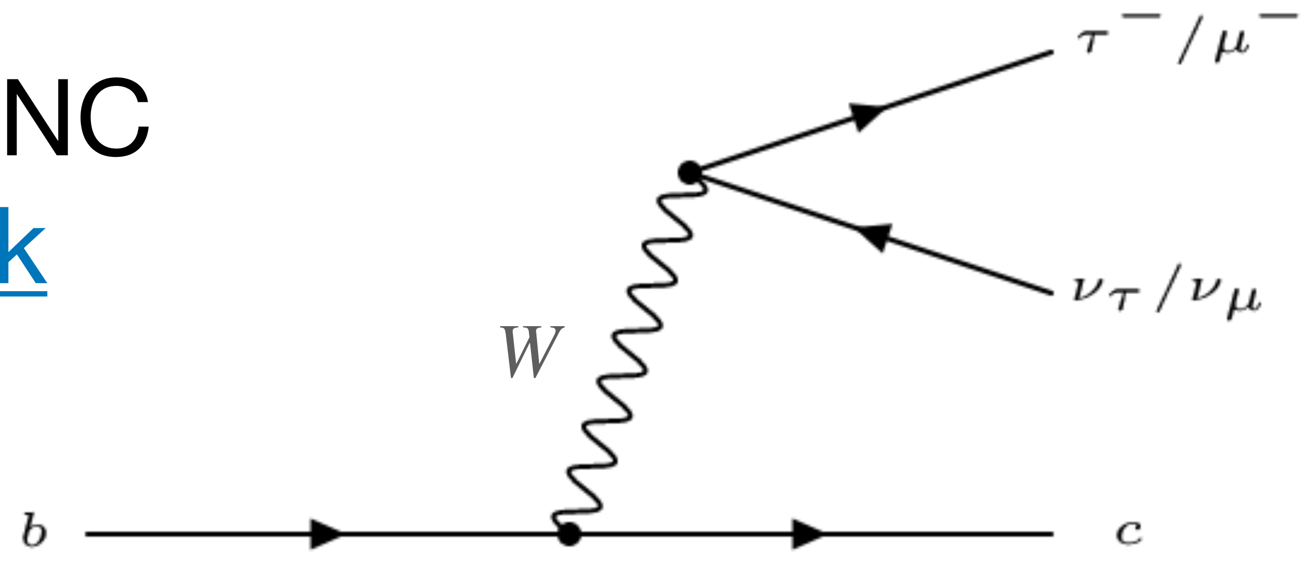
- An accidental lepton (l=e, μ, τ) flavour symmetry
- Broken in the Standard Model (SM) only by M_{l^-}
- New physics (NP) particles coupling to τ can lead to LFU violation (LFUV)

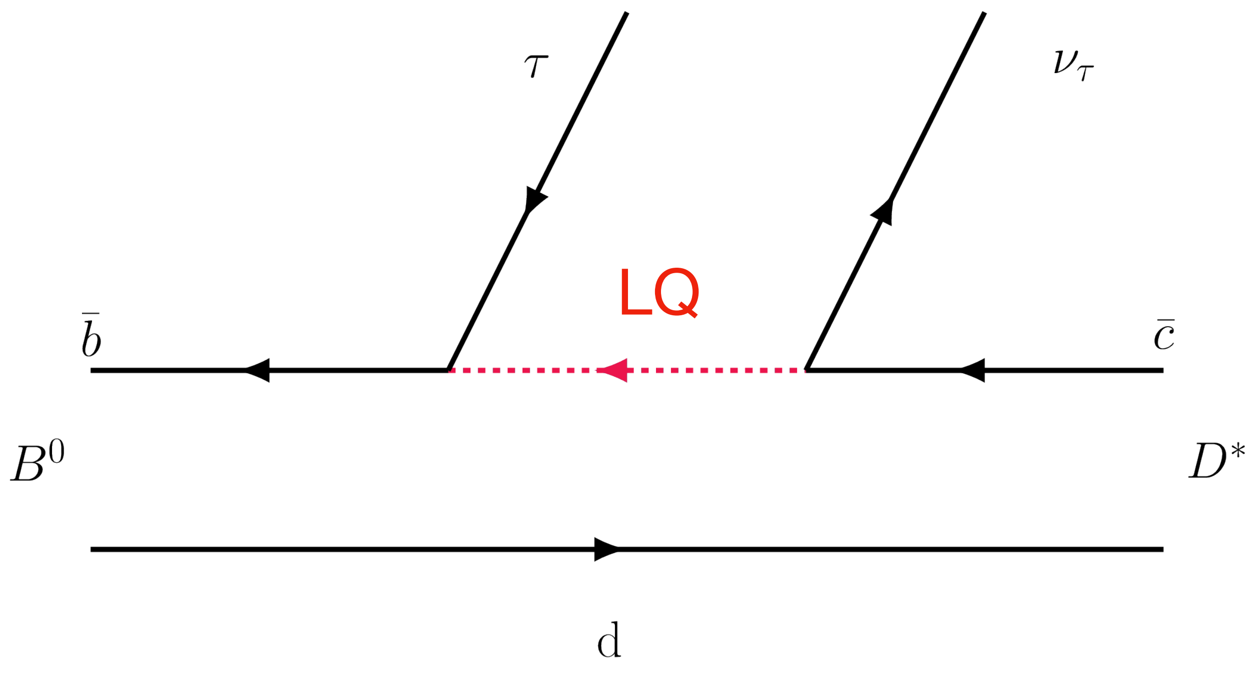
Semitauonic Beauty decays as tests of LFUV

$b \to cl\nu$ transitions: $R(X_c) = \dfrac{Br(X_b \to X_c\tau\nu_\tau)}{Br(X_b \to X_c\mu\nu_\mu)}$

e.g. possible contribution from leptoquark [PRL 116(2016)081801]

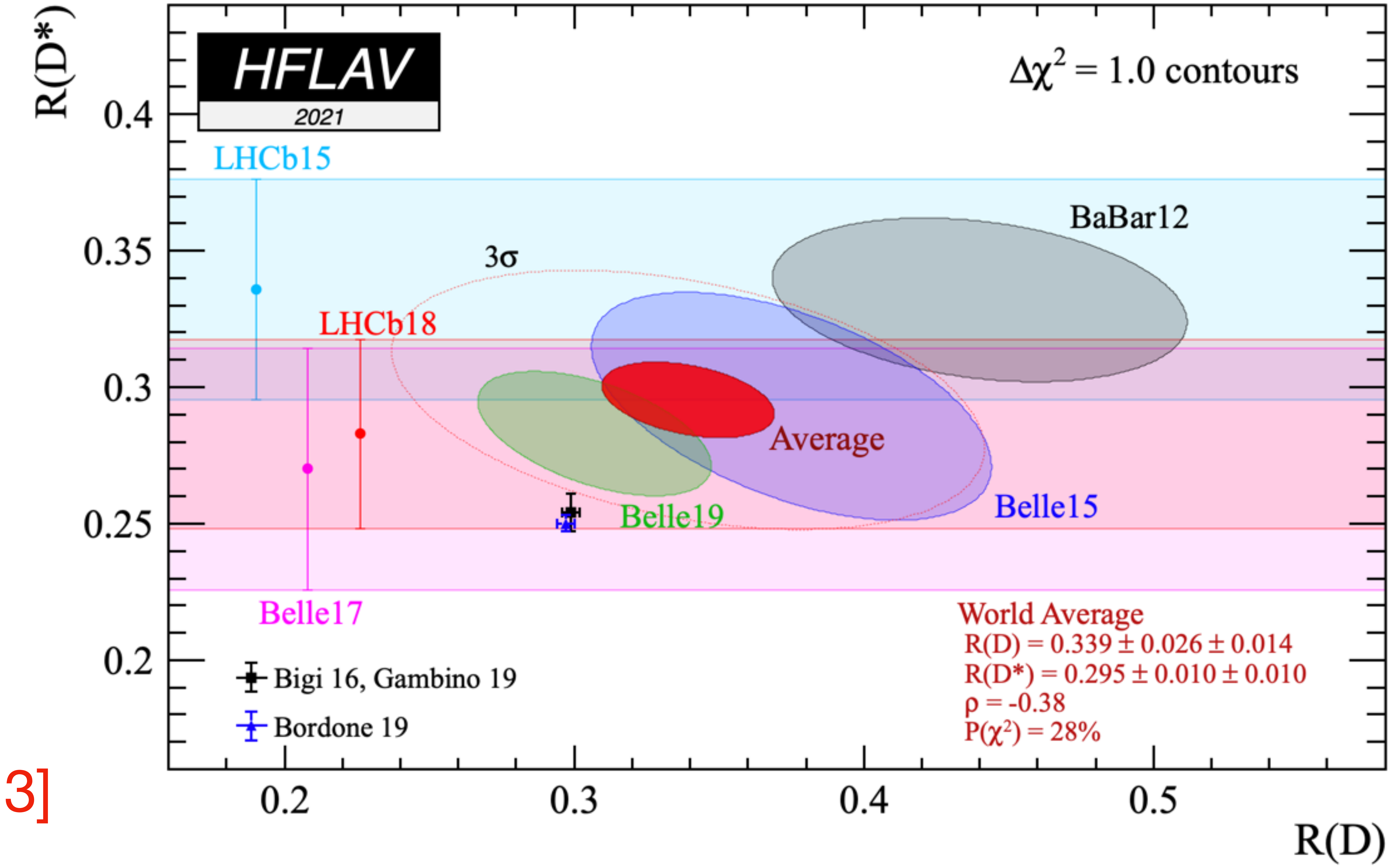
More info about FCNC see Andreas's talk





Previous experimental results about semitauonic B decays

- $R(D)$ and $R(D^*)$ combined results: 3.3σ away from SM predictions



Previous results from LHCb

- Muonic $R(D^*)$ with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ [PRL 115(2015)111803]
- Hadronic $R(D^*)$ with $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ [PRL 120(2018)171802, PRD 97(2018)072013]
- $R(J/\psi) = \dfrac{Br(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{Br(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$ ~2σ from SM [PRL 120(2018)121801]

All published LHCb results are based so far on 3fb^{-1} data at $\sqrt{s} = 7,8$ TeV.

The LHCb detector

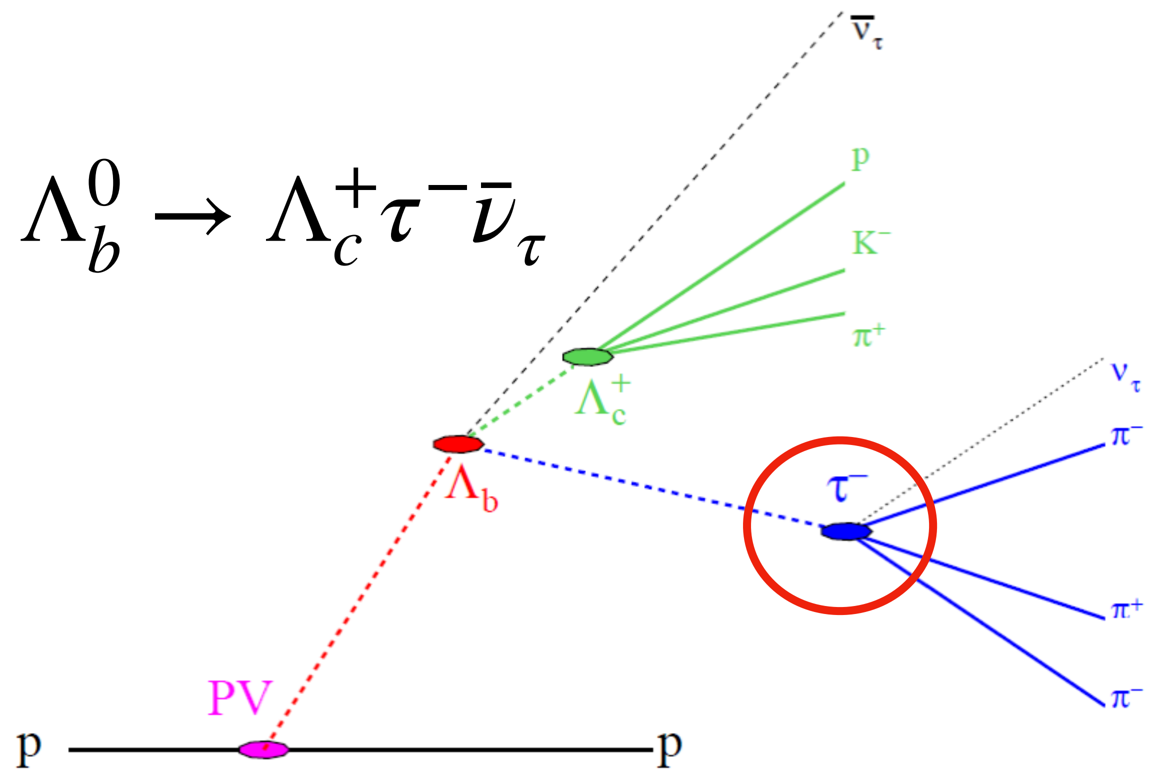
Int. J. Mod. Phys. A 30(2015)153002
JINST 3(2008)S08005

