EXPERIMENTAL OVERVIEW OF LEPTON FLAVOUR UNIVERSALITY TESTS

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ICCUB
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The LHCb group at ICCUB

The LHCb analysis group:

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- **Postdocs:** Lukas Calefice, Alessandra Gioventù
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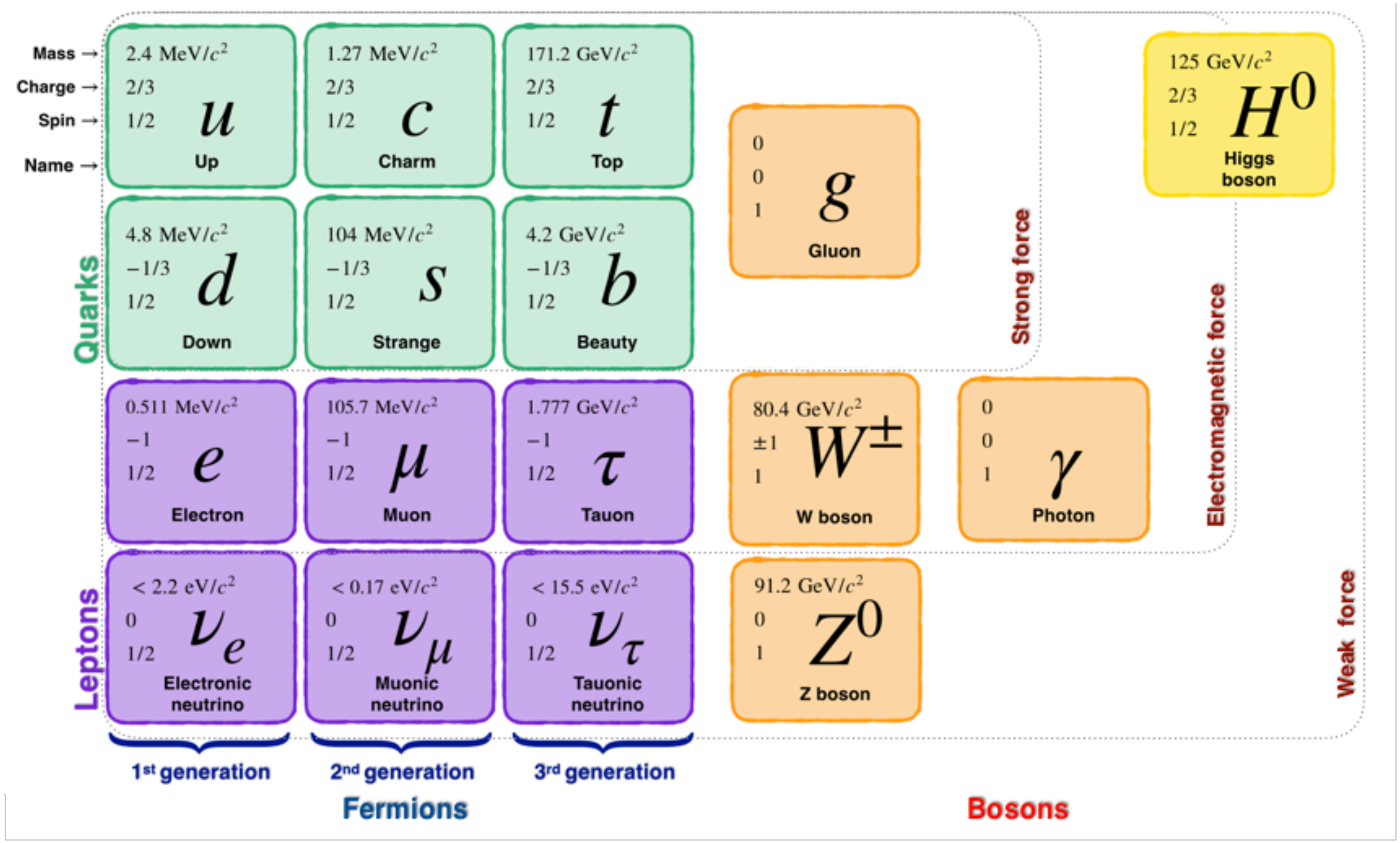
Analysis topics:

- Lepton Flavour Universality (LFU) tests in $b \to c\ell\nu_\ell$ and $b \to s\ell\ell$ transitions **This presentation**
- Electroweak penguin decays analyses, $b \to d\ell\ell$ transitions
- Radiative decays studies
- Electron reconstruction at LHCb

Lepton Flavour Universality



- The SM predicts equal couplings between gauge bosons and the three lepton generations. This is called **Lepton Flavour Universality (LFU)**
  - **Observation of LFU violation $\longrightarrow$ sign of new physics (NP)**

Lepton Flavour Universality tests

- Tensions between measurements and SM predictions in $b \to c$ and $b \to s$ decays
- Different observables to test LFU:
  - Integrated and differential branching fractions
  - **Angular observables** → need high statistics
  - Branching fractions of fully leptonic decays such as $BR(B_s \to \mu^+\mu^-)$
  - **Ratio observables** $R(q^2) = \frac{d\Gamma^{\ell}}{dq^2} \Big/ \frac{d\Gamma^{\ell'}}{dq^2}$

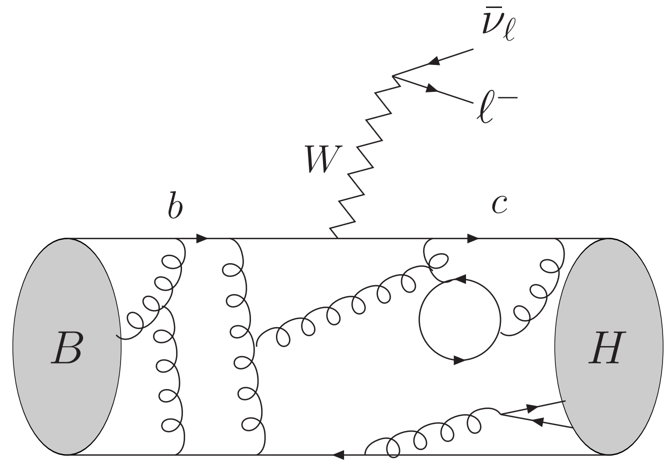
$$R_{D*}(q^2) = \frac{d\Gamma(B \to D^{*-}\tau^+\nu_\tau)}{dq^2} \Big/ \frac{d\Gamma(B \to D^{*-}\ell^+\nu_\ell)}{dq^2}$$

- Very well predicted
- **Cancellation of** theoretical and experimental **uncertainties** in the ratio

$$q^2 = (p_B - p_{D^0})^2$$

Main features of LFU tests

Flavour Changing Charged Current (FCCC)

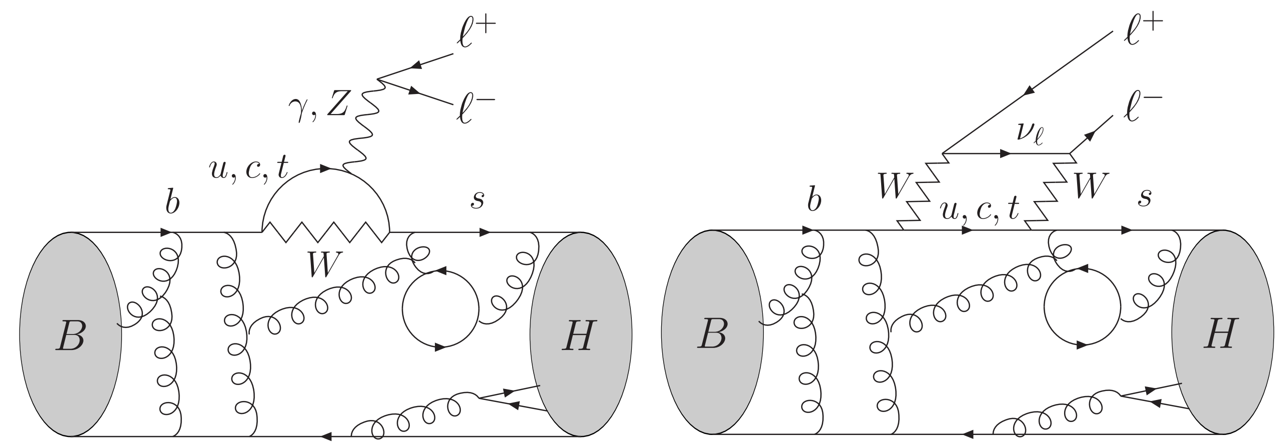


$$b \to c \ell^- \bar{\nu}_\ell$$

$\ell = \tau, \mu$ (e only B factories)

- **Tree level** processes. In the SM mediated by a W boson
- Potential NP in different couplings between generations
- At least one undetectable ν in the final state

Flavour Changing Neutral Current (FCNC)



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

$\ell = \mu, e$

- Only loop diagrams in SM $\Rightarrow$ lower branching fractions
- Sensitive to either tree or loop NP contributions
- Electrons in the final state

FCNC processes

- LFU tests: definition of $R(H_s)$
- Electron recovery at LHCb
- $R(pK)$
- $R(H_s)$ measurements status

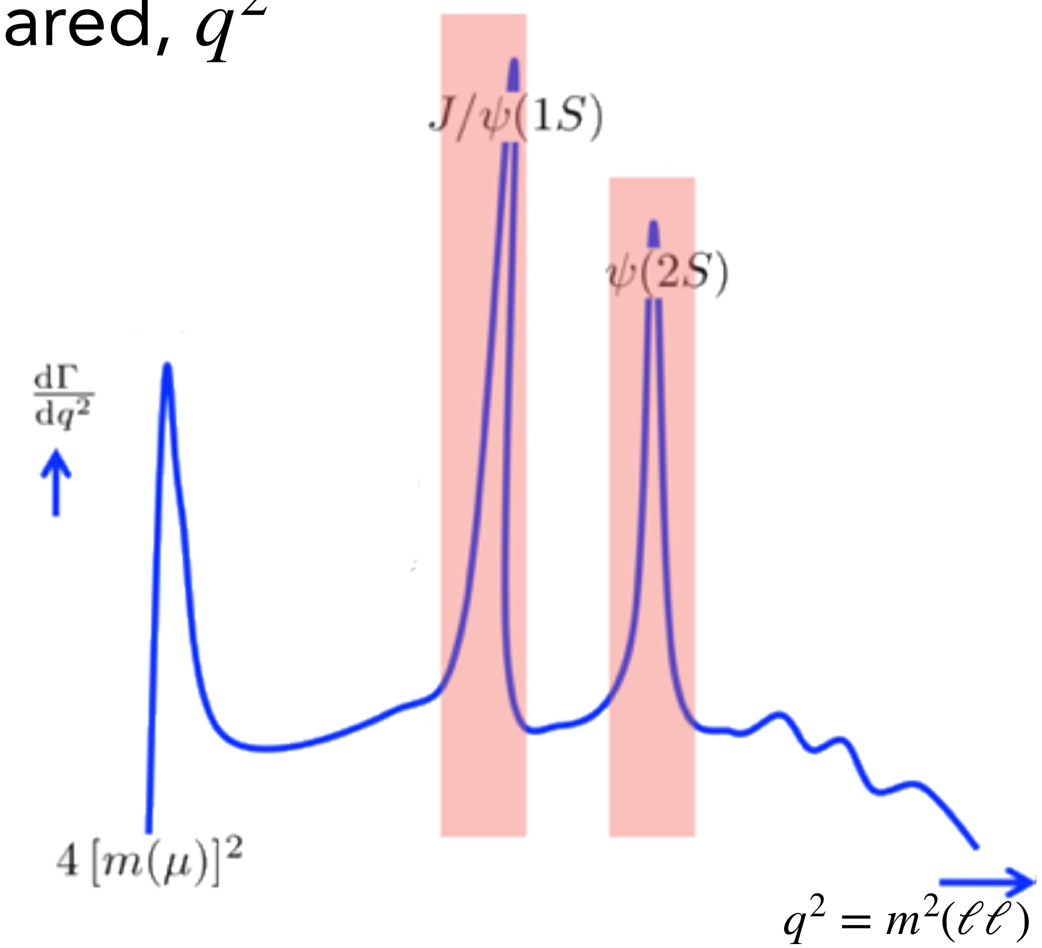
Tests of LFU in $b \to s\ell^+\ell^-$ transitions

[JHEP 12 040 (2007)]
[EPJ C 1676 440 (2016)]

➡ Within a given range of di-lepton mass squared, q^2

$$R(H_s)[q^2_{min}, q^2_{max}] = \frac{\int dq^2 \frac{d\Gamma(H_b \to H_s\mu^+\mu^-)}{dq^2}}{\int dq^2 \frac{d\Gamma(H_b \to H_s e^+e^-)}{dq^2}}$$

where $H_b = B,\ \Lambda_b^0$ and $H_s = K,\ K^*,\ K_S^0,\ \phi,\ pK$



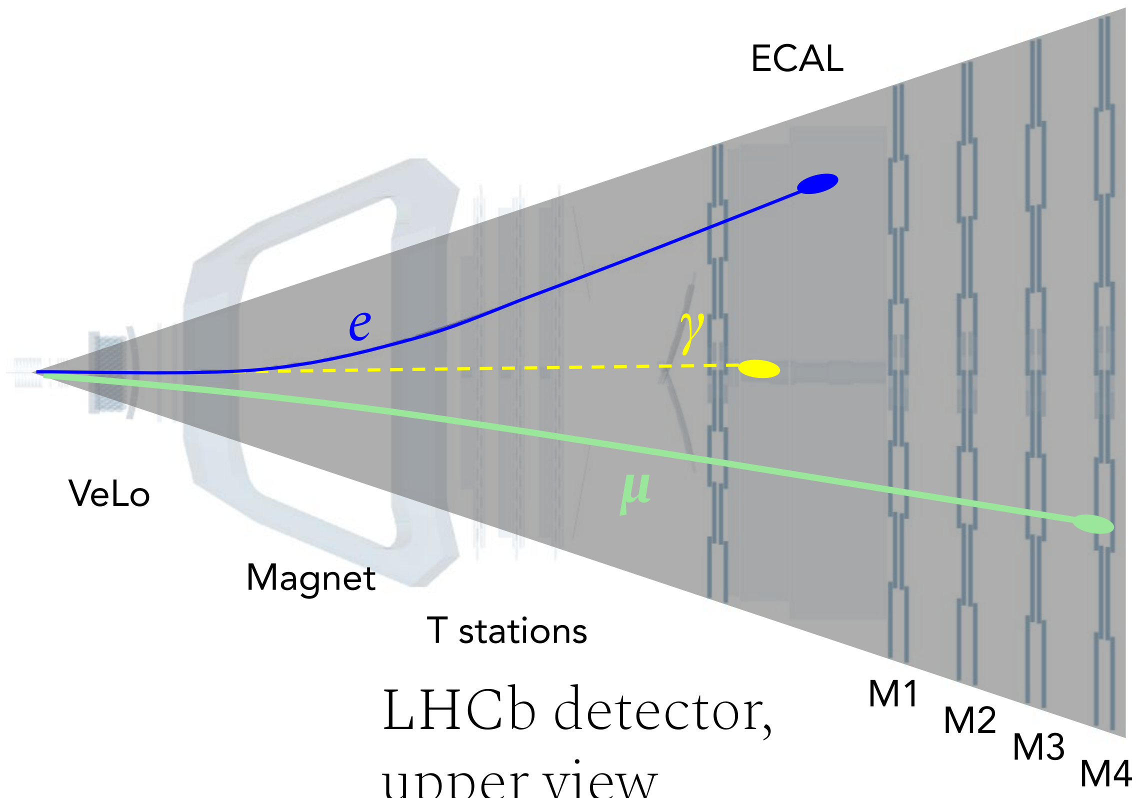
- SM expectation $R(H_s) = 1 \pm \mathcal{O}(1\%)$
- Exploit $r_{J/\psi} = 1 \Rightarrow$ double ratio to reduce systematics:

$$R(H_s) = \frac{BR(H_b \to H_s\mu^+\mu^-)}{BR(H_b \to H_sJ/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{BR(H_b \to H_se^+e^-)}{BR(H_b \to H_sJ/\psi(\to e^+e^-))}$$

