Lepton Flavour Universality tests in electroweak penguin decays at LHCb

ICHEP 2022

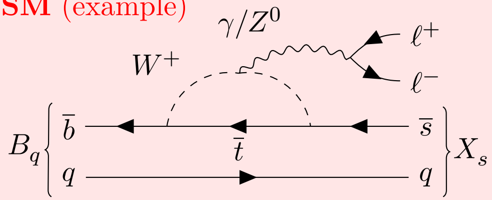
Sebastian Schmitt[1],
On behalf of the LHCb collaboration

[1]RWTH Aachen University

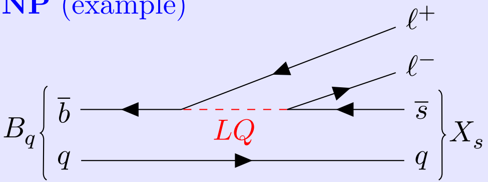
Bologna, July 9, 2022

- Electroweak Penguins (**EWP**) mediate rare $\boldsymbol{b \to s\ell^+\ell^-}$ transitions
- Strongly **suppressed** in the Standard Model of Particle Physics (**SM**)
- New Physics (NP) may have **significant contribution** to SM amplitudes
- Intriguing **tensions** w.r.t. the SM, e.g.:
  - **Angular analyses**, e.g. $B^0 \to K^{*0}\mu^+\mu^-$ decays [PRL 125 011802 (2020)]
  - **Branching fractions**, e.g. $B_s^0 \to \phi\mu^+\mu^-$ decays [PRL 127 151801 (2021)]
- **EWP decays at LHCb** by Sara Celani

SM (example)



NP (example)



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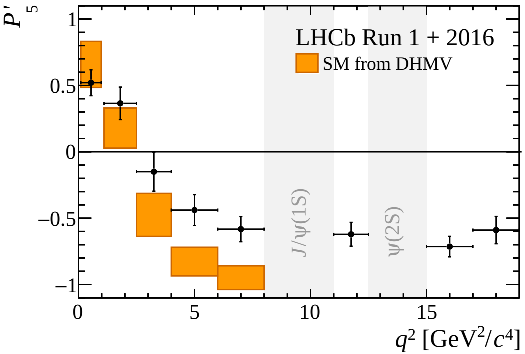

- With $q^2 = m(\ell^+\ell^-)^2$
- **But:** Discussion about **hadronic** uncertainties of SM prediction

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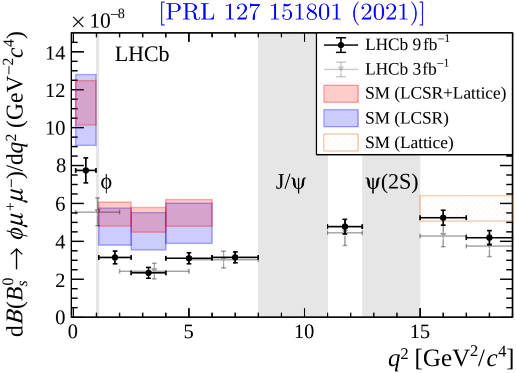


- With $\boldsymbol{q^2 = m(\ell^+\ell^-)^2}$
- **But:** Discussion about **hadronic** uncertainties of SM prediction

Flavour Universality Ratios

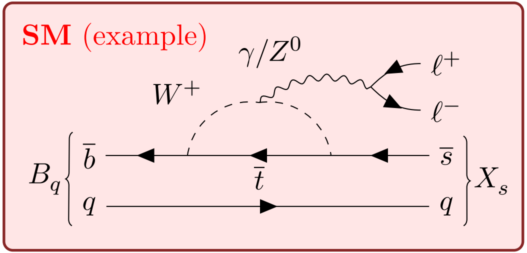
- SM is Lepton Flavour Universal (**LFU**)
- Test LFU in $b \to s\ell^+\ell^-$ transitions using:

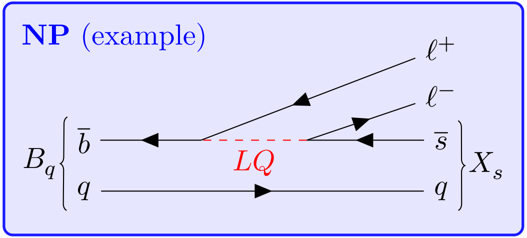
$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_q \to X_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_q \to X_s e^+e^-)}{dq^2} dq^2} = 1 \pm \mathcal{O}(1\,\%)^1$$

- With $q^2 = m(\ell^+\ell^-)^2$
- Hadronic **uncertainties** cancel in ratio

⇒ R_X can be **precisely** predicted in the SM

- Here X_s: K^+, K^0_S, K^{*+}, pK, K^{*0}



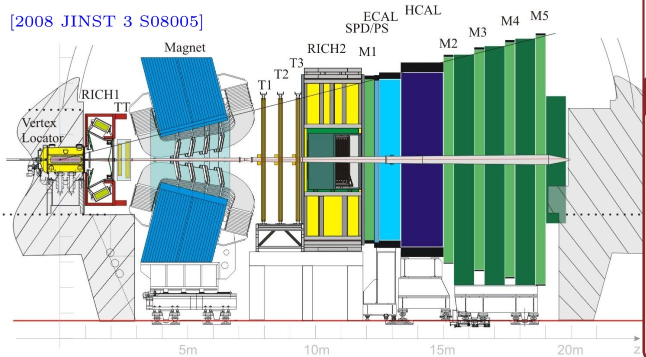


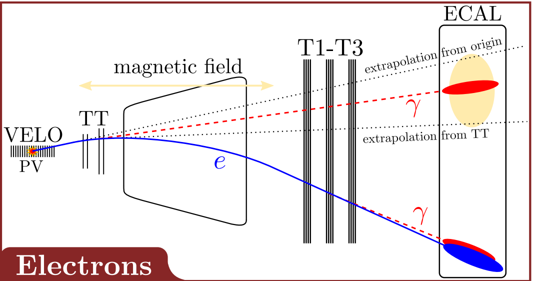
[1] [Eur. Phys. J. C 76, 440 (2016)]

Muons

- Low trigger thresholds (2012: $p_T \gtrsim 1.5\,\text{GeV}/c$)
- Good p-resolution and identification (ID)
  - $\mu \to \mu : 97\,\%$, $\pi \to \mu : 1 - 3\,\%$

[2008 JINST 3 S08005]





Electrons

- Higher trigger thresholds (2012: $E_T \gtrsim 3\,\text{GeV}$)
- Bremsstrahlung emission dilutes p-resolution
- Recovery not 100 % efficient
- ID more challenging
  - $e \to e : 90\,\%$, $h \to e : 5\,\%$

