Status of flavour anomalies from LHCb

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on behalf of the **LHCb collaboration**

ALpine Particle physics Symposium *Alps2023*

26-31 March, 2023
Obergurgl University Centre, Tyrol, Austria

Status of flavour anomalies from LHCb

- **introduction**
- **LHCb in a nutshell**
- FCNC b→sll **transitions**
- **tree level semileptonic** b→cτν **transitions**

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anomalies about the Lepton Flavour Universality

✗ Standard Model (**SM**) features Lepton Flavour Universality (**LFU**): charged leptons have universal coupling and differ only by their masses ➔ *any further deviation is a key signature of physics processes beyond the SM*

✗ ***no evidence of deviation from the SM*** in the precise (per-mil) tests of LFU in semileptonic K and π decays, purely τ leptonic decays, and in the electroweak precision observables

✗ ***in the last decade numerous hints of deviations from SM in semileptonic B decays:***

✓ FCNC $b \to s\ell\ell$ transitions
- ***differential decay rates*** $\sigma_{th} \sim \mathcal{O}(20\text{–}30\%)$
- ***angular observables***
- ***ratios of decay rates*** $\sigma_{th} \sim \mathcal{O}(1\%)$

✓ tree level semileptonic $b \to c\tau\nu_\tau$ transitions
- ***ratios of decay rates*** $\sigma_{th} \sim \mathcal{O}(1\%)$

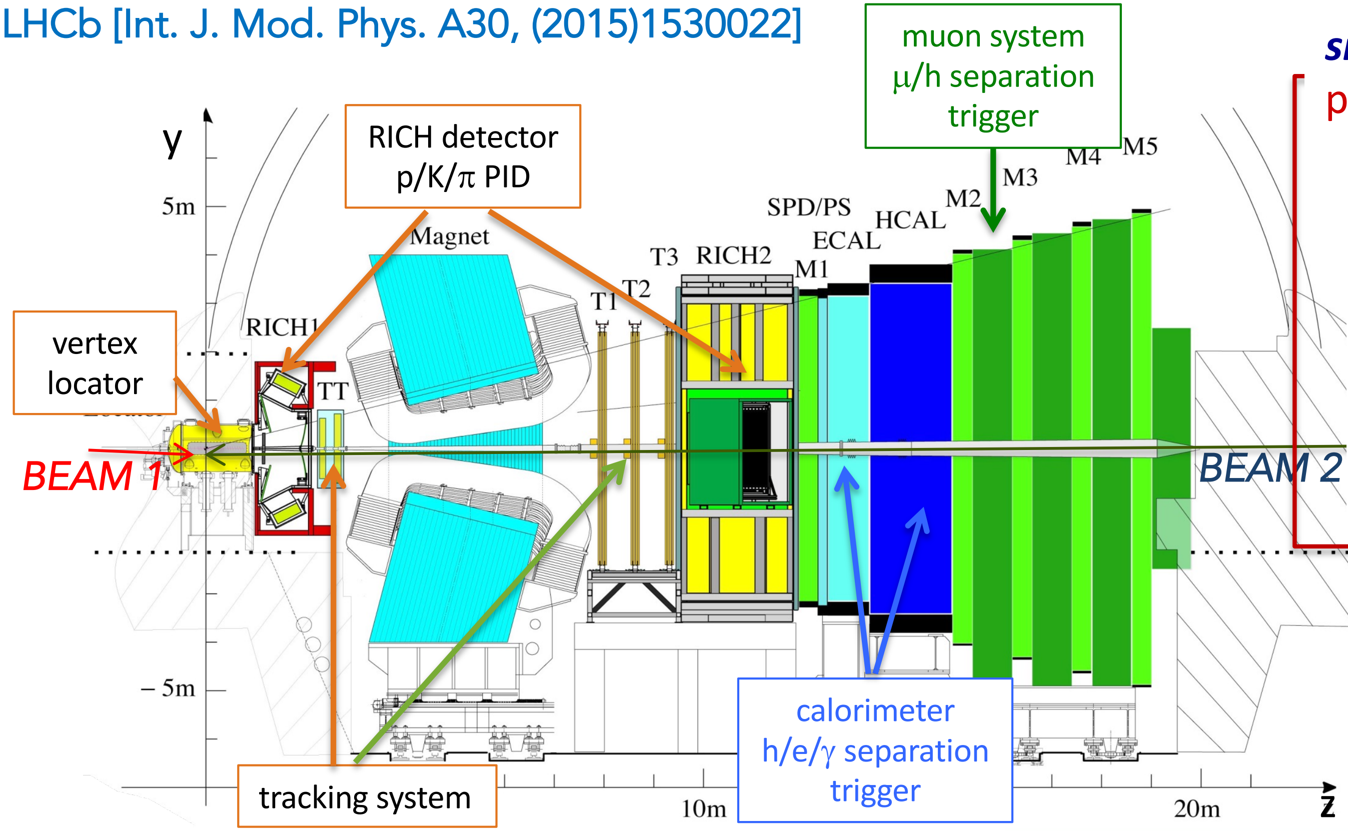
✗ SM theory predictions need to compute hadronic matrix elements affected by local (form-factors) and non-local ($c\bar{c}$-loops) contributions

✗ possible NP scenarios: leptoquarks, new heavy vector bosons, $H^{\pm}$, ...

LHCb in a nutshell

detection of B semileptonic decays at LHCb

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



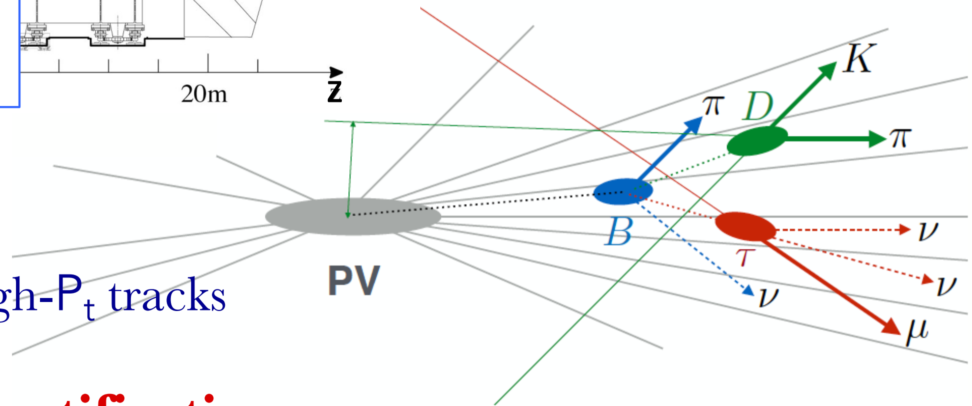
single-arm forward spectrometer

pseudorapidity range ➔ $2 < \eta < 5$

- ◎ σ_{bb}~500 μb
- ◎ ~ 25% of bb-bar pairs in LHCb acceptance
- ◎ large boost → B mesons fly ~1 cm

precise tracking → excellent resolutions

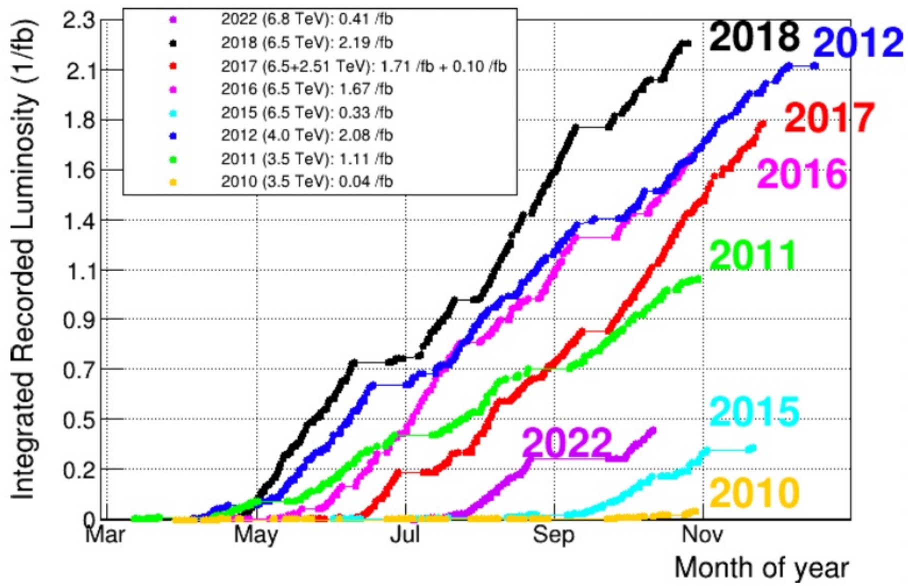
✓ decay time resolution ~ 45 fs
✓ Impact Parameter resolution ~ 20 μm for high-P_t tracks
✓ $\Delta p/p$ ~ 0.5% at 5 GeV



excellent particle IDentification

✓ π/K separation over 2-100 GeV, ε_K~90% for ~5% (π→K) misID
✓ powerful muon ID, ε_μ~97% for 1-3% π→μ misID

dataset and schedule



Run 1 & Run 2

2010-11	~1.1 fb^{-1}	at 7 TeV
2012	~2.1 fb^{-1}	at 8 TeV
2015-18	~6. fb^{-1}	at 13 TeV

✓ upgrade 1 is already here with an improved detector: 40MHz readout/software trigger and new tracking

✓ detector upgrade qualified to accumulate 50 fb^{-1} at the end of Run4, LHCb-TDR{13,14,15,66}

✓ LS3 consolidation of the detector

✓ LS4 to take full advantage of the High Lumi-LHC, $\mathcal{L}$ up to 1-2 $\times 10^{34}$ $cm^{-2}s^{-1}$ ➔ major upgrade of the detector to collect 300 fb^{-1} at the end of Run5

CERN/LHCC 2021-012, CERN/LHCC 2018-027

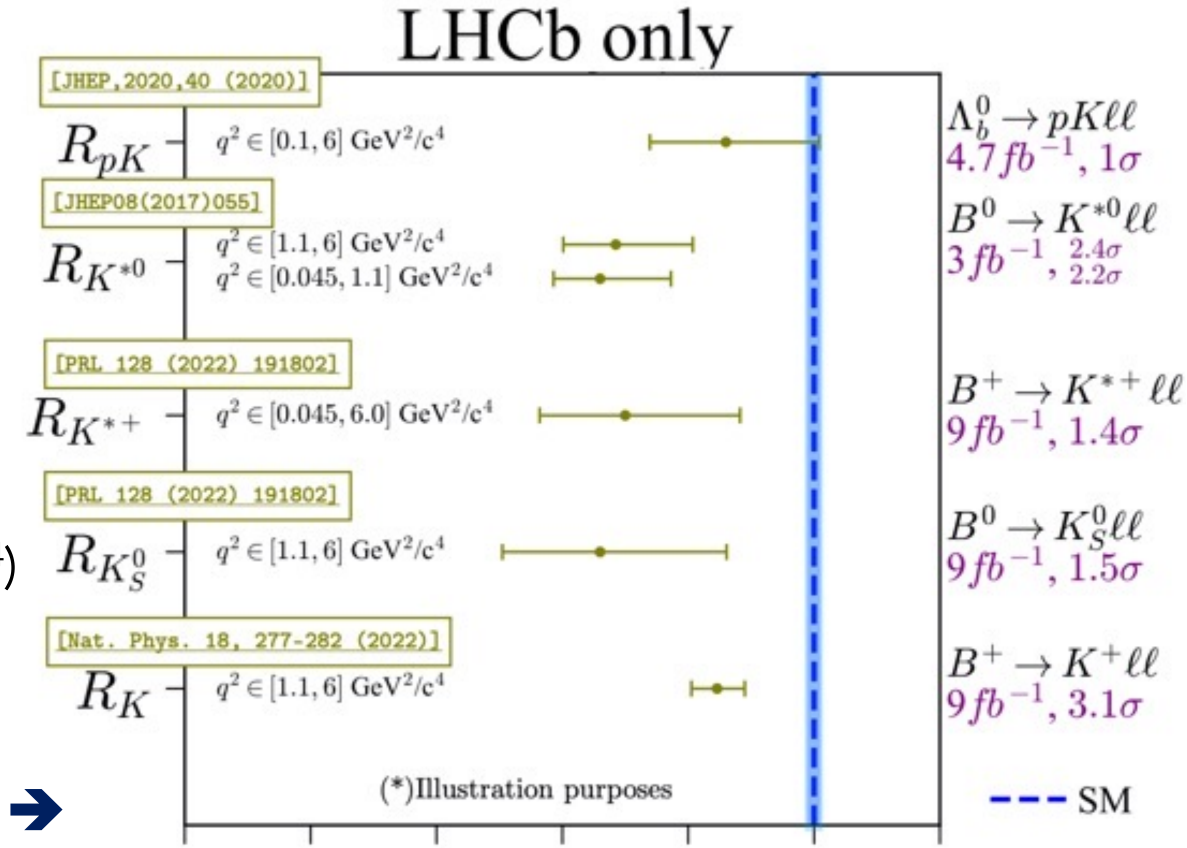
FCNC $b \to s\ell\ell$ transitions

test of LFU in b→ sℓℓ decays

- ✗ FCNC transitions occur via loop in the SM ➔ expected $\mathcal{B} < 10^{-6}$
- ✗ test LFU using ratios of branching fractions

$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

- ✗ R-ratios are close to unity in SM
- ✗ QED corrections $\mathcal{O}(1\%)$ [EPJC 76 (2016) 8, 440]
- ✗ free from QCD uncertainties $\mathcal{O}(10^{-4})$ [JHEP 07 (2007) 040]
- ✗ **R_X status at LHCb late 2022 ➔**



latest LFU test in b→ sℓℓ decays

[arXiv:2212.09152] submitted to PRL
[arXiv:2212.09153] submitted to PRD

✗ ***simultaneous measurement R_K and R_{K^*}***

$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q_a^2}^{q_b^2} \frac{d\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{dq^2} dq^2}$$

- ✓ full LHCb dataset ~9 fb^{-1}

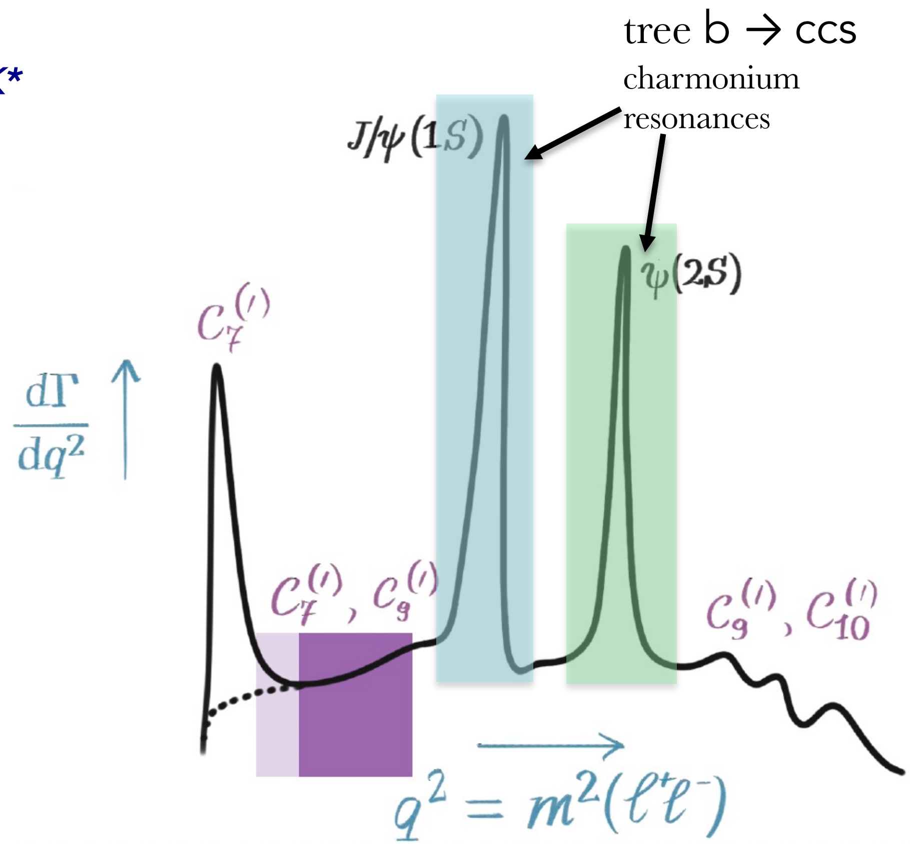
✗ q^2 ranges:

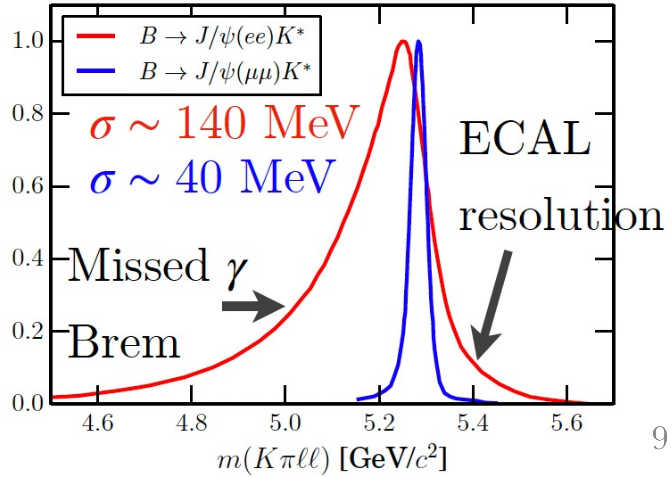
- ✓ low-q^2 ∈ [0.1,1.1] GeV^2/c^4
- ✓ central-q^2 ∈ [1.1,6.0] GeV^2/c^4

✗ R_{K^*}: K^{*0} mass cut ∈ [792,992] MeV/c^2

✗ ***the ee channel is the challenge of these analyses***

- ✓ **Bremsstrahlung** affects P_e
- ✓ γ recovery is $\mathcal{O}$(50%) efficient





latest LFU test in b→ s$\ell\ell$ decays: strategy

- ✗ $R_{K,K*}$ is measured as a double ratio to cancel most of the ε systematics in **e/μ** differences

$$R_{(K,K^*)} = \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}$$

  - ✓ $\mathcal{N}$ from mass fits, ε evaluated from data-driven corrected simulation
  - ✓ the resonant J/ψ sample also used for ε calibration

- ✗ J/ψ sample used to cross-check the goodness of the **ε calibration** testing the ratio

$$\frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}$$

measured to be 1 [PLB 731 (2014) 227]

- ✗ ψ(2S) sample used to cress-check the goodness of the **strategy** testing the double ratio

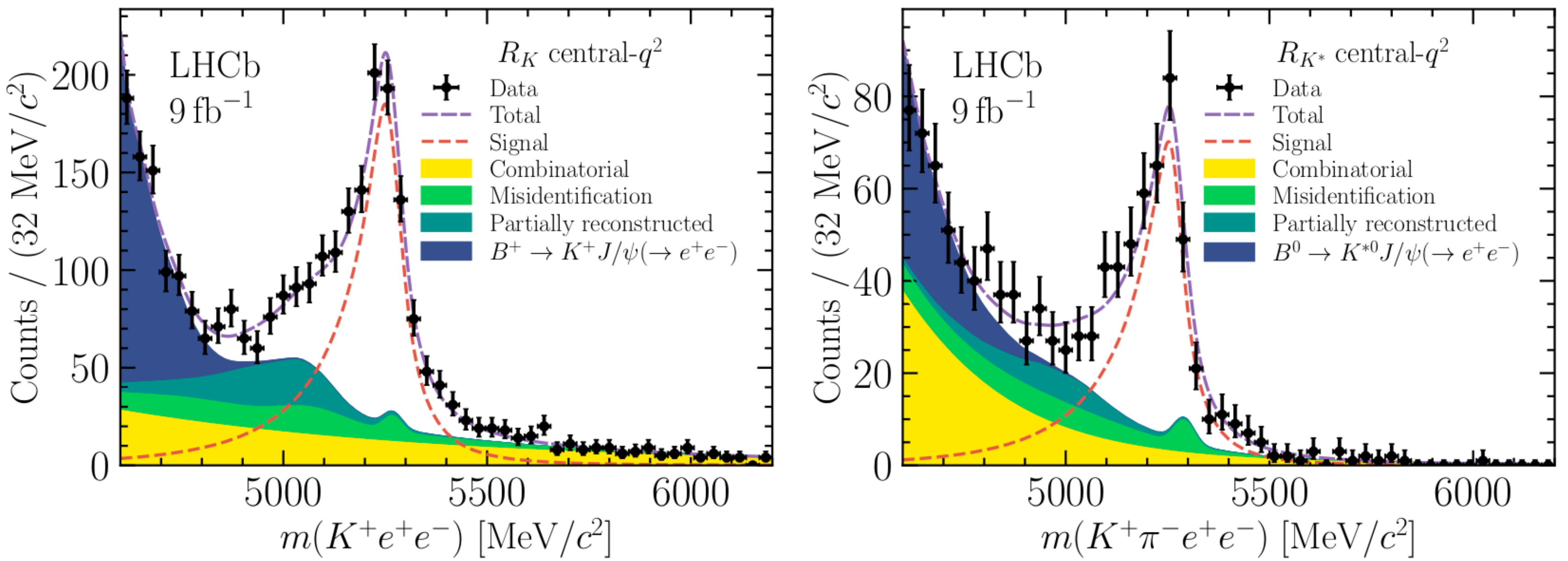
$$\frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\psi(2S)(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\psi(2S)(e^+e^-))} \times \frac{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\mu^+\mu^-))}{\frac{\mathcal{N}}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(e^+e^-))}$$

measured to be 1 [PDG 2022]

latest LFU test in $b \to s\ell\ell$ decays: backgrounds

✓ combination of kinematic and particle identification criteria
✓ $B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-$ and $B^{(+,0)} \to K^{(+,*0)}e^+e^-$: suppress residual combinatorial with multivariate classifier using kinematic and vertex quality information
✓ $B^{(+,0)} \to K^{(+,*0)}e^+e^-$: dedicated classifier to fight partially reconstructed background exploiting vertex and track isolation
✓ specific vetoes under electron misID hypothesis to remove mainly semileptonic decays:
$B^+ \to D^0(K\pi_{\to e})e\nu$, $B^0 \to D(K^*(K\pi)\pi_{\to e})e\nu$, $B^0 \to D^*(D^0(K\pi)\pi_{\to e})e\nu$, …

➤ tighter e identification criteria led to uncovering previously understimated peaking backgrounds, e.g. $B \to K_{\to e}K_{\to e}K$ and other single/double misID
➤ a data sample enriched of background from misID has been used to model this contribution

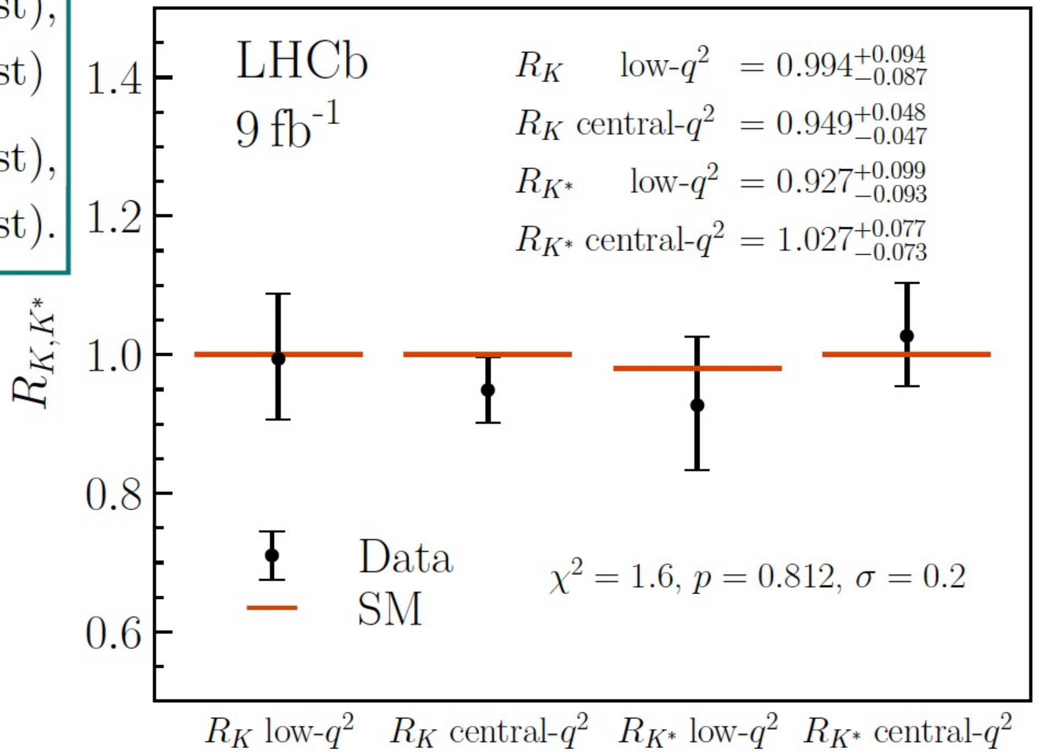


latest LFU test in b→ s$\ell\ell$ decays: result

[arXiv:2212.09152] submitted to PRL
[arXiv:2212.09153] submitted to PRD

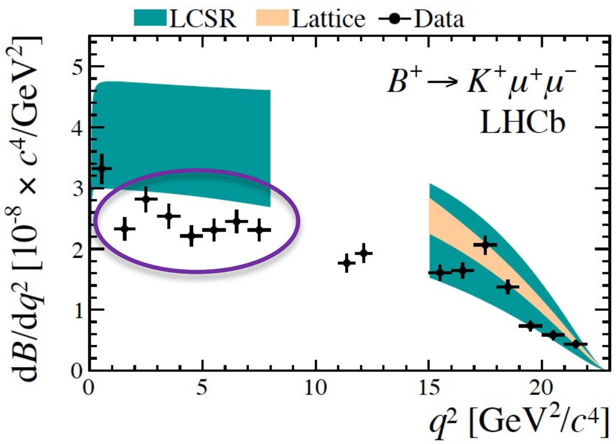
$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\ (\text{stat})\ ^{+0.027}_{-0.029}\ (\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\ (\text{stat})\ ^{+0.034}_{-0.033}\ (\text{syst}) \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\ (\text{stat})\ ^{+0.023}_{-0.023}\ (\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\ (\text{stat})\ ^{+0.027}_{-0.027}\ (\text{syst}). \end{cases}$$

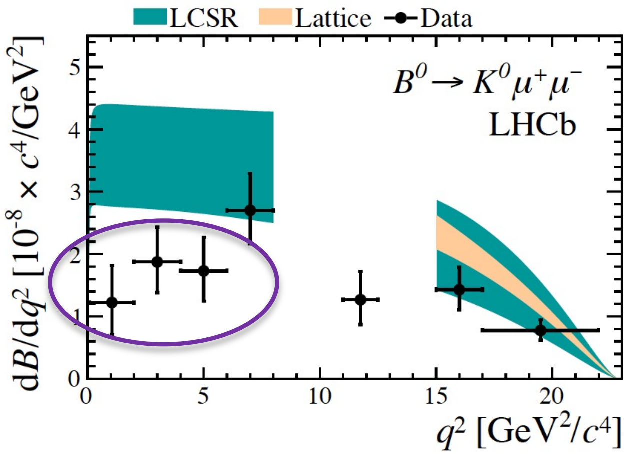


- ✓ measurement still statistically dominated
- ✓ most precise and accurate LFU test to date
- ✓ compatible with the SM at 0.2 σ level
- ✓ R_K central q^2 result superseded Nature Physics 18, 277 (2022)
- ✓ experimental uncertainties still far from the theoretical ones
- ✓ if LFU holds, anomalies should show up also in dB/dq^2 and angular observables for the electronic channel

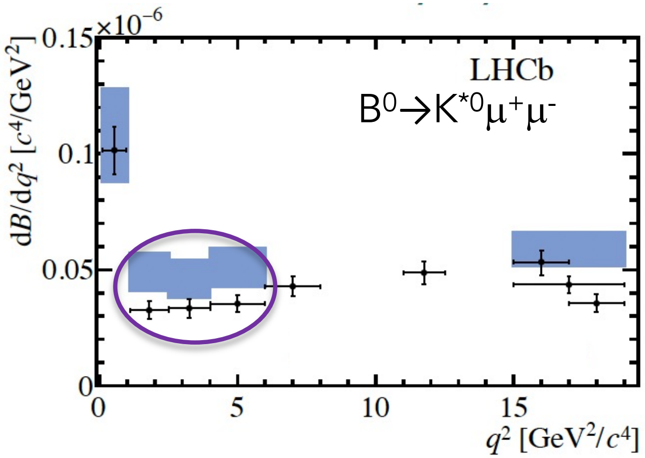
b→ sμμ differential decay rates



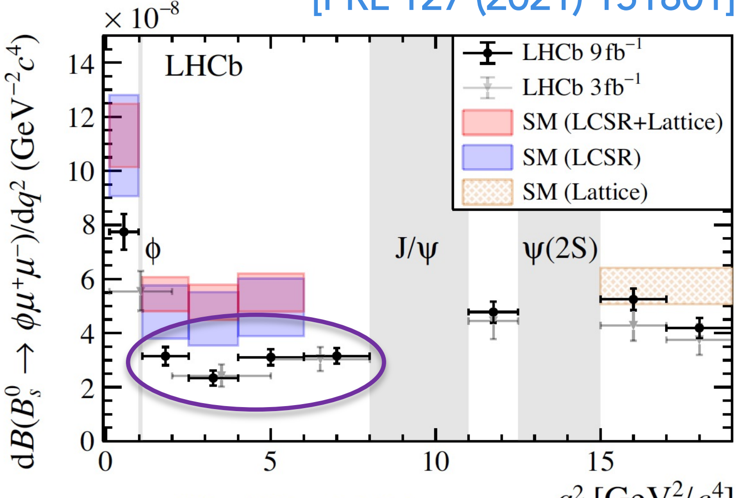
[JHEP 1406 (2014) 133]



[JHEP 04 (2017) 142]



[PRL 127 (2021) 151801]

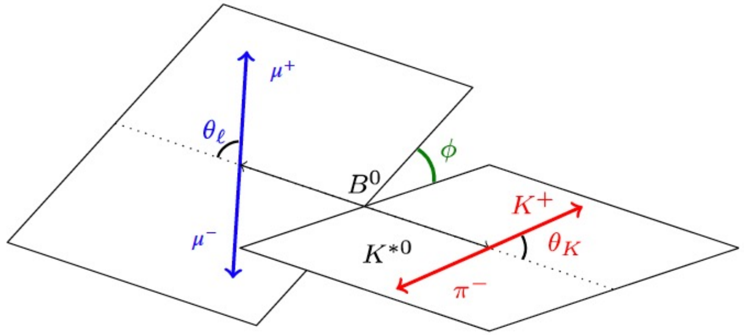


[PRL 127 (2021) 151801]

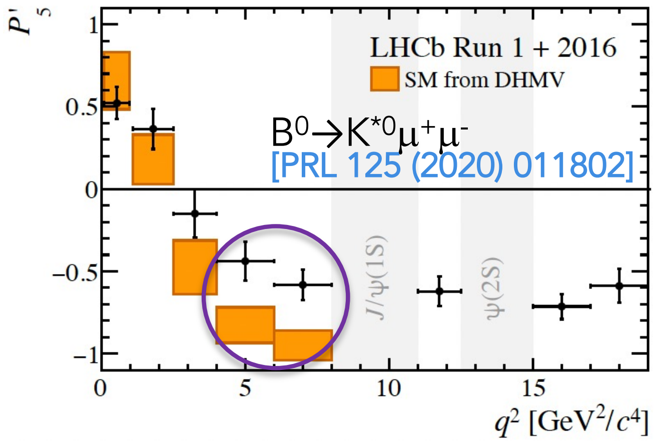
- ✓ SM prediction heavely affected by hadronic uncertainties $\sigma_{th} \sim \mathcal{O}(20 - 30\ \%)$: form factors, cc-loop
- ✓ dB/dq^2 in exclusive b→sμμ seems to undershoot SM

anomaly or a common issue with hadronic contributions from SM ?

