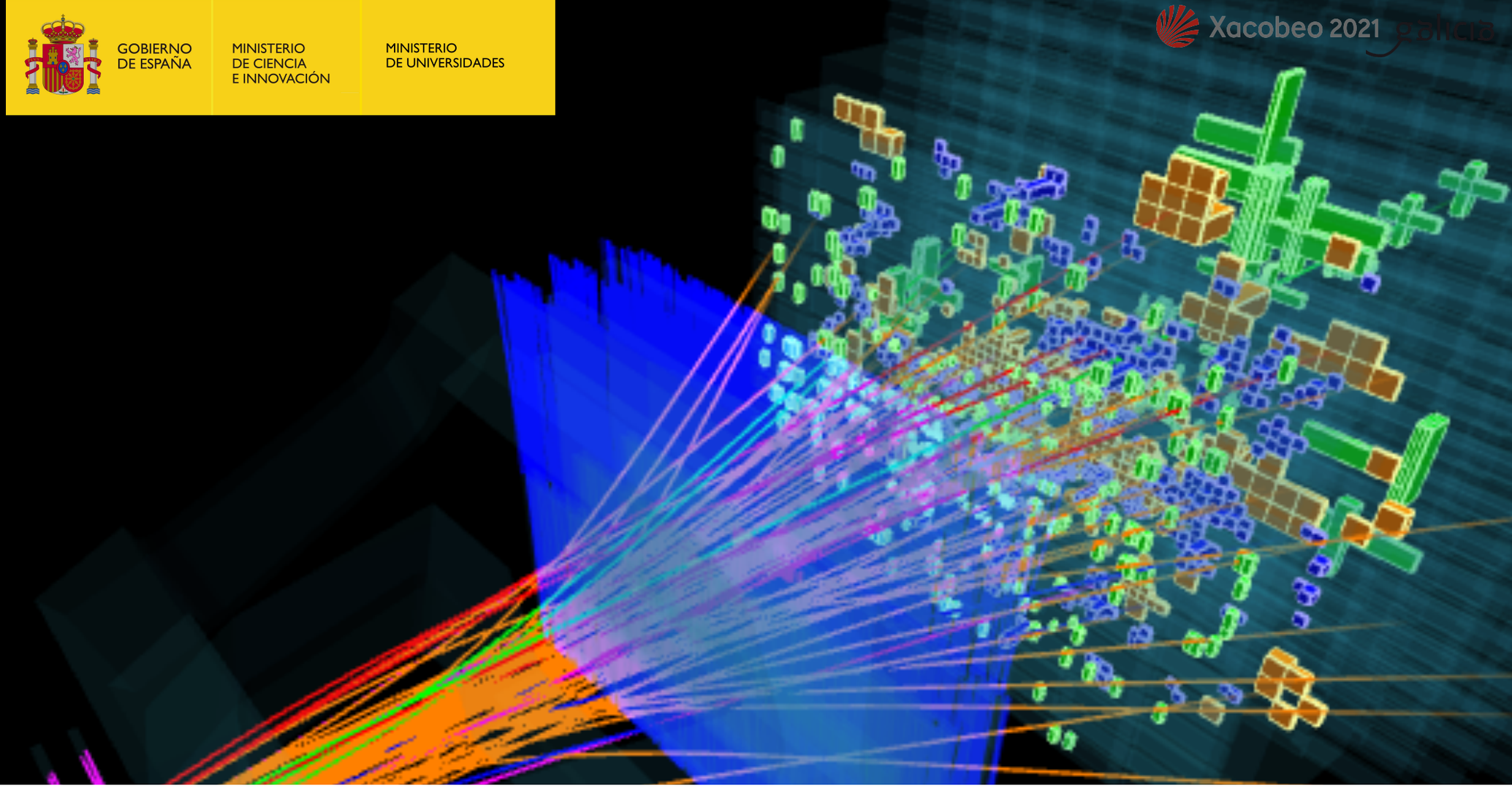

Lepton Flavour Universality tests at LHCb

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Red LHC

10/05/2021
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The (old) LHCb detector

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

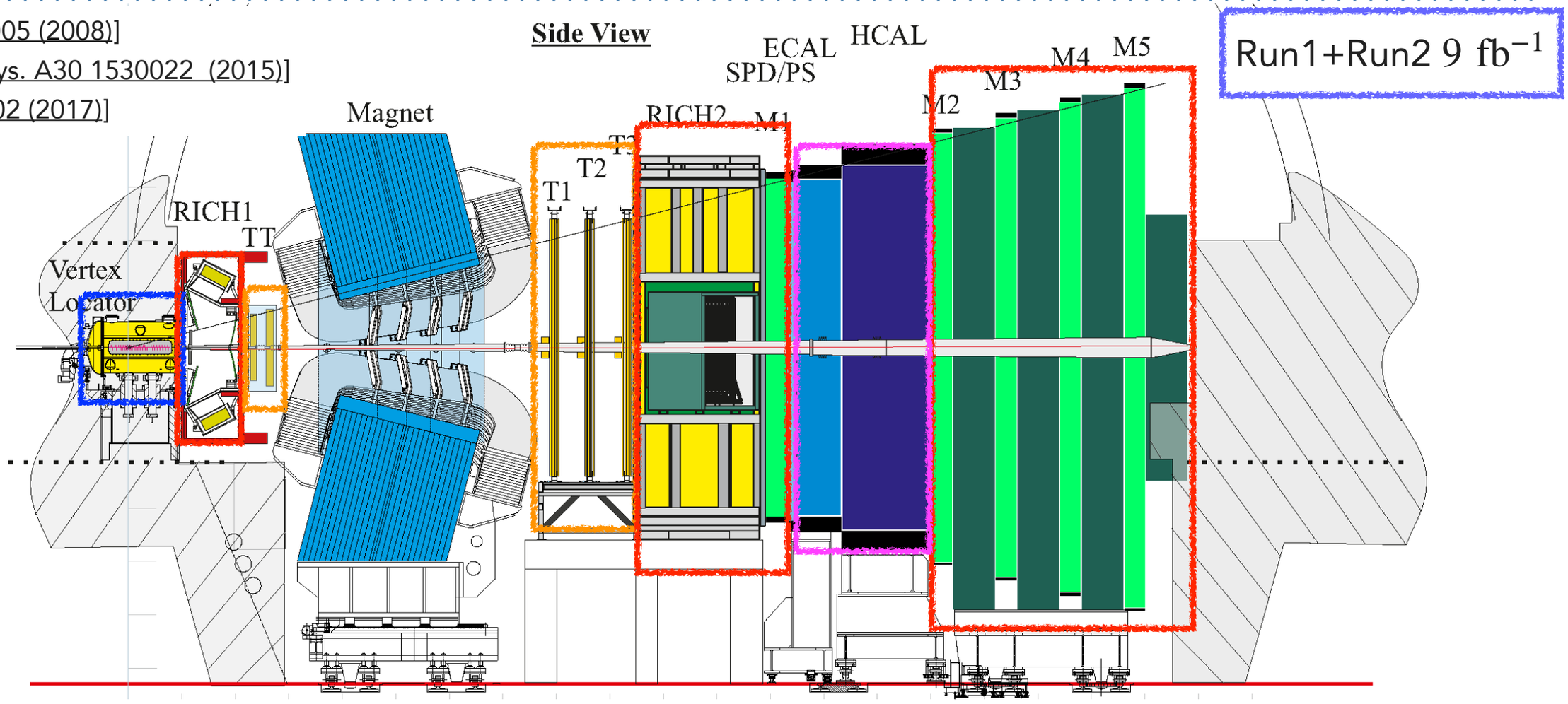
➡ Run 2 (2015 - 2018) $\sqrt{s} = 13$ TeV

[JINST 3 S080005 (2008)]

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

[PRL 118 052002 (2017)]

Run1+Run2 9 fb^{-1}



- Large amount of b and c hadrons produced, $\sigma_b = (144 \pm 1 \pm 21)\ \mu\text{b}$ at 13 TeV
- Forward spectrometer for $b-$ and $c-$hadron decays $(2 < \eta < 5)$
  - Good vertex and impact parameter resolution ($\sigma(\text{IP}) \sim 20\ \mu\text{m}$)
  - 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

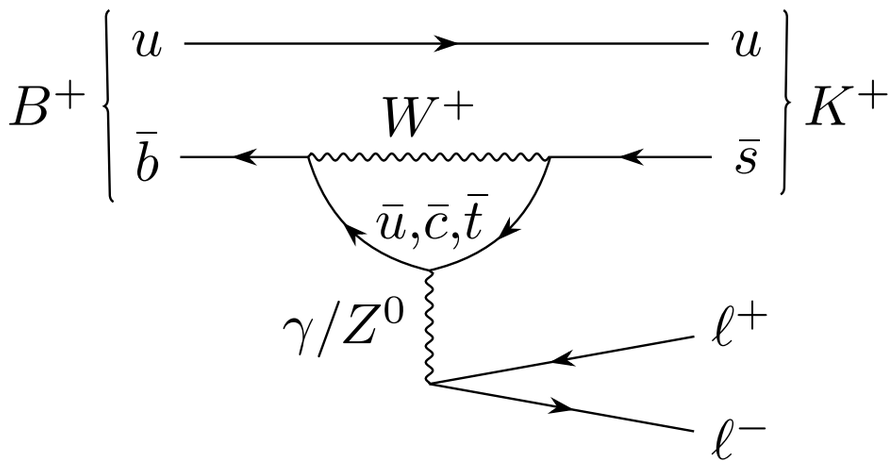
Lepton Flavour Universality

- The SM predicts equal couplings between gauge bosons and the three lepton families. This is called Lepton Flavour Universality (LFU)
  - Observation of LFU violation ⟶ sign of new physics (NP)
- Semileptonic decays show tensions between SM expectation and experimental results:
  - ➡ Rare Flavour Changing Neutral Current (FCNC) decays: $b \to s$
  - ➡ Charged current semileptonic (SL) decays: $b \to c$
- LFU can be probed by studying different observables:
  - Differential branching fractions
  - Angular analyses
  - ➡ Ratio observables

Latest results not covered in this talk:
[JHEP 12 (2020) 144] [PRD96 (2017) 112005 [PRL 126 (2021) 161802] [PRD96 (2017) 112005] [$R(J/\psi)$: PRL 120 (2018) 121801]