LHCb Detector

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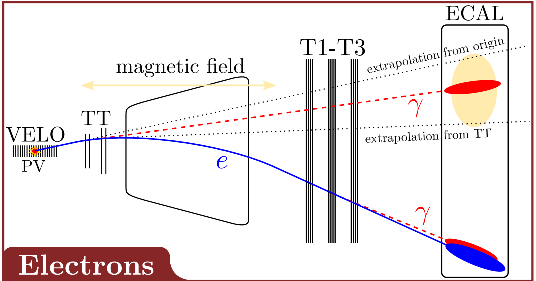
Trigger Strategy LFU

- Increase data sample size by triggering on
  - Electron in signal candidate
  - Hadron in signal candidate
  - Rest of event
- Using mutually **exclusive** combination
- Separate treatment of trigger and bremstrahlung categories when needed



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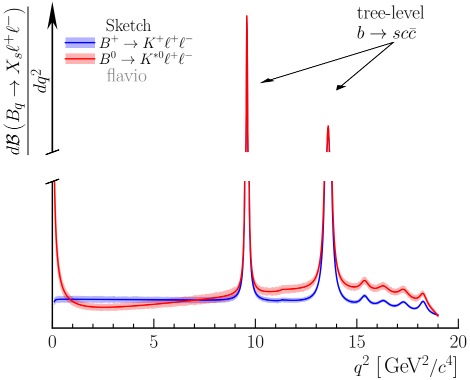
Analysis Strategy

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

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

  - Large **majority** of **systematic** uncertainties **cancel** to first order
  - **LFU** in $J/\psi \to \ell^+\ell^-$ decays established at ‰ level [PDG]
- **Blind** analysis minimises experimenters bias
- Ratio experimentally determined using: **yields** and **efficiencies**
  - Luminosities, cross-sections, etc cancel
  - Calibrate efficiencies using **control data**
- **Validate** procedure using resonant decays $B_q \to X_s J/\psi(\ell^+\ell^-)$ and $B_q \to X_s \psi(2S)(\ell^+\ell^-)$



Analysis Validation

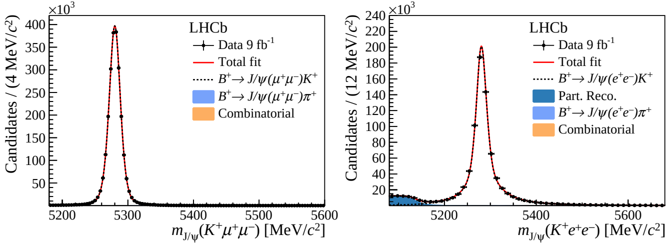
- Validation using ratio of resonant branching fractions:

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

$r_{J/\psi}$

- **Single ratio** of branching fractions
  - Probe electrons directly versus muons
  - Limited cancellation of systematics
  - ⇒ **Stringent validation**
- $r_{J/\psi} = 0.981 \pm 0.020$ (stat. $\oplus$ syst.)

Using R_K as example [Nat. Phys. 18, 277–282 (2022)]



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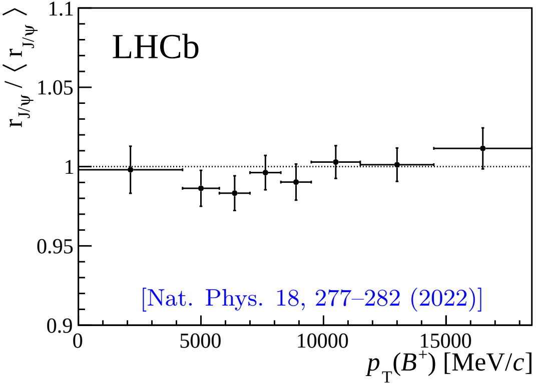
- $r_{J/\psi} = 0.981 \pm 0.020$ (stat. $\oplus$ syst.)
- Independent of kinematics



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$R_{\psi(2S)}$

- **Double ratio** of branching fractions
  - – Measured like R_X
  - – Same cancellation of systematics
  - $\Rightarrow$ "Rehearsal" of R_X
- $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat. $\oplus$ syst.)

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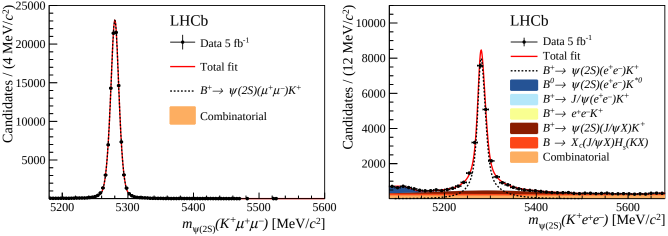


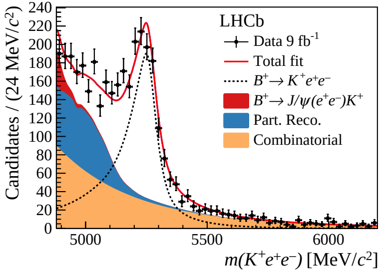
- Decay: $B^+ \to K^+\ell^+\ell^-$
- Measured in $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$
- Run 1 and Run 2 dataset ($9\,\mathrm{fb}^{-1}$)
- Most abundant LFU mode

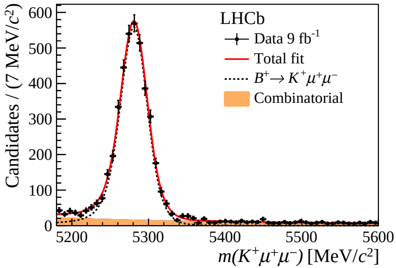
Validation

- $r_{J/\psi} = 0.981 \pm 0.020$ (stat. $\oplus$ syst.)
- $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat. $\oplus$ syst.)

Result

- $R_K = 0.846^{+0.042}_{-0.039}\,(\text{stat.})\,^{+0.013}_{-0.012}\,(\text{syst.})$
- Tension of $3.1\,\sigma$ with the SM





$R_{K^0_S}$ [PRL 128, No. 19]

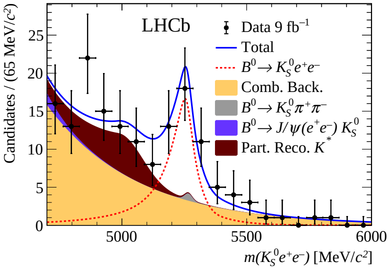
- Decay: $B^0 \to K^0_S \ell^+ \ell^-$
- Measured in $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$
- Run 1 and 2016-18 dataset ($9\,\mathrm{fb}^{-1}$)
- First observation of $B^0 \to K^0_S e^+ e^-$