See Angelo’s talk
for more details

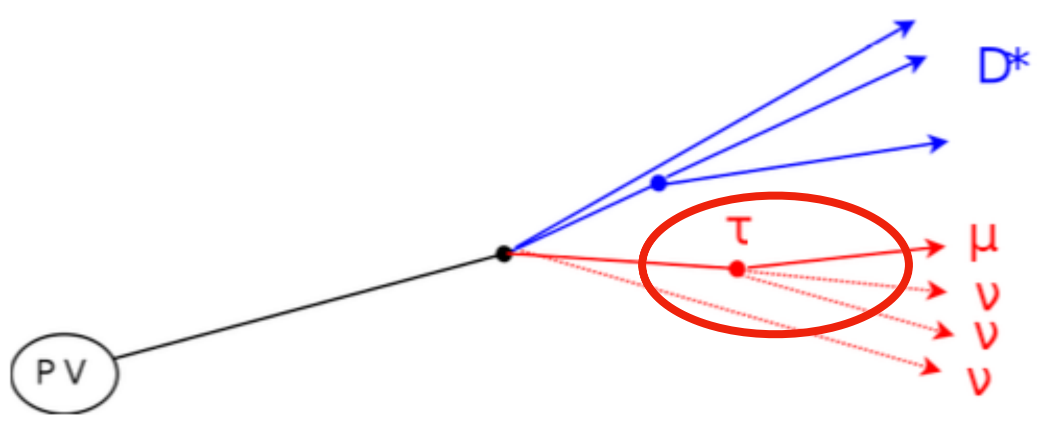
A single-arm forward spectrometer, designed for the study of heavy flavour physics

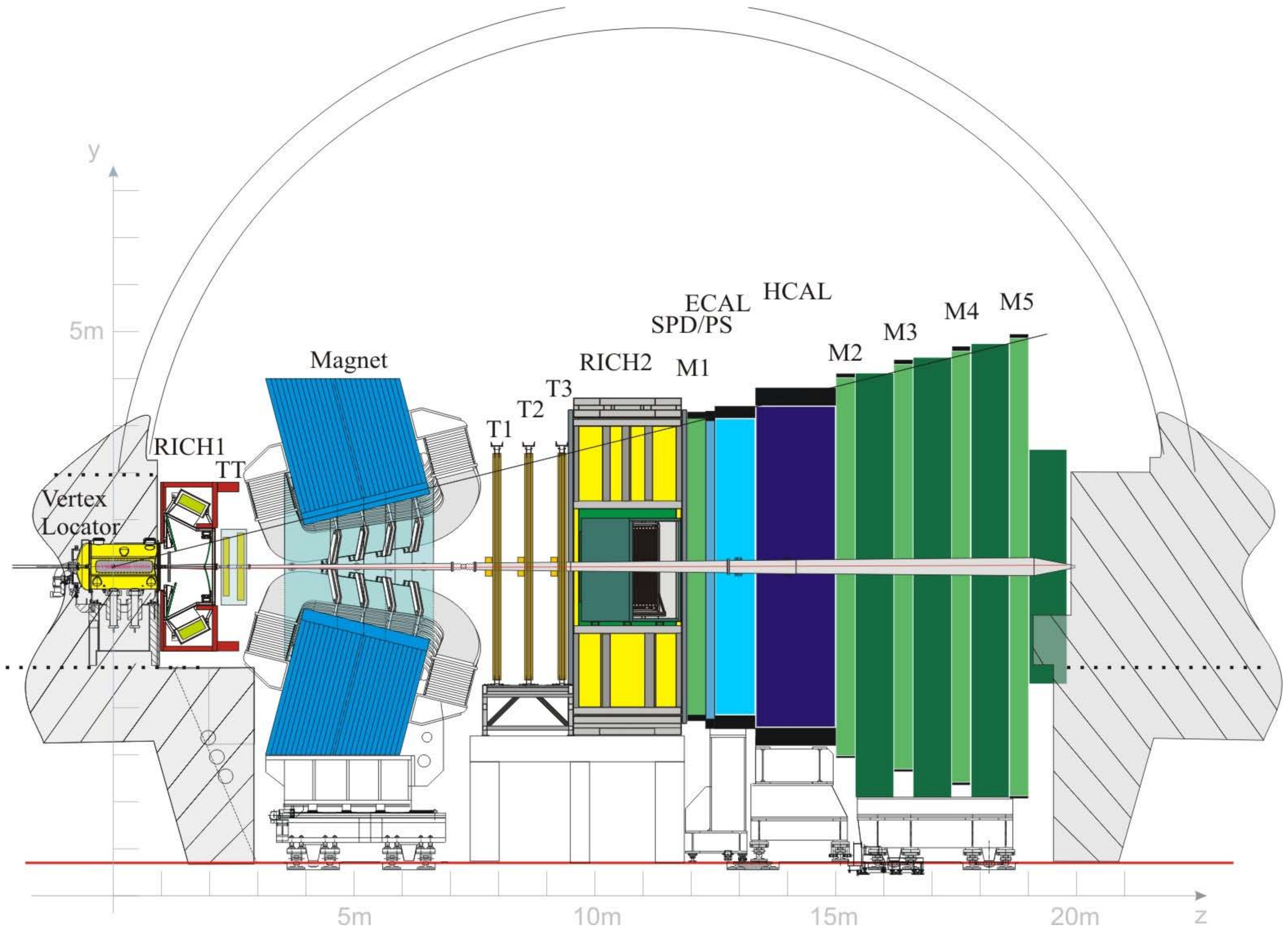
- Excellent vertex, IP and decay-time resolution
- Very good momentum resolution
- Good hadron and muon identification
- $2 < \eta < 5$ range (LHCb acceptance):
  ~$3 \times 10^4/s\ b\bar{b}$ pairs@ 7 TeV ~x2 yield@ 13 TeV

$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$



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





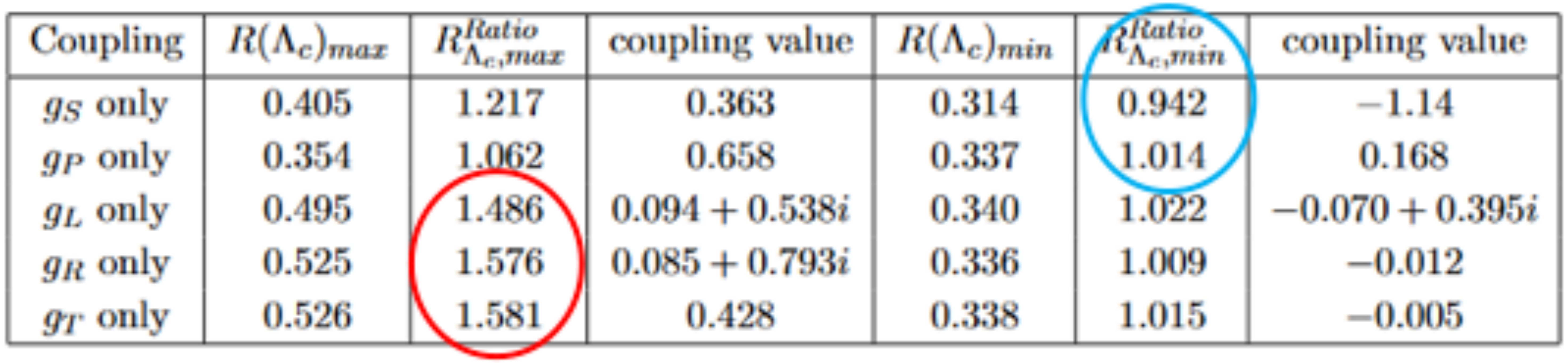
First observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ and measurement of $R(\Lambda_c^+)$ with hadronic tau decays

[PRL 128(2021)191803]

Why LFUV tests with Λ_b^0 decays are interesting?

- The spin $\frac{1}{2}$ baryonic channel is complementary to mesonic channels ($R(D^*)$…).
- SM prediction:
  $R(\Lambda_c^+)_{SM} = 0.324 \pm 0.004$ [PRD 99(2019)055008]
- But different new physics(NP) couplings: could help to constrain NP models
- Unique measurement to LHCb. Never searched for before!

NP predictions with all present constraints from the meson sector



Coupling	$R(\Lambda_c)_{max}$	$R^{Ratio}_{\Lambda_c,max}$	coupling value	$R(\Lambda_c)_{min}$	$R^{Ratio}_{\Lambda_c,min}$	coupling value
g_S only	0.405	1.217	0.363	0.314	0.942	-1.14
g_P only	0.354	1.062	0.658	0.337	1.014	0.168
g_L only	0.495	1.486	$0.094 + 0.538i$	0.340	1.022	$-0.070 + 0.395i$
g_R only	0.525	1.576	$0.085 + 0.793i$	0.336	1.009	-0.012
g_T only	0.526	1.581	0.428	0.338	1.015	-0.005

$$R^{Ratio}_{\Lambda_c} = \frac{R(\Lambda_c)_{exp}}{R(\Lambda_c)_{SM}}$$

[JHEP 1708(2017)131]

Searching for $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ at LHCb… [PRL 128(2021)191803]

Data samples: 3 fb^{-1} pp collision data @ 7,8 TeV from Run1

Λ_c^+ reconstructed by $pK^-\pi^+$, and τ^- by $\pi^-\pi^+\pi^-$

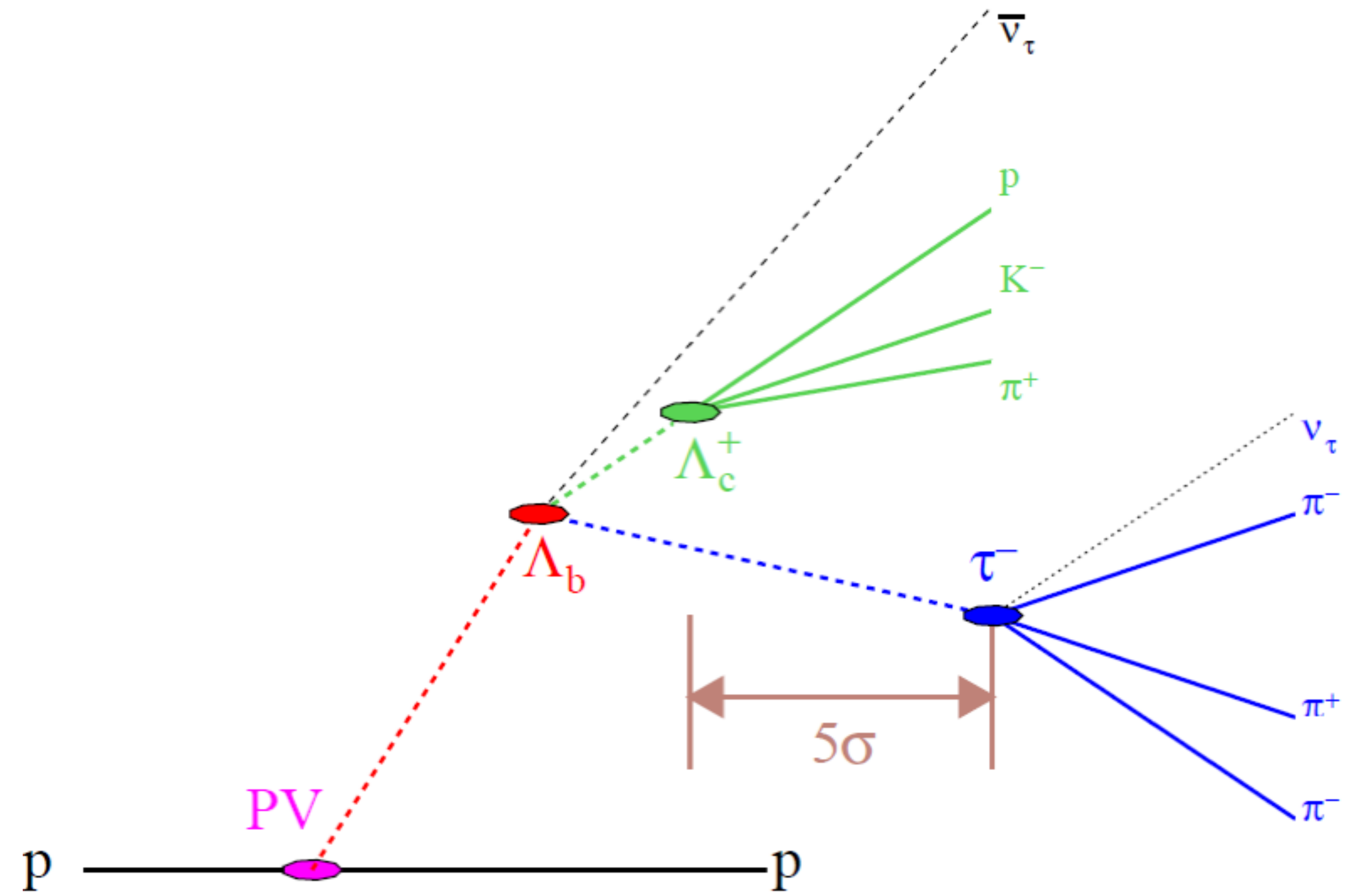
$$R(\Lambda_c^+) = \boxed{\frac{Br(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{Br(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)}} \times \boxed{\frac{Br(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)}{Br(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}}$$

