Lepton Flavour Universality tests with $b \to s\ell^+\ell^-$ decays at LHCb

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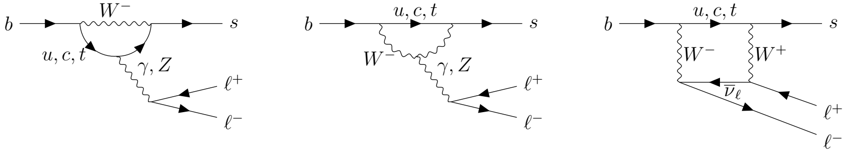
on behalf of the LHCb collaboration

Lake Louise Winter Institute 2023

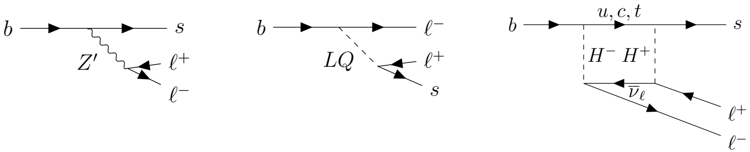
24th February 2023

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

$b \to s\ell^+\ell^-$ transitions suppressed in the Standard Model (SM) :

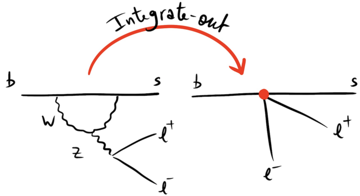


New Physics (NP) processes could contribute :

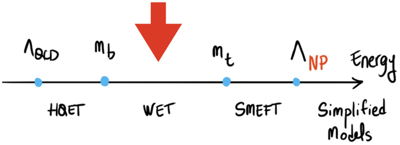


Highly sensitive to NP and accessible with existing data.

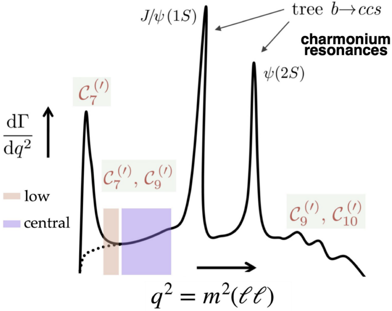
Key of indirect measurements



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i')$$



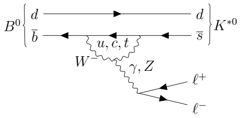
Parametrisation of NP via Wilson Coefficients $\mathcal{C}_i$.

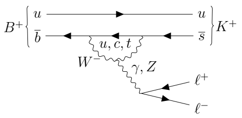


The rare mode is sensitive to NP!

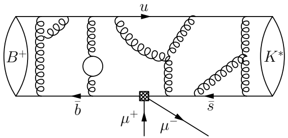
Detected are hadrons ...

... with different spectator quarks ...

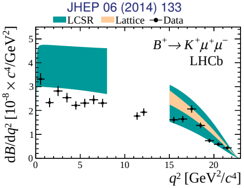




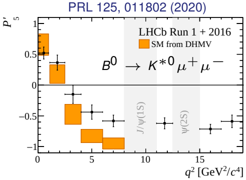
...and hadronic interactions.



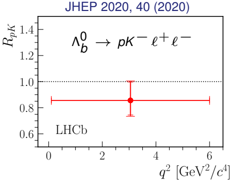
Theoretical "cleanness" depends on hadronic uncertainties.



(a) Differential BFs <



(b) Angular observables <



(c) LFU tests

Sensitivity to different NP. **Lepton Flavor Universality (LFU) tests are cleanest !**

LFU tests

How?