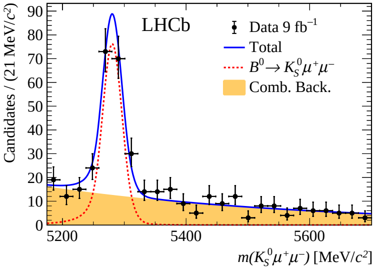
Validation

- $r^{-1}_{J/\psi} = 0.977 \pm 0.008(\mathrm{stat.}) \pm 0.027(\mathrm{syst.})$
- $R^{-1}_{\psi(2S)} = 1.014 \pm 0.030(\mathrm{stat.}) \pm 0.020(\mathrm{syst.})$

Result

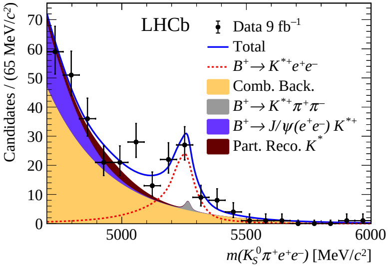
- $R_{K^0_S} = 0.66^{+0.20}_{-0.14}\,(\mathrm{stat.})\,^{+0.02}_{-0.04}\,(\mathrm{syst.})$
- Agreement with SM at $1.5\,\sigma$ level





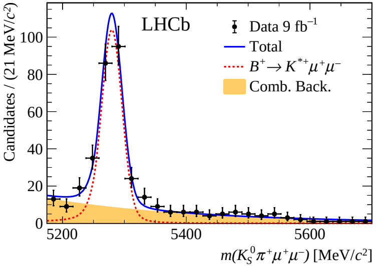
$R_{K^{*+}}$ [PRL 128, No. 19]

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



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 $1.4\,\sigma$ level

R_{pK} [JHEP 05 (2020) 040]

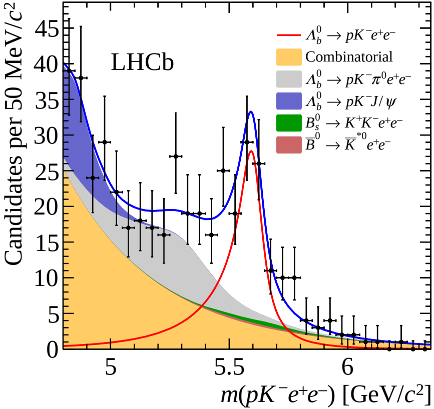
- Decay: $\Lambda_b \to pK^-\ell^+\ell^-$
- Measured in $q^2 \in [0.1, 6.0]\,\text{GeV}^2/c^4$ and $m(pK^-) < 2600\,\text{MeV}/c^2$
- Run 1 and 2016 dataset ($5\,\text{fb}^{-1}$)
- Only LFU test using baryons so far

Validation

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

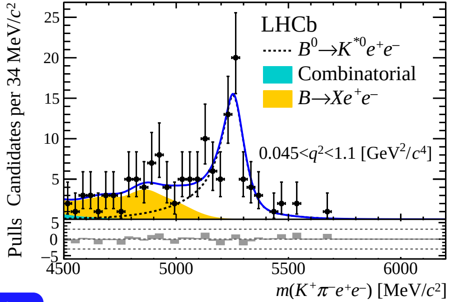
Result

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



$R_{K^{*0}}$ [JHEP 08 (2017) 055]

- Decay: $B^0 \to K^{*0}\ell^+\ell^-$
- Two separate q^2-regions:
  - "low"-q^2: $[0.045, 1.1]\,\mathrm{GeV}^2/c^4$
  - "central"-q^2: $[1.1, 6.0]\,\mathrm{GeV}^2/c^4$
- Run 1 dataset ($3\,\mathrm{fb}^{-1}$)
- Only dedicated analysis in low-q^2 so far



Validation

- $r_{J/\psi} = 1.043 \pm 0.006\,(\text{stat.}) \pm 0.045\,(\text{syst.})$
- $R_{\psi(2S)}$ compatible with unity within $1\,\sigma$

Results

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.}), \text{low} \\ 0.69^{+0.11}_{-0.07}(\text{stat.}) \pm 0.05(\text{syst.}), \text{central} \end{cases}$$

- Compatible with SM at 2.1 and $2.4\,\sigma$

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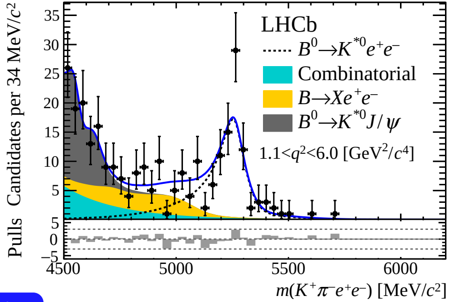

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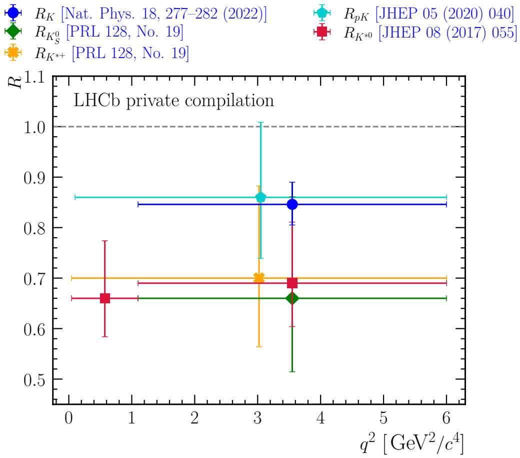
- Compatible with SM at 2.1 and $2.4\,\sigma$

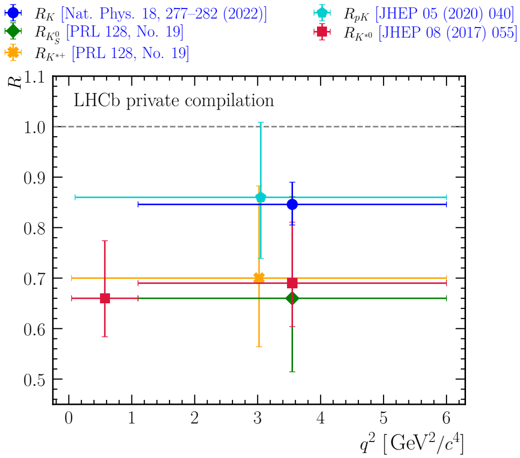
On the R_K and $R_{K^{*0}}$ Update

- Working on **unified analysis** of R_K and $R_{K^{*0}}$
- Will provide **final** Run 1 and Run 2 results
- Efforts lead to a deeper understanding of the LFU measurements
- This will be reflected in the results
- Work is **high priority** for the collaboration
- We appreciate your patience until the results become available