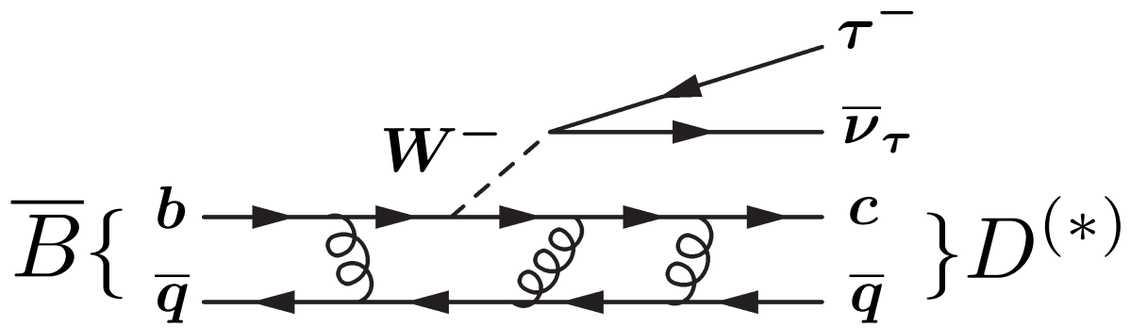
Searches for LFU

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



- **FCNC process**. Only loop diagrams in SM
- Sensitive to either tree or loop NP contributions

$b \to c\ell\nu_\ell$ transitions



- **Tree level** process. In the SM mediated by a W boson
- Potential NP in different couplings between generations

FCNC DECAYS

$b \to s\ell\ell$ transitions

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

➡ Within a given range of dilepton mass squared, q^2

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

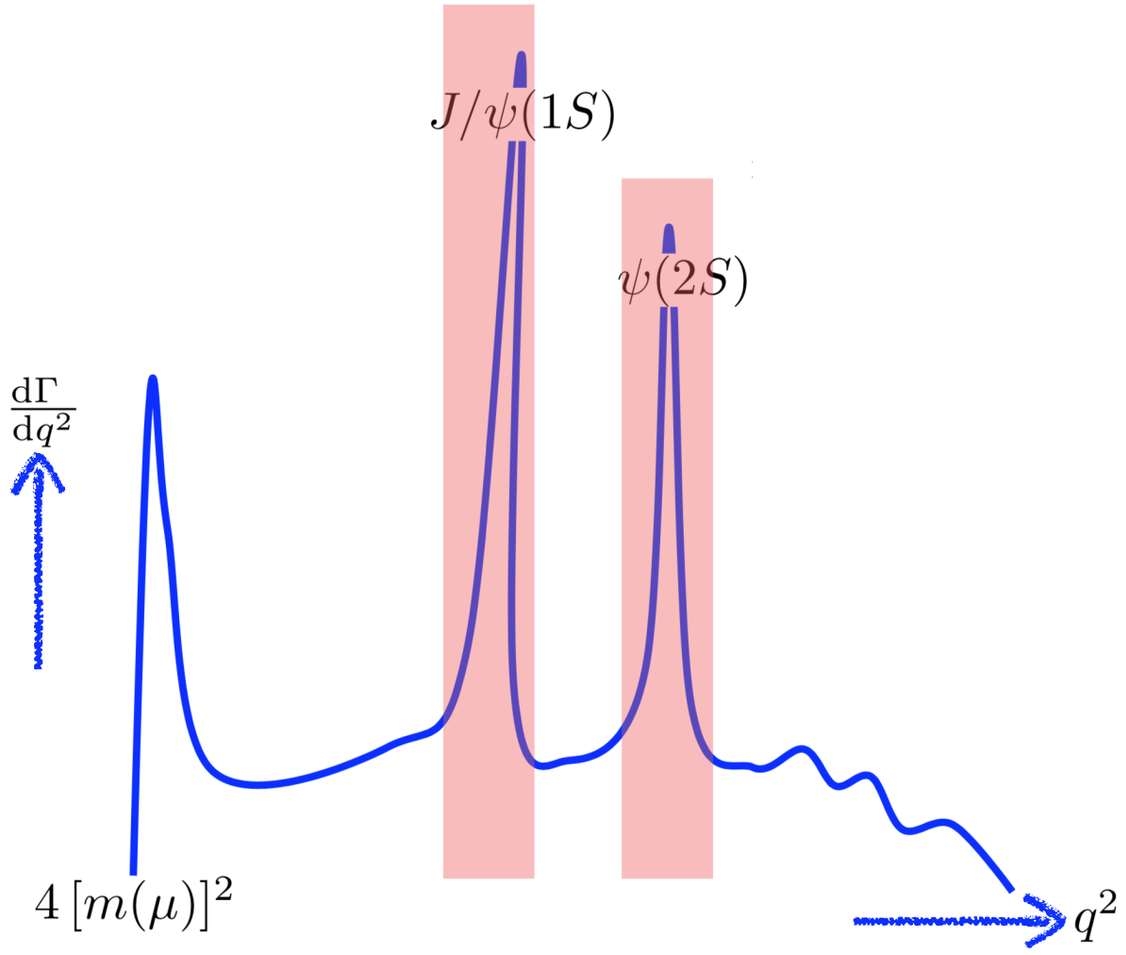
where $H_b = B,\ \Lambda_b^0$

where $H_s = K,\ K^*,\ \phi,\ pK$

- Partial cancellation of hadronic uncertainties in theoretical predictions

➡ SM expectation
$R(H_s) = 1 \pm \mathcal{O}(1\%)$

➡ More sensitive to NP



$b \to s\ell\ell$ transitions

[arXiv:2103.11769]
[PRL122 (2019) 191801]

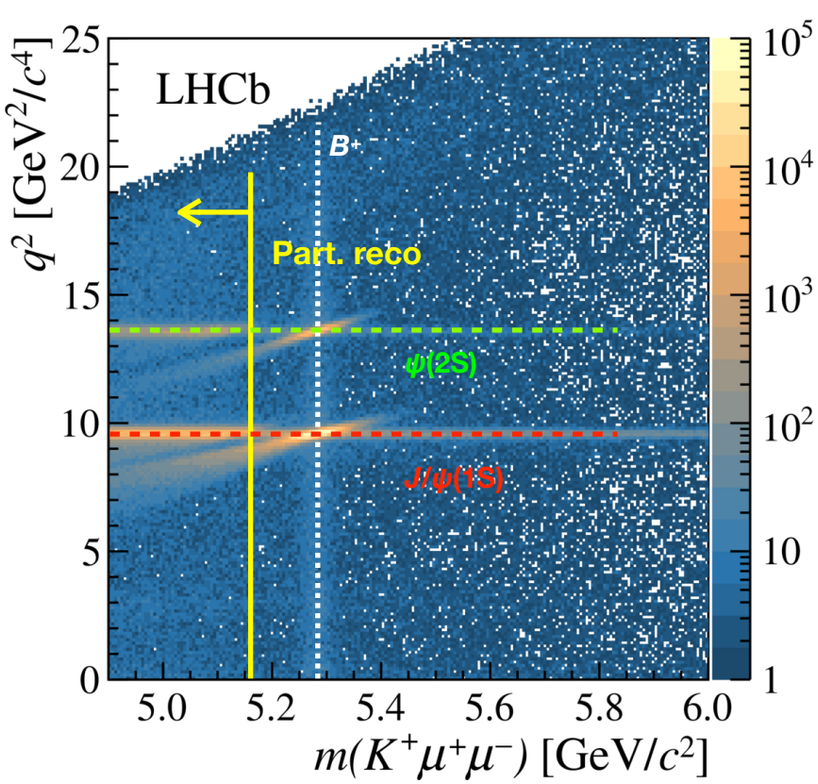
Run 1+2

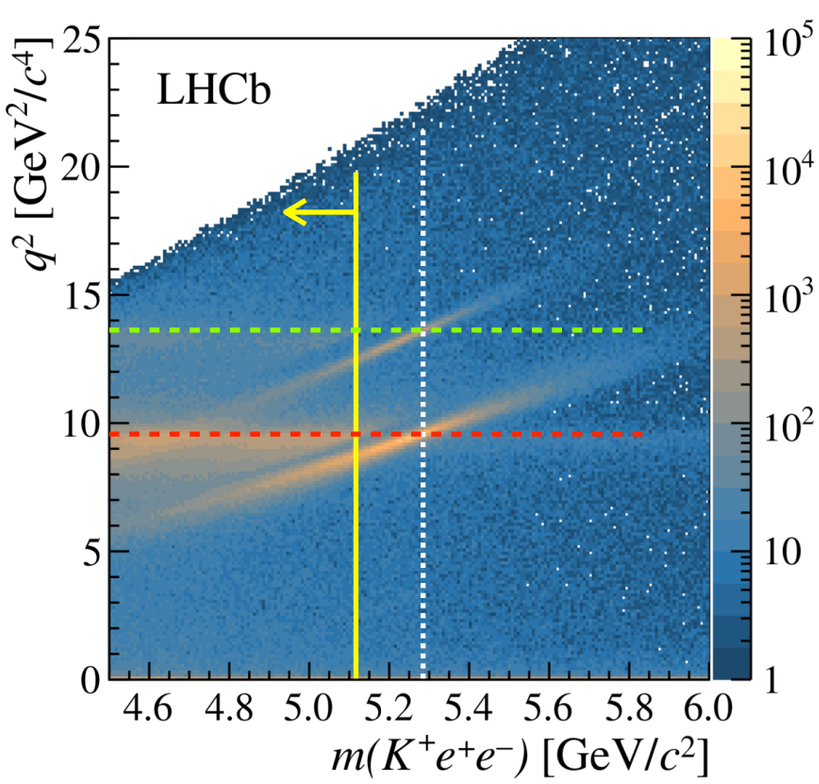
- Double ratio to reduce systematics:

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

- Final result obtained by performing a simultaneous fit of B mass distribution in the $J/\psi(\to \ell^+\ell^-)$ and non-resonant channels, $M(K^+\pi^-\ell^+\ell^-)$

- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
  - Main background channels due to partially reconstructed electrons