- Electrons and muons → different reconstruction

Electron recovery procedure in LHCb

- Electrons lose a large fraction of their energy through **Bremsstrahlung radiation**
- **Improve electron energy resolution** by using a recovery procedure:
  - Look for photon clusters in the calorimeter compatible with the electron direction before the magnet



LHCb detector, upper view

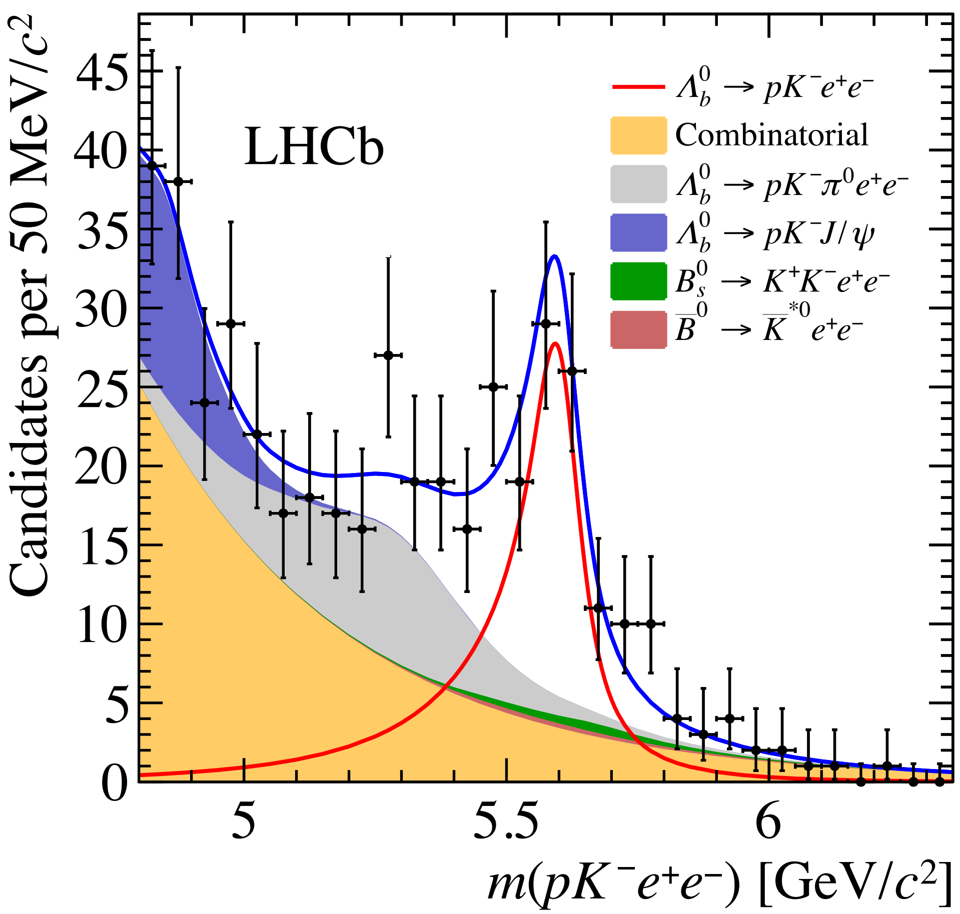
$R(pK)$ measurement

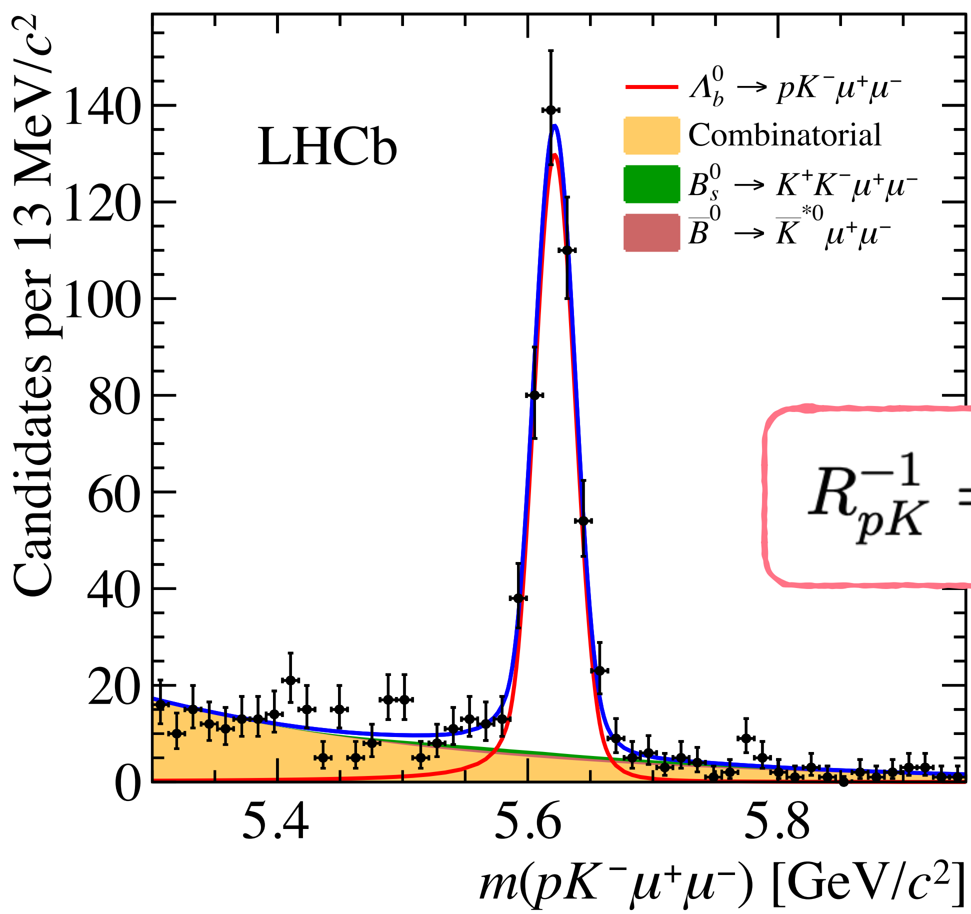
- Test LFU in $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays by measuring the inverse of $R(pK)$:

$$R^{-1}(pK) = \frac{BR(\Lambda_b^0 \to pK^-e^+e^-)}{BR(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))} \Bigg/ \frac{BR(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{BR(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}$$

- First test of LFU using Λ_b^0 baryon
- LHCb Run 1+2016 measurement (4.7 fb^{-1}) → Update with full sample (9 fb^{-1})

JHEP 05 (2020) 040



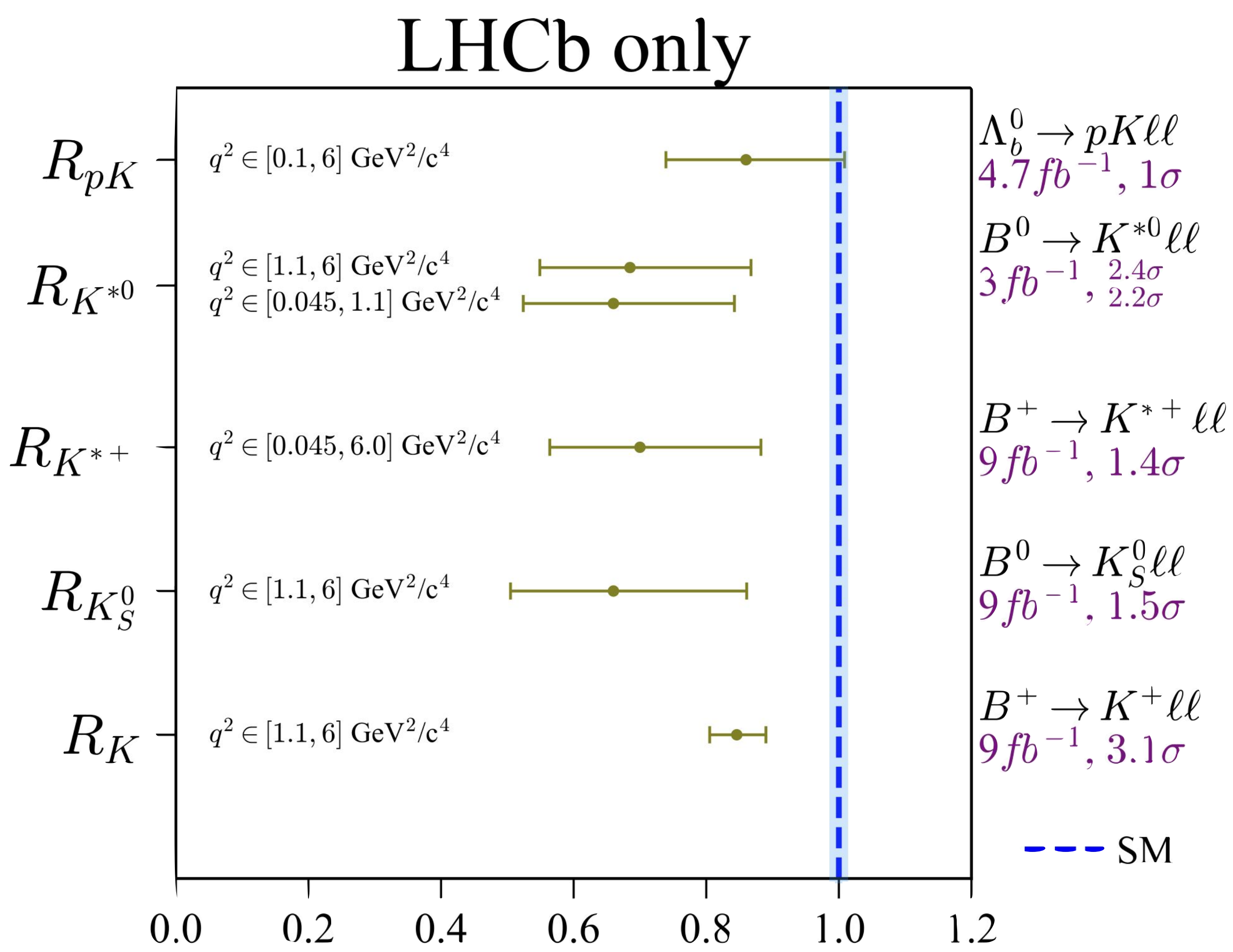


Run1+2016, 4.7 fb^{-1}
JHEP 05 (2020) 040

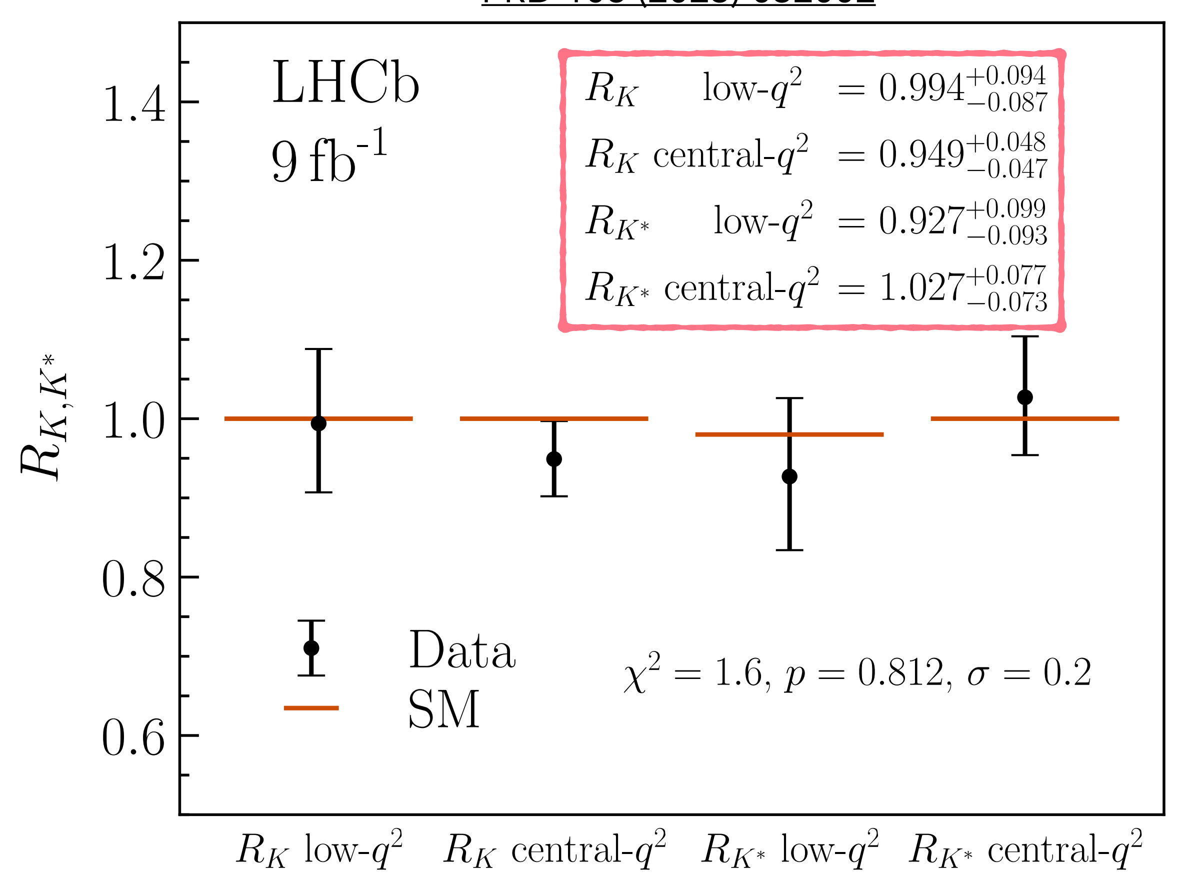
$$R_{pK}^{-1} = 1.17^{+0.18}_{-0.16} \pm 0.07$$

$R(H_s)$ status

- First measurements of $R(K)$ and $R(K^*)$ performed at B factories: Belle and BaBar
- Several measurements considering different b and s hadrons
- Currently all measurements in agreement with SM predictions



PRD 108 (2023) 032002



FCCC processes

- Strategies for LFU tests: muonic vs hadronic τ decays
- LHCb measurements:
  - $R(D^{*-})$ with $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
  - $R(D^{(*)})$ with $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
- $R(D^{*-})$ and $R(D)$ experimental status

LFU tests with $b \to c\ell\nu_\ell$ transitions

- Test LFU by measuring $R(H_c) = \frac{BR(H_b \to H_c\tau^+\nu_\tau)}{BR(H_b \to H_c\ell^+\nu_\ell)}$

  where $H_b = B^0, B^+_{(c)}, \Lambda_b^0, B_s^0, \ldots$
  and $H_c = D^{(*)\pm}, D^0, D_s, \Lambda_c^+, J/\psi, \ldots$