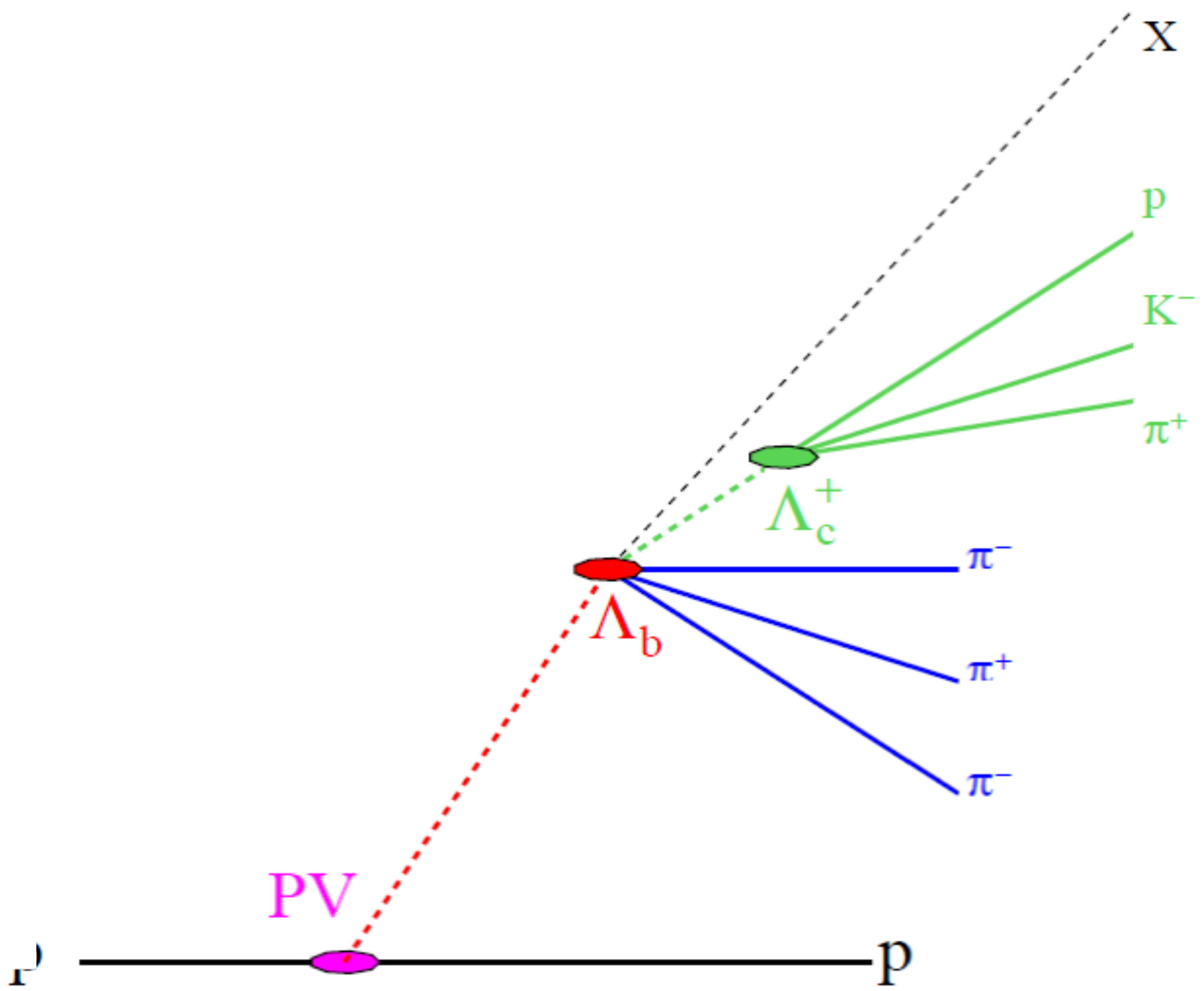
Measured $K(\Lambda_c^+)$

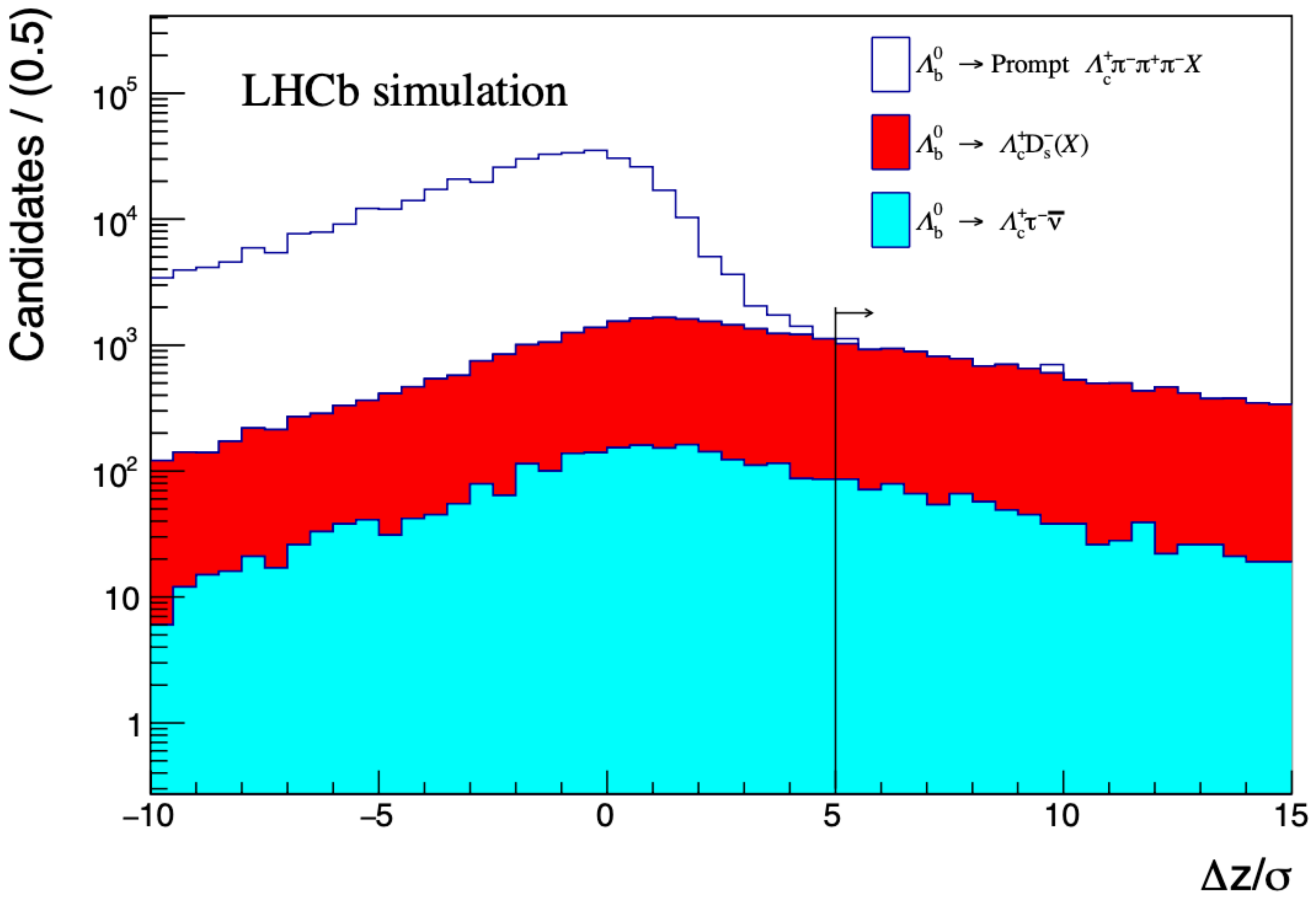
External inputs

Prompt rejection ~5×10^3 level

$\Delta z = z(3\pi) - z(\Lambda_c^+) > 5\sigma_{vtx}$



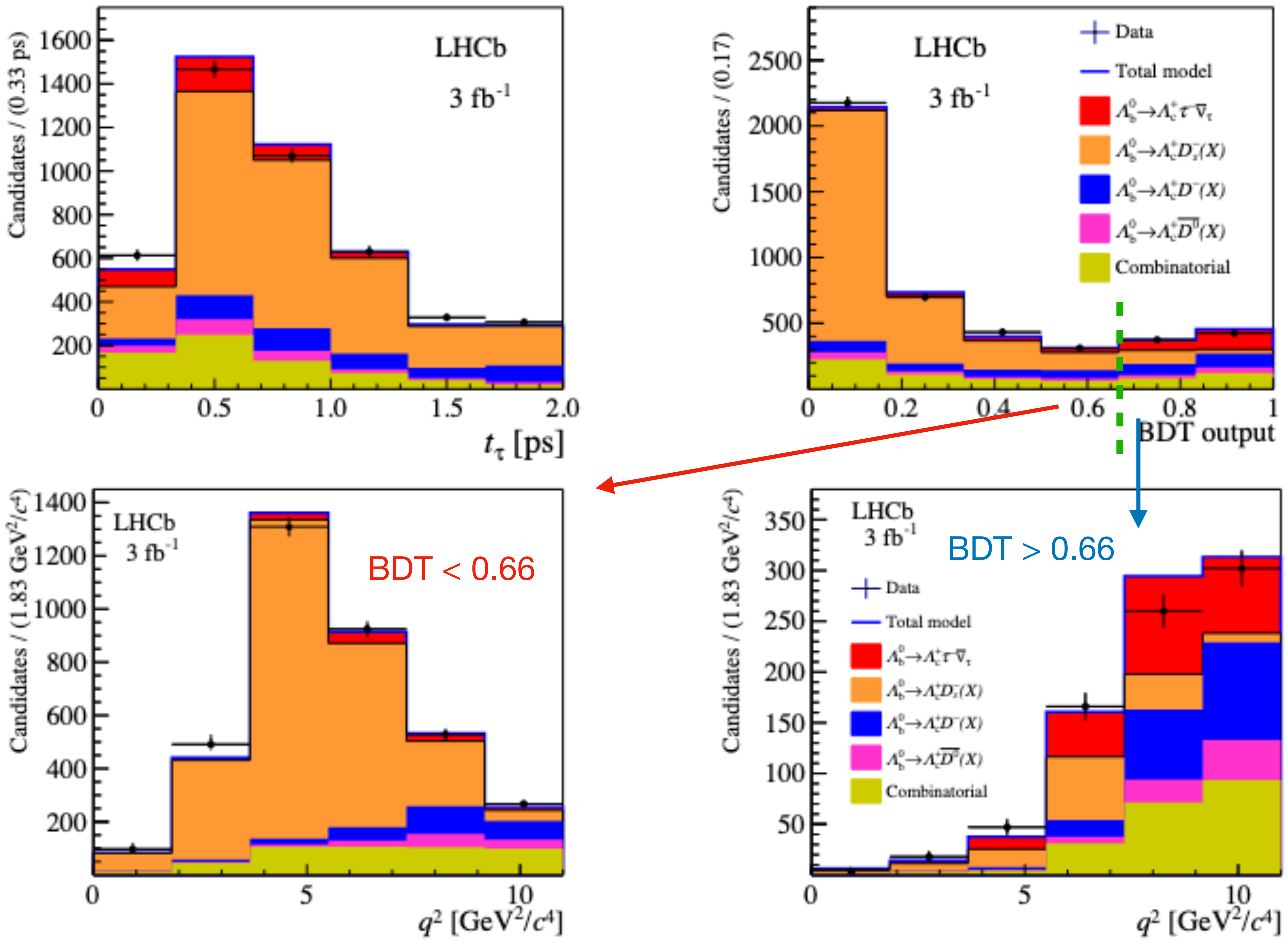




Searching for $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ at LHCb… [PRL 128(2021)191803]