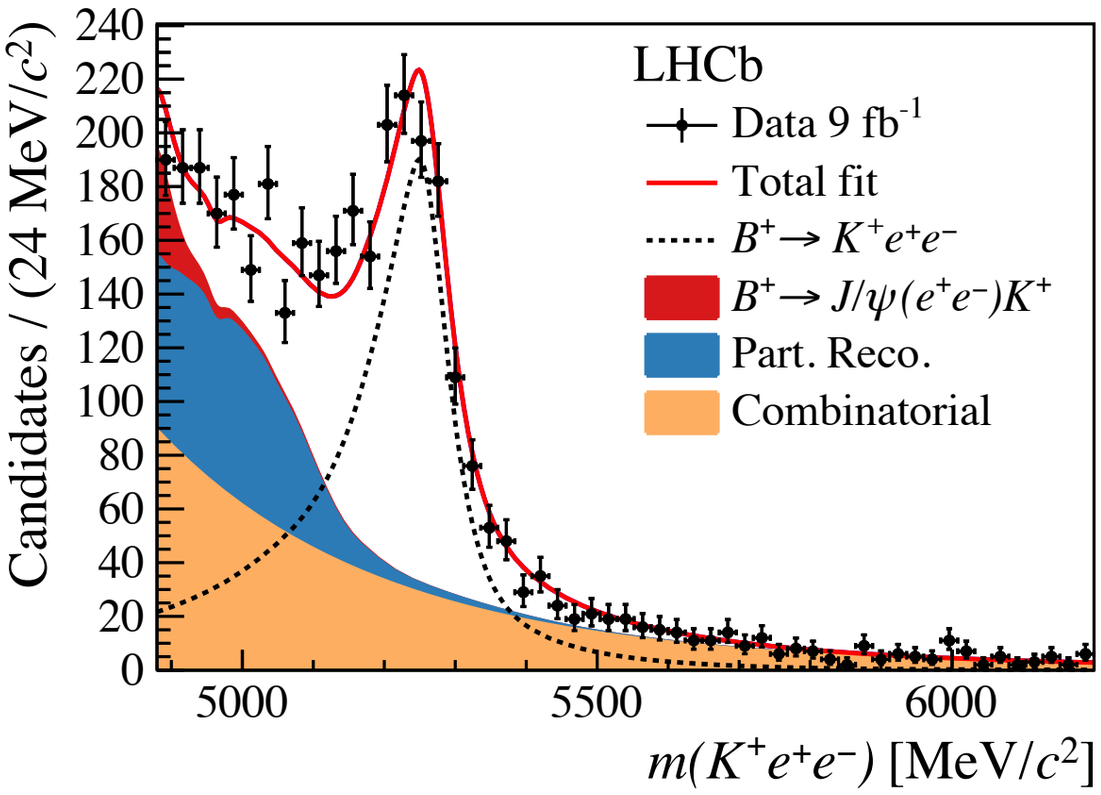


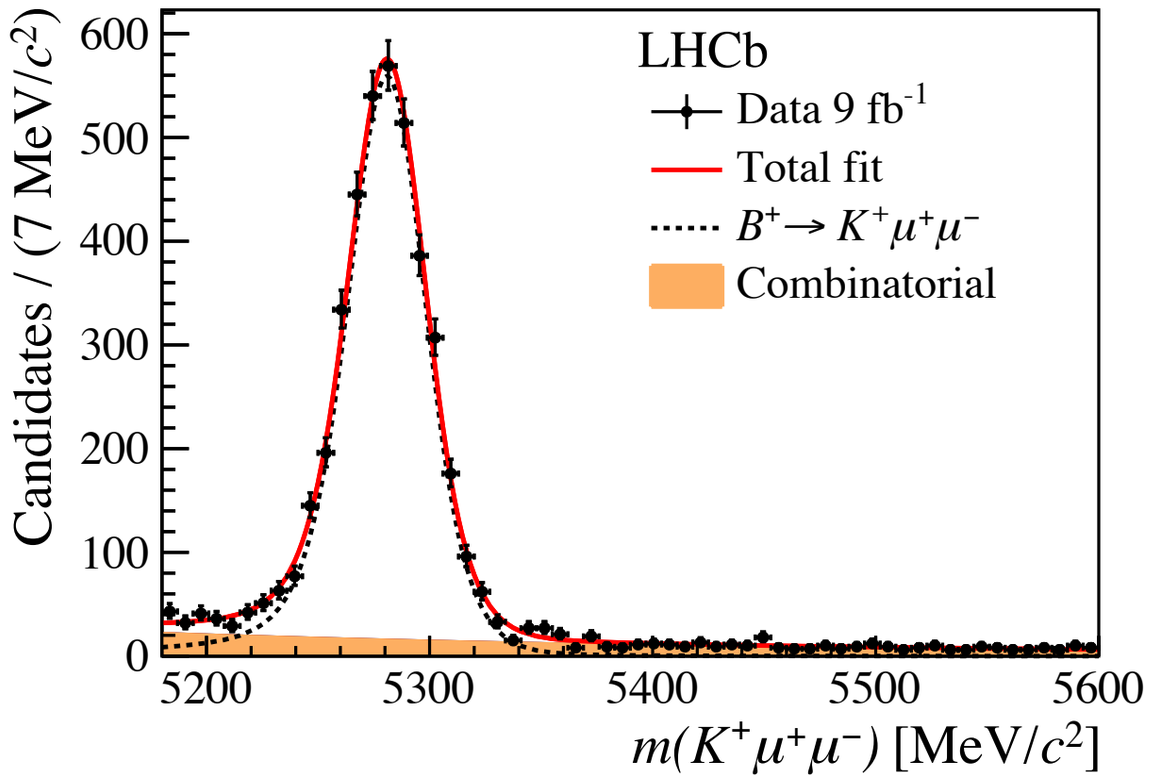
$R(K)$ measurement

NEW [arXiv:2103.11769]

Run 1+2

- Final result obtained by performing a simultaneous fit of B^+ mass distribution to $M(K^+\mu^+\mu^-)$ and $M(K^+e^+e^-)$



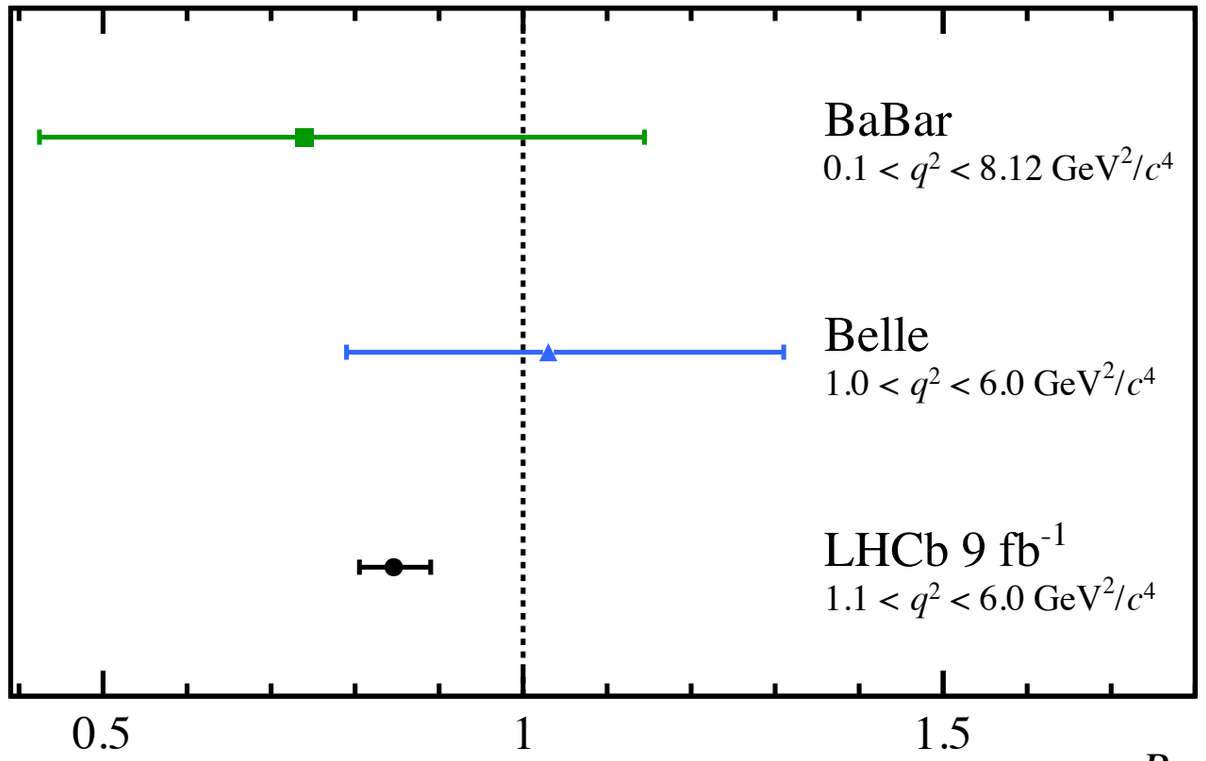


➡ $R(K) = 0.846^{+0.042}_{-0.039}(\text{stat.})^{+0.013}_{-0.012}(\text{syst.})$ for $1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$

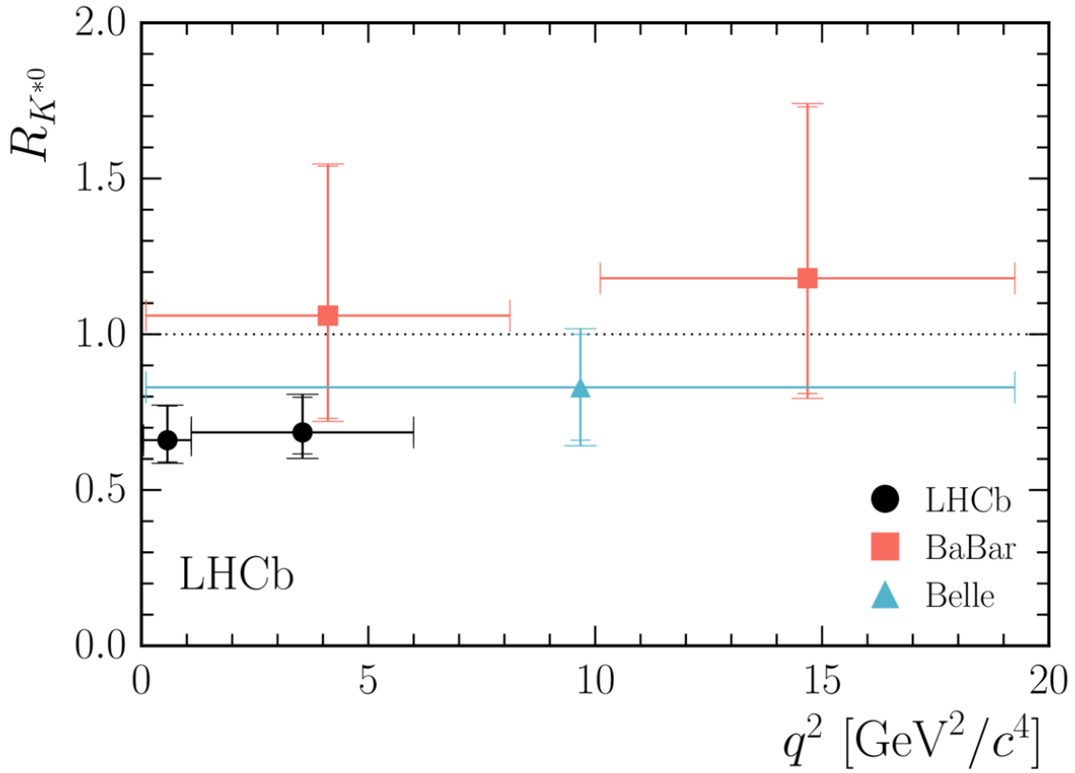
➡ **3.1 standard deviations** away from the SM prediction