Summary of Results

- Brief rundown of the **LFU tests in $b \to s\ell^+\ell^-$-transitions** at LHCb
- Highlighted **key differences** of electrons at muons at LHCb
- Discussed analysis **strategy** and **validation**
- Intriguing tensions with the SM observed
- Measurements of $R_{K^{*0}}$, R_K, R_{pK}, R_ϕ, $R_{K\pi\pi}$, and more with full $9\,\mathrm{fb}^{-1}$ dataset ongoing




Photographer: Wolfgang Kaehler/Getty Images

Planned Future Measurements

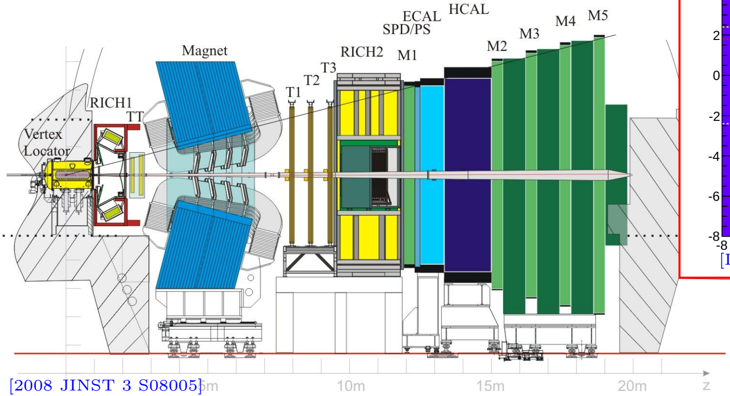
- **Expected** sensitivities on the planned measurements
- Uses Run 1 measurements or **muon branching fraction** to extrapolate

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

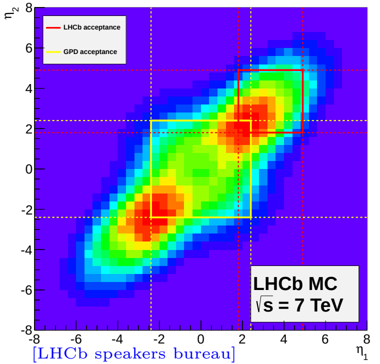
R_X	$9\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$
R_K	0.043	0.017
$R_{K^{*0}}$	0.052	0.020
R_ϕ	0.130	0.050
R_{pK}	0.105	0.041
R_π	0.302	0.117

LHCb Detector

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

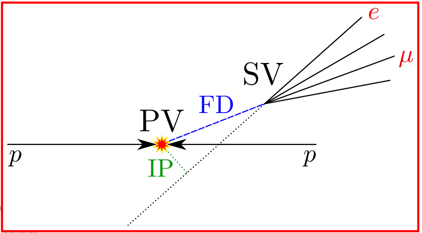


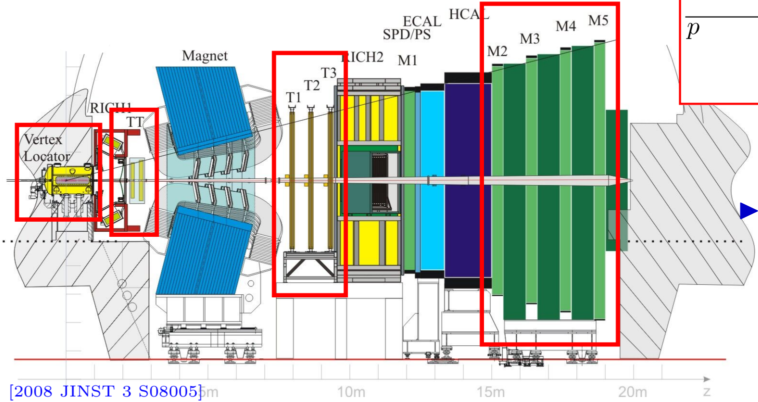
[2008 JINST 3 S08005]



[LHCb speakers bureau]

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

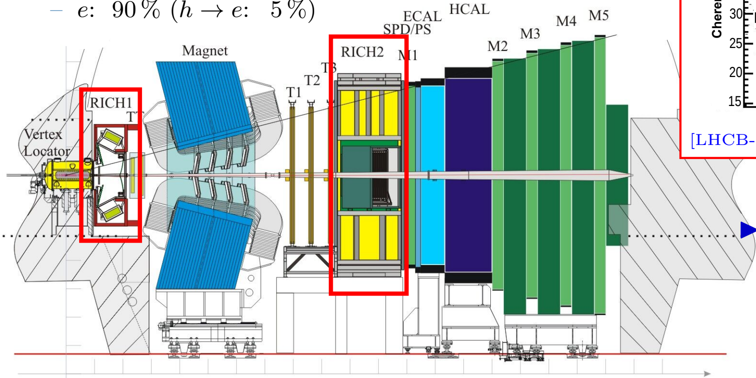




[2008 JINST 3 S08005]

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

- **PID key figures:**
  - μ: 97 % ($\pi \to \mu$: 1 – 3 %)
  - K: 95 % ($\pi \to K$: 5 %)
  - e: 90 % ($h \to e$: 5 %)



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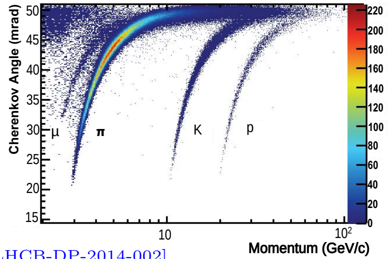
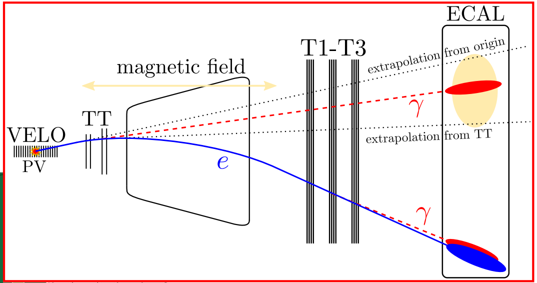
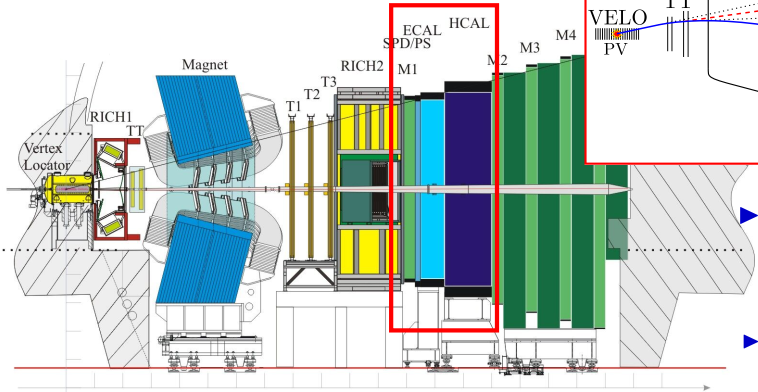


