

Tests of Lepton Flavour Universality and Searches for Lepton Flavour Violation at LHCb

FPCP 2023

Sebastian Schmitt¹,
On behalf of the LHCb collaboration

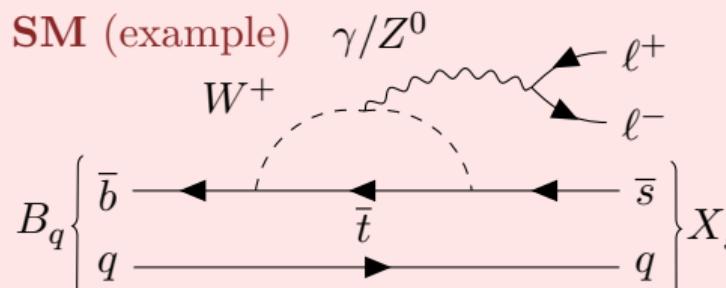
¹RWTH Aachen University



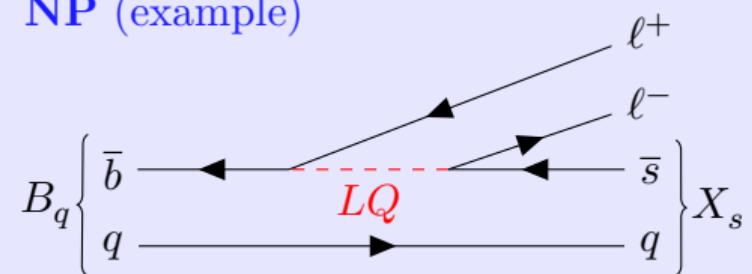
Lyon, May 30, 2023

- ▶ $b \rightarrow s\ell^+\ell^-$ transitions **strongly suppressed** in Standard Model (SM)
 - Loop topology and CKM suppression
 - ▶ New particles (NP) may significantly **alter observables**:
 - E.g. branching fractions \mathcal{B} , angular distributions, etc.
- ⇒ Rare b decays: **potent laboratory** to test SM

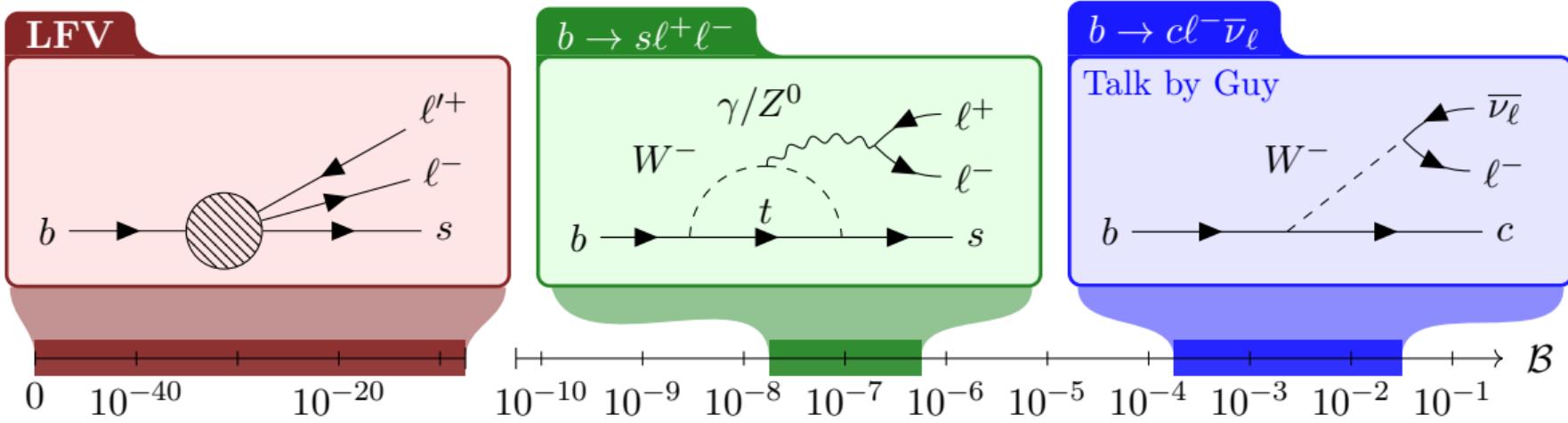
SM (example)



NP (example)



- ▶ Measurements span **big range of branching fractions**
- ▶ **Forbidden** decay topologies violating flavour universality (**LFV**)
- ▶ Rare $b \rightarrow s\ell^+\ell^-$ transitions, $b \rightarrow s\mu^+\mu^-$ covered by Jake
- ▶ Tree-level $b \rightarrow c\ell^-\bar{\nu}_\ell$ transitions covered by Guy

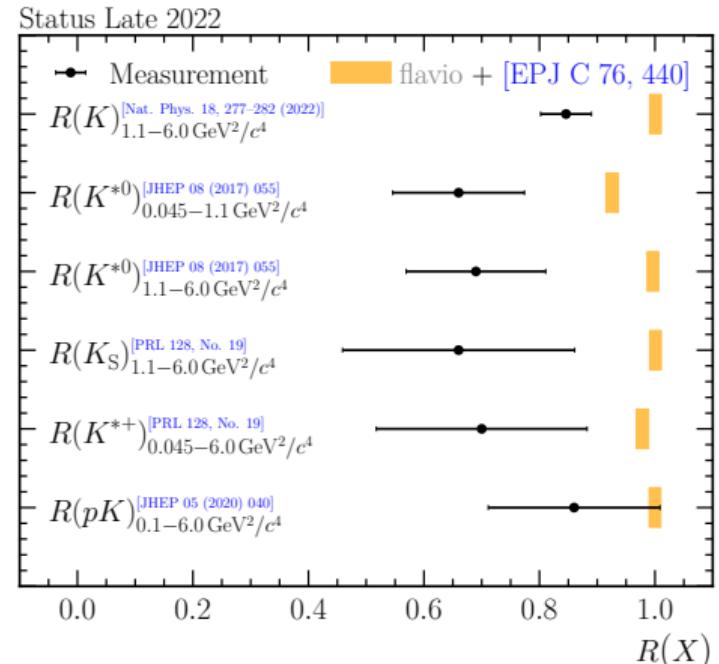


- ▶ Test LFU in $b \rightarrow s\ell^+\ell^-$ transitions using:

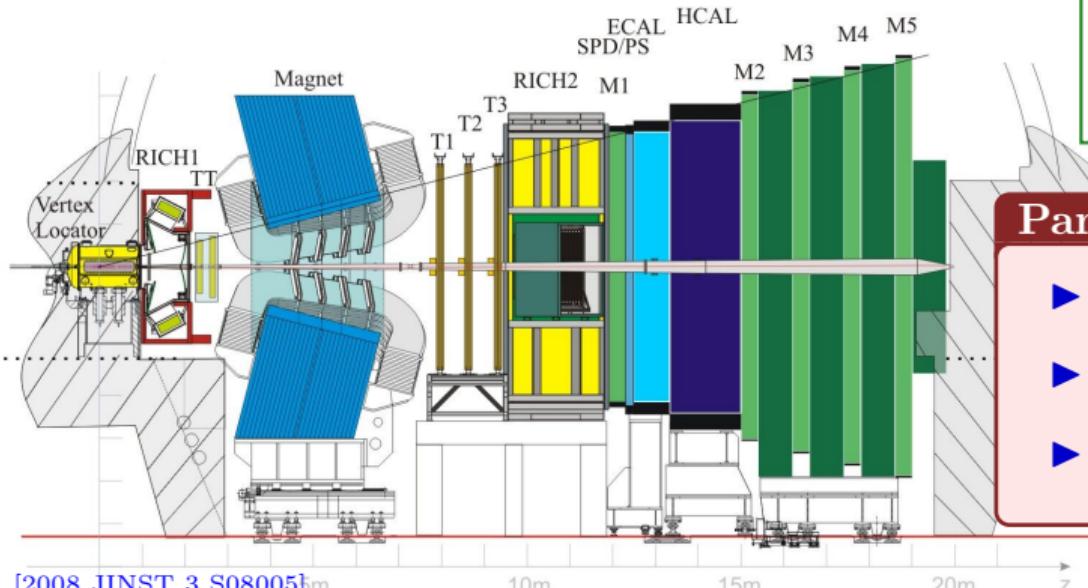
$$R_X = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B_q \rightarrow X_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B_q \rightarrow X_s e^+ e^-)}{dq^2} dq^2} = 1 \pm \mathcal{O}(1\%)^1$$

- ▶ With $q^2 = m(\ell^+\ell^-)^2$
- ▶ Hadronic **uncertainties** cancel in ratio
- ⇒ R_X can be **precisely** predicted in the SM
- ▶ Here focus on X_s : K^+ , K^{*0}
[LHCb-Paper 2022 045]

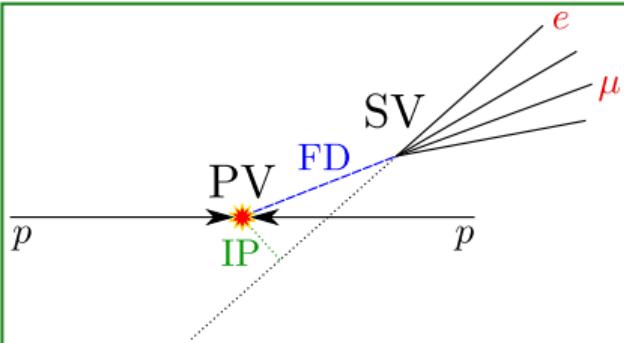
¹[Eur. Phys. J. C 76, 440 (2016)]



- ▶ IP resolution: $(15 + 29/p_T[\text{GeV}]) \mu\text{m}$
- ▶ Momentum resolution: $\sigma_p/p \approx 0.5 - 1\%$



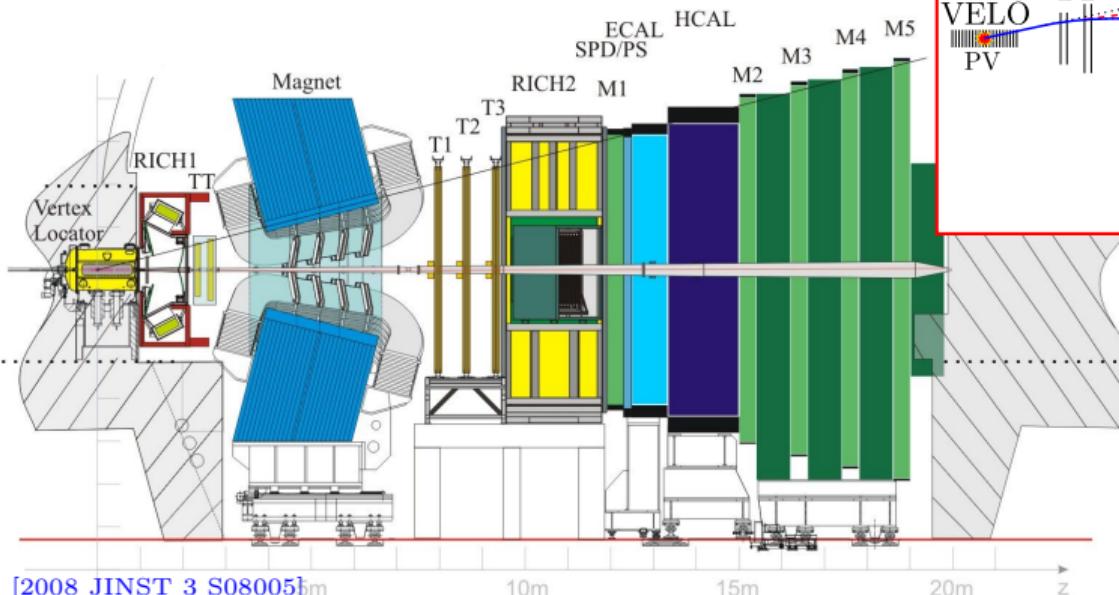
[2008 JINST 3 S08005]pm



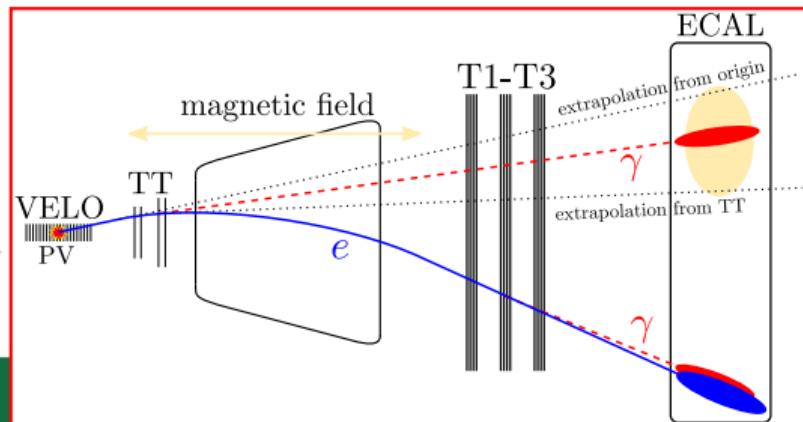
Particle Identification

- ▶ $\epsilon_{\mu \rightarrow \mu} \approx 97\%$ for $\epsilon_{\pi \rightarrow \mu} \approx 3\%$
- ▶ $\epsilon_{K \rightarrow K} \approx 95\%$ for $\epsilon_{\pi \rightarrow K} \approx 5\%$
- ▶ $\epsilon_{e \rightarrow e} \approx 90\%$ for $\epsilon_{h \rightarrow e} \approx 5\%$