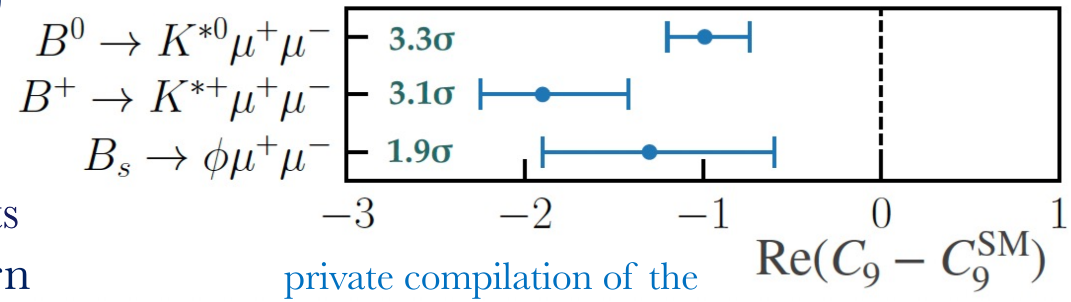
b→ sμμ angular analysis



- ✗ angular decay rates are function of q^2 and 3 angles
- ✗ SM predictions are challenging, but with uncertainties smaller than dB/dq^2 ➔ optimised variables where local hadronic uncertainties cancel out at leading order, e.g. P'_5



- ✗ recent LHCb angular analysis
  - ✓ $B^0 \to K^{*0}\mu^+\mu^-$ with 6 fb^{-1} (~4600 evts.) [PRL 125 (2020) 011802]
  - ✓ $B^+ \to K^{*+}\mu^+\mu^-$ with 9 fb^{-1} (~700 evts.) [PRL 126 (2021) 161802]
  - ✓ $B_s \to \phi\,\mu^+\mu^-$ with 9 fb^{-1} (~1900 evts) [JHEP 11 (2021) 043]



private compilation of the `flavio` [arXiv:1810.08132] fits results presented in the LHCb papers

- ✗ fits of vector coupling C_9 reported with LHCb angular analysis give consistent results
- ✗ intriguing coherent and consistent pattern
  - ✓ however, cc-loops could mimic the shift in C_9

tree level semileptonic $b \to c\tau\nu_\tau$ transitions

test of LFU in tree level semileptonic $b \to c\tau\nu_\tau$ transitions

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$$

τ : ***signal channel***

μ : ***normalization channel***

LHCb Run 1 data sample 3 fb^{-1}:

✗ measurements with muonic τ decays

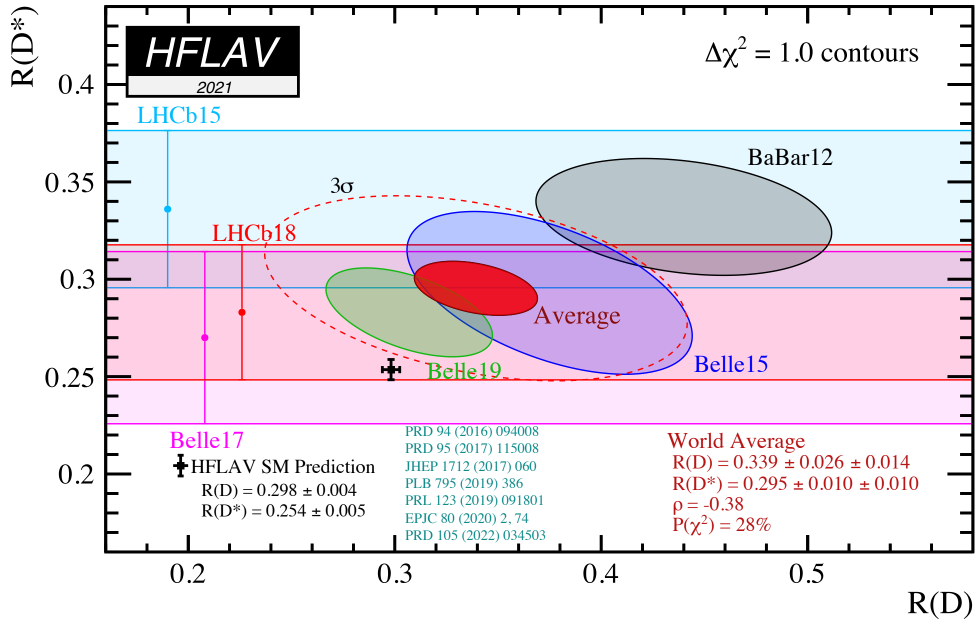
- ✓ $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$
- ✓ R(D*) and R(J/ψ)

[PRL 115 (2015) 111803], [PRL 120 (2018) 121801]

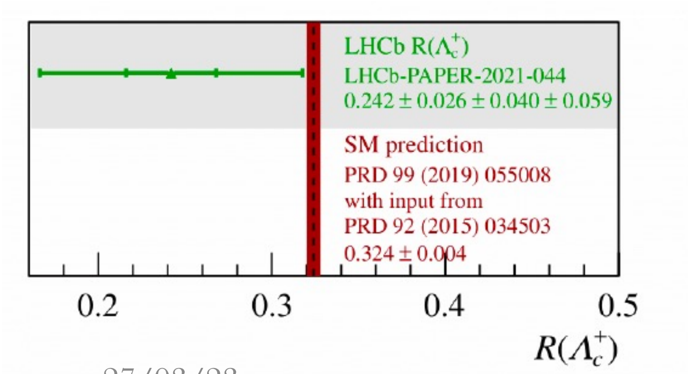
✗ measurements with hadronic τ decays

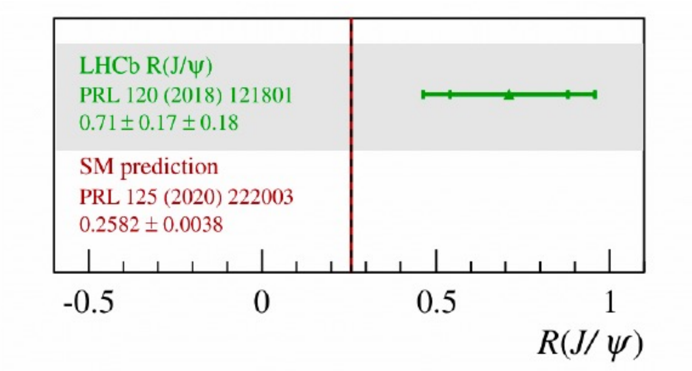
- ✓ $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$
- ✓ R(D*) and R(Λ_c) measurements

[PRL 120 (2018) 171802], [PRD 97 (2018) 072013]
[PRL 128 (2022) 191803]



combination of **R(D)-R(D*)** 3.3σ away from SM





test of LFU in tree level semileptonic $b \to c\tau\nu_\tau$ transitions

two very recent LHCb results →

1) $R(D^{(*)})$ with $\tau \to \mu\nu_\mu\nu_\tau$ [arXiv:2302.02886] submitted to PRL
first simultaneous measurement of R(D) and R(D*) with Run 1 data
will be covered this afternoon by the **Martina Ferrillo talk**

2) $R(D^{*})$ with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$ [LHCb-PAPER-2023-052] *in preparation*
will be covered by this talk

advantages

- ✓ good statistical precision thanks to large $\mathcal{B}$

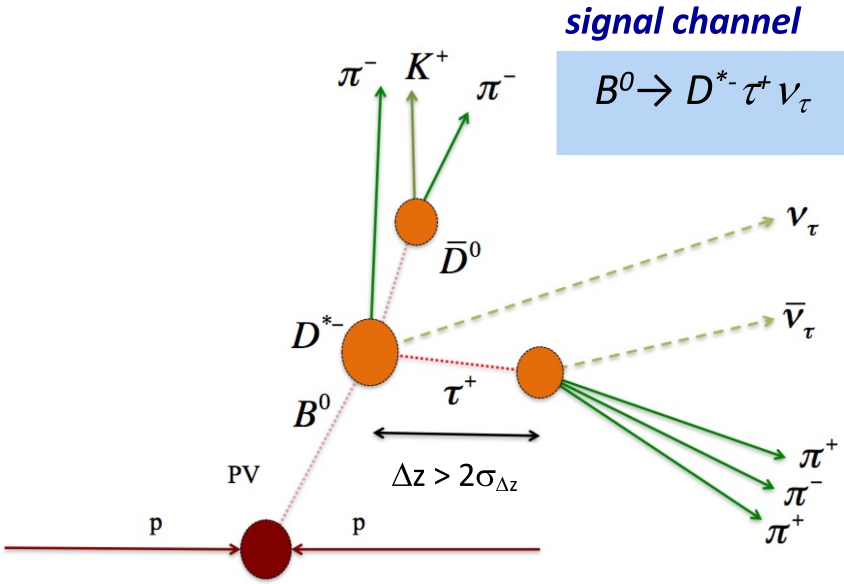
main challenges

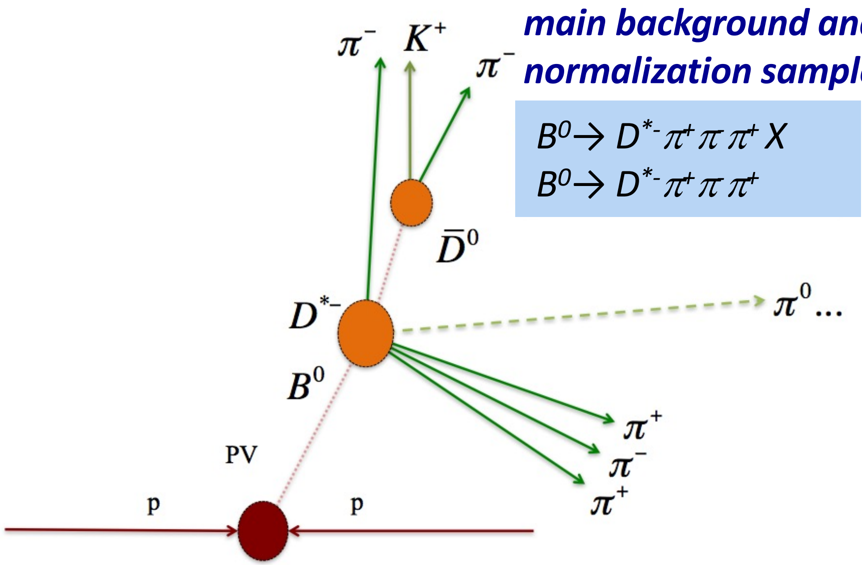
- ✓ missing neutrinos → no narrow peak to fit
- ✓ large backgrounds from partially reconstructed B decays
- ✓ large MC samples required for template shapes

R(D*) with τ → $3\pi^{\pm}(\pi^0)\nu_\tau$ [LHCb-PAPER-2023-052] *in preparation*

- ✓ update of the LHCb R(D*) analysis [PRL 115 (2015) 111803], [PRL 120 (2018) 121801]
- ✓ partial Run 2 data: 2fb^{-1} at $\sqrt{s}$ = 13 TeV ➔ ~1.5×Run 1 signal sample
- ✓ experimental systematic uncertainty reduced normalizing to a decay **with same visible final state:** $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^{\pm})} = \frac{N_{\rm sig}}{N_{\rm norm}}\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}\frac{1}{\mathcal{B}(\tau^+ \to 3\pi^{\pm}(\pi^0)\overline{\nu}_\tau)}$$



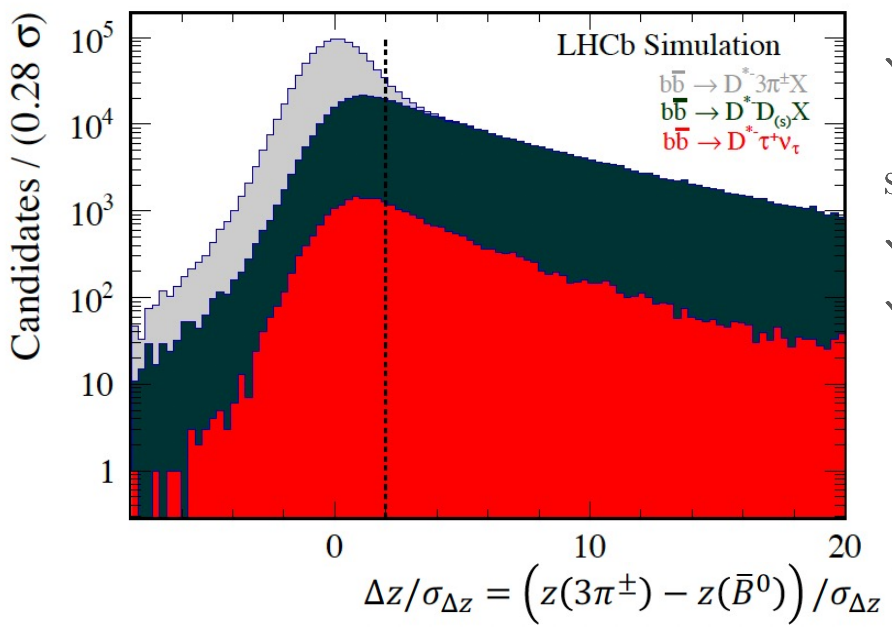


- ✓ derive R(D*) by dividing by known semimuonic $\mathcal{B}(B^0 \to D^*\mu\nu)$

$$R(D^*) = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^{\pm})}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