[LHCB-DP-2014-002]

- Also important for PID:
  - Calorimetry
  - Muon chambers

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





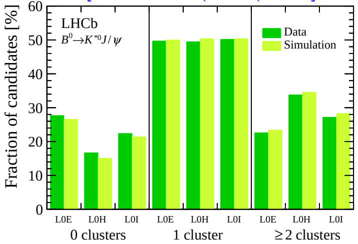
[2008 JINST 3 S08005]

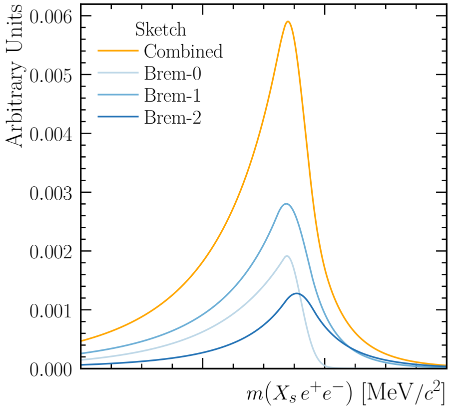
- Extrapolate **search window**
  - From VeLo
  - From TT
- Add photons in search window

Bremstrahlung Categories

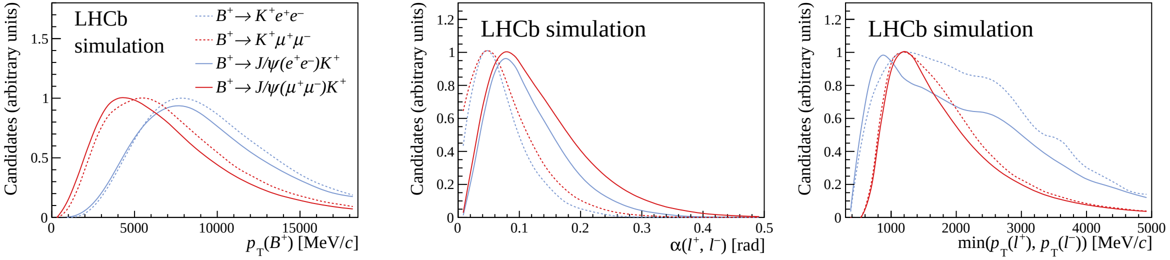
- **Bremstrahlung** categories based on **number of photons** added to electron candidates:
  - "Brem-0": No γ added to either e
  - "Brem-1": One γ added to one of the e
  - "Brem-2": Two or more γ added to the e
- Brem. fractions well modelled in sim.
- Fit shapes are determined for each category

[JHEP 08 (2017) 055]





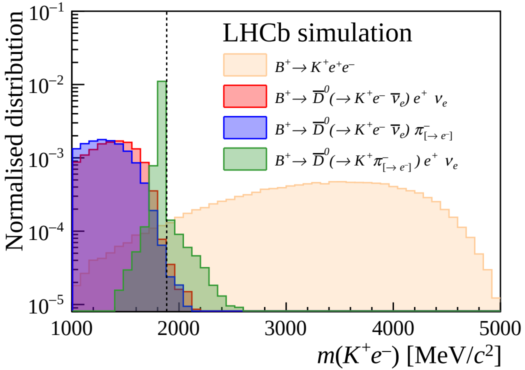
- Overlap of $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to K^+J/\psi\,(\ell^+\ell^-)$ samples:

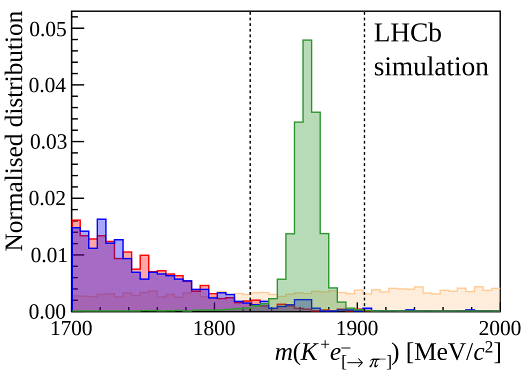


- [Nat. Phys. 18, 277–282 (2022)]

R_K Background Vetoes

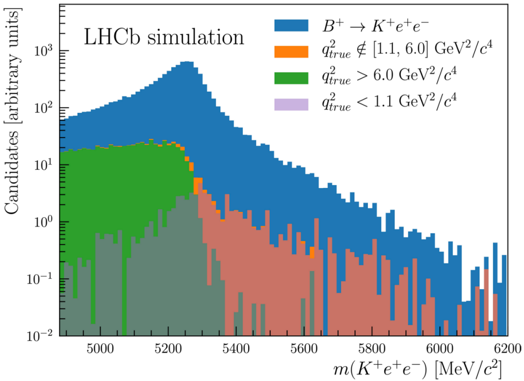
- Particle identification and **mass vetoes** against **physics backgrounds**
- **Boosted decision tree** (based on kinematics) against **combinatorial**
- [Nat. Phys. 18, 277–282 (2022)]



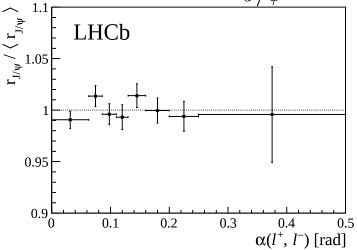


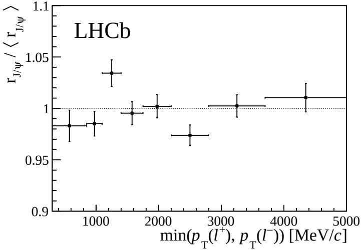
- Migration into and out of defined region: $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$
- Migration at $\mathcal{O}(10\,\%)$
- Studied on simulation and consequently taken into account

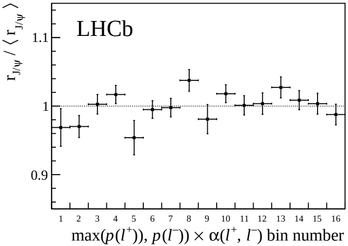
[Nat. Phys. 18, 277–282 (2022)]



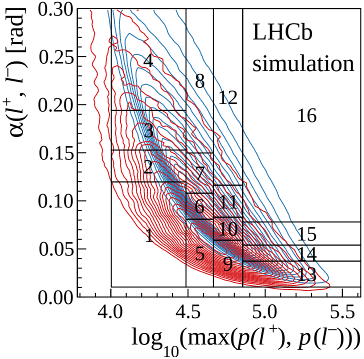
- Differential $r_{J/\psi}$ measurements, lepton kinematics:







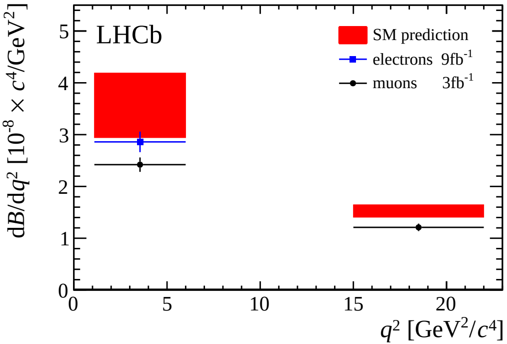
[Nat. Phys. 18, 277–282 (2022)]

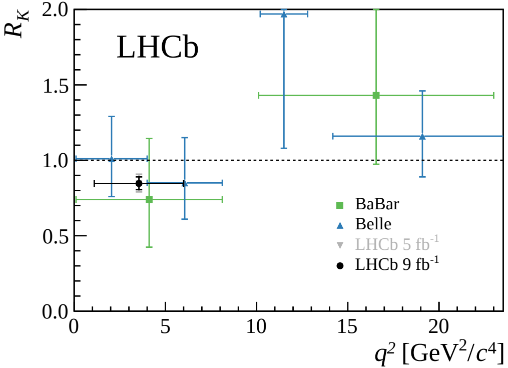


R_K Branching Fractions

- Updated $B^+ \to K^+ e^+ e^-$ branching fraction measurement
- Electrons are found compatible with the SM prediction

[Nat. Phys. 18, 277–282 (2022)]





R_K Uncertainties

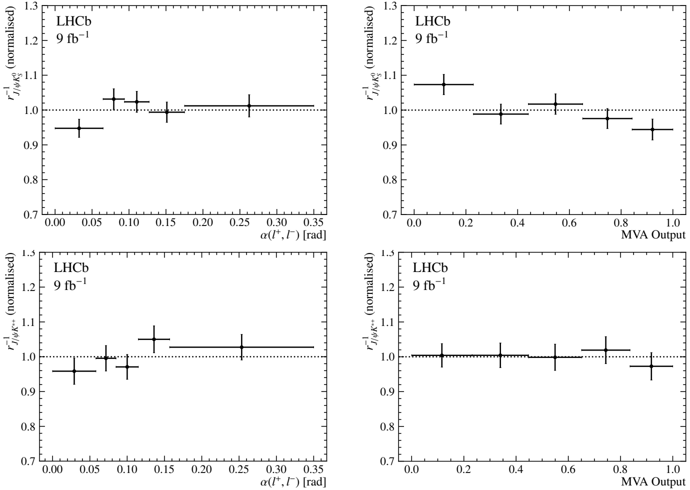
- **Statistical** sources from measured **yields** for $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to K^+ J/\psi\,(\ell^+\ell^-)$ processes:
  - Performed **unbinned extended maximum likelihood fit**
  - Dominated by $B^+ \to K^+e^+e^-$ yield

Table: Extended Data Table 2: [Nat. Phys. 18, 277–282 (2022)]

Decay Mode	Yield
$B^+ \to K^+e^+e^-$	1640 ± 70
$B^+ \to K^+\mu^+\mu^-$	3850 ± 70
$B^+ \to K^+ J/\psi\,(e^+e^-)$	743300 ± 900
$B^+ \to K^+ J/\psi\,(\mu^+\mu^-)$	2288500 ± 1500

- Various sources of **systematic** uncertainties [Nat. Phys. 18, 277–282 (2022)]:
  - Biggest studied sources:
  - **Fit model**, using alternative shapes for the model ($\mathcal{O}(1\,\%)$)
  - **Simulation calibration** sample size, taken into account using multivariate gaussian constraints in fit ($\mathcal{O}(1\,\%)$)

- Differential $r_{J/\psi}$ measurements [PRL 128, No. 19]:
- $B^0 \to K^0_S J/\psi(\ell^+\ell^-)$
- $B^+ \to K^{*+}\left(K^0_S\pi^+\right) J/\psi(\ell^+\ell^-)$



$R_{K^0_S}$ / $R_{K^{*+}}$ Uncertainties

- **Statistical** Sources from measured **yields**:
  - Performed **unbinned extended maximum likelihood fit**
  - Dominated by uncertainty on $B^0 \to K^0_S e^+ e^-$ / $B^+ \to K^{*+} (K^0_S \pi^+) e^+ e^-$

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

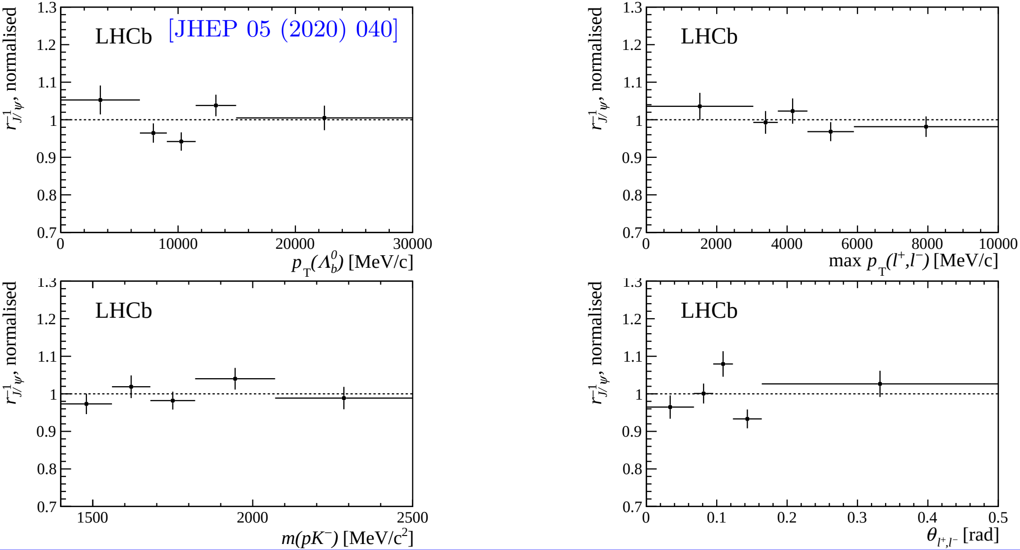
Decay Mode	Yield
$B^0 \to K^0_S e^+ e^-$	45 ± 10
$B^0 \to K^0_S \mu^+ \mu^-$	155 ± 15
$B^0 \to K^0_S J/\psi(e^+ e^-)$	21080 ± 170
$B^0 \to K^0_S J/\psi(\mu^+ \mu^-)$	118750 ± 360