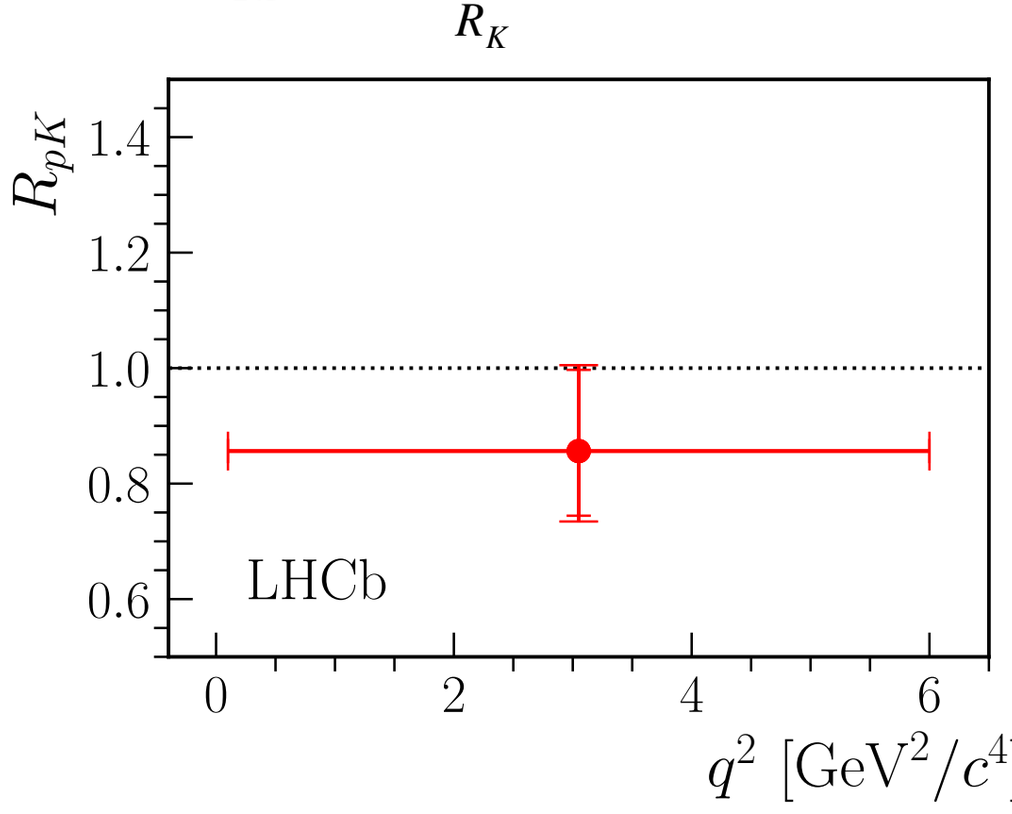
$R(K)$, $R(K^*)$ and $R(pK)$ measurements

[arXiv:2103.11769]
[JHEP 05 (2020) 040]
[JHEP 08 (2017) 055]



NEW





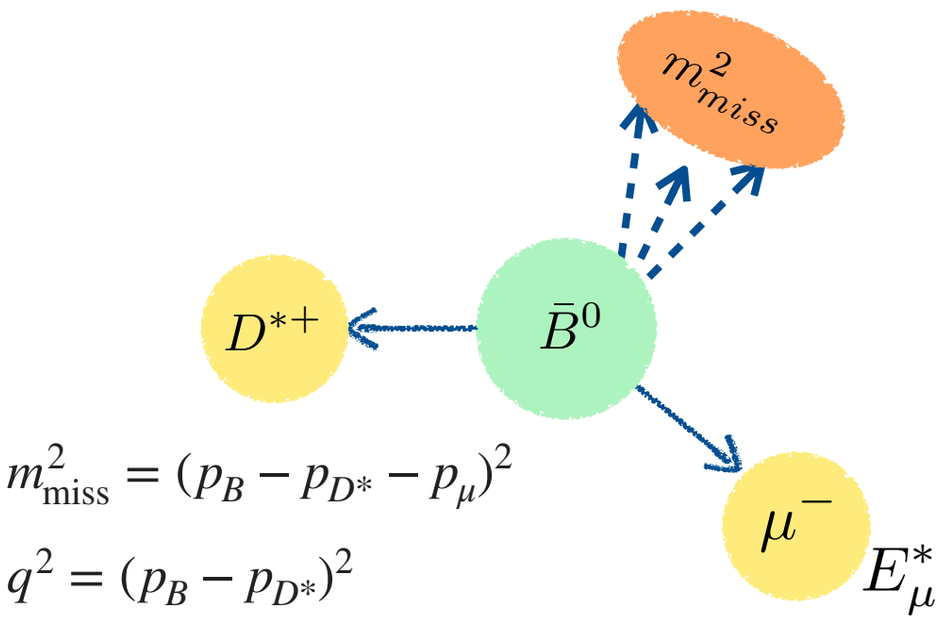
CHARGED CURRENT SL DECAYS

$b \to c\ell\nu$ transitions

[PRD 97 072013 (2018)] [PRL 115 111803 (2015)]
[PRL 120 171802 (2018)] [HFLAV 2019]
[PRL 120 121801 (2018)]

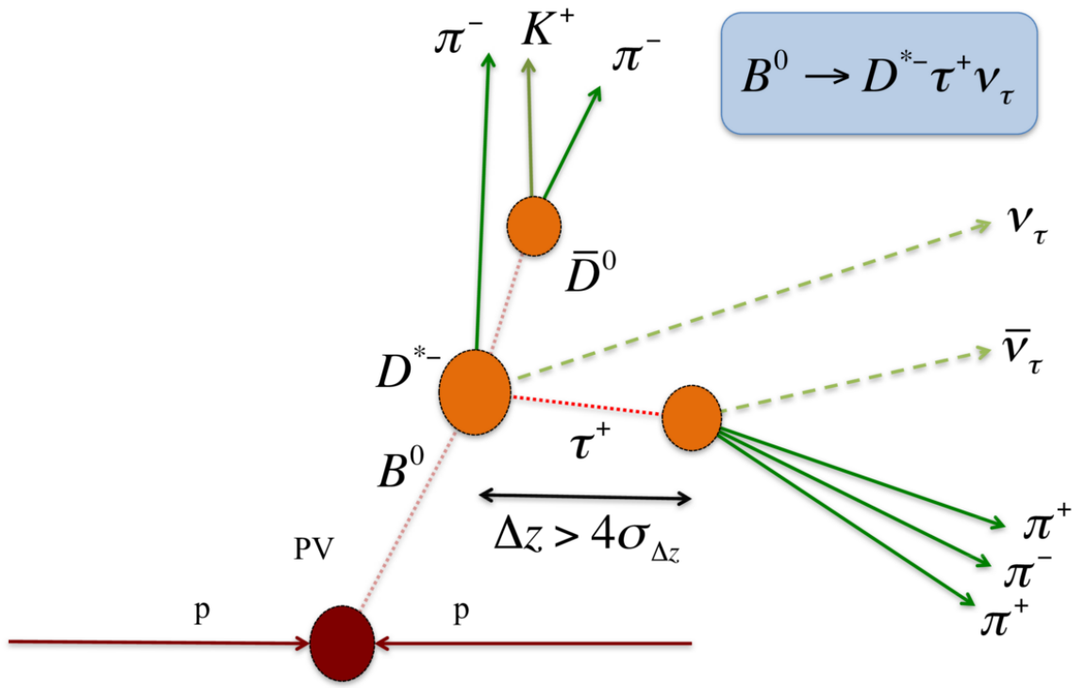
- Test LFU by measuring $R(H_c) = \dfrac{BR(H_b \to H_c \tau^+ \nu_\tau)}{BR(H_b \to H_c \mu^+ \nu_\mu)}$ where $H_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s, \ldots$ where $H_c = D^{(*)\pm}, D^0, D_s, \Lambda^+_c, J/\psi, \ldots$
- Clean theoretical prediction
- $R(H_c)$ deviates from unity due to different lepton masses $m_\tau \sim \begin{cases} 17 \cdot m_\mu \\ 3500 \cdot m_e \end{cases}$
- Different strategies:
  - Muonic decay of the tau: $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$
  - 3-prong decay: $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
- Missing momentum of neutrino