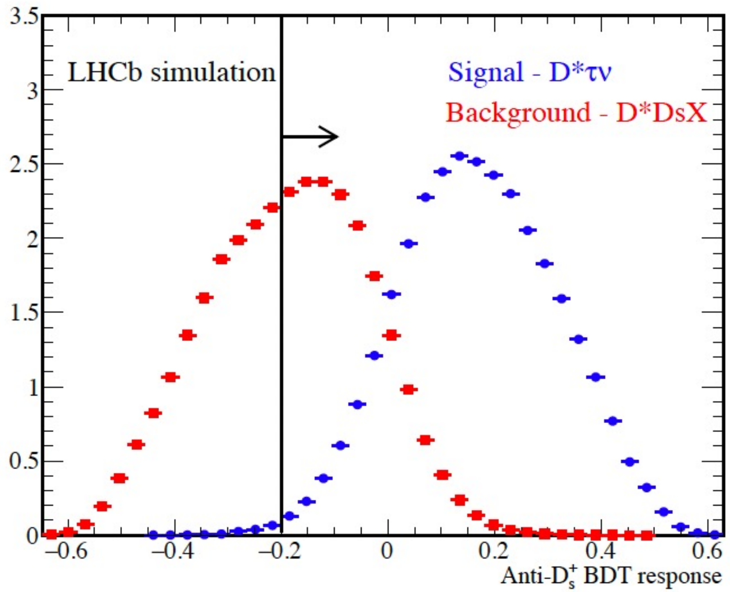
R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$: backgrounds

- ✓ signal candidates are built based on the **6 final-state charged tracks** ➔ tracks/vertex quality, particle identification and mass constraints
- ✓ **the 3-prong topology enables the precise reconstruction of τ vertex**



- ✓ the requirement of a 3π vertex to be downstream w.r.t. the B vertex along the beam direction suppresses D^{*}-3πX background (~100 × signal)
- ✓ BDT classifier based on vertex separation variables
- ✓ **final rejection of D^{*}-3πX is > 99%**

- ✓ the largest contributor of the double charm background is $B \to D^{*-}D_s^{+}(3\pi X)X$ (~10 × the signal)
- ✓ BDT classifier based on kinematic and resonant structure: anti-D_s^+ BDT
- ✓ anti-D_s^+ BDT output is used as fit variable



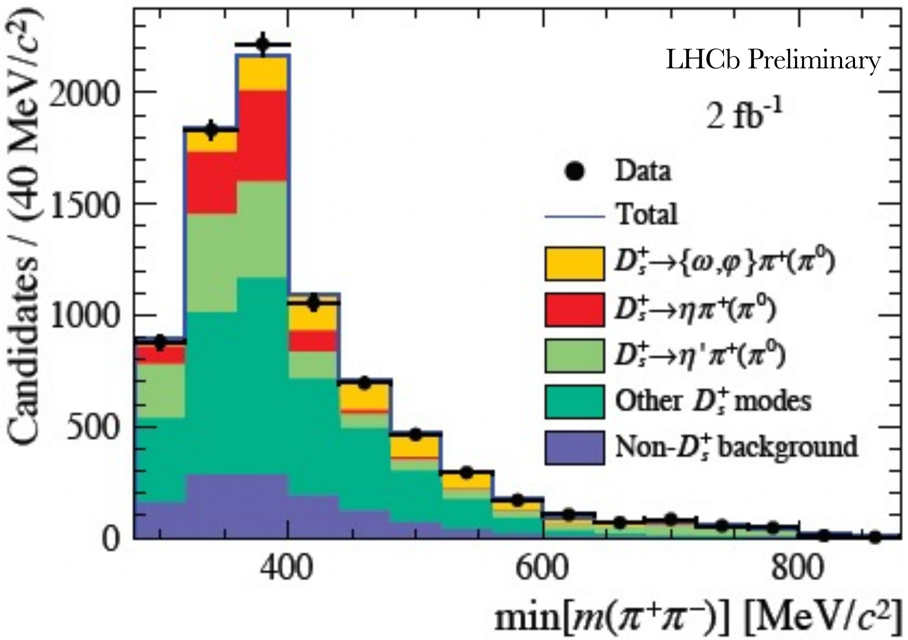
rejection of $B \to D^{*-}D_s^{+}X$ is 40%, keeping 97% signal efficiency

R(D*) with τ → 3π±(π0)ντ: backgrounds

✓ the dominant background after the full selection is due to $B \to D^{*-} D_s^+(3\pi X)X$
✓ templates used in the signal fit derived from simulation ➔ corrections need to be applied

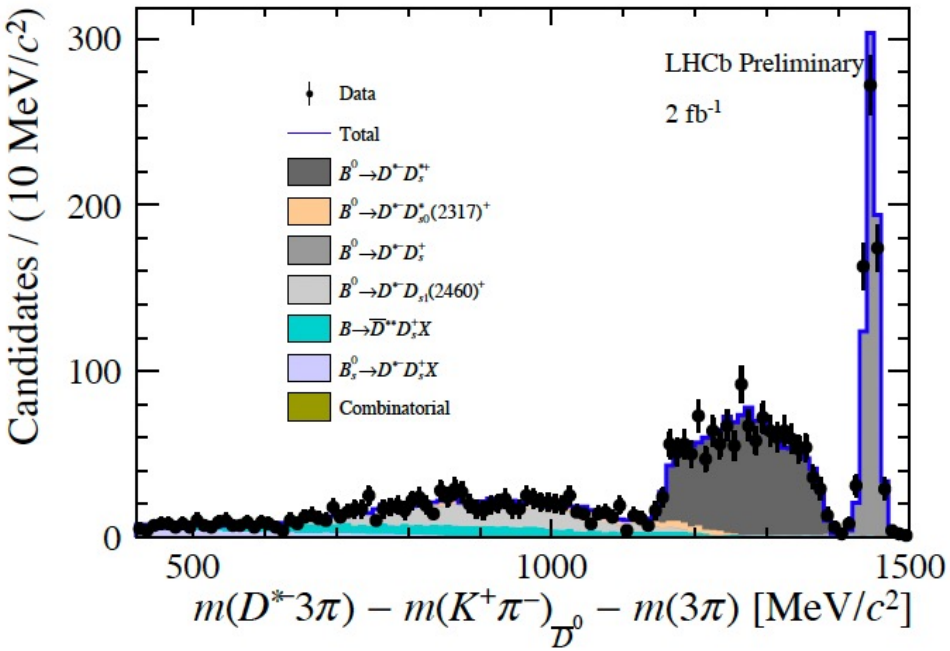
D_s^+ decay

✓ $D_s^+ \to 3\pi X$ relative fractions are evaluated from a fit to data control sample enriched in D_s^+ with reverse anti-D_s^+ BDT selection
✓ the results are used to reweight the simulation



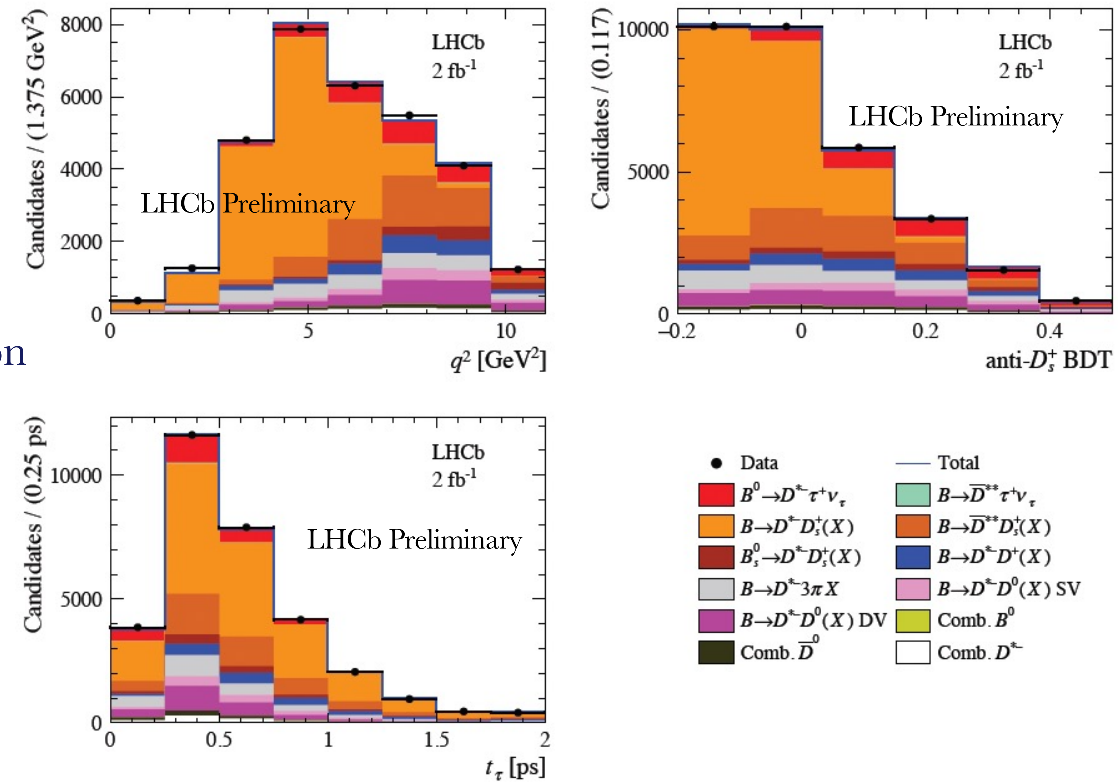
D_s^+ production

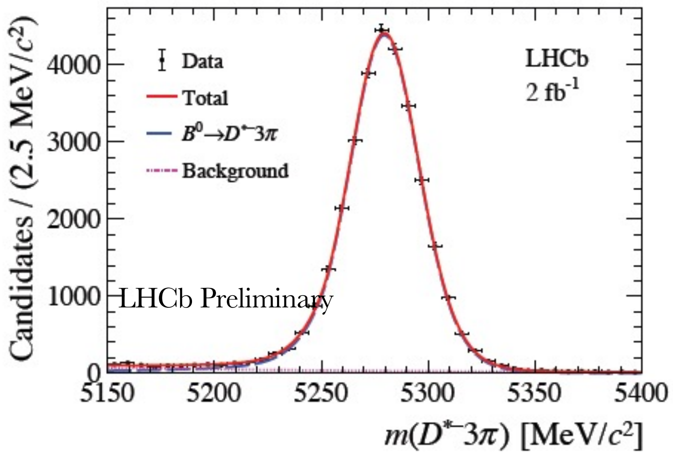
✓ $B \to D^{*-} D_s^{(*,**)}X$ data control sample selected with $m(3\pi)$ around D_s^+ mass
✓ fractions of each component used as gaussian constraints in the signal extraction fit



R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$: fits

- ✗ 3D binned template fit to
  - ✓ $q^2 \equiv (p_{B0} - p_{D*})^2$
  - ✓ τ^+ decay time
  - ✓ anti-D_s^+ BDT output
- ✗ form factor correction: reweight MC signal sample using CLN parametrization [HFLAV, EPJC 81(2021)226]
- ✗ efficiencies from MC, validated using data control samples
- ✗ $N(B^0 \to D^{*-}\tau^+\nu_\tau) = 2469 \pm 154$





- ✗ $B^0 \to D^{*-}3\pi$ normalization yield from a fit to $m(D^{*-}3\pi)$ ➔ 30540 ± 182

- ✗ dominant systematic uncertainty from double charm background modelling
- ✗ systematic from limited simulation samples reduced to half the Run 1 value thanks to fast simulation technique (ReDecay) ➔ production of larger simulation samples

R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$: result

preliminary

[LHCb-PAPER-2023-052] *in preparation*

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^{\pm})} = 1.700 \pm 1.101(stat)\,^{+0.105}_{-0.100}(syst)$$

✗ using the most recent $\mathcal{B}(B^0 \to D^{*-}3\pi)$ and $\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ from PDG 2022

$$R(D^*) = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^{\pm})}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = 0.247 \pm 0.015(stat) \pm 0.015(syst) \pm 0.012(ext)$$

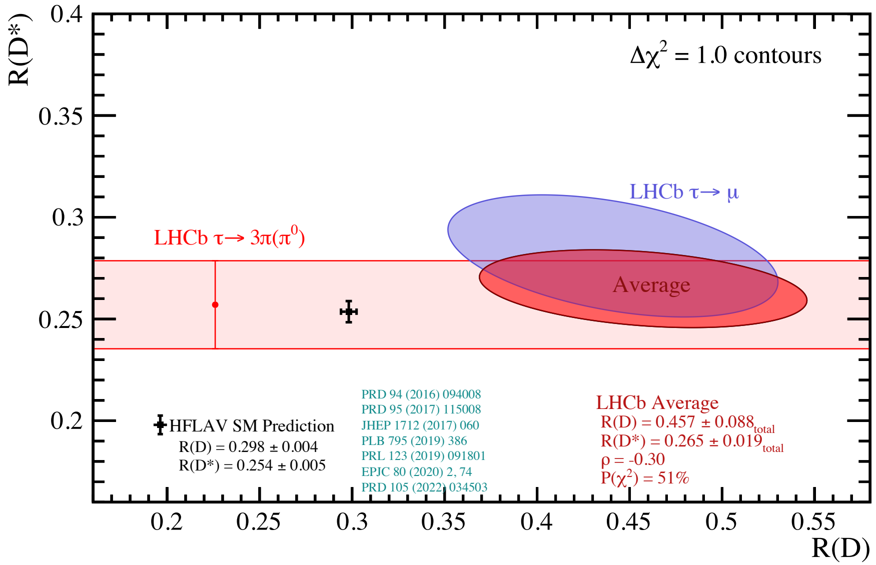
✗ absolute $\mathcal{B}$ of the B^0 semitauonic decay

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.23 \pm 0.07_{stat} \pm 0.08_{syst} \pm 0.05_{ext}) \times 10^{-2}$$

✗ combining with the Run 1 result

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

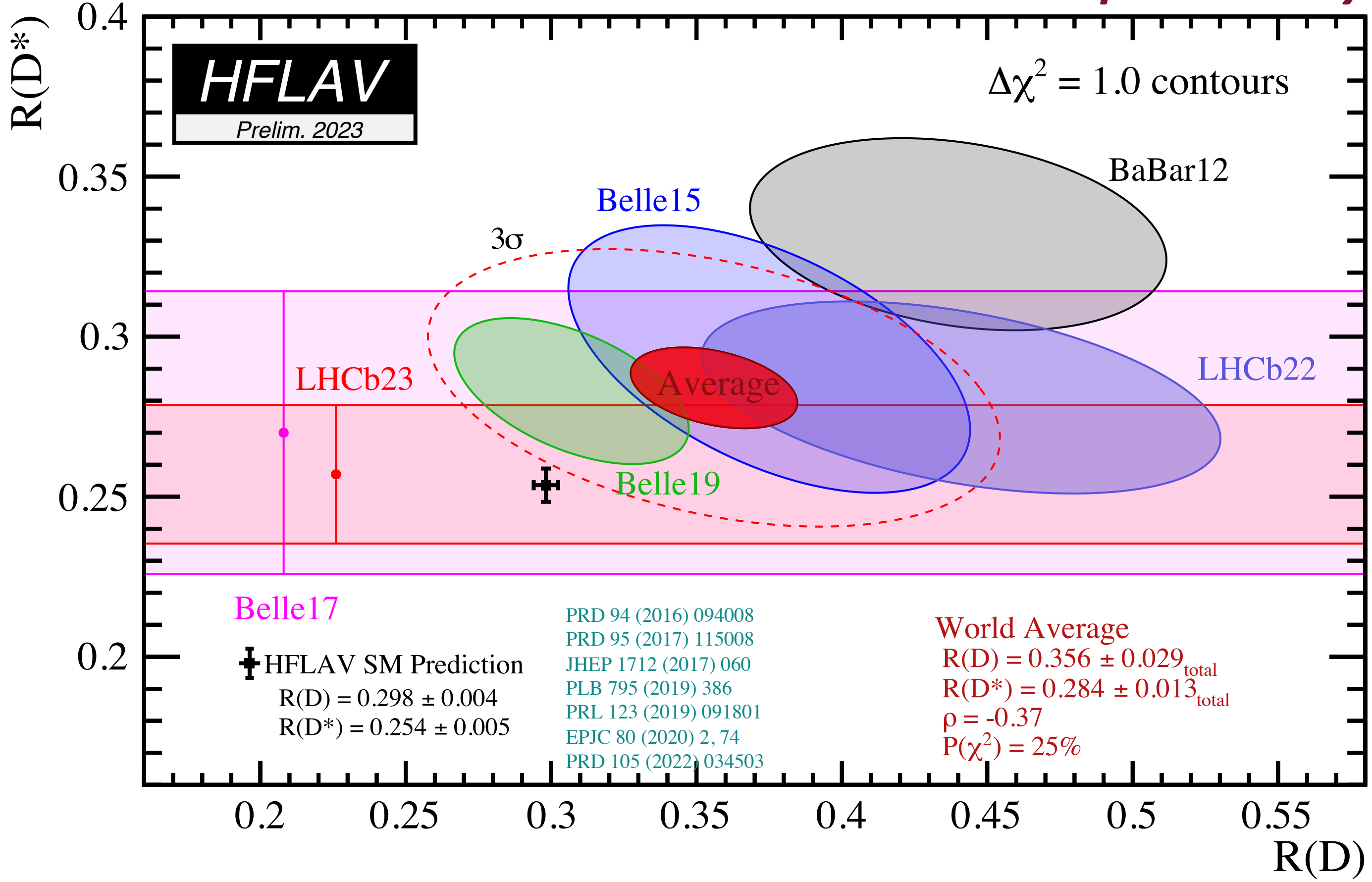
agreement within 1σ to SM



<u>LHCb average</u>: approcing the Belle precision on R(D*)

world average

HFLAV preliminary



✓ **including** $R(D^{(*)})$ with muonic τ decays [arXiv:2302.02886] submitted to PRL and $R(D^*)$ with hadronic τ decays [LHCb-PAPER-2023-052] *in preparation* the world average becomes ➔ R(D*) = 0.284 ± 0.013; R(D) = 0.356 ± 0.029