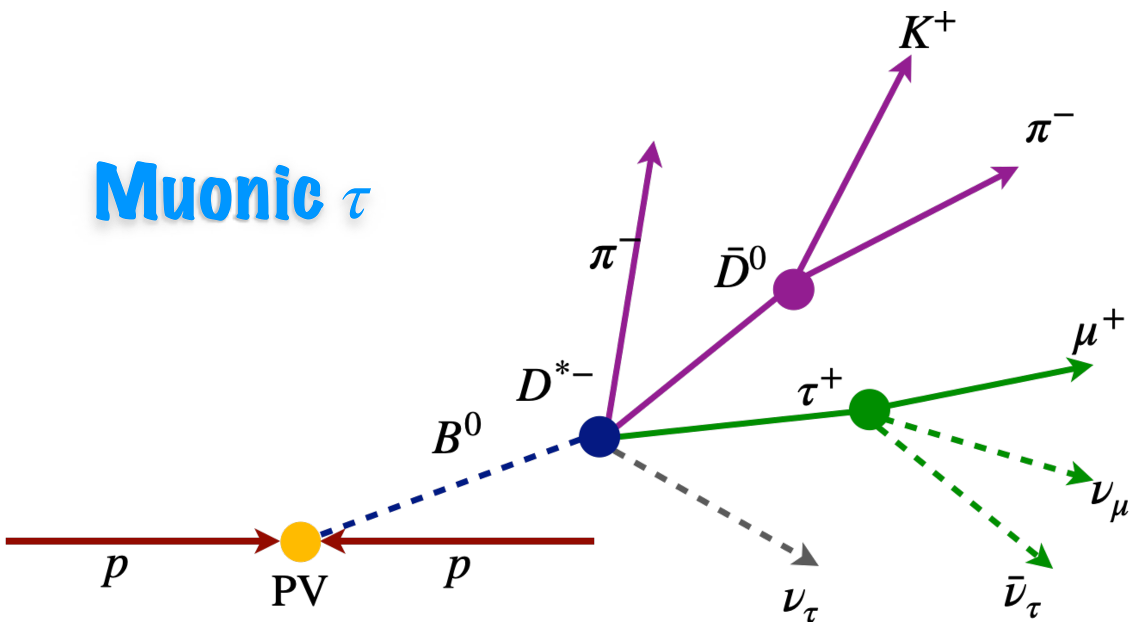
- Clean theoretical prediction

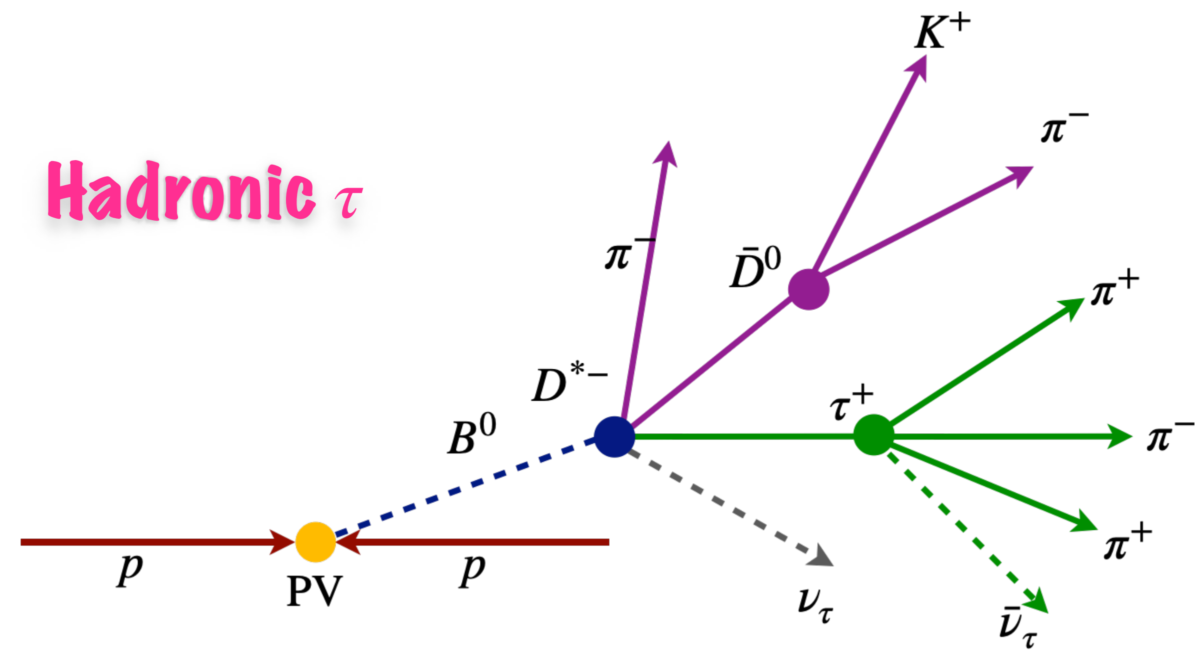
  $m_\tau \sim \begin{cases} 17 \cdot m_\mu \\ 3500 \cdot m_e \end{cases}$

- $R(H_c)$ **deviates from unity** due to different lepton masses
- **Missing momentum of neutrinos**
- B factories (BaBar and Belle (II)):
  - Consider both $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ and $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ decays for the denominator
- LHCb:
  - **Muonic decay of the tau**: $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
  - **3-prong decays**: $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

Channel	$\mathcal{B}$ $(\times 10^{-3})$
$\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$	17.39 ± 0.04
$\tau^- \to e^-\overline{\nu}_e\nu_\tau$	17.82 ± 0.04
$\tau^- \to \pi^-\pi^0\nu_\tau$	25.49 ± 0.09
$\tau^- \to \pi^-\nu_\tau$	10.82 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$	9.02 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$	4.49 ± 0.05

τ decays at LHCb





- **Same final states** for signal and normalisation
- No τ vertex reconstruction
- B-frame approximation
  $\rightarrow (p_z)_B = \frac{m_B}{m_{D^*\mu}}(p_z)_{D^*\mu}$
- Large **partially-reconstructed** B backgrounds

- Different final state for signal and normalisation
- τ **vertex reconstruction**
- Background contributions:
  - ***Prompt*** $B \rightarrow D_s^{(*)}3\pi(X)$ decays
  - **Doubly charmed inclusive decays,** with $H_c \rightarrow 3\pi(X)$

$R(D^*)$ measurement, hadronic τ

Run 1, 3 fb^{-1}: PRD 97 072013 (2018), PRL 120 171802 (2018)

15+16, 2 fb^{-1}: PRD108 (2023) 012018

- τ reconstructed with 3-prong τ decays $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
- Measure $BR(B^0 \to D^{*-}\tau^+\nu_\tau)$ w.r.t. the normalisation mode $B^0 \to D^{*-}\pi^+\pi^-\pi^+$:

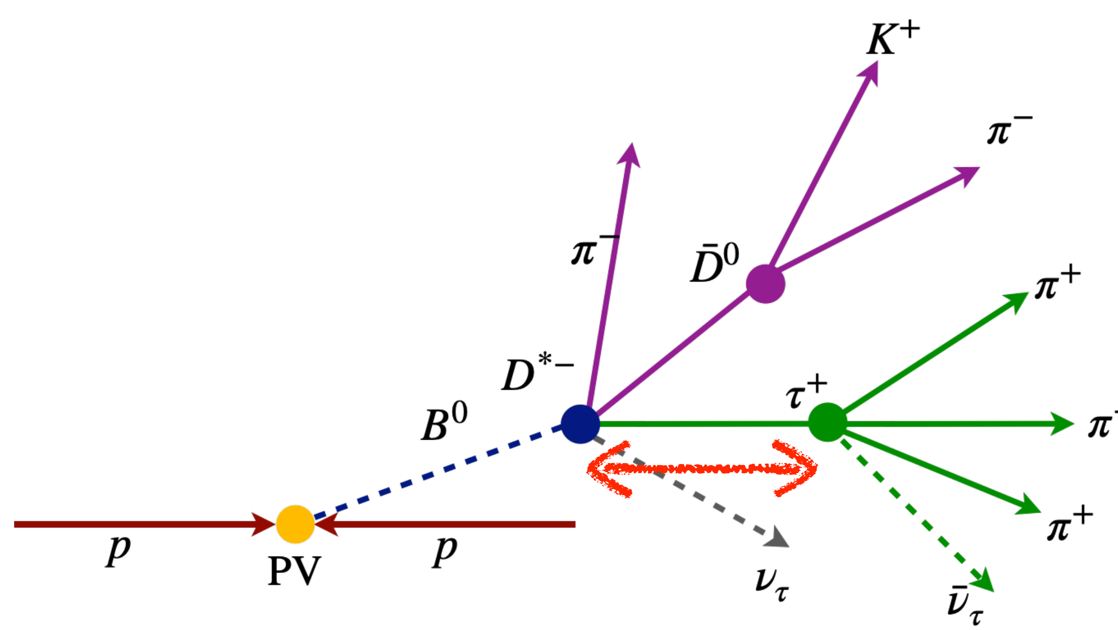
$$K(D^*) = \frac{N_{sig}}{N_{norm}} \cdot \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \cdot \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau)}$$

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

External inputs

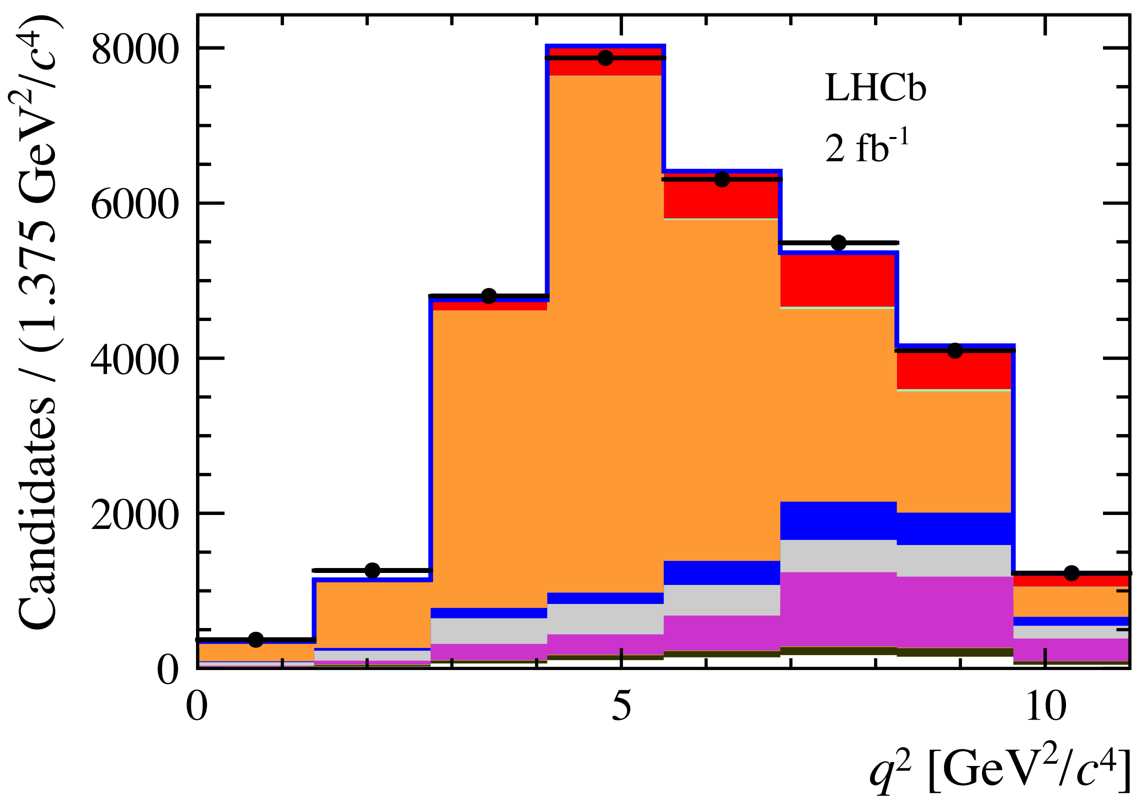
$BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+) = (7.21 \pm 0.29) \cdot 10^{-3}$
$BR(B^0 \to D^{*-}\mu^+\nu_\mu) = (5.05 \pm 0.14)\,\%$
$BR(\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau) = (9.02 \pm 0.05)\,\%$
$BR(\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau) = (4.49 \pm 0.05)\,\%$

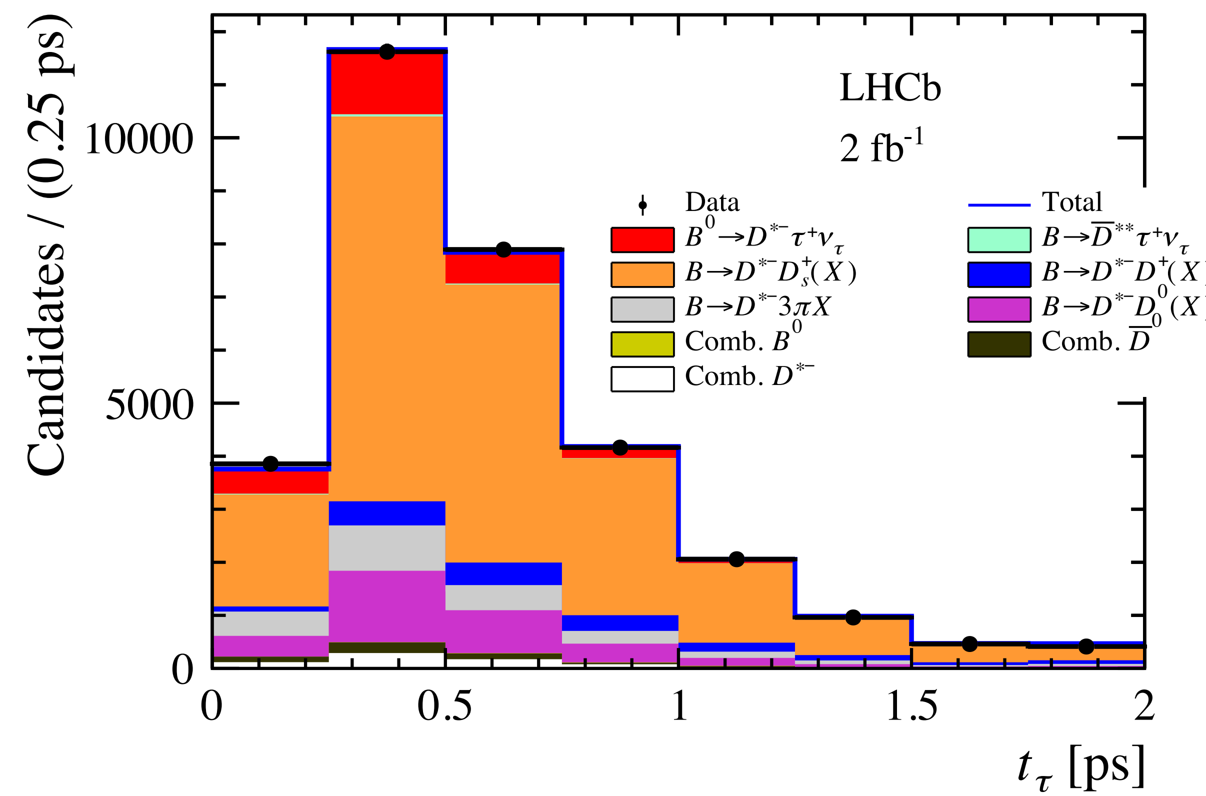
- Approximations to estimate B and τ momenta
- Largest background channels:
  - **Prompt** $B^0 \to D^{*-}\pi^+\pi^-\pi^+(X)$ background suppressed by $\Delta z > 4\sigma_{\Delta z}$
  - **Doubly charmed** $B \to D^{*-}D_s^+(\to 3\pi)(X)$, treated with multivariate analysis (BDT)