- ▶ ECAL resolution: $1\% + 10\%/\sqrt{E[\text{GeV}]}$
- ▶ Bremsstrahlung recovery for electrons:

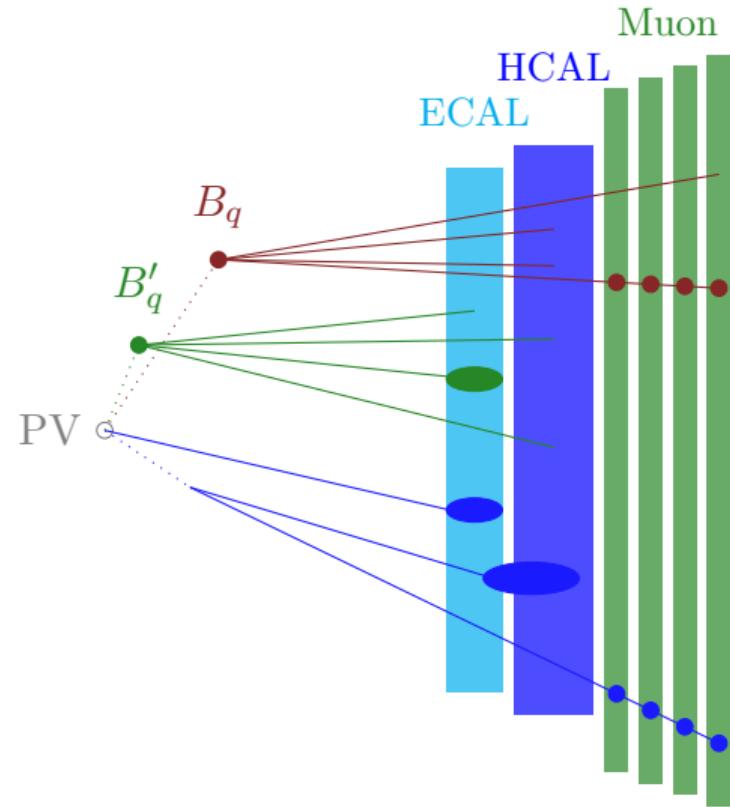


[2008 JINST 3 S08005]



- ▶ Extrapolate search window
 - From VeLo
 - From TT
- ▶ Add photons in search window

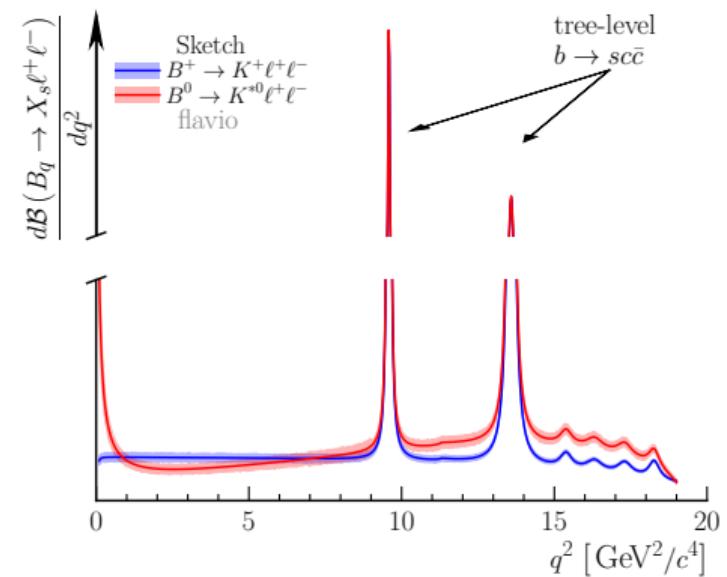
- ▶ Different **trigger-signatures** for decays involving **muons** and **electrons**
- ▶ Trigger **thresholds** consequently different:
 - **Muons:** $p_T \gtrsim 1.5 \text{ GeV}/c$ (2012)
 - **Electrons:** $E_T \gtrsim 3.0 \text{ GeV}/c^2$ (2012)
- ▶ Trigger on **signatures independent of signal** that fire **any** trigger
- ▶ **Exclusively combine** trigger categories to improve efficiency:
 1. Trigger **independent of signal**
 2. Trigger on **signal lepton (μ/e)** (and not 1.)



- ▶ Experimentally R_X measured as **double ratio** of branching fractions:

$$R_X = \frac{\mathcal{B}(B_q \rightarrow X_s \mu^+ \mu^-)}{\mathcal{B}(B_q \rightarrow X_s J/\psi(\mu^+ \mu^-))} \cdot \frac{\mathcal{B}(B_q \rightarrow X_s J/\psi(e^+ e^-))}{\mathcal{B}(B_q \rightarrow X_s e^+ e^-)}$$

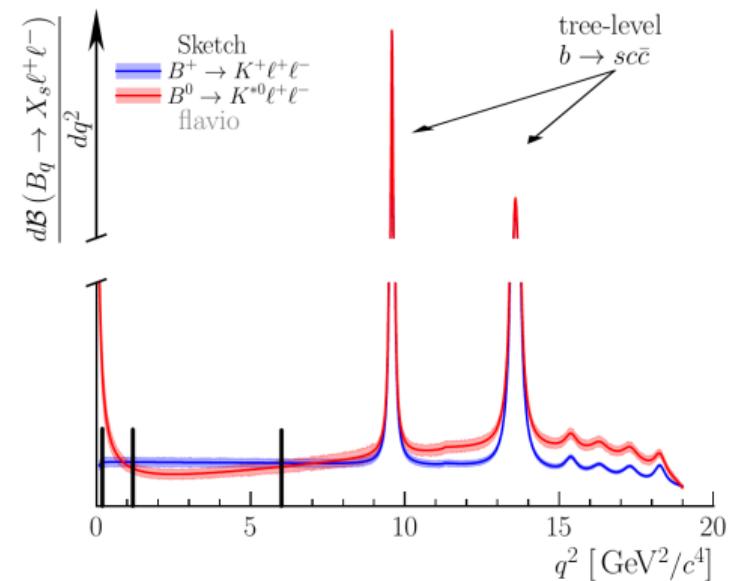
- Large **majority of systematic** uncertainties **cancel** to first order
- **LFU** in $J/\psi \rightarrow \ell^+ \ell^-$ decays established at $\%$ level [PRD 88, 032007]
- ▶ Measurement in **two q^2 regions**:
 - **low- q^2** : $0.1 < q^2 < 1.1 \text{ GeV}^2/c^4$
 - **central- q^2** : $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$
- ▶ Ratio experimentally determined using:
yields and calibrated **efficiencies**
- ▶ Selection to **enrich signal** in dataset and **remove background** contributions



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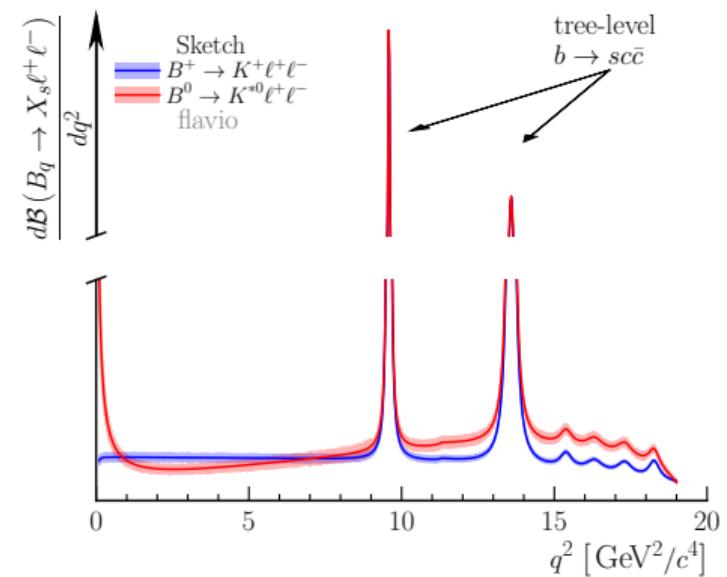
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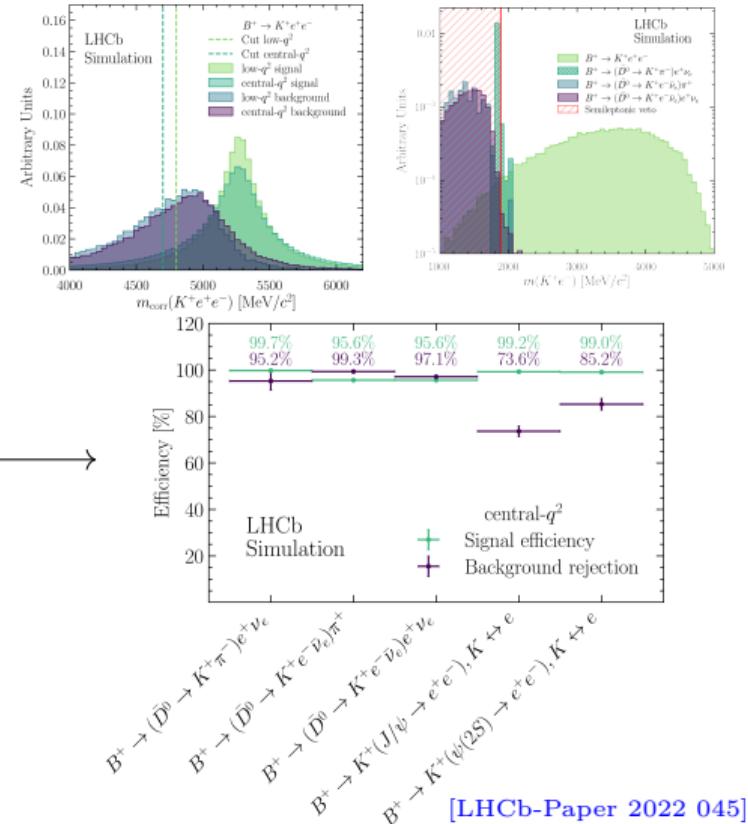
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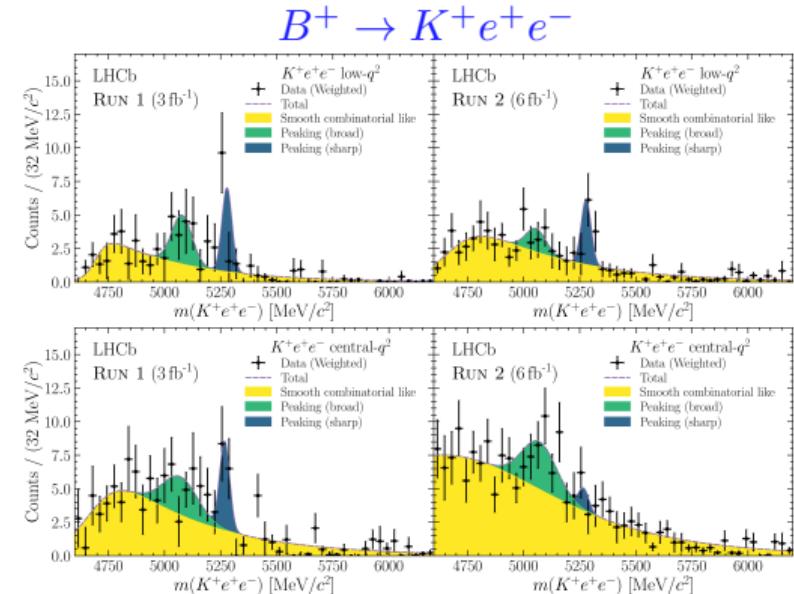
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- ▶ Combinatorial background
 - Multivariate classifier using kinematics and vertex information
- ▶ Partially reconstructed (e^+e^-)
 - Multivariate classifier
 - Cut on **corrected** $K^{(*)}e^+e^-$ mass
- ▶ Explicit vetoes for specific decays
- ▶ Mis-identified decays
 - Novel data-driven approach to estimate pollution and shape
 - Explicitly modelled in fit to data
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[LHCb-Paper 2022 045]

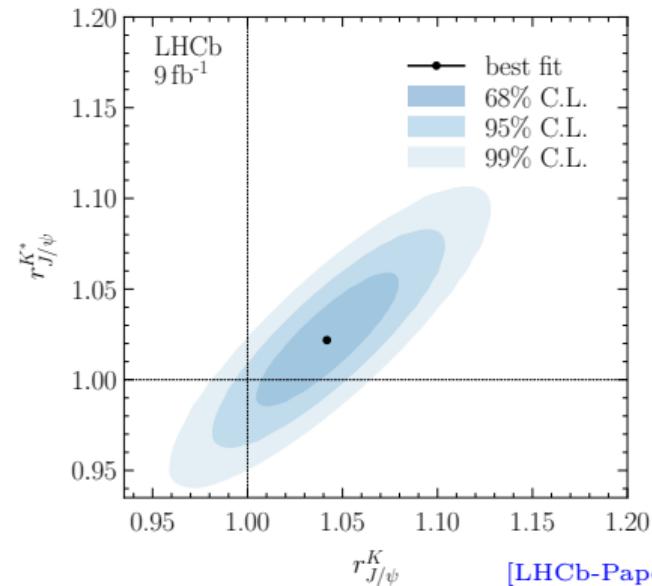
- ▶ Validation using ratio of resonant branching fractions:

$$r_{J/\psi} = \frac{\mathcal{B}(B_q \rightarrow X_s J/\psi(\mu^+ \mu^-))}{\mathcal{B}(B_q \rightarrow X_s J/\psi(e^+ e^-))},$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B_q \rightarrow X_s \psi(2S)(\mu^+ \mu^-))}{\mathcal{B}(B_q \rightarrow X_s \psi(2S)(e^+ e^-))} \cdot r_{J/\psi}^{-1}$$