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

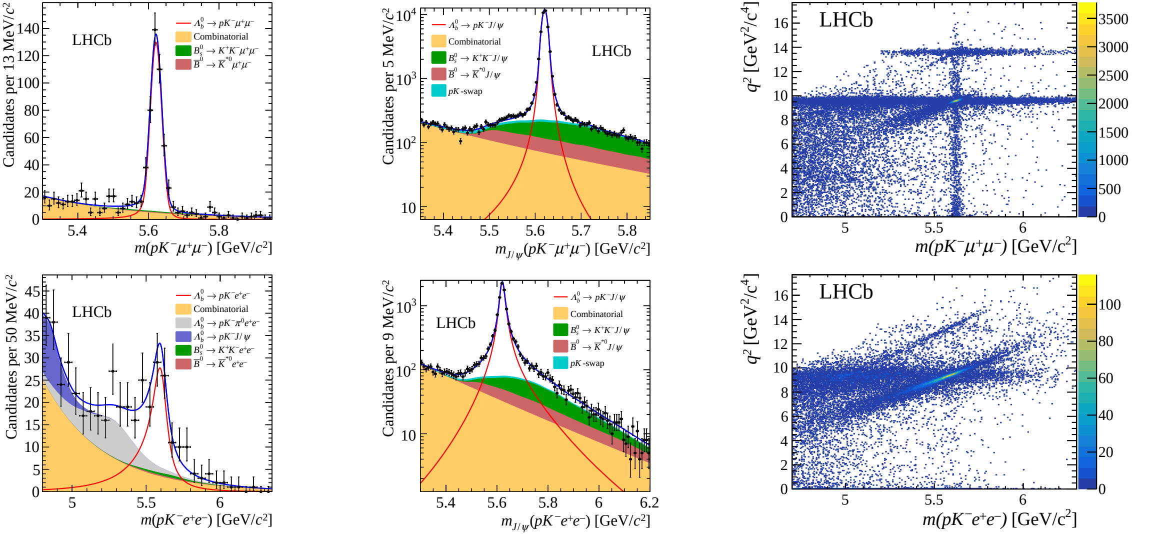
Decay Mode	Yield
$B^+ \to K^{*+} (K^0_S \pi^+) e^+ e^-$	67 ± 13
$B^+ \to K^{*+} (K^0_S \pi^+) \mu^+ \mu^-$	221 ± 17
$B^+ \to K^{*+} (K^0_S \pi^+) J/\psi(e^+ e^-)$	14330 ± 170
$B^+ \to K^{*+} (K^0_S \pi^+) J/\psi(\mu^+ \mu^-)$	75420 ± 290

- 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, $B^0 \to D^-(K^0_S X)Y$, $B^+ \to \overline{D}^0(K^0_S \pi^+ X)Y$ ($\lesssim \mathcal{O}(1\,\%)$)

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



R_{pK} Mass Fits [JHEP 05 (2020) 040]

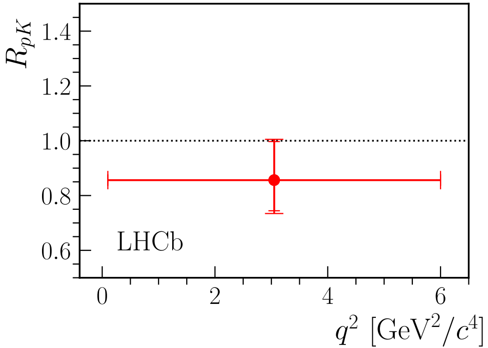


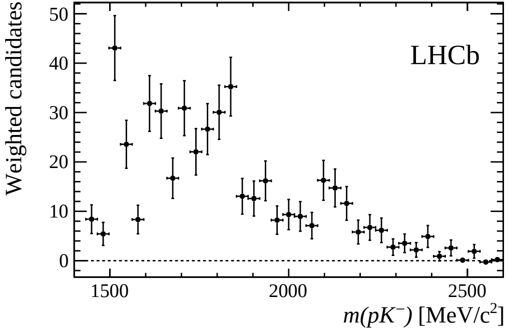
R_{pK} Future Opportunities

[JHEP 05 (2020) 040]

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

$\Rightarrow$ Easier **interpretability** of the result





R_{pK} Uncertainties [JHEP 05 (2020) 040]

- **Statistical** uncertainties from unbinned extended maximum likelihood fit:
  - $\mathrm{N}(\Lambda_b \to pK^- e^+ e^-) = 122 \pm 17$
  - $\mathrm{N}(\Lambda_b \to pK^- \mu^+ \mu^-) = 444 \pm 23$
  - $\mathrm{N}(\Lambda_b \to pK^- J/\psi(e^+ e^-)) = 10180 \pm 140$
  - $\mathrm{N}(\Lambda_b \to pK^- J/\psi(\mu^+ \mu^-)) = 40980 \pm 220$

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

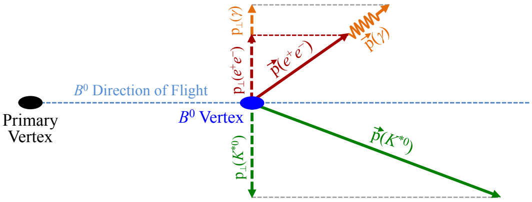
Source	Run 1 L0I	Run 1 L0E	Run 2 L0I	Run 2 L0E	Correlated
Decay model	–	–	–	–	1.9
Efficiency corrections	3.4	3.6	3.6	3.2	–
Normalisation modes	3.7	3.7	3.5	2.7	–
q^2 migration	–	–	–	–	2.0
m_{corr} cut efficiency	–	–	–	–	0.5
Fit model	–	–	–	–	5.2
Total uncorrelated	5.0	5.2	5.0	4.2	–
Total correlated	–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

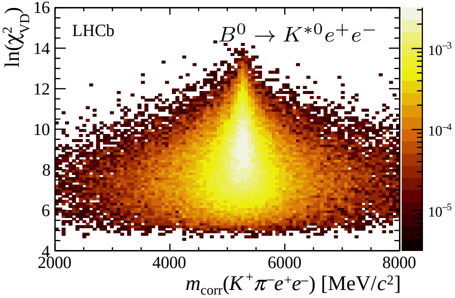
- Developed corrected mass m_{corr}
  - Missing energy evaluated from ratio of p_{T}

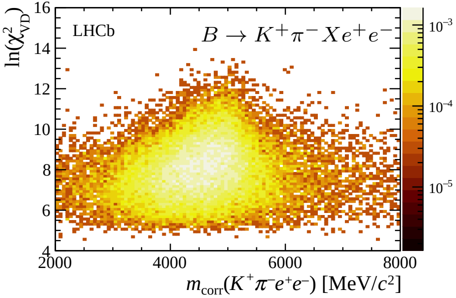
$$\alpha = \frac{p_{\text{T}}(K^+\pi^-)}{p_{\text{T}}(e^+e^-)} \quad \text{and} \quad p_{\text{corr}} = \alpha \cdot p_{e^+e^-}$$