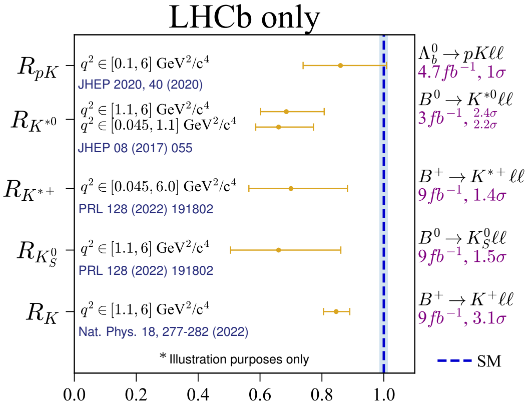
$$R_{H_s} = \frac{\int_{q_{\min}}^{q_{\max}} \frac{d\mathcal{B}(H_b \to H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}}^{q_{\max}} \frac{d\mathcal{B}(H_b \to H_s e^+ e^-)}{dq^2} dq^2}$$

- ⊕ Theoretical uncertainties cancel.
- ⊕ QED effects at $\mathcal{O}(1\%)$.

  Eur. Phys. J. C. 76 (2016) 8
- ⊕ Statistically limited.

Deviations from the SM prediction are a sign of NP.

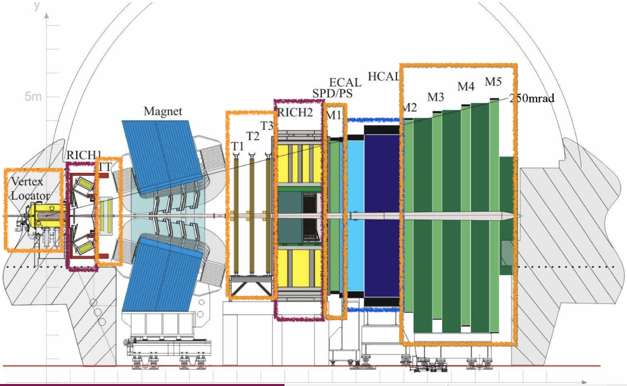
Experimental status in 2022:

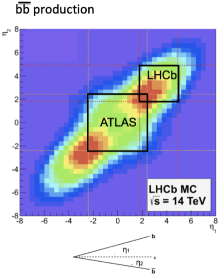


Tensions of the measured R_{H_s} with the SM.

LHCb detector

- $b\bar{b}$ production mostly in forward region
- Run 1 and 2 : 9 fb^{-1} of pp-collisions
- Forward spectrometer with excellent vertexing, tracking, momentum resolution and particle identification





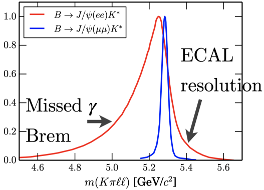
CHEAT SHEET

- Good vertex and impact parameter resolution σ (IP) = 15+29/p_T mm.
- Excellent momentum resolution ~ 25 MeV/c² two-body decays.
- Excellent particle ID (μ-ID 97% for (π → μ) misID of 1-3%).
- Versatile & efficient trigger.

Difference of muons and electrons in LHCb

Muons:

- ∗ Small losses in ECAL
- ∗ Tracks in muon stations
- ∗ Lower trigger threshold
- → Clean signatures

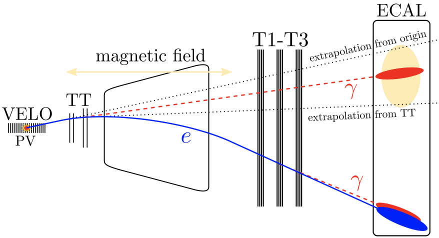


Electrons:

- ∗ Bremsstrahlung
- ∗ Worse energy resolution
- ∗ More background
- → Difficult

Bremsstrahlung photon recovery:

- ▷ Emission before magnet problematic
- ▷ Algorithm is $\sim$ 50% efficient
- ▷ Well modelled in simulation



Simultaneous determination of R_K and R_{K^*}

arXiv:2212.09152 & arXiv:2212.09153 submitted to PRL and PRD

Measurement of double ratio :

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

since $\frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(J/\psi \to \mu^+\mu^-)} \approx 1$ Phys. Lett. B731, 227 (2014)

$\longrightarrow$ Cancel most of systematics due to μ/e difference

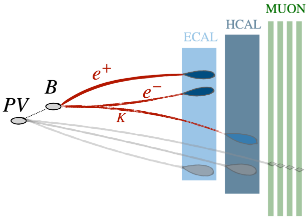
Cross-check efficiencies with :