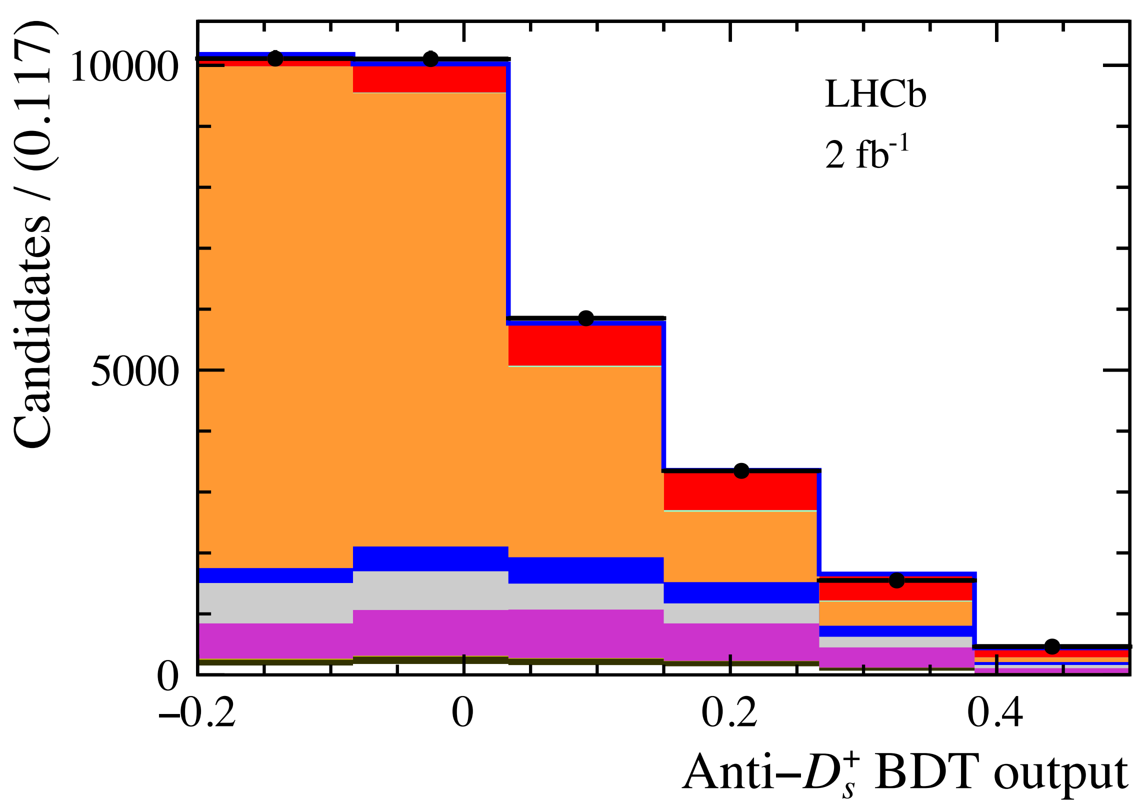


$R(D^*)$ measurement, hadronic τ

15+16, , 2 fb^{-1}: PRD108 (2023) 012018







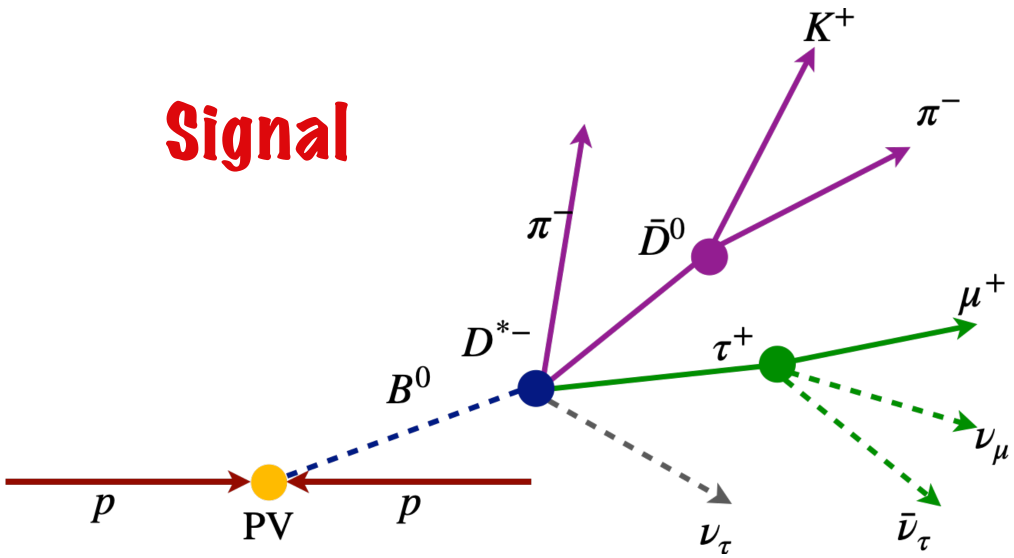
- **Normalisation yield** → invariant mass fit to $m(D^{*-}3\pi)$
- **Signal yield** → 3D template fit in τ decay time, q^2 and BDT
- Including Run 1 result:

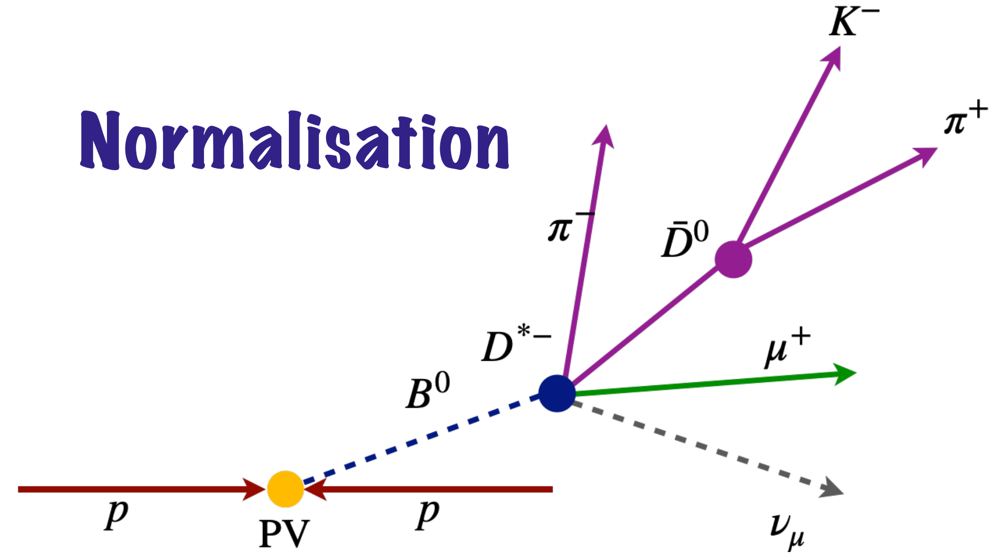
$$R(D^*)_{(2011-2016)} = 0.257 \pm 0.012 \pm 0.014 \pm 0.012$$

- Agreement with $R(D^*)_{SM} = 0.254 \pm 0.005$

$R(D^*)$ and $R(D)$ measurement $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

Study $B \to D^{(*)} \tau^+ \nu_\tau$ decays using the **muonic τ decay**





$$R(D^{(*)}) = \frac{BR(B^0 \to D^{(*)} \tau^+ \nu_\tau)}{BR(B^0 \to D^{(*)} \mu^+ \nu_\mu)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}$$

Run 1 $3\ \text{fb}^{-1}$
PRL131 (2023)111802

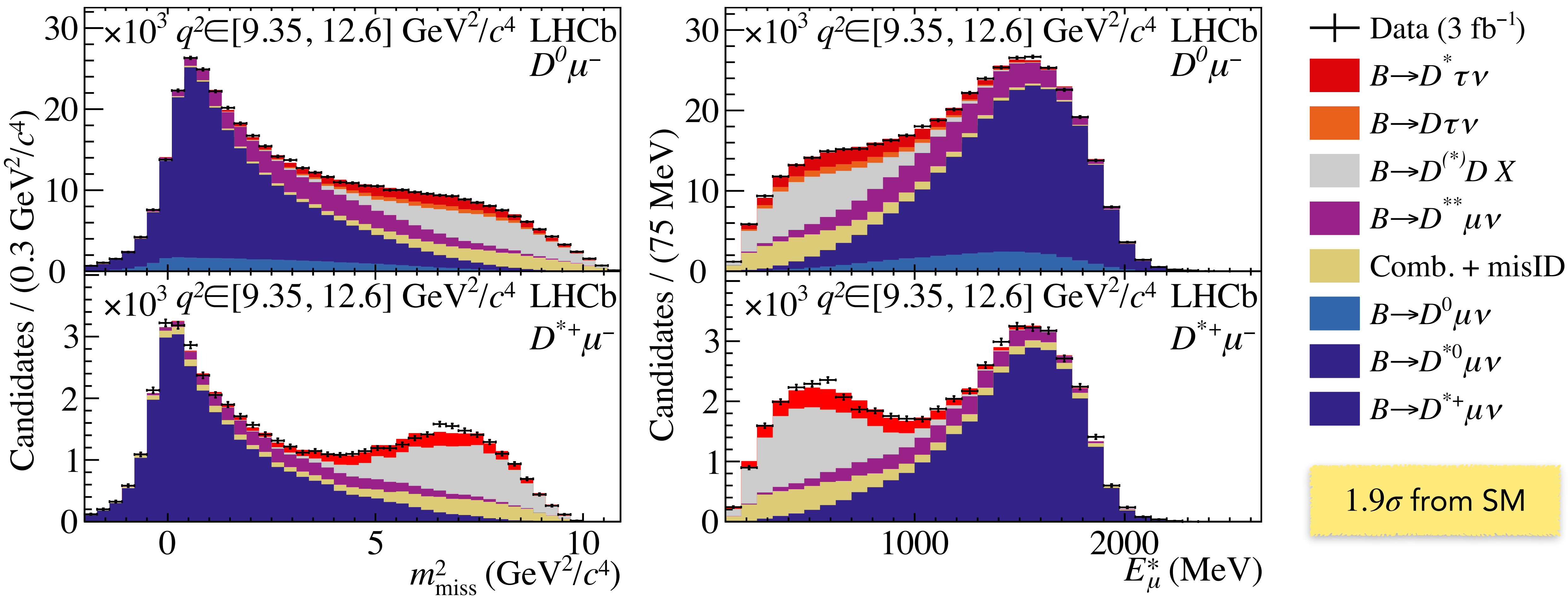
- **Muonic τ decay** → Same final state for signal and control channel
- B^0 boost along z axis $\gg$ boost of decay products in B^0 rest frame →

$$(p_z)_B = \frac{m_B}{m_{D^*\mu}} (p_z)_{D^*\mu}$$

- Main background **partially reconstructed muons**
- $R(D_s^{*-})$ **measurement** (ICCUB) → Analogue strategy with $B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$ decays

$R(D^*)$ and $R(D)$ measurement $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

- Separation of τ and μ channels via a 3D binned template fit to data:
  - $q^2 = (p_B - p_{D^*})^2$
  - $m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$
  - μ energy in the B rest frame, E^*_μ



1.9σ from SM

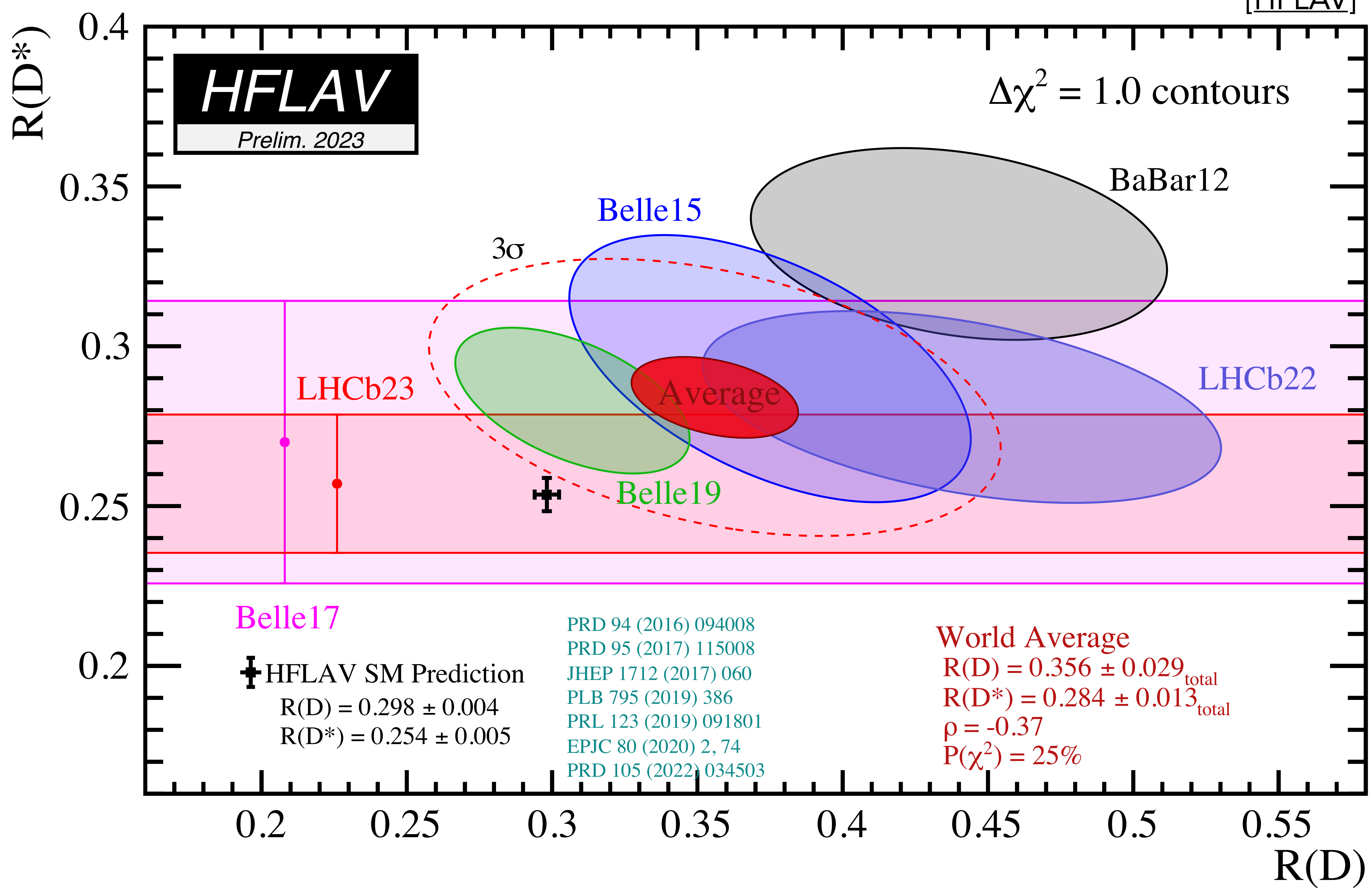
$R(D^*) = 0.281 \pm 0.018 \pm 0.024$

$R(D) = 0.441 \pm 0.060 \pm 0.066$

Global picture

- Combined $R(D)$ and $R(D^*)$ measurement in **tensions with SM predictions by** 3.2σ