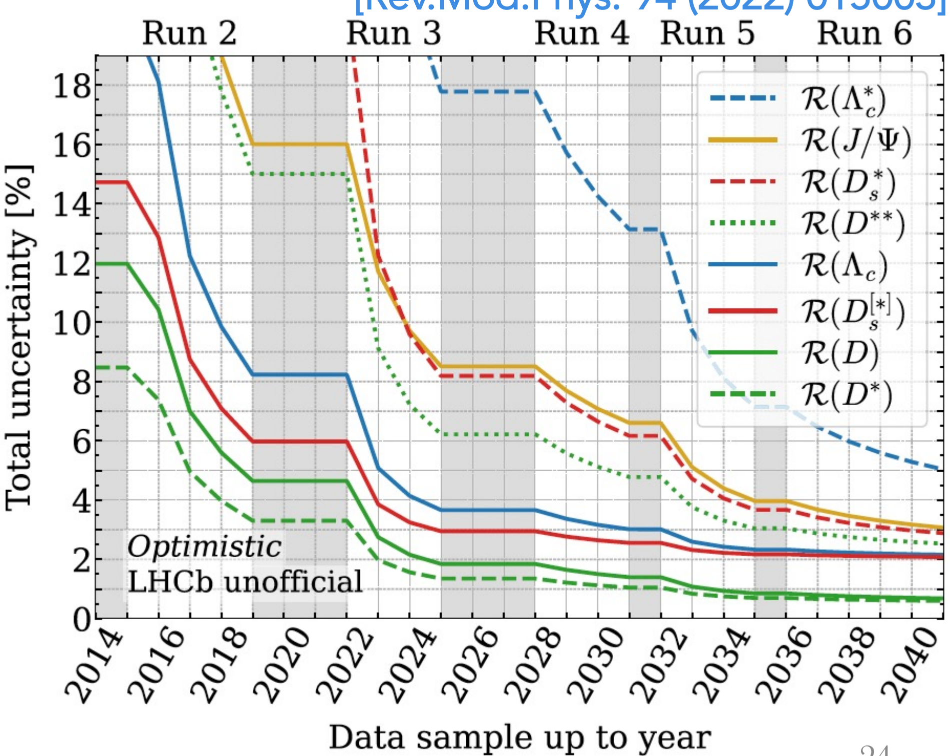
✓ the deviation w.r.t. the SM stays at 3.2σ level for the combination of R(D)-R(D*)

outlook

- ✗ **FCNC b→sℓℓ transitions**
  - ✓ *b→see angular analysis*
    - *experimental orthogonal way to test the anomalies observed in the muon channel*
  - ✓ *unbinned $B^0 \to K^{*0}\mu\mu$ analysis*
    - *parametrize hadronic non-local contributions (cc-loops) and fit them to data*

- ✗ **tree level semileptonic $b \to c\tau\nu_\tau$ transitions**
  - ✓ *adding full Run 2 dataset*
  - ✓ *many new measurements underway : simultaneous $R(D^{+(*)})$ muonic, $R(D_s^{*})$ muonic, $R(\Lambda_c)$ muonic, …*
  - ✓ *the recent BESIII results on inclusive $D \to 3\pi$ rates for D^0, D^+, D^+_S* [arXiv:2212.13072][arXiv:2301.03214] *will significantly lower the systematic uncertainties in the legacy measurements to come*

[Rev.Mod.Phys. 94 (2022) 015003]



conclusions

- ✗ new combined measurement of R_K and R_{K^*} with full Run 1 and Run 2 dataset
  - most precise LFU test in b→sll transitions
  - the results are compatible with the SM at 0.2σ level
- ✗ angular analysis and differential $\mathcal{B}$ measurements in b→sμμ
  - a pattern of anomalies is visible

✗ new simultaneous $R(D^{(*)})$ measurement using the muonic τ decay with the Run 1 dataset will be presented this afternoon

✗ new $R(D^*)$ measurement using the hadronic τ decay $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$ with partial Run 2 dataset

- compatible with the SM at 1σ level

✗ global picture unchanged for $R(D)$-$R(D^*)$ combination

- tension with SM at the 3.2σ level

✗ we have started taking data with first update of LHCb, new and more data will help to disentangle these puzzles *exciting times ahead !*

conclusions

- ✗ new combined measurement of R_K and R_{K^*} with full Run 1 and Run 2 dataset
  - most precise LFU test in $b \to sll$ transitions
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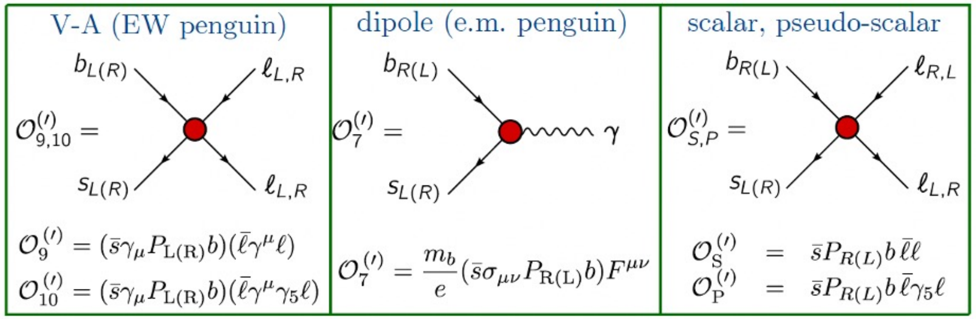
  - compatible with the SM at 1σ level
- ✗ global picture unchanged for $R(D)$-$R(D^*)$ combination
  - tension with SM at the 3σ level

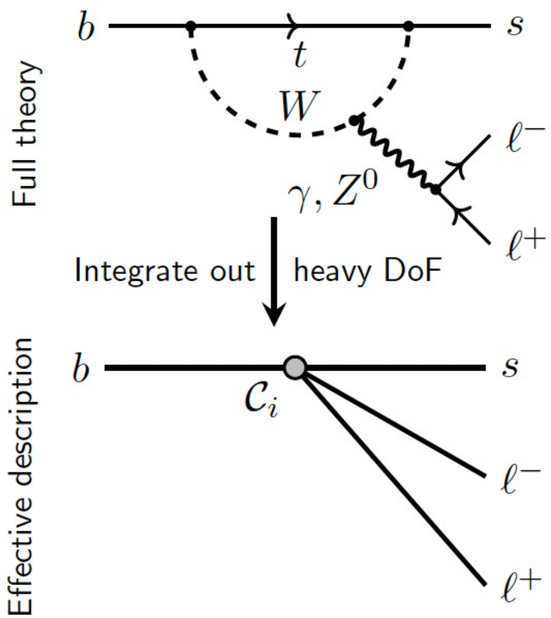
- ✗ we have started taking data with first upgrade of LHCb, new and more data will help to disentangle these puzzles *exciting times ahead !*

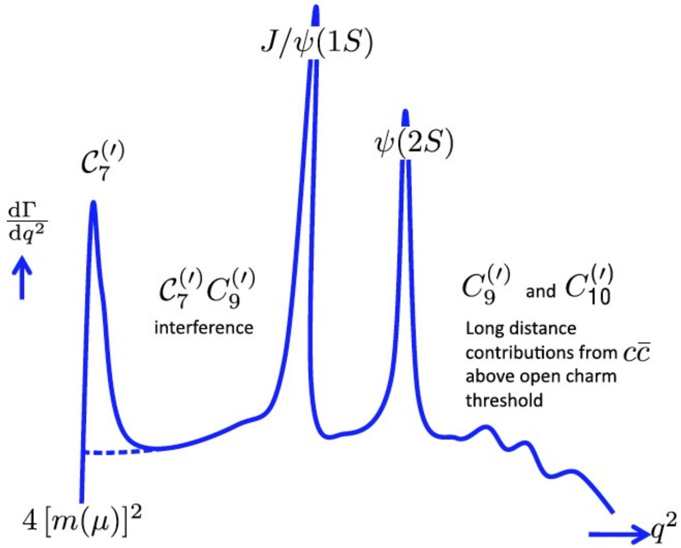
Thank you for your attention !

spares

b→ sℓℓ decays







- $b \to s\ell\ell$ transitions described model-independently in effective theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local operator ($\mathcal{O}_i$)

Wilson coefficient ("effective coupling") ($\mathcal{C}_i$)

Effective couplings in $b \to s\ell\ell$ transitions

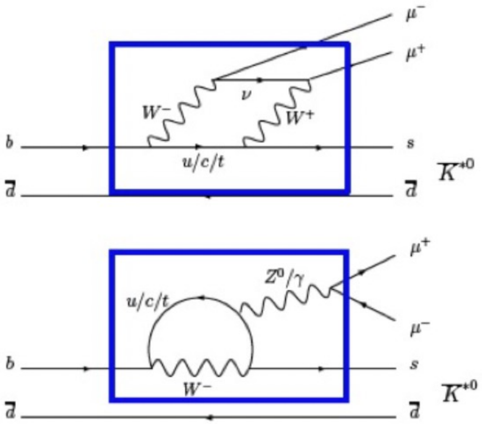
	Wilson coefficient	Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

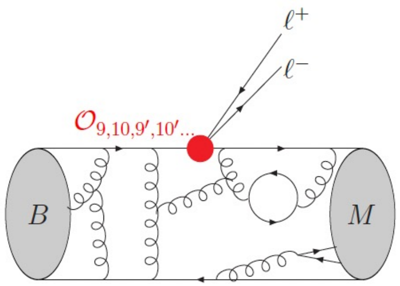
For completeness

- Different $q^2 = m^2(\ell^+\ell^-)$ regions probe different operator combinations

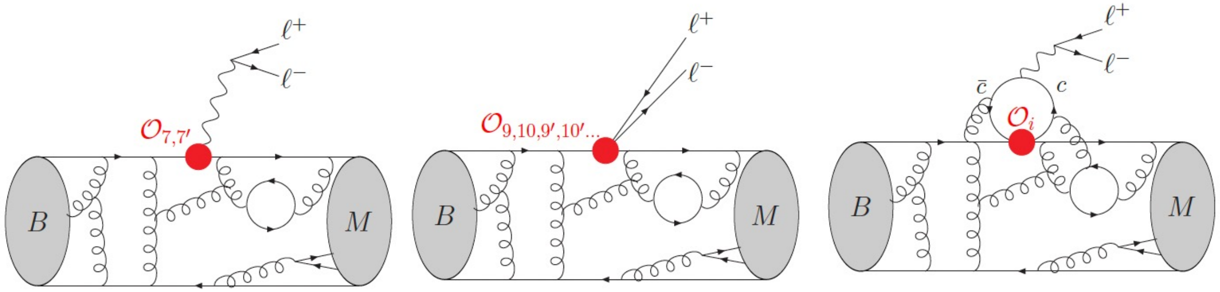
b→ sℓℓ decays: hadronic effects

Hadronic effects





Use the **Operator Product Expansion** to handle theoretically

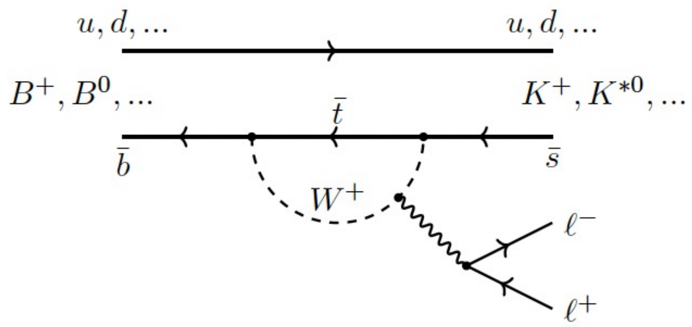


Form factors (local) Form factors (local) Charm loop (non-local)