Extracting signal yield from 3D fit

- $q^2(= (p_B - p_{D^{*+}})^2)$, t_τ and anti-D_s BDT output



- Signal significance: 6.1σ
  -> first observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

- $$K(\Lambda_c^+) = \frac{Br(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{Br(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)}$$
  $$= 2.46 \pm 0.27(stat) \pm 0.40(syst)$$

- Using $Br(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)$ & $Br(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)$,
  $R(\Lambda_c^+) = 0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$
  (SM prediction: 0.324 ± 0.004)

- ~1σ from SM

- Could exclude some NP parameter space

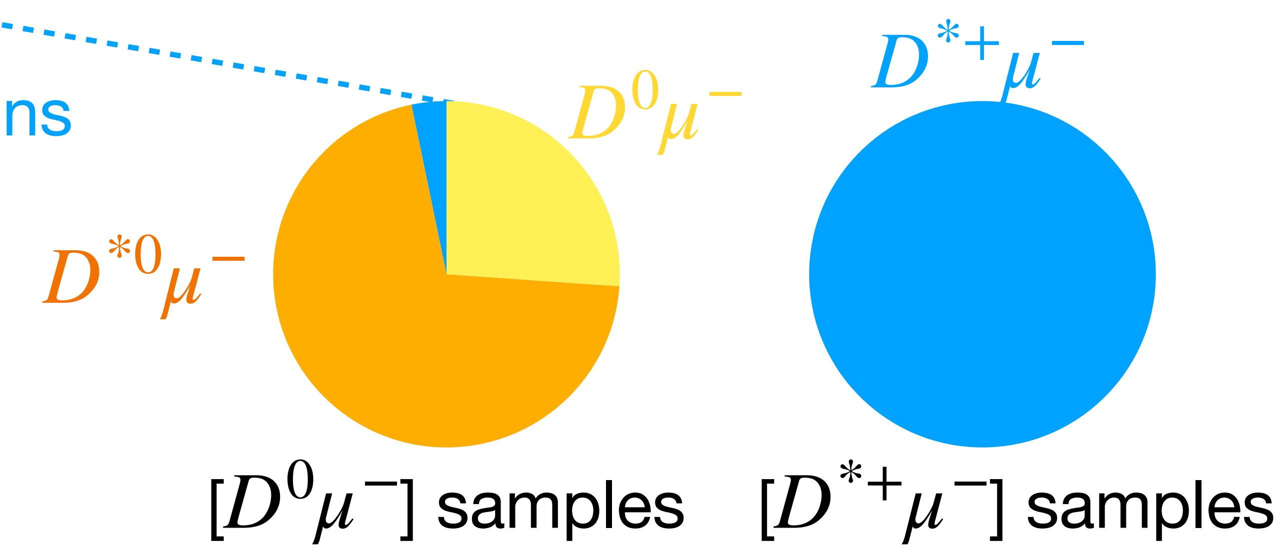
Simultaneous measurement of $R(D^*)$ and $R(D)$ with muonic tau decays [LHCb-PAPER-2022-039 in preparation]

More details see CERN seminar by Greg

[LHCb-PAPER-2022-039 in preparation]

Comparison with previous muonic $R(D^*)$ [PRL 115(2015)111803] at LHCb

- Before: measure $R(D^*)$ with Run1 $[D^{*+}\mu^-]$ data
- Now: simultaneously measure $R(D)$ & $R(D^*)$ with Run1 $[D^0\mu^-]$ and $[D^{*+}\mu^-]$ data
  - $D^0 \to K^+\pi^-, D^{*+} \to D^0\pi^+$
    - Veto $D^{*+} \to D^0\pi^+$ in $[D^0\mu^+]$ sample
  - Trigger on D^0 - preserve acceptance for soft muons
  - New: custom muon ID classifier, flatter in kinematic acceptance[JINST 8 P12013]
    - Reduce misID background (dominant systematics in previous muonic $R(D^*)$)
  - Higher statistics: $[D^0\mu^-]$ sample - 5x larger than $[D^{*+}\mu^-]$



Remaining $D^{*+}\mu^-$ in $[D^0\mu^-]$ samples with soft pions

Experimental challenge

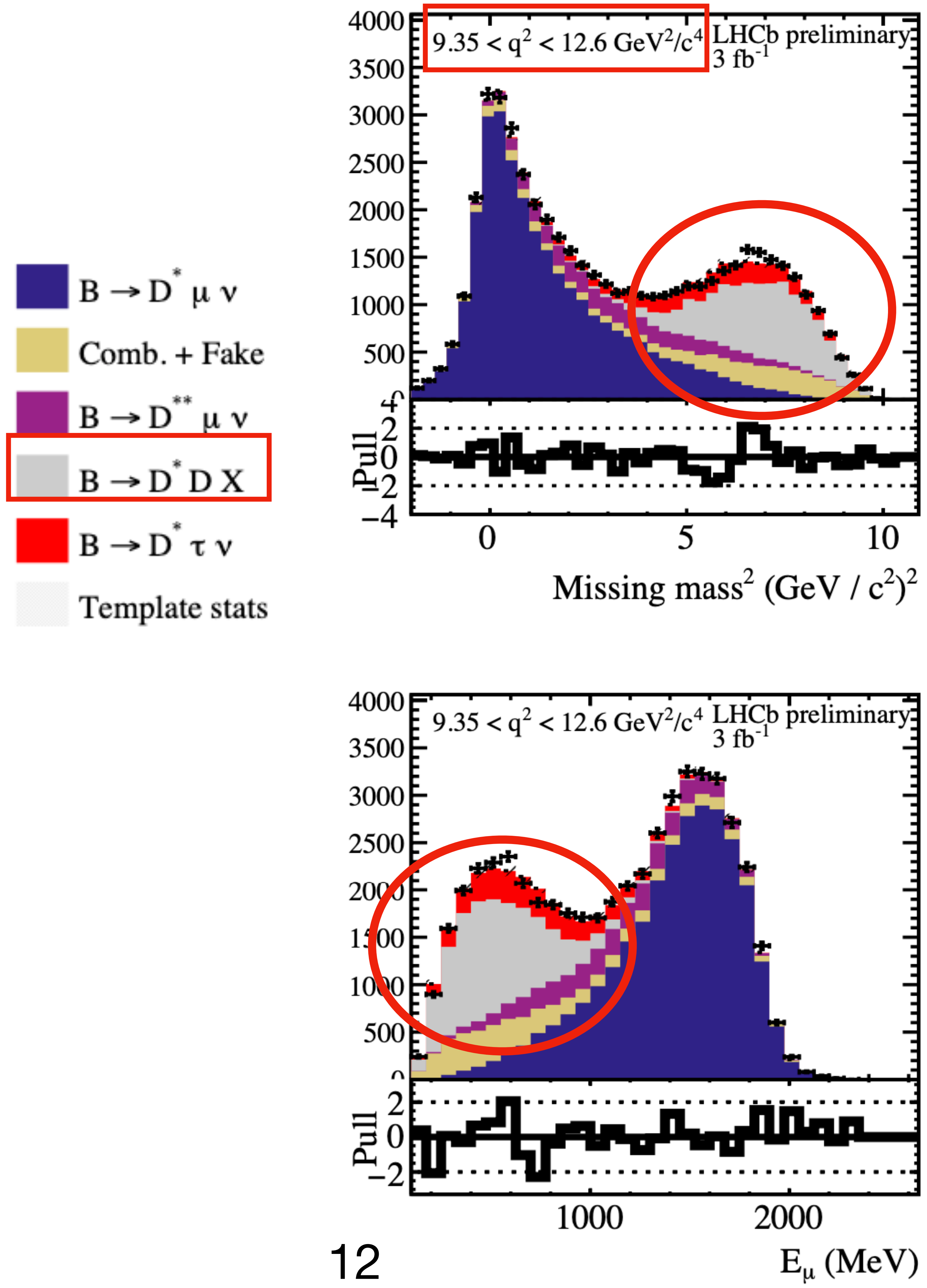
[LHCb-PAPER-2022-039 in preparation]

- Numerous background from different sources:
  - Partially reconstructed B decays
    - $B \to D^*\mu\nu, B \to D^{**}\mu\nu,$ $B \to D^{*(*)}D^{(*)}(\to \mu X)X\ldots$
  - Misidentified background
  - Combinatorial background

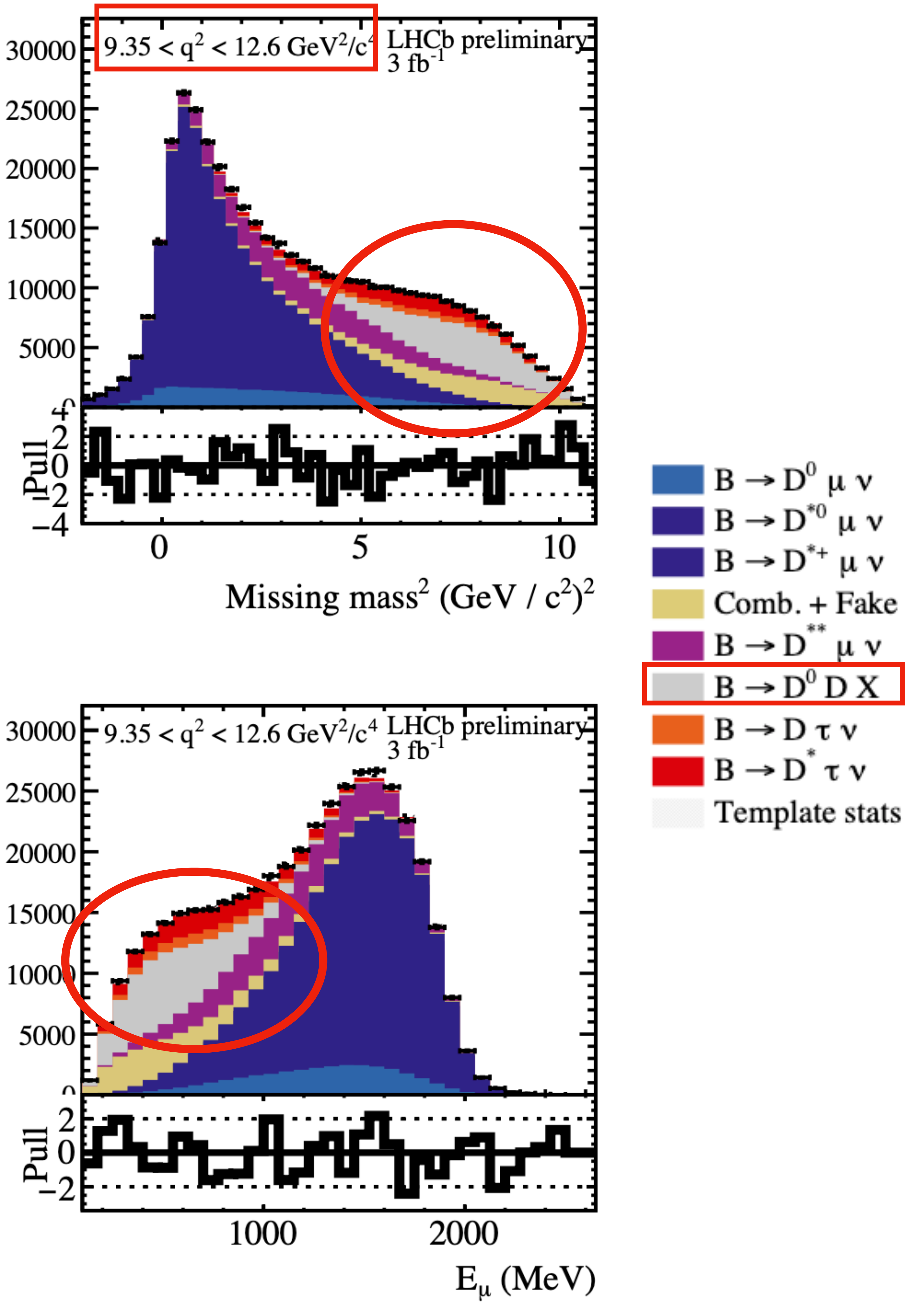
3D Fit

- $q^2 = (p_B - p_{D^{(*)}})^2$
- $m^2_{miss} = (p_B - p_{D^{(*)}} - p_\mu)^2$
- Energy of μ: E_μ
- 8 samples in total (for D^0 & D^{*+}):
  - Signal sample
  - Three isolated control samples (with extra π, $\pi\pi$ or K)
- Simultaneous fit of all 8 samples