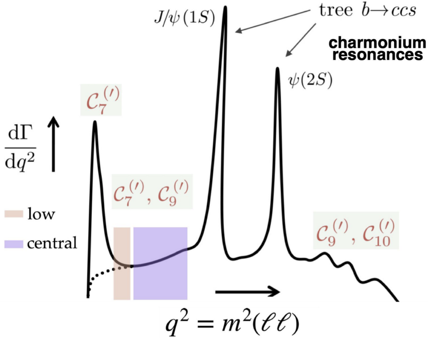
$$r_{J/\psi}^{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B \to K^{(*)}J/\psi(\to e^+e^-))} \stackrel{!}{=} 1$$

& double ratio with $\psi(2S)$ mode instead of rare mode

$$\mathcal{B} = \frac{N}{\varepsilon} = \frac{\text{Yields from mass fits}}{\text{Efficiencies from corrected MC using data-driven techniques}}$$

Analysis strategy





- Trigger On Signal and Independent of Signal for muonic and electronic final state
- K^{*0} mass window : $m(K^+\pi^-) \in [792, 992]\,\text{MeV}/c^2$

—$B^0 \to K^{*0}\ell^+\ell^-$, $\cdots$ $B^+ \to K^+\ell^+\ell^-$

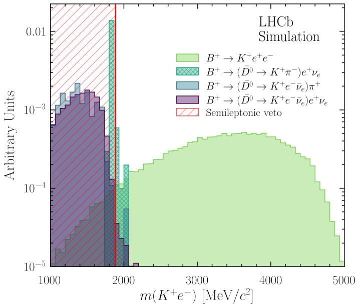
low-q^2 : $[0.1, 1.1]\,\text{GeV}^2/c^4$,

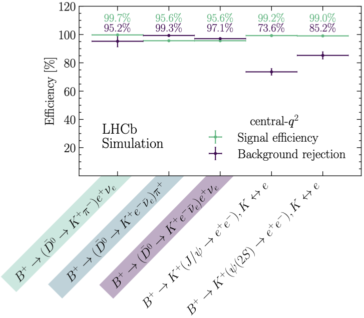
central-q^2 : $[1.1, 6.0]\,\text{GeV}^2/c^4$

Background suppression

Misidentification:	Tight lepton and hadron particle identification (PID).
Combinatorial:	Multivariate classifier, optimization per decay mode, q^2 region and run period.
Partially reconstructed:	Multivariate classifier in electron mode + cut on corrected B mass.

Decays with large branching ratios can be vetoed (f.ex. in $B^+ \to K^+ e^+ e^-$):





Suppressing critical $\pi_{\to e}$ misidentification and $K \leftrightarrow e$ swaps.

Variations induced by corrections of simulation sample

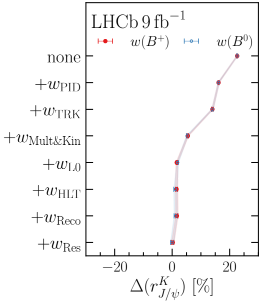
Exemplary for $B^+ \to K^+\ell^+\ell^-$.

Calibration with resonant B^+ and B^0 decay modes are equivalent.

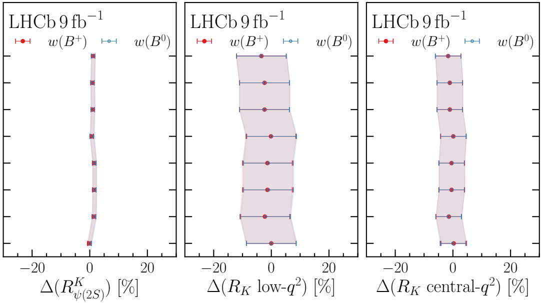
$\longrightarrow$ Calibrate with B^0 decay to decouple from normalization mode.

Perform simultaneous fit to treat correlations appropriately.