Run 1



$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$

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



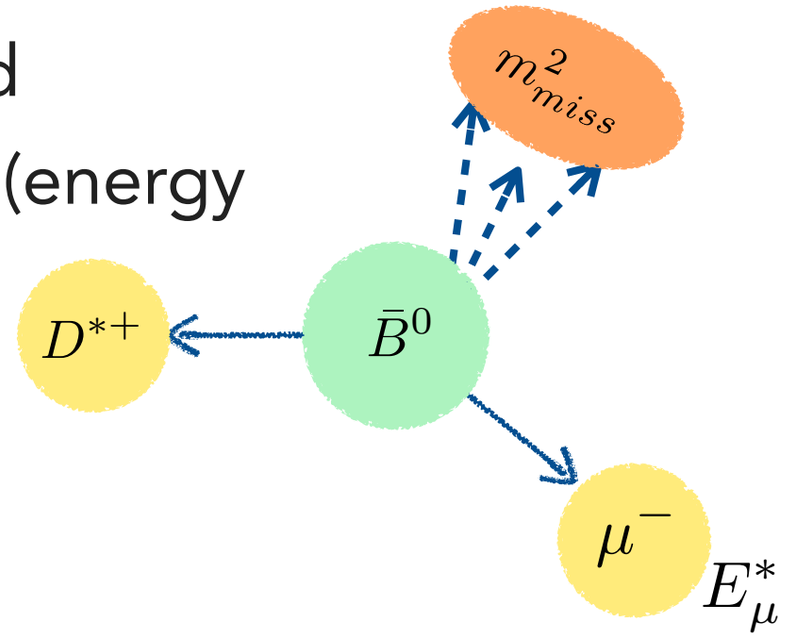
Muonic $R(D^*)$ measurement

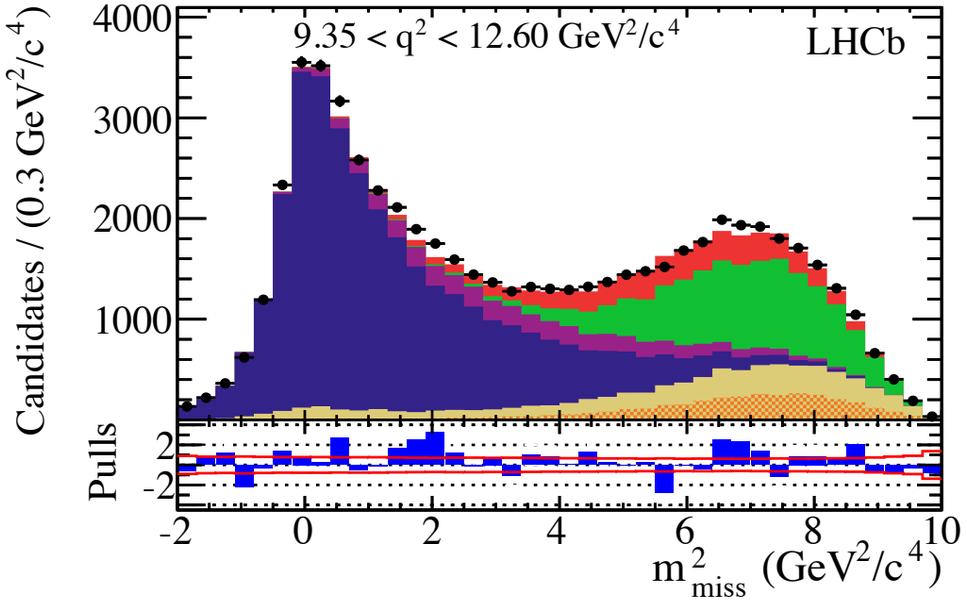
Run 1

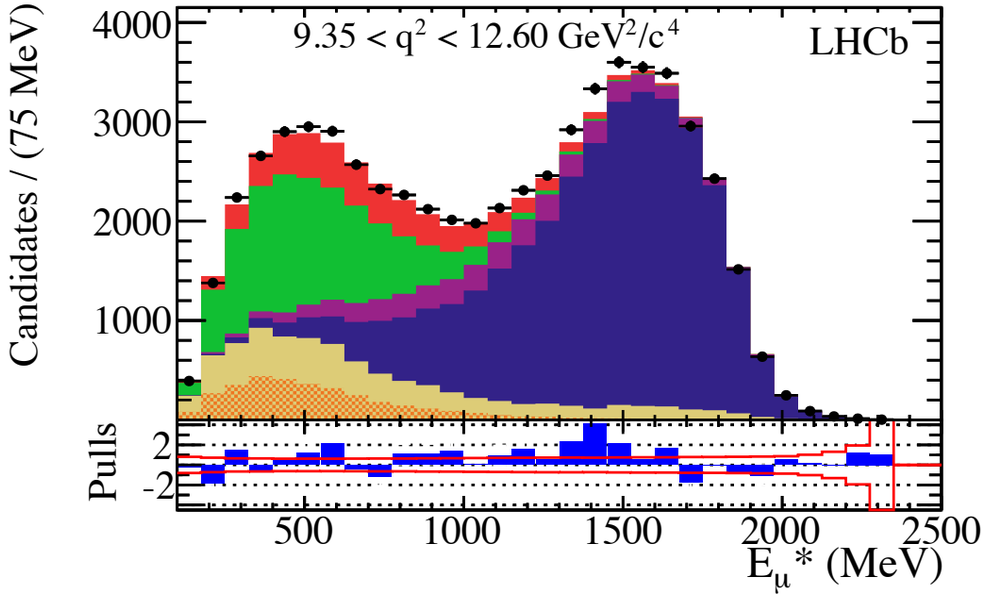
[PRL 115 111803 (2015)]
[HFLAV 2019]

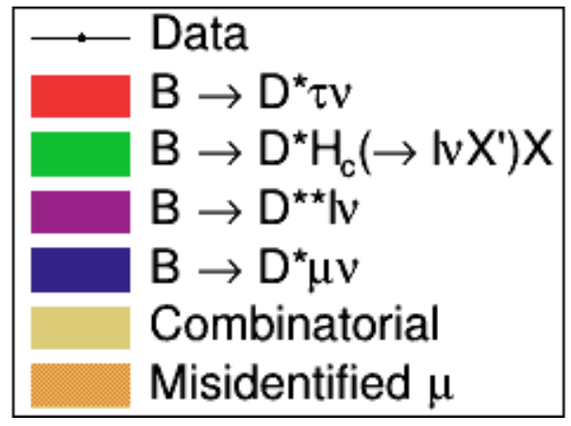
- Separation of τ and μ channels via a 3D binned template fit to data including q^2, m^2_{miss} and E^*_μ (energy in the B^0 rest frame)
- Fit projections of m^2_{miss} and E^*_μ in the region of $q^2 \in [9.35,\ 12.60]\ \text{GeV}^2/c^4$

where $m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$ and $q^2 = (p_B - p_{D^*})^2$









$$R(D^*) = 0.366 \pm 0.027\ (\text{stat}) \pm 0.030\ (\text{syst})\ .$$

$\sim 2.1\sigma$
$R(D^*)_{SM} = 0.258 \pm 0.005$

Hadronic $R(D^*)$ measurement

Run 1

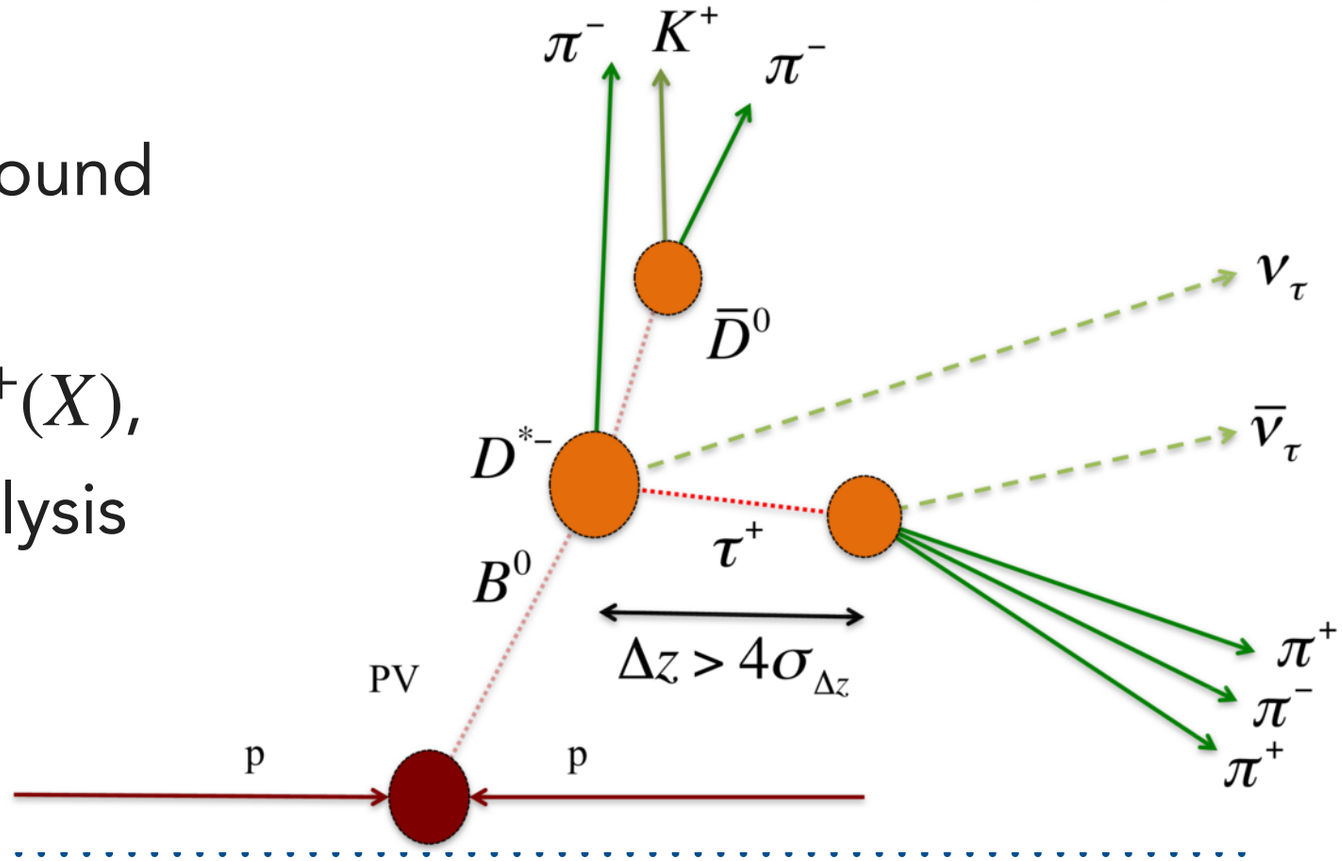
[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]
[HFLAV 2019]

- First measurement using 3-prong tauonic decay $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
- Measure

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

From PDG [2020]:
$BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+) = (7.21 \pm 0.29) \cdot 10^{-3}$
$BR(B^0 \to D^{*-}\mu^+\nu_\mu) = (5.05 \pm 0.14)\,\%$