[HFLAV]

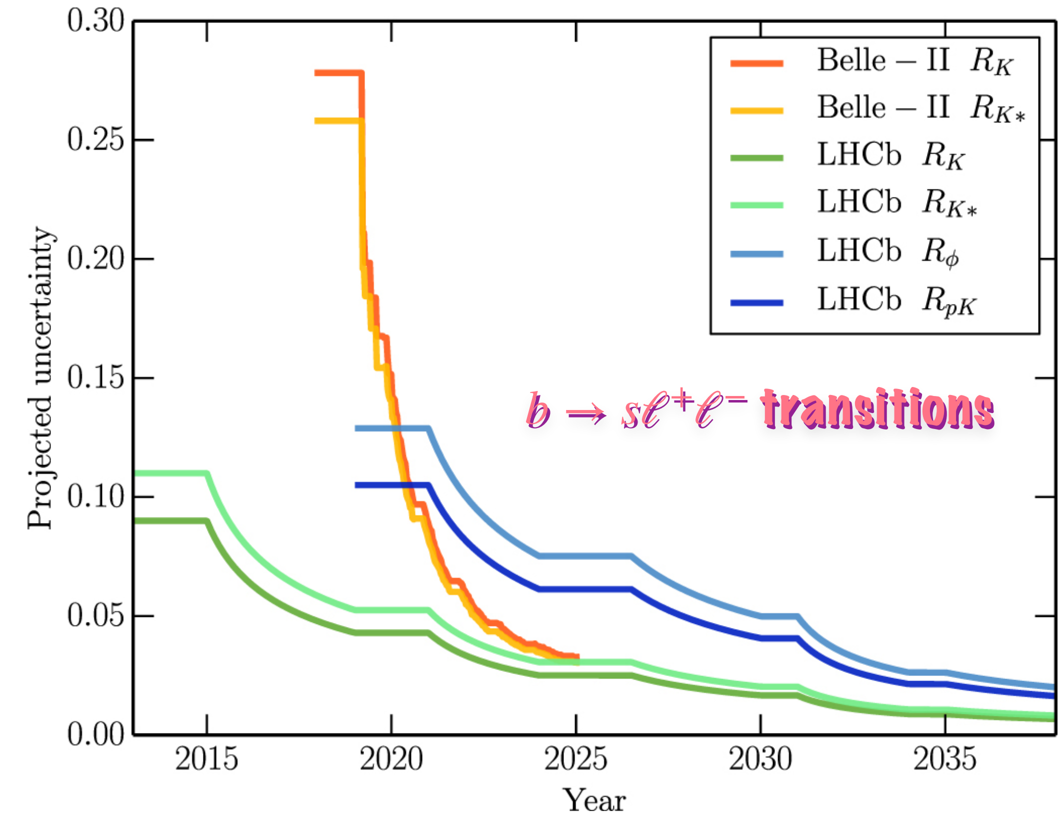


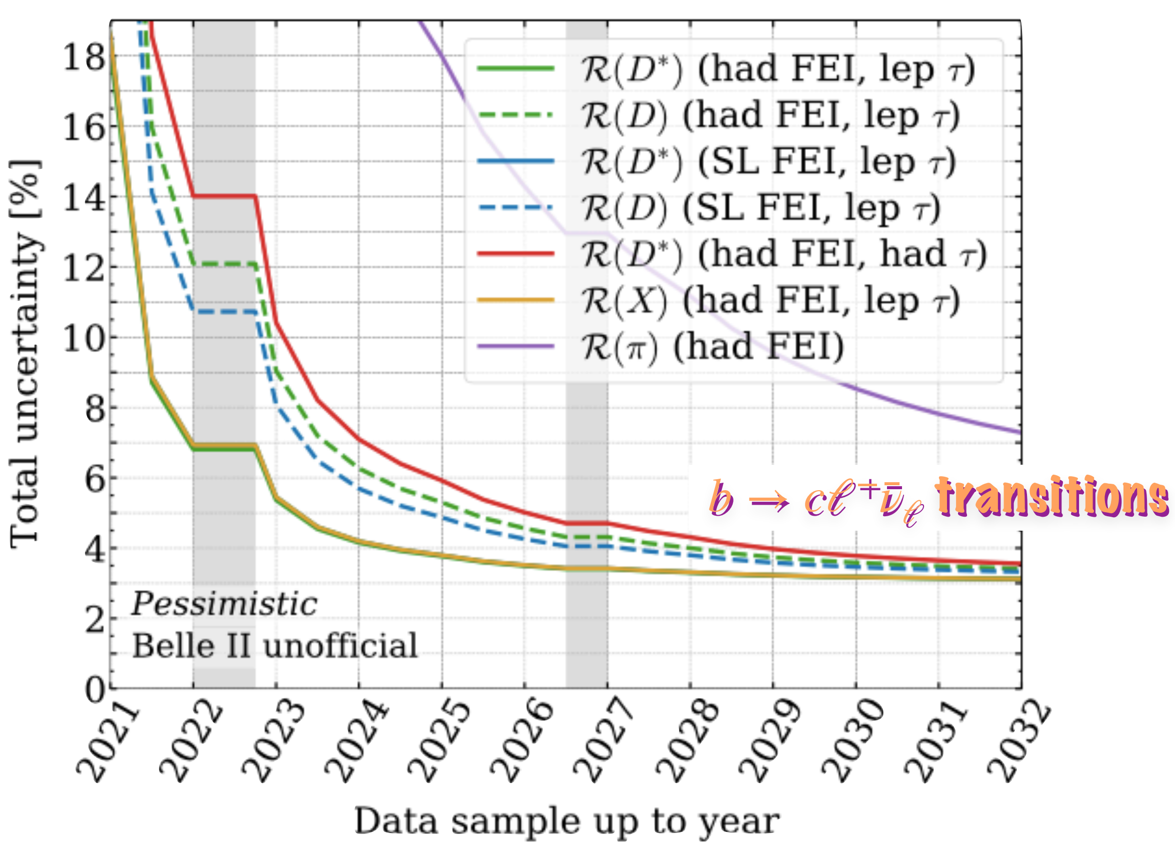
$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau^+\nu_\tau)}{BR(B \to D^{(*)}\ell^+\nu_\ell)}$$

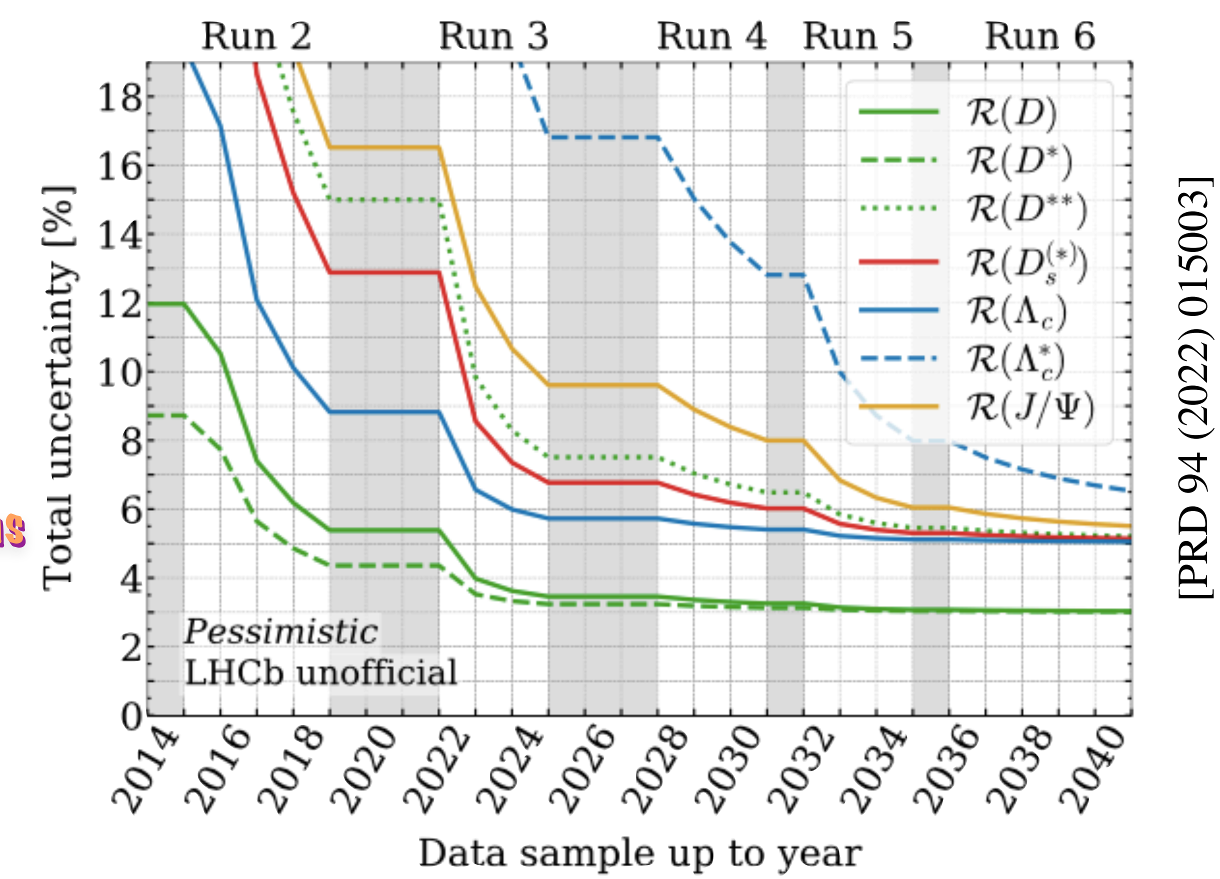
PROSPECTS AND CONCLUSIONS

Future prospects

- Several analyses ongoing with larger data samples
  - **Reduce** data-driven systematics and statistical **uncertainties**
- Expect new results from Belle II
- LHCb Upgrade I detector started Run 3 in 2022
- Starting new projects at ICCUB on $b \to d\ell\ell$ transitions related to the ERC-CLIMB







Conclusions

- Perform **Lepton Flavour Universality tests to probe the SM**
- **Several measurements** considering both $b \to s\ell^+\ell^-$ and $b \to c\ell^-\bar{\nu}_\ell$ transitions
  - No observation of LFU violation at 5 standard deviations
- The global average of $R(D)$-$R(D^*)$ **combination** is in **tension with the SM** by 3.2σ
- New measurements → more hints on the LFU puzzle
- The LHCb group of ICCUB has a central role in LFU tests

THANK YOU

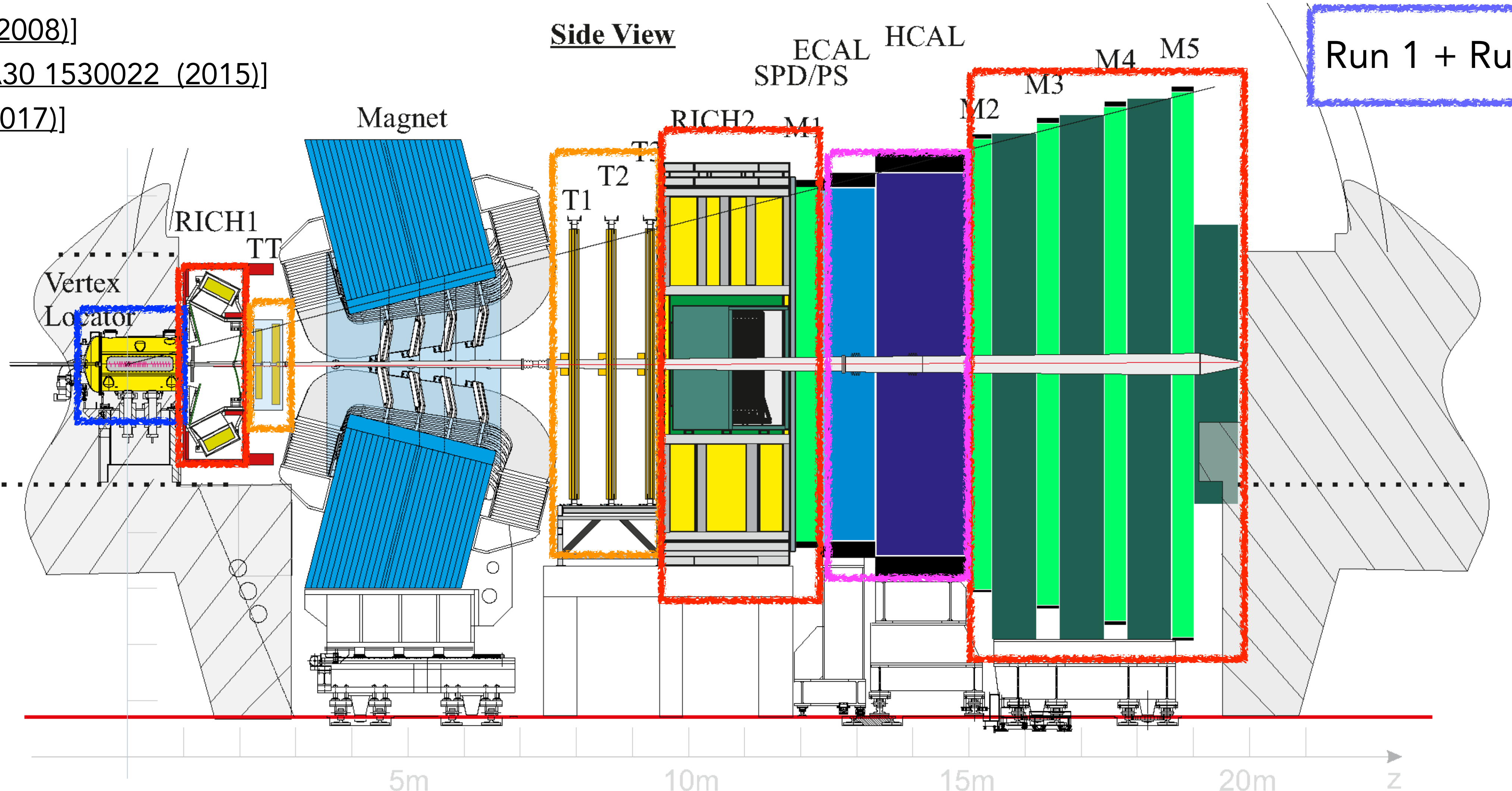
BACKUP

The LHCb detector

- ➡ Run 1 (2010 - 2012) $\sqrt{s} = 7$ TeV(8 TeV)
- ➡ Run 2 (2015 - 2018) $\sqrt{s} = 13$ TeV