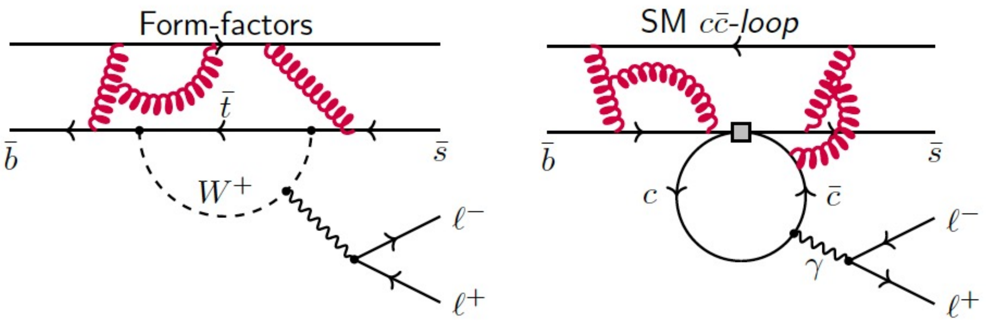
→ BFs have relatively large theoretical uncertainties

observables in b→sℓℓ decays and their cleanliness

Quarks bound in hadrons, *e.g.*



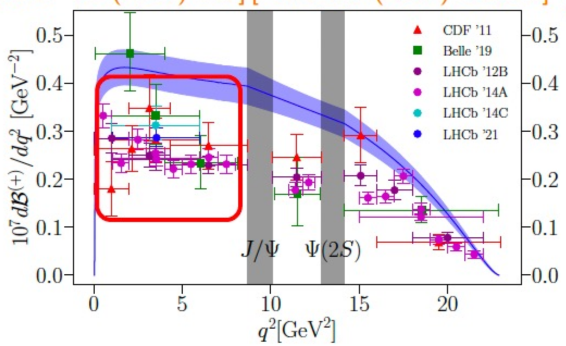
Hadronic uncertainties



$b \to s\ell\ell$ Observables

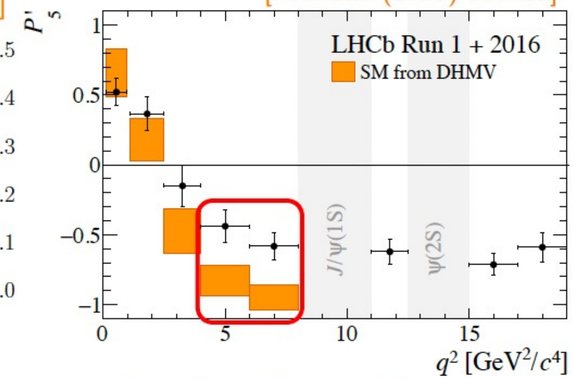
Increasing precision of SM prediction

[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



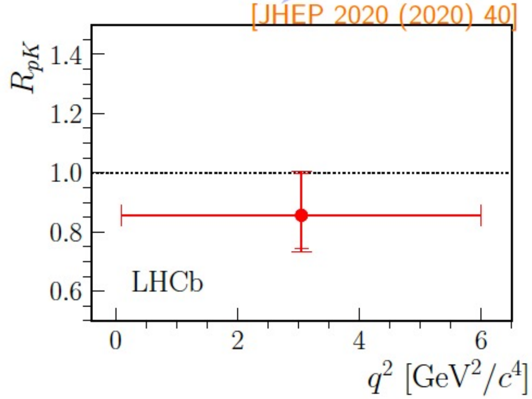
Branching fractions
affected by form-factors
and $c\bar{c}$-loop

[PRL 125 (2020) 011802]



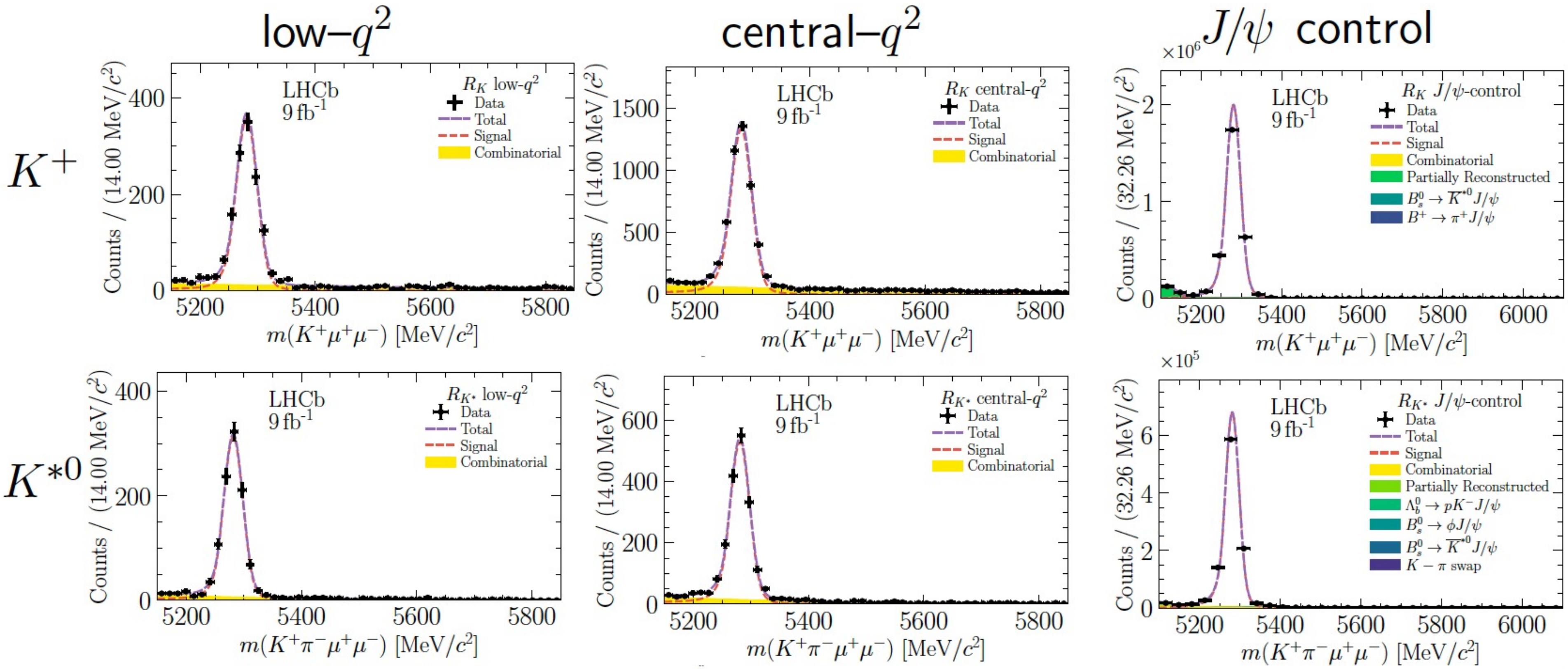
Angular observables
affected by $c\bar{c}$-loop

[JHEP 2020 (2020) 40]



Lepton Universality Tests
clean

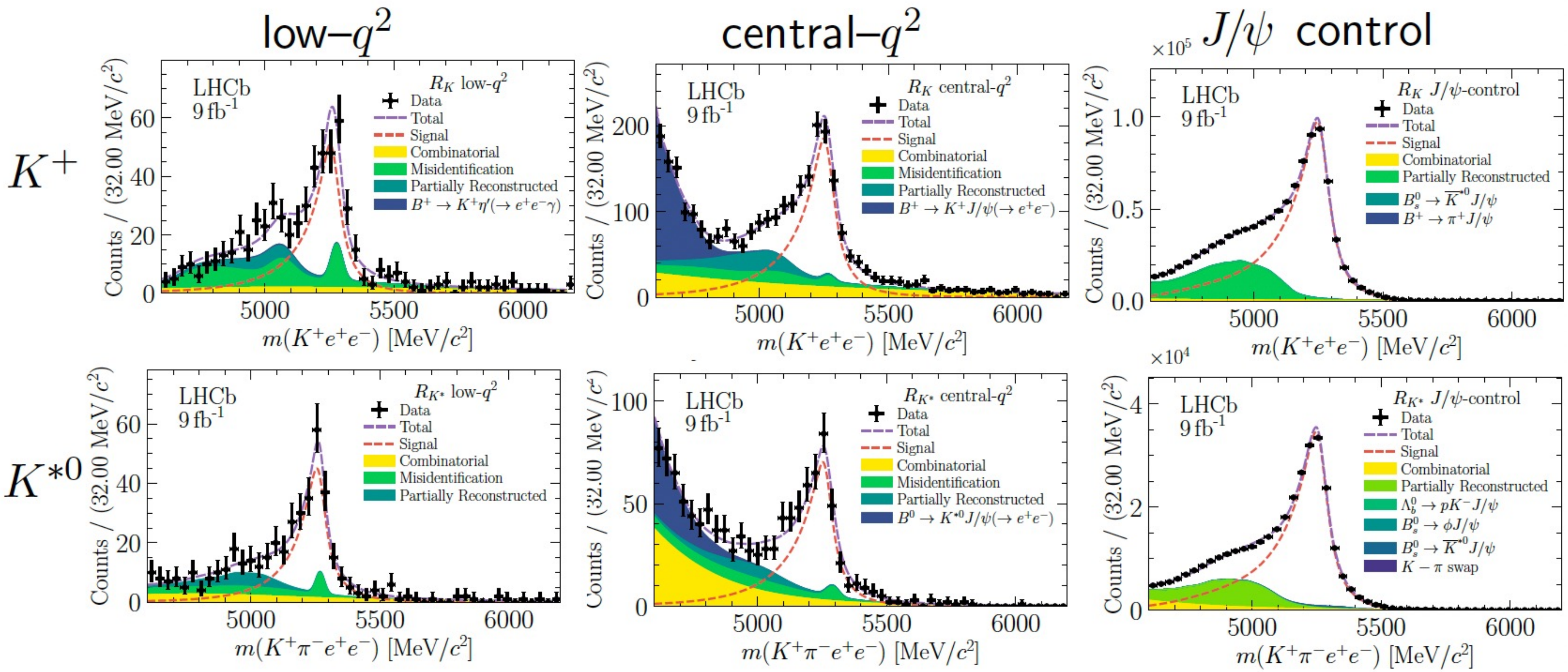
muon modes fits



- Muon mode is very clean!
- Muon branching fraction compatible with published results

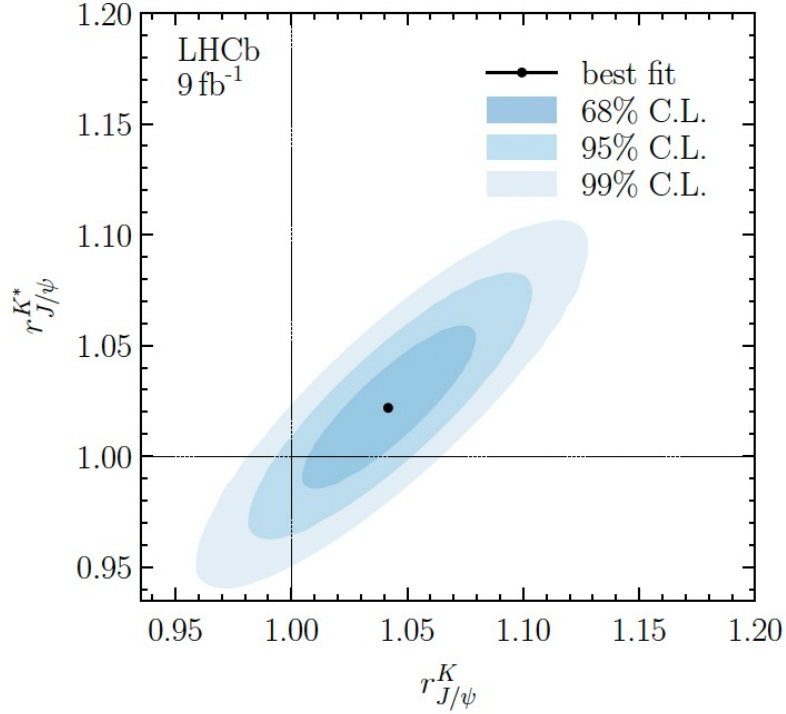
  [JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

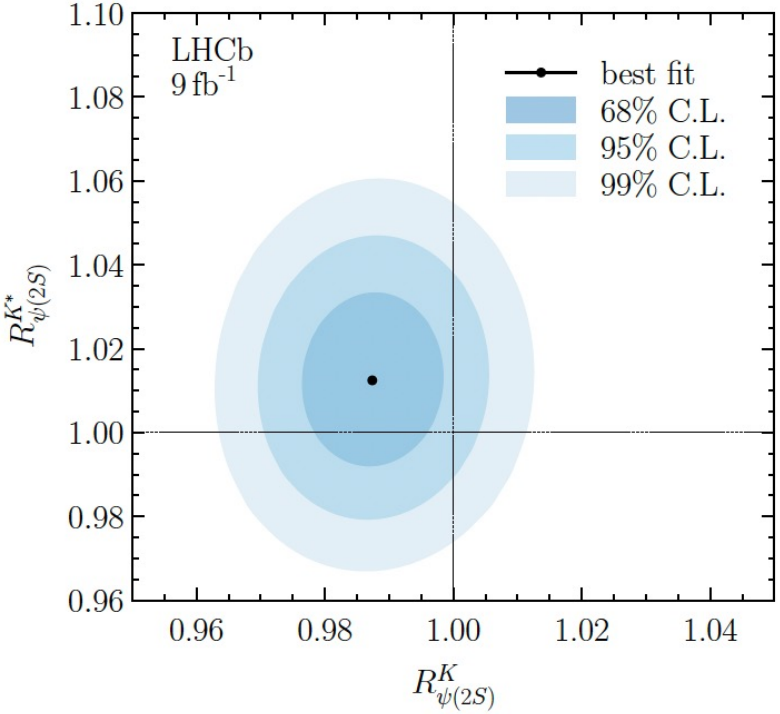
electron modes fits



- Good fit quality when including all components
- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bgk. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

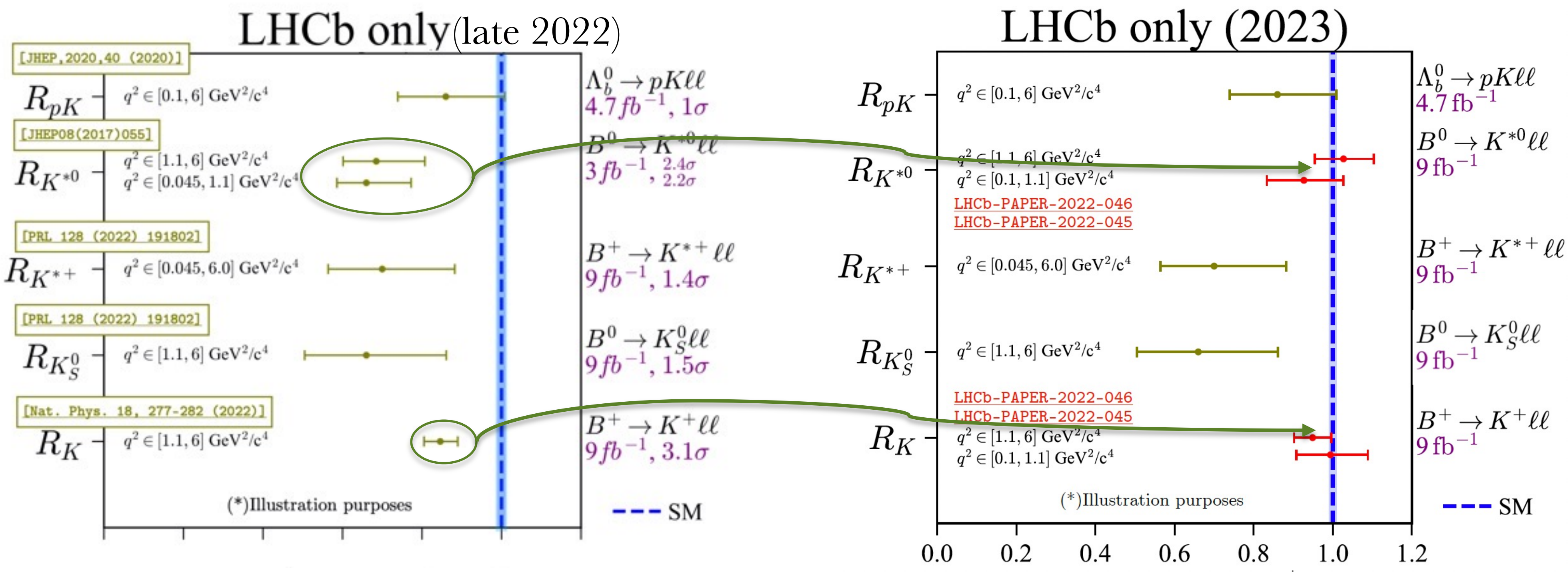
crosschecks with J/ψ and ψ(2S) samples





- Both $r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity at better than $2\,\sigma$

test of LFU in $b \to s\ell\ell$ decays



difference R_K central: partly due to tighter ePID criteria and partly due to the modeling of the residual hadronic background