Single ratio $r_{J/\psi}$



Double ratios $R_{\psi(2S)}$, R_K in low- and central-q^2



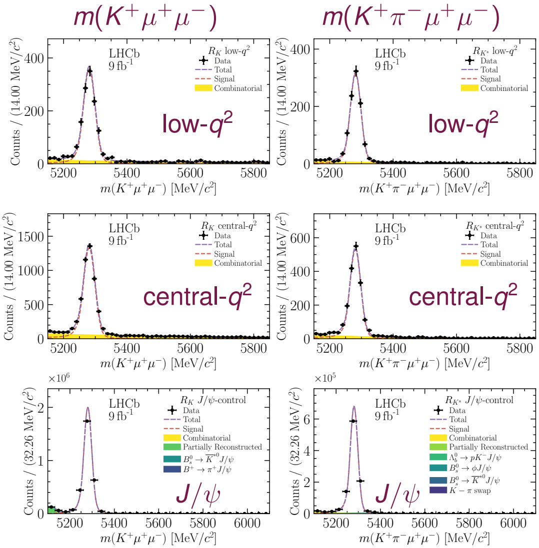
Single ratio varies, while double-ratios remain stable.

Mass fit procedure

Simulatenous fits of

- B^+ and B^0 mass
- in three run periods,
- in the two trigger categories,
- in the three q^2 regions,
- in the e^- and μ^- modes.

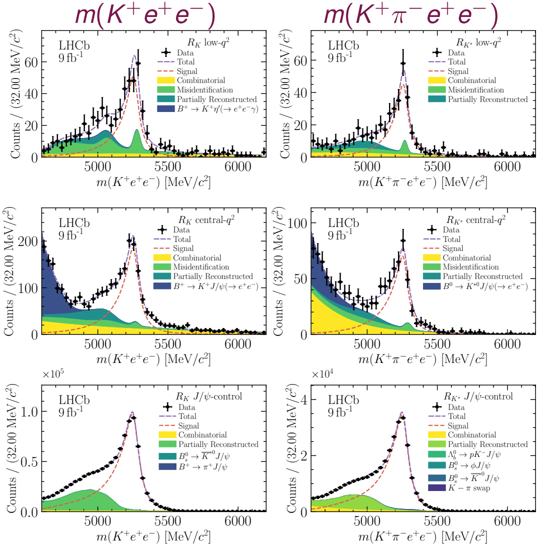
Clean (stacked) signal peak of the muon mode.



Mass fits of the electron mode

- Residual misidentification background present under signal peak.
- Bulk of partially reconstructed background in low B mass region.
- Leakage of J/ψ mode in central q^2 region.

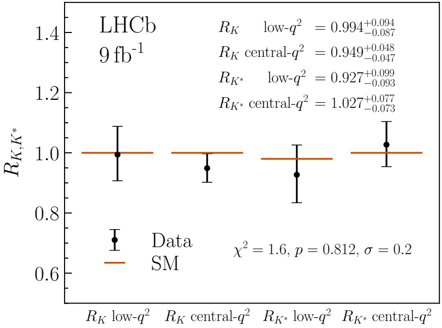
Good control of backgrounds.



Results

Cross-check:

$$r_{J/\psi}^{K} = 1.047 \pm 0.024$$
$$r_{J/\psi}^{K^*} = 1.028 \pm 0.024$$



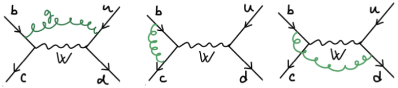
- Most precise and accurate values of LFU test in $b \to s\ell^+\ell^-$.
- Supersedes previous results.
- Compatible with SM at $0.2\,\sigma$.
- Statistical uncertainty dominates.

Is this the end of the story ?

- ⋆ Better precision needed.
- ⋆ Deviations in differential branching fractions and angular analyses of muon mode remain.
- ⋆ Run 3 started with higher luminosity.