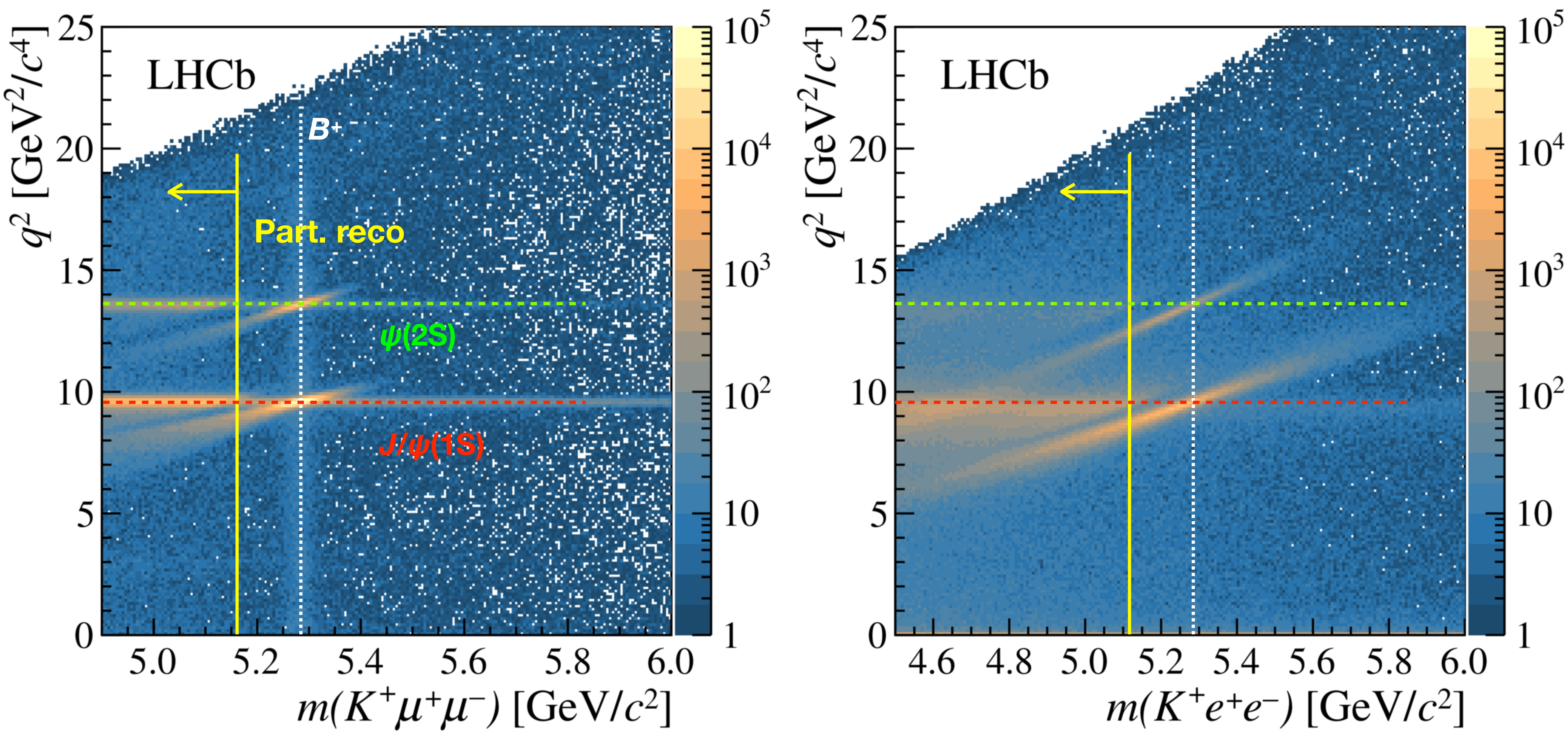
Run 1 + Run2 9 fb^{-1}

[JINST 3 S080005 (2008)]
[Int. J. Mod Phys. A30 1530022 (2015)]
[PRL 118 052002 (2017)]



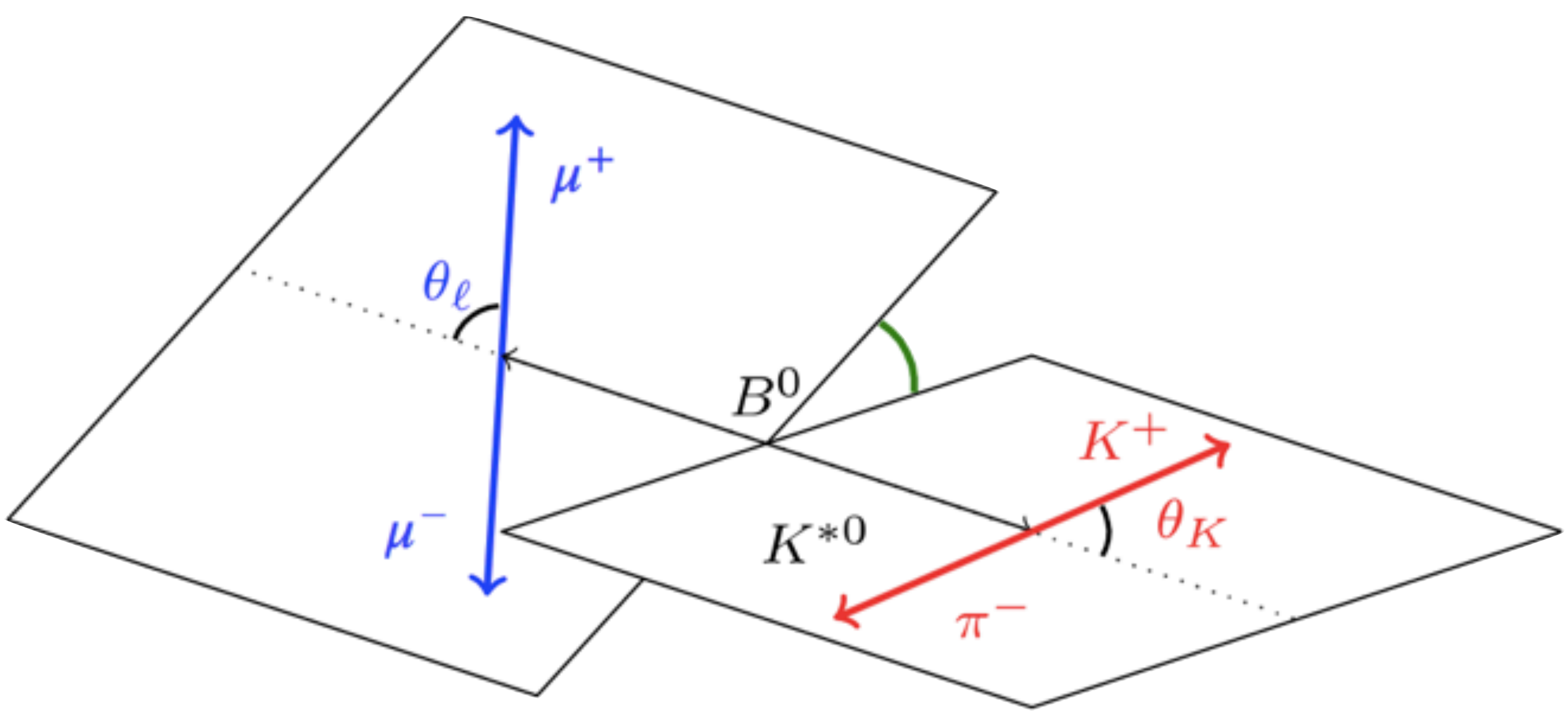
- Large amount of b and c hadrons produced, $\sigma_b = (144 \pm 1 \pm 21)\ \mu$b at 13 TeV
- Forward spectrometer for $b-$ and $c-$hadron decays $(2 < \eta < 5)$
  - Good vertex and impact parameter resolution (σ(IP) $\sim 20\ \mu$m)
  - Excellent momentum resolution ($\delta p/p = [0.5-1]\,\%\ \ p < 200$ GeV)
  - Excellent charged particle identification (μ ID 97% for ($\mu \to \pi$) misID of 1-3%)
  - Capability for neutral identification

e vs μ reconstruction



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

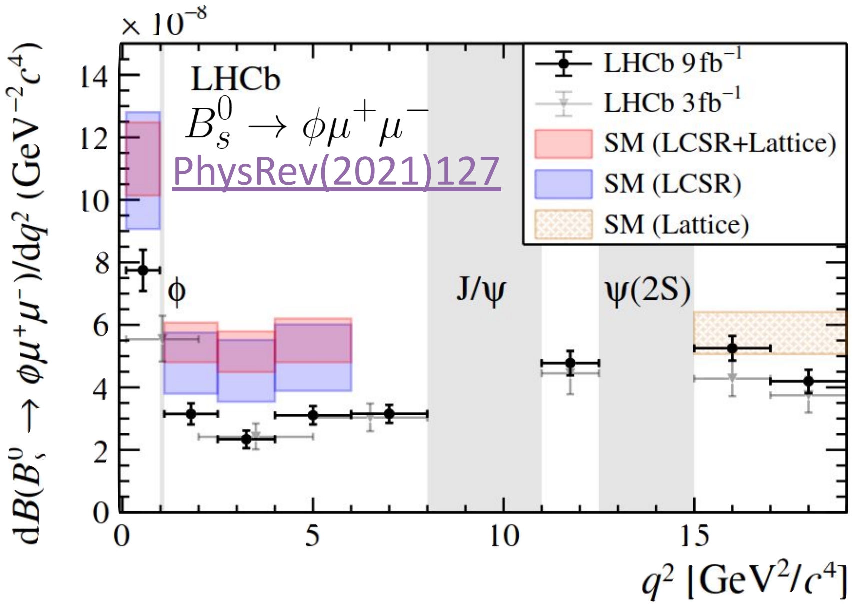
- The decay is governed by the angles θ_l, ϕ, θ_K (angular analysis) and the squared momentum transfer to the dilepton system q^2
- At $q^2 = 0$ the two leptons are at rest.
- Usually lower values of q^2 have less uncertainties from the theory $\Rightarrow$ many observables are measured on the low q^2region.

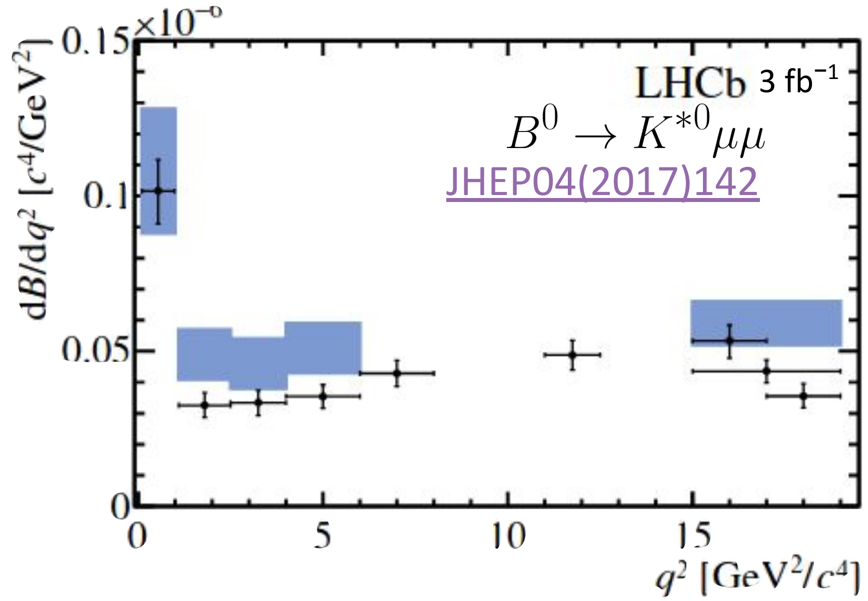


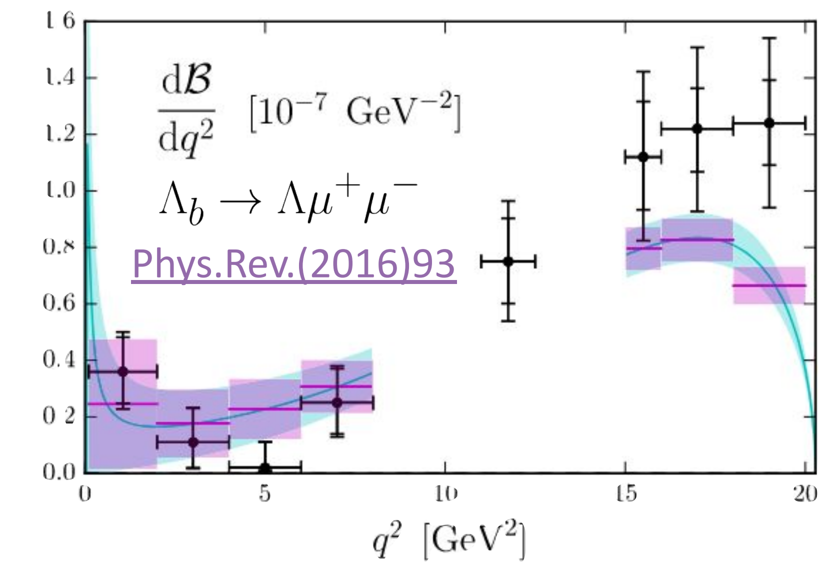
$$q^2 = (p_{B^0} - p_{K^*})^2$$

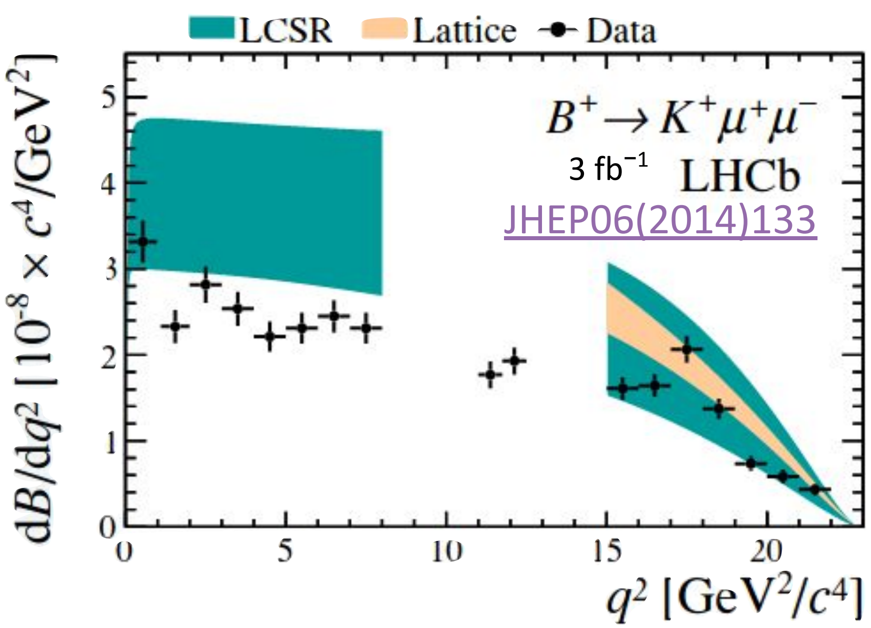
Differential branching fractions

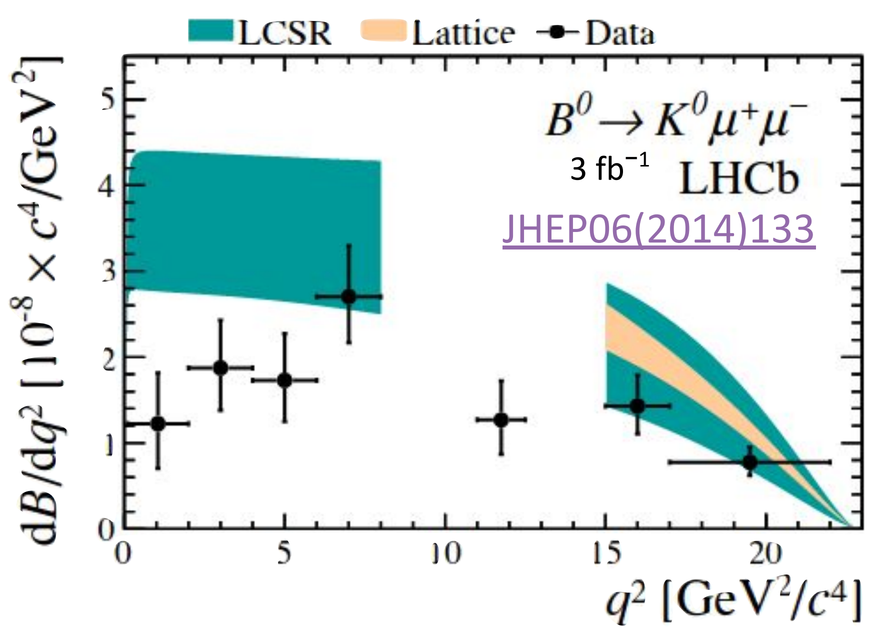
- Measurements of differential branching fractions of $b \to s\mu^+\mu^-$ transitions
- Below SM predictions