- Discriminant between part. reco. backgrounds and signal

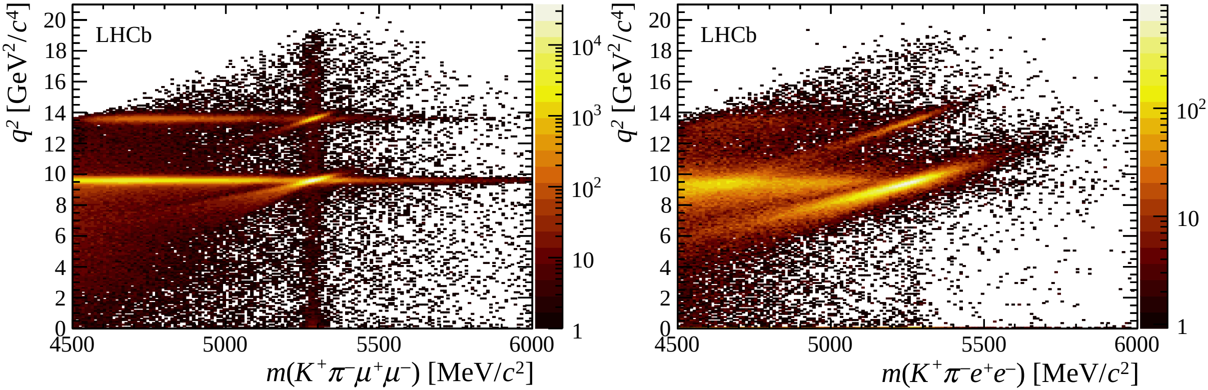
[JHEP 08 (2017) 055]





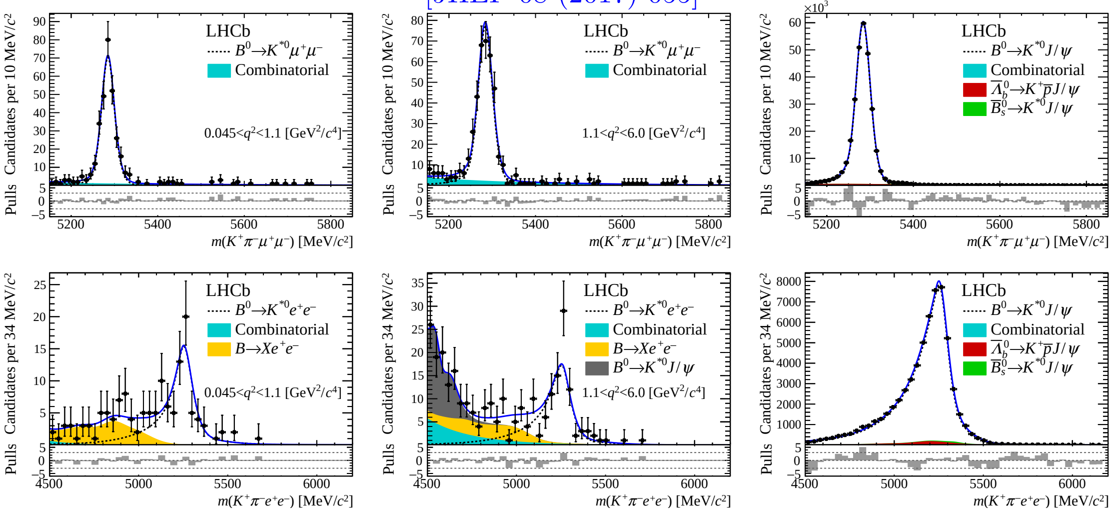


[JHEP 08 (2017) 055]



$R_{K^{*0}}$ Mass Fits

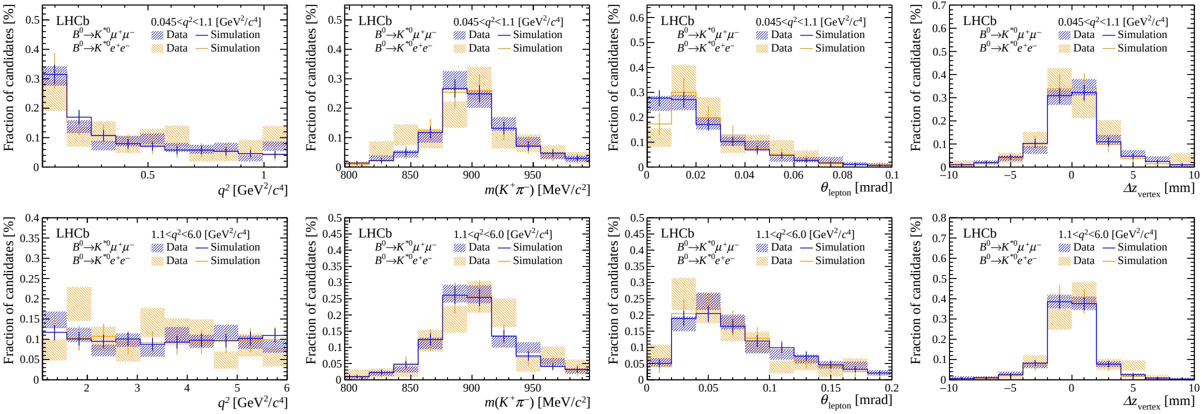
[JHEP 08 (2017) 055]



$R_{K^{*0}}$ Post Unblinding Checks

[JHEP 08 (2017) 055]

- Post-unblinding check background subtracted data and simulation agreement



$R_{K^{*0}}$ Uncertainties

[JHEP 08 (2017) 055]

- **Statistical** uncertainties:

Table: Yields for $B^0 \to K^{*0}\ell^+\ell^-$ modes

$\ell^+\ell^-$	$B^0 \to K^{*0}\ell^+\ell^-$ low	$B^0 \to K^{*0}\ell^+\ell^-$ central	$B^0 \to K^{*0}J/\psi\,(\ell^+\ell^-)$
$\mu^+\mu^-$	285^{+18}_{-18}	353^{+21}_{-21}	274416^{+602}_{-654}
e^+e^- (L0E)	$55\ ^{+9}_{-8}$	$67\ ^{+10}_{-10}$	$43468\ ^{+222}_{-221}$
e^+e^- (L0H)	$13\ ^{+5}_{-5}$	$19\ ^{+6}_{-5}$	$3388\ ^{+62}_{-61}$
e^+e^- (L0I)	$21\ ^{+5}_{-4}$	$25\ ^{+7}_{-6}$	$11505\ ^{+115}_{-114}$

- **Systematic** sources:

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7