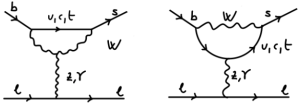
Back-up

Operators (from Claudia Cornella)



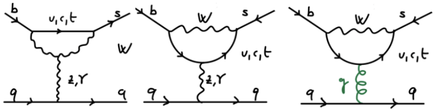
CURRENT-CURRENT operators

$$\mathcal{O}_1^{(c)} = (\bar{s}\gamma_\mu P_L c)\,(\bar{c}\gamma_\mu P_L b)$$
$$\mathcal{O}_2^{(c)} = (\bar{s}^j\gamma_\mu P_L c^i)\,(\bar{c}^i\gamma_\mu P_L b^j)$$



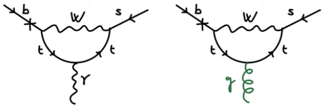
SEMILEPTONIC operators

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}\,(\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}\,(\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu\gamma^5 \ell)$$



QCD penguins

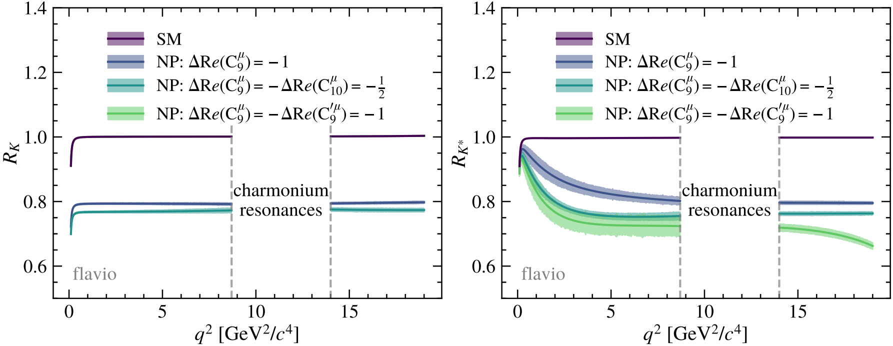
$$\mathcal{O}_3 = (\bar{s}\gamma_\mu P_L b) \sum_{q=u,d,s,c,b} (\bar{q}\gamma^\mu P_L q)$$
$$\mathcal{O}_4 = (\bar{s}^i\gamma_\mu P_L b^j) \sum_{q=u,d,s,c,b} (\bar{q}^j\gamma^\mu P_L q^i)$$



DIPOLE operators

$$\mathcal{O}_7 = m_b \frac{e}{(4\pi)^2}\,(\bar{s}\sigma^{\mu\nu} P_R b)\,F_{\mu\nu}$$
$$\mathcal{O}_8 = m_b \frac{g_s}{(4\pi)^2}\,(\bar{s}\sigma^{\mu\nu} P_R T^a b)\,G^a_{\mu\nu}$$

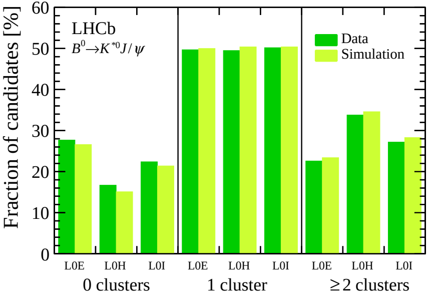
Sensitivity to New Physics



Uncertainties of Standard Model predictions are tiny.
New Physics model show large deviations from unity.

Bremsstrahlung photon recovery in simulation and data

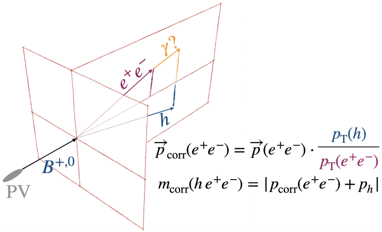
JHEP08(2017)055

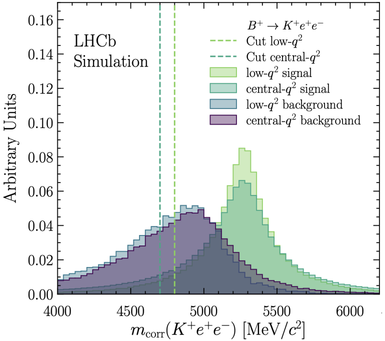


Fraction of candidates with Bremsstrahlung photon is comparable between data and simulation.