$r_{J/\psi}$

- ▶ Single ratio of branching fractions
 - Probe electrons directly versus muons
 - Limited cancellation of systematics
 - ⇒ Stringent validation
- ▶ $r_{J/\psi}$ compatible with unity
- ▶ Independent of kinematics



[LHCb-Paper 2022 045]

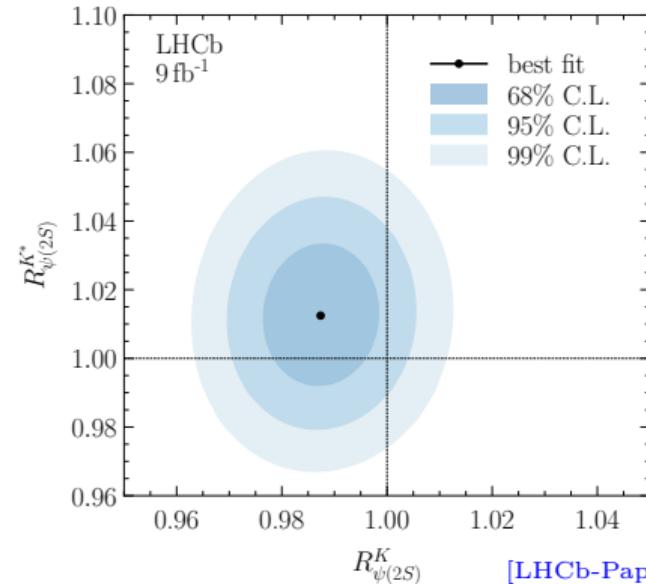
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$R_{\psi(2S)}$

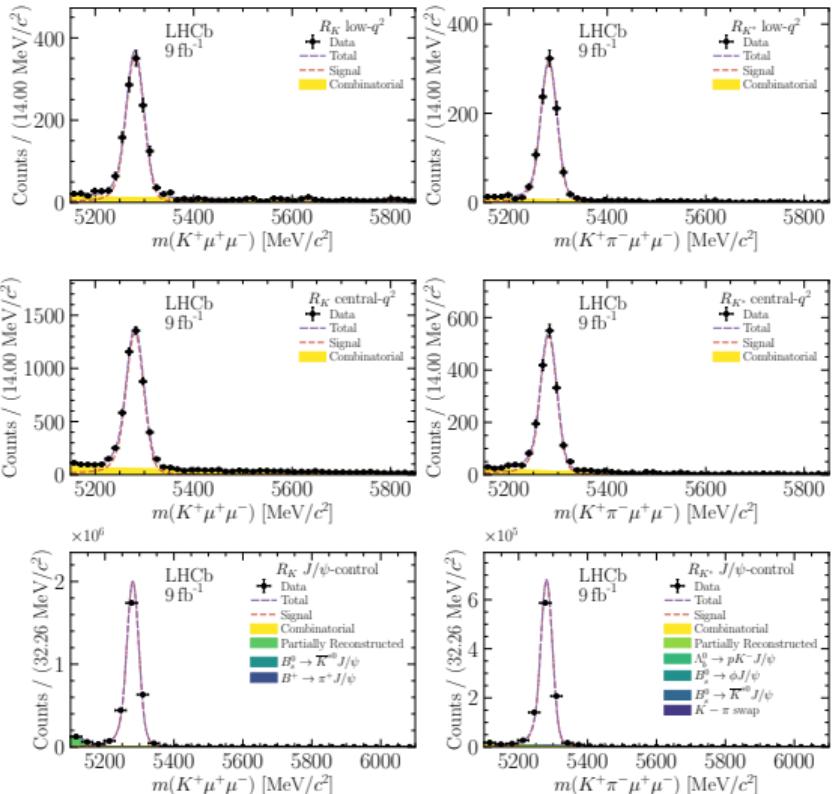
- ▶ Double ratio of branching fractions
 - Measured like R_X
 - Same cancellation of systematics
 - ⇒ “Rehearsal” of R_X
- ▶ $R_{\psi(2S)}$ compatible with unity



$R_{\psi(2S)}^K$

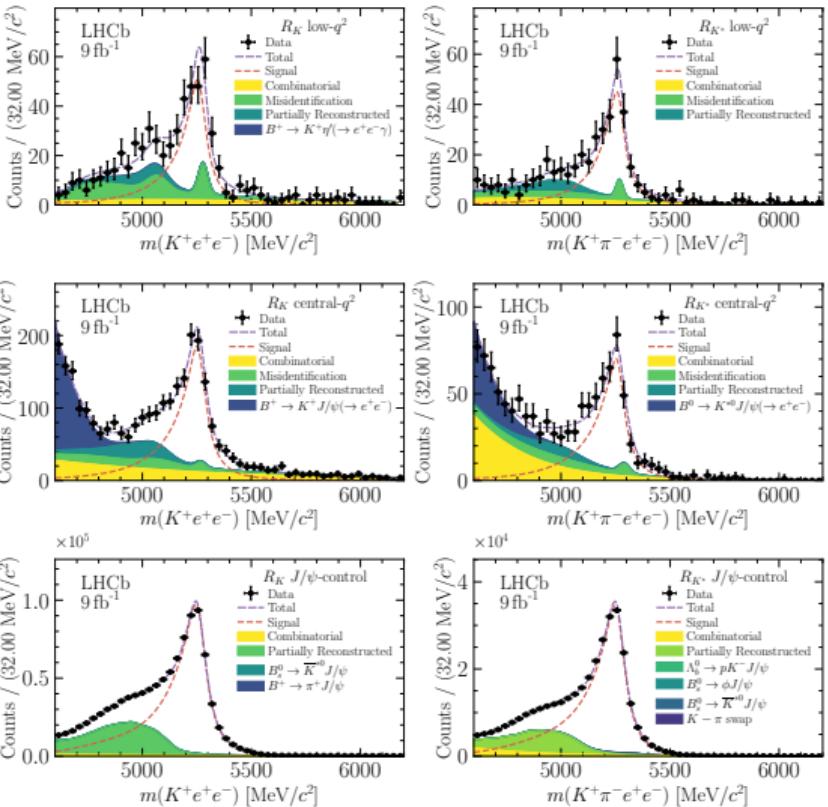
[LHCb-Paper 2022 045]

- ▶ Very clean muon final states
- ▶ Branching fraction compatible with previous measurement
- ▶ Electron mode more challenging
- ▶ Part. reco. $B^0 \rightarrow K^{*0} e^+ e^-$ constrained in $B^+ \rightarrow K^+ e^+ e^-$
- ▶ Bremstrahlungs tails from $B_q \rightarrow X_s J/\psi$ constrained in central- q^2 region



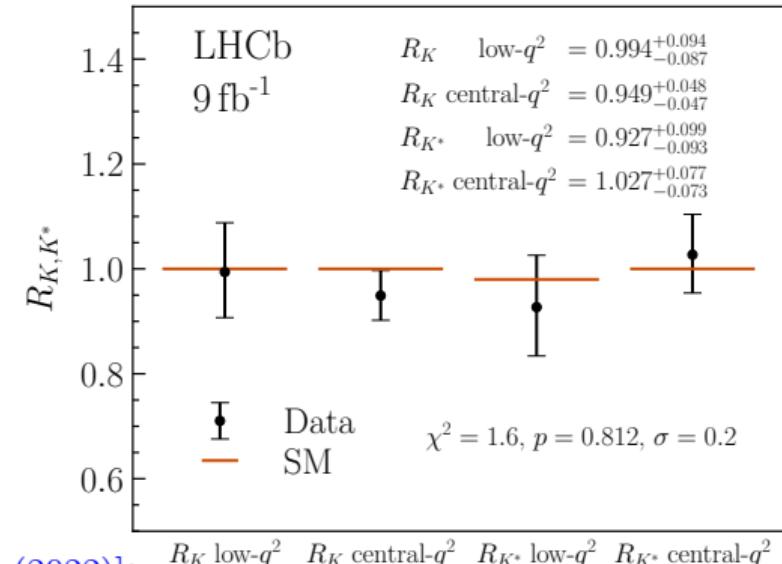
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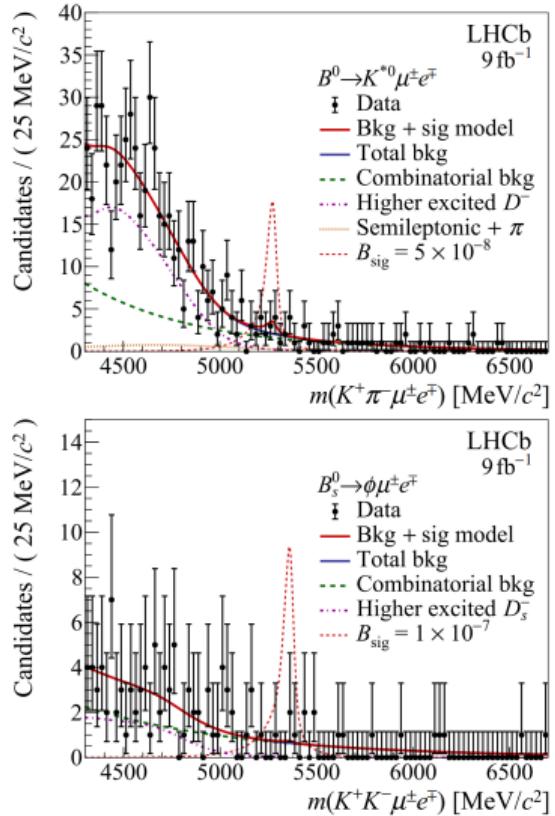
[LHCb-Paper 2022 045]

- ▶ **Most precise test of LFU in $b \rightarrow s\ell^+\ell^-$ transitions**
- ▶ **Supersedes previous result** and marks final result on R_K and $R_{K^{*0}}$ with Run 1 and Run 2 data
- ▶ **Compatible with SM prediction** at 0.2σ level
- ▶ **Statistical uncertainties dominate**
- ▶ Leading systematic from mis-identified backgrounds
- ▶ Shift with respect to [Nat. Phys. 18, 277–282 (2022)]:
 - Tighter PID working point (+0.064)
 - Correctly accounting for mis-identified backgrounds in fit (+0.038)



[LHCb-Paper 2022 045]

- ▶ LFU violation in most NP models tied to **existence of LFV decays**
- ▶ Here, parallel search for
 - $B^0 \rightarrow K^{*0}(K^+\pi^-)\mu^\pm e^\mp$
 - Split into $K^+\mu^+$ and $K^-\mu^-$ combinations
 - $B_s^0 \rightarrow \phi(K^+K^-)\mu^\pm e^\mp$
- ▶ **Trigger on muon** in final state
- ▶ **Tight selection** criteria against backgrounds
 - Tight particle identification requirements
 - Multivariate classifier + explicit vetoes
- ▶ **Limits** set using CL_s method



[LHCb-Paper 2022 008]

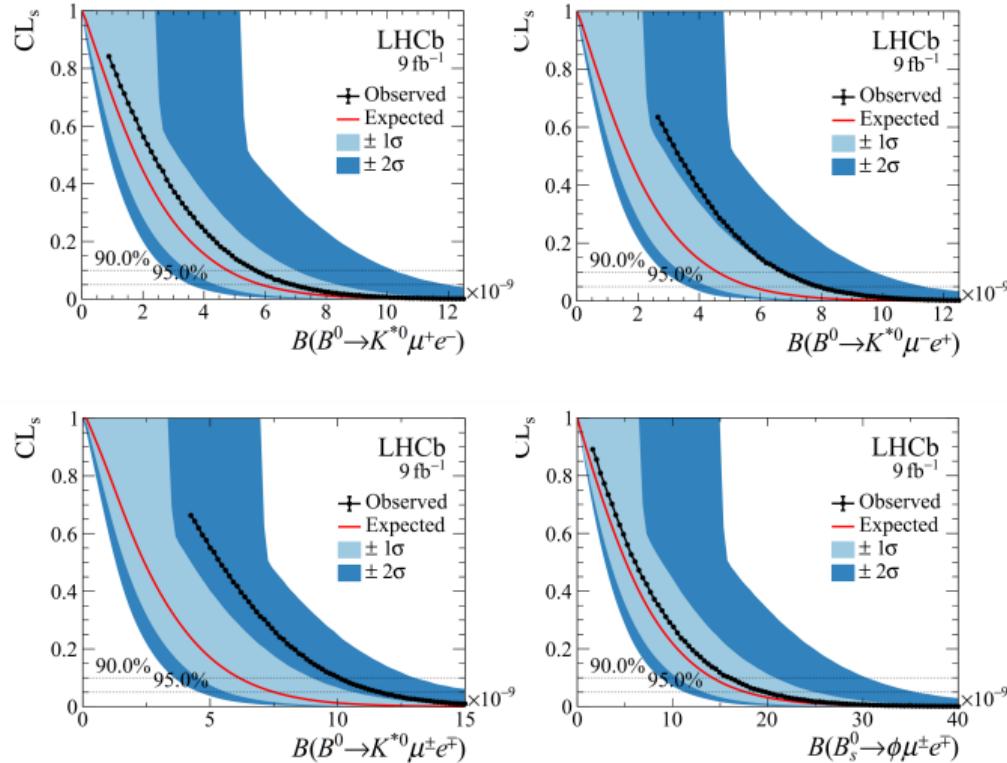
► No signal observed

Limits

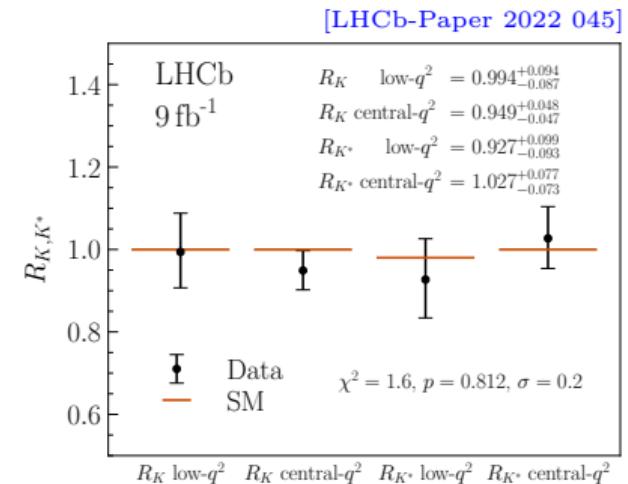
- Limits given at 90 % CL
- $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ e^-) < 5.7 \times 10^{-9}$
- $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^- e^+) < 6.7 \times 10^{-9}$
- $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^\pm e^\mp) < 9.9 \times 10^{-9}$
- $\mathcal{B}(B_s^0 \rightarrow \phi \mu^\pm e^\mp) < 16 \times 10^{-9}$

