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Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays with Run 1-2

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Annual meeting of the German LHCb groups (Theory and Experiment)

Aachen | 02.10.26

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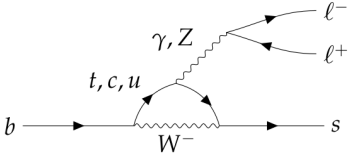
Introduction to Lepton Flavour Universality tests

- $b \to s\ell^+\ell^-$ transitions as probes of New Physics

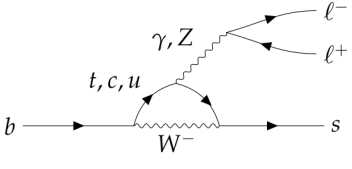


- Property of the SM: gauge boson couplings to leptons are independent of lepton flavour

→ Lepton Flavour Universality tests = null tests of the SM

Introduction to Lepton Flavour Universality tests

- $b \to s\ell^+\ell^-$ transitions as probes of New Physics



- Property of the SM: gauge boson couplings to leptons are independent of lepton flavour

→ Lepton Flavour Universality tests = null tests of the SM

- SM gauge boson couplings in tree-level decays: measurements in good agreement with unity
- LFU in b-meson decays ($B^0 \to K^{*0}\ell^+\ell^-$ and $B^+ \to K^+\ell^+\ell^-$) in good agreement with SM [LHCb-PAPER-2022-046]

- Exchange the spectator quarks for LFU tests: ($B^0 = |\bar{b}d\rangle \Rightarrow \Lambda_b^0 = |bdu\rangle$)
- Test for spin dependence of New Physics (b-meson spin = 0, b-baryon spin = 1/2)

→ Use decays of Λ baryons: $\Lambda_b^0 \to pK\ell^+\ell^-$

Strategy and previous analysis

- Measurement of inverse double ratio:
  $R_{pK}^{-1} = \frac{BR(\Lambda_b^0 \to pKe^+e^-)}{BR(\Lambda_b^0 \to pK\mu^+\mu^-)} \times \frac{BR(\Lambda_b^0 \to pKJ/\psi(\to \mu^+\mu^-))}{BR(\Lambda_b^0 \to pKJ/\psi(\to e^+e^-))}$
- Cancellation of uncertainties in double ratio

Goals:

Measure R_{pK}^{-1} with full Run 1 + 2016 + 2017 + 2018 and improved analysis strategy and tools

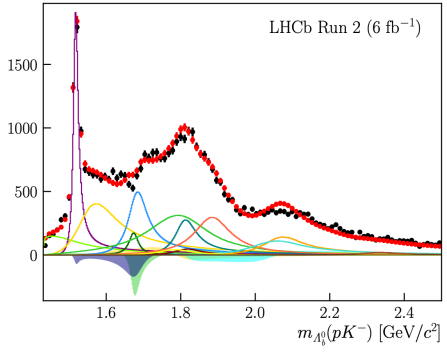
- Measure in two q^2 bins
  - Low bin: $0.1 < q^2 < 1.1\,\mathrm{GeV}^2/\mathrm{c}^4$
  - Central bin: $1.1 < q^2 < 6\,\mathrm{GeV}^2/\mathrm{c}^4$
  - Single low+central bin for more statistics.
- Additionally planned:
  - $R_{\Lambda(1520)}$ with low+central bins.

Blinding strategy: Only rare mode efficiencies will be blinded.

Previous analysis: [JHEP 05 (2020) 040]

- $R_{pK}^{-1} = 1.17^{-0.16}_{+0.18} \pm 0.07$
  in the range $0.1 < q^2 < 6\,\mathrm{GeV}^2/\mathrm{c}^4$
  and $m(pK) < 2600\,\mathrm{MeV}/\mathrm{c}^2$
- Data from Run 1 + 2016 ($4.7\,\mathrm{fb}^{-1}$)

[LHCb-PAPER-2023-036]



Overview of the selection

Trigger: L0I and L0L! categories, HLT1 AllL0/TrackMVA, HLT2 Topo{2,3,4}Body
Stripping: Bu2LLK_mmLine (muons) / Bu2LLK_eeLine2 (electrons)

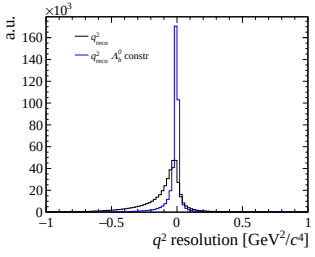
Preselection

- Track quality and subdetector acceptance
- Momenta cuts for alignment to calibration samples
- Exclusive vetoes to specific backgrounds
- Electron PID optimisation to suppress $h \to e$ misID
- Λ_b-constrained q^2 to reduce J/ψ leakage
- $m(pK)$ and HOP cut
- Removal of multiple candidates

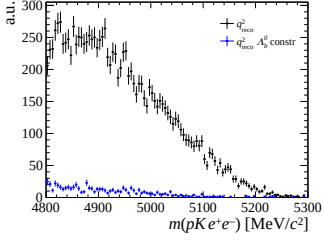
MVA selection

- Two BDTs with the same features, including hadron PID
- Trained to reject misID and combinatorial backgrounds

Resolution



J/ψ leakage



Simulation Corrections

Baseline: R_X correction chain

- Prior chain used to compute Kin&Mult weights

Particularities:

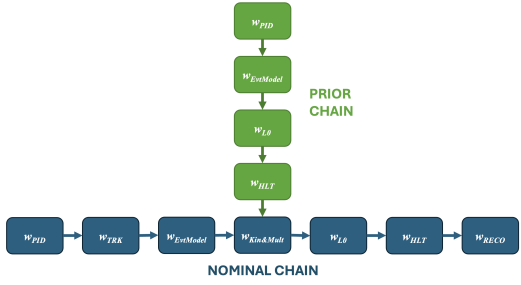
- Λ_b^0 kinematics, poorly reproduced
- L0 trigger: use weights from $B^+ \to J/\psi K^+$ from RX
- Event model: make use of available amplitude analyses in $\Lambda_b^0 \to J/\psi pK^-$

→ 1D $m(pK)$ corrections for rare mode

- Reco. corrections derived from $\Lambda_b^0 \to J/\psi pK^-$ with modified feature set: $\eta(\Lambda_b^0)$, $p_{\mathrm{T}}(\Lambda_b^0)$ $\chi^2_{\mathrm{vtx}}(\Lambda_b^0)$, $\chi^2_{\mathrm{vtx}}(J/\psi)$, $\chi^2_{\mathrm{IP}}(\Lambda_b^0)$, $\chi^2_{\mathrm{IP}}(J/\psi)$

Trigger alignment:

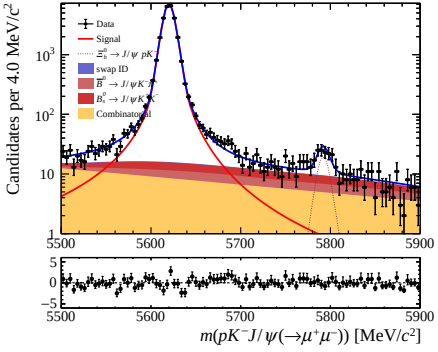
- Extra L0E trigger cut to account for L0 vs. offline ECAL energy calibration differences
- Align 2016 `Hlt1TrackMVA` to match data thresholds



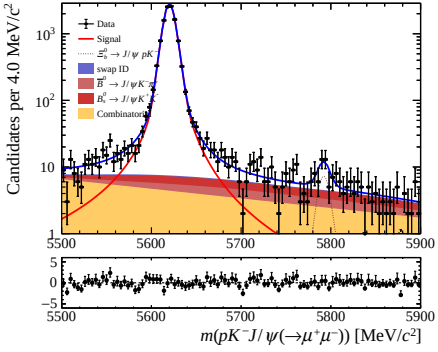
Mass fits in the J/ψ muon mode with J/ψ mass constraint

- Signal: DSCB+Gaussian, tails constrained in simulation
- Combinatorial: Floating exponential
- Residual hadron misID: `RooKeysPdf` for $B_s^0 \to KK\ell^+\ell^-/B^0 \to K^*\ell^+\ell^-$ and DSCB for $pK \leftrightarrow Kp$ swap with the yields constrained relative to the signal

2017+2018 L0M!



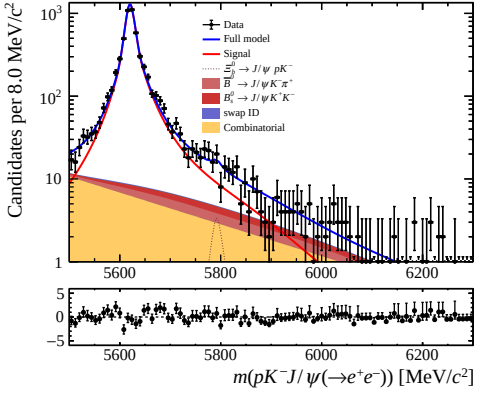
2017+2018 L0I



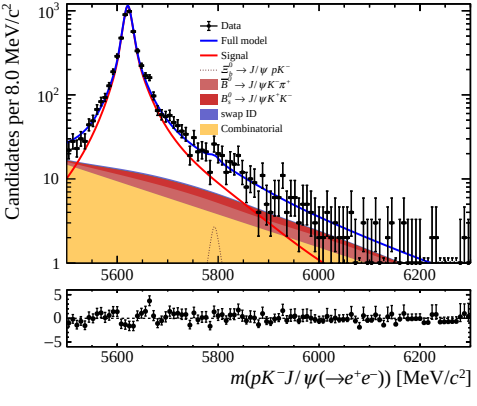
Mass fits in the J/ψ electron mode with J/ψ mass constraint

- Same model as in the muon mode

2017+2018 L0E!



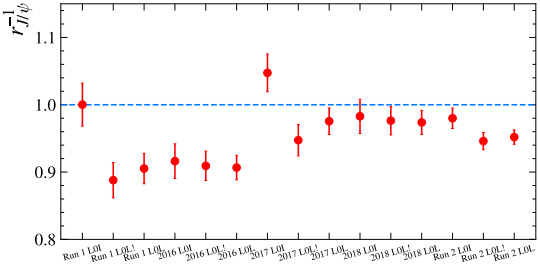
2017+2018 L0I

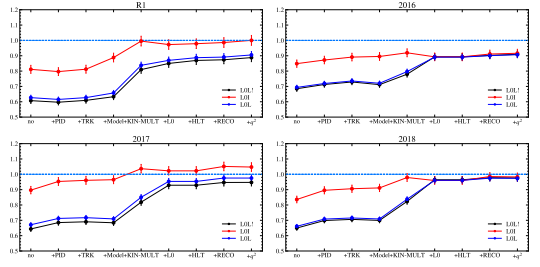


$r^{-1}_{J/\psi}$

- Cross-check for validating the efficiencies
  $r^{-1}_{J/\psi} = \frac{\frac{N}{\epsilon}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}{\frac{N}{\epsilon}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))} = 0.954 \pm 0.009$
- Fully corrected $r_{J/\psi}$ (only statistical uncertainties) for all datasets and trigger categories
- Significantly below unity in Run 1 TOS categories and 2016

→ Deviations are from different systematic sources, around $8\,\%$ in previous analysis





Evolution of $r_{J/\psi}$ when adding corrections →

$r^{-1}_{J/\psi}$

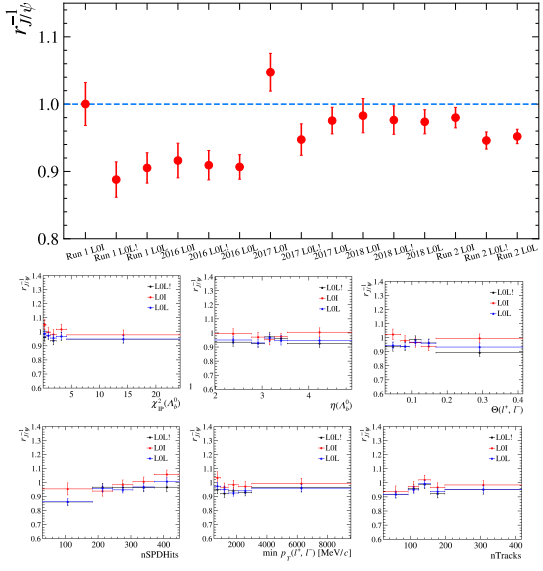
- Cross-check for validating the efficiencies

  $r^{-1}_{J/\psi} = \frac{\frac{N}{\epsilon}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))}{\frac{N}{\epsilon}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))} = 0.954 \pm 0.009$

- Fully corrected $r_{J/\psi}$ (only statistical uncertainties) for all datasets and trigger categories
- Significantly below unity in Run 1 TOS categories and 2016

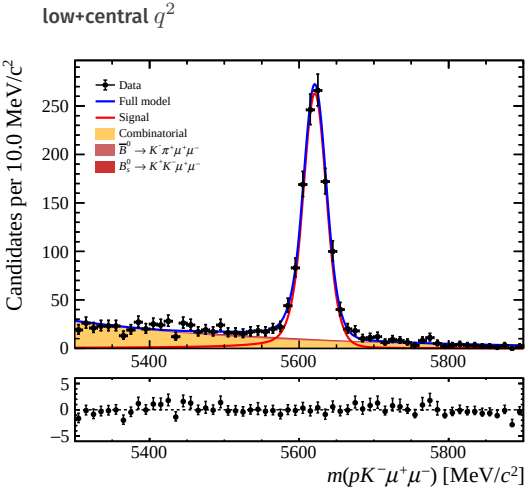
→ Deviations are from different systematic sources, around 8 % in previous analysis

Checked flatness of $r_{J/\psi}$ regarding kinematic and reconstructions variables →



Mass fits in the rare muon mode

- Rare muon fit of all datasets and trigger categories
- Same model as for J/ψ muon mode minus hadron swap component
- Yields:
  - low 355 ± 20
  - central 784 ± 32
  - low+central 1145 ± 37

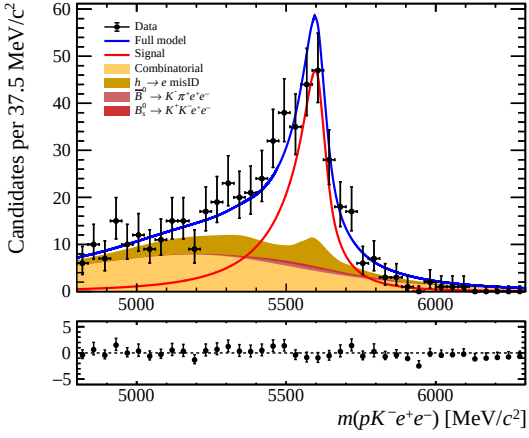


Mass fits in the rare electron mode

- Rare electron fit of all datasets and trigger categories
- Signal:
  - One DSCB is fitted per Bremsstrahlung category
  - Combined respecting their respective proportions in simulation
- $h \to e$ misID contribution estimated with Fail-to-Pass method
- HOP cut is sculpting the combinatorial background $\longrightarrow$ the following model is fitted to same-sign data:

  $f(m) = \frac{1}{1+e^{-a(m-m_0)}} e^{sm}$
- Yields:
  - low 102 ± 13
  - central 167 ± 17
  - low+central 260 ± 22

low+central q^2



Overview of most relevant systematics

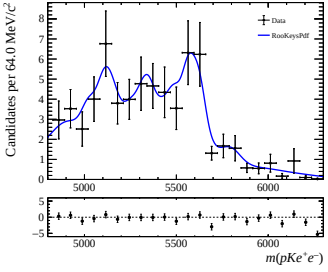
Fit model

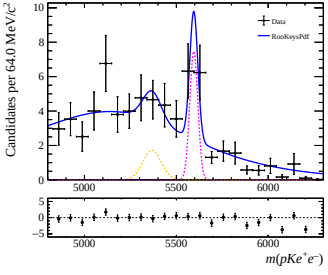
- Generate toys with alternative model, fit with nominal
- Largest effect:
  - Alternative shape for the $h \to e$ misID background
  - Adding part. reco. component $\Lambda_b^0 \to pK^-\pi^0 e^+ e^-$

Efficiencies

L0 trigger

Non-flatness of $r_{J/\psi}^{-1}$





Overview of most relevant systematics

Fit model

Efficiencies

- Limited statistics of the calibration samples
- Evaluated with bootstrapping technique

L0 trigger

Non-flatness of $r^{-1}_{J/\psi}$

Relative uncertainty given by the bootstrapping in %

Year	L0I	L0L	L0L incl.
Run 1	1.38	1.27	1.12
2016	0.67	0.60	0.51
2017	0.85	0.74	0.63
2018	0.89	0.75	0.65

Overview of most relevant systematics

Fit model

Efficiencies

L0 trigger

- Assumption in calibration of L0 efficiency:
  Signal of electron candidates in the ECAL are independent between them
- Test it by evaluating efficiency directly on the condition that the dielectron pair satisfies the L0Electron

Non-flatness of $r_{J/\psi}^{-1}$

Relative shift in the efficiency between the nominal L0E approach vs the combined di-electron.

Sample	Trigger	low [%]	central [%]	rare [%]
R1	L0E	-0.399	0.028	-0.075
	L0Einc	-0.327	0.143	0.015
2016	L0E	-0.289	-0.356	-0.342
	L0Einc	-0.458	-0.421	-0.428
R2p2	L0E	-0.220	-0.225	-0.222
	L0Einc	-0.398	-0.269	-0.306

Overview of most relevant systematics

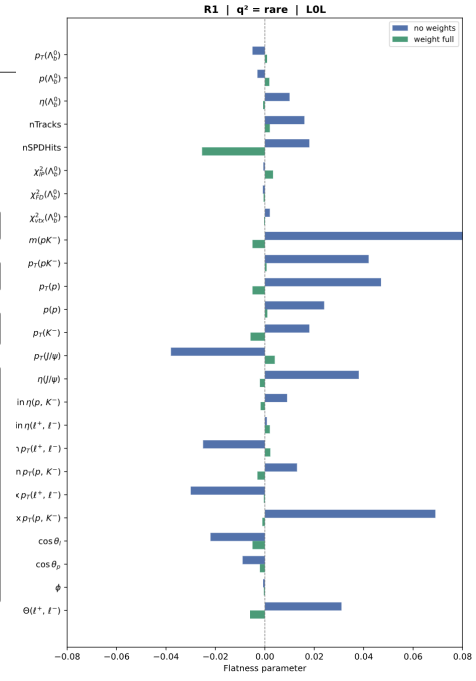
Fit model

Efficiencies

L0 trigger

Non-flatness of $r^{-1}_{J/\psi}$

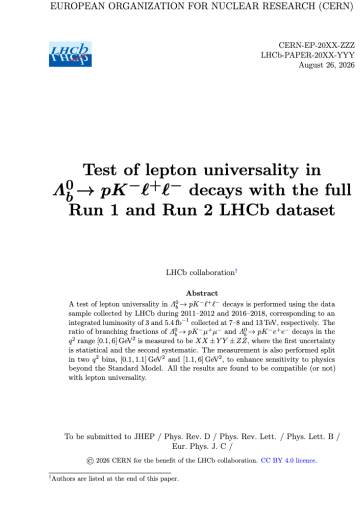
- Caused due to a bias in the efficiency calculation introduced by the simulation corrections
- Calculation of pseudo double ratio by replacing the rare mode yields with the efficiency-rescaled yields obtained in the J/ψ fit →flatness parameter
- Majority below $1\,\%$, largest outlier $8\,\%$



Summary and Outlook

- Presented LFU test with $\Lambda_b^0 \to pK\ell^+\ell^-$ decays
- Analysis is in RC review
- Finalising systematical uncertainties, plan to unblind soon
- Expected to improve statistical precision from $15\,\%$ to $9\,\%$

→ Efforts for LFU measurements are continuing in Dortmund with Run 3: See Gabriele's talk



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-20XX-ZZZ
LHCb-PAPER-20XX-YYY
August 26, 2026

Test of lepton universality in $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays with the full Run 1 and Run 2 LHCb dataset

LHCb collaboration[†]

Abstract

A test of lepton universality in $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays is performed using the data sample collected by LHCb during 2011–2012 and 2016–2018, corresponding to an integrated luminosity of 3 and 5.4 fb^{-1} collected at 7–8 and 13 TeV, respectively. The ratio of branching fractions of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ and $\Lambda_b^0 \to pK^-e^+e^-$ decays in the q^2 range $[0.1, 6]$ GeV^2 is measured to be $XX \pm YY \pm ZZ$, where the first uncertainty is statistical and the second systematic. The measurement is also performed split in two q^2 bins, $[0.1, 1.1]$ GeV^2 and $[1.1, 6]$ GeV^2, to enhance sensitivity to physics beyond the Standard Model. All the results are found to be compatible (or not) with lepton universality.

To be submitted to JHEP / Phys. Rev. D / Phys. Rev. Lett. / Phys. Lett. B / Eur. Phys. J. C /

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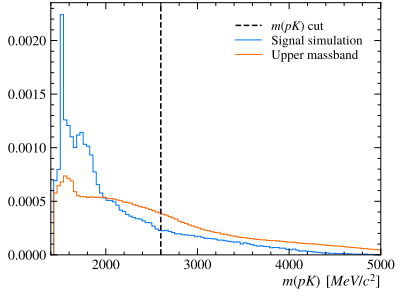
[†]Authors are listed at the end of this paper.

Backup

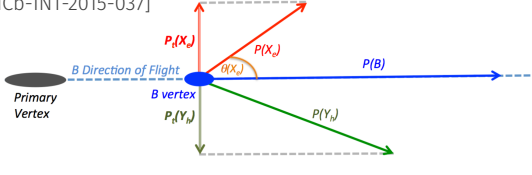
$m(pK)$ and HOP cut

- New Stripping lines select larger $m(pK$ range than in previous analysis
- But no significant signal gain is observed, while combinatorial background increases a lot
- Confirmed in recent measurement of $\Lambda_b^0 \to pK\mu^+\mu^-$ [LHCb-PAPER-2024-024]
- Cut: $m(pK) < 2600\,\text{MeV/c}^2$



- Semileptonic cascade Λ_b decays with excited Λ_c resonances are a poorly known background polluting the lower-mass sideband.
- The HOP variable $\alpha_{\text{HOP}} = p_T(pK)/p_T(ee)$ quantifies missing energy in the final state
- Corrected momentum $p_{\text{corr}} = \alpha_{\text{HOP}} \cdot p(ee) \longrightarrow$ Corrected mass $m_{\text{HOP}}(\Lambda_b)$
- $m_{\text{HOP}}(\Lambda_b)$ is used in a 2D cut against $\log_{10}\chi^2_{\text{FD}}(\Lambda_b)$: $m_{\text{HOP}}(\Lambda_b^0) > \alpha_{\text{HOP}} + b_{\text{HOP}} \cdot \log_{10}\chi^2_{\text{FD}}(\Lambda_b^0)$

[LHCb-INT-2015-037]



Background vetoes

Decay	Veto	Cut
All	$B^+ \to K^+\ell\ell$ + random track	$\lvert m(K\ell\ell) - 5279\,\text{MeV}\rvert > 100\,\text{MeV}$ $\lvert m(p_{\to K}\ell\ell) - 5279\,\text{MeV}\rvert > 100\,\text{MeV}$
All	$\phi(1020) \to KK$ from $B^0_{(s)} \to K^+K^-\ell\ell$	$\lvert m(p_{\to K}K^-) - 1020\,\text{MeV}\rvert > 12\,\text{MeV}$
All	Pion-lepton misidentification from Λ_c^+ decays	$m(pK\ell) > 2320\,\text{MeV}$ $m(p_{\to K}K^-_{\to p}\ell^+) > 2320\,\text{MeV}$
All	$\Lambda_b^0 \to pD^0\ell^-\nu$ with subsequent $D^0 \to K^-\pi^+$	$\lvert m(K^-\ell^+_{\to\pi}) - 1865\,\text{MeV}\rvert > 20\,\text{MeV}$ $\lvert m(p^+_{\to K}\ell^-_{\to\pi}) - 1865\,\text{MeV}\rvert > 20\,\text{MeV}$
All	Clone tracks	$\theta(p_1, p_2) > 1\,\text{mrad}$

BDT - Overview

Two goals:

1. Reduce combinatorial background
2. Reduce hadron misidentification backgrounds

BDT setup:

- 21 kinematic and topological features + corrected Proton and Kaon ProbNN{pi,K,p}
- Trained on the rare mode, applied to both
- Trained BDTs for electron and muon modes
- Separate BDT for data taking period: 2011+2012, 2016 and 2017+2018

BDT for combinatorial backgrounds:

- Signal proxy: simulation of the rare mode $\Lambda_b^0 \to pK\ell^+\ell^-$
- Proxy for combinatorial backgrounds: upper sideband data with $m(pK\ell^+\ell^-) > 5825\,\mathrm{MeV/c^2}$

BDT for misidentification backgrounds:

- Signal proxy: simulation of the rare mode $\Lambda_b^0 \to pK\ell^+\ell^-$
- Proxy for misidentification backgrounds: simulation of $B_s^0 \to KK\ell^+\ell^-$ and $B^0 \to K^*\ell^+\ell^-$

BDT - Cut optimization in the muon mode

Figure of merit:

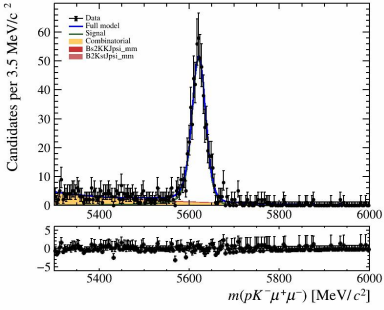
- Significance is chosen as the metric
  $FOM = \frac{S}{\sqrt{S+B}}$
- 2D scan over set of cut values for the misID BDT and combinatorial BDT

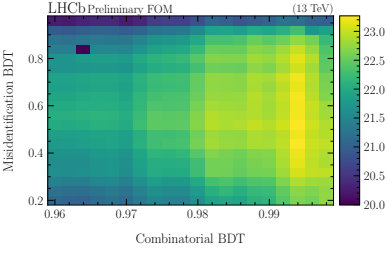
Signal yield:

- Calculated with signal efficiency extracted from MC relative to reference fit

Background yield:

- Yield of combinatorial background from sidebands + Estimate misID contribution by modelling it in the fit





BDT - Cut optimization in the electron mode

Figure of merit:

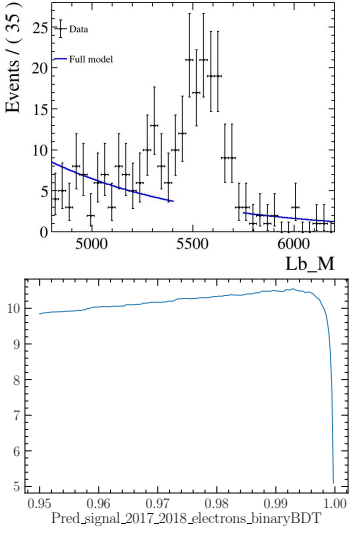
- Same Figure of Merit, but different strategy needed
- Due to low statistics ⟶ instable fits
- First step: fix misID BDT cut relative to muon mode
  - Get signal efficiency of misID BDT in muon mode
  - Pick cut with the same efficiency in electron mode
- Second step: 1D scan over set of cut values for combinatorial BDT

Signal yield:

- Calculated with signal efficiency extracted from MC relative to reference fit **from the muon mode**

Background yield:

- Yield of combinatorial background from fit to sidebands



$R_{\psi(2S)}$

$$R^{-1}_{\psi(2S)} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\psi(2S)(\to e^+e^-))}{\mathcal{B}(\Lambda_b^0 \to pK^-\psi(2S)(\to \mu^+\mu^-))} \times \frac{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))}$$

- Validate double ratio strategy.

Dataset	Result
Run 1	0.85 ± 0.15
2016	1.07 ± 0.14
2017 & 2018	0.879 ± 0.080

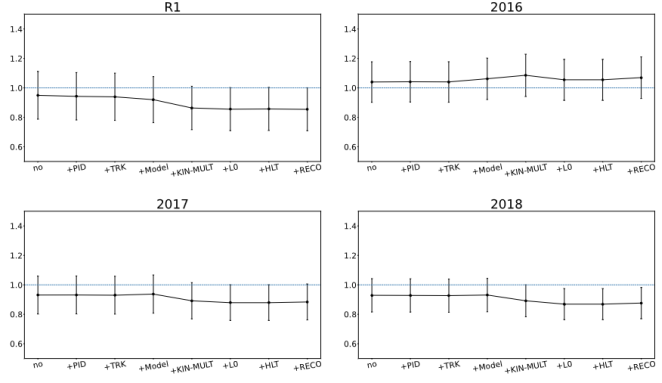
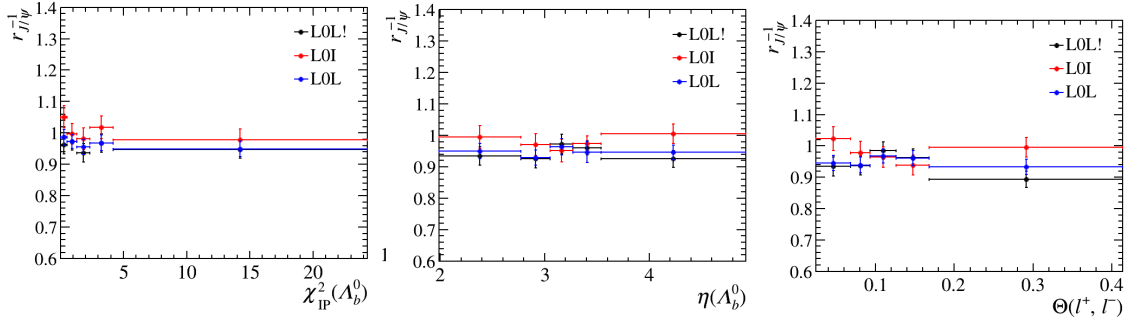


Table of $r^{-1}_{J/\psi}$ values

Year(s)	Category	$r^{-1}_{J/\psi}$ non corrected	$r^{-1}_{J/\psi}$ corrected
Run 1	L0I	0.811 ± 0.026	1.000 ± 0.032
	L0L!	0.607 ± 0.018	0.888 ± 0.026
	L0L	0.627 ± 0.016	0.905 ± 0.023
2016	L0I	0.849 ± 0.024	0.916 ± 0.026
	L0L!	0.685 ± 0.016	0.909 ± 0.022
	L0L	0.694 ± 0.014	0.907 ± 0.018
2017	L0I	0.897 ± 0.024	1.047 ± 0.028
	L0L!	0.644 ± 0.016	0.947 ± 0.023
	L0L	0.671 ± 0.014	0.976 ± 0.020
2018	L0I	0.836 ± 0.022	0.983 ± 0.025
	L0L!	0.650 ± 0.014	0.976 ± 0.021
	L0L	0.661 ± 0.012	0.974 ± 0.018
Run 2	L0I	0.857 ± 0.013	0.980 ± 0.015
	L0L!	0.658 ± 0.009	0.946 ± 0.013
	L0L	0.673 ± 0.008	0.952 ± 0.011

Flatness check of $r_{J/\psi}$

- $r_{J\psi}$ should be independent of the reconstruction and across the phase space
- → $r_{J\psi}$ measurement performed as a function of relevant variables
- No significant trends have been found
- Overview of a chosen set of variables in Run 2



Flatness check of $r_{J/\psi}$

- $r_{J\psi}$ should be independent of the reconstruction and across the phase space
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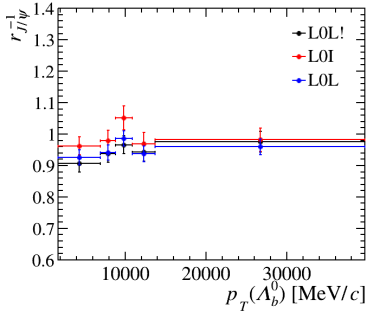
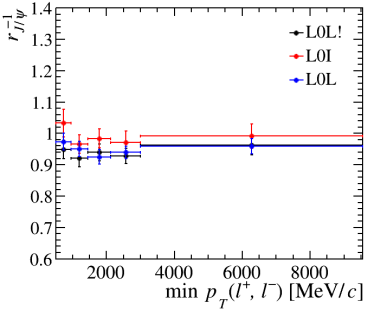
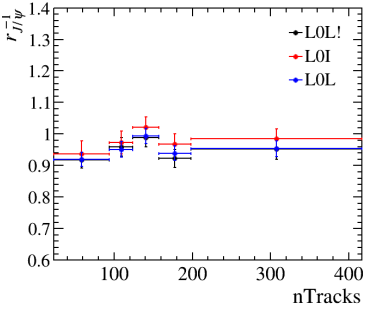
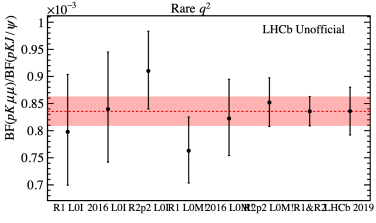
- Overview of a chosen set of variables in Run 2

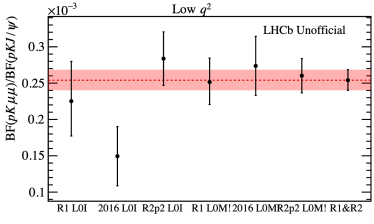


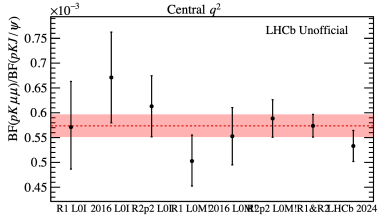
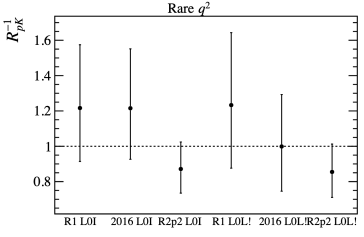
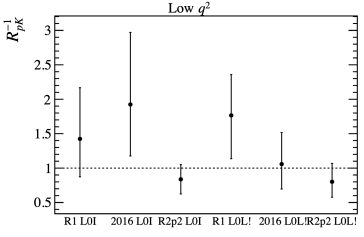
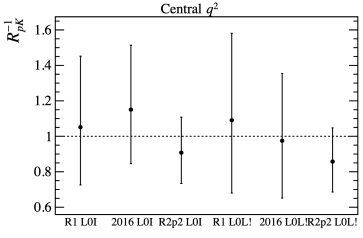




Compatibility check of $BR(\Lambda_b^0 \to pK\mu^+\mu^-)$







Consistency check of blinded R_{pK}^{-1}