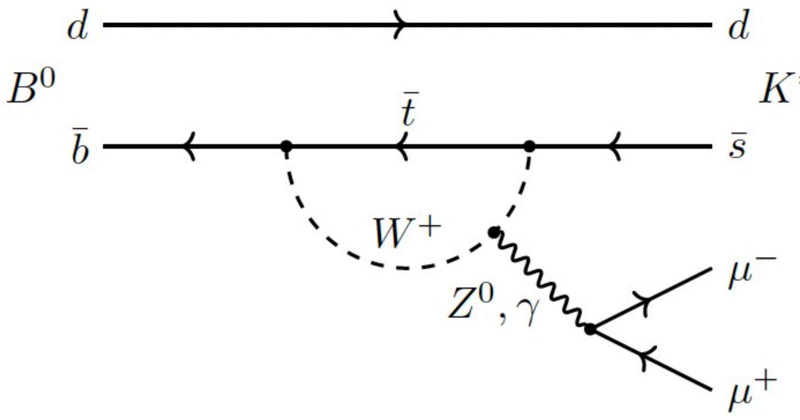
there is also a statistical component because the selected samples are quite different

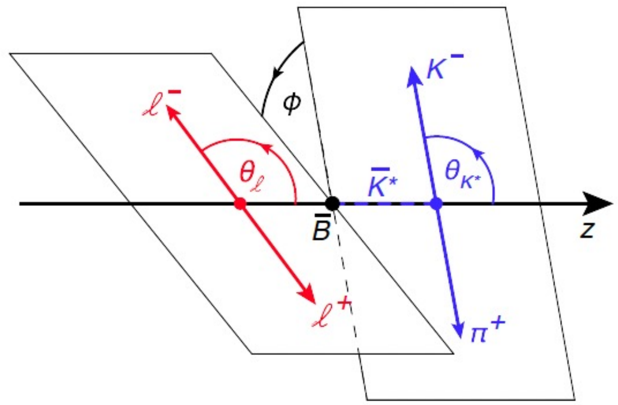
difference R_{K^*} : the statistical component of the difference is dominant, as the previous measurement is based on a much smaller data sample

✓ for R_{KS} $R_{K^{*+}}$ and R_{pK} the statistical uncertainties are large ➔ effects changing treatment of misidentified background will have small impact

✓ for R_{pK} there is a full RUN 1-2 update ongoing

b→ sμμ angular analysis





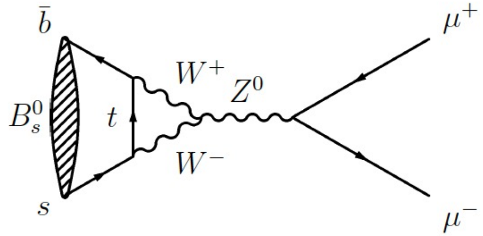
- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

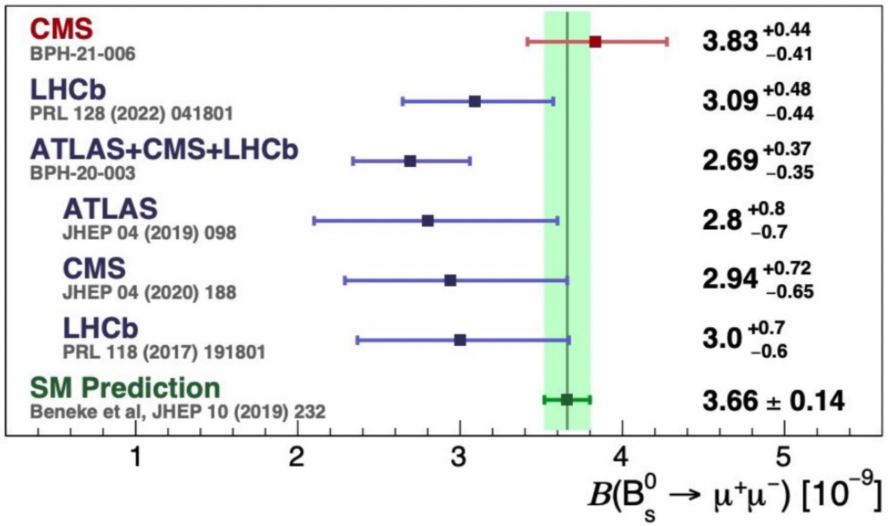
For completeness

- Angular observables $F_\mathrm{L}, A_\mathrm{FB}, S_i$ sensitive to NP contributions
- Perform ratios of observables where form factors cancel at leading order
  Example: $P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

The connection to BF(B→μμ)

- The low BF for b→sll can be explained by a shift in the vector (C_9) or axial-vector (C_{10}) couplings
  - latter cannot be explained by most pernicious non-local effects
- Connection to BF(B→μμ), which is very well predicted
- Dec 2022 CMS update has made a C_{10} explanation look less likely





Unbinned $B^0 \to K^{*0}\mu\mu$ analyses

- Can write $B^0 \to K^{*0}\mu\mu$ amplitudes,

$$\mathcal{A}_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]\right\}$$

✦ Wilson coefficients

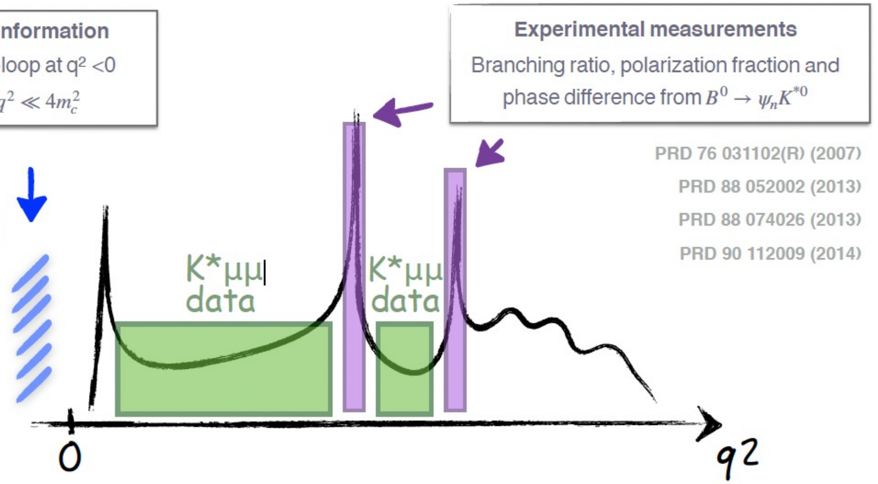
✦ Form factors

✦ Non-local hadronic matrix elements

- Expand $H_\lambda(q^2)$ as a polynomial in $z(q^2)$ fitting simultaneously pseudo-observables from J/ψ and $\Psi(2S)$ and theory points at negative q^2

- Analysis is in final stages of review

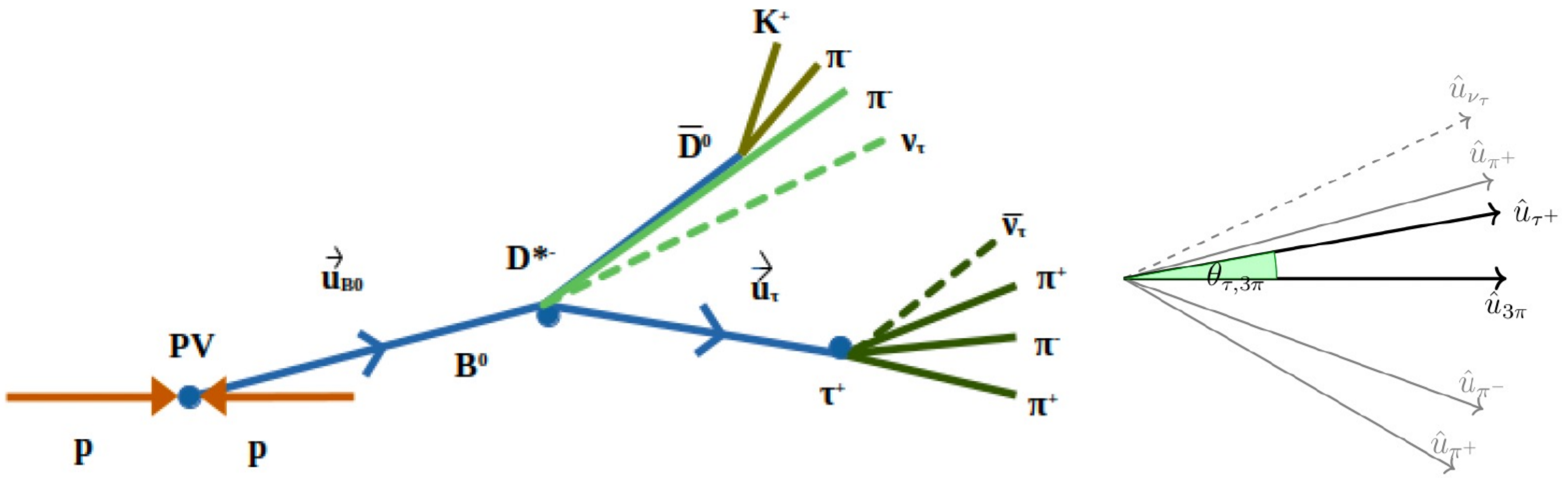
[JHEP 10 (2019) 236]
[EPJC 78 (2018) 6, 451]



Parametrise the full q^2 spectrum using Wilson Coefficients for the short-distance part of the amplitude, LCSR+LQCD results for the local form factors, and a data-driven dispersion relation to model the non-local contributions

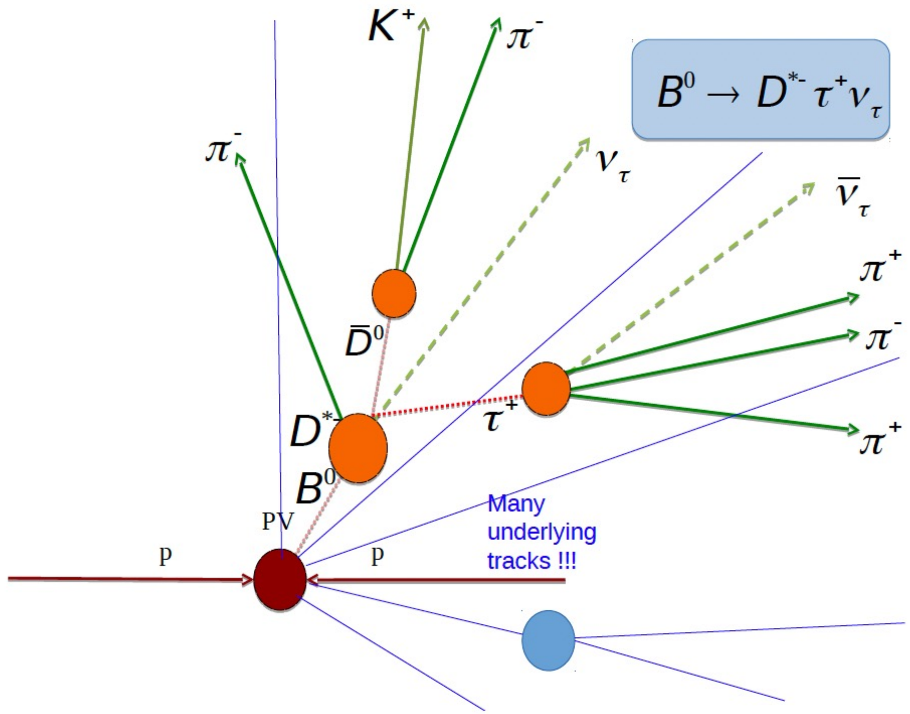
R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$: kinematics

- Neutrinos not detected; approximation needed for B reconstruction
- Well measured B^0 and τ^+ vertices allow reconstruction of flight directions
- Momentum as a function of angle between the systems



- Maximum allowed values for the angles ⇒ unambiguous estimate of momentum

R(D*) with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$: ReDecay



[EPJC **78**, 1009 (2018)]

❶ Generate 1 complete event: signal + underlying event

❷ Re-generate the *B* decay 100 times and merge each with the underlying event

❸ Repeat ❶ and ❷ *N* times

→ Factor $\mathcal{O}(10)$ faster simulation

R(D*) with $\tau \rightarrow 3\pi^{\pm}(\pi^0)\nu_\tau$: systematics

Compared to Run 1 analysis, the size is halved from employing fast simulation techniques [ReDecay].

Other dominant sources include signal and background modelling

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-} D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-} D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\bar{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-} D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-} D^0(X)$ template shapes	1.2
$B \to D^{*-} D_s^+(X)$ template shapes	0.3
$B \to D^{*-} 3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

BESIII results from $D \rightarrow 3\pi^{\pm}$ should help reduce this systematic in future.

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

[arXiv:2302.02886] submitted to PRL

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

where D$^{(*)}$ stands for a D^0, a D^{*+} or a D^{*0}

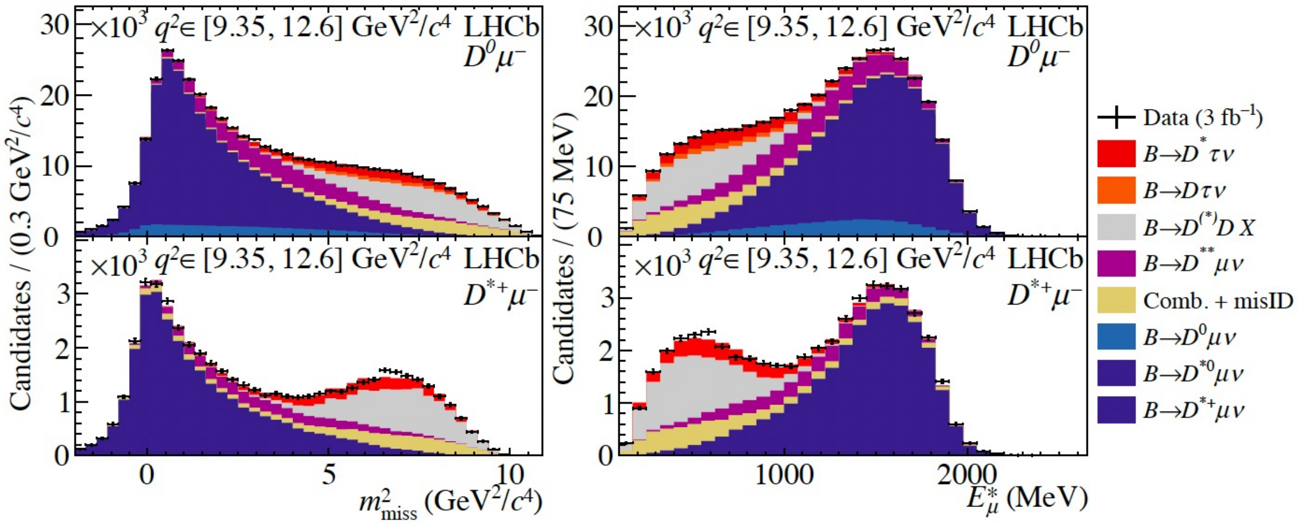
✓ select $D^0\mu^-$ and $D^{*+}\mu^-$ candidates with $D^0 \to K^-\pi^+$, $D^{*+} \to D^0(K^-\pi^+)\pi^+$

signal and normalization decay chains with identical visible final states, many uncertainties cancel on R(D$^{(*)}$)

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data using muonic $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

3D template fit to

- $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- $m^2_{\text{miss}} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- E^*_μ energy of μ



$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$
$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