- Most stringent limits to date

[LHCb-Paper 2022 008]



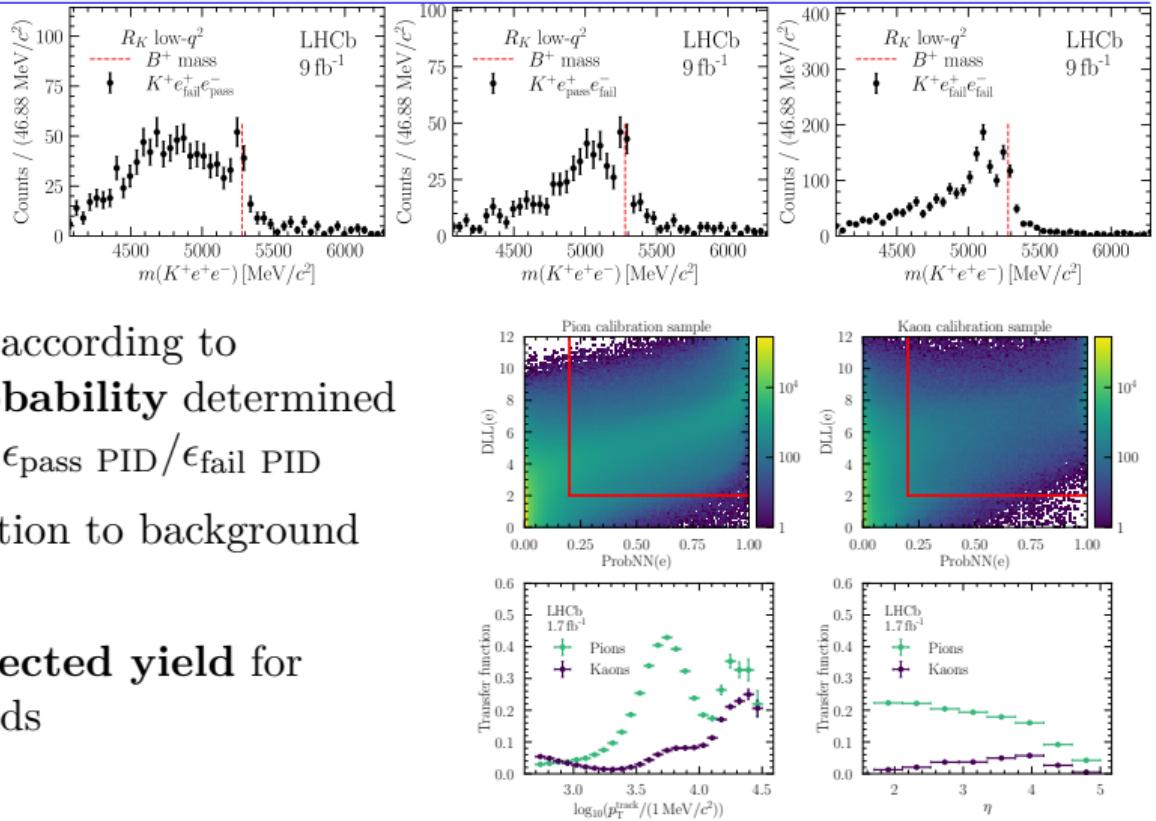
- ▶ $b \rightarrow s\ell^+\ell^-$ decays are a **potent laboratory** to test the SM
 - ▶ **LFU** ratios and searches for **LFV** decays are among the **cleanest probes** in $b \rightarrow s\ell^+\ell^-$
 - ▶ Data in **excellent agreement** with SM predictions
 - ▶ All measurements are **statistically dominated**
 - ▶ **Run 3** will increase sample size by approximately factor 5
- ⇒ Unrivaled precision and new possibilities in LFU and LFV observables
- ▶ Tensions in $b \rightarrow s\mu^+\mu^-$ remain, see [talk by Jake](#)





Photographer: Wolfgang Kaehler/Getty Images

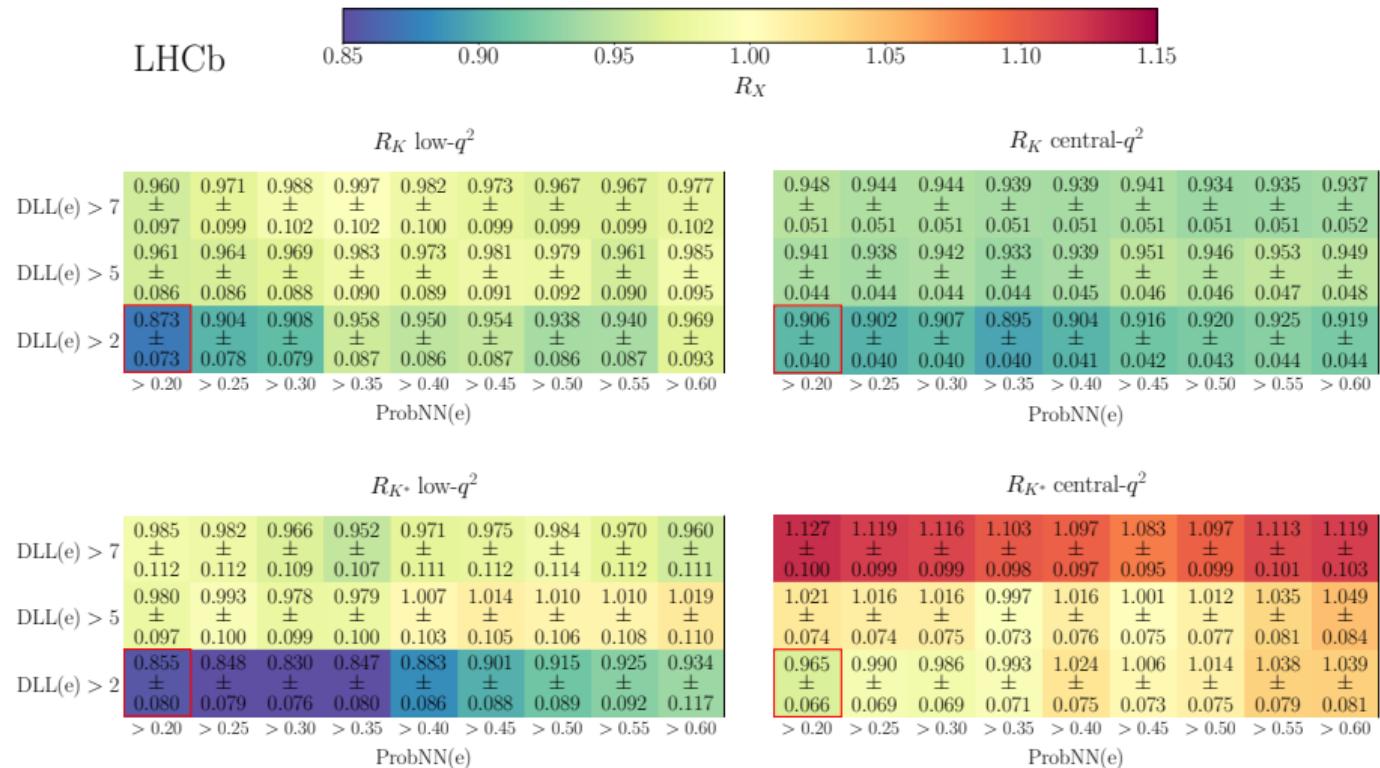
- ▶ Invert electron PID criteria to build background enriched sample
- ▶ Weigh background-data according to mis-identification probability determined on calibration data $w = \epsilon_{\text{pass}} \text{ PID} / \epsilon_{\text{fail}} \text{ PID}$
- ▶ Subtract signal contribution to background data
- ▶ Obtain shape and expected yield for mis-identified backgrounds



Source	low- q^2 R_K	central- q^2 R_K	low- q^2 $R_{K^{*}}$	central- q^2 $R_{K^{*}}$
Form factors	0.09	0.08	0.83	0.76
q^2 smearing	0.30	0.19	0.28	0.31
Particle identification	0.17	0.22	0.10	0.12
Kinematics and multiplicity	0.35	0.26	0.57	0.52
Trigger	0.27	0.16	0.26	0.13
Stability of $r_{J/\psi}^K$ and $r_{J/\psi}^{K^{*}}$	0.78	0.38	1.79	0.47
J/ψ fit model	0.35	0.35	0.40	0.40
Fixed fit parameters	0.14	0.07	0.25	0.16
Combinatorial shape	0.99	0.16	1.39	0.38
Specific backgrounds	0.24	0.20	1.24	0.51
Misidentified backgrounds	2.50	2.22	1.87	2.29
Modeling of m_{corr}	0.25	0.24	0.33	0.33
Total	2.86	2.33	3.73	2.52

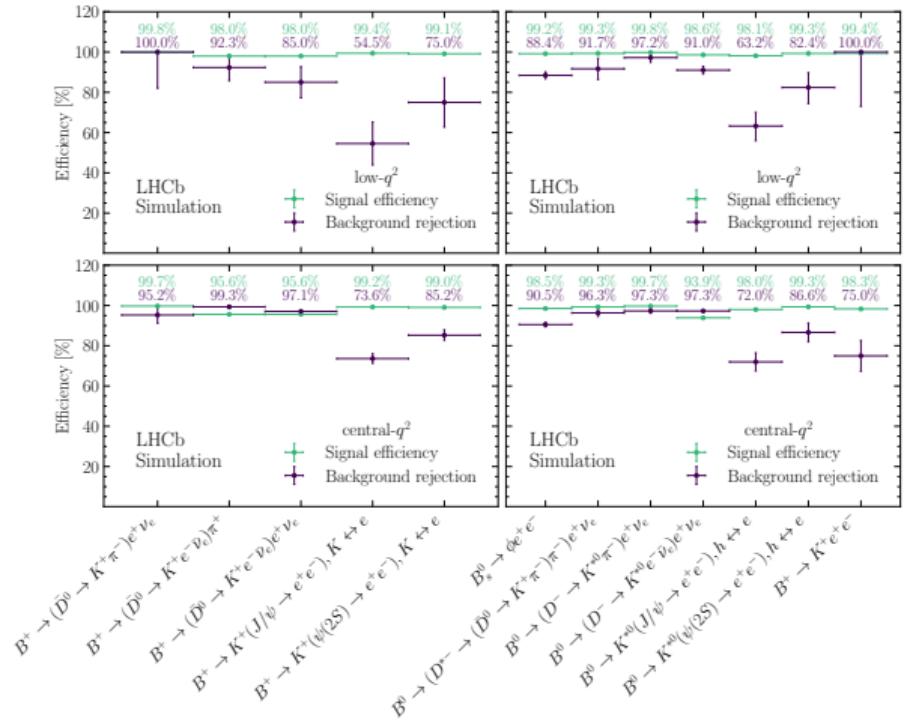
[LHCb-Paper 2022 045]