Partially reconstructed background in electron mode

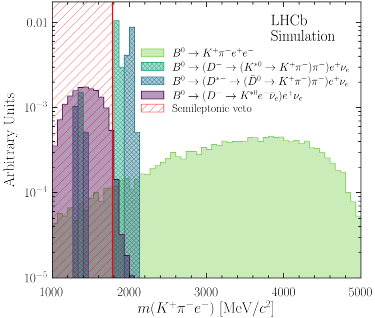
1. Multivariate classifier to suppress $B \to K^{(*)} e^+ e^- X$ decays ($X \geq 1$ hadron).
2. Corrected transverese dielectron momentum wrt B flight direction $\vec{p}_{\text{corr}}$ used to compute corrected B mass m_{corr}.

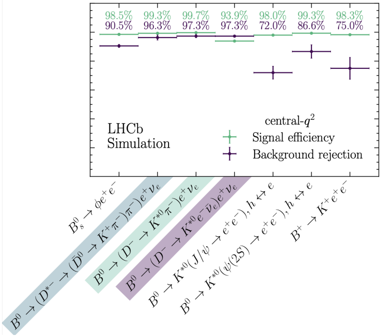




m_{corr} suppresses partially reconstructed and combinatorial background further
$\to$ employed in electron modes after multivariate classifiers

Vetos of large branching ratio backgrounds in the $B^0 \to K^{*0} e^+ e^-$ decay mode



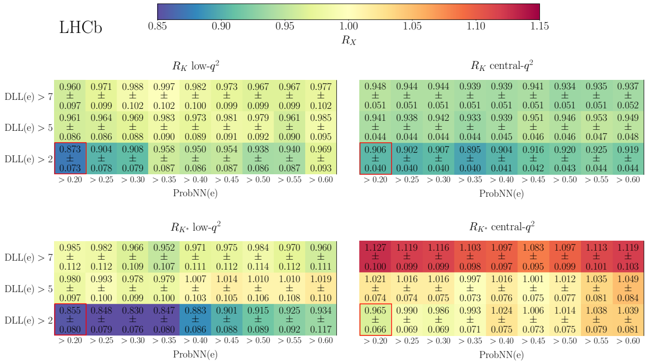


Removing critical $\pi_{\to e}$, $K_{\to e}$ misidentification, $\pi \leftrightarrow e$ and $K \leftrightarrow e$ swaps and over-reconstructed events ($B^+ \to K^+ e^+ e^-$ + random π^-).

Misidentification background detection

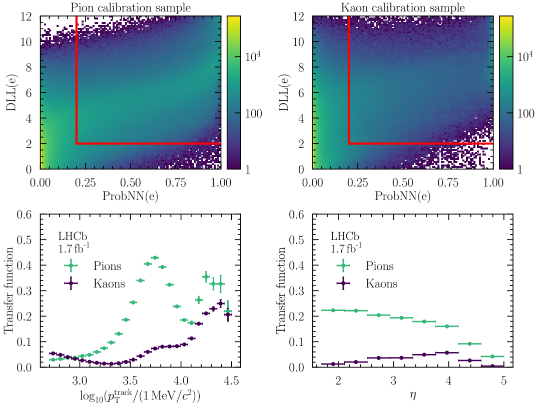
- One double misidentification background is small, but accumulation of many decay modes with often unknown Dalitz structures (e.g. $K^{*0}\pi^+\pi^-$)
- Coherent changes of R ratios by scanning ProbNNe