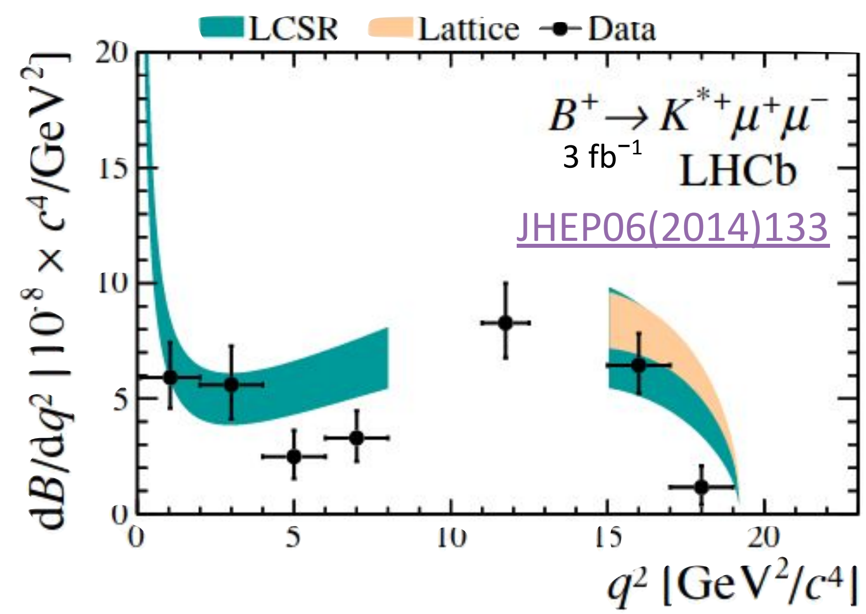




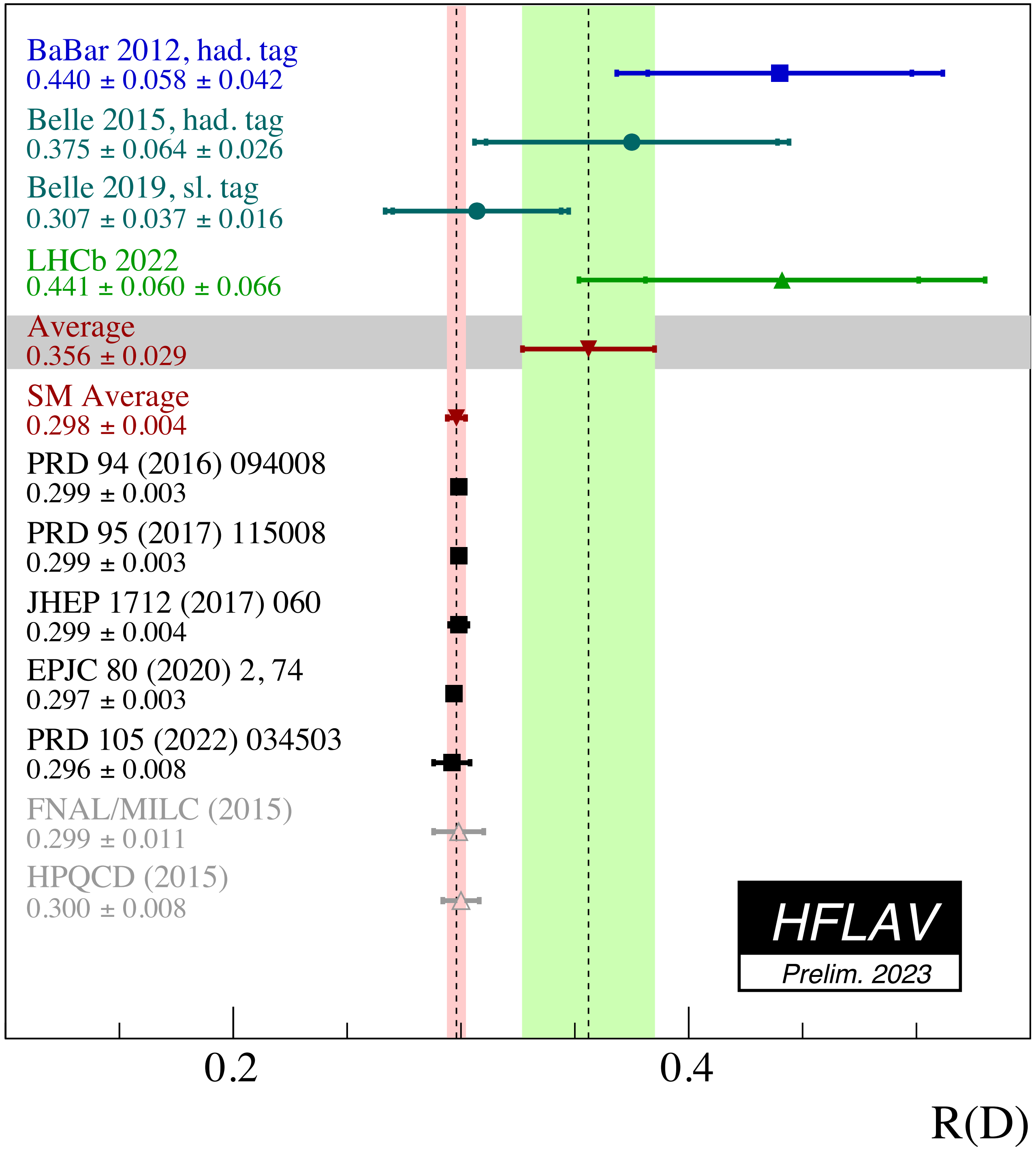


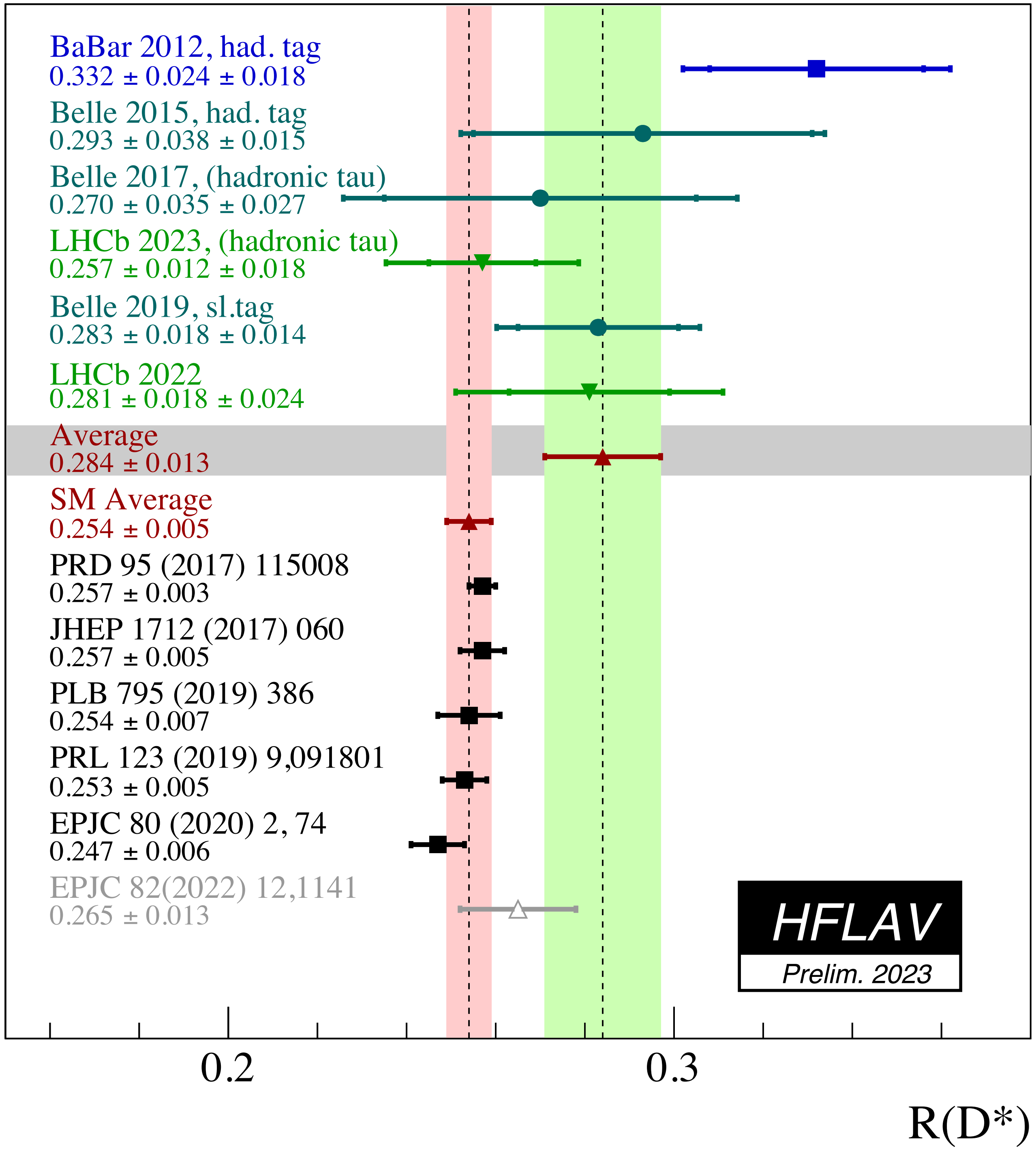






$R(D)$ and $R(D^*)$ status

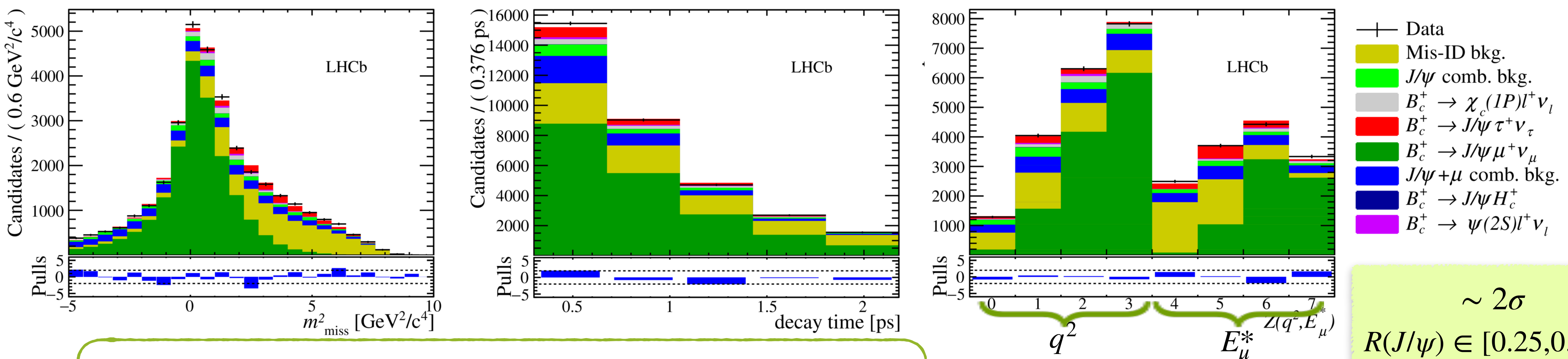




$R(J/\psi)$ and $R(\Lambda_c^+)$ measurements

$$R(J/\psi) = \frac{BR(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$ with $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$ decays

Run 1
3 fb^{-1}



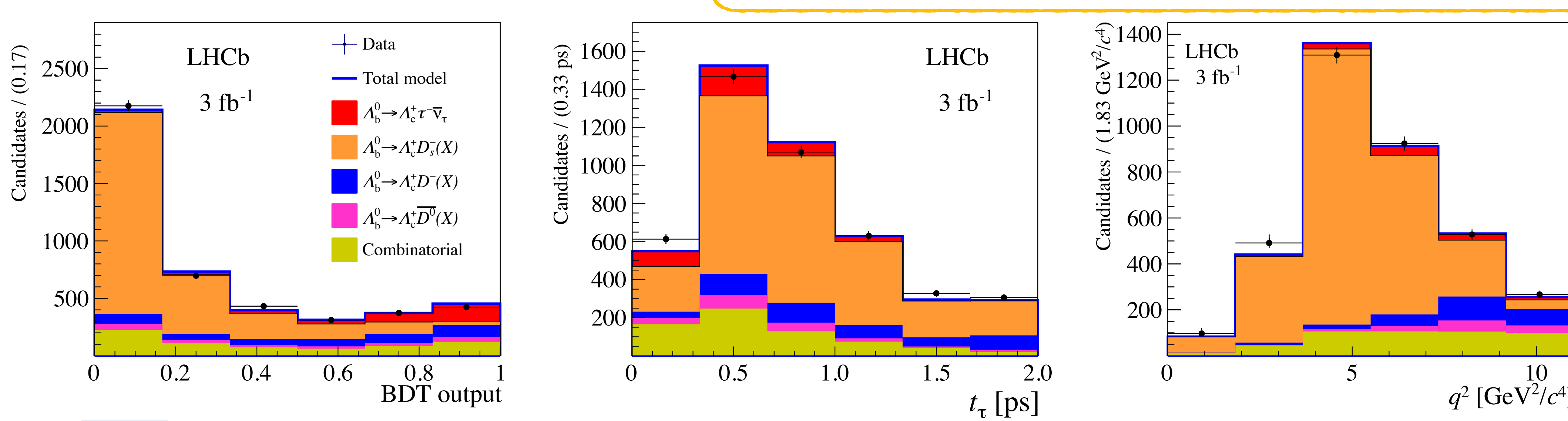
$$R(J/\psi) = 0.71 \pm 0.17\ (\text{stat}) \pm 0.18\ (\text{syst})$$

$\sim 2\sigma$
$R(J/\psi) \in [0.25, 0.28]$

[PLB 452 129 (1999)]
[arXiv:hep-ph/0211021]
[PRD 73 054024 (2006)]
[PRD 74 074008 (2006)]
[PRL 115 111803 (2015)]
[HFLAV]

$$R(\Lambda_c^+) = \frac{BR(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{BR(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$ with **3-prong τ decays**

$$R(\Lambda_c^+) = 0.242 \pm 0.026\ (\text{stat}) \pm 0.040\ (\text{syst}) \pm 0.0597\ (\text{ext})$$