Stability versus PID Requirement

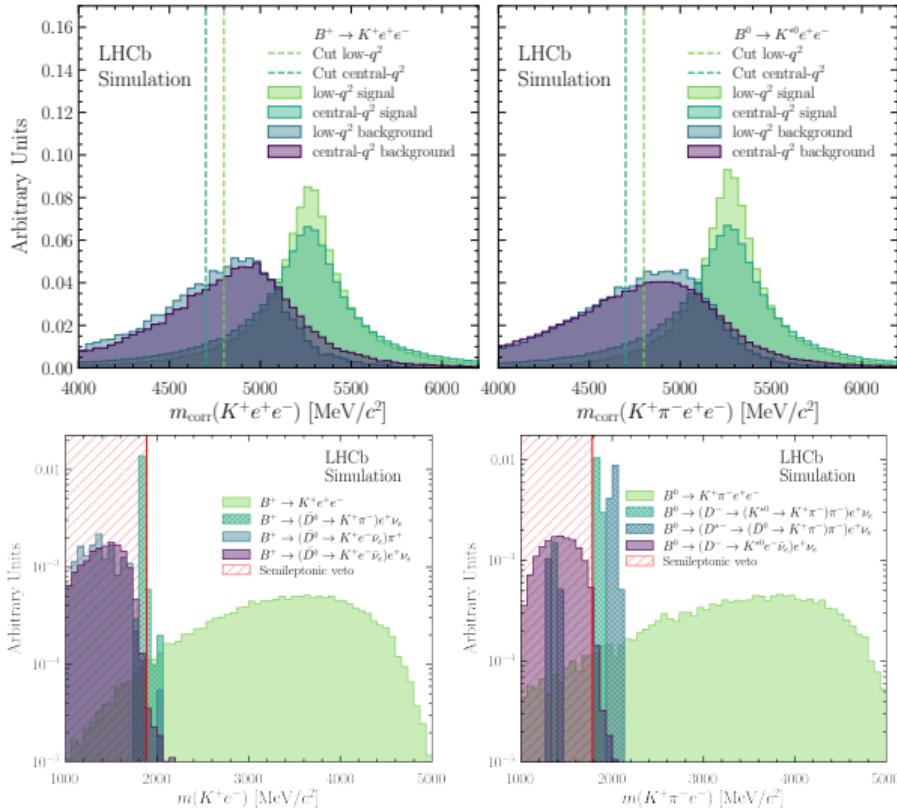


[LHCb-Paper 2022 045]

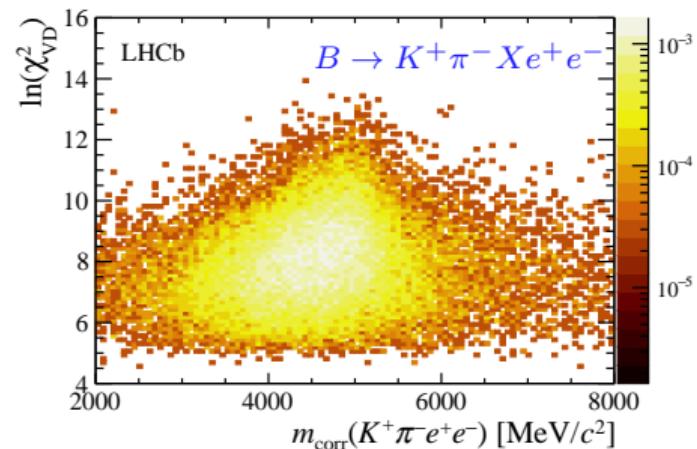
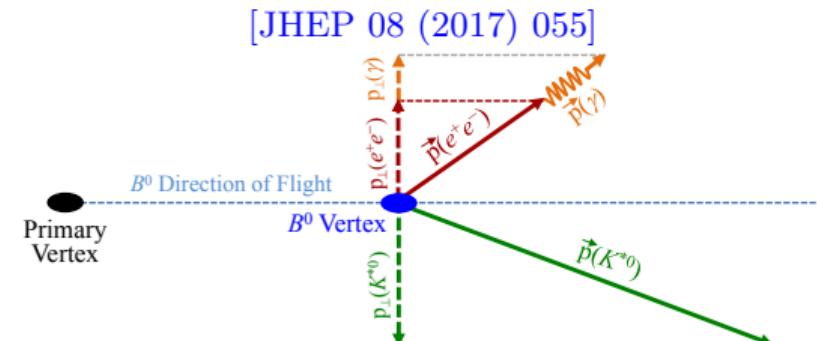
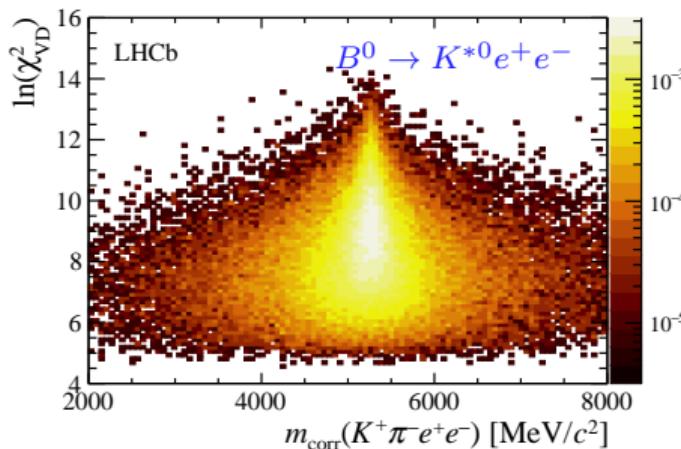
Background Veto



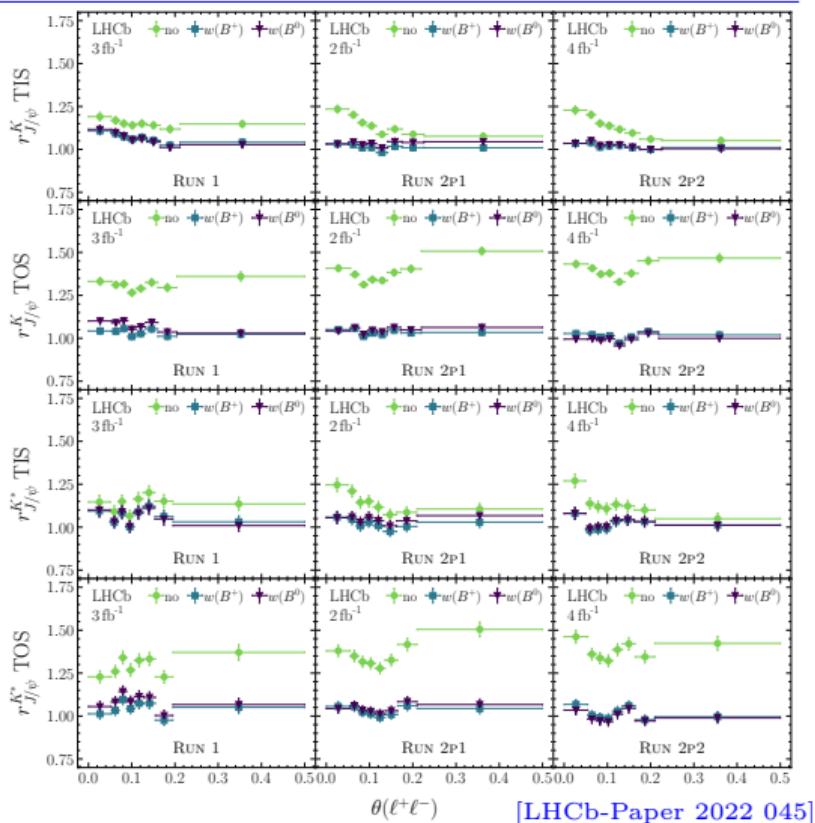
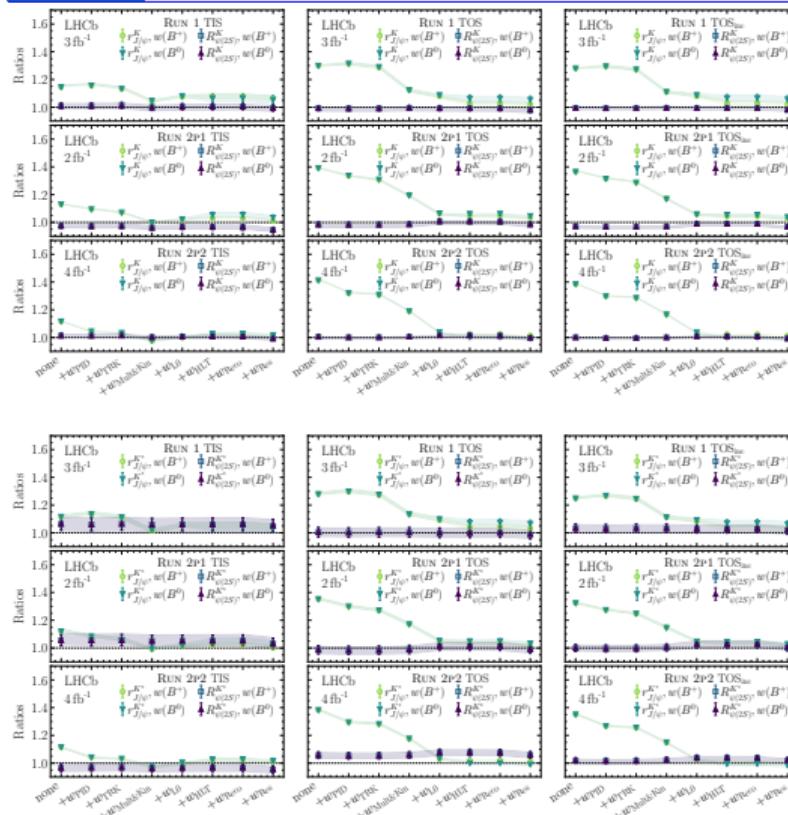
[LHCb-Paper 2022 045]

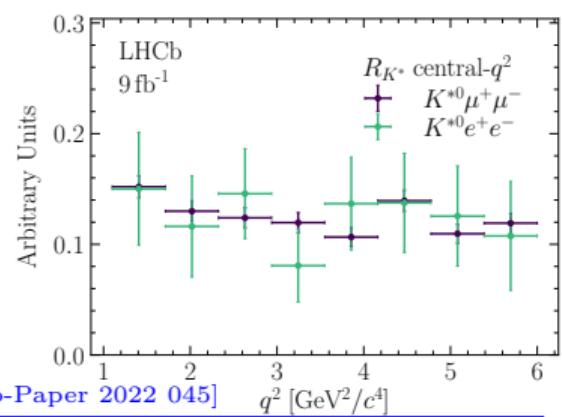
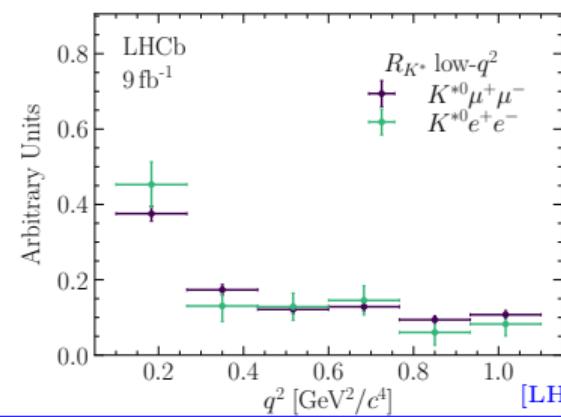
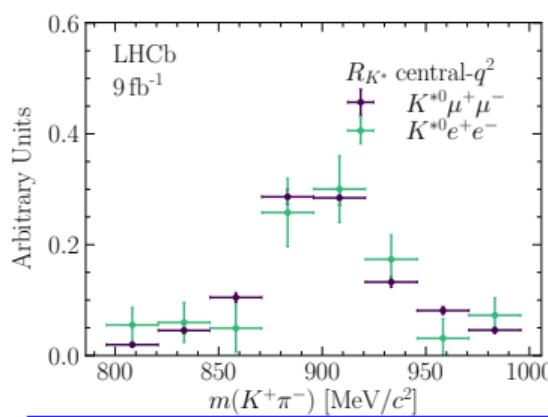
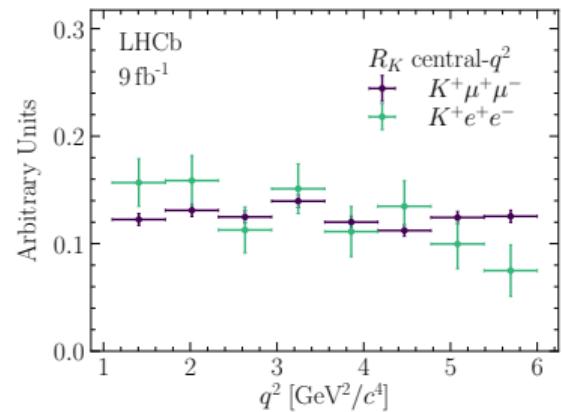
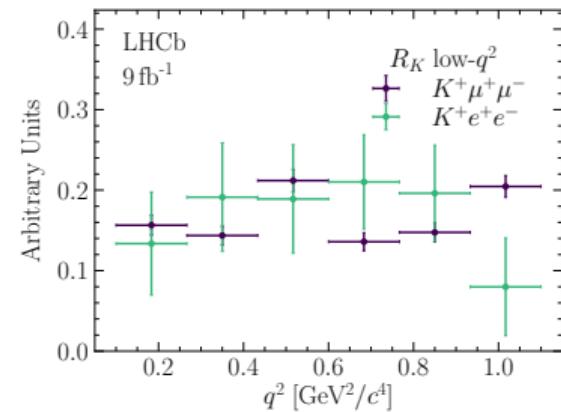
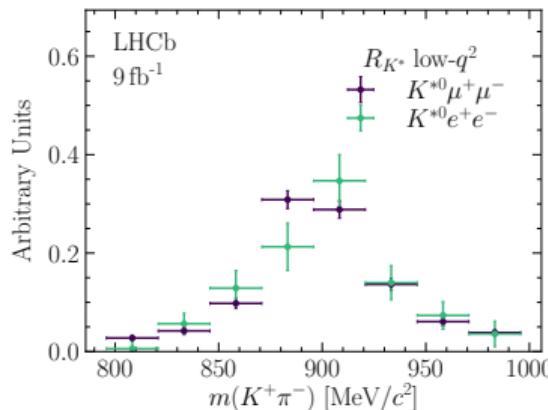