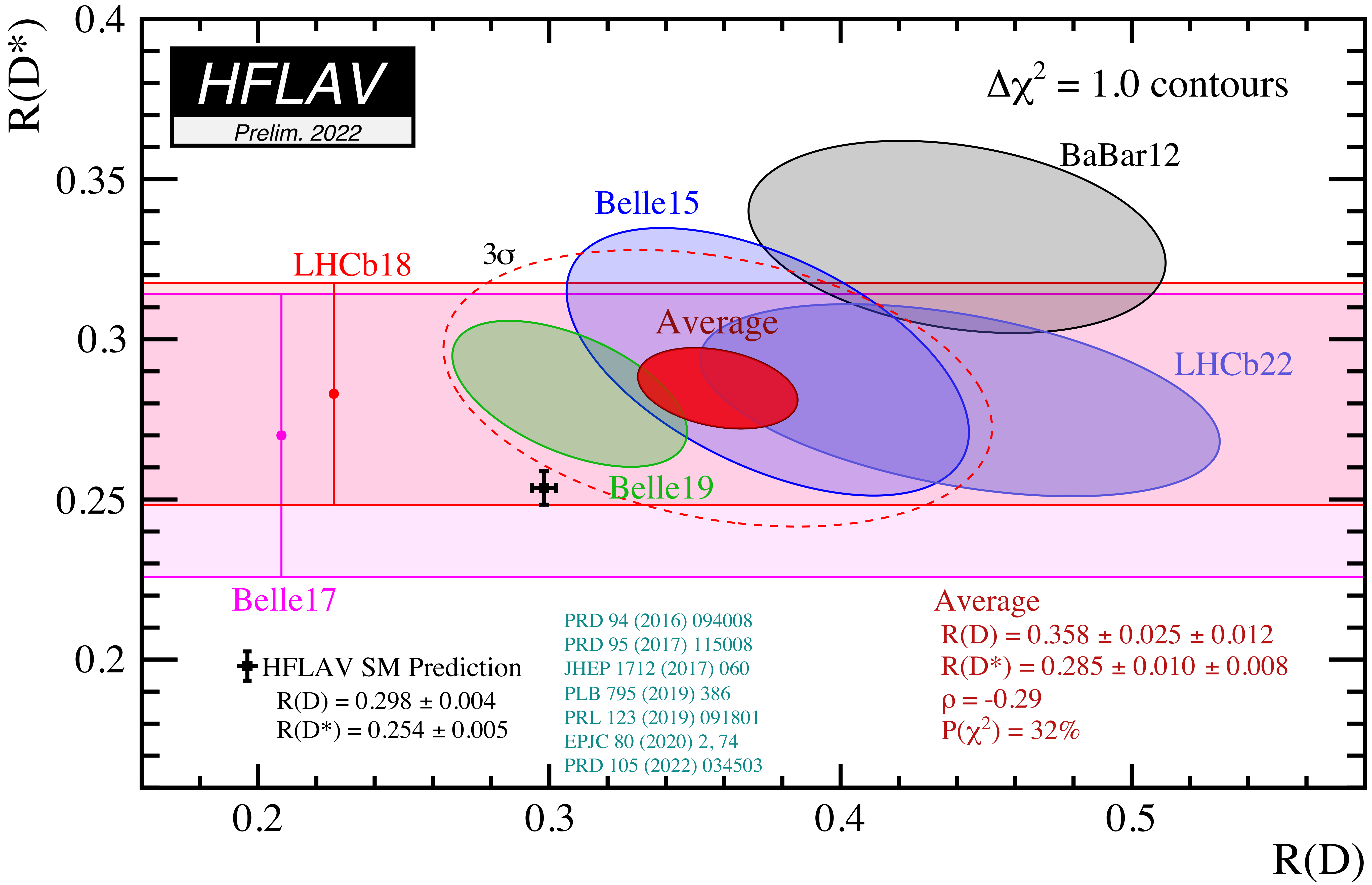
$D^{*+}\mu^-$ signal sample



$D^0\mu^-$ signal sample



[LHCb-PAPER-2022-039 in preparation]



Result of this measurement:

- $R(D^*) = 0.281 \pm 0.018(stat) \pm 0.024(syst)$
- $R(D) = 0.441 \pm 0.060(stat) \pm 0.066(syst)$
- Correlation $\rho = -0.43$
- 1.9σ agreement with SM

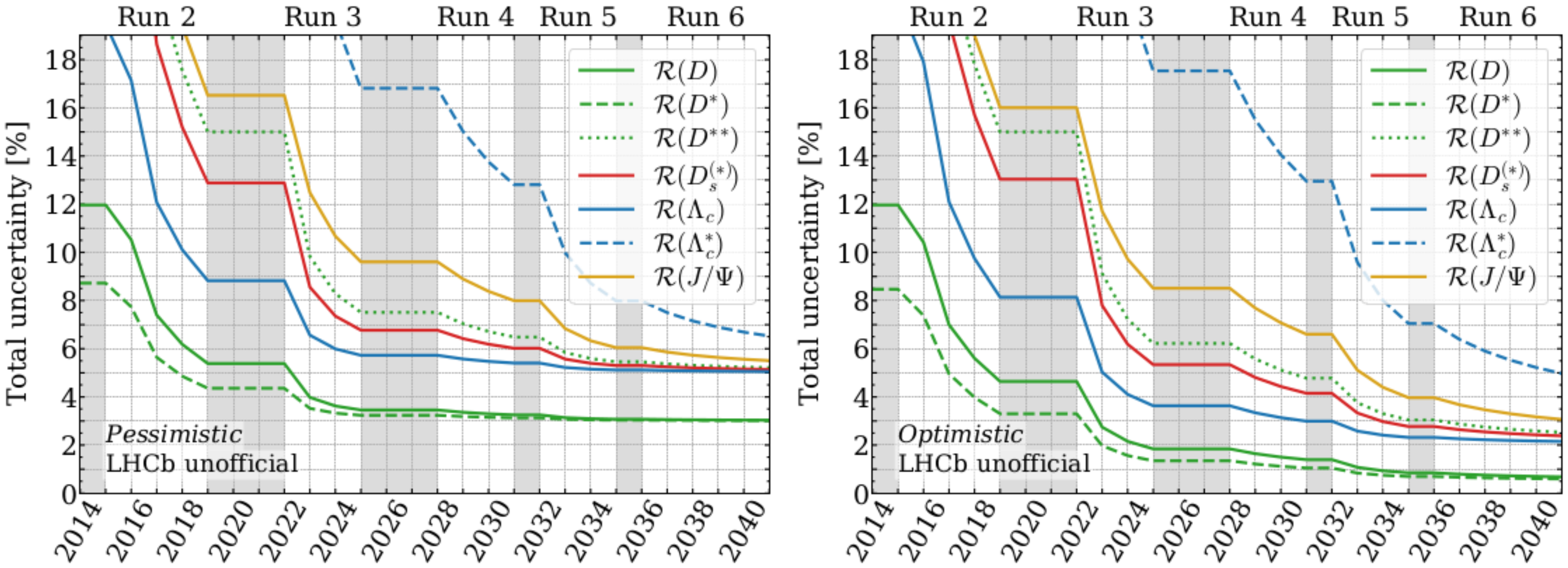
New preliminary average:

- Slightly lower $R(D^*)$, slightly higher $R(D)$, reduced correlation
- $3.3\sigma \rightarrow 3.2\sigma$ away from SM
- Global picture unchanged…

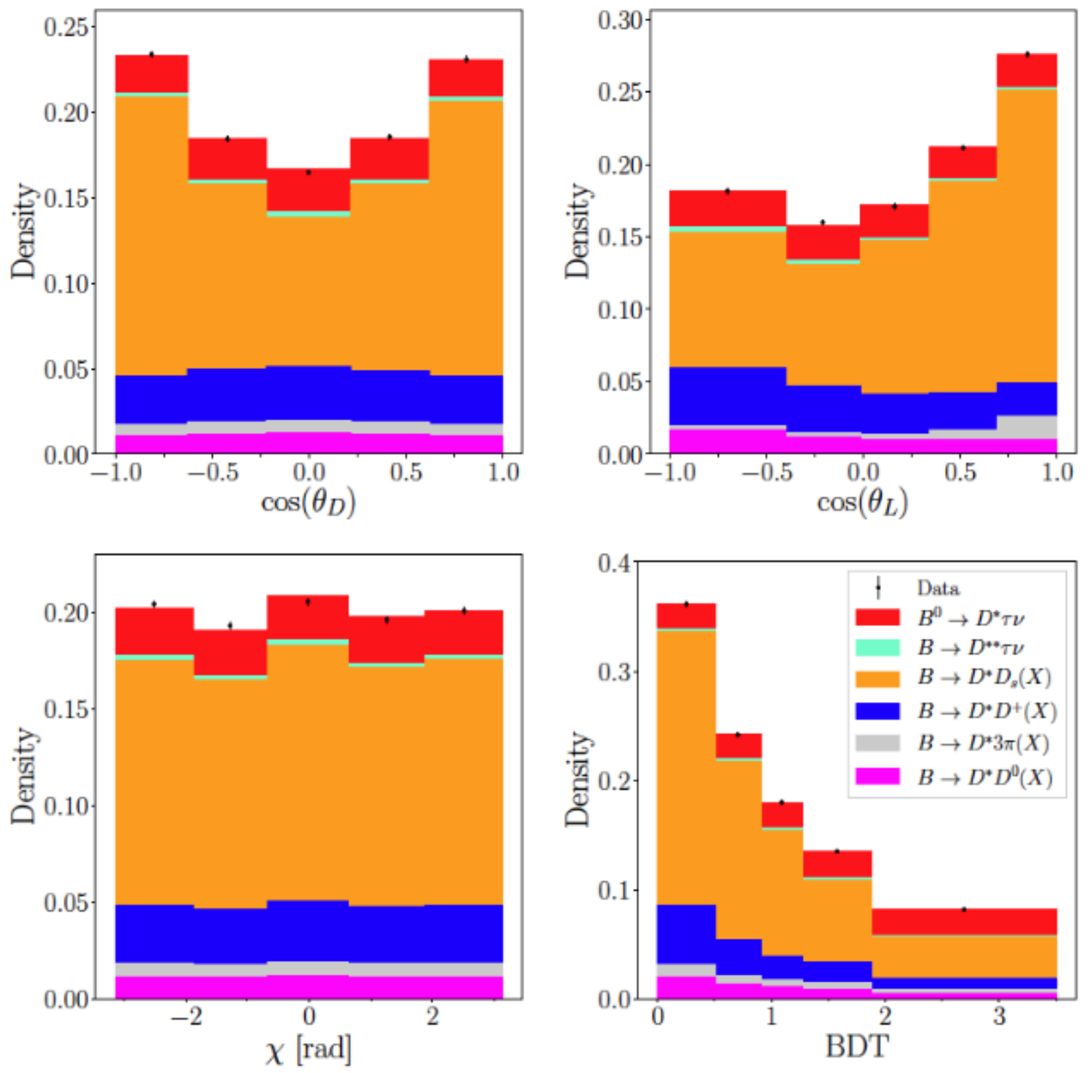
Prospects for LFUV tests with semitauonic decays at LHCb

[Rev. Mod. Phys. 94, 015003]

F. U. Bernlochner, M. F. Sevilla, D. J. Robinson, and G. Wormser



- More statistics
  - Analyses including Run2 6 fb^{-1} data samples ongoing
  - Upcoming data taking in Run3
- Control of systematics
  - New technologies (fast simulation, multivariate selection…)
  - Inputs from other experiments and theorists
  - …
- Probe into other observables
  - Polarisation measurement
  - Angular analysis
  - …



[JHEP 11(2019)133]

D. Hill, M. John, W. Ke and A. Poluektov

Prospects of angular analysis of $B^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ with full Run1+Run2 data sample from simulation

Summary

- First observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ and first measurement of $R(\Lambda_c^+)$

  [PRL 128(2021)191803]

  - Significance 6.1σ
  - Measured $R(\Lambda_c^+) = 0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$, in agreement with SM
- First joint $R(D)$ & $R(D^*)$ measurement at hadron collider

  [LHCb-PAPER-2022-039 in preparation]

  - Excellent agreement with world average, 1.9σ beyond SM
  - New preliminary average: $3.3\sigma \to 3.2\sigma$ away from SM, remains intriguing
- Complementary measurement to each other: different constraint
  - Baryonic and mesonic Beauty decays: different spin, different form factor
  - Hadronic and muonic τ decays: different background, different normalisation
- More results upcoming! Stay tuned!