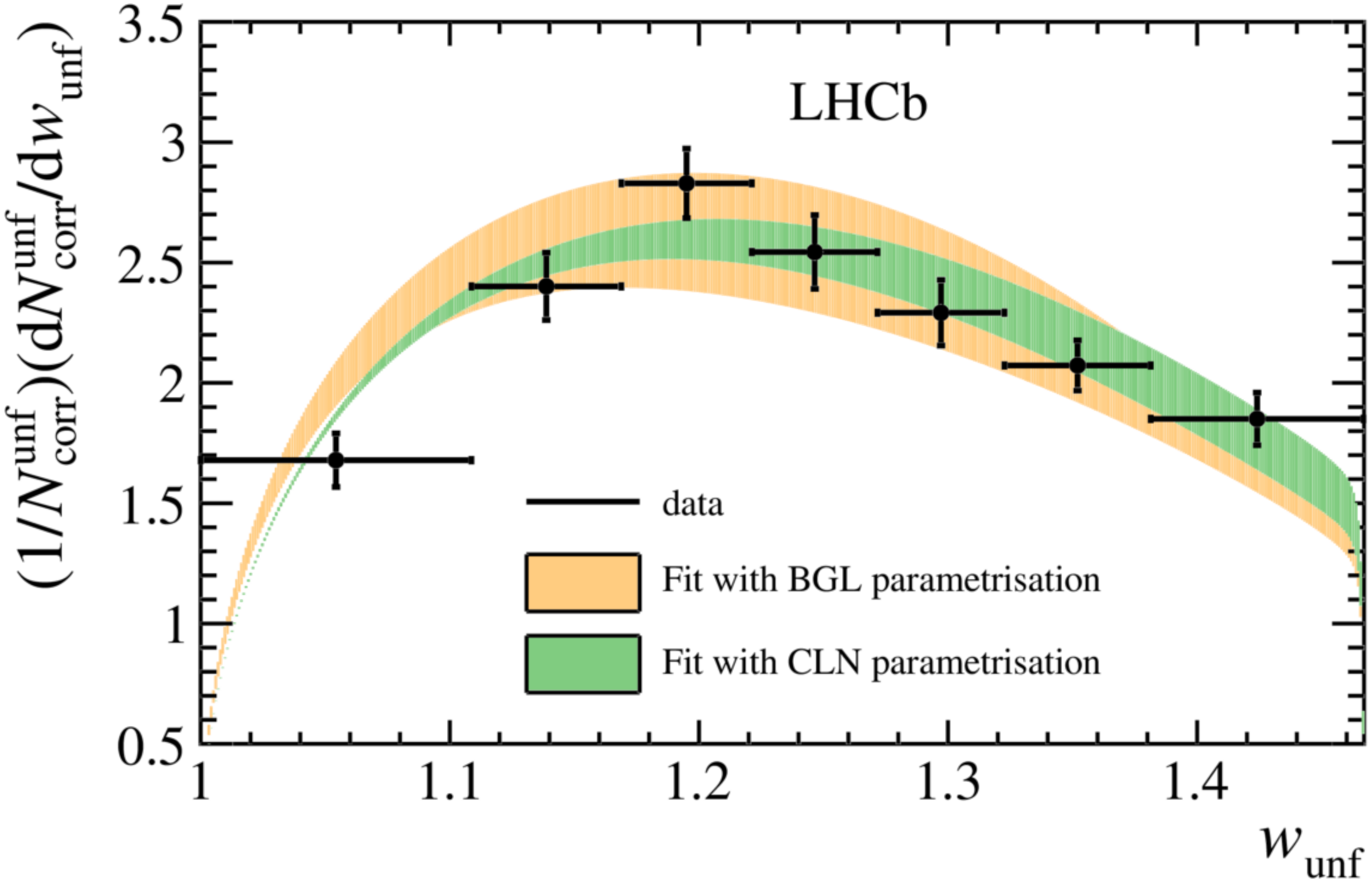
[arXiv:2201.03497]

$\sim 1\sigma$
$R(\Lambda_c^+) = 0.324 \pm 0.004$

[PRD99 (2019) 055008]

$B_s \to D_s^{*+}\mu^+\nu_\mu$ FF measurement at LHCb

- Analysis of the $B_s \to D_s^{*+}\mu^+\nu_\mu$ hadronic form factors and measurement of $R(D_s^{*+})$.

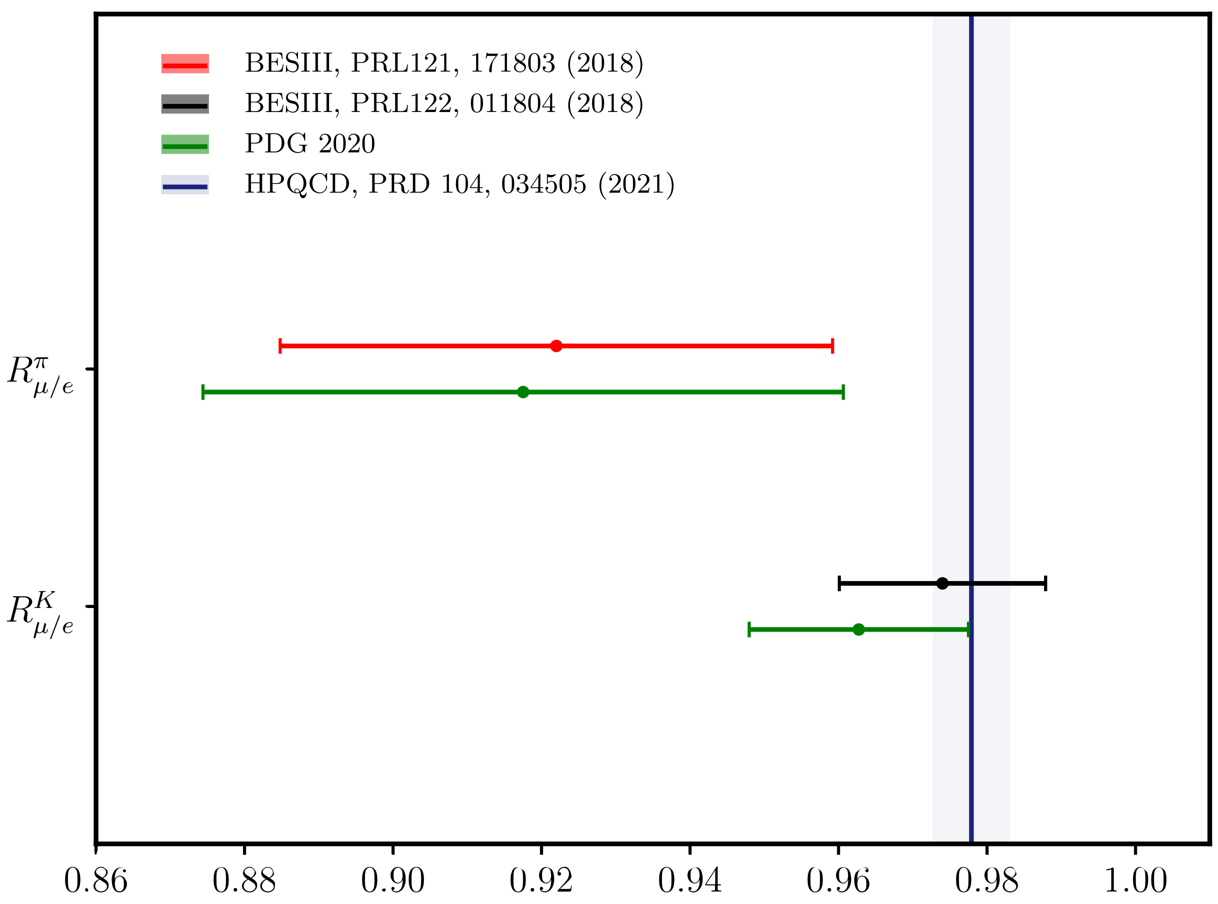


[Phys. Rev. D101 (2020) 072004]

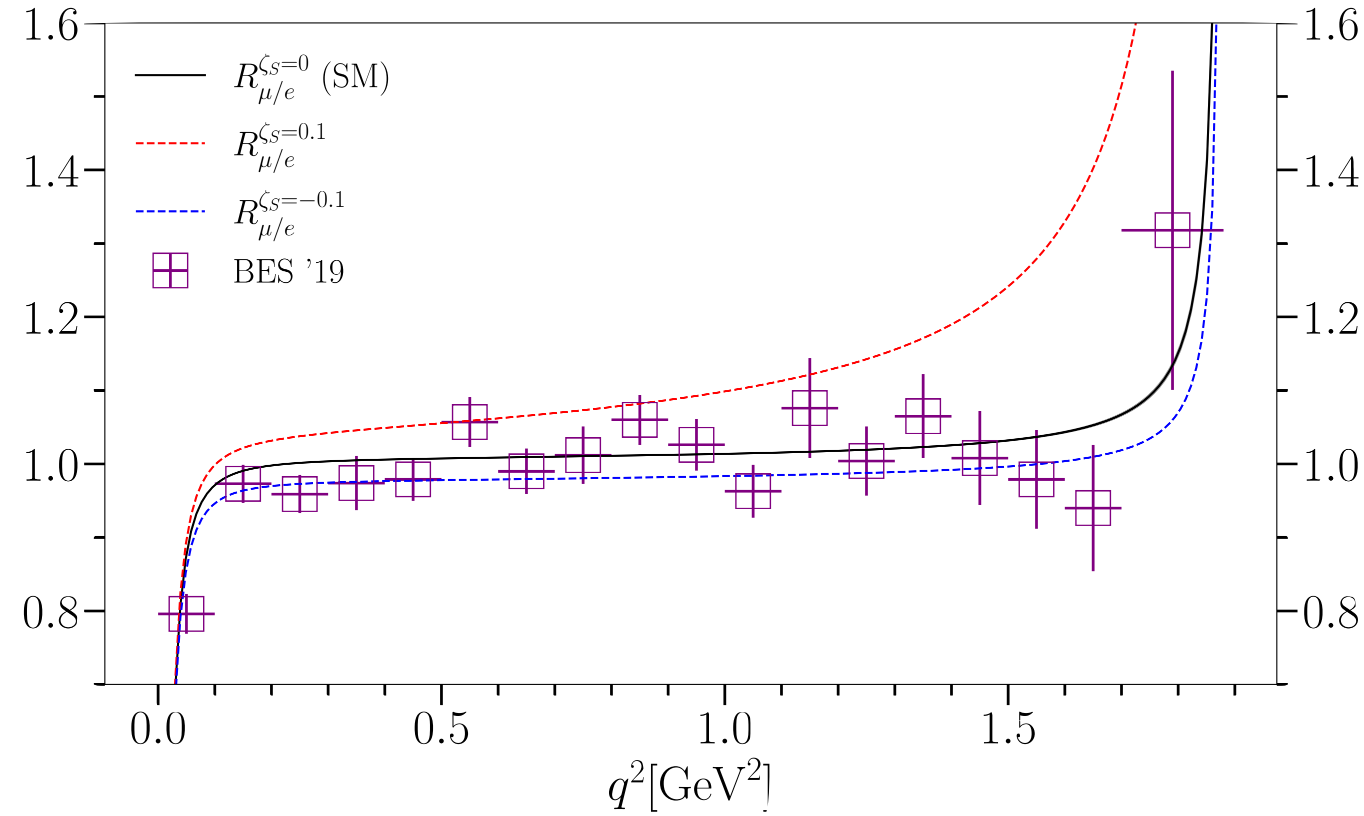
LFU tests in charm sector

- Measurements of $c \to s\ell^+\nu_\ell$ and $c \to d\ell^+\nu_\ell$ transitions→ $R_{\mu/e} = \dfrac{BR(D^0 \to K^-\mu^+\nu_\mu)}{BR(D^0 \to K^-e^+\nu_e)}$
- BESIII results are compatible with the SM predictions within 2σ
- Lattice prediction: $R_{\mu/e} = 0.9779 \pm 0.0002(\text{latt}) \pm 0.0050(\text{EM})$

$q^2 = (p_{D^0} - p_K)^2$



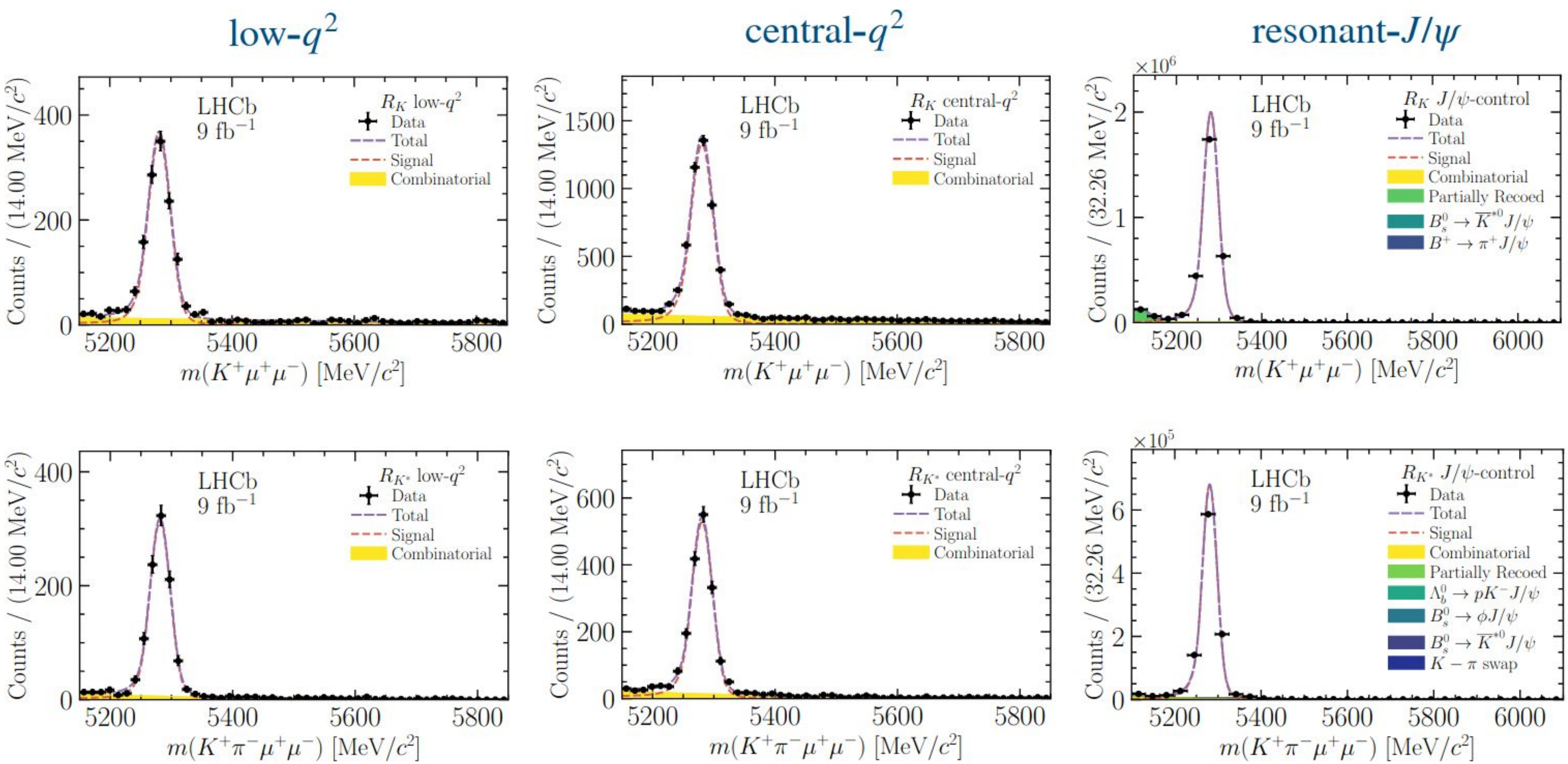
[PRD104 (2021) 034505]



$R(K^{(*)})$ measurement

- Mass fit. Muon mode

PRD 108 (2023) 032002



$R(K^{(*)})$ measurement

- Mass fit. Electron mode

PRD 108 (2023) 032002