$\rightarrow$ Points to mixture of different background sources



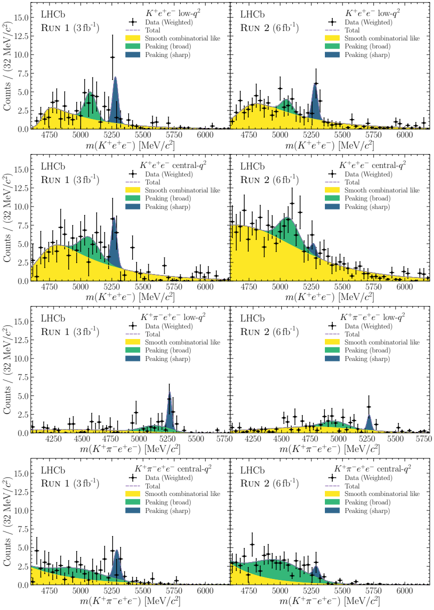
Misidentification background treatment

- Inversion of PID requirements for one or two electrons $\Rightarrow$ "control regions"
- Transfer function : defines K/π misidentified as e, obtained from the $D^{*-} \to \bar{D}^0(\to K^+\pi^-)\pi^-$ calibration data sample



Shape of misidentication background in $m(K^+e^+e^-)$ and $m(K^+\pi^-e^+e^-)$

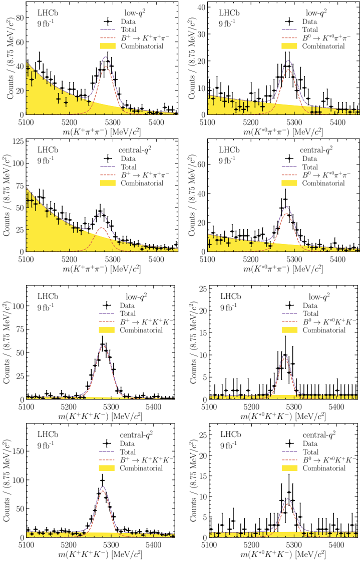
Extrapolated via transfer functions and used as constraints in nominal fit.



Misidentification background type

1. **Peaking structures** from fully reconstructed misidentified decays, f.ex. :
   - $B \to K^{(*)}\pi^+\pi^-$
   - $B \to K^{(*)}K^+K^-$
   - $e^+_{fail}e^-_{fail}$ control regions replacing e mass hypotheses by π/K (upper/lower right)

2. **Complex structures** from single or double misidentification backgrounds with missing energy, f.ex.
   - $B \to K^{(*)}\pi^-\pi^0(\to e^+e^-\gamma)$ with missed e^- and π^- as e^- misidentified



Simulation correction chain via data-driven techniques

- Particle identification (PID)
- Tracking (TRK)
- *B* kinematics and event multiplicity (BKIN&MULT)
- Hardware trigger (L0)
- High level software trigger (HLT)
- *B* decay vertex reconstruction (RECO)
- q^2 resolution and bin migration (RES)

$$\mathcal{W}_i = \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{simulation}}}$$

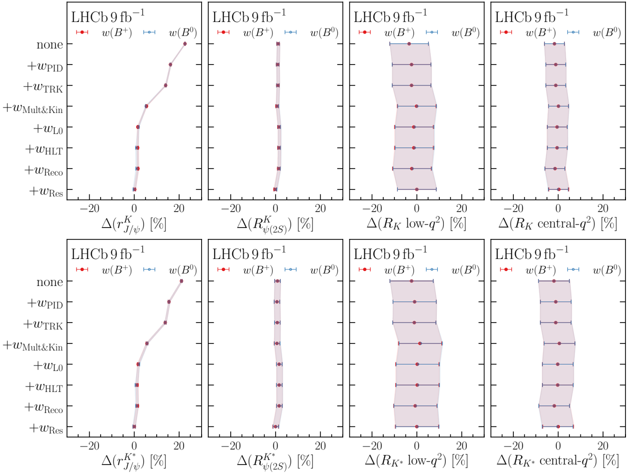
Evaluation of correction chain with both resonant modes :

$B^{+,0} \to K^{+,*0} J/\psi(\mu^+\mu^-)$: $w_{\text{PID}} \to w_{\text{L0}} \to w_{\text{HLT}}$ $\downarrow$

$B^{+,0} \to K^{+,*0} J/\psi(\ell^+\ell^-)$: $w_{\text{PID}} \to w_{\text{TRK}} \to w_{\text{BKIN\&MULT}} \to w_{\text{L0}} \to w_{\text{HLT}} \to w_{\text{RECO}} \to w_{\text{RES}}$

Corrections from B^+ and B^0 resonant mode are shown to be interchangeable.
Complementary chain is nominal.