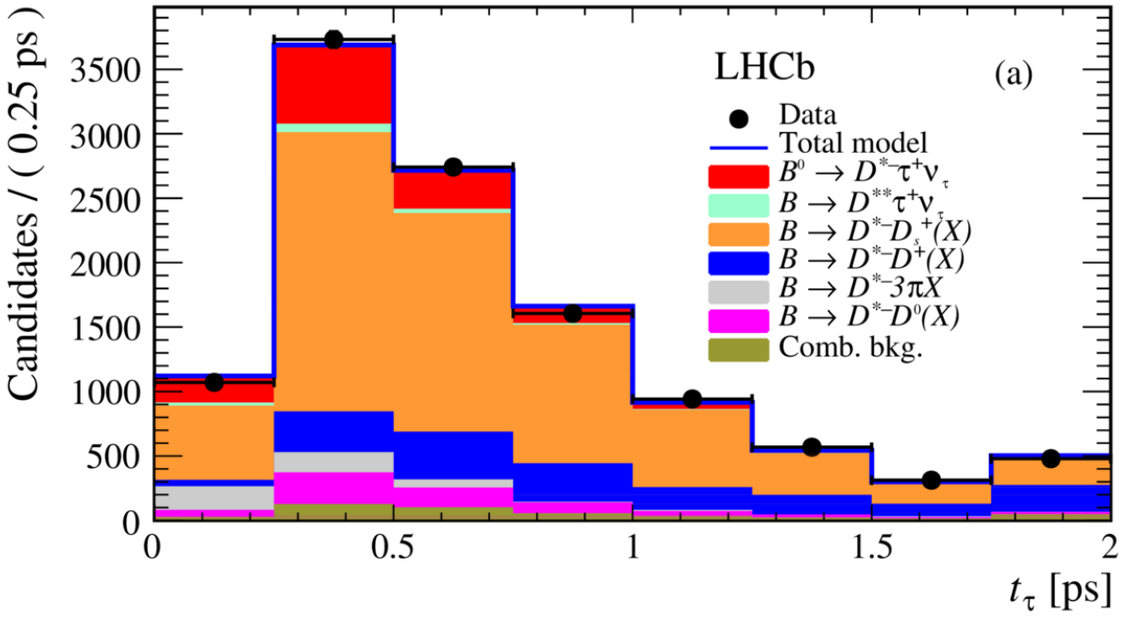
- Approximations to estimate B and τ momenta
- Largest background channels:
  - $B^0 \to D^{*-}\pi^+\pi^-\pi^+(X)$ background suppressed by $\Delta z > 4\sigma_{\Delta z}$
  - Doubly charmed $B \to D^{*-}D_s^+(X)$, treated with multivariate analysis (BDT)

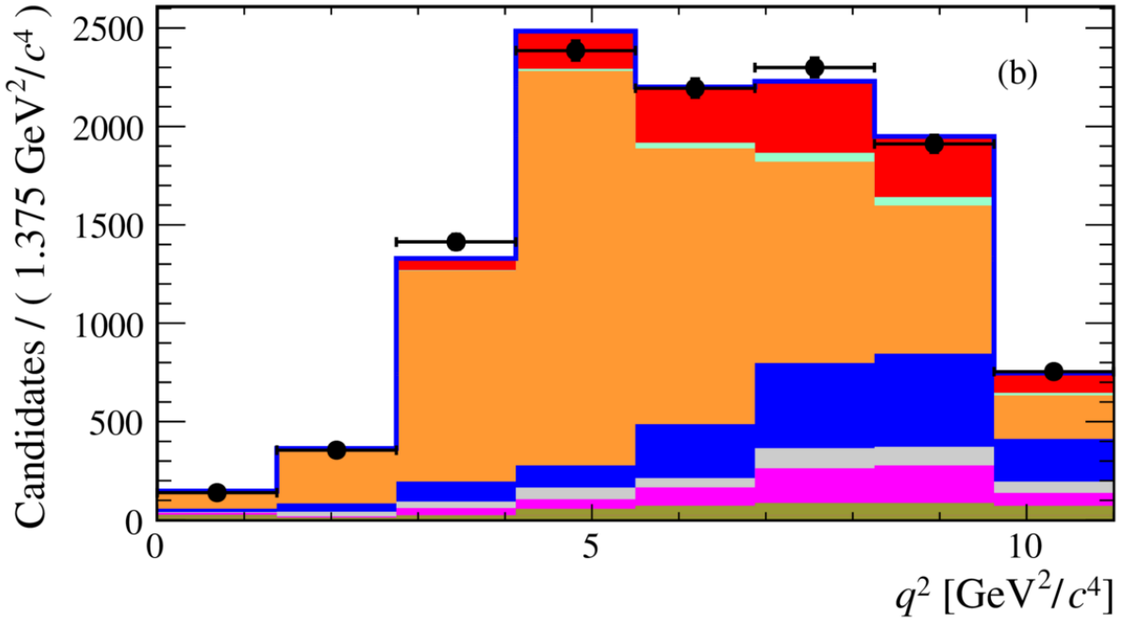


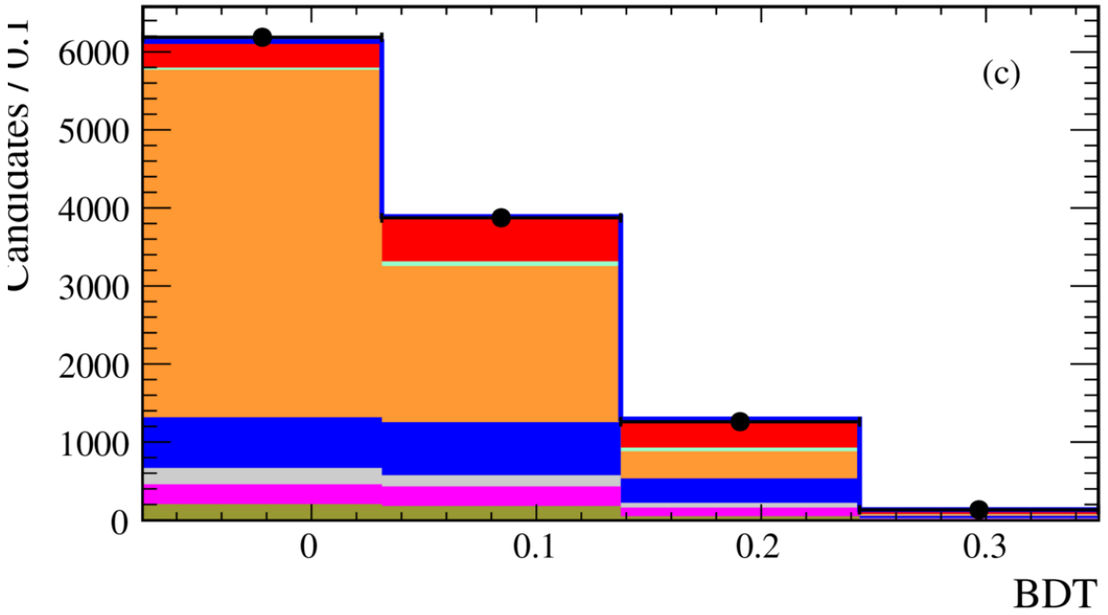
$R(D^*)$ result

Run 1

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]
[HFLAV 2019]







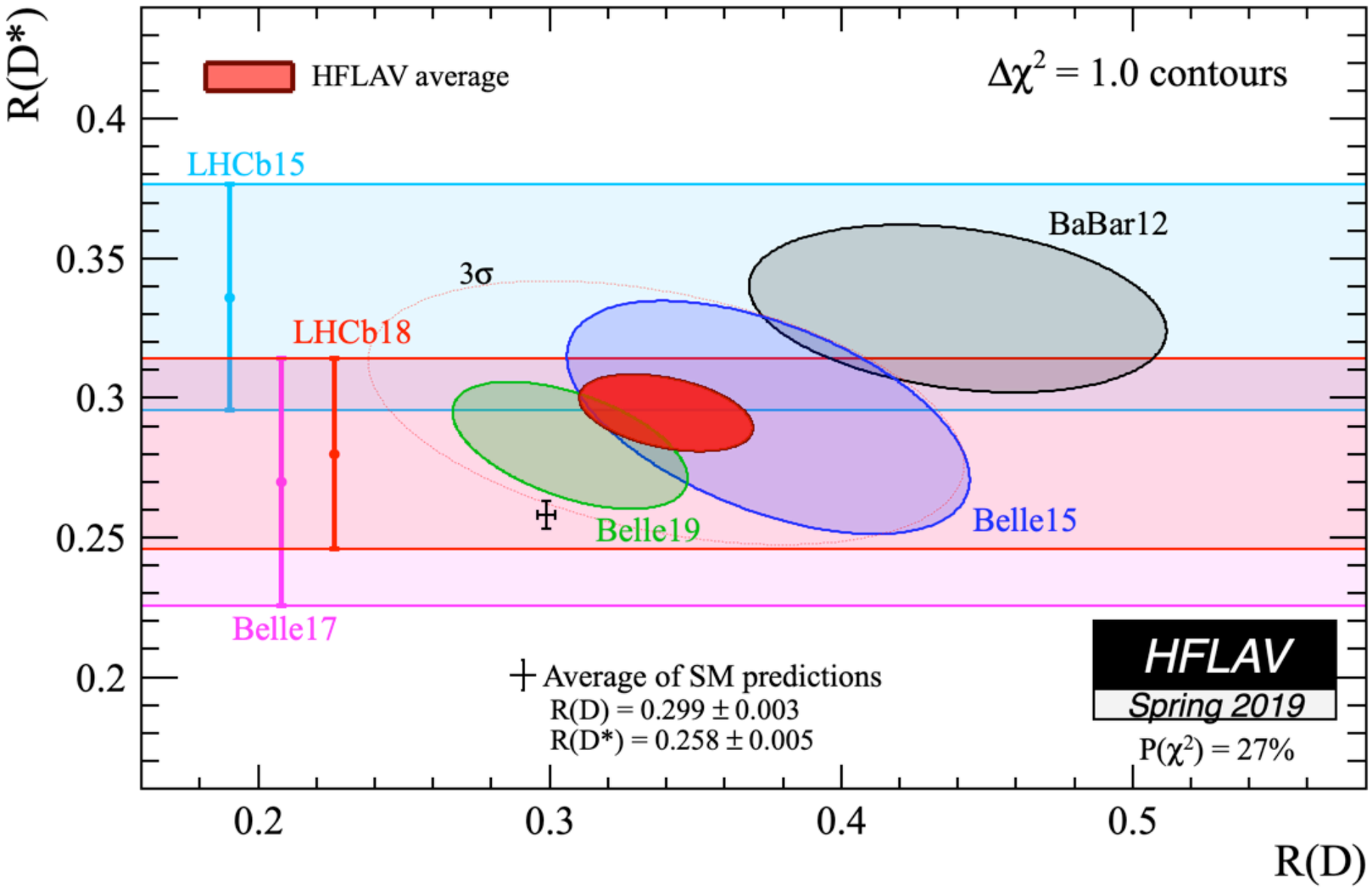
- Projection of τ decay time, q^2 and BDT output
  - $N(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ by unbinned likelihood fit to $M(D^{*-}\pi^+\pi^-\pi^+)$
  - $N(B^0 \to D^{*-}\tau^+\nu_\tau)$ obtained by a 3D binned fit to data