Thank you for listening!

Backup

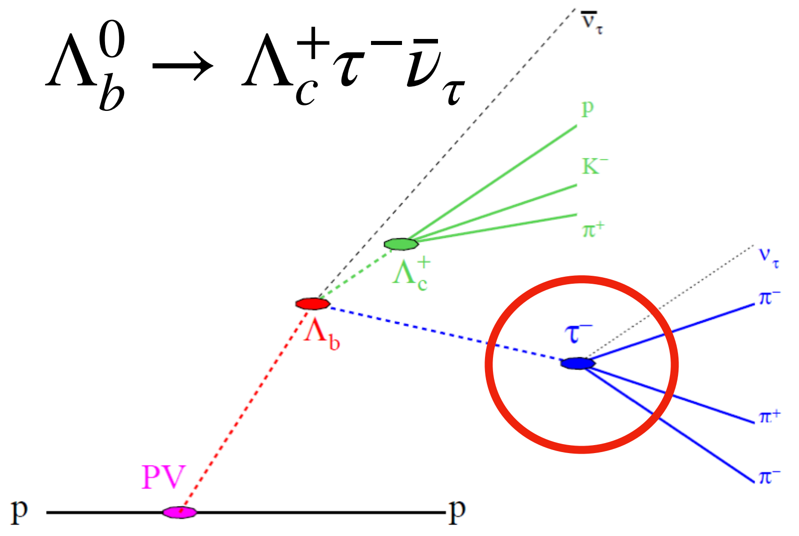
The LHCb detector

Int. J. Mod. Phys. A 30(2015)153002
JINST 3(2008)S08005

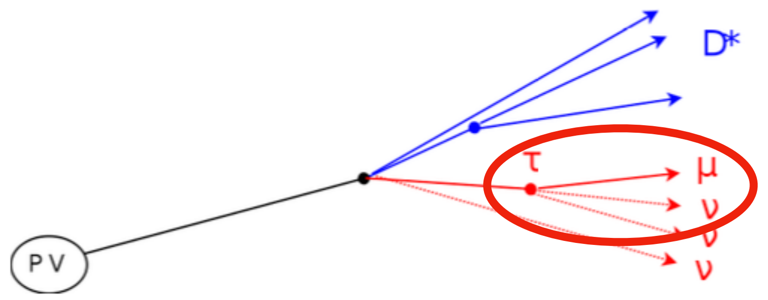
A single-arm forward spectrometer, designed for the study of heavy flavour physics

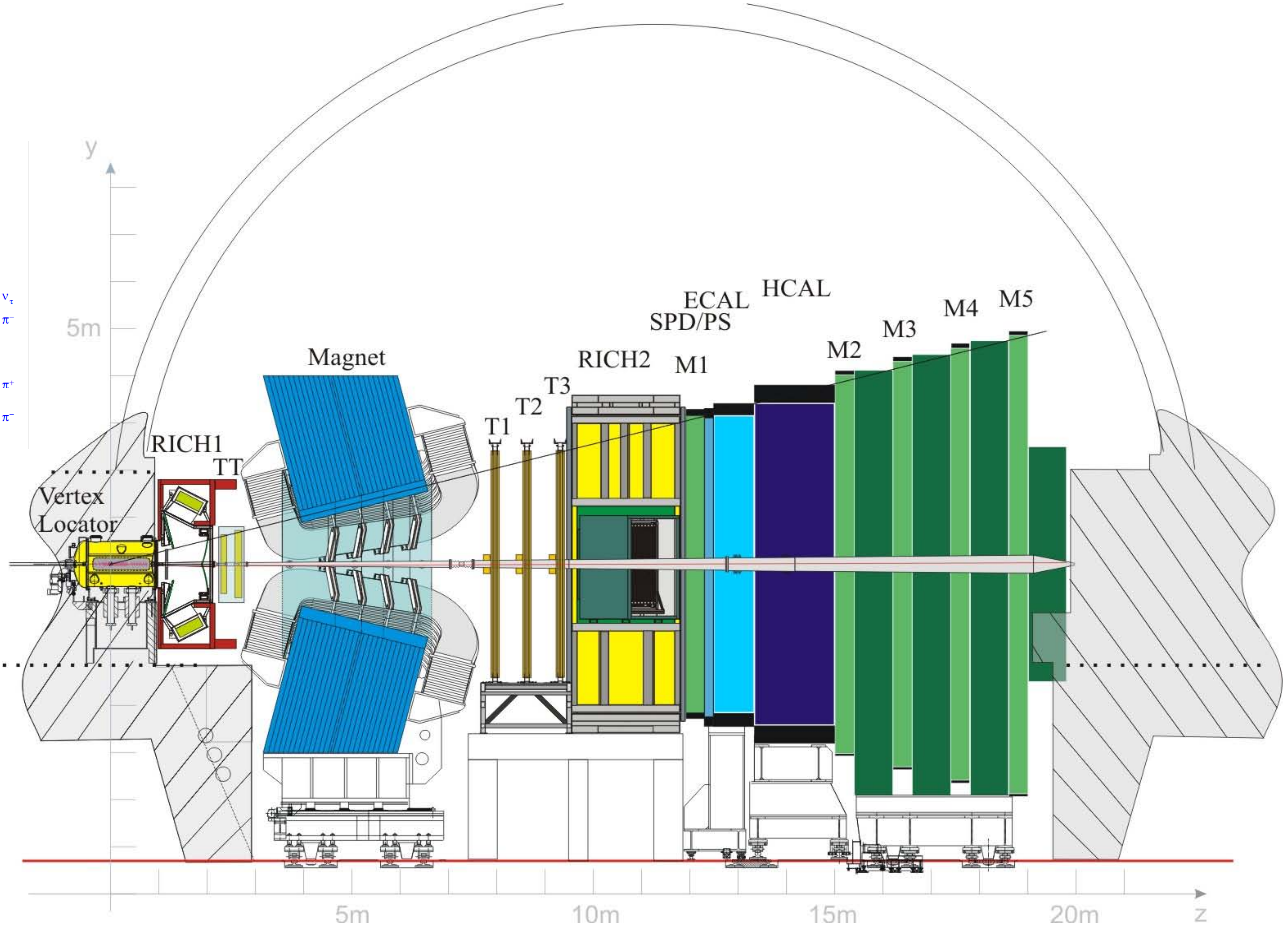
- Excellent vertex, IP and decay-time resolution
  - σ(IP) ≈ 20 μm for high-p_T tracks
  - $\sigma(\tau)$ ≈ 45 fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$
- Very good momentum resolution
  - $\delta p/p$ ≈ 0.5%-1% for $p \in$ (0,200) GeV
  - $\sigma(m_B)$ ≈ 24 MeV for two-body decays
- Hadron and muon identification
  - $\varepsilon_{K\to K}$ ≈ 95% for $\varepsilon_{\pi\to K}$ ≈ 5% up to 100 GeV
  - $\varepsilon_{\mu\to\mu}$ ≈ 97% for $\varepsilon_{\pi\to\mu}$ ≈ 1%-3%
- $2 < \eta < 5$ range (LHCb acceptance):
  ~$3 \times 10^4/s$ $b\bar{b}$ pairs@ 7 TeV ~x2 yield@ 13 TeV

$\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau$



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



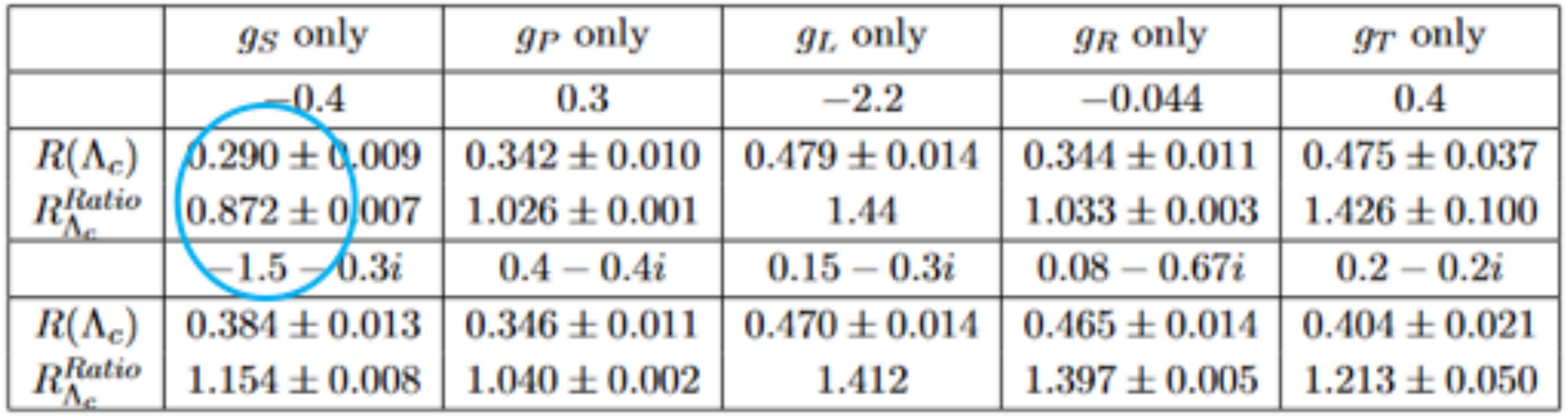


Why LFUV tests with Λ_b^0 decays are interesting?

- Different new physics(NP) couplings: could help to constrain NP models

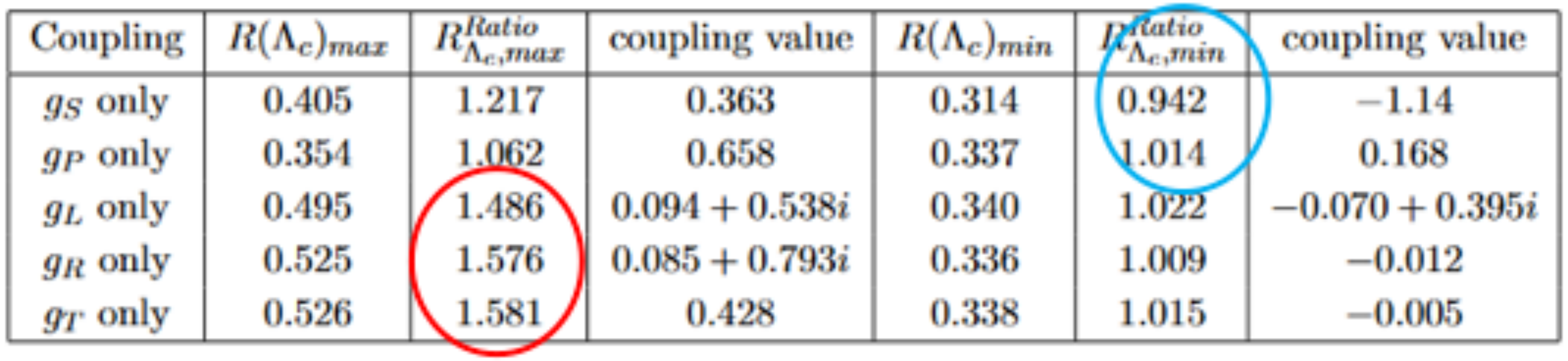
NP expectations for R(Λ_c^+) in various models

A. Datta et al.. Journal of High Energy Physics 1708 (2017) 131



	g_S only	g_P only	g_L only	g_R only	g_T only
	-0.4	0.3	-2.2	-0.044	0.4
$R(\Lambda_c)$	0.290 ± 0.009	0.342 ± 0.010	0.479 ± 0.014	0.344 ± 0.011	0.475 ± 0.037
$R_{\Lambda_c}^{Ratio}$	0.872 ± 0.007	1.026 ± 0.001	1.44	1.033 ± 0.003	1.426 ± 0.100
	$-1.5 - 0.3i$	$0.4 - 0.4i$	$0.15 - 0.3i$	$0.08 - 0.67i$	$0.2 - 0.2i$
$R(\Lambda_c)$	0.384 ± 0.013	0.346 ± 0.011	0.470 ± 0.014	0.465 ± 0.014	0.404 ± 0.021
$R_{\Lambda_c}^{Ratio}$	1.154 ± 0.008	1.040 ± 0.002	1.412	1.397 ± 0.005	1.213 ± 0.050