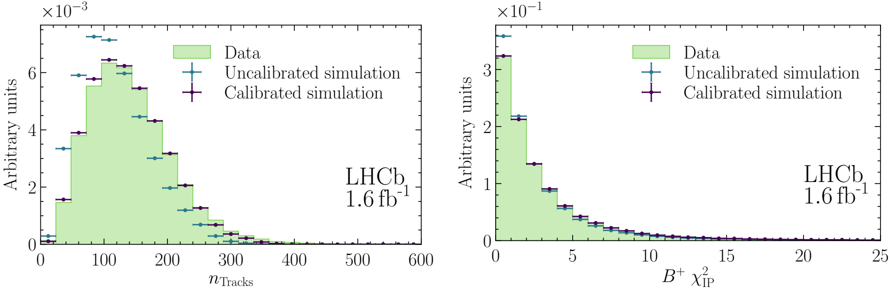
Variations induced by corrections of simulation sample



Single ratio varies, while double-ratios remain stable.

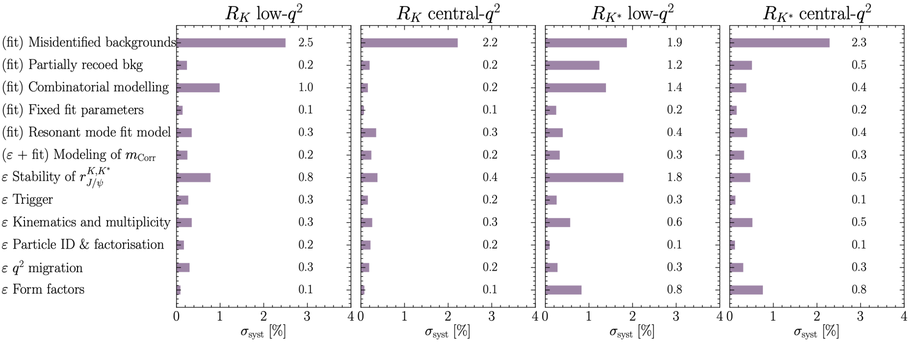
Examples of simulation corrections

Correction of event multiplicity (left) and *B* decay vertex reconstruction (right)



Excellent data/simulation agreement per run period after all corrections.

Systematic uncertainties



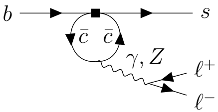
Measurement is still statistically dominated.

What differs to previous measurement

1. Different selection requirements.
2. New understanding that absorption of misidentification background in combinatorial shape is not sufficient.
3. Electron identification criteria are tightened.
4. Modelling misidentification background with shape from data-driven method.
5. Cross-validation via four *R*-ratios.
6. Simultaneous fit accounts for correlations between ratios.

Simultaneous measurement of R_K and R_{K^*} supersede previous results.

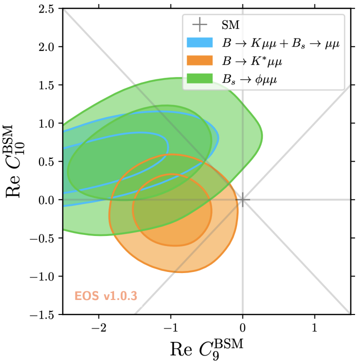
Charm loops



- Non-local effect for small charm quark energies
- Problematic since can mimic NP contributions in $\mathcal{C}_7$ and $\mathcal{C}_9$
- Cannot be computed from first principles
- Subject of debates in theory community

Global fits of angular observables and differential branching fractions

EOS-2022-02, arXiv:2206.03797



Slight tensions with respect to the SM prediction.