Agreement with SM at 1.9σ

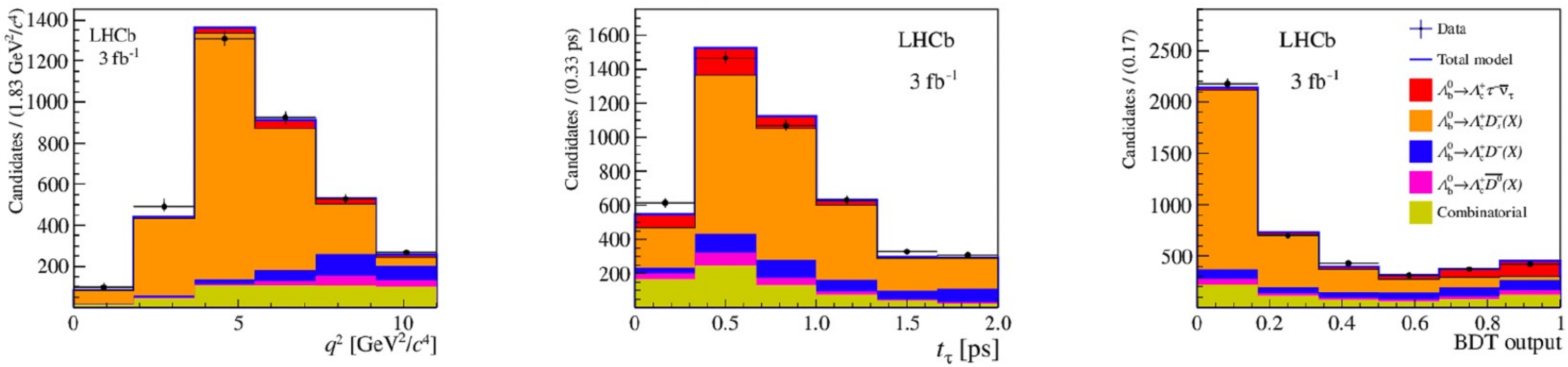
$R(\Lambda_c)$ with $\tau \to 3\pi^{\pm}(\pi^0)\nu_\tau$

[PRL 128 (2022) 191803]

- First LFU test in a baryonic $b \to c\ell\nu_\ell$ decay with Run 1 data using hadronic $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
- Normalisation channel $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} \qquad R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \left\{ \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} \right\}_{\text{ext. input}}$$

- 3D template fit to extract signal yield



$$\mathcal{K}(\Lambda_c^+) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst})$$
$$R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$$

Agreement within 1.0σ to SM

R(D*) and R(J/ψ) with τ→μνν at LHCb

LHCb [PRL 115 (2015) 111803]

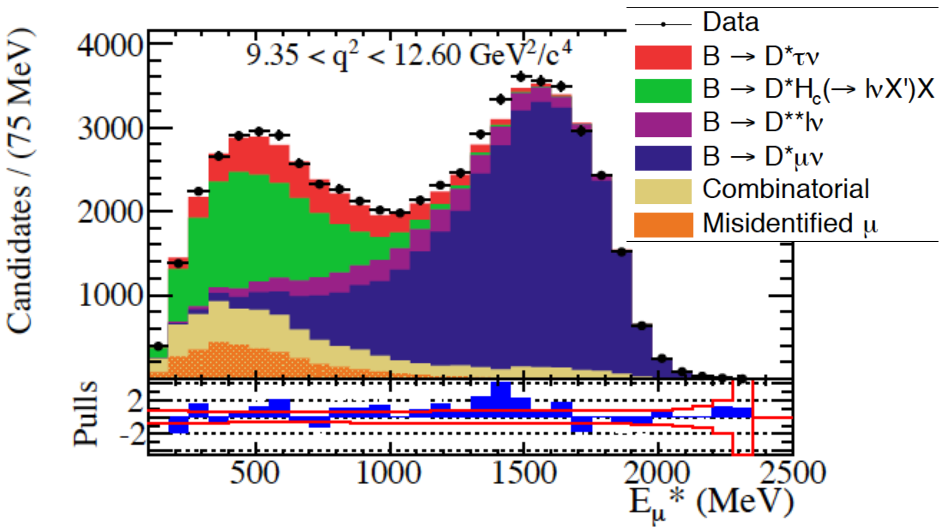
$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

using $D^{*-} \to D^0(\to K^+\pi^-)\,\pi^-$

visible final state ➔ π (Kπ) μ

large backgrounds from partially reco B decays

➔ ***MVA techniques based on μ isolation***



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

1.9 σ above Standard Model

LHCb [PRL 120 (2018) 121801]

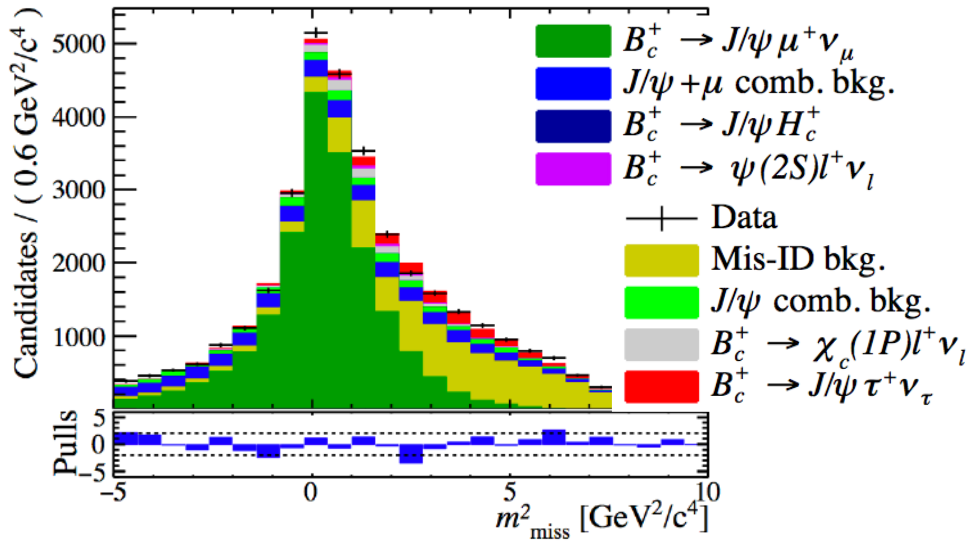
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)}$$

using $J/\psi \to \mu^+\mu^-$

visible final state ➔ (μμ)μ

shorter B_c decay time helps to discriminate

large background from lighter b hadrons



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

~ 2. σ above Standard Model

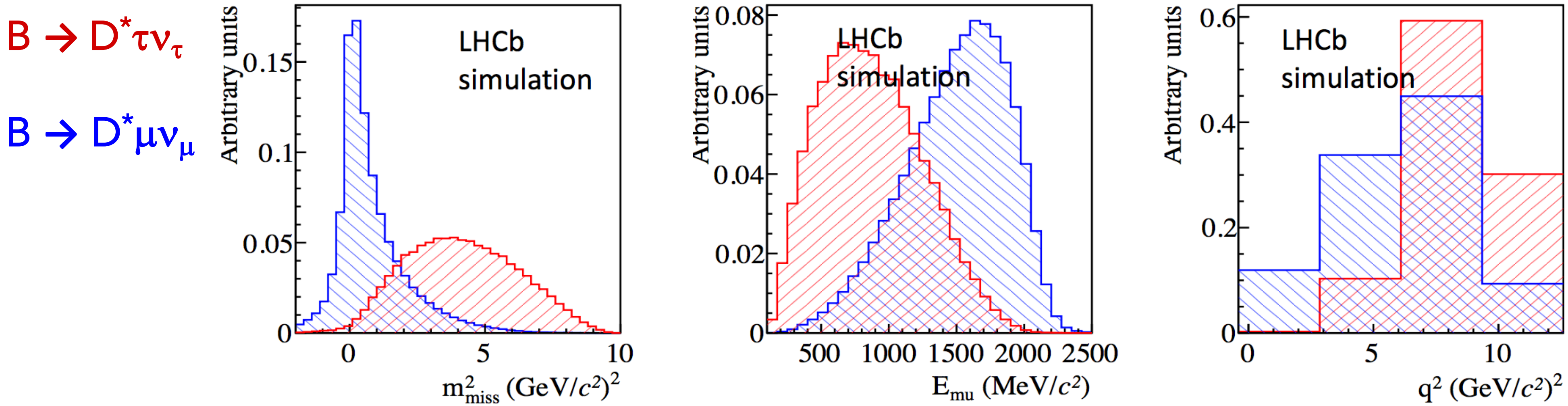
Run 1 data sample, **about 3 fb^{-1} at √s = 7, 8 TeV**

R(D*) from $\tau \to \mu \nu_\mu \bar{\nu}_\tau$

✓ statistics from high $pp \to bb$ cross section at LHC
✓ use B flight direction to measure transverse component of missing momentum
✓ B boost along beam direction approximated with boost of the **visible final state**
$(p_B)_z = (m_B/m_{D^*\mu})(p_{D^*\mu})_z$
✓can then calculate rest frame quantities:

1. $m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2$
2. E^*_μ
3. $q^2 = (p_B - p_{D^*})^2$

~18% resolution sufficient to retain discriminating power between signal and normalization channel



the LHCb upgrade

- restart data taking in 2021 at $\mathcal{L}$ up to 2×10^{33} cm^{-2}s^{-1}
- upgrade detector qualified to accumulate 50 fb^{-1} ➔

upgrade all sub-detector electronics to 40 MHz readout
make all trigger decision in software and some new detectors

VELO from microstrip sensors (R,ϕ) to 55×55 μm^2 pixel sensors
closer to the beam, from 5.5 mm to 3.5 mm

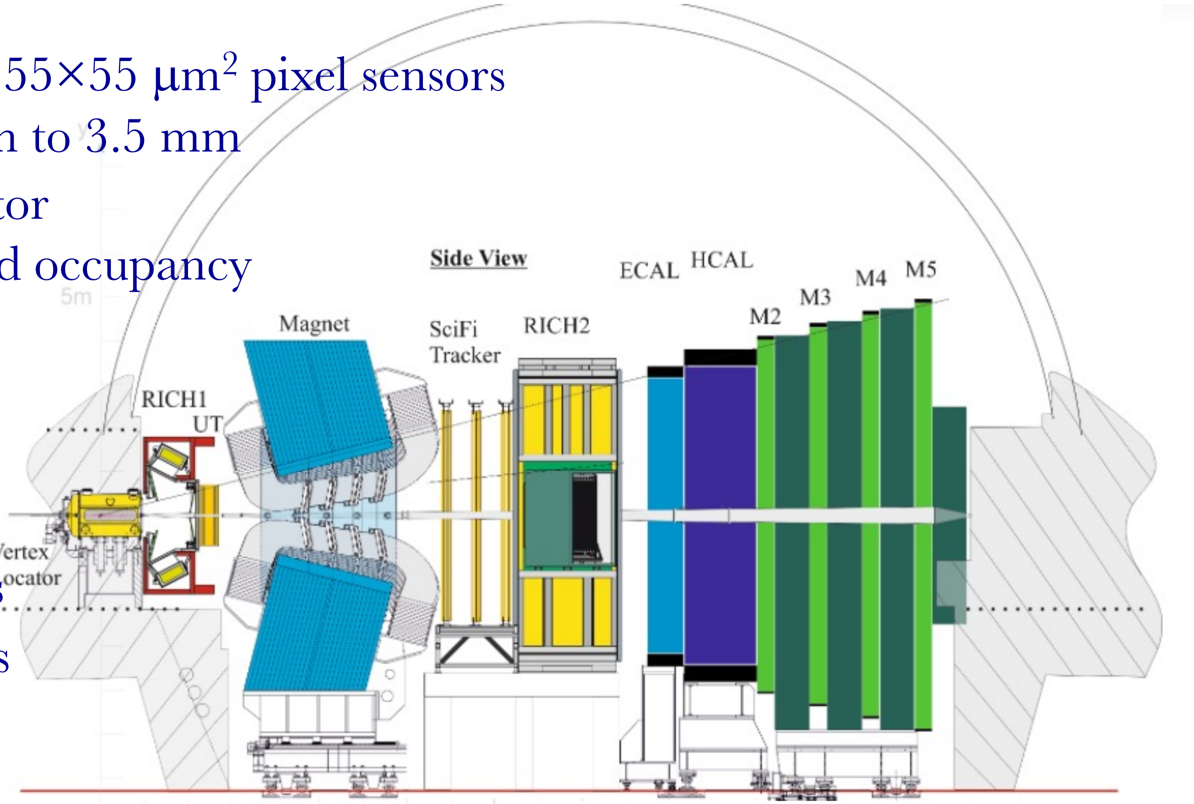
Upstream Tracker silicon strip detector
adapt segmentation to increased occupancy

SciFi Tracker 3 stations of X-U-V-X
scintillating fibre planes

PID new photodetectors for RICH1
and RICH2

Calorimetry new readout electronics

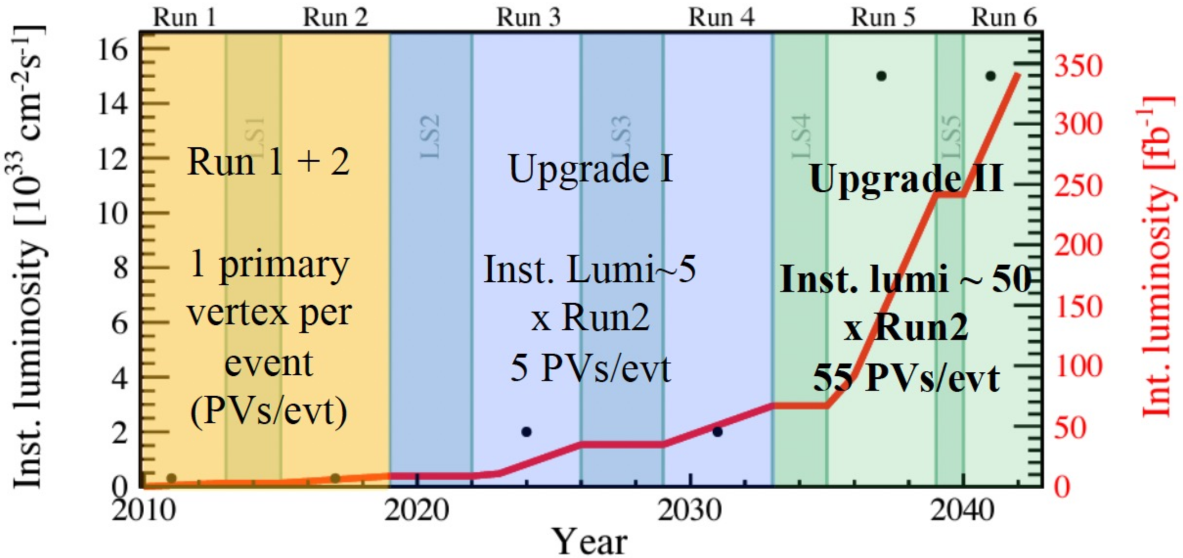
Muon System new readout electronics



➔ ***less than 10% of all channels will be kept***

LHCb-TDR-{13,14,15,66}

LHCb Upgrade 2 @ HL-LHC (2035 – 2042)



[CERN-LHCC-2021-012]

- Starting R&D phase of new technologies

bridge to future accelerators {
- precision timing for tracking and PID
- extreme radiation hardness
- low-cost monolithic pixels
- cryogenic cooling (for SiPMs)

→ **LHCb welcomes new collaborators!**