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

$\sim 1\sigma$
$R(D^*)_{SM} = 0.258 \pm 0.005$

$R(D)$ and $R(D^*)$ result and global average

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]
[HFLAV 2019]



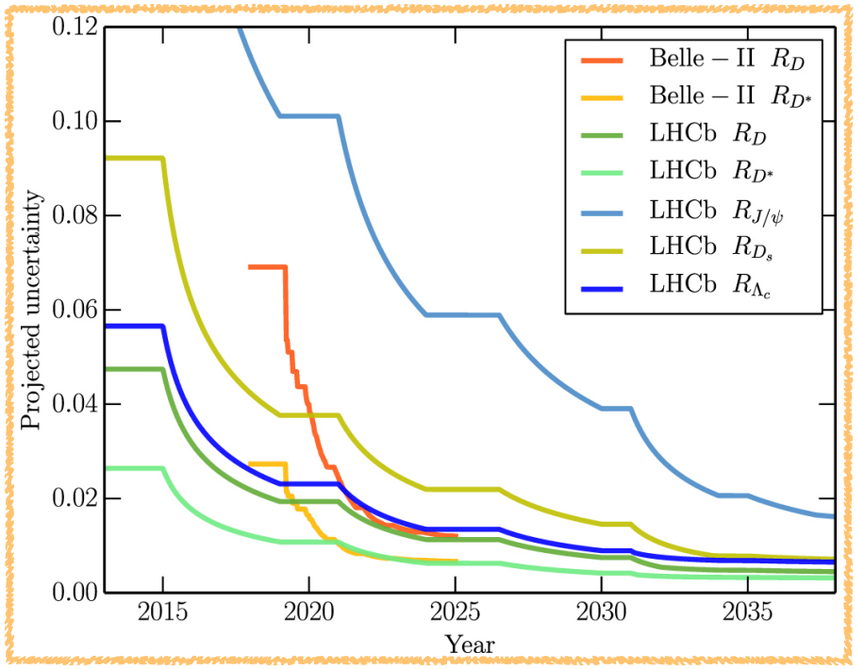
- The **global average** of the combination of $R(D)$ and $R(D^*)$ measurements differ from SM by 3.1σ

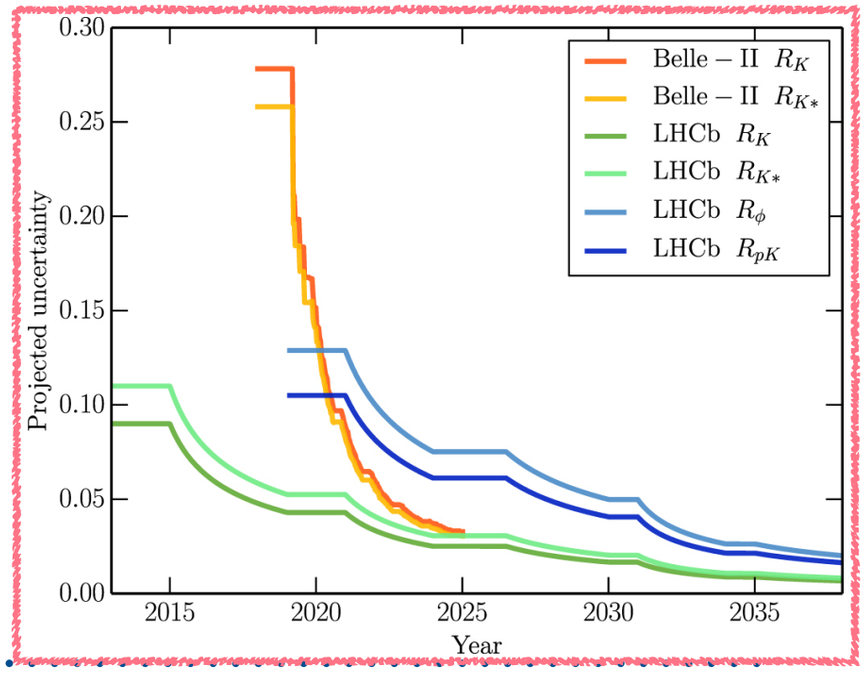
WHAT'S NEXT

Future prospects

[JoP G 46 2 (2018)]

- In Run 1 and Run 2, LHCb has recorded a data sample corresponding to an integrated luminosity of $9\ \mathrm{fb}^{-1}$
  - Reduction of statistical uncertainties
- Measurements of $R(H_c)$ both muonic and hadronic:
  - $R(D^{(*)})$, $R(\Lambda_c)$, $R(J/\psi)$,…
  - Systematic external uncertainties improved by new measurements (Belle II and BESIII)
- Measurements of $R(H_s)$:
  - $R(K^{(*)})$, $R(pK)$, $R(\phi)$, …





Conclusions

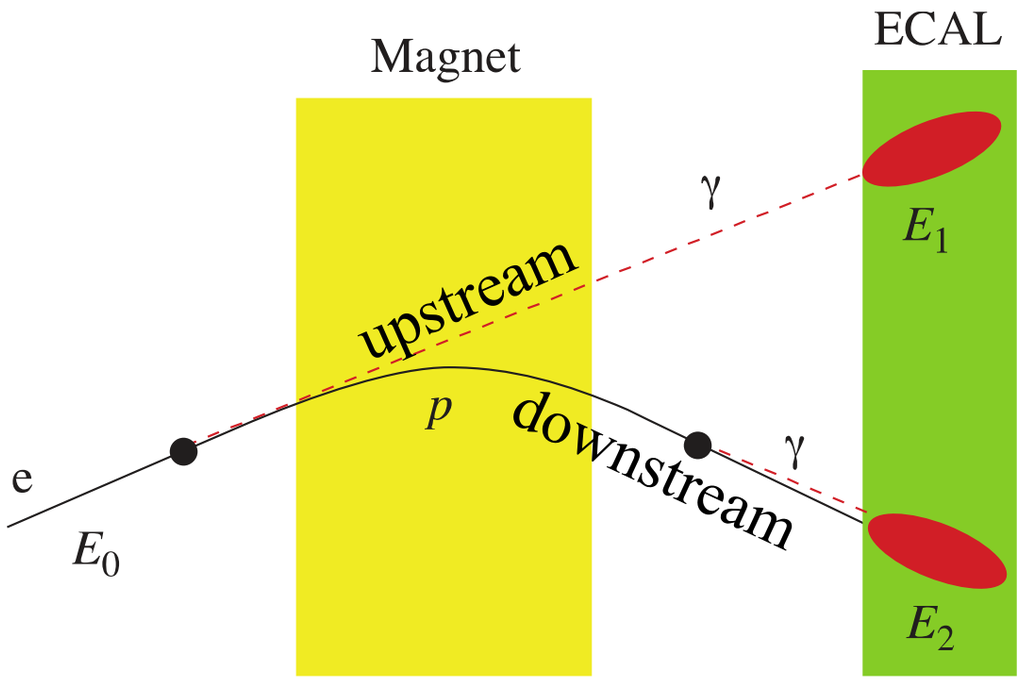
- LFU violating processes are a potential road to New Physics
- Different observables to probe LFU
- Exciting results from LFU tests in semileptonic decays show tensions to the SM predictions in both $b \to s\ell\ell$ and $b \to c\ell\nu_\ell$ transitions
- Many analyses are ongoing in LHCb with Run 1 and Run 2 data sample ($9\ \text{fb}^{-1}$)
  - Expected a reduction of statistical uncertainties with the complete data sample