- Developed corrected mass m_{corr}
 - Missing energy evaluated from ratio of p_T
- $$\alpha = \frac{p_T(K^+\pi^-)}{p_T(e^+e^-)}$$
 and $p_{\text{corr}} = \alpha \cdot p_{e^+e^-}$
- Discriminant between part. reco. backgrounds and signal



$r_{J/\psi}$ Measurement



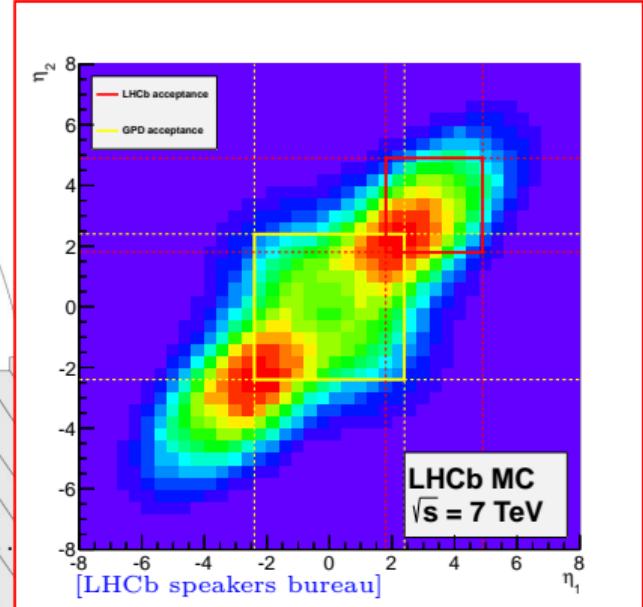
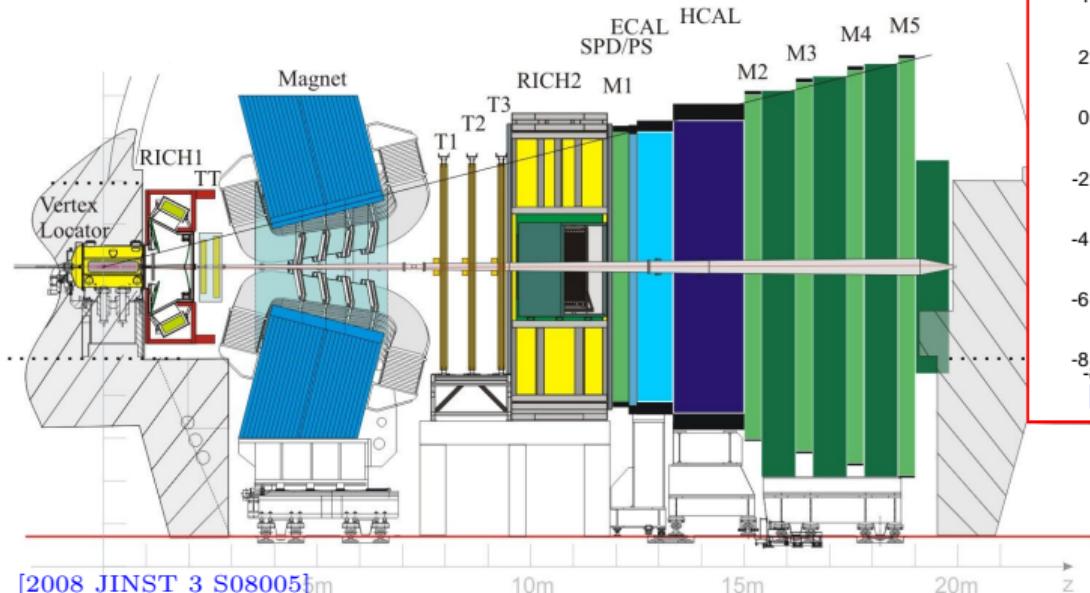


- ▶ **Expected** sensitivities on the planned measurements
- ▶ Uses Run 1 measurements or **muon branching fraction** to extrapolate

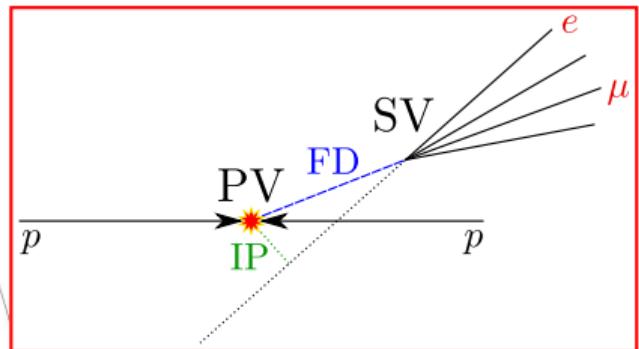
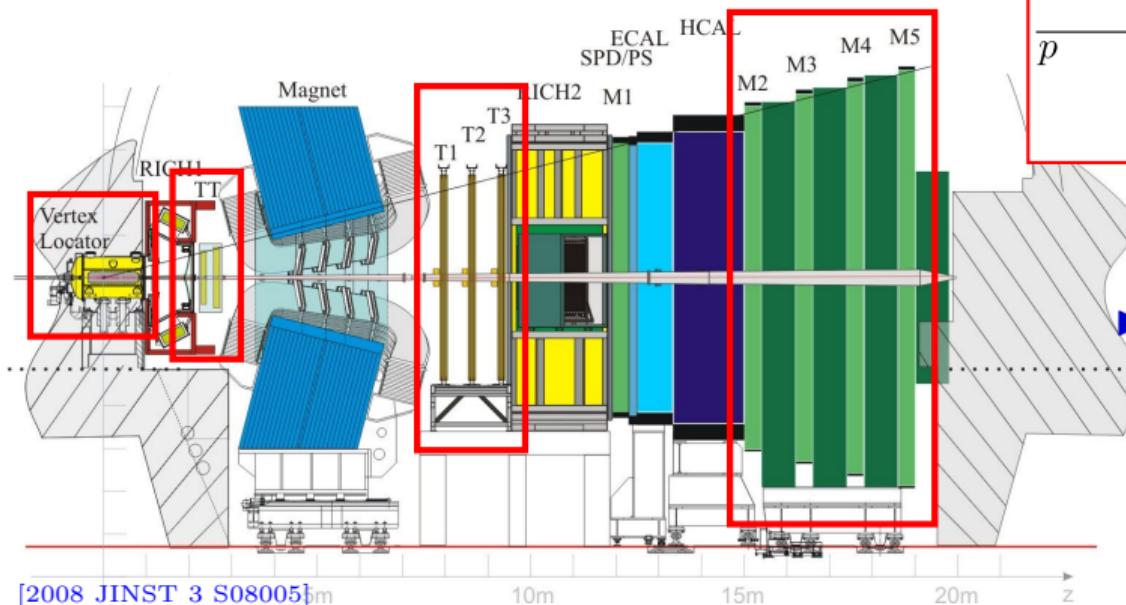
Table: Expected sensitivity on R_X with different dataset sizes, extrapolation from 2018 Physics Case [1808.08865].

R_X	9 fb^{-1}	50 fb^{-1}
R_K	0.043	0.017
$R_{K^{*0}}$	0.052	0.020
R_ϕ	0.130	0.050
R_{pK}	0.105	0.041
R_π	0.302	0.117

- ▶ Single arm **forward spectrometer**
- ▶ Coverage: $2 < \eta < 5$
- ▶ Designed for heavy **flavour physics**



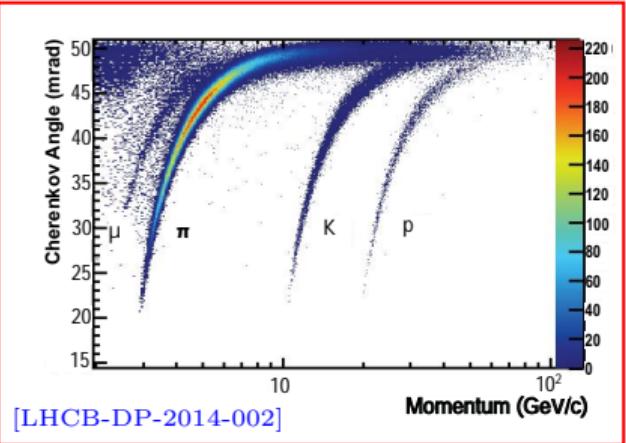
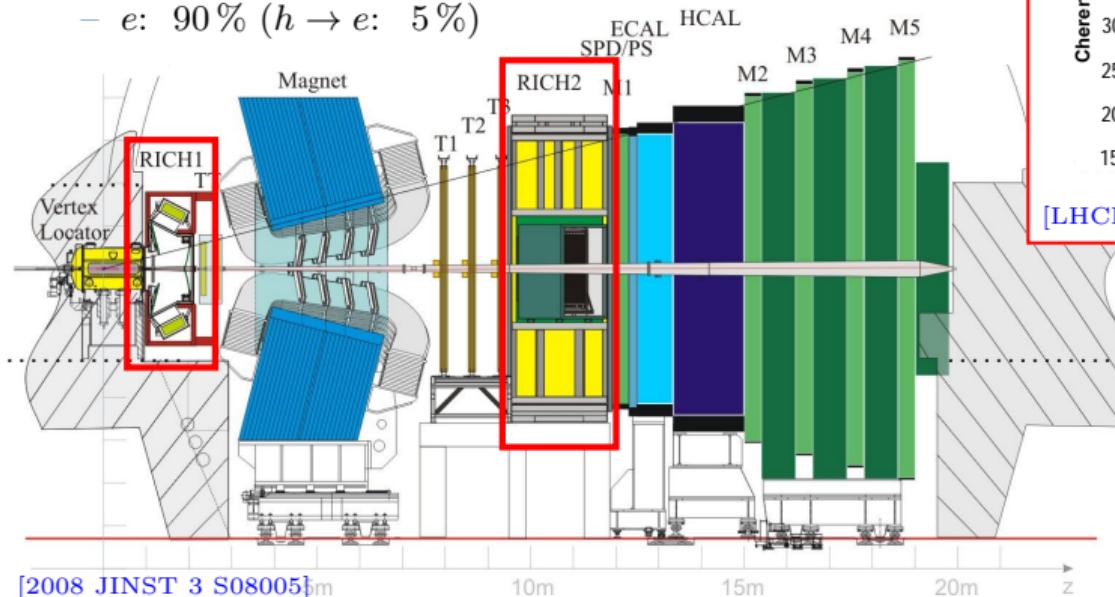
- ▶ B mesons are **longlived**, $\tau \approx \mathcal{O}(\text{ps})$
- ▶ Impact Parameter (**IP**) resolution:
 $(15 + 29/\text{p}_T[\text{GeV}])\mu\text{m}$



▶ **Momentum** resolution:
$$\frac{\Delta(p)}{p} \approx 0.5 - 1 \%$$

► PID key figures:

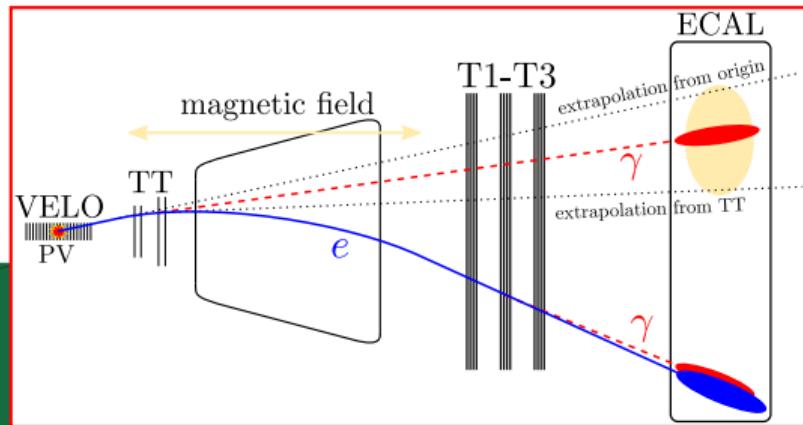
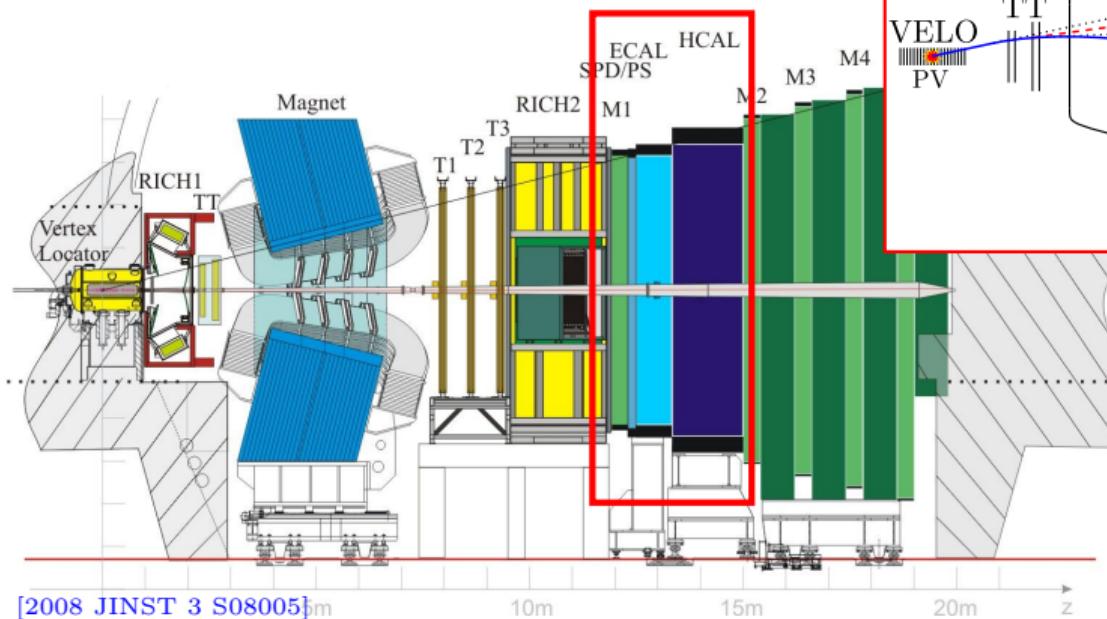
- μ : 97 % ($\pi \rightarrow \mu$: 1 – 3 %)
- K : 95 % ($\pi \rightarrow K$: 5 %)
- e : 90 % ($h \rightarrow e$: 5 %)