NP predictions with all present constraints from the meson sector



Coupling	$R(\Lambda_c)_{max}$	$R_{\Lambda_c,max}^{Ratio}$	coupling value	$R(\Lambda_c)_{min}$	$R_{\Lambda_c,min}^{Ratio}$	coupling value
g_S only	0.405	1.217	0.363	0.314	0.942	-1.14
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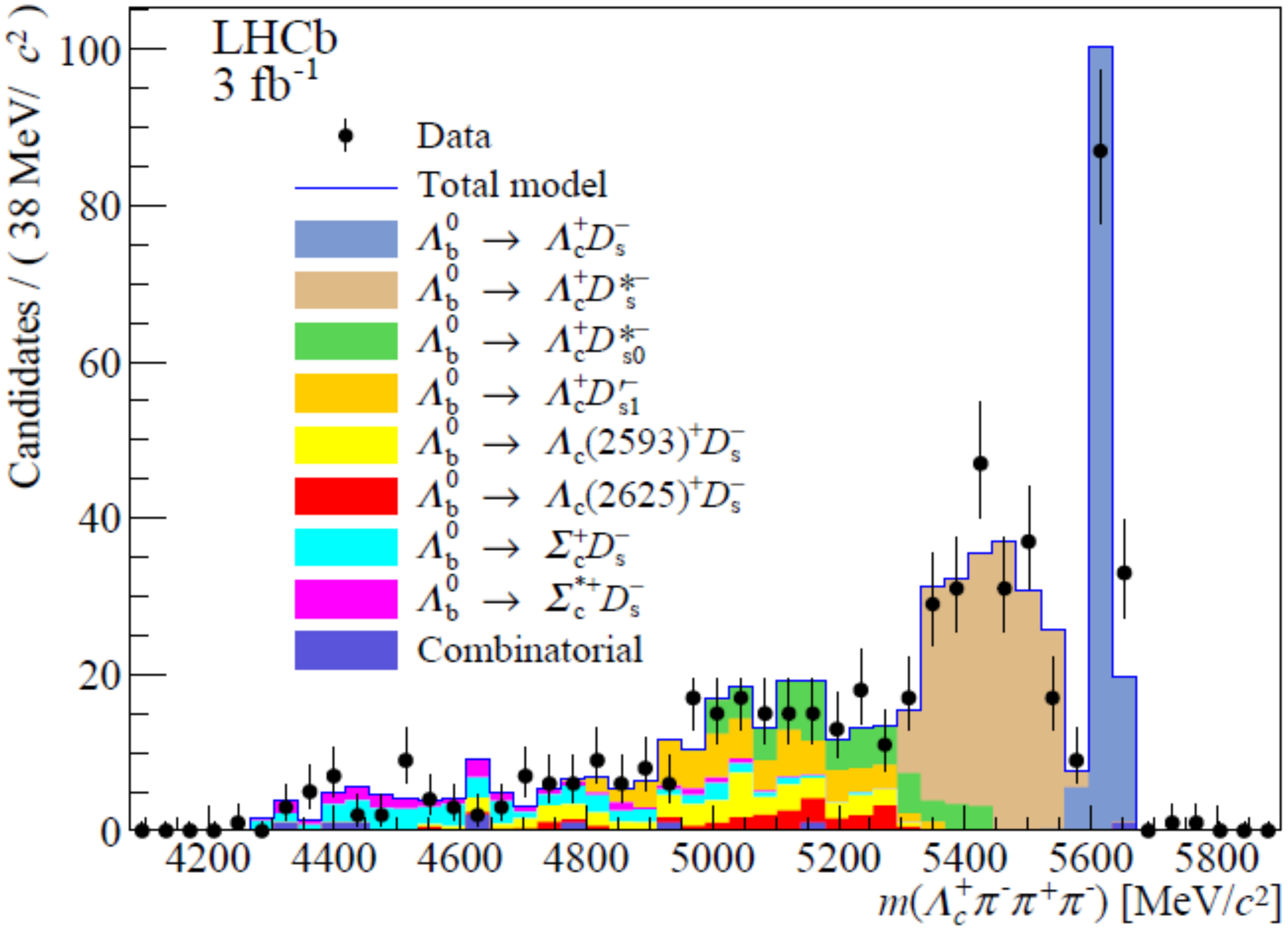
Searching for $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ at LHCb…

[PRL 128(2021)191803]

- Main backgrounds
  - Prompt background from $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^- X$ decays
  - Double charm background from $\Lambda_b^0 \rightarrow \Lambda_c^+ \{D^-, D^0, D_s^-\} X$ decays
  - Feed-down background from $\Lambda_b^0 \rightarrow \Lambda_c^{*(*)} D_s^{*(*)-}$ decays
  - Combinatorial background -> Controlled by data-based samples

Controlled by fitting
$\Lambda_c^+ \pi^- \pi^+ \pi^-$
mass distribution



Systematic uncertainties in $R(\Lambda_c^+)$ measurement

[PRL 128(2021)191803]

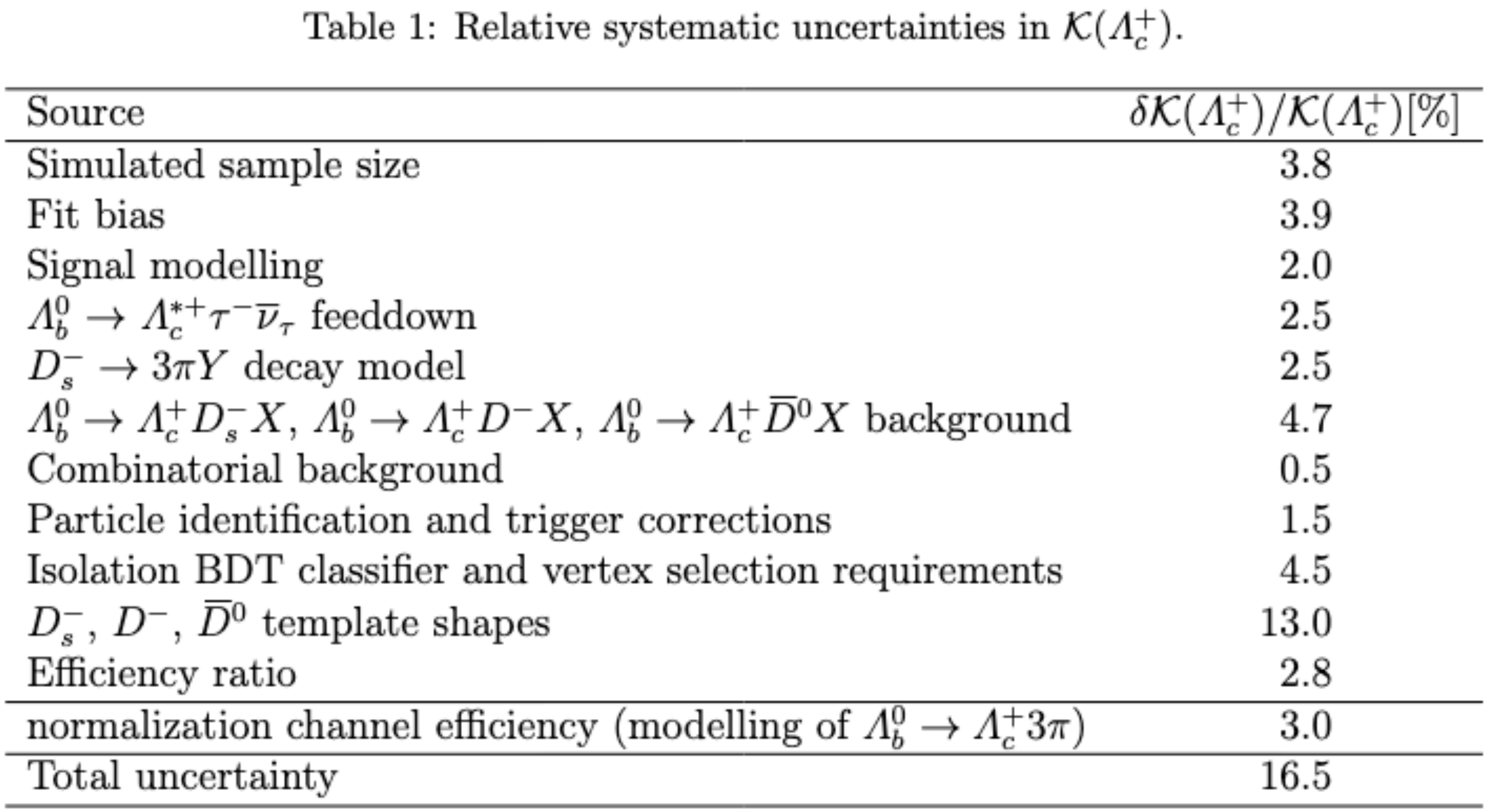


Table 1: Relative systematic uncertainties in $\mathcal{K}(\Lambda_c^+)$.

Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\overline{\nu}_\tau$ feeddown	2.5
$D_s^- \to 3\pi Y$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^-, D^-, $\overline{D}^0$ template shapes	13.0
Efficiency ratio	2.8
normalization channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

[PRL 115(2015)111803]

Systematic uncertainties in muonic $R(D^*)$ measurement at LHCb

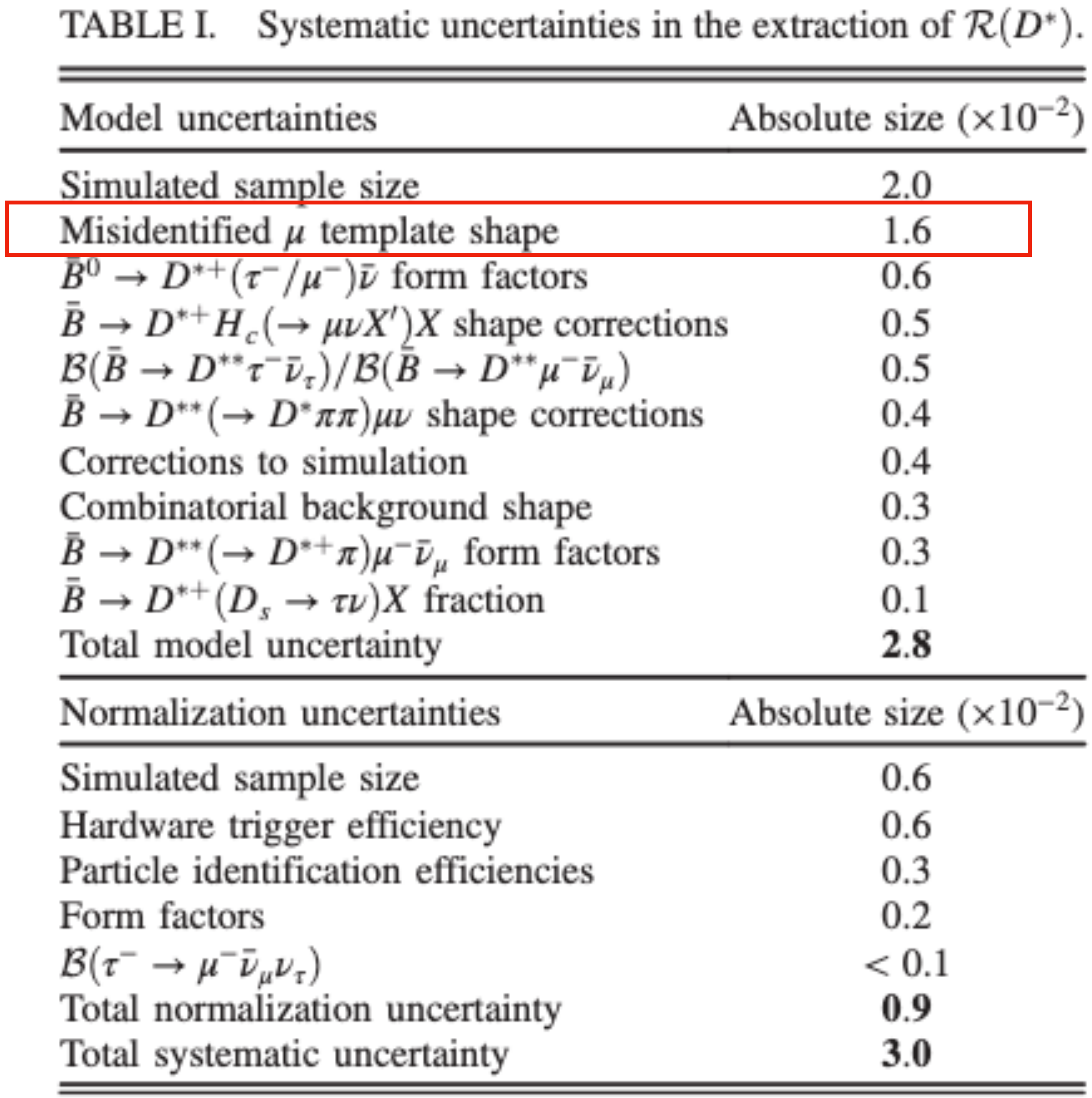
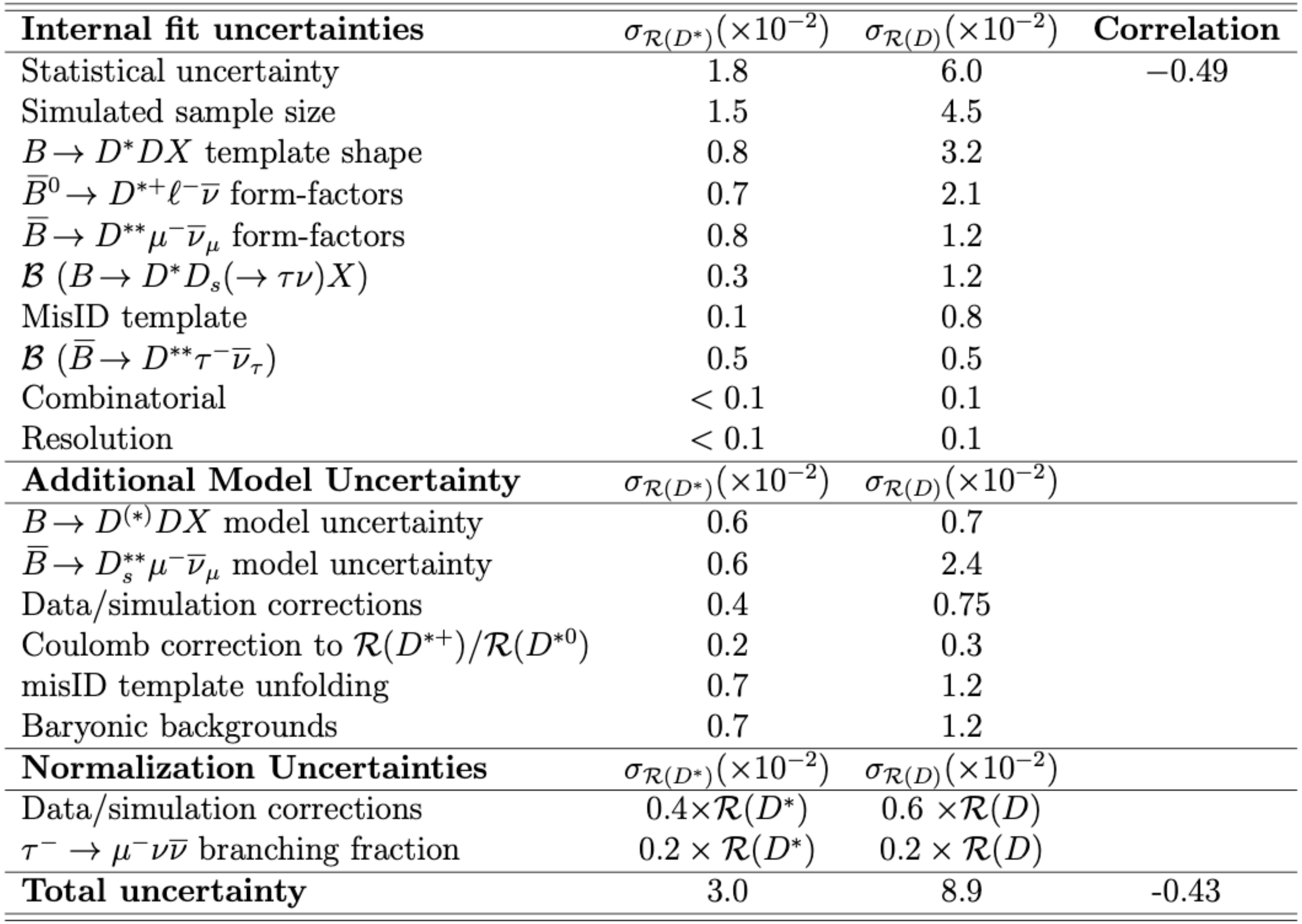


TABLE I. Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

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

[LHCb-PAPER-2022-039 in preparation]

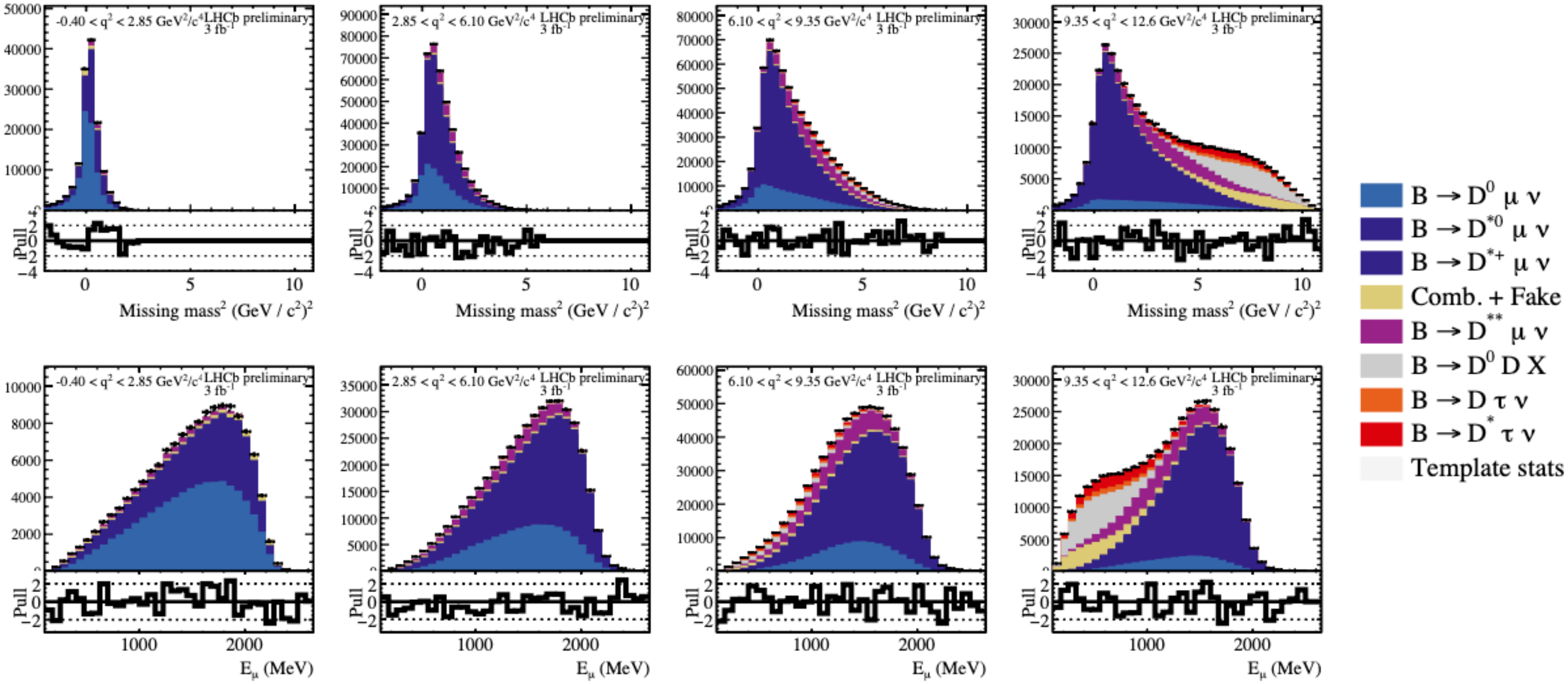
Systematic uncertainties in $R(D)$ & $R(D^*)$ measurement



Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	-0.49
Simulated sample size	1.5	4.5	
$B \to D^* D X$ template shape	0.8	3.2	
$\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}$ form-factors	0.7	2.1	
$\overline{B} \to D^{**} \mu^- \overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (B \to D^* D_s (\to \tau\nu) X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**} \tau^- \overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional Model Uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$	
$B \to D^{(*)} D X$ model uncertainty	0.6	0.7	
$\overline{B} \to D_s^{**} \mu^- \overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.75	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
misID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization Uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D)$	
$\tau^- \to \mu^- \nu \overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D)$	
Total uncertainty	3.0	8.9	-0.43

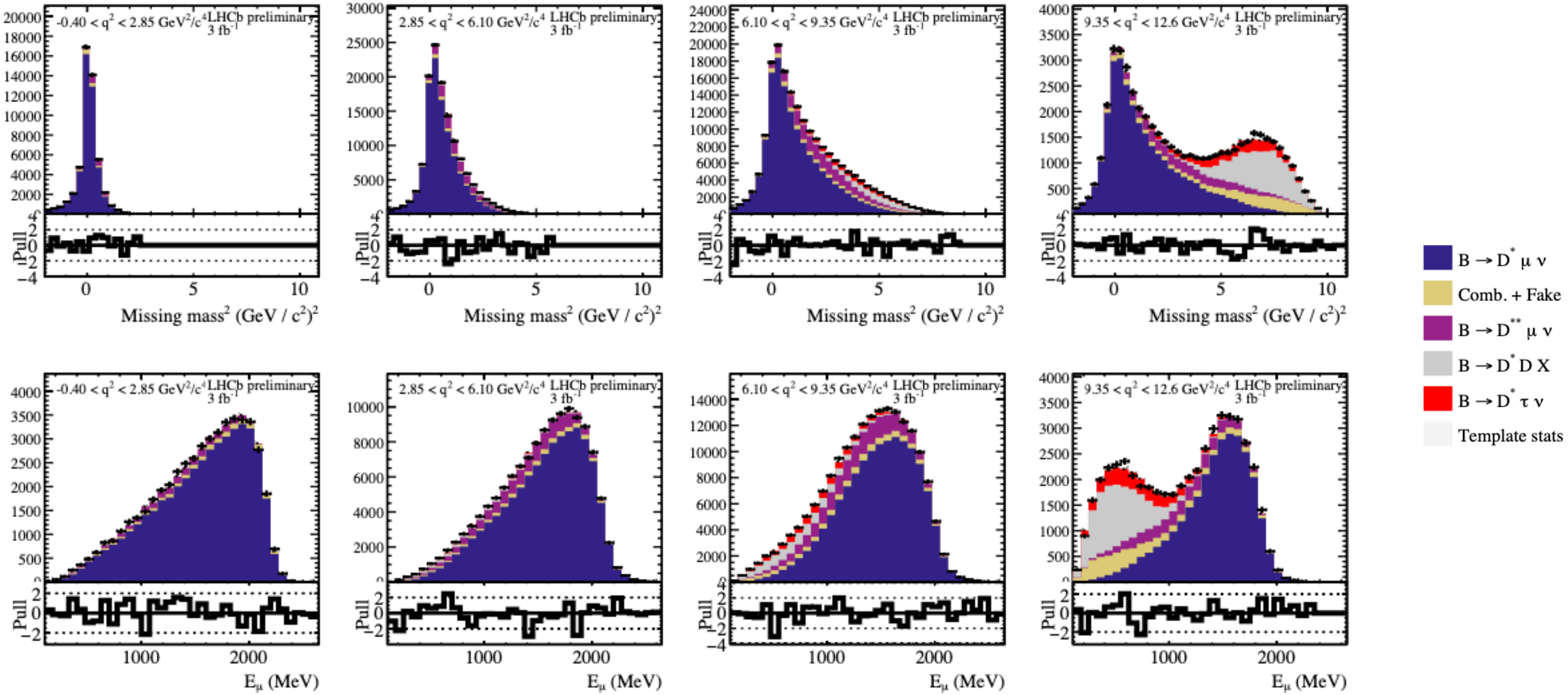
[LHCb-PAPER-2022-039 in preparation]

$D^0\mu^-$ signal sample fit



[LHCb-PAPER-2022-039 in preparation]

$D^{*+}\mu^-$ signal sample fit



Comparison between measuring $R(D^*)$ by using $\tau \to \mu\bar{\nu}\nu$ and $\tau \to 3\pi(\pi^0)\nu$

$\tau \to \mu\bar{\nu}\nu$

- Advantage
  - Direct normalisation from identical (visible) final state
- Disadvantage
  - Background from many different sources and hard to suppress

$\tau \to 3\pi(\pi^0)\nu$

- Advantages
  - Can reconstruct τ vertex from three pion tracks, higher purity
  - Three pion dynamics help to distinguish signal from main physical background
  - No normal semileptonic background
- Disadvantage
  - Need external input to normalise