STAY TUNED

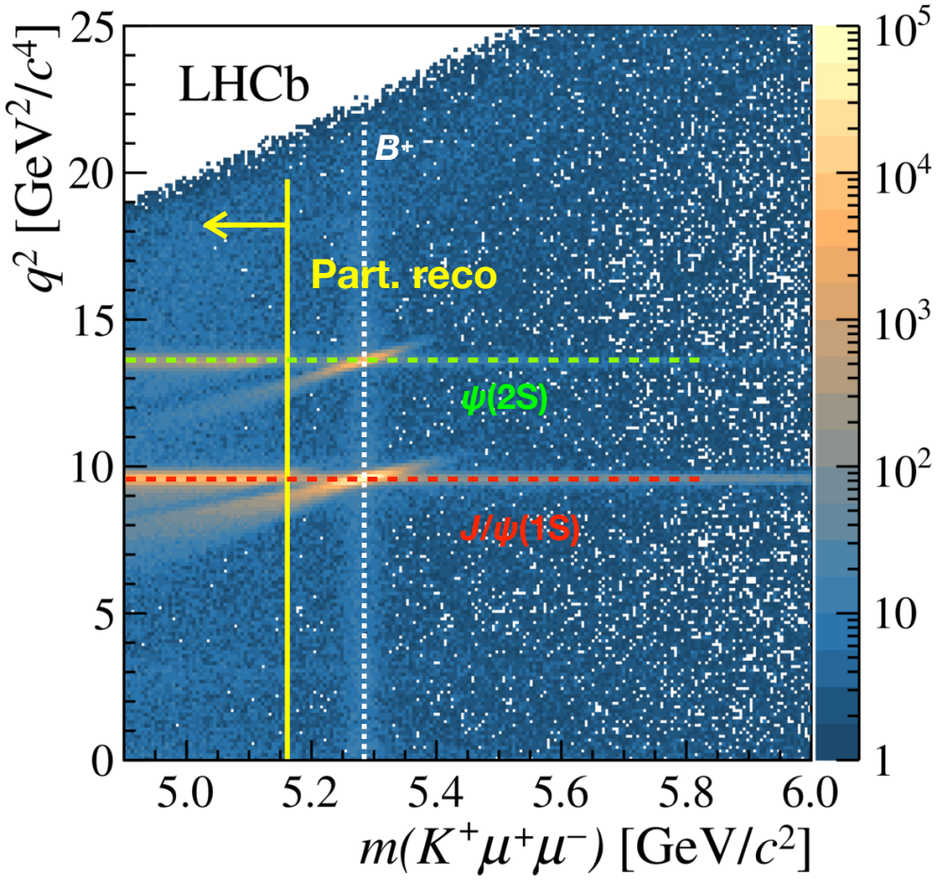
BACKUP

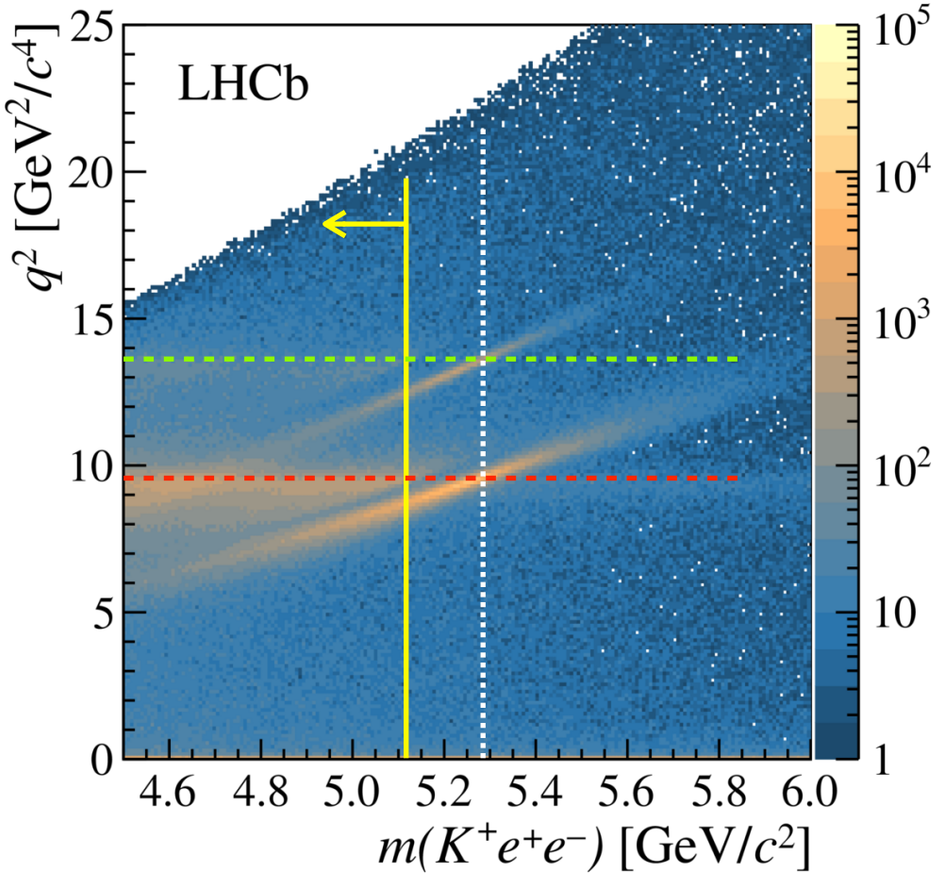
Electron tracks reconstruction

[arXiv:2103.11769]
[PRL122 (2019) 191801]



- 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 electron direction before magnet





Hadronic $R(D^*)$ measurement

Run 1

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]
[HFLAV 2019]

- First measurement using 3-prong tauonic decay

  $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- Measure

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

➡ $K(D^*) = 1.97 \pm 0.13\ (\text{stat}) \pm 0.18\ (\text{syst})$

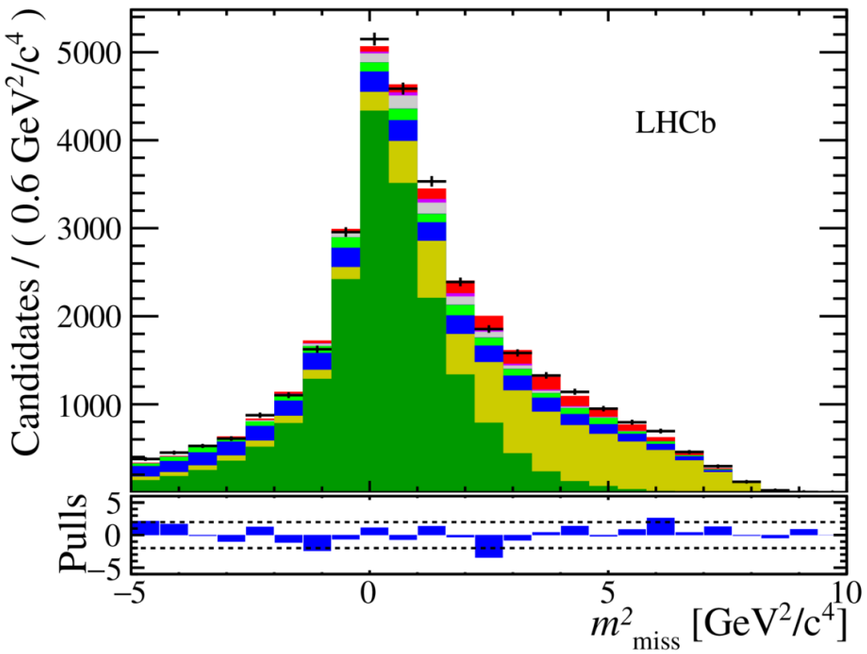
- From PDG [2020]:
  - $BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+) = (7.21 \pm 0.29) \cdot 10^{-3}$
  - $BR(B^0 \to D^{*-}\mu^+\nu_\mu) = (5.05 \pm 0.14)\,\%$

$R(J/\psi)$ measurement

[PRL 120 121801 (2018)]

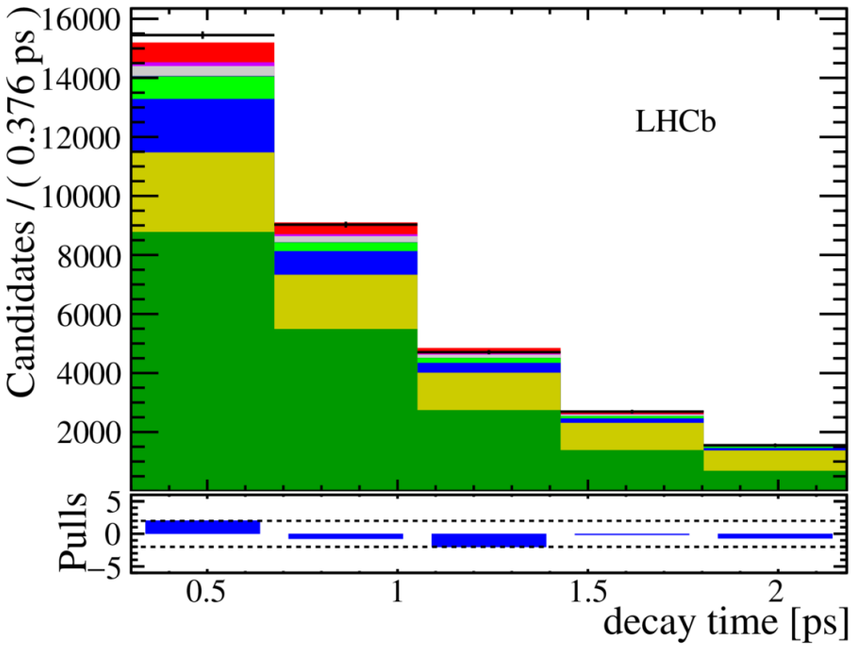
- Generalisation of $R(D^*)$ in the B_c sector $\quad R(J/\psi) = \dfrac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$

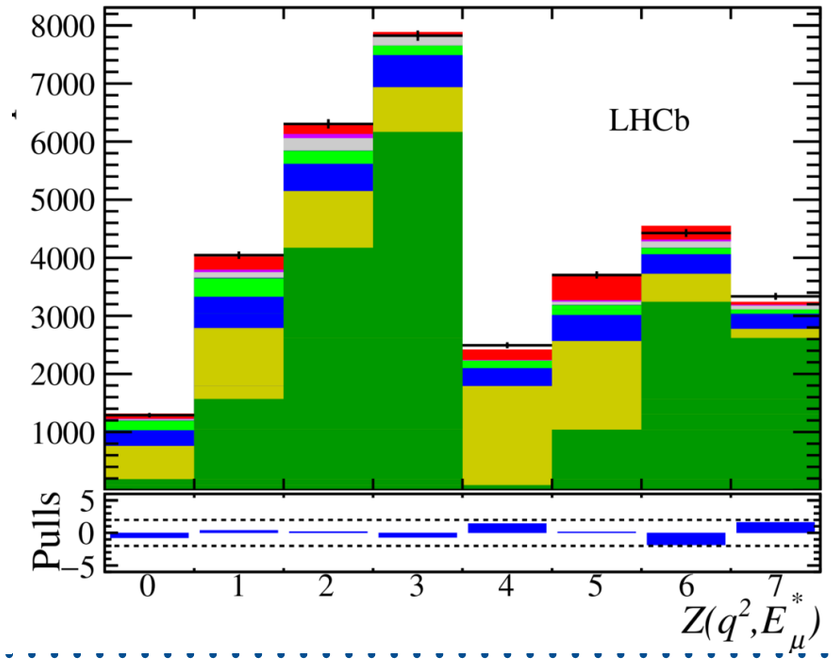
where $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$



- B_c momentum approximated as muonic $R(D^*)$ analysis
- Form factors unconstrained experimentally
- 3D binned fit to data of B_c decay time, $m^2_{\rm miss}$ and $Z(q^2, E^*_\mu)$

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





~2σ from SM

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

[Phys. Lett. B452 129 (1999)] [arXiv:hep-ph/0211021]
[PRD 73 054024 (2006)] [PRD 74 074008 (2006)]

Data
Mis-ID bkg.
J/ψ comb. bkg.
$B_c^+ \to \chi_c(1P) l^+ \nu_l$
$B_c^+ \to J/\psi \tau^+ \nu_\tau$
$B_c^+ \to J/\psi \mu^+ \nu_\mu$
$J/\psi + \mu$ comb. bkg.
$B_c^+ \to J/\psi H_c^+$
$B_c^+ \to \psi(2S) l^+ \nu_l$