► Also important for PID:

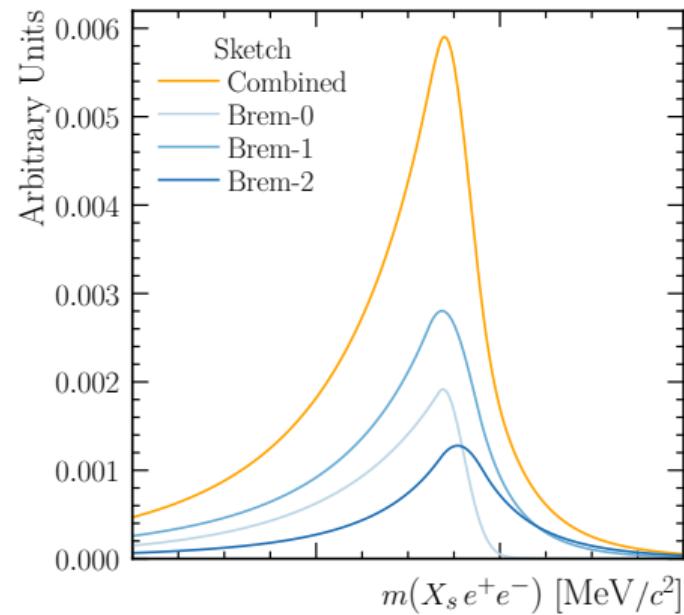
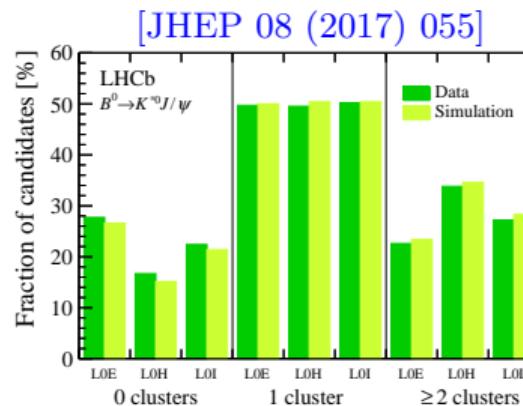
- Calorimetry
- Muon chambers

- ▶ ECAL resolution: $1\% + 10\%/\sqrt{E[\text{GeV}]}$
- ▶ Bremsstrahlung recovery for electrons:



- ▶ Extrapolate **search window**
 - From VeLo
 - From TT
- ▶ Add photons in search window

- ▶ Bremstrahlung categories based on **number of photons** added to electron candidates:
 - “Brem-0”: No γ added to either e
 - “Brem-1”: One γ added to one of the e
 - “Brem-2”: Two or more γ added to the e
- ▶ Brem. fractions well modelled in sim.
- ▶ Fit shapes are determined for each category



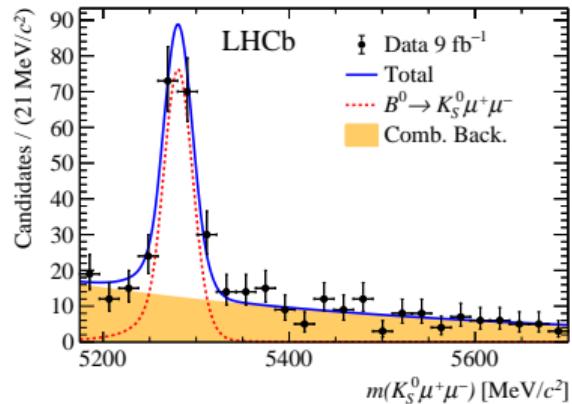
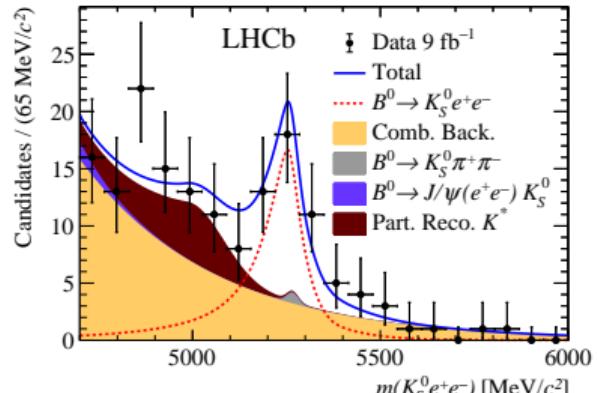
- Decay: $B^0 \rightarrow K_S^0 \ell^+ \ell^-$
- Measured in $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$
- Run 1 and 2016-18 dataset (9 fb^{-1})
- First observation of $B^0 \rightarrow K_S^0 e^+ e^-$

Validation

- $r_{J/\psi}^{-1} = 0.977 \pm 0.008(\text{stat.}) \pm 0.027(\text{syst.})$
- $R_{\psi(2S)}^{-1} = 1.014 \pm 0.030(\text{stat.}) \pm 0.020(\text{syst.})$

Result

- $R_{K_S^0} = 0.66^{+0.20}_{-0.14} (\text{stat.})^{+0.02}_{-0.04} (\text{syst.})$
- Agreement with SM at 1.5σ level



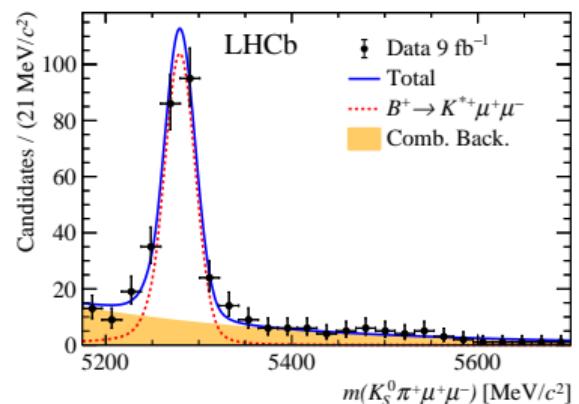
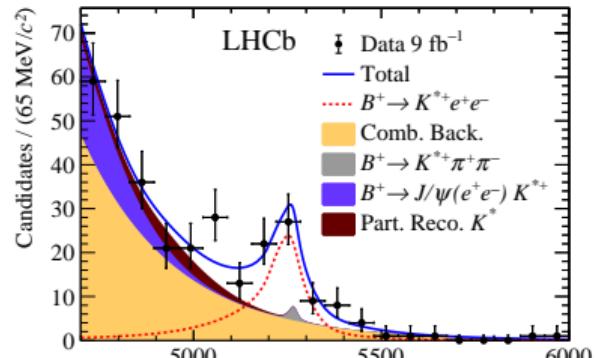
- Decay: $B^+ \rightarrow K^{*+} (K_S^0 \pi^+) \ell^+ \ell^-$
- Measured in $q^2 \in [0.045, 6.0] \text{ GeV}^2/c^4$
- Run 1 and 2016-18 dataset (9 fb^{-1})
- First observation of $B^+ \rightarrow K^{*+} (K_S^0 \pi^+) e^+ e^-$

Validation

- $r_{J/\psi}^{-1} = 0.965 \pm 0.011(\text{stat.}) \pm 0.032(\text{syst.})$
- $R_{\psi(2S)}^{-1} = 1.017 \pm 0.045(\text{stat.}) \pm 0.023(\text{syst.})$

Result

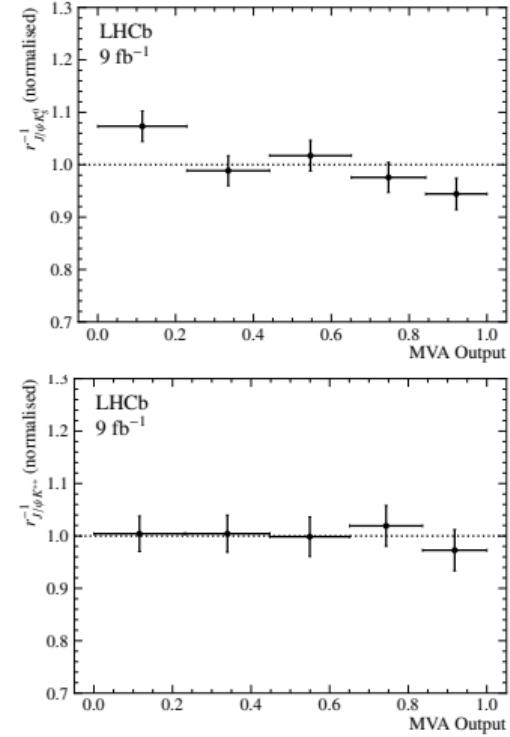
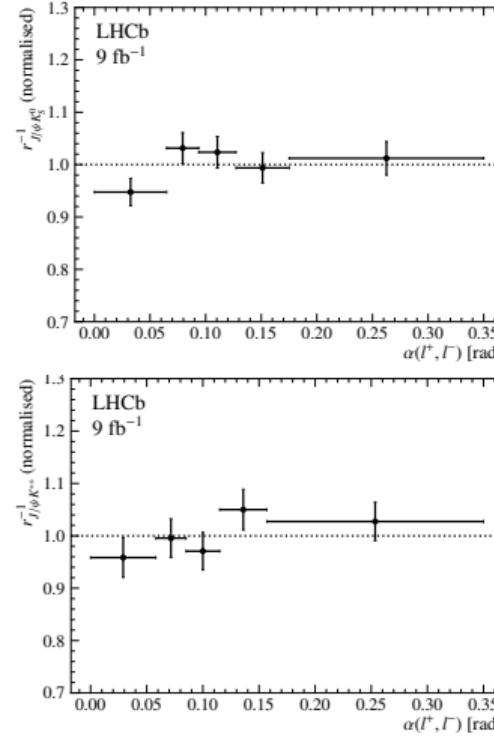
- $R_{K^{*+}} = 0.70^{+0.18}_{-0.13} (\text{stat.})^{+0.03}_{-0.04} (\text{syst.})$
- Agreement with SM at 1.4σ level



- Differential $r_{J/\psi}$ measurements [PRL 128, No. 19]:

- $B^0 \rightarrow K_S^0 J/\psi(\ell^+ \ell^-)$

- $B^+ \rightarrow K^{*+} (K_S^0 \pi^+) J/\psi(\ell^+ \ell^-)$



► Statistical Sources from measured yields:

- Performed unbinned extended maximum likelihood fit
- Dominated by uncertainty on $B^0 \rightarrow K_S^0 e^+ e^-$ / $B^+ \rightarrow K^{*+} (K_S^0 \pi^+) e^+ e^-$

Table: Yields $R_{K_S^0}$: [PRL 128, No. 19]

Decay Mode	Yield	
$B^0 \rightarrow K_S^0 e^+ e^-$	45	± 10
$B^0 \rightarrow K_S^0 \mu^+ \mu^-$	155	± 15
$B^0 \rightarrow K_S^0 J/\psi(e^+ e^-)$	21080	± 170
$B^0 \rightarrow K_S^0 J/\psi(\mu^+ \mu^-)$	118750	± 360

Table: Yields $R_{K^{*+}}$: [PRL 128, No. 19]

Decay Mode	Yield	
$B^+ \rightarrow K^{*+} (K_S^0 \pi^+) e^+ e^-$	67	± 13
$B^+ \rightarrow K^{*+} (K_S^0 \pi^+) \mu^+ \mu^-$	221	± 17
$B^+ \rightarrow K^{*+} (K_S^0 \pi^+) J/\psi(e^+ e^-)$	14330	± 170
$B^+ \rightarrow K^{*+} (K_S^0 \pi^+) J/\psi(\mu^+ \mu^-)$	75420	± 290

► Various systematic uncertainty sources studied [PRL 128, No. 19]:

- Simulation sample size ($\mathcal{O}(2 - 3\%)$)
- Fit model, shape determination ($\mathcal{O}(1 - 2\%)$)
- Simulation calibration ($\lesssim \mathcal{O}(1\%)$)
- Residual background contamination,
 $B^0 \rightarrow D^-(K_S^0 X) Y$, $B^+ \rightarrow \overline{D}^0 (K_S^0 \pi^+ X) Y$ ($\lesssim \mathcal{O}(1\%)$)

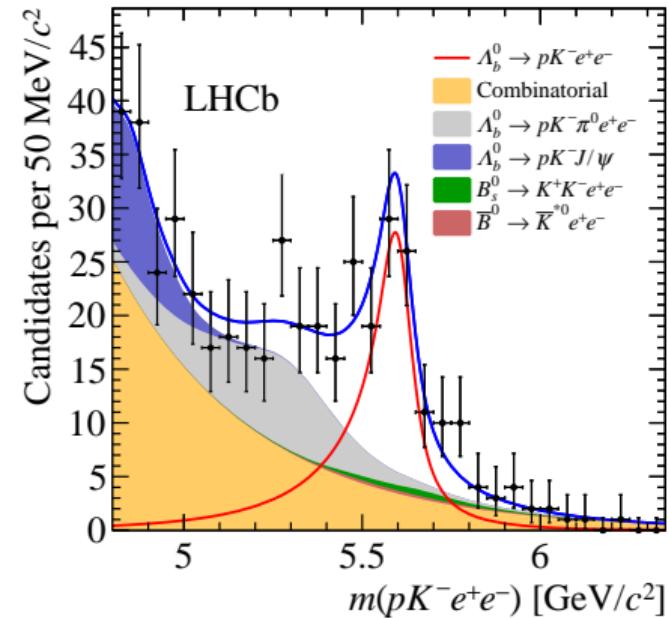
- Decay: $\Lambda_b \rightarrow pK^-\ell^+\ell^-$
- Measured in $q^2 \in [0.1, 6.0] \text{ GeV}^2/c^4$ and $m(pK^-) < 2600 \text{ MeV}/c^2$
- Run 1 and 2016 dataset (5 fb^{-1})
- Only LFU test using baryons so far

Validation

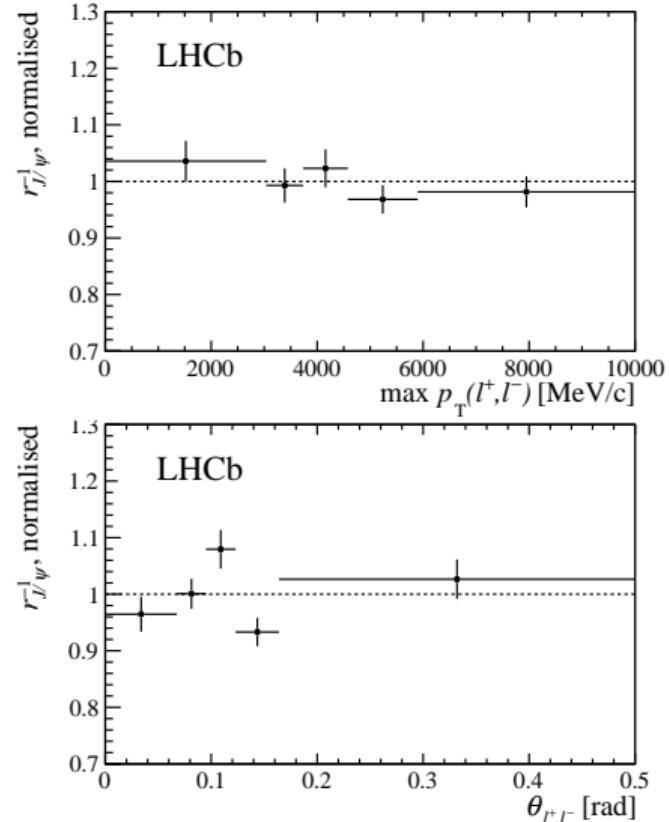
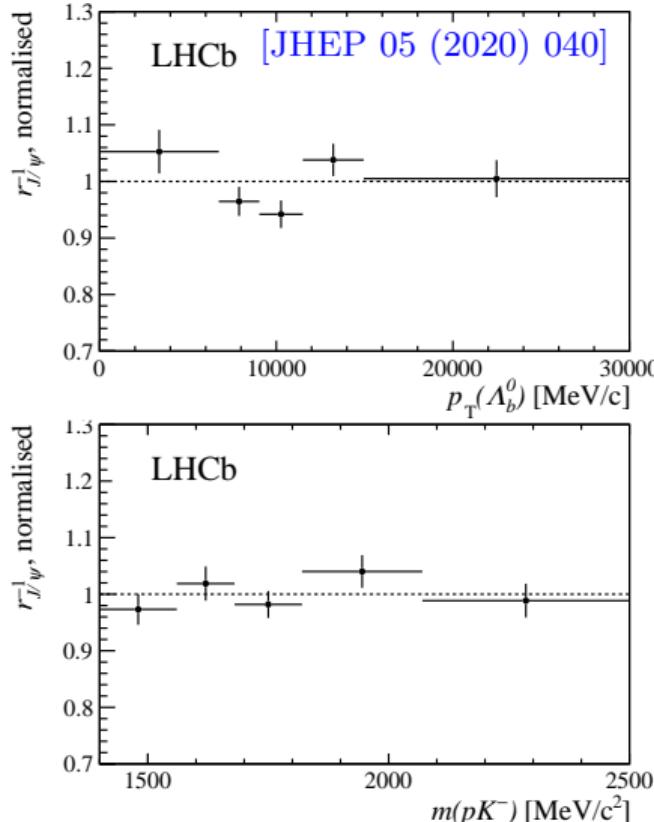
- $r_{J/\psi}^{-1} = 0.96 \pm 0.05$ (stat. \oplus syst.)
- $R_{\psi(2S)}$ compatible with unity within 1σ

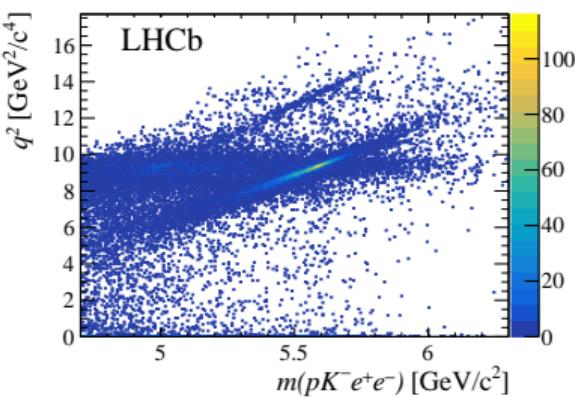
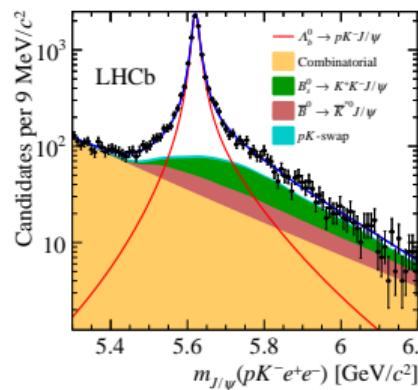
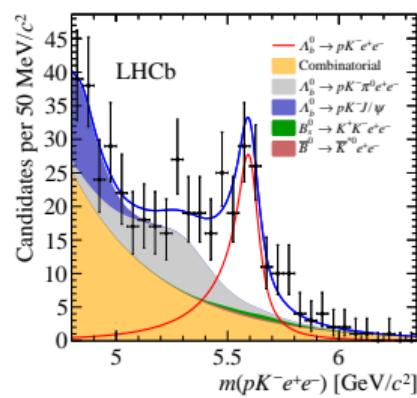
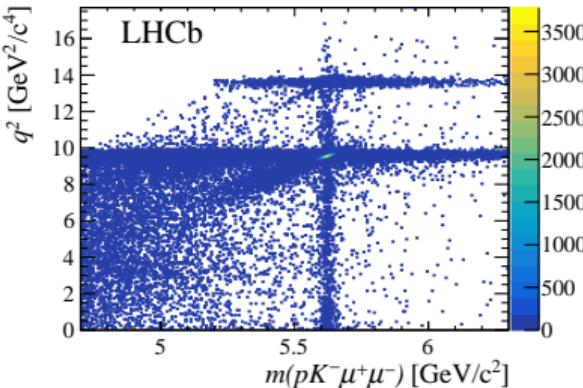
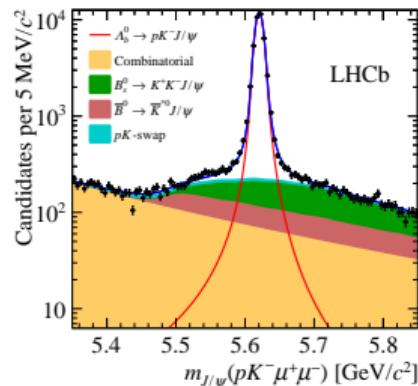
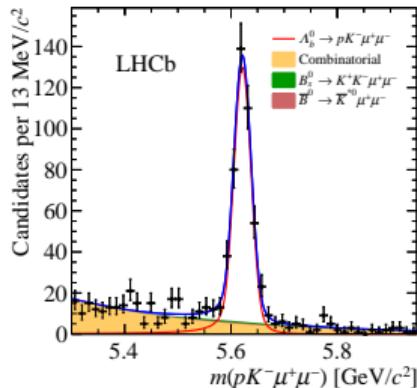
Result

- $R_{pK} = 0.86^{+0.14}_{-0.11}$ (stat.) ± 0.05 (syst.)
- Agreement with SM at $< 1\sigma$ level



R_{pK} Differential $r_{J/\psi}$ Measurement

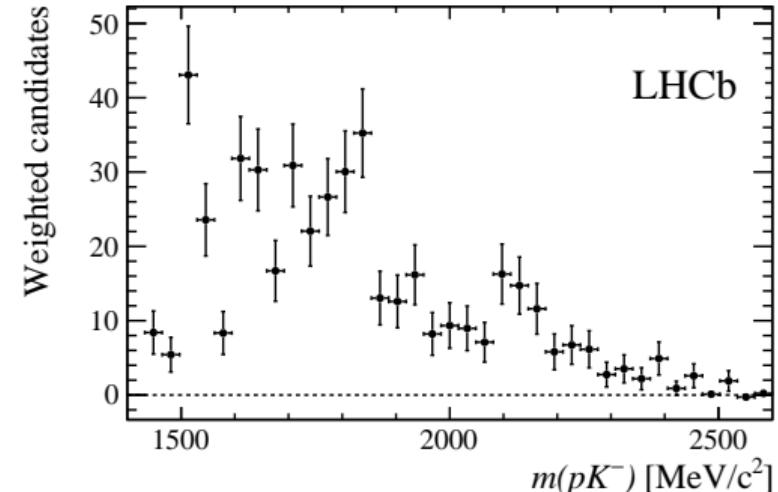
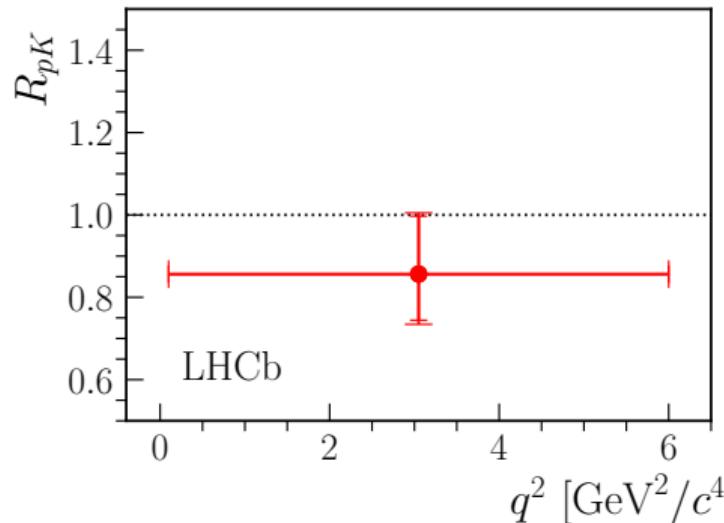




► Future opportunities:

[JHEP 05 (2020) 040]

- Dedicated analysis in **split q^2** regions
- Study the **rich $m(pK)$** spectrum

⇒ Easier **interpretability** of the result

► Statistical uncertainties from unbinned extended maximum likelihood fit:

- $N(\Lambda_b \rightarrow pK^- e^+ e^-) = 122 \pm 17$
- $N(\Lambda_b \rightarrow pK^- \mu^+ \mu^-) = 444 \pm 23$
- $N(\Lambda_b \rightarrow pK^- J/\psi(e^+ e^-)) = 10180 \pm 140$
- $N(\Lambda_b \rightarrow pK^- J/\psi(\mu^+ \mu^-)) = 40980 \pm 220$

► Systematic uncertainties (on R_{pK}^{-1}):

Source	Run 1 L0I	Run 1 L0E	Run 2 L0I	Run 2 L0E	Correlated
Decay model	–	–	–	–	1.9
Efficiency corrections	3.4	3.6	3.6	3.2	–
Normalisation modes	3.7	3.7	3.5	2.7	–
q^2 migration	–	–	–	–	2.0
m_{corr} cut efficiency	–	–	–	–	0.5
Fit model	–	–	–	–	5.2
Total uncorrelated	5.0	5.2	5.0	4.2	–
Total correlated	–	–	